HSE

Health and Safety Executive

Evaluation of current rigging and dismantling practices used in arboriculture

Prepared by **Treevolution** and **Brudi & Partner TreeConsult**
for the Health and Safety Executive and
the Forestry Commission 2008

RR668
Research Report

Health and Safety Executive

Evaluation of current rigging and dismantling practices used in arboriculture

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This report presents the results of a comprehensive study into a number of topics related to rigging operations used in the dismantling of trees in the UK. The information it contains should enable the arboricultural industry to determine good practice in:

- carrying out risk assessments prior to dismantling a tree;
- planning and organising rigging operations; and
- selecting measures to mitigate against risks and accidents.

The project received additional funds from the Hyland John's Grant Programme of the TREE Fund (Grant No 06-HJ-05), in order to extend the investigation on the load-bearing capacity of branches beyond the scope of the original project plan.

This report and the work it describes were jointly funded by the Health and Safety Executive (HSE) and the Forestry Commission (FC). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE or FC policy.

HSE Books

First published 2008

ACKNOWLEDGEMENTS

This report describes work undertaken by a number of people, principal among them being Andreas Detter (*Brudi & Partner TreeConsult, Germany*), Chris Cowell (*TreePartner, UK*), Paul Howard (*ArBO, Germany*) and Liam McKeown (*Treevolution Ltd, UK*). However, the work would not have been possible without contributions from many other arborists, consultants and researchers from around the world.

Both the pilot study and the present research could not have been undertaken without the support of Erk Brudi and Frank Bischoff (*Brudi & Partner TreeConsult, Germany*), who provided the initial budget and freed up the time required by their partner to undertake the work.

Chapters 1, 3 and 4 represent the results of close collaboration between a number of arborists, with major inputs from Chris Cowell (*TreePartner, UK*), Richard Allmond and Phil Watkin (both of *Treevolution Ltd, UK*) and Mark Bridge (*Treemagineers, UK*), the latter providing the excellent technical illustrations.

Dwayne Neustaeter’s work (which provided an introduction to the system of coloured flag indicators) was an inspiration for Chapter 2. Erk Brudi (*Brudi & Partner TreeConsult, Germany*) improved this chapter by performing a studied and detailed review of its contents.

Chapter 6 benefited considerably from previous work on log weights undertaken by Uwe Thomson (*Baumpflege Thomsen, Germany*) and Klaus Schöpe (*Germany*), both of whom kindly gave permission for their results to be used. Volker Genenz (*Germany*) also provided valuable data from his original publication in 1977.

Ken Palmer and Michael Tain (*ArborMaster Training, USA*) provided valuable data to support the work described in Chapter 7, and also provided background information to facilitate the data analysis. Randy Nulle, Rafael Chou and Howard Wright (*Samson Rope Technologies, USA*) made significant contributions to data collection and evaluation. The rope manufacturers *Edelmann & Ridder* (Germany) and *Teufelberger* (Austria) provided laboratory facilities and manpower for rope testing. Dan Pockmann (*Bucaneer Ropes*) sponsored the project by providing the ropes used in the preliminary laboratory studies and field tests.

The field tests described in Chapter 8 were carried out in co-operation with Elisabeth Eberl and Christian Höhne, two students who were in the process of completing courses in the studies of forestry and landscape management respectively (work undertaken in the course of this project formed part of their final submissions). Prof. Peter Glos and Dr. Georg Gaede (*Institut für Holzforschung, Munich*) provided laboratory facilities, supported the determination of density and moisture content of specimens, and enabled the calibration of the load sensors. Numerous discussions with Ken Palmer (*ArborMaster Training, USA*), his involvement in the development of the specialist software Rigging 1.0, and the accumulated knowledge base of ArborMaster Training, all provided an essential source of both information and inspiration for Chapter 8.

Jens Heinrich (*CCC Campus Computer Center*) provided the Utilius® EasyInspect computer software free of charge. W. Schröppel (*Partner GmbH Baumpflege*) sponsored the hydraulic lift used for video recording field tests. The custom-made load sensors were developed with support from Sigmund Glaser (*HBM*), who also provided data acquisition equipment. Trees were provided courtesy of *Deutsche Bundeswehr, Standortverwaltung Fliegerhorst Erding*, with the kind permission of Erhardt Worofka (*Staatliches Hochbauamt Freising*). Mike Neuheimer gave generously of his time and provided numerous helpful suggestions.

The published work of the late Dr. Peter Donzelli provided particular inspiration to the project. Sharon Lilly donated some of Peter's unpublished notes that originated from studies of drop tests funded by the TREE Fund's Hylands John Grant Programme. Ken Palmer (*ArborMaster Training, USA*) was able to provide video footage and other information to support the notes.

The initial studies of the kinematics of rigging operations would not have been possible without the technical input and constant support of Prof. Klaus Schneider (*Universität der Bundeswehr, Neubiberg*), who provided laboratory facilities, manpower, and support for data evaluation. Dr. Norbert Praxl (*DeMotu*) aided the understanding of the effects of rigging forces on a climber's body through fruitful discussions and a simulation based on the test data. Paul Howard and Oriol Campaña (*ArBO Baumpflege*) donated both time and effort. Johannes Bilharz and Erich Rotheimer (*Freeworker Baumpflegefachhandel oHG*) were always willing to take part in discussions, and supported the project by donating items of arborist equipment.

Numerous arborists provided (or gave permission for the use of) drawings, photographs and other illustrations included in the report. Other colleagues and friends supported the work by sharing information and ideas in fruitful discussions, while there were others who helped the project by proof-reading sections of the report and providing comments based on their specific areas of expertise. Phil Watkin and Julia Harding (*Treevolution Ltd, UK*) shouldered the enormous task of editing the work of numerous authors based in both the UK and Germany.

Notwithstanding any previous mentions in these acknowledgements (and with apologies to anyone who has been inadvertently omitted), the authors would especially like to thank:

> Mark Adams, Richard Allmond, Scott Baker, Edgar Berger, Andreas Born, Mark Bridge, Malcolm Chaffer, Julian Dunster, Mike Greer, Ken James, Professor Heinrich Kreuzinger, Sharon Lilly, Dirk Lingens, Professor Frieder Luz, Guy Meilleur, Thomas Reuschel, Lars Rodrigues, Wolfgang Scholz and Professor Hanns-Christof Spatz.

Finally, Frances Hirst, Alison Richards and Val Jones of the Health and Safety Executive, and, last but not least, James Dewar of the Forestry Commission, must all be thanked for the co-operation, enthusiasm and patience that they displayed throughout the course of the project.

CONTENTS

EXECUTIVE SUMMARY

INTRODUCTION

Andreas Detter (*Brudi & Partner TreeConsult, Germany*), Chris Cowell (*Treepartner, UK*), Paul Howard (*ArBO, Germany*) and Liam McKeown (*Treevolution Ltd, UK*) have prepared this report for the Health and Safety Executive (HSE) and the Forestry Commission (FC). The report presents the results of a comprehensive study into a number of topics related to rigging operations used in the dismantling of trees in the UK. The information it contains should enable the arboricultural industry to determine good practices in:

- carrying out risk assessments prior to dismantling trees
- planning and organising rigging operations
- selecting and applying measures to mitigate against risks and accidents

In addition to funding provided by the HSE and the FC, the project received additional funds from the Hyland John's Grant Programme of the TREE Fund (Grant No. 06-HJ-05), in order to extend the investigation on the load-bearing capacity of branches beyond the scope of the original project plan.

Arboricultural work is physically demanding. It is often carried out at height and carries a high risk of injury. HSE estimates that fatal and major incidence rates for arboriculture are at least double those of the construction industry. Recent analysis of arboricultural accidents has shown that just under 10 % of these are due to high falls, a further 6 % are due to low or unspecified falls, and another 6% are due to uncontrolled swings in the tree.

When dismantling a tree, a variety of rigging techniques can be used to move cut sections. These techniques can range from using a single rope, wrapped round the trunk of the tree in order to add friction control to the descent of a cut section, to the use of more sophisticated equipment such as rigging blocks, pulleys and slings and other complex specialist devices. Concerns have been raised that some practitioners in the industry may be using equipment and techniques without a full appreciation of either the forces generated or the limitations of the hardware and/or tree. The loads generated are not easy to quantify and can vary dramatically, depending not only on the mass of the section and the rigging set-up, but also on tree species and condition.

Preliminary research funded by the Forestry Commission (FC), which included an initial assessment of rigging equipment, working methods and training standards used in dismantling operations in the UK arboricultural industry, identified that further investigations were necessary. The initial assessment was completed in November 2005 with the publication of a report entitled *An initial assessment of rigging equipment, work methods and training standards used in dismantling operations in the UK*. The HSE, supported by the FC, subsequently funded the additional research now described in this report.

BACKGROUND

The report presents the results of research carried out into a number of aspects of ‘rigging’ as applied to tree work operations in the UK. In this context, rigging is the application of specialised tools and ropes by tree workers, in order to lower cut sections of trees to the ground in a controlled manner. Rigging operations can also be referred to as dismantling operations, although the term ‘dismantling’ normally covers all methods of bringing cut sections of a tree to the ground, including the free falling of sections (i.e. allowing cut sections to fall to the ground). Rigging methods are normally adopted where it is not possible to allow the cut sections to fall freely, either because of the danger of hitting unwanted targets on the ground, or because of the difficulty of extracting the fallen timber from the target area (i.e. the area in which the timber would otherwise fall).

Rigging operations are normally undertaken by a team of tree workers, with one worker positioned in the tree, working in conjunction with one or more other workers on the ground. In simple terms, the worker in the tree is responsible for ‘rigging’ the section of timber to be cut, whilst the other worker(s) assists in lowering the ‘rigged’ section to the ground after it has first been cut.

Over recent years, rigging methods used in the UK have developed from ‘traditional’ techniques, which utilised ropes in conjunction with only the natural features of the tree, to ‘more advanced’ techniques, which use a wide variety of tools and equipment designed specifically for the purposes of rigging. Many of the newer techniques have been imported from other countries, in which they were originally developed and practised, while much of the specialised equipment has been adapted from other areas of use (e.g. mountaineering).

Due to the way in which the newer methods have been adopted, the tree work industry may not have developed the most satisfactory approach to their use. In particular, a number of engineering companies have developed products for use in rigging operations that have not, as yet, been incorporated into industry literature. Furthermore, the arboricultural industry in the UK has complex training and certification systems, developed primarily as a result of health and safety legislation, which currently do not necessarily provide the most suitable responses to the new techniques.

OVERALL OBJECTIVES

The research project was primarily concerned with investigating specific aspects of arboricultural rigging, with the overall objective of establishing information that could assist in the introduction of improved standards of operation and safety throughout the arboricultural industry.

In particular, the research project investigated issues relating to:

- the carrying out of risk assessments prior to undertaking dismantling/rigging operations
- the planning and organising of rigging operations
- means by which risks might be reduced/minimised and accidents prevented
- the selection and configuration of appropriate work equipment
- the assessment of safety factors in different rigging scenarios

The ultimate objective of the research was to provide information relating to rigging operations that can feed through, by appropriate mechanisms, to personnel involved in rigging operations in the arboricultural industry, in such a way that standards are improved and, correspondingly, a reduction in accidents/injuries is achieved.

SPECIFIC AIMS

The specific aims of the project included the production, or development, of:

- a checklist of points that should be considered prior to undertaking a rigging operation
- a working description of the methodology of, and points to be considered when carrying out, a visual tree inspection prior to undertaking a rigging operation
- flow diagrams charting the items to be considered, and the decisions to be taken, when determining a safe strategy and techniques for dismantling a tree
- information in tabular form that can be used to estimate typical weights of green timber in a variety of lengths and diameters for different species of tree commonly found in the UK
- a means of identifying the forces generated by a variety of different rigging scenarios
- information that can be used to identify the maximum forces sustainable for a range of rope diameters
- information that can be used to identify the size of anchor point required for rigging systems using different rope diameters, for a range of common UK tree species
- means of identifying, through the use of line drawings, photographs or otherwise, aspects of rigging including:
    - how pulleys share loads
    - how slings share loads
    - correct configurations of installed rigging equipment
    - correct configurations of knots used in rigging

METHODOLOGY

Three main methods were adopted in pursuit of the stated aims and objectives of the project, namely:

- identification, collection and collation of information and/or data from previously published sources
- field studies, carried out in the vicinity of Munich, Germany
- evaluation of laboratory studies at the University of the Federal Army, Neubiberg, Germany

For some aspects of the project, extensive reviews of the available literature were carried out. Where required, such reviews were carried out simultaneously in the UK and Germany, involving accessing publications from Europe, North America and Australia. Published data on the properties of green wood and trees was collected from as many sources as possible, and collated to provide an up-to-date database of information.

In the case of rigging equipment, data on the material properties of both cordage and hardware items was collected from manufacturers of internationally available products originating from within the UK, France, Germany and America.

In the pursuit of other aims of the project, field studies were carried out on real trees, which were subject to scientific data collection and the recording of events using video techniques. The results of these tests were evaluated by a team of engineers and arborists. Other tests were carried out under strict laboratory conditions, so that the process details could be more accurately monitored, and detailed measurements could be taken of parameters affecting the forces generated in simulated rigging operations.

TOPICS COVERED

The main topics covered by the research project, for which in-depth information and discussion is included in the main body of the report, include:

- managing a rigging operation
- visual tree inspection
- safe rigging strategy and systems
- rigging hardware, cordage and textile components
- bearing capacity of trees
- estimating the weight of sections
- strength loss in cordage
- forces generated in rigging operations

KEY CONCLUSIONS

The following list covers the key conclusions derived from the research:

- The hazards involved in rigging, and the potential consequences for the climber, are significantly greater in number, and higher in risk, than those arising in most other arboricultural operations. Therefore, in order to undertake operations safely, a different level of experience, training and individual work planning is also required.
- With regard to a prospective rigging operation, the visual inspection of the tree forms an essential part of safety considerations and work planning.
- Correctly assessing the severity of visible damage with regard to rigging loads, or detecting hidden weaknesses in trees, requires both experience and specialist knowledge. Specialist training is necessary to develop the skills of arborists in visual tree inspection. In particular, guidance is required on which symptoms may indicate that a tree really does have the potential to fail during a prospective rigging operation.
- The ability to differentiate between the following three types of damaged trees requires profound knowledge and training, but is essential for arborist safety:
    - a tree that is still safe to climb and safe to rig
    - a tree that is safe to climb (considering the forces likely to arise in an arrested fall or slip), but not safe to be rigged (taking into account the forces generated in a worst-case loading scenario)
    - a tree that is not safe to either climb or rig

- Besides considering the tree itself, the development of a safe rigging strategy should also include consideration of the strengths and properties of the equipment used, such as ropes, slings, pulleys and friction devices. The condition of the equipment (age, wear and damage), and the specific way it is intended to be used in a rigging system, can alter its load-bearing capacity. At the same time, the specific configuration of a rigging system will determine the load its components will be exposed to.
- When considering rigging operations, safety considerations should always be based on a worst-case scenario.
- In order to ensure that any safety assessment errs on the side of caution, sufficient factors of safety must be incorporated in any calculations. Based on the results of the studies carried out to date, it is suggested that a factor of safety of 1.5 should be generally applied to calculations of anticipated loads in rigging operations and the strengths of stems and branches used as temporary anchor points in a tree.
- The selection of rigging strategies should always strive to avoid shock loading of the rigging components.
- There is a lack of proper user instructions and load rating information for many rigging components commonly used in arboriculture. It is essential that users are equipped with the required instructions and load ratings, in order to ensure that the products concerned can continue to be deployed safely in arboricultural rigging operations in the future.
- The selection of an appropriate anchor point in a tree requires not only a good work plan, but also an ability to correctly assess the load-bearing capacities of tree stems and branches. Whilst it is not currently possible to provide arborists with charts or tables of minimum diameters of branches required to sustain rigging operations, knowledge of the specific strengths of branches of individual species may assist practitioners in making better assessments of the bearing capacities of potential anchor points.
- Weight estimations for more or less regularly shaped logs (conical or cylindrical) can be performed by using reference charts, diagrams and/or worksheets. An illustration of a possible worksheet for making such estimations is included in the report, and a worked example is appended. On the other hand, consistently accurate weight estimates are not currently possible for irregularly shaped logs or crown sections.
- The shock loading of standard rigging systems with logs of great mass will increase the likelihood of damage to the rigging components, and inevitably shorten their potential working life. As a precaution, cordage that has been shock loaded significantly by heavy loads during a snubbing-off process, may very well need to be removed from service immediately afterwards.
- In training and education, the use of specialised software (such as Rigging 1.0 and RescueRigger 6.0) may be a valuable way of making arborists sensitive to the forces generated in rigging operations, particularly relating to shock loading scenarios and the dissipation of forces in a rigging system.
- Arborists should always include the possibility of unexpected shock loading, and its potential consequences, in any work plan that they develop for a rigging operation. This can be done, for example, in the following ways:
    - by careful system design, including the incorporation of appropriate correctly configured components (in order to minimise the likelihood of accidental shock loading occurring)

  - by cutting shorter sections, and using appropriate cutting techniques (in order to reduce the magnitude of the forces that equipment, tree and climber are exposed to)
  - by proper work positioning, communication and site organisation (in order to prevent injuries and other consequential incidents arising from an unexpected failure).
- It is recommended that rigging systems should be designed so that the rope is the weakest link. In the case of failure of an item of equipment other than the rope, the energy stored in the intact rope could otherwise turn any failed hardware component into a deadly projectile. That is not to say that the recoil of a failed rope is without risk, but it may well be the lesser of two evils.

PROPOSALS FOR PUBLICATIONS/DISSEMINATION OF INFORMATION

As part of the overall study, consideration was given to ways of ensuring that information can be made readily available to practising arborists. The extent to which the awareness of rigging techniques, and the body of knowledge relating to them, is developing, indicates a pressing need for a mechanism whereby arborists can be updated with regard to current good practice. It is proposed that an Arboriculture and Forestry Advisory Group (AFAG) working group review the findings of the research with a view to proposing the best way to make the findings available to the industry. This is likely to be through:

- the development of a carefully designed and evaluated checklist, capable of being revised appropriately as practices and procedures change, which could be used to progress rigging work from the initial planning stage through to its completion.
- the development of a series of worksheets or *aides-mémoire* that could be made available to practising arborists, covering such topics as:
  - aids to visual tree inspection
  - establishing a safe strategy for carrying out a rigging operation
  - selecting an appropriate rigging technique
  - estimating the weights of sections
- a publication incorporating all of the available arboricultural dismantling techniques, in a way that indicates fully, and without bias, their relative merits, and places them in the context of current requirements arising from legislation. Such a document would include information on at least the free falling of sections, rigging operations, use of cranes and mobile elevated work platforms (MEWPs), and on any other dismantling techniques that might be considered to be appropriate for use by the industry.
- a detailed publication relating specifically to arboricultural rigging that can serve as an operational manual for practising arborists. Such a publication might be entitled *A Guide to Good Rigging Practice* and published alongside the currently existing A *Guide to Climbing Practice* (published by the Arboricultural Association), which already serves as an operational manual for arborists engaged in general tree climbing activities. The report contains a detailed listing of topics suggested for inclusion in such a publication.
- dissemination of information included in the report through the publication of separate, more specific articles, or via other educational material or media, aimed at practising arborists.

FURTHER WORK

The work carried out during the research project raised a number of questions that could be worthy of further investigation. These include:

Characteristics of rigging equipment

- What are the mechanical properties (tensile strength and rope modulus) of used arborist rigging ropes?
- How and to what extent does damage like abrasion, cut strands or melted fibres influence the tensile strength and stiffness of arborist rigging lines?
- What constitutes an adequate test for simulating the loading of arborist ropes in a worst-case scenario?
- Can reference values be determined for ‘cycles to failure’ of different arborist rigging ropes exposed to shock loads typical of a worst-case rigging scenario?
- What are the dynamic (not static) friction coefficients of different arborist blocks, at different levels of load and speed of rotation?
- Can the figures for strength of knotted lowering lines be statistically verified, eventually adding other knot configurations and an evaluation of knot stability in different loading directions?

Properties of trees and tree sections

- What are the strength characteristics of branches, used as anchor points, in other tree species than those so far tested?
- Are the figures for the strength of branch unions/crotches suitable for application to branches that are equivalent in size to those typically selected as anchor points? (Only one recent study actually tested samples of a size typical of potential anchor points i.e. greater than 8 cm diameter.)
- Are there differences in the bearing capacities of living branches between quasi-static loading and the rapid (shock) loading such as occurs in a worst-case rigging scenario (snubbing-off logs)?
- What are the masses of major branches and crown sections; what are suitable form factors for estimating such masses; and how can the positions of the centres of gravity of such structures be effectively determined (e.g. in top sections of conifers, with or without cones)?

Rigging and dismantling techniques

- What are the advantages and disadvantages of different rope access systems that might be used during rigging operations? Specifically, what is the best position for an arborist to adopt whilst cutting a section? How can movement in rigging and climbing anchor points best be accommodated? How can multiple tie-in points be achieved most effectively?
- Are there differences in the stability and strength of typical log attachment knots (e.g. Half Hitch with Running Bowline) where, either 1: the rope is wrapped around the log in the same direction in both knots (C/U/n-shaped), or 2: the direction of the rope alternates from primary to subordinate knot (S/Z-shaped)?

Kinematics of, and forces generated in, dismantling operations

- Does the cutting technique (e.g. notch form and depth, hinge height and thickness) affect the rotation and flight path of a log?
- How does the damping effect of retained branches on conifers and broad-leaved trees affect tree sway during rigging operations, and does it also effectively reduce peak loads generated in a worst-case scenario?
- Can the positioning of the friction device at an adjacent tree opposite to the drop zone effectively reduce peak loads? Are there any other safety implications arising from such a scenario?
- How great is the influence of the rope modulus and rope length on peak loads generated in a worst-case scenario?
- What is the effect of other parameters such as log size, aerodynamic resistance, stem dimension etc. on the kinematics of, and forces generated in, snatching logs?
- What are the kinematics of, and how great are the forces generated in, other rigging scenarios (including speedlines)? Is there a rigging technique that effectively reduces forces in snatching? Is there a rigging scenario that generates even greater forces than snubbing logs off (e.g. letting a section run and then suddenly stopping it)?
- How does applying friction at the rigging point affect peak forces and the reactions of the tree? How much does friction reduce the damping effect of the rope?

INTRODUCTION

BACKGROUND

This report presents the results of research carried out into a number of aspects of 'rigging' as applied to tree work operations in the UK. In this context, rigging is the application of specialised tools and ropes by tree workers, in order to lower cut sections of trees to the ground in a controlled manner. Rigging operations can also be referred to as dismantling operations, although the term 'dismantling' normally covers all methods of bringing cut sections of a tree to the ground, including the free falling of sections (i.e. allowing cut sections to fall to the ground).

Rigging methods are normally adopted where it is not possible to allow the cut sections to fall freely, either because of the danger of hitting unwanted targets on the ground, or because of the difficulty of extracting the fallen timber from the target area (i.e. the area in which the timber would otherwise fall).

Rigging operations are normally undertaken by a team of tree workers, with one worker positioned in the tree, working in conjunction with one or more other workers on the ground. In simple terms, the worker in the tree is responsible for 'rigging' the section of timber to be cut, whilst the other worker(s) assist in lowering the 'rigged' section to the ground after it has first been cut.

Over recent years, rigging methods used in the UK have developed from 'traditional' techniques, which utilised ropes in conjunction with only the natural features of the tree, to 'more advanced' techniques, which use a wide variety of tools and equipment designed specifically for the purposes of rigging. Many of the newer techniques have been imported from other countries, in which they were originally developed and practised, while much of the specialised equipment has been adapted from other areas of use (e.g. mountaineering).

Due to the way in which the newer methods have been adopted, the tree work industry may not have developed the most satisfactory approach to their use. In particular, a number of engineering companies have developed products for use in rigging operations that have not, as yet, been incorporated into industry literature. Furthermore, the arboricultural industry in the UK has complex training and certification systems, developed primarily as a result of health and safety legislation, which currently do not necessarily provide the most suitable responses to the new techniques.

In view of the above considerations, in the latter part of 2004 the Forestry Commission (FC) placed a contract with Treevolution Ltd for a preliminary assessment of rigging methods being used in the UK. This assessment was completed in November 2005 with the publication of a report entitled *An initial assessment of rigging equipment, work methods and training standards used in dismantling operations in the UK*. This report identified specific requirements for detailed research, and subsequently led, in May 2006, to a contract being placed, by the Health & Safety Executive (HSE), as part of its Injury Reduction Programme, with Treevolution Ltd in the UK and Brudi & Partner TreeConsult in Germany. The contract specified in-depth research into a number of rigging-related topics, and was co-funded by the Health & Safety Executive and the Forestry Commission.

This report presents the results of the in-depth research. It is hoped that the information contained in the report, together with the proposals developed from the studies concerned, will ultimately lead to the adoption of improved safety standards throughout the arboricultural industry.

OVERALL OBJECTIVES

In accordance with the main aims of the HSE's Injury Reduction Programme, this research project was primarily concerned with investigating specific aspects of arboricultural rigging, with the overall objective of establishing information that could assist in the introduction of improved standards of operation and safety throughout the arboricultural industry.

An expressed objective of the research was the securing of information that could inform the eventual publication of a document entitled *A Guide to Good Rigging Practice*, possibly to be published as a companion to the already existing *A Guide to Good Climbing Practice* (published by the Arboricultural Association) – a highly successful reference work covering general tree climbing activities for practising arborists in the UK.

In particular the research project was charged with the task of investigating issues relating to:

- the carrying out of risk assessments prior to undertaking dismantling/rigging operations
- the planning and organising of rigging operations
- means by which risks might be reduced/minimised and accidents prevented
- the selection and configuration of appropriate work equipment
- the assessment of safety factors in different rigging scenarios

The ultimate objective of the research was to provide information relating to rigging operations that can feed through, by appropriate mechanisms, to personnel involved in rigging operations in the arboricultural industry, in such a way that standards are improved and, correspondingly, a reduction in accidents/injuries is achieved.

SPECIFIC AIMS

In line with the tender specification for the research, specific aims of the project included the production, or development, of:

- a checklist of points that should be considered prior to undertaking a rigging operation
- a working description of the methodology of, and points to be considered when carrying out, a visual tree inspection prior to undertaking a rigging operation
- flow diagrams charting the items to be considered, and the decisions to be taken, when determining a safe strategy and techniques for dismantling a tree
- information in tabular form that can be used to estimate typical weights of green timber in a variety of lengths and diameters for different species of tree commonly found in the UK
- a means of identifying the forces generated by a variety of different rigging scenarios
- information that can be used to identify the maximum forces sustainable for a range of rope diameters
- information that can be used to identify the size of anchor point required for rigging systems using different rope diameters, for a range of common UK tree species

- Means of identifying, through the use of line drawings, photographs or otherwise, aspects of rigging including:
  - how pulleys share loads
  - how slings share loads
  - correct configurations of installed rigging equipment
  - correct configurations of knots used in rigging

METHODOLOGY

Three main methods were adopted in pursuit of the stated aims and objectives of the project, namely:

- identification, collection and collation of information and/or data from previously published sources
- field studies, carried out in the vicinity of Munich, Germany
- evaluation of laboratory studies at the University of the Federal Army, Neubiberg, Germany

For some aspects of the project, extensive reviews of the available literature were carried out. Where required, such reviews were carried out simultaneously in the UK and Germany, involving accessing publications from Europe, North America and Australia. Published data on the properties of green wood and trees was collected from as many sources as possible, and collated to provide an up-to-date database of information. All sources of information are indicated in the body of the report, and a full list of references is provided in Appendix 3.

In the case of rigging equipment, data on the material properties of both cordage and hardware items was collected from manufacturers of internationally available products originating from within the UK, France, Germany and America.

In the pursuit of other aims of the project, field studies were carried out on real trees, which were subject to scientific data collection and the recording of events using video techniques. The results of these tests were evaluated by a team of engineers and arborists. Other tests were carried out under strict laboratory conditions, so that the process details could be more accurately monitored, and detailed measurements could be taken of parameters affecting the forces generated in simulated rigging operations.

1 MANAGING A RIGGING OPERATION

The bulk of this report deals with highly technical issues relating to the selection and use of equipment in rigging systems used by arborists in the dismantling of trees. However, whatever the technicalities involved in such systems, it will always be necessary for the work involved to be managed in a manner that ensures, amongst other things, that:

- the work is appropriately planned
- all necessary risk assessments are carried out
- contingency plans are in place for dealing with unexpected or emergency situations
- sufficient resources are available for the work to be carried out as planned
- there is sufficient flexibility to allow the plan to be varied if circumstances change
- the work is appropriately supervised

All of these issues are dependent on the way the work is managed. This chapter seeks to describe a management system that can be applied by organisations or individuals involved in carrying out rigging operations. The procedures described here have been developed out of discussions with a number of highly experienced arborists working either as individuals, or for companies of varying size and scope. The information presented, therefore, represents current best practice in the UK as assessed by the authors.

By definition, all rigging operations are carried out outside, on site, and often away from any base from which the arborists concerned may be operating. Since trees, and the locations in which they are situated, are infinitely variable, with no two rigging operations ever being identical, it is inevitable that much of the detailed decision-making will have to be taken on site, at the time of carrying out the work. However, this does not negate the need for careful consideration and planning of the work prior to going on site. In fact, the success of a rigging operation on site will, in many ways, depend on the extent to which appropriate plans are developed in anticipation of the work actually being carried out.

Although rigging operations generally require the involvement of more than one person for their successful execution, the way in which the workers involved are brought together can vary considerably. At one extreme, a self-employed, individual arborist, with the appropriate skills, may bring together a group of independent treeworkers in order to undertake a rigging operation. At the other extreme, all the workers involved may be employees of a large, multi-department organisation offering tree care as just one of their services. In the subsequent sections of this chapter it is assumed, for the sake of simplicity, that the workers involved in the rigging operation are all employees of a business which, as a minimum, has its own base facilities consisting of equipment storage and office services. It should be self-evident how the procedures would apply in other situations, although these may also be referred to from time to time.

1.1 RESPONSIBLE AND COMPETENT PERSONS

Because of the detailed decision-making required whilst actually carrying out a rigging operation, it is of vital importance that there is one, and only one, member of the work team who is charged with total responsibility for carrying out the operation. This person is referred to as the ‘Competent Person’. Because of the highly technical nature of the work it is essential that this person has the necessary knowledge, training and experience to be able to effectively and safely manage and control the work, as it is being undertaken. The Competent Person in such a situation is often also called the Site Safety Co-ordinator.

Since the Competent Person is key to the success or otherwise of the entire venture, it is vitally important that a person is so designated, only after appropriate consideration of the work to be undertaken and the qualifications and abilities of those available to fill the role. Appointing someone to be the Competent Person in a rigging operation, should not be taken lightly, since appointing someone who lacks the required expertise would not only be unfair to that person, but could also lead to unexpected and/or tragic consequences. For this reason, it is equally important that the person who appoints the Competent Person has sufficient status to be able to do this without fear or favour, and has the knowledge, training and experience necessary for a full understanding of all issues involved in the work being considered. This latter person is referred to as the 'Responsible Person'. (In a situation where a self-employed individual is undertaking rigging work, the Responsible Person and the Competent Person might well be the same person.)

Although the Responsible Person is the person ultimately responsible for ensuring that the work is organised appropriately, that person would not normally be present on site when the work is actually being carried out. However, the Competent Person, whose role does necessitate being on site, should be able to request that the Responsible Person also be on site, if this is judged to be desirable.

In addition to being regarded as current good practice, the roles of Responsible Person and Competent Person, as described here, are implicit in a number of Health & Safety regulations, and further information relating to these roles can be obtained by referring to:

- The Management of Health and Safety at Work Regulations (1999)
- The Lifting Operations and Lifting Equipment Regulations (1998)
- The Work at Height Regulations (2005)

The following definition, taken from a commentary on the Work at Height Regulations (2005), emphasises the essential requirements of a Competent Person:

> *"**A competent person** is a person who can demonstrate that they have sufficient professional or technical training, knowledge, actual experience, and authority to enable them to:-*
>
> *a. carry out their assigned duties at the level of responsibility allocated to them:*
> *b. understand any potential hazards related to the work (or equipment) under consideration;*
> *c. detect any technical defects or omissions in that work (or equipment), recognise any implications for health and safety caused by those defects or omissions, and be able to specify a remedial action to mitigate those implications." (Holden 2007)*

1.2 OFF-SITE PREPARATIONS

As indicated in the previous section, the first step in preparing to undertake a rigging operation must be the appointment or identification of a Responsible Person. This is normally done off-site, in an office environment. The Responsible Person should be made fully aware of, or should take the necessary steps to become fully aware of, the nature and requirements of the work involved. Once the work has been so identified, the Responsible Person must appoint a Competent Person who will be charged with the task of carrying out the work. This is also normally done in the office environment. At this stage it is the responsibility of the Responsible Person to ensure that the Competent Person is made fully aware of all the relevant details of the work under consideration. For his part, the Competent Person must also take whatever steps are necessary to become fully informed of the work requirements.

Before the work can be progressed to a point where personnel can go on site to carry out the work, the Responsible Person and the Competent Person must carry out a number of procedures. A draft checklist that can be used to ensure that these matters are appropriately dealt with, and that can be used as a working document through to the point at which the work is carried out, is presented at Figure 1.1. This 'Checklist prior to rigging operations' is divided into two main sections, with the upper section (consisting of Part A and Part B) relating to the off-site preparations. The different parts of the checklist are such that each part should have all its items appropriately initialled before the next part is embarked upon.

The first four items of the checklist in Figure 1.1 (Part A) are the responsibility of the Responsible Person (RP), who should only initial the tick against each item if these items have been completed to his/her satisfaction (i.e. if each question can be answered positively). Part B should not be commenced until all items in Part A have been dealt with.

The remaining items in the upper section of the checklist (Part B) require the attention of both the Responsible Person and the Competent Person (CP), and both of these persons should initial the ticks alongside each item to indicate that they have been satisfactorily dealt with. As with Part A of the checklist, the remaining parts of the checklist (Parts C & D) should not be embarked upon until all items in Part B have been dealt with satisfactorily and initialled to indicate this.

The items in Part B, which need to be jointly addressed by the Responsible Person and the Competent Person, fall into four main categories, each of which is discussed in the subsequent paragraphs, namely:

- risk assessments
- manpower and supervision
- equipment and other resources
- communications

1.2.1 Risk assessments

Risk assessments are an essential part of the preparation for carrying out rigging operations. They are not only necessary to satisfy current health and safety legislation, but in view of the complex nature of rigging operations, and the potential consequences arising from the failure of equipment and/or systems of working, they are an essential means of safeguarding both people (workers and the general public) and property. A properly executed risk assessment should enable all potential hazards to be identified and taken into account in the eventual work plan. However, some hazards may not be immediately identifiable at the planning stage (for example, a particular hazard may not become apparent until an aerial operative is able to view the situation from a position in the tree). For this reason, the risk assessment process must to some extent be an ongoing (or 'live') process, and although it is normally initiated off-site, it is important that there is an ongoing mechanism whereby the risk assessment can be updated and/or revised as the work plan is carried out.

Two different risk assessments are referred to in the checklist at Figure 1.1, namely a generic risk assessment and a site-specific risk assessment. The generic risk assessment should already be in existence and is a document which the organisation concerned should maintain to cover all general issues relating to the type of work which is being considered. The site-specific risk assessment is prepared for the particular job of work under consideration, and is therefore specific to the actual location of the intended work, and to the nature of the work itself, including the personnel involved, the equipment to be used and the envisaged methods of working.

Job ref.__________

Date __________

Checklist prior to rigging operations

All ticks to be initialled when satisfied — **RP** **CP**

Off-site checks Complete Part A before proceeding to Part B

A

- **Has a Responsible Person (RP) been appropriately identified?** (NAME ____________________) ✓
- **Has the work been clearly identified by the Responsible Person?** ✓
- **Has a Competent Person (CP) been appointed and notified?** (NAME ____________________) ✓
- **Has the work been identified and assessed by the Competent Person?** ✓

B

Risk assessments

- Has the appropriate generic risk assessment been referred to? ✓ ✓
- Has a site-specific risk assessment been initiated? ✓ ✓
- Does the site-specific risk assessment contain an emergency contingency plan? ✓ ✓
- Has the need for any additional technical support (personnel or equipment) been considered? ✓ ✓

Manpower and supervision

- Is there appropriate supervision for managing the rigging operation? ✓ ✓
- Are there sufficient competent operatives for the emergency contingency plan to be actioned? ✓ ✓
- Are all operatives competent to carry out their anticipated duties? ✓ ✓

Equipment & other resources

- Has appropriate equipment for the operation(s) been provided/selected? ✓ ✓
- Is there sufficient equipment for an aerial rescue to be performed if necessary? ✓ ✓
- Has any requirement for additional technical support been satisfied? ✓ ✓

Communications

- Are there feedback systems in place for both during and after the work? ✓ ✓
- Do all operatives understand the importance of the feedback systems, and how they work? ✓ ✓

On-site checks Complete Part C before proceeding to Part D

C

Prior to starting the work

- Do all operatives understand and agree with the risk assessment(s)? ✓
- Have all the controls specified in the risk assessment been implemented? ✓
- Has a safe strategy and system for the rigging operation(s) been identified? ✓
- Do all operatives understand the strategy and system for the operation(s)? ✓
- Can the work be done without the Responsible Person being on site *or* if not, is the RP present? ✓
- Do all operatives understand the procedures for pre-use checks, set-up and operation of the equipment they will be working with? ✓

D

Prior to removing the first section

- Has due consideration been given to the nature (weight, size, shape etc) of the section to be removed? ✓
- Has due consideration been given to the risk and/or consequences of anchor and/or equipment failure? ✓
- Have suitable aerial, landing and processing work zones been determined? ✓
- Does the risk assessment cover the transport corridors between all working zones? ✓
- Is each component of the rigging system correctly configured? ✓
- Is each component of the rigging system compatible with its neighbouring components? ✓
- Is appropriate supervision in place for the operation? ✓
- Do all operatives understand their assigned duties? ✓
- Has a communication system been agreed and understood by all operatives? ✓
- Can all operatives communicate clearly with one another? ✓
- Do all operatives understand their responsibility to STOP the operation if they believe that it could or has become unsafe, or if there is a change from the agreed plan, or if they are unsure about any aspect of the operation? ✓

NB All checks in Part D must be applied before the removal of each subsequent section

Figure 1.1 Checklist prior to rigging operations (draft)

Amongst other things, the site-specific risk assessment should include an emergency contingency plan, designed to deal with any emergencies that could, in the opinions of those responsible for carrying out the assessments, arise during any part of the work operations. The site-specific risk assessment should also identify any controls that need to be implemented to safeguard the worksite, or to safeguard persons who may, directly or indirectly, be involved in the work, and may identify the need for additional resources to be made available on site, in terms of both personnel and equipment.

Although the site-specific risk assessment would normally be initiated away from the worksite (i.e. in the office environment), it may well be necessary for the Competent Person and/or Responsible Person to make a special visit to the worksite as part of the risk assessment process, prior to carrying out the work. It may also be necessary at this stage to obtain additional information by consulting with persons having particular technical expertise, or by referring to the available literature.

Whatever the initial processes involved, the site-specific risk assessment must remain subject to re-evaluation, and for this reason it should be seen as a working document that should be carried to the worksite by the Competent Person. It is, therefore, envisaged that the checklist shown in Figure 1.1 would have the site-specific risk assessment attached to it, and that both documents would be carried through to the worksite.

1.2.2 Manpower and supervision

The selection of manpower to undertake a particular rigging operation may or may not be the primary responsibility of either the Responsible Person or the Competent Person. However, both of these persons should satisfy themselves that both the number of operatives, and the competencies of the operatives, are appropriate for the work being considered, including its effective supervision. As with the risk assessments, the checklist presented in Figure 1.1 requires both persons to initial the ticks to indicate that they are satisfied that the questions can be answered positively, and that the necessary requirements have therefore been met.

In particular, both the Responsible Person and the Competent Person must be satisfied that sufficient competent operatives have been allocated to the work, not only so that the work can be efficiently carried out, but also to enable any emergency contingency plans to be put into action if necessary. There will be occasions when the latter requirement demands the presence on site of more operatives than would strictly be necessary to simply carry out the rigging operations as envisaged.

1.2.3 Equipment and other resources

As with the selection of manpower, the provision of equipment and/or other resources may not be the primary responsibility of either the Responsible Person or the Competent Person. However, both of these persons must satisfy themselves that appropriate and sufficient equipment and other resources are being provided. As with the manpower requirement, they should also ensure that sufficient equipment is being taken to the worksite to enable any emergency contingency plans to be carried out. In particular, there should be sufficient equipment to enable an aerial rescue to be performed should any of the climbers need to be rescued from within a tree.

1.2.4 Communications

The facility for individual personnel to be able to effectively communicate with each other, and the corresponding ability to learn from experience, are both essential elements of any effective organisation. To that extent, the inclusion of this heading in the Figure 1.1 checklist is designed to serve as a reminder that these considerations need to be constantly reviewed and maintained. Although they should be in place at all times, systems designed to facilitate communications can all too easily be given too low a priority, with the result that they can fail to operate effectively.

By ensuring there is a requirement to initial the ticks on the checklist of Figure 1.1, both the Responsible Person and the Competent Person will be reminded of the importance of communications:

1. between all operatives involved in carrying out a particular rigging operation, and
2. at the end of the work, when the recording of outcomes (both informally and formally) can provide information, that may prove to be invaluable when considering similar work in the future.

It is rarely sufficient to simply inform personnel of their responsibilities in this area. They must also be told (and from time to time reminded) how the communication processes operate. They should also be monitored at all times to ensure that they do actually carry out these responsibilities.

1.3 ON-SITE PREPARATIONS

Only when all the questions in the upper half of the Figure 1.1 checklist have been initialled positively, is it appropriate to move onto the worksite in order to carry out the work. At this point, it is envisaged that the checklist, together with the site-specific risk assessment, will be taken to the worksite by the Competent Person. It is then the responsibility of the Competent Person to ensure that Parts C and D of the checklist are positively initialled prior to any work taking place. In undertaking the completion of the checklist (and as a result of any other relevant information becoming available), the Competent Person is also responsible for updating the site-specific risk assessment, and modifying the work plan accordingly.

1.3.1 Prior to starting the work

Part C of the checklist (Figure 1.1) relates to checks that need to be carried out prior to any tree-cutting work (removal of sections) being carried out. These checks are all concerned with getting everything in order prior to starting the work. They include checking with all operatives that they understand and agree with the proposals for carrying out the work. They also include checking that all operatives fully understand what they are being expected to do.

At some point during the ‘Prior to starting the work’ checks, the Competent Person will become fully assured that all necessary preparations have been made, and that it is therefore appropriate to proceed to actually carry out the work. At this point, all the questions in Section C of the checklist should have been initialled to indicate that they can be answered positively. If any doubt remains, and any of the questions cannot be initialled, the work should not proceed. Where such a situation arises, the Competent Person must have the facility (and the authority) to cancel the work or to call for further support, and may well feel that the presence on site of the Responsible Person is desirable. If the latter is the case, that part of the work that requires the presence of the Responsible person should not be commenced until the Responsible Person is on site and the appropriate checklist question can be initialled.

1.3.2 Prior to each section

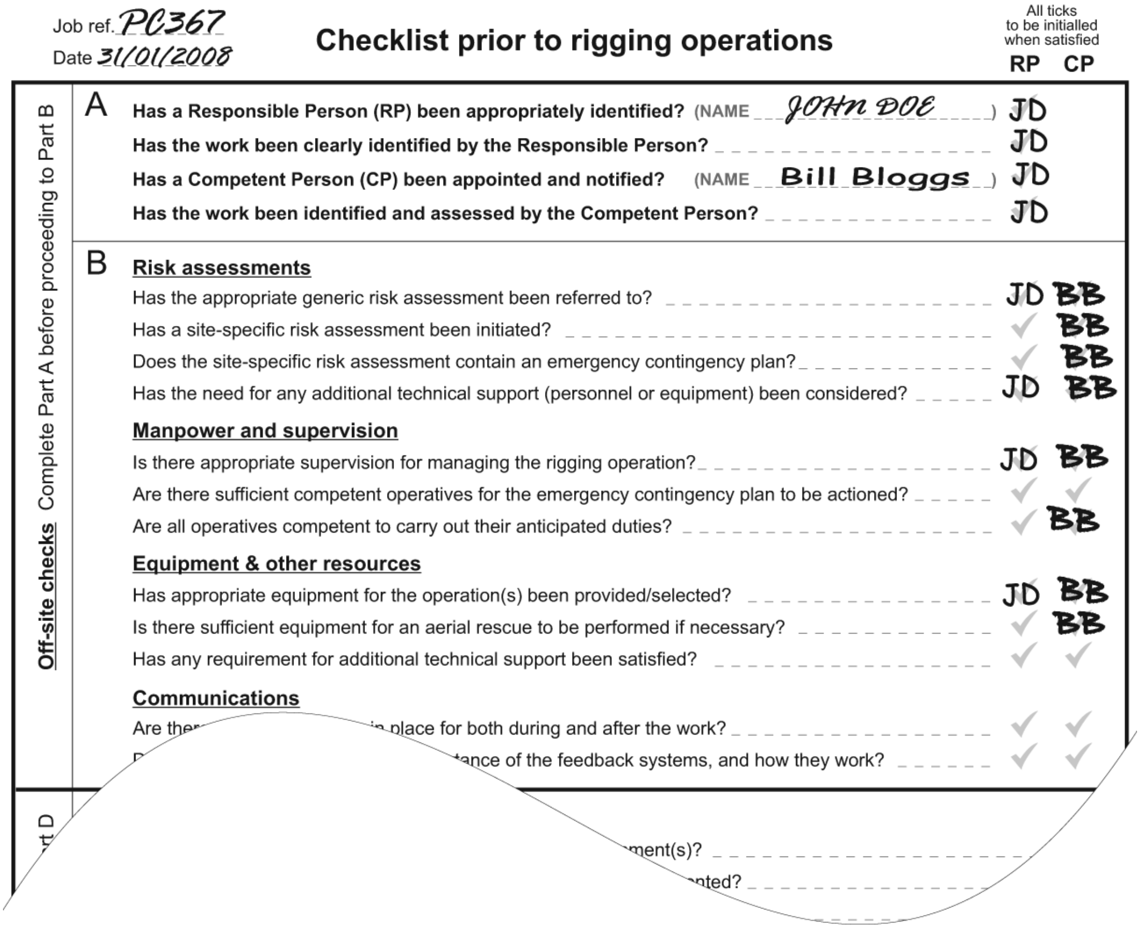
The final part of the checklist (Figure 1.1) is concerned with checks that should be undertaken immediately prior to the ***first*** section of a tree being removed (using the method which has been selected, and set up, subject to the earlier checks). For this reason, these checks are more concerned with specific details (or technicalities) of the operation. In particular, all equipment must be checked, not only to ensure that it is correctly configured, but also to make certain that the different components of the system are compatible. It is also necessary to make a final check that all working areas have been considered fully in the risk assessment procedure. Finally, it is imperative that a check is made that all operatives are able to communicate with each other, and know their responsibilities in this area. Each operative must fully understand that they have a responsibility to interrupt the proceedings if they believe anything has become (or could become) unsafe; or if there is a change from the agreed plan; or if they are at all unsure about any aspect of the operation.

Although the checklist is designed so that the checks in Part D are only subject to initialling by the Competent Person prior to the first section being cut, it cannot be overemphasised that the same degree of caution also needs to be taken with regard to every subsequent section that is cut. Following the successful removal of one section, the rigging equipment must be re-configured in preparation for the next section. It is obviously equally important that all Part D checks are made after every re-configuration. It is intended that the formal initialling of the Part D checks before the first section, together with the reminder (included at the bottom of the checklist) of the importance of similarly checking before each subsequent section, will serve to encourage the Competent Person to adopt an appropriately rigorous approach to the work.

1.4 GENERAL CONSIDERATIONS

A partially completed checklist is presented at Figure 1.2. This illustrates the way the checklist can be associated with the work, by being annotated with a Job Reference (name and/or number) and date (i.e. the date of carrying out the work). It also illustrates the way in which the names of the Responsible Person and Competent Person can be added, and how they would proceed to initial the ticks, as and when they are satisfied that the related issues have been satisfactorily dealt with. It is not intended that the different items should be ticked in any particular order, although in many cases there is an implied order in the wording of the checks themselves. However, it is regarded as fundamentally important to the process that all ticks within any one part of the checklist (A, B, C or D) are initialled before proceeding to the next part.

It must be emphasised that the checklist is not intended to be a document that dictates how a rigging operation is planned and executed. Rather it is a document that is designed to introduce checks at appropriate points in the process, that can serve to ensure that all necessary considerations have been taken. The overall aim of the checklist is to assist in ensuring that rigging operations are undertaken not only successfully, but also, and even more importantly, as safely as possible. A checklist of this type will only have such an effect if it is rigorously applied. For that reason, it is suggested that not only should the initialling of each tick (and ultimately of all ticks) by the appropriate person(s) be an absolute requirement, but also that the completed checklist should form an essential part of the 'paper-chain' relating to the work concerned. To that extent, once the work is completed, the checklist should be filed together with any other essential documents, and kept safely as evidence of good practice in work planning and execution.



Job ref. PC367
Date 31/01/2008

Checklist prior to rigging operations

All ticks to be initialled when satisfied

Off-site checks Complete Part A before proceeding to Part B

		RP	CP
A	**Has a Responsible Person (RP) been appropriately identified?** (NAME JOHN DOE)	JD	
	Has the work been clearly identified by the Responsible Person?	JD	
	Has a Competent Person (CP) been appointed and notified? (NAME Bill Bloggs)	JD	
	Has the work been identified and assessed by the Competent Person?	JD	
B	**Risk assessments**		
	Has the appropriate generic risk assessment been referred to?	JD	BB
	Has a site-specific risk assessment been initiated?	✓	BB
	Does the site-specific risk assessment contain an emergency contingency plan?	✓	BB
	Has the need for any additional technical support (personnel or equipment) been considered?	JD	BB
	Manpower and supervision		
	Is there appropriate supervision for managing the rigging operation?	JD	BB
	Are there sufficient competent operatives for the emergency contingency plan to be actioned?	✓	✓
	Are all operatives competent to carry out their anticipated duties?	✓	BB
	Equipment & other resources		
	Has appropriate equipment for the operation(s) been provided/selected?	JD	BB
	Is there sufficient equipment for an aerial rescue to be performed if necessary?	✓	BB
	Has any requirement for additional technical support been satisfied?	✓	✓
	Communications		
	Are ther… …n place for both during and after the work?	✓	✓
	… …tance of the feedback systems, and how they work?	✓	✓

…rt D

…ment(s)?

…nted?

Figure 1.2 Rigging checklist partially completed

Whilst the difficulties of handling paperwork on a worksite must be acknowledged, it must also be recognised that the current regulations relating to risk assessment already necessitate the handling of paperwork on site. In designing the checklist presented in this chapter, care has been taken to not unduly introduce further complications to worksite procedures. The checklist has deliberately been kept to no more than an A4 sheet of plain paper. In this format it should be easy to reproduce in any administrative setting, from a home office to an office in a large organisation. It should also be easy to handle on site, even in wet conditions, as it can easily be accommodated in a waterproof document folder. For the same reasons, the entries to be made on the checklist, although they may represent the conclusions of substantial and serious enquiries/decision-making, have been limited to simple initialling of items that can be done quickly with nothing more than a pencil or ball point pen.

It must be emphasised that the checklist presented in Figure 1.1 is currently only in draft form. Before a checklist of this type can be universally recommended for adoption in rigging operations, it will be necessary for field trials to be undertaken in order to finalise the items included in the list and the exact wordings and details of its layout.

2 VISUAL TREE INSPECTION PRIOR TO UNDERTAKING A RIGGING OPERATION

The objective of this part of the Rigging Research is to provide:

> *"a working description of the methodology of and points to be considered when carrying out a Visual Tree Inspection before climbing and rigging"*

The focus is set on the detection of structural defects in limbs, forks, the stem and the root system. Impacts like lightning strike and mechanical defects, such as cracks, will be considered, besides the deterioration of a tree's load-bearing structure due to biological processes.

2.1 GENERAL

2.1.1 Hazard and risk

Terms used, with regard to tree inspection:

- Defect — *a visible sign that a tree has the potential to fail* (Meilleur 2006)
- Hazard — *disposition of a thing, a condition or a situation to produce injury* (HSE 1995)
  potential to cause harm to people or property (Ellison 2005)
- Magnitude of hazard — *the capacity to cause harm* (Lonsdale 1999)
- Risk — *the chance of something adverse happening* (as above)
- Risk assessment — *combines magnitude of hazard, probability of occurrence and the likelihood of damage to result from such incident*
- Hazard tree — *tree with an unacceptable level of risk to a target* (Meilleur 2006)

In order to match these definitions, tree inspections prior to dismantling a tree should therefore comprise:

- an analysis of the magnitude of hazard (e.g. species of stinging insects, size and position of tree part likely to fail, presence of electrical conductors)
- an estimation of the likelihood of occurrence during the prospective operation (e.g. remaining load-bearing capacity, in combination with the loading scenario)
- an assessment of the likelihood of damage (e.g. allergies to insect stings, position of the climber, use of redundant anchor points)

2.1.2 Factors of safety

The actual probability of tree failure during a rigging operation strongly depends on the factor of safety involved. A safety factor usually is defined as the load a structure is safely able to sustain *versus* the actual load applied (*cf* Gordon 1978). While an open cavity might severely compromise the ability of a small diameter tree to withstand loads, the same defect could leave a mature or veteran tree with remarkable safety margins.

> *"Trees have an inherent margin of safety or 'safety factor', as they are usually able to withstand much stronger mechanical loading than occurs under average conditions" (Lonsdale 1999).*

Loads generated from dismantling operations vary greatly. They do not necessarily depend upon the average wind load a tree experiences during its lifetime. Natural safety factors against wind-induced fracture have been studied (e.g. Niklas 2000), and systems have been developed for assessing the actual safety factor of a tree against stem fracture in a gale (Wessolly 1995).

However, it is difficult to provide a clear answer on whether a certain defect makes it impossible to climb a tree, and therefore requires other technical solutions for its removal, as loads generated from rigging operations vary strongly and are not well understood at the present time.

2.1.3 Failure modes

In many cases, before a structure actually collapses, its material yields due to overloading. Most trees have additional load tolerance beyond that point where some wooden fibres start to buckle (Arnold 2003). That is why, for example, some branches remain bent after excessive loading due to heavy snow. They do not fully fracture (which would have registered as 'secondary failure'), yet they are severely damaged.

This failure mode is called ***primary failure***. It is defined as permanent deformation of a load-bearing structure. The material does not regain its original state after loads have been removed. When trees are almost blown over by the wind, their stems and root plates might show an increased lean, and sometimes cracks in the soil around the stem bases might appear. These trees pose an acute threat because they are likely to fail in the next, even less strong, wind.

That is the reason why primary failure is not permissible in an engineering assessment of stability. Once the material or structure of a tree is permanently deformed, there is no way of predicting under what load it is going to collapse to the full extent. This lack of predictability can be compared with the situation applying to metal karabiners, in which karabiner manufacturers find it necessary to recommend their products be removed from service as soon as they show significant deformation. Although there may be no other visual evidence of damage, cracks may have developed inside the metal body of a deformed karabiner, considerably reducing its load-bearing capacity. It might take only an additional fraction of the load previously applied to cause ultimate or secondary failure. For timber (i.e. wood at low moisture content), fracture usually occurs immediately after primary failure. But for green wood, primary failure generally occurs at considerably lower loads than fracture.

Usually, primary failure in the wooden body of a tree, while registering on a micrometer scale, is not visible to the human eye. Yet there might be symptoms like loose bark, acute changes in the direction of the axis, strongly bent branches or a heaving root plate. In these cases, further inspection is required if loading of those parts, suspected to be pre-damaged, cannot be avoided during dismantling operations.

A collapse of the load-bearing geometry is called ***structural failure***. It is usually much easier to identify, as significant delamination cracks or splits are often visible. It occurs before primary failure only on trees that show severe structural defects like extensive decay or cracks. Mattheck, Breloer (1997) describe such failures as shear failure, hose-pipe kinking and shell buckling. Other authors (e.g. Spatz *et al* 1993) have shown that such failure is limited to severely decayed cross-sections (*cf* Chapter 5.4).

Structural failure of a stem[*]

Solid cross-sections, or tree parts with a more limited amount of decay, will usually fail by simple bending fracture, or by fracture caused by torsion. The load-bearing capacity of solid stems and branches, and the influence of decay, can be assessed using standard engineering formulae derived from cantilever beam theory, up to an advanced degree of hollowness (see Chapter 5 on the Bearing Capacity of Tree Species).

A frequent form of failure in trees is uprooting, or the fracture of roots at the stem base. In both cases, the whole tree will fail. During rigging operations tipping poses a danger when the root system is severely compromised, or when a great portion of the stem base is decayed. Generally speaking, an applied moment of force reaches its maximum at the stem base. Yet most trees have adapted to this by expanding their stem diameter towards the base and developing a root system capable of dissipating the loads it is exposed to.

2.1.4 Tree-related hazards

Failure of the load-bearing structure (roots, stem or branch) may occur during rigging and dismantling operations due to one or several of the following reasons:

- strength loss due to biotic effects (e.g. fungal decay, cavities, damage generated by wood-boring insects)
- abiotic damage like lightning strike, sunscald, severed roots, old cracks
- poor structural development (included bark, poor grafts, weak anchorage)
- previous failure (e.g. inclined root plate, split crotches, over-bent branches, fresh cracks)
- insufficient load-bearing capacity of the anchor point (inappropriate diameter, long lever arms, using dead branches)

[*] *Picture courtesy of C. Luley, Urban Forestry LLC, Naples, NY*

Other hazards in trees may result in personal injuries or failure of the rigging system, including:

- dead major branches
- overgrown objects within the wooden body
- stinging insects, harmful animals
- extraneous vegetation (vines), objects suspended from the tree
- electrical conductors running through, or in the vicinity of, the crown

2.2 VISUAL INSPECTION

Generally, the first step in any tree hazard assessment is a visual inspection, combined with the use of simple tools to measure tree-related parameters (e.g. stem diameter, tree height) and to detect, and/or locate, eventual defects (e.g. loose bark by sounding with a mallet). Limitations of this kind of inspection result from low visibility, due to obscuring features, but might also be a product of the great height of the tree, a narrow angle of view into the crown and hidden underground implications (e.g. compromised roots).

> *"[…] most types of defects can be detected through visual inspection from the ground, reasonable care should be taken to examine parts of the tree that may be hard to see due to their height or obscuring features such as covering of ivy." (Lonsdale 1999)*

Several systems for carrying out visual assessment have been published and are currently being used internationally. Mostly, the different methods provide a catalogue of defects that compromise the structural stability of a tree. Some authors have developed ratings to detect potential risks from trees (e.g. Matheny, Clark 1994, Ellison 2005). Others provide thresholds for the critical size of a defect (e.g. Mattheck, Breloer 1997) or the permissible spread of damage (e.g. Fraedrich, Smiley 2002).

In a second step, eventual defects are usually assessed for their severity and impact on tree hazard via a more thorough investigation. Several methods and systems for carrying out such diagnoses have been developed. They are not part of a visual inspection, but might in some cases be suitable for deciding whether or not a tree is safe to climb.

Major disagreement between different authors exists on how to rate defects, with regard to the likelihood of failure and what means and criteria are applicable. Among such parameters are:

- thickness of remaining residual wall (t/R-ratio e.g. Wagener 1963, Smiley, Fraedrich 1992, Mattheck, Breloer 1997)
- margins of safety against bending fracture (basic safety, Wessolly 1995)
- diameter of the root plate (Mattheck, Bethge 2003)
- inclination of the stem base and elastic deformation (strain) in marginal fibres under simulated load (Wessolly 1996)
- slenderness of the stem (h/D ratio e.g. Mattheck *et al* 2001; l/D ratio e.g. Koch 2007)

2.3 SOURCES IN LITERATURE

2.3.1 Things to be considered

Shigo (Shigo and Trees, Associates *nd*) lists 13 questions to be answered when inspecting trees for hazard:

"1. Target: If the tree falls will it hit cars, houses, power lines or people? If so, the need for immediate action becomes much greater.

2. Architecture: Has the tree grown beyond its normal form into a dangerous form?

3. History: Has the tree lost large branches recently?

4. Edge Tree: Were neighbouring trees cut away recently, leaving tall trees at the edge?

5. Dead Branches: Are there dead tops or branches? Is the tree dead?

6. Cracks: Are there deep, open cracks in the trunk and branches? Cracks are major starting points for trunk and branch failures. Crack drying is just as important a factor leading to failures as overloading and decaying wood.

7. Crotch Cracks: Are there deep, open cracks below joining stems?

8. Living Branches: Do living branches bend abruptly upward or downward, where tips of large branches were cut off? Living branches may pull out of trunks that are weakened by rot or cracks. Long periods of hot, dry weather may dry out the rot or cracks and weaken the union of the branch on the trunk. Beware of large branches on rotten or cracked trunks.

9. Topping: Are large branches growing rapidly from topping cuts on big trees? Sprouts that lean away from topping cuts have weak attachments. Sprouts near the edge of a cut may roll inward as it grows and further weaken the attachment.

10. Storm Injury: Are there broken branches, split trunks, or injured roots? Are branches close to power lines?

11. Root Rot: Are there fungus fruit bodies (mushrooms) on roots? Were roots injured by construction?

12. Rots and Cankers: Are there hollows or cankers (dead spots), some with fungus fruit bodies? Is the tree leaning?

13. Construction injury: Have roots, trunk, or branches been injured? Is there a new lawn or garden over injured roots?"

A number of authors have depicted defects in a tree associated with hazard, and a greater likelihood of failure, in a single drawing (Smiley, Fraedrich 1992, Arboricultural Association 2005). Such visualisation may be suitable for use by practitioners on site. An example is shown in Figure 2.1 overleaf.

2.3.2 Methodology for visual tree inspection

Several attempts have been made to systematise Visual Tree Inspection (e.g. Matheny, Clark 1994; Mattheck, Breloer 1997, Reinartz, Schlag 1997, Lonsdale 1999, Ellison 2005). Also, practical guides for tree owners and practical arborists have been published in order to foster the recognition of hazard trees (e.g. Clark, Matheny 1993, Lonsdale 2000). These were designed to evaluate the risk of failure of structural parts of trees due to wind loading, or due to the weight of the crown (eventually adding loads like ice, snow or rain).

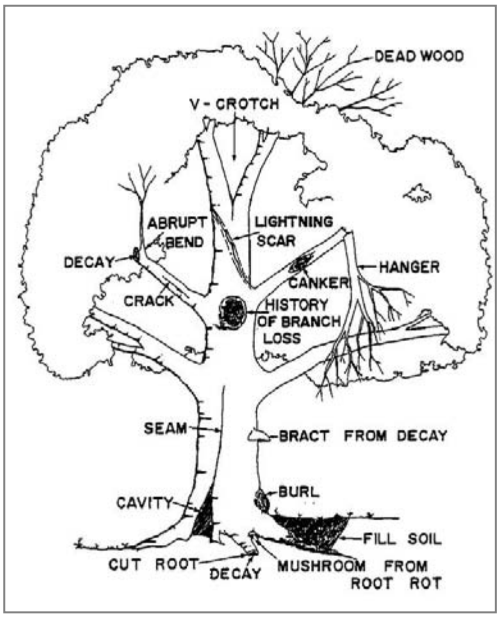


Figure 2.1 Defects in trees*

It is widely understood that not all defects automatically lead to a high likelihood of failure. The structural parts of the tree have to be able to sustain the loads generated from the respective impact. In order to apply general methods of visual tree inspection to a safety assessment prior to tree work, it is essential to consider the loads generated in climbing and rigging operations (see Chapter 8).

Wind pressure and drag usually act in a more or less horizontal direction, and therefore cause great bending stresses in the stems and torque in the root systems. Generally speaking, forces generated from rigging operations act upon the tree and its structural parts in a much more vertical direction and therefore cause less severe deflection on vertical stems and limbs. Thus, impacts from rigging operations are usually more comparable to gravitational loads from snow, ice and rain.

At the same time, peak forces usually cause a short term loading of the tree only. Wood is able to tolerate much greater stresses under dynamic conditions as compared to static loading (e.g. loads resulting from snow and ice, *cf* Dorren, Berger 2005). Such considerations add to the assumption that only rather severe defects in the structural parts of a tree will result in a greater proneness to failure during rigging and dismantling operations.

2.3.3 Tree inspection for climbing and rigging

The NPTC Assessment Schedule CS41 (NPTC, 2003) lists nine symptoms and issues the pre-climb inspection should look for:

- evidence of cavities, decay or decay fungi
- deadwood and broken branches
- dead or flaking bark
- V-shaped unions

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* *Picture from Smiley, Fraedrich 1992, reprinted courtesy of T. Smiley*

- cracks
- nesting insects
- timber characteristics of the tree species should be commented on
- the presence of power lines or telephone wires
- targets and obstacles underneath the tree

Neustaeter (2002) describes a number of so-called red flag indicators i.e. symptoms or signs of structural defects that might have implications for arborist safety during climbing and rigging operations. Included among such indicators are:

- longitudinal and/or horizontal cracks
- root decay, buttress roots not developed/visible
- lightning damage
- conks and mushrooms
- recent branch failure
- cavities, with little or no wound wood or local increment growth
- certain wood-boring insects like the Asian Long-horned Beetle (ALB[*]).

Other authors have also listed symptoms of a high potential for failure during climbing or dismantling operations, and visualised tree-related hazards for climbers in drawings (e.g. Jepson 2000, Arboricultural Association 2005).

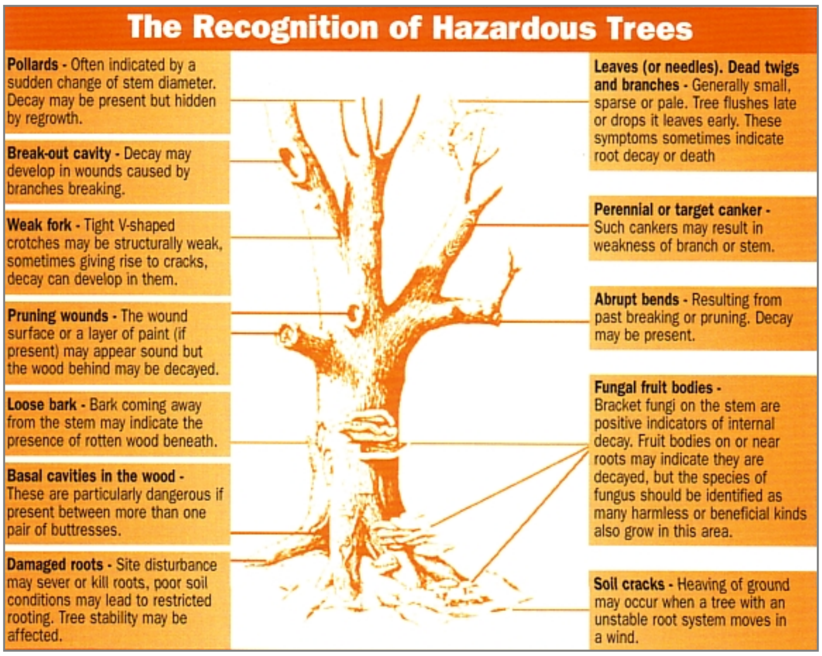

Figure 2.2 Hazard recognition[†]

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[*] *The ALB or Asian long-horned beetle (Anoplophora glabripennis), a species currently threatening to invade Europe, has a high potential to reduce the stability of both stems and limbs (Weiss 2004)*
[†] *Drawing reprinted from Arboricultural Association, 2005*

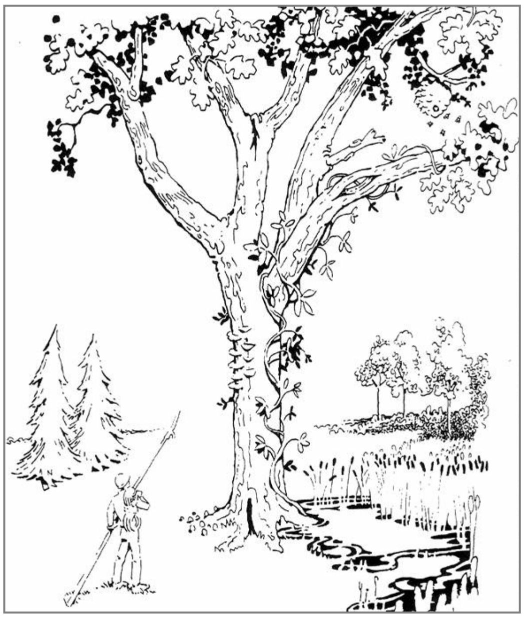

Figure 2.3 Tree hazards*

The visual inspection, as described in these publications, is focussed on risk mitigation by recognising areas of limited load-bearing capacity in the tree, choosing a suitable anchor point, and avoiding hazards in and around the tree.

A recent publication (Kane 2006) highlights four common issues with respect to pre-climb tree inspection: root defects, stem decay, weak forks with included bark and dead branches. Kane recommends thresholds beyond which trees are no longer safe to climb and proposes methods for testing tree stability, prior to climbing, some of which will be discussed in this chapter.

2.3.4 Further diagnosis

In order to assess the severity of structural defects, several methods have been developed in the past. They are not part of a purely visual assessment, but are listed as an addition. Methods and devices that serve as a means of assessing the margins of safety of a compromised tree are as follows (but not limited to):

- Devices for determining wood properties: fractometer, resistograph, metrigard, sound tomograph
- geometry-based criteria: degree of hollowness (wall thickness/radius-ratio), degree of slenderness (height/diameter-ratio), strength loss due to decay
- statics integrated methods: SIA-method (basic safety), Elasto-Inclinomethod and AfB-method (pulling test with high resolution instruments)

According to Rust, only statics integrated pulling tests measure values that relate directly to the stability of trees and provide information on the bearing capacity of the structure (Rust, Weihs 2007). Also, they are the only approaches that enable the practitioner to incorporate an estimated load (generated from rigging operations) into a safety assessment.

* *Drawing reprinted from Jepson 2000, courtesy of J. Jepson, USA*

2.3.5 Hazard calculations and hazard rating

The concept of hazard rating was applied by Matheny, Clark (1994) to trees, in order to mitigate risks when managing greater tree stands in recreational or urban areas. The three basic parameters of their rating system are probability of failure, size of the failing part and the potential target. Lonsdale (1999) added the term 'tolerable risk', to make up for the specific site conditions and the expected degree of safety in a specific environment. The concept has recently been updated by the original authors in a series of three articles (Matheny, Clark 2007).

Neustaeter (2002) proposes a systematic approach to risk inspection for climbers that involves calculations for determining risk of failure, as well as rating the prescribed work according to the risk posed by the conditions of tree parts and the severity of a potential risk of failure.

Risk of Failure Calculations

	Description	Calculations	Result
D	Diameter of stem	Measured at the area of concentrated stress & weakness	D =
R	Radius of stem	R = D / 2	R =
C	Circumference of stem	C = diameter x 3.14	C =
T	Thickness of outer wall	measured at thickest point or average around stem	T =
W	Width of cavity or crack	measured at widest opening of cavity or crack	W =
S	Severity of crack or cavity	S = W / C	S =
F	• Failure potential for trees with cavities, cracks & hollows: • Failure potential for hollow trees:	F = {T – (T x S)} / R F = T / R	F =

Structural Risk Inspection Report

Arborist Name: ______ Certification #: ______
Date: ______ Work Order/Job #: ______
Site Details
Address: ______
Phone / Fax / E-mail: ______
On-Site Contact / Details: ______
Tree Details
Species: ______ DBH: ______ Height/Width: ______ Lean: ______ Roots: ______

A. Prescribed Work Risk Rating Guide: (choose the most appropriate work risk rating)

Prune	Scaffold Limb Removal	Top Removal / Cable or Brace	Top Removal & Rig	Whole Tree Rig
5 6 7 8 9 10	11 12 13 14 15	16 17 18 19 20	21 22 23 24 25	26 27 28 29 30
Risk Rating # ______ +	Special Conditions (scale of 1 – 10) 1 2 3 4 5 6 7 8 9 10	= ______		

TOTAL WORK RISK RATING: a = ______

B. Structural Risk and Tree Dynamics Risk Assessment (visual assessment)

Location Rating

Rate the following areas of the tree according to the severity of the conditions below on a scale of 1 – 5 (least severe) 0 1 2 3 4 5 (most severe)	Scaffolds	Trunk	Pedestal	Roots
Defects				
Cavities				
Decay				
Other (Lightning)				
Total Rating for each column (area of tree)			**	**

TOTAL STRUCTURAL RISK VISUAL ASSESSMENT:
(add total rating for each section of tree above): b = ______

** If either the pedestal or roots total rating is higher than 7, it is recommended that a more formal calculation and assessment be done (in addition to visual assessment) due to the seriousness of failure in these parts of the tree.

C. Risk of Failure Calculations: c = ______

Calculated Failure Value (page 2)	Risk Potential	Structural Risk Rating
0.0 - .30	Severe	46 - 60
.31 - .60	High	31 - 45
.61 - .90	Moderate	16 - 30
.91 – 1.00	Low	0 - 15

D. *Calculations: choose the applicable following calculations for your assessment:*

(Option #1)
1. If risk of failure calculation has been calculated: (b+c)/2 + a = ______

(Option #2)
2. If risk of failure calculation has NOT been calculated: a + b = ______

Final Risk Abatement Rating (either from Option #1 or #2): ______

76 – 100	Should not be climbed, work cannot be completed safely from the tree.
51 – 75	Extreme caution required, implement risk abatement tools & techniques.
26 – 50	Caution required in specifically identified areas.
25 or lower	Proceed with usual caution and technique.

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Figure 2.4 Risk rating for arborists*

The term '*Climber's Tree Assessment'*, first introduced by Mark Bridge (2003), refers to risk assessment prior to climbing and dismantling operations. In a graphical depiction of his proposed method of assessment, Bridge combines increasing degrees of difficulty of the prescribed arboricultural operation with the declining condition of the tree. The matrix (overleaf) indicates a level of experience and training (competence) required from the performing arborist, in relation to these two variables.

* *from Neustaeter2002, courtesy of D. Neustaeter, Canada*

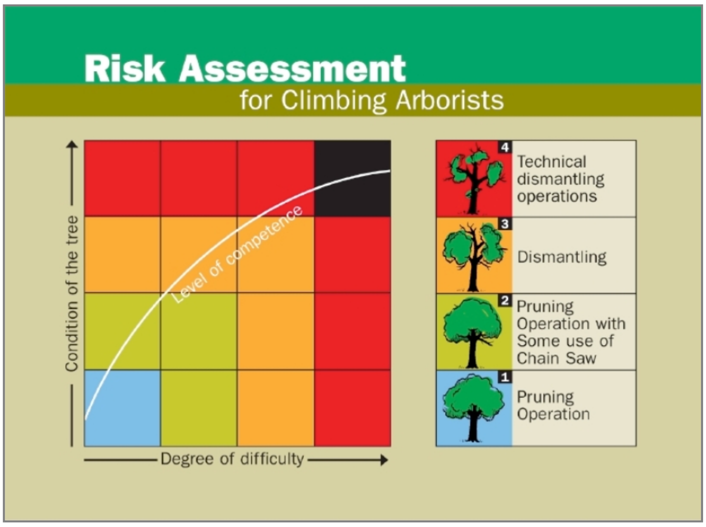

Figure 2.5 Climber's tree assessment*

2.4 A METHODOLOGY FOR VISUAL TREE INSPECTION PRIOR TO CLIMBING AND RIGGING

2.4.1 Red and yellow flag indicators

Arborists should be aware of a number of symptoms for conditions that could make climbing and rigging operations hazardous. Such situations are often recognisable from the extent or severity of structural defects. Among these are also signs of specific tree conditions, which may indicate greater failure potential, and the presence of biotic or abiotic implications for tree work.

These include (but are not limited to):

- condition of the tree — dead branches, epicormic growth, die-back in the crown, strips of dead or loose bark, small and/or chloriotic leaves, large openings in the crown
- site conditions — root restricting barriers, overfilling, previous or ongoing construction work
- climatic conditions — slippery bark in rain, ice, or snow, water saturated soil
- previous failure/damage — wood cracks, lightning scars, over-bent or broken branches, buckled fibres, heaving of (or cracks in) the root plate
- structural defects — cavities, decay, included bark/weak forks, girdling roots, compromised roots, lean/unbalanced crown shape, abrupt bends in branches or stem, former cuts
- presence of pathogens — conks/mushrooms of wood decaying fungi, cankers, other biotic wood decomposers (e.g. xylobiontic insects)
- other sources of danger — harmful animals and plants (stinging insects, poisonous vines), electrical power lines, enclosed objects (e.g. bolts).

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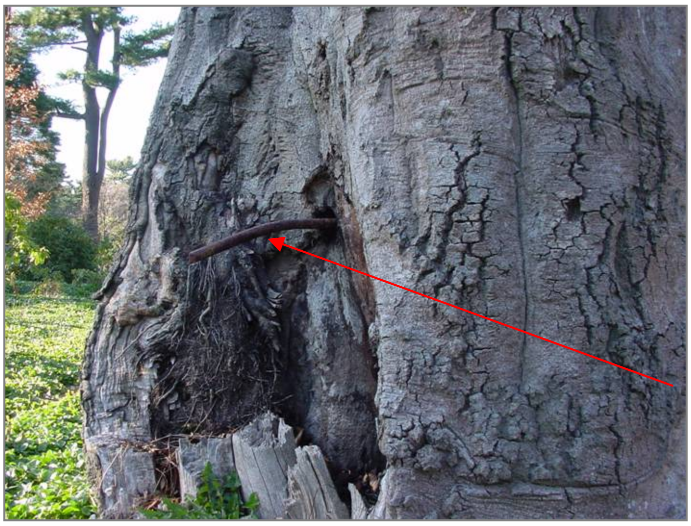
* *Reprinted from Bridge 2005, courtesy of M. Bridge, Switzerland*



Old metal rods, formerly bolting a broken crotch, may cause injury to climbers and damage to rigging lines.

Included object[*]

In the following display of symptoms of structural defects (see section 2.5), the ***red flag*** will be used to indicate the most severe symptoms, or to highlight the extent to which the defects should be considered hazardous for arborist operations. In most cases, these trees will not be sufficiently strong to be dismantled by using climbing techniques, and other access techniques, including the use of cranes, may need to be considered. The ***yellow flag*** will be used to indicate symptoms that demand an evaluation of severity and/or measures in order to mitigate the risks.

Allowances must be made for tree and timber characteristics (such as their specific proneness to failure and the typical strength of their wood fibres), weather conditions and any surrounding hazards (*cf* Arboricultural Association 2005).

2.4.2 Evaluation of severity

An accurate determination as to whether or not a tree is strong enough to be dismantled using climbing techniques might not generally be feasible. Yet some methods may be able to describe the likelihood of failure more precisely, by taking into account the strength loss due to decay and the initial safety margins of the trunk against fracture.

The Statics Integrated Assessment (SIA) method is a practitioners' application that is based on international engineering principles (*cf* Wessolly, Erb 1998, Wessolly 1995 and Brudi 2001). Using SIA, the safety margins of a specific tree against failure due to wind loading can be properly assessed from the trunk diameter and crown dimensions. The remaining load-bearing capacity of both solid and compromised stems is taken into account with regard to structural defects, like cracks or cavities. Mattheck *et al* (2006) criticise this approach to the likelihood of fracture, which is based on bending theory. Yet it has been successfully applied to a great number of trees in Europe, in combination with the material properties for different tree species listed in the Stuttgart Strength Tables (Wessolly, Erb 1998).

Failure of trees that have sufficient safety margins against fracture in strong winds will be very unlikely during dismantling operations, because usually the loads generated are significantly lower. Yet the extent of bending and the frequency under which load is applied to the trunk vary considerably in different rigging scenarios.

[*] *Picture courtesy of D. Neustaeter, Canada*

Assessing the severity of defects should always involve assessing the initial safety of a structure. It may be claimed that strength rapidly decreases when certain geometrical parameters fall below specific thresholds (e.g. sound wood having a residual wall thickness of less than 30% of the radius [t/R ratio 0.3] according to Mattheck, Breloer [1994]). But this can be compensated for to a much greater degree if the tree initially had a higher capability to sustain loads. Thus, a tree that is in a state where occurring loads reach the limit of its load-bearing capacity, may already be insufficiently safe, at a rather low degree of hollowness (Wessolly 1996, Detter *et al* 2005).

Old trees will have built up higher safety margins, due to their age and continuing incremental growth. Therefore, they can make up for a greater strength loss without a significant risk of failure. When referring to strength loss due to open cavities and decay, it is therefore important to consider the initial strength of the tree as a structure, when attempting to determine its load-bearing capacity in its current state.

The strength of a tree's anchorage in the ground can rarely be accurately assessed on a visual basis. Yet several sources describe a relation between the extent of root decay and the likelihood of failure:

> *"If more than one-third of the major buttress roots are missing or severely decayed, the tree should be considered a high risk. If more than one-half of the major buttress roots are missing or severely decayed, the tree should be considered a critical risk." (Fraedrich, Smiley 2002, S. 162)*

Coder (2004) refers to a spread of fruit bodies/conks or decay, along the circumference of the trunk to the extent of 50%, as being a threshold for critical risk of failure. As an example, he also states that the loss of one-third of all major roots could lead to a significant risk of failure. According to Kane (2006), trees should be considered hazardous and unsafe to climb if they have lost more than 50% of their root system.

If symptoms of severe defects are present, practical tests could enable arborists to evaluate the actual stability of the tree. Pulling tests designed according to engineering standards (like the Elasto-Inclinomethod, *cf* Wessolly 1995) involve a great deal of technical equipment and computer analysis. Simplified tests are familiar to many arborists, who may probe their anchor points before accessing the canopy by, for example, loading them with twice the climbing arborist's weight.

The Arboricultural Association (2005) recommends testing anchor points before climbing with the weight of two climbers or '*bouncing on the rope'*. Kane (2006) proposes a pull test for assessing the structural integrity of forks, the stem and the root system. From the motion of the stem, as a reaction to repeated loading, major defects could be detected. In a similar approach, Neustaeter (2006) presented a system of on-site tests for rating temporary anchor points, by applying '*load tests, pull tests or surge tests'*. He indicates that these practical methods for testing the stability of anchor points might also be applicable to testing the overall stability of trees (Neustaeter 2007). Yet, as long as no instrumentation is applied to monitor the small-scale reactions of stem and root system during a pulling test, no objective and reliable information can be obtained on a tree's structural integrity. Equally, this method will not be able to detect an eventual overloading of the structure during the test.

Practical arborists report that severely hazardous trees with strongly decayed roots could be diagnosed when installing the access line, and initially loading the anchor point, prior to ascending. In these cases, strong movements of the root plate and a strong inclination of the stem were visible (e.g. Howard 2006).

2.4.3 Key steps

The following system of key steps can be applied to visual tree inspection prior to rigging and dismantling operations, with regard to structural defects and failure of the tree as a load-bearing structure:

- rank the overall susceptibility of the tree species for failure of tree parts.
- identify compromised tree parts (branch, major crotch, stem, roots) and the magnitude of hazard.
- consider structural characteristics of the tree (tree form and development, stem inclination, pruning history, incremental growth).
- assess the potential loading of the compromised tree part in a rigging system (e.g. used as anchor point, redirect or main support, subjected to unilateral bending, torsion or compression).
- evaluate the likelihood of failure during the prospective rigging operation, eventually by probing the stability with simple load tests.
- evaluate the risk for climber, ground personnel and property.
- check if loading can be avoided, or if appropriate remedial measures can be applied.
- determine whether the tree is safe to climb and dismantle using standard practices, or consider the use of advanced techniques or machine supported felling.
- continue visual inspection while climbing and dismantling/rigging.

2.5 SYMPTOMS FOR TREE-RELATED HAZARD

2.5.1 Root system

In most cases, the anchor strength of the root system, counteracting any tipping forces, cannot be assessed visually. Only on rare occasions, when the stability of the tree is severely affected, will it be possible to detect a significant strength reduction when testing anchor points (e.g. by weight tests such as those described in the penultimate paragraph of the previous page).

Destabilised or tilted root flare, cracks in soil

A tilted root plate and a leaning stem are obvious indicators of lost anchoring strength. However, such acute signs of hazard are not always still visible when arborists are called in. Other symptoms, which frequently occur when root strength is compromised, may also point to a potential hazard when dismantling a tree.

> *"Soil mounding, cracking or similar disturbances at the base of the trunk behind the lean and/or broken roots are indicators of higher probability of failure." (Matheny, Clark 1994)*

According to Wessolly, Erb (1998), the static effective root zone extends over a distance around the stem base that roughly equals 1 to 1.5-times the diameter of the stem base. In this zone, cracks in the soil may be found after primary failure of the anchoring roots (Lonsdale 2000), or soil mounding may remain visible. Figure 2.6 (overleaf) illustrates how cracks may occur in the effective root zone (*cf* Wessolly, Erb 1998; Bader 2000).

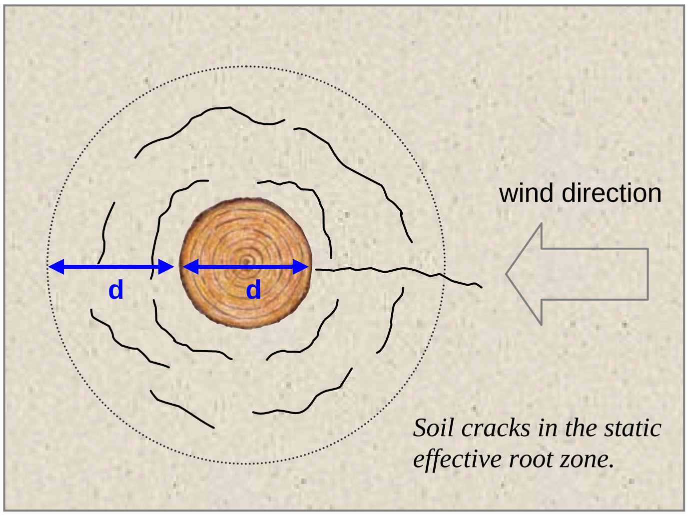


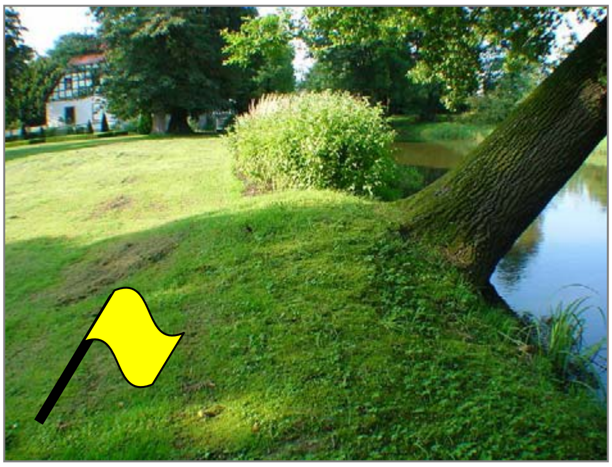
Figure 2.6 Effective root zone

Tilted root flare

A raised root flare and cracks in the soil indicate primary tipping failure. These trees may be very unstable.

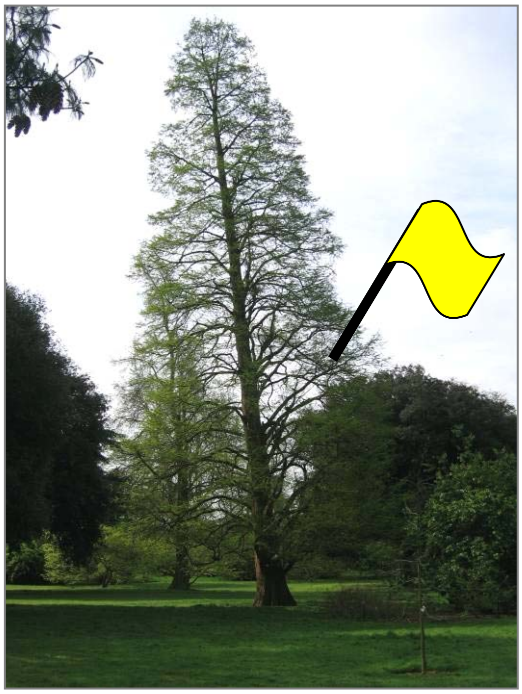
Cracks in the soil

It is possible for a tree to re-stabilise its root system after primary tipping failure, with such re-stabilisation often leaving soil mounding on one side of the stem base (see illustration overleaf). Whether or not such a tree is safe to climb is not sufficiently assessable by visual inspection alone. In the European Tree Worker Handbook, increased lean of the stem without a righting response of the leader is listed as an indicator of overloading and initiation of tipping failure. Trees with leaders that have changed to the vertical direction again as a result of negative geotropism are not considered hazardous (European Arboricultural Council 2005). However, this cannot be taken for granted, due to the fact that decay, or subsequent damage in the static effective root zone, may have occurred without there being any visible lean, and may still be present despite an apparent righting response.



Soil mounding

Due to overloading by wind, ice or snow, the roots might have been permanently deformed. Such primary failure may be detected by increased lean, without any visible change in the growth direction of the stem.



Leaning tree without righting response

Leaning trees experience additional loads generated from the eccentric weight of the crown. Findings from tree hazard assessments, based on tree-statics, indicate that this influence is only significant if lean exceeds an angle of roughly 15° from the vertical (tests carried out by the authors as well as Heilmann B., pers. comm. May 2007).

Due to stem inclination, loads generated from rigging operations may also increase. As shown in Chapter 5, the bending moment depends on the rope angle relative to the stem axis at the instant when the peak force occurs (i.e. when the fall of a log is being stopped by the rope). This angle may be increased on a slanting stem. Furthermore, the impact of a log hitting the stem tends to increase if the tree leans away from the direction of fall (see Chapter 8). Therefore, significant lean should always be considered as a hazard in a risk assessment.

Trees on slopes or embankments may also be destabilised as a result of erosion and landslide effects. If the root system is exposed from the soil, the soil-root matrix is detached (see illustration overleaf) and anchoring strength usually decreases. Strong, swaying movements may also reduce the stability of trees if their root systems are not adapted, or if soil conditions are adverse for oscillating loads (e.g. due to the 'parodontosis-effect', see section 2.6.4). Water-saturated soil, especially on trees that develop shallow root systems, may enhance these effects and reduce the anchoring force of the roots. Similarly, holes in the ground within the static effective root zone, often dug by animals (e.g. rabbits), may also destabilise the root system and result in an increased likelihood of failure, especially in a leaning tree.

Compromised roots in the static effective area

Mostly, root damage occurs when excavations for construction or roadworks are being carried out in the vicinity of trees. Lopping of roots, severing with machinery, overfilling of the root plate, or compressing the soil may result in severe damage and the loss of stability.

Eroded root-soil matrix

If large portions of the soil have been removed, the stability of a tree is often compromised.

Lopped roots with decay[*]

Root damage usually causes decay in the stem base. Vigorous trees react to the strength loss experienced from root lopping, by an increased formation of reaction wood (compensation growth). If this is not the case, the load-bearing capacity may be severely reduced.

Lopped roots are not always obvious. Signs like newly-constructed sewerage systems, underground cables, walls or buildings, fresh tar cover on pavements, or level changes in the surrounding terrain, hint at defects in the root system, especially if accompanied by die-back in the crown. Therefore, the vigour of a tree is also an important factor in visual inspection. Yet, in many cases, arborists are called in to dismantle trees because of obviously poor vigour. In such cases, it is essential to check for potential root damage by inspecting the site, talking to the tree owner and/or neighbours, and eventually excavating any suspect areas of the root zone.

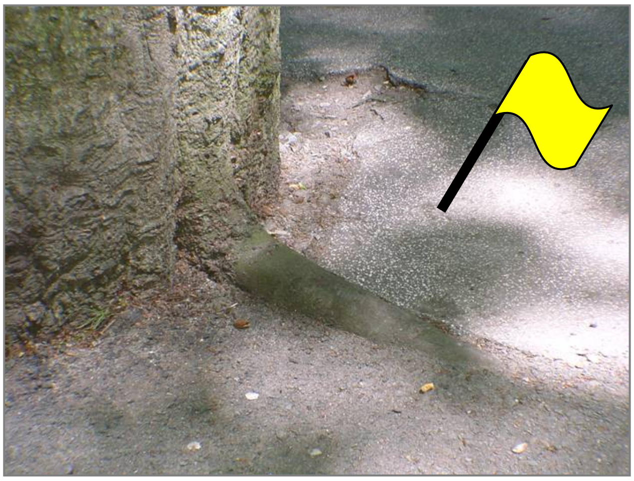
Severing of roots often leads to the formation of adventitious roots at the base of the trunk. These smaller roots are put out to supply the crown with sufficient amounts of water and nutrients. Yet, they are not able to support the tree mechanically due to their place of origin, angle of attachment and insufficient size. The formation of adventitious roots at the stem base can be a sign of extensive damage in the root system and may also indicate that the stability of the tree is compromised (Matheny, Clark 1994).

[*] *Picture courtesy of P. van Wassenaer, Canada*

Construction works

Construction work in the root zone may have resulted in severe lopping of roots. If construction has been carried out recently, the defect may very well be betrayed by a vigorous crown.

If roots were lopped a longer time ago, die-back in the crown, and eventually fruiting bodies of wood-decaying fungi, may be present.



Adventitious root

When the primary root system is not able to sustain water and nutrient supply, trees develop adventitious roots near the soil surface.

Root lopping or changes in the soil (compaction, overfilling, sealing of by tarmac) are often indicated by this symptom (Costello 2005).

Straight lines on a root flare should generally be taken as an indicator that mechanical damage has been done to the roots at some time during construction (Kane 2006). Trees that have been overfilled usually do not show buttress formation, and their stems enter the ground in a more or less parallel direction. If trees are not able to compensate for the loss of fine absorbent roots resulting from root damage, the bark on the buttress roots will often become dysfunctional and may even die back. In these cases, loose bark and other signs of cambial necrosis, as well as mycelia or fruiting bodies of sapwood-decaying fungi (such as, for example, the honey fungus *Armillaria spp*) may be detectable. Such signs would serve as indicators of reduced anchoring strength of the root system (*cf* Reinartz, Schlag 2006).

Many defects within the root area may only be detected if soil is removed from around the stem base. A root-trenching experiment indicated that a tree lost its stability gradually, when root and soil were removed at a decreasing distance from the stem. When the static effective root zone (expanding around the stem base at a distance of 1 to 1.5 times the diameter at the base) was affected, the tree lost its stability against occurring wind forces (Bader 2000).

Bark damage at the root crown

In the long term, dysfunction of major roots leads to visible defects, like sunken areas, or dead bark at the stem base.

In such cases, a root crown examination would be required, to investigate the extent of damage to roots in the static effective area.

The straight line formed by the newly constructed curb is also an indicator of root damage – obviously, no regard was paid to existing tree roots when excavating.

Therefore, an inspection of the roots and the stem of the base can focus on the immediate surrounding area of the stem base, and does not necessarily have to cover more than the static effective root zone (root crown inspection acc. to Matheny, Clark 1994). Also, it cannot be fully discounted that root damage at a greater distance from the stem may affect the stability of the tree. Large wounds will eventually cause rot in the static effective roots and in the stem base, thus affecting the load-bearing capacity.

The decision as to whether or not a tree is safe to dismantle by climbing techniques depends greatly on the secured information available, on the remaining load-bearing capacity of the tree and the loads generated by the rigging operations. It is essential that any safety assessment should rather err on the side of caution.

Root crown inspection[*]

If the root zone has been overfilled with soil, a thorough root crown examination might be required, to detect areas of dead bark, decay, lopped roots or adventitious roots that originate from the stem base.

[*] *Picture courtesy of D. Neustaeter, Canada*

Confined root spread

If the development of anchoring roots is confined, the stability may be compromised. In particular, species that are nitrogen independent and drought resistant (e.g. *Robinia pseudoacacia*) are capable of reaching reasonable height and enduring in sites with very limited root space. However, their stability could still be compromised.

In rigging operations, the loads applied are usually rather small when compared to wind loads occurring during storms. Therefore, it is unlikely that trees will be unable to withstand the loads generated from dismantling, if they were able to survive at the site they are growing in, even if it is very confined. But even a small extent of decay could considerably affect their stability.

Confined root zone

Some trees grow in narrow spaces and may not always be able to develop sufficiently strong anchoring systems.

Yet, in many cases, they will be perfectly stable against the wind loading they experience and, therefore, will also be safe to climb.

Fruit bodies of wood-decaying fungi

Decay in roots at a distance from the stem base may very well leave the tree with sufficient safety margins for regular dismantling scenarios to be applied, particularly if buttress roots that compensate for the decay have developed (*cf* Reinartz, Schlag 2006). As a precaution, adequate measures should be taken to reduce loads generated from rigging operations, or to avoid anchoring in the compromised tree.

If fruiting bodies of wood-decaying fungi are present at the very base of the stem, and the tree does not show signs of compensation growth, the load-bearing capacity may be significantly reduced. If decay extends to more than one-third of the roots, the tree should not be considered safe to climb, or further diagnosis should be carried out initially.

Meripilus giganteus at roots of Fagus sylvatica

The fruiting bodies of the Giant Polypore appear at a rather small distance from the stem. But the stem base shows an increase in diameter, due to compensation growth and formation of buttress roots.

This tree could be dismantled using climbing techniques, if no other symptoms for structural defects are present. However, other techniques should be preferred or (as a precaution) loads from rigging operations should be reduced as much as possible.

Kretzschmaria deusta on Betula pendula

The fruit bodies of Kretzschmaria deusta *on Birch indicate extensive decay at the stem base and a great likelihood of root damage. There are no visible signs of adequate compensation growth.*

The load-bearing capacity of this tree is severely reduced and loads generated from dismantling operations might lead to failure.

2.5.2 Stem base, root crown

Missing or decayed buttress roots

If buttress roots are decayed, the resistance of the tree to uprooting may be affected. It is virtually impossible to tell, simply from visual assessment, whether or not the tree is able to withstand loads generated from rigging in a worst-case scenario. If required, load tests could be applied to determine the residual strength of the respective tree's anchoring system.

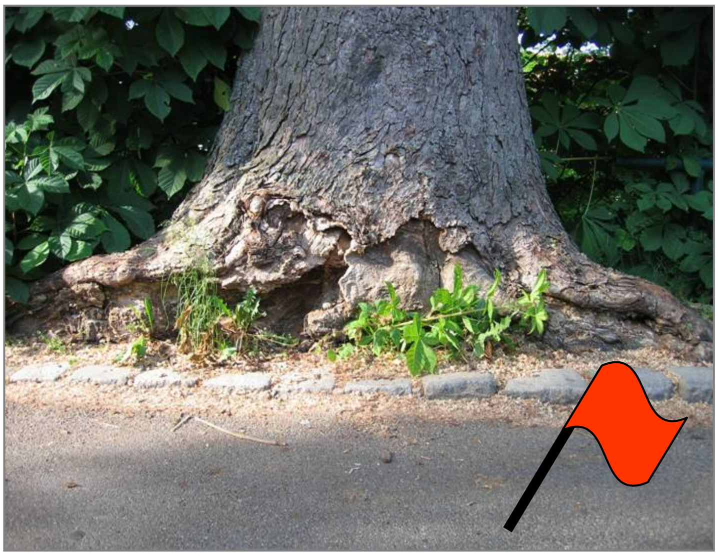
If more than one-third of the major roots are lopped, there is a great likelihood of failure due to wind forces. According to Fraedrich, Smiley (2002), the threshold for critical risk of failure is set at a loss of 50% of all major buttress roots. Kane (2006) states that a tree may very well be prone to failure during a dismantling operation, if buttress roots are decayed on more than half of the circumference.

It seems reasonable to recommend further consideration where more than one-third of the circumference is decayed on one side of the stem base, or where more than 50% of all buttress roots show structural damage. In these cases, alternative technical methods to climbing should be used to dismantle the tree, or, if rigging cannot be avoided, loads generated should be reduced as much as possible.

Decay in the root crown

In this case, two structural roots have been severed and one is already decayed. It depends on how many others are still intact, and able to withstand the loads generated from the wind, as to whether this tree would be safe to climb or not.

Generally speaking, wind loads can reach many times the bending moments generated during a dismantling operation. However, when a tree survives storms, no reliable conclusions can be drawn on its current stability.



Loss of buttress roots in more than one-third of the stem base

If decay at the buttress roots is not clearly restricted to a distinct area and not being compensated for by increased radial growth, a greater likelihood of failure should be expected.

Girdling roots

If trees develop roots that circle the stem base near the soil surface, bark will be included between root and stem. Growth in diameter will eventually result in girdling of the stem base, causing deformation of wood fibres and, sometimes, where damage occurs to the cambial layer under great pressure, this may provide an entry point for wood-decaying fungi.

Therefore, girdling roots …

> *"[…] may affect the health and structural stability of container-grown or field-grown trees. The severity of these defects is determined by their location (in the root system) and the amount of root system that remains unaffected. Severe defects may cause tree decline or structural failure." (Costello 2004)*

This is a common phenomenon in street trees, but it also occurs in park, garden and forest trees. It affects incremental growth and thus the tree's ability to gain strength with increasing height, or when decay occurs. Due to the fact that loads generated from rigging operations are rather small, girdling roots will not generally cause hazards for dismantling operations, but the presence of severe decay may eventually prove otherwise. It may, therefore, be necessary to inspect the root crown in order to detect stem decay in the vicinity of girdling roots.

Girdling root

This girdling root has affected diameter growth of the stem base at half its circumference. The formation of reaction wood and compensation growth is inhibited here.

In this case, the load-bearing capacity of the stem at the girdled base was measured by a pulling test. It was reduced to half of the stem's strength at greater height.

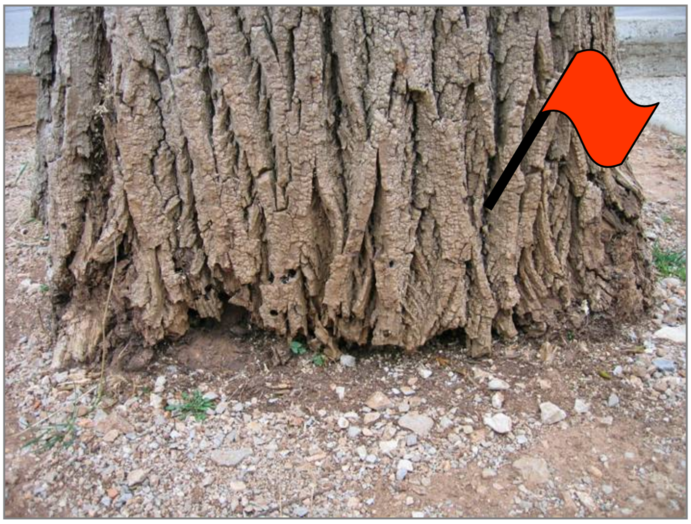
Failure of girdled tree

Due to the restrictions in incremental growth, this tree was unable to increase the diameter of its stem base.

The hazard was enhanced by wood-decaying fungi that were able to penetrate through the dysfunctional bark enclosed in the area of girdling.

Growth depressions, inclusions, loose bark

Growth depressions or sunken areas may result from cambial dysfunction and are often a consequence of hidden decay or root damage (Reinartz, Schlag 2006). If loose bark or cracks especially are found in a flattened area of the stem's circumference, it should be suspected that the load-bearing capacity is decreased due to rot.



This Poplar shows no signs of incremental growth at its base. No buttress roots are present.

Obviously more than half of the stem circumference is affected by decay.

Growth depression

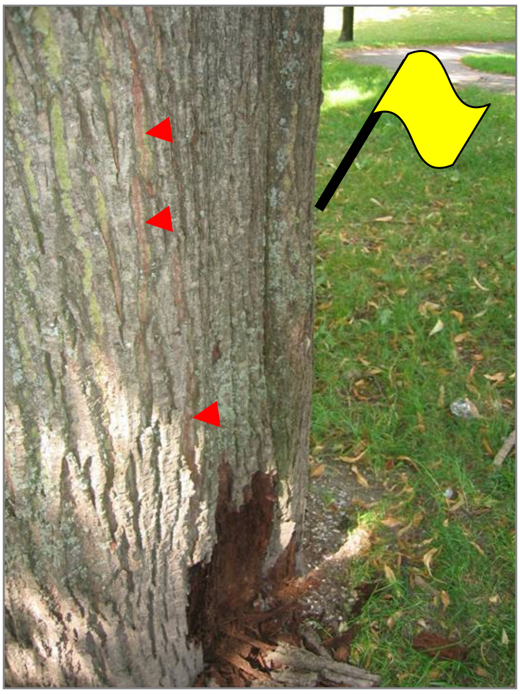
Grooves, seams or sunken areas at the stem base may be a result of, or be connected to, decay in the inner perimeter of the trunk. Some species, however, show a typical growth pattern, with deep inclusions on the trunk, e.g. *Carpinus betulus* or *Robinia pseudoacacia*. Also, developing buttress roots at the stem base often produce areas of reduced incremental growth. Even though the load may be supported mainly by the buttress roots, the sunken areas play an important role in visual inspection. Fruiting bodies of fungi, causing decay in the stem base, may appear in these grooves at first, simply because the rate of wood production (i.e. compensation growth counterbalancing decay processes) is slowed down. Therefore, it becomes easier for fungal mycelium to reach the cambium and form sporopores.

This decay column in F. sylvatica would not necessarily have posed any hazard during regular rigging and dismantling operations. Its presence in the cross-section was indicated by the groove on the left (red arrowhead).

Note the smaller distance between grooves on the right side of the cross-section, where residual walls are significantly thinner (red arrows).

Grooves and hidden decay

Typically, the distance between two grooves decreases as residual walls get thinner, due to lacking compensation growth. Bark damages in the vicinity of grooves, or along the circumference of the stem base, are clear indicators of a fungal infection and advanced spread of decay.



The sunken area above the loose section of bark has caused strong zones of growing compensation wood at its sides, discernible by the brown striation stripes.

Dead bark at the stem base

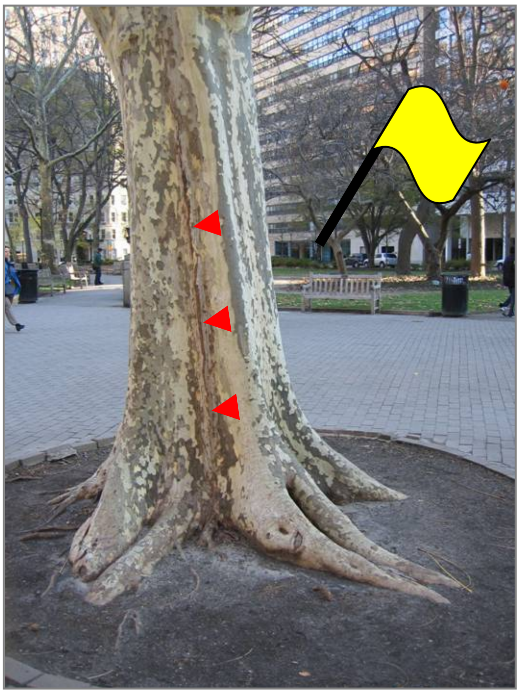
Another symptom of extensive decay eventually affecting the structural integrity of the lower trunk may be sawdust, milled by insects such as ants and large beetles.

Cracks

Cracks in the lower stem zone are often referred to as shear cracks. They are reported to occur in slanting trees (Mattheck, Breloer 1994, Hayes 2000), but also at the base of upright specimens, supposedly due to shear stress concentrations (according to Mattheck *et al* 2006). Typical shear cracks form on two opposite sides of the stem, because the entire stem is split in a vertical plane (*cf* Meilluer 2007). This effect seems to be limited to species that show great differences between longitudinal and tangential strength in their wood fibres (e.g. spruce). A strongly growing seam running along the stem axis, on the opposite side of a visible crack, often indicates that only a small residual wall is preventing splitting.

Cracks on one side only, and higher up along the stem, are often the result of excessive torsion, induced by asymmetric wind loads due to eccentric crown shape or lean. In such cases, a typical sideways skipping of the crack (stepwise) may often be noticed. This is a result of the formation of delamination cracks, between bundles of fibres, as the stem is twisted around its axis and splits in different places along its perimeter.

Not all cracks are formed due to mechanical failure. Recent publications indicate that initial damage may result from a variety of factors, including exposure to sunlight, temperature changes, poor genetic material and infection by *Verticillium* (Schneidewind 2006, Wilhelm *et al* 2006).



'*Shear crack' in* Platanus x acerifolia

In leaning trees, cracks (red arrowheads) may form due to the uneven dissipation of stresses in the perimeter of the cross-section.

If thin-shelled parts of the circumference are located between the thick buttress roots, loaded in compression and tension respectively, stresses may reach a critical value and cause longitudinal splitting of the residual wall.

These trees should be regarded as hazardous due to the eventual presence of decay and the primary failure of the residual wall. In cases where other techniques cannot be applied, precautionary measures have to be considered to prevent further splitting of the stem (e.g. using ratchet straps - see section 2.8).

On the opposite side of the crack, only a small residual wall is present (red arrow). This is indicated by a seam of strong cambial activity, which results in a ridge with younger bark at the surface.

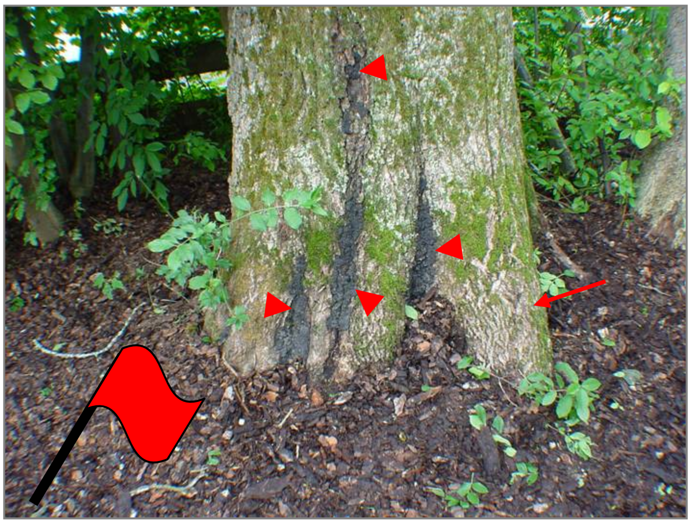
*Cracked cross-section with seam opposite the opening**

Decay, conks and other fungal fruiting bodies

Fruiting bodies appearing at the stem base indicate the presence of decay. If conks or mushrooms appear on one side of the stem base only, and if they are situated in grooves, between strongly growing buttress roots, the residual strength of the tree as a structure is usually still strong enough to bear regular dismantling operations. Even so, every precaution should still be taken to minimise loads generated and to secure a safe working position for the climber.

Where fruiting bodies occur on the actual buttress roots, the likelihood of failure is often greater. Generally speaking, the load-bearing capacity decreases as the areas of sound tissue between grooves or fruiting bodies get smaller, indicating only small residual walls.

* *Picture reprinted from Shigo 1989a, courtesy of Shigo and Trees Associates*



Kretzschmaria deusta on Fraxinus excelsior

On this side of the stem only small seams of sound wood are left between grooves with black fruiting bodies of Kretzschmaria deusta *(arrowheads).*

The load-bearing capacity is significantly diminished, yet at least one of the visible buttress roots (red arrow on the right) shows signs of compensation growth and solid wood.

If the buttress roots on the other sides are not affected, the tree could be considered safe to climb. Should the back side be decayed to a similar degree, the likelihood of failure during dismantling would be too great.

At a further stage of decay, Kane (2006) reports cracks that appear in buttress roots. Also Sinn (2000) lists cracks in buttress roots as a typical sign of immediate hazard. These cracks usually appear when a large portion of the stem is decayed and only small residual walls are left. Apparently, all types of recent primary failure indicate significant strength loss and are symptoms of very dangerous situations.

2.5.3 Stem

Decay, conks, cavities

Decay reduces the load-bearing capacity of stems. Kane (2006) indicates that stems are safe against fracture when they are less than 70% hollow – a criterion for proneness to wind breakage of conifers in the western parts of the USA (published by Wagener in 1963). Even the strength of trees that are not adequately safe against wind forces may be sufficient to withstand standard dismantling operations. Yet, the presence of decay, cavities, or fruit bodies (conks) demands a thorough risk assessment prior to climbing or rigging and, where necessary, even the use of diagnostic tools and expert consultation. Common methods of assessment and published thresholds for determining strength loss due to decay are described in Chapter 5.

Whether or not a compromised stem is sufficiently strong to sustain the load it is subjected to during rigging operations depends on the diameter, geometry and integrity of the stem, the material properties of sound wood tissues, the presence of compensation wood and, most importantly, the actual forces generated from rigging.

With regard to purely visual assessment, it seems important to state that critical stages of decay, where residual walls become very thin and mechanical failure under comparably small loads may occur, are often indicated by the presence of several symptoms like dead bark, growth depressions, crack formation, inrollings or seams and fruiting bodies of wood-decaying fungi. Accordingly, signs of compensation growth, strong wound-wood formation around cavity openings (often indicated by growth striations) and the absence of the above-mentioned symptoms for dysfunction in bark or sapwood, hint at a lower degree of strength loss.

Even proponents of conflicting methods of tree diagnosis agree that compensation growth, e.g. by the formation of wound-wood tissue around the opening of a cavity, acts as a reinforcement and restores some of the strength loss caused by decay in central parts of the trunk (Mattheck, Bethge 2003; Wessolly 2005).

Conks in and around a cavity in the lower trunk

The stem of this Celtis *would not have had sufficient strength to withstand an estimated wind load at speed 12 Beaufort, according to results of a pulling test (Elasto-Inclinomethod).*

Despite the strong formation of wound-wood next to the cavity, and the increased diameter at the base, the tree exhibits cracks in the bark on the right side (see arrowhead), indicating damage to the cambium and a thin residual wall at the stem base. In these cases, it is essential to carefully examine the amount and spread of sound wood fibres in the cross-section of the stem.

Lightning scars

Lightning can cause severe cracks in the stems and branches of trees (*cf* Coder 2004, Meilleur 2007). It is believed that initial cracks are able to propagate through the timber as a result of temperature changes, as well as bending or torsion generated by storms, or from dismantling operations. These cracks are suspected of having caused fatal accidents during rigging operations (Palmer, pers. comm. 2003). They may also be symptoms of decay because the openings improve the microclimatic conditions for wood-decaying fungi inside the trunk (better gaseous exchange, i.e. more oxygen and less carbon dioxide) until they have been successfully closed by wound wood (*cf* Schlag, 2006). Even slight movements of the crack surfaces, often induced by torsion of the crown in moderate wind, will effectively prevent the wood tissue from joining again.

In many cases, old trees (often Oaks) show several lightning scars along the perimeter of their stems. In order for an old, overgrown crack to propagate during dismantling operations, extensive shock loading, severe log impacts on the stem or considerable torsion stress would be required. Whether or not old cracks initiate failure of the entire structure depends very much on the diameter of the trunk and the loads generated. Slender stems with hidden cracks will require considerably lower stress to fail than trunks with greater diameter. But during exceptional storm events, it has been observed that old cracks reopened and may very well have initiated failure of mature Oaks. Therefore, it is essential to monitor old, overgrown cracks during the course of dismantling operations, and to be prepared to mitigate the risk of failure.

Stem split by lightning

Grooves, inrollings, seams

In a similar way to defects at the stem base, grooves, inrollings or seams, running in a longitudinal direction along the stem, may originate from central decay or old cracks that were closed by wound-wood formation. In both cases, a significant reduction of the load-bearing capacity should be anticipated.

Inrolling related to decay

It is unclear whether the internal decay results from a crack now closed by wound-wood, or if the decay extended from the perimeter of the trunk outward and at one point was able to penetrate the sapwood.

For a visual inspection, the consequences remain the same – an inrolling or groove indicates potential presence of extensive decay in the stem.

As grooves appear typically on some tree species, it is sometimes hard to differentiate between a defect or hazard and an unspecific phenomenon of growth. If grooves occur along a greater length of the stem of species of *Tilia*, for example, they are very often a result of an infection by wood-decaying fungi e.g. *Kr. deusta* (Reinartz, H., pers. comm. May 2007).

Cracks, poor grafts

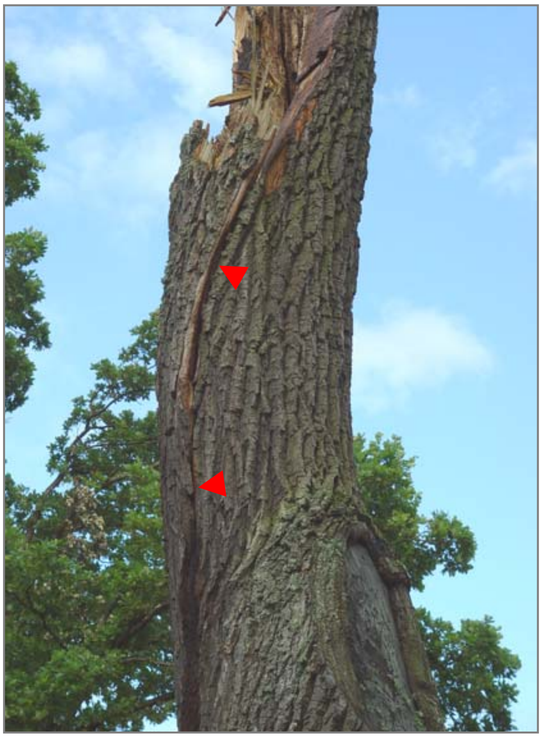
Hidden cracks may be indicated by rib-like protrusions (Lonsdale 1999), as well as grooves, both eventually showing signs of wound-wood formation. Generally speaking, fresh cracks without wound-wood can be considered more hazardous, because they are likely to propagate through the wooden body, along the fibre grain, when load is applied.

Cracks generated some time ago may be surrounded by newly-formed tissue that may be able to stop the crack propagating, by releasing stress concentrations at the extremities of the crack (Gordon 1991). However, it has also been observed that old cracks, especially if they have never been entirely closed by wound-wood, may open up again under extensive loads.

Fresh crack through the stem

If cracks are found on both sides of the stem, the load-bearing capacity may be significantly reduced (by more than 50%).

If rigging loads have to be applied, precautionary actions are recommended, to prevent failure due to longitudinal splitting (see section 2.8).



An old crack opened when the tree failed

This radial crack was indicated only by a groove on the perimeter of the stem. Since trees of the species Robinia pseudoacacia *typically form a structured stem, with long ribs and sunken areas, the crack would probably not have been detected.*

The residual load-bearing capacity was greater in the direction parallel to the crack. Therefore, it would have been advantageous to set up the rigging in this direction (cf Wessolly, Erb 1998).

Hidden cracks

The load-bearing capacity of a stem with a radial crack is significantly diminished where the crack reaches from one side to the other. One-sided longitudinal cracks of limited depth (such as many lightning scars) hardly reduce the strength in bending, provided the stem is loaded in a direction parallel to the direction of the opening (Wessolly, Erb 1998). However, crack propagation and reopening can present significant hazards.

Grafts can eventually form very weak connections because of included bark and the hidden presence of decay (Lonsdale 2000). A ring of sound wood may surround a cracked or severely compromised inner section, betraying an imminent risk of failure.

Poor graft connection[*]

[*] *Picture courtesy of U. Thomsen, Baumpflege Thomsen, Germany*

Other than grafts, horizontal cracks are rarely encountered in living trees. It is hard to determine whether stiff bark plates have cracked in a horizontal plane due to strong incremental growth, or if wood tissue actually has been fractured. Horizontal seams on the bark may also indicate overgrown objects like wire or steel bandages. Local restrictions in diameter growth and stress concentrations around such objects, may initiate cracks in the wooden body when stems containing them are loaded in bending. Cracks frequently appear in dead wood due to shrinkage resulting from drying and rot. If present, they are a distinct sign of strength loss in degraded wood, although the strength of living fibres could be adequate.

Horizontal crack[*]

The horizontal crack in the opened and degraded wood tissue indicates that the strength in the wounded section of this Beech has been reduced significantly.

It is essential to determine whether or not the sound wood around the decayed part is sufficiently strong to bear loads generated from prospective rigging operations.

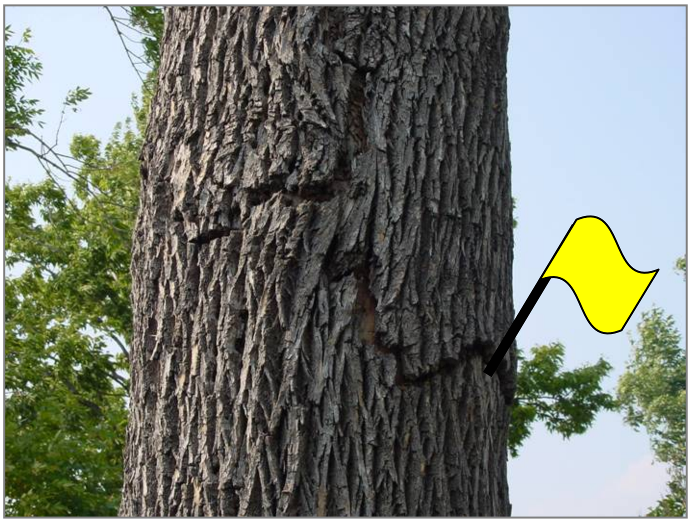
Loose or dead bark

Loose or cracked sections of bark indicate that bark and cambium are dead. This may result from mechanical damage, decay or dysfunction in the sapwood or fungal infections of the active vascular system. In such cases, the very parts of the trunk that would eventually have been able to compensate for strength loss by adaptive growth, are the parts that are compromised, and a tree showing such signs may very well be in a terminal condition.

Dead bark or cambial necrosis resulting from sun scald is usually a local problem that does not affect the strength of the underlying wood fibres during initial stages. But trees with these symptoms are no longer able to prevent fungal infections and compensate for decay in the load-bearing structure. They are, therefore, often prone to failure in their future development, and may be hazardous at the point in time when arborists are called in to dismantle them.

On the other hand, striation and extension cracks in the bark are signs of strong incremental growth. In general, the occurrence of striations is a sign of good vigour and an ability to compensate for decay, cracks and other structural defects (see Lonsdale 1999).

[*] *Picture courtesy of J. Scott, Vine & Branch, IN, USA*



Loose bark also poses an imminent danger to the climber, when strips of bark suddenly detach and cause the climber's spurs to lose their grip.

*Dead bark**

In a progressive state of the disease, the fibres may degrade due to fungal attack and decay.

Sun scald on Fagus sylvatica

Perennial canker

Target or perennial cankers may cause significantly weak regions in the stem, due to repeated degradation of fibres and the infection of newly-formed wound tissue and reaction wood (Lonsdale 2000). Cankers should be thoroughly inspected to determine the extent of decay.

However, determining the potential strength loss poses the same problems and uncertainty as is the case for central decay. Cankers also affect the outermost fibres that bear most of the load in bending (bending stresses concentrate on the periphery of a round section on two opposite sides). Therefore, decay initiated by cankers has a greater potential to affect the load-bearing capacity than central cavities decayed to the same extent.

* *Picture courtesy of D. Neustaeter, Canada*

Perennial canker on Ash

Some canker (resulting from infections by Netria) cause large wounds that cannot be closed by the formation of wound-wood. Even though the canker may not actively cause decay (Dujesiefken et al. 2005), it may enhance the effect of subsequent infections by other fungi.

2.5.4 Branch attachments

Included bark, V-shaped crotches

Included bark in V-shaped crotches significantly reduces the load-bearing capacity of the branch junction. Mattheck, Breloer (1997) even advocate the theory that incremental growth forces the two limbs apart. On the other hand, limb diameters are usually significantly reduced inside a V-shaped crotch, in comparison with their diameters higher above. This indicates that limited space inside the V-shaped crotch confines incremental growth and may compromise the cambium.

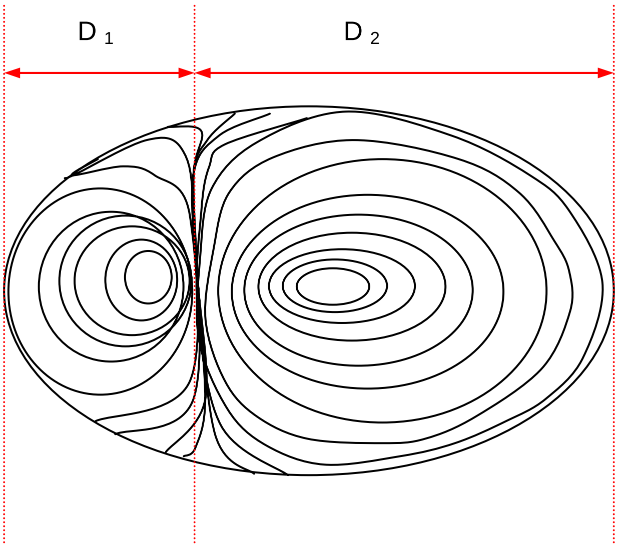
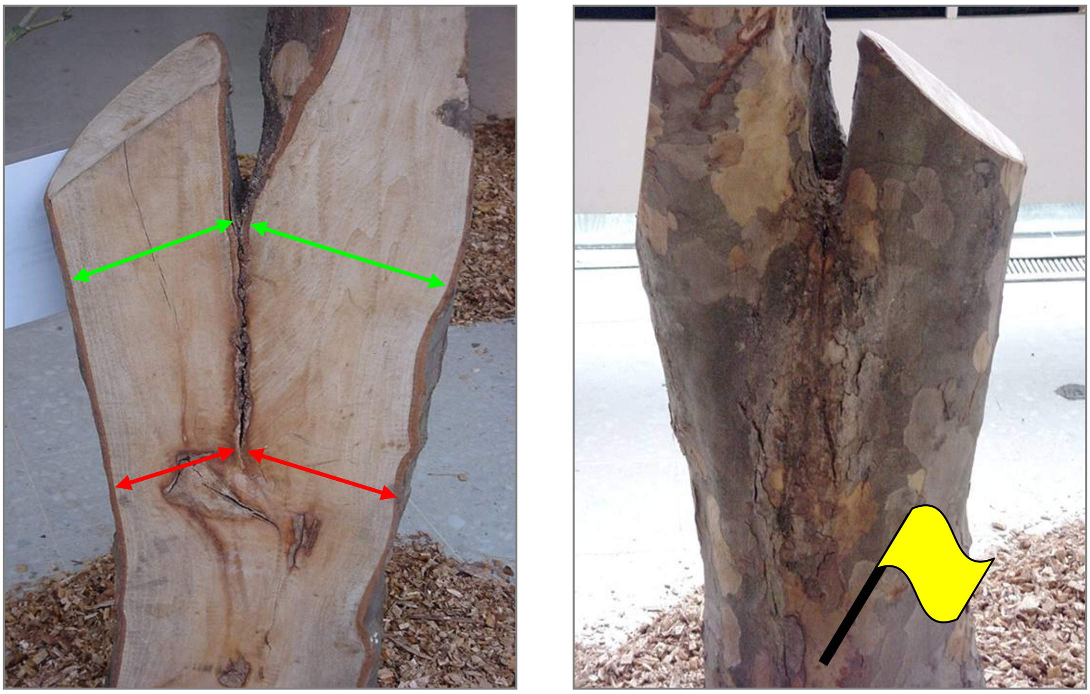


Figure 2.7 Cross-section of a V-shaped crotch with included bark

Often, the bark dies when enclosed in the crotch, a condition that may give rise to infestations by fungi and often leads to decay in the crotch (the strength of which is already reduced due to inhibited incremental growth). Dead bark in a crotch is hard to detect, yet it is an important sign of a higher probability of failure. In some cases, dead bark may be visible at the sides of a V-shaped crotch, where growth forms rib-like extrusions, also referred to as 'ears' (Mattheck, Breloer 1997). Sometimes, this symptom is the only indicator of extensive decay caused by *Kretzschmaira deusta* in V-shaped crotches of Beech.



*V-shaped crotch, longitudinal section and outside view**

The lack of a stable connection of wood fibres inside the crotch and the inhibited growth in diameter results in a greater likelihood of failure of V-shaped crotches with included bark. Smiley (2003) postulated that all co-dominant forks should be considered weak, whether bark was included or not. Lonsdale (2000) lists signs of significant hazard in forks and other unions. Among them are:

- structure of the branch bark ridge, which becomes a double ridge if bark is included
- angle above the union: co-dominants that do not bend upwards just above the union may bear excessive leverage from the weight of the crown

Species or cultivars of trees show different susceptibility to crotch failure. High risk types include, according to Lonsdale (2000):

- species of Willow and Poplar
- Horse Chestnut
- Beech
- Ash
- true Cedars

* *Exhibit courtesy of U. Thomsen, Pinneberg*

With reference to other publications (Hauer *et al* 1993), and also drawing on the experience of the authors, other tree species should be included:

- *Acer saccharinum*
- *Gleditsia triacanthos*
- *Robinia pseudoacacia*
- species of Elm
- some species and cultivars of Linden e.g. *Tilia tomemtosa*

Lonsdale reports a low risk of crotch failure for *Carpinus betulus, Alnus* and many conifers, among them Larch, Spruce and Redwood.

Generally speaking, V-shaped crotches with included bark should not be loaded when used as temporary anchor points in trees. Using redirects, or choosing a suitable rigging set-up that ensures that forks are being loaded in compression only, may reduce the likelihood of failure, even for structurally weak crotches. It seems natural that compression should be transferred through included bark and that the entire crotch should be able to withstand compression forces (as indicated in Mattheck, Breloer 1997). However, no study was found in the course of the present review that showed, on a reliable basis, that it is safe to load V-shaped crotches in compression.

Branches arising all at one level may also have a decreased load-bearing capacity (Clark, Matheny 1993). Another sign of a hazardous weak junction, according to Lonsdale (2000), is the presence of cracks and decay (see following paragraphs).

Old and active cracks

Cracks in a junction indicate that failure has occurred when the fork has been exposed to excessive loads. Crotches have to dissipate the load from two or more limbs and, therefore, often have to bear greater stress than other parts of the crown. Failure modes for crotches with included bark are described in Mattheck, Breloer 1997. Included bark acts like internal cracks, because notch stresses are concentrated when the fork is loaded in tension (Gordon 1978).

Crack in branch union, Horse Chestnut

The load-bearing capacity of a cracked fork may be so much reduced that failure could occur when the limbs are loaded.

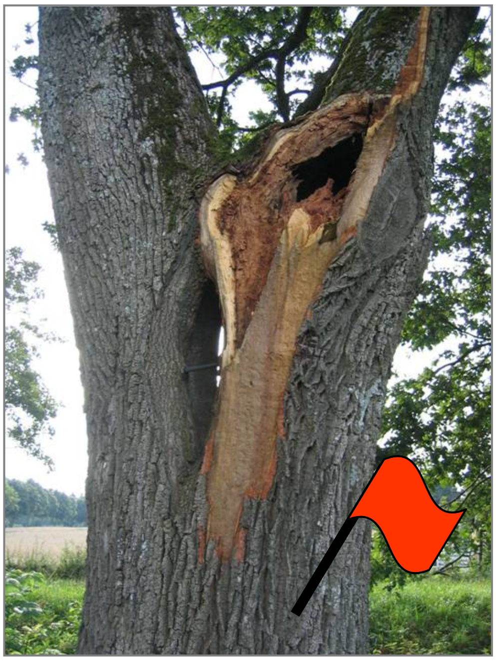
In some cases, the initial strength of the union may have been so great that even the separated halves are strong enough to support fairly low loads from climbing or rigging operations.

But without reliable tests on how much load the compromised structure can bear, and without precautionary measures to mitigate the risk of failure, it would be irresponsible to use such a stem as an anchor point (akin, for example, to using a karabiner with a crack in its metal).

If fresh or old cracks are present, the load-bearing capacity of branch attachments may be significantly reduced. Therefore, limbs attached here should not be used as anchor points without further investigation (load test). Regardless of whether load is applied in tension or compression, these cracks may result in failure.

Decay

Due to the increased stresses in a fork during storm gusts or rigging operations, thin-shelled cross-sections are prone to failure, due to shear and tangential splitting (delamination) of wood fibres. Often, the application of load produces cracks and the whole limb is torn out from the junction because the wood fibres are exposed to tangential tension, in response to which they are significantly less robust.



Thin-shelled crotch

If the sound wood in a branch union's cross-section is reduced to a thin wall only, the likelihood of failure increases because fibres are being pulled out.

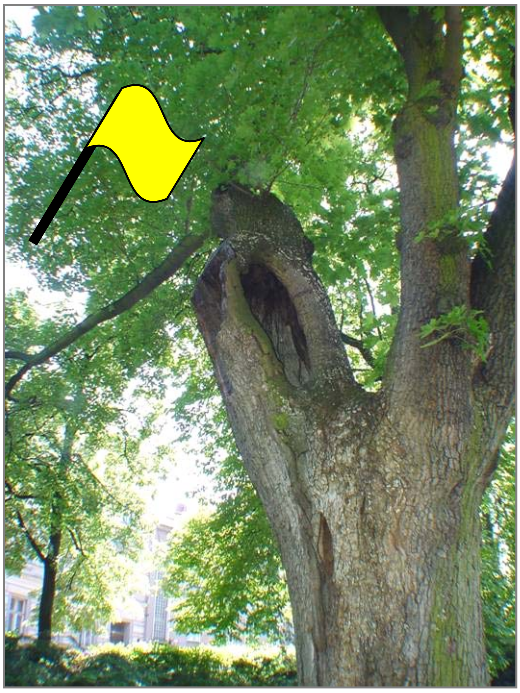
High forces lead to a longitudinal separation of the wood fibres, causing tear-out failure of the thin-walled shell. In these cases, compression failure of marginal fibres generated from bending stresses is not a relevant measure for the bearing capacity (cf chapter 5).

The same is true where the stem behind a branch attachment is severely decayed. Then the mechanical support, provided by overlapping layers of stem and branch tissue inside the trunk and in the branch collar (Shigo 1989), is lacking and, more or less, only the tangential hold of the wood fibres will be able to prevent fracture. This is a very weak connection that may fail under little load.

Large wounds extending into the centre of a branch, where living parenchyma cells are absent, lead to decay. Along the branch centre, near the pith, decay can spread rather quickly along the axis of a branch into the branch attachment and, depending on the vigour and species-dependent properties of the tree, even into the trunk. Therefore, decay in the vicinity of branch unions may also indicate a decreased bearing capacity of the attachment. At the same time, the lever of gravitational forces (the weight of the crown, at times increased by rain, snow and ice) is greater at the base of the branch. Therefore, branch decay in the vicinity of the crotch may increase the likelihood of failure significantly.

Stem decayed at the attachment

In sound trunks, anchorage of branches is provided by a sequence of branch and stem collars. If the stem is entirely hollow, the overlapping collars are absent and the branch is held only by the tangential strength of the residual wall.



Cavity next to the branch attachment

Due to poor compartmentalisation along the axis, decay often spreads into the fork, thus decreasing the load-bearing capacity of the limb.

2.5.5 Limbs, branches

Generally speaking, symptoms of structural weakness in limbs and branches do not differ much from those already previously discussed. Most defects, like central decay (finally resulting in thin-shelled cross-sections), cracks leading to reduced load-bearing diameters, and dead bark, occur both in the crown and in the stem. However, some special aspects may be added to those already mentioned.

Decay

Fracture is most likely on branches where decay has reduced the residual wall to a thin shell. These hazardous cross-sections are usually detectable by a dull, hollow sound, when using a mallet. Inspection from the ground may not reveal the likelihood of failure, especially in species that are anatomically capable of sustaining their crowns with only a small number of active annual rings (e.g. Ash, Horse Chestnut, Willow, Oak).

Thin-shelled branch

Thin-shelled cross-sections are susceptible to failure under impact loads and torsion stresses. If the residual wall falls below 4 cm thickness, they are often detectable with a mallet.

At the same time, further symptoms like little diameter growth, bark damage, woodpecker holes and conks usually become visible at such an extent of decay. Both sapwood and cambial layer may be dysfunctional and prone to penetration by pathogens.

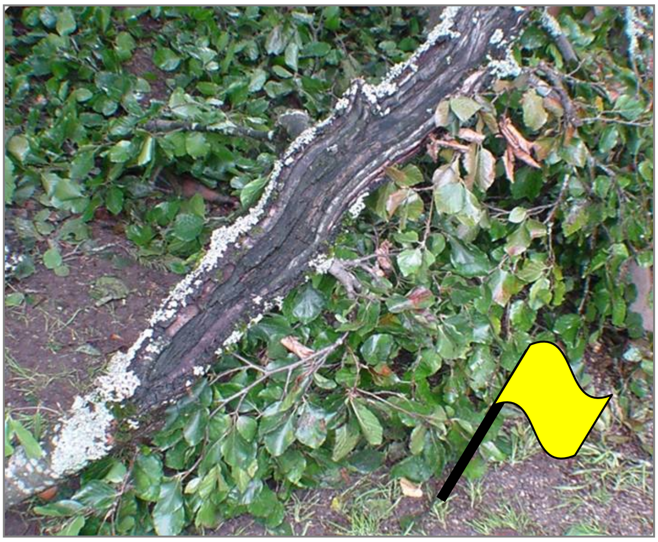
Depending on the ability of the species to compartmentalise infections, woodpecker holes and conks can be signs of extensive decay, as can growth depressions, bark damage and cavities. If such symptoms are present, visual inspection focussing on the integrity of anchor points is required to identify hazard branches, prior to undertaking rigging operations. For this purpose, the use of binoculars may sometimes be necessary. A tree's vigour and its ability to form compensation wood may be an important criterion in assessing the severity of such defects. If further inspection is required, primary anchor points that are considered to be safe could be used to access the canopy, in order to more closely investigate the bearing capacity of other anchor points that might be used in rigging operations.

Decay initially spreading from large pruning wounds may affect the strength of branches (Shigo 1991). If multiple branches have formed at the perimeter of a large topping cut, bark inclusions and poor incremental growth (due to lack of space) may give rise to weak attachments (Matheny, Clark 1994). Ornamental trees that form overhanging crowns may show substantial damage on the upward side of their top branches. Cultivars of Beech (*F. sylvatica 'Pendula'*), especially, are susceptible to sun scald that may give rise to extensive decay on the topside of the branches in the periphery of the crown (although, due to the successive growth in height of such trees, limbs in the centre of the crown may also be affected by decay). In particular, the fungus *Oudemansiella mucida* is reported to cause significant strength loss on Beech branches damaged by sun scald (K. Schöpe, pers. comm. 2007).

Woodpecker hole

The activity of a woodpecker may indicate extensive decay in the cross-section of a branch, that might otherwise be available for use as an anchor point in climbing or rigging operations.

If foliage and twigs show signs of decline, it may be concluded that decay has spread into the sapwood of the branch and caused a wide and extended decay column.



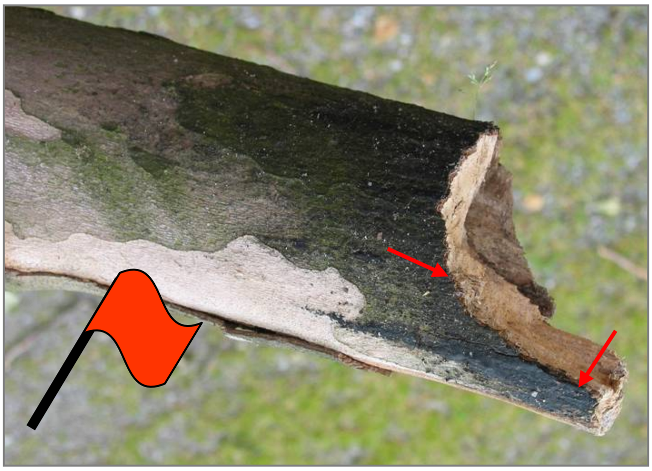
Bark necrosis and decay on Beech

A large portion of the cross-section is missing as a result of sun scald.

The defect is hard to detect by visual inspection from the ground.

These defects are often discernible from the ground only by an altered shape of the branch. Wound-wood develops at the sides of the branch in order to close the wound. Due to repeated necrosis of the newly-formed bark, the width of the branch increases locally and uneven structured bark may be visible from underneath. These branches show a greater likelihood of failure, and should not be used as anchor points if their residual load-bearing capacity cannot be reliably assessed.

In recent times, the Massaria-disease, caused by *Splanchnonema platani* ([Ces.] Barr), has led to decay in branches of London Plane (*Platanus acerifolia*) and subsequent failures in Germany and Switzerland (Dujesiefken *et al* 2005, Wohlers 2005). These defects often become visible on the upside of branches of up to 25 cm diameter only (see illustration overleaf). The infection renders a pinkish bark before the occurrence of sporopores changes the colour to black. The extensive decay under discoloured bark is reported to cause brittle failure under loading, especially after the black fruiting bodies develop (Wohlers, pers. comm. 2007). It is quite likely that this disease will, eventually, also colonise British trees, unless it can be held in check by the less favourable climatic conditions.



Failure of branch infected by the Massaria-disease*

The upside of the branch is often covered with black, dust-like sporopores (red arrows) after an infection by the Massaria-disease.

Fracture of branch with the Massaria-disease†

Previous mechanical failure

As with other defects, internal cracks are reported to change the form of a branch as a result of compensation growth. Therefore, irregularities in the shape of a branch should be rated as signs of an eventual hidden structural defect.

> *"Branches and trunks may possess internal cracks without any obvious external indication. We have observed sections of branches with internal cracks to be asymmetric in form, sometimes diamond-shaped [...]." (Matheny, Clark 1994)*

Mechanical failure decreases the strength of branches significantly. Split forks may leave the remaining co-dominant structurally weak (strength loss of 75% in the direction perpendicular to the split, according to Wessolly, Erb 1998). Similarly, horizontal cracks in solid cross sections, arising from radial delamination of fibres in an upward bent branch ('hazard beam' according to Mattheck, Breloer 1994), are associated with a 50% reduction in strength (*cf* Wessolly, Erb 1998; Mattheck *et al* 2006).

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* *Picture courtesy of A. Wohlers, Zürich*
† *Picture courtesy of R. Kehr, Göttingen*

The strength of this delaminated branch will be roughly 50% of the intact cross-section (according to static calculations). However, even smaller loads may result in failure due to crack propagation.

Split branch ('hazard beam')

Splitting a branch in half reduces its strength to 25% of the load-bearing capacity of the round cross-section in a perpendicular plane to the surface of the crack.

Split fork

Large gaps in the crown of a tree are also common signs of previous mechanical failure of branches. If limbs are loaded beyond their elastic limit by the weight of snow, or the force of a gust, they can be permanently deformed (primary failure). If this occurs, the branches can change their position in the crown and may open up a formerly dense crown. This may be used as an indicator of reduced bearing capacity of the respective branches, and of the need for a closer inspection of this part of the crown.

Xylobiontic insects

Wood-boring beetles are capable of damaging large fractions of a branch's wooden body, thus reducing its strength significantly. The Large Poplar Longhorned Beetle (*Saperda carcharias*) is responsible for damage mainly in the poplar genus, whereas the Asian Longhorned Beetle (*Anoplophora glabripennis*), recently also found in Europe, seems to infest any species of broad-leaved tree. The damage affecting stability is hidden inside the branches and may only be detected by bore holes, sawdust or die-back of the branch and eventual bark damage.

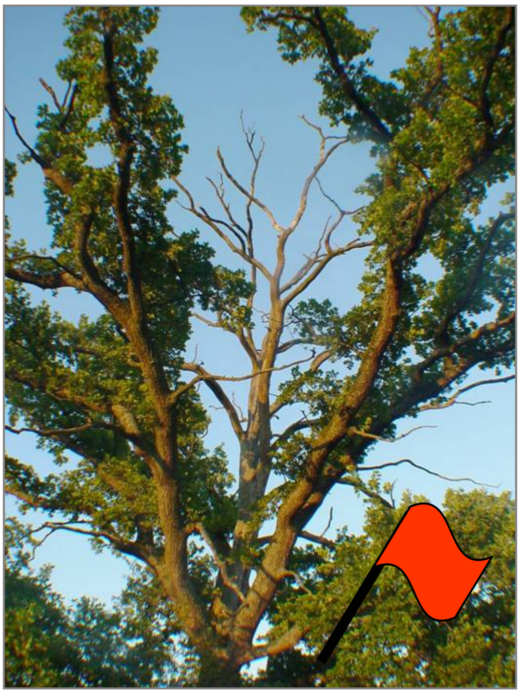
Bore holes of S. carcharias

Large cavities, formed by the larvae, reach the perimeter of the branch and expose the wooden fibres to infestations of wood-decaying fungi.

Some branches found in this research, on a 20 year old specimen of P. canescens *in Germany, were so largely hollowed that they posed a hazard to the road traffic beneath.*

Dead or loose parts of the crown

Dead branches are an obvious hazard to tree climbers and their crew. As the actual risk is hard to determine, dead branches should always be removed early in the course of a dismantling operation. They should never be used as anchor points for rigging or climbing operations.



Dead branches in Oak

The likelihood of fracture of dead branches varies with species. Dead wood in Beech and Ash, for example, is known to break easily at the base. In Oak trees, strong branches usually remain in the crown after they die back and decompose before falling to the ground in small pieces.

Nevertheless, oscillations induced by rigging operations may give rise to cracks in the dead wood and also lead to fracture of these dead branches. The risk of injury and damages can be avoided by removing all dead branches from the tree being dismantled, as early as possible during a dismantling operation.

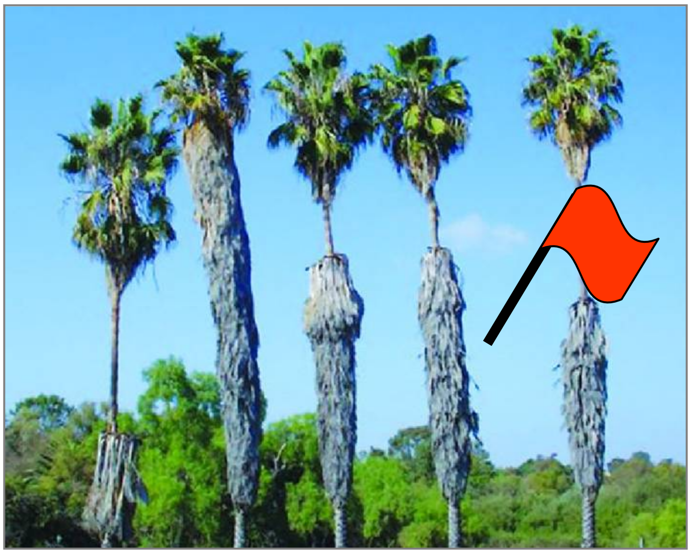
Dead branches cannot provide reliable support for anchor points.

Hanging and broken branches also pose risks to climbers and other personnel on site, and should, therefore, be removed at the beginning of a dismantling operation, or at least when the climber or groundworkers need to position themselves under, or in the vicinity of, such branches.

Hanging branches

Even though the broken top seems to be 'firmly stuck' in a crotch, it may very well come loose, due to sways of the crown induced by climbing or dismantling the tree.

A specific hazard from Palms was reported by Magargal (2007). Skirts of loose Palm fronds may slide down the trunk while a climber is ascending the palm. Under the weight of the fronds, the arborist is immobilised in his climbing system and usually unable to lift the load. In several cases, suffocation caused death within minutes, whilst in other cases rescue by a qualified colleague was required. Magargal lists signs of increased probability of sloughing (shedding of skirts of fronds) on Palms, a phenomenon that seems to be limited to the genus Washingtonia (Pedersen, pers. comm. 2007).



Hazardous sloughing in Washingtonia palms[*]

[*] *Picture reprinted from Magargan (2007), courtesy of A. Pedersen*

Structurally weak branches

Re-growth after topping, watersprouts or, generally speaking, epicormic shoots, have to be considered structurally weak and prone to failure (Shigo 1991).

> *"Watersprouts were found to be 49% weaker than naturally occurring silver maple branches and strength appeared to decrease as the watersprouts grew in size. (Dahle et al 2006)"*

Also, abrupt bends in branches (often occurring as a result of old pruning cuts) or other deviations of the longitudinal axis should be considered less strong (Lonsdale 2000), and should therefore be avoided as anchor points. Weakness may also occur due to poor weight distribution, multiple pruning wounds (Clark, Matheney 1993), flush cuts and poor taper.

Long limbs, with heavy end-weight may furthermore be susceptible to sudden limb drop, which is reported to be *"associated with rains that break a drought"* (Matheny, Clark 1994). Mattheck, Breloer (1993) also states that the mechanical function of wood rays contributes to crack formation and fracture of limbs under hot and dry conditions.

The mechanism is as yet unclear. The likelihood of sudden limb drop happening during a dismantling operation appears to be rather low. It may be worth being aware of the fact that the load-bearing capacity of horizontal limbs of certain species may be reduced under certain climatic conditions. According to a list contained in Matheny, Clark (1994), species for which this may be a characteristic are included in the following genera:

- Aesculus
- Castanaea
- Eucalyptus
- Fagus
- Fraxinus
- Liquidambar
- Pinus
- Platanus
- Populus
- Quercus
- Salix
- Ulmus

2.6 OVERALL STRENGTH AND STRUCTURAL STABILITY

2.6.1 Susceptibility to storm damage

Trees that are easily damaged by storms may also be regarded as more prone to failure during dismantling operations. This is only partially true, because the likelihood of wind breakage is also affected by the typical aerodynamic features of a tree species, but the strength of the load-bearing structure also plays an important role.

Nevertheless, a list of tree species that are considered to be more prone to failure in storms may serve as an indicator of the overall strength of trees of those species. In considering vegetation typical to North America, Hauer (1993) classified tree species in terms of their susceptibility to storm damage, as follows:

Susceptible

- *Acer saccharinum*
- *Celtis occidentalis*
- *Fraxinus pennsylvanica*
- *Gleditsia triacanthos*
- *Prunus serotina*
- *Pyrus calleryana ‘Bradford’*
- *Quercus palustris*
- *Robinia pseudoacacia*
- *Tilia americana*
- *Ulmus americana*
- *Ulmus pumila*

Intermediate

- *Acer pseudoplatanus*
- *Acer rubrum*
- *Acer saccharum*
- *Fraxinus americana*
- *Liriodendron tulipifera*
- *Pinus strobus*
- *Quercus macrocarpa*
- *Quercus rubra*

Resistant

- *Acer platanoides*
- *Carpinus caroliniana*
- *Catalpa ssp.*
- *Gingko biloba*
- *Gymnocladus dioicus*
- *Juglans nigra*
- *Liquidambar styraciflua*
- *Ostrya virginiana*
- *Quercus alba*
- *Quercus bicolor*
- *Taxodium distichum*
- *Thuja occidentalis*
- *Tilia cordata*
- *Tilia tomentosa*
- *Tsuga canadensis*

This classification may be worth discussing and extending to the tree species commonly found in the UK.

2.6.2 Observations on proneness to failure of genera and species

Lonsdale (1999) provides observations on several species that mirror the experiences of a number of tree experts. This list contains data on prevailing forms of failure, material properties of the species’ wood fibres and proneness to failure.

Among genera that were named frequently as prone to decay-related failure were *Aesculus*, *Fagus*, *Populus* and *Salix*. The frequency of failure due to weak forks was evaluated as moderate to high for the genera *Aesculus*, *Cedrus*, *Chamaecyparis*, *Cupressocyparis*, *Fagus*, *Fraxinus*, *Liriodendron*, *Populus* and *Salix*.

Also, the International Tree Failure Database, in continuation of the California Tree Failure Database, can serve as a source of information about predominant modes of, and the susceptibility to, failure. For example, an excerpt from the Tree Failure Database (provided by K. Jones on April 24th 2006) shows significantly greater numbers of limb failures for:

- *Cupressus macrocarpa*
- *Eucalyptus globulus*
- *Fraxinus velutina*
- *Liquidambar styraciflua*
- *Pinus pinea*
- *Pinus radiata*
- *Quercus agrifolia*
- *Quercus lobata*

However, as the figures provided in the International Tree Failure Database are absolute numbers, they do not provide information that can be used to calculate the actual likelihood of branch failure in a certain tree species.

In the course of the present study, strength properties of green wood fibres, as found in a review of the available literature, were transformed into tables and diagrams. The resulting species-dependent characteristics of stem and branch wood are listed in Chapter 5, which is more particularly concerned with the load-bearing capacity of tree species. The information presented in that chapter may serve as a reference for practitioners in assessing the load-bearing capacity of trees as structures, and improve their ability to assess risks with regard to tree-related hazards.

2.6.3 Slenderness and susceptibility to oscillation

If slender trees have been deprived of their lower branches, they may be susceptible to strong sway during rigging operations. The harmonic response of the tree stem may lead to increased loads and, thus, to a greater likelihood of failure (Lonsdale 1999, James 2003). The so-called 'paradontosis-effect' occurs when the water-saturated root plate of a tree begins to slip, which often occurs on impermeable layers in the soil. This phenomenon is confined mainly to forest trees or high, slender conifers growing in unfavourable soil conditions (*cf* Wessolly, Erb 1998).

However, under water saturation, the likelihood of slippage in the root-soil matrix increases even without periodic oscillation (see Chapter 5). When dismantling slender trees with structurally weak stems and/or water-saturated root systems, or trees prone to root failure, the generation of strong oscillations should be avoided (e.g. by retaining lateral branches along the stem when cutting the top, see 2.8), and loads from rigging operations should be minimised (see Chapter 8).

While slenderness is a decisive criterion for the risk involved in stem oscillation, there does not seem to be a definite threshold for slenderness with regard to proneness to failure of tree stems and branches. Despite existing publications by Mattheck *et al* (2001), other authors have not been able to determine that the likelihood of failure increases above a particular slenderness ratio (h/d or height *vs* diameter for stems). Gruber (2007) published data on slenderness for stems that does not indicate that the likelihood of failure increases above the h/d ratio of 50, as claimed by Mattheck *et al* (2001).

Enhanced susceptibility to oscillation*

Broad-leaved trees with an intact crown generally do not show a distinct natural frequency of oscillation (James et al 2006).

The bare stem of a conifer may very well be susceptible to strong sway when the tip is cut and lowered, independent of whether a lowering line is being used, or the section is being dropped directly to the ground.

Adamietz (2006) studied branches of two tree species with regard to their ratio of length *vs* diameter (l/D). The findings did not support the existence of a distinct threshold of an l/d ratio of 40 for the safety of branches against fracture, as recently postulated in Mattheck's VTA method (Koch 2007).

2.7 WOOD-DECAYING FUNGI

Strength loss, due to fungal decay of wood fibres, strongly depends on the capacity of fungal hyphae to advance through reaction zones and the ability of an infected tree to compensate for decay by increased incremental growth. By gaining a larger diameter and compartmentalising damage inside the wooden body, trees may remain safe to climb for a long time, despite the presence of decay.

Reinartz, Schlag (2006) describe the basic principles of decay and compensation growth, and list specific parameters for determining hazards from trees which are infected by wood-decaying fungi. Among these parameters are:

- die-back of the crown
- lack of the formation of buttress roots or other compensation growth (growth deficiencies)
- areas of dead bark at the buttress roots
- extensive decay, without discrete margins or the formation of wound-tissue
- formation of fruit bodies close to the stem, or at visually intact stem sections

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** Picture courtesy of S. Klima, Germany*

Arborists are frequently given the task of removing trees infected by fungi, often even in advanced states of decline. In such circumstances, it is essential to determine when structural damage may render the tree unsafe to climb. Naturally, authors of publications on this issue cannot give incontrovertible advice on how to judge when a tree is sufficiently strong, or when climbing a tree may be dangerous. The factors involved are too complex to be described in an article or visualised in pictures and drawings.

Therefore, in this report too, only indications can be given of occasions when the rapid degradation of a tree's structural integrity has been reported in the past, and so should be considered as a possibility. The evaluation of the symptoms of decay, and the assessment of the residual strength of a tree infected with wood-decaying fungi, can only be made after training and years of experience.

Some trees with decay may be potentially hazardous during a standard rigging operation. If stability is in question, these trees should preferably be dismantled using aerial lifts or cranes. In cases where no other technical option is at hand, the stability of a tree may have to be evaluated by specific experts using diagnostic devices (sound-tomography, high sensitivity pulling test, e.g. using the Elasto-Inclinomethod).

2.7.1 Root plate and stem base

The following fungi usually occur as a result of root damage and are found in roots or at the base of the stem. *Kretzschmaria deusta* has been reported as a reason for failure during rigging or climbing operations (Wessolly, pers. comm. 2005). Due to their ability to cause rapid and severe decay in roots, and/or the stem base, some species should be considered a hazard for climbing arborists. Species known to have such potential are (but are not limited to):

- *Armillaria spec.*
- *Ganoderma adspersum* e.g. on Ash (Reinartz, Schlag 1999a; Schwarze 2003)
- *Heterobasidion annosum* e.g. on Spruce
- *Kretzschmaria deusta* e.g. on Lime (Reinartz, Schlag 1999b)
- *Meripilus giganteus* in an advanced stage of infection

Conks of Ganoderma

A fruiting body of Birch polypore on Birch

2.7.2 Stem and limbs

Especially in the advanced stages of decay, the following fungi species are able to cause a significant degradation of wood strength, resulting in a greater likelihood of failure. Failure during climbing operations was reported on an advanced infection of Birch by *Piptoporus betulina*. In such cases, wood fibres were found to be severely degraded, even though they did not visibly appear to have altered greatly. Some species of fungi, commonly found on stems or in the crown, that may indicate a greater risk of failure during dismantling operations are (but are not limited to):

- *Piptoporus betulinus*, almost exclusively on Birch
- *Fomes fomentarius*
- *Kretzschmaria deusta*, in V-shaped crotches on Beech
- *Polyporus squammosus*, on Sycamore (*Acer pseudoplatanus*)
- *Oudemansiella mucida*, on branches of Beech (*Fagus sylvatica*)

2.8 POTENTIAL REMEDIAL ACTION

Several authors (e.g. Donzelli, Lilly 2002; Kane 2006) list eventual measures for mitigating risks when compromised trees need to be dismantled. Also, practical arborists recommend a number of options in order to avoid hazardous scenarios. Among these are:

1. Avoid climbing the compromised tree by:

- using aerial lifts and mobile elevating work platforms (MEWPs)
- carrying out crane removal
- working from adjacent trees (which in itself poses the problem of still having to attach a lanyard to the compromised tree, in order to obtain correct work positioning)

2. Reduce the likelihood of failure by:

- tying or cinching up the trunk with ratchet straps, in order to prevent splitting
- bolting split crotches to stop crack propagation
- loading crotches with included bark in compression only
- guying the tree to the ground, or to adjacent trees, in order to dissipate peak loads and prevent stem fracture and/or tipping failure

Use of ratchet straps[*]

3. Reduce loads generated in rigging operations (see Chapter 8) by:

- cutting shorter sections, thus reducing their weight and distance of fall.
- using appropriate arborist techniques (e.g. the fish-pole technique, *cf* Donzelli, S. Lilly 2001).
- positioning the friction device at the best position (with regards to stem inclination and cutting direction).
- adding more rope to the rigging system, by including another arborist block at the base of the tree being dismantled, and shifting the friction device to an adjacent tree (Palmer, K., pers. comm. 2003).
- retaining lower branches while taking the top out, in order to damp stem oscillations.

[*] *Picture courtesy of K. Palmer, USA*

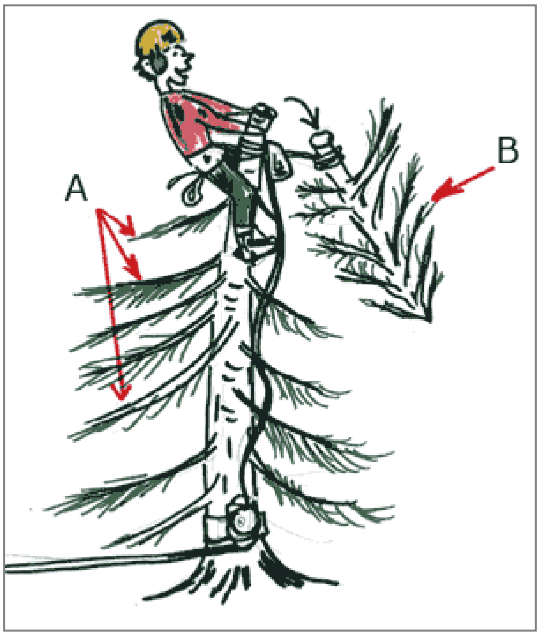

Figure 2.8 Damping of sway*

Figure 2.8 illustrates the retention of the lower branches along the stem, in order to avoid strong oscillation before removing and lowering the top of the crown (*cf* James 2003).

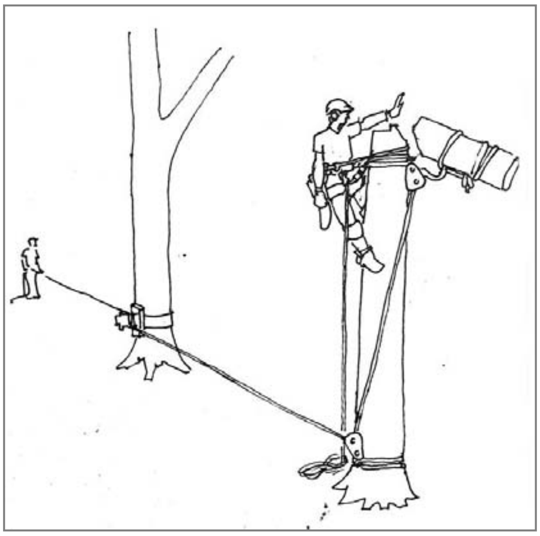

Figure 2.9 Adding more rope to the rigging†

Figure 2.9 illustrates the principle of adding more rope to the rigging system, by diverting the fall of the lowering line through an additional block at the base of the trunk and placing the friction device on an adjacent tree. By this method, more rope can be added to the rigging system without altering the rope angles at the rigging point (changing the rope angles could eventually increase the bending moment generated in the stem).

* *Drawing courtesy of Q. Adjei-Freeman, Berlin*
† *Modified, original drawings by Brian Kotwica reprinted from Donzelli, Lilly 2001 courtesy of International Society of Arboriculture, USA*

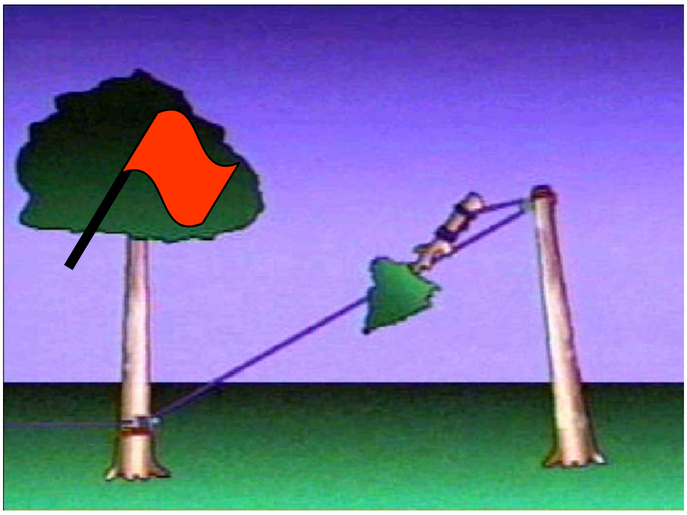

Figure 2.10 Adverse rigging set-up*

The rigging set-up shown in Figure 2.10 has been warned against by experienced arborists. A set-up of this type is disadvantageous because it generates a greater bending moment on the tree (in both the trunk and the anchoring roots) than the standard procedure (i.e. friction device at the base of the tree being felled). In order to add rope to the rigging system, the fall of the rope should be redirected at the base of the tree as shown in Figure 2.9.

* *Diagram courtesy of K. Palmer, USA*

3 SAFE RIGGING STRATEGY AND SYSTEMS

The aim of this chapter is to present means by which practising arborists can carry out assessments of proposed tree rigging operations, and arrive at strategies, systems and techniques appropriate to the situations under consideration. The process described in this chapter involves referring to a hierarchy of charts/diagrams which can give assistance in:

- establishing a safe overall strategy for carrying out the work
- deciding on a specific rigging technique for removing a particular section
- selecting and setting up appropriate equipment for removing the section
- carrying out the removal operation
- reviewing the outcome and proceeding to the next section

The contents of the charts/diagrams have been established via extended discussions with a number of practising arborists who have had considerable experience, over many years, in undertaking rigging operations They therefore represent the accumulated wisdom of those professional persons concerned. They have not been developed through scientific research in the same way as other results in this report may have been. As such, they can only be regarded as representing current practice, and will undoubtedly be subject to change with future experience.

3.1 ESTABLISHING A SAFE STRATEGY

In deciding how to carry out dismantling work on a tree, it is essential to first make an assessment of the best way to undertake the work i.e. to determine an overall strategy for the work. The first stage of this process is a Visual Tree Inspection i.e. an inspection of the tree from the ground or other available vantage point(s), in order to assess any features of the tree, or related hazards, that might influence the manner in which the work is carried out. The previous chapter of this report dealt in some detail with the many issues that may need to be considered in the Visual Tree Inspection. Here we are concerned with the steps necessary to progressing from the inspection stage through to safely carrying out the work.

A flow chart that can be used in conjunction with a Visual Tree Inspection, in order to determine an appropriate strategy for carrying out a particular dismantling operation, is presented in Figure 3.1. This flow chart focuses on two main aspects, namely:

1. deciding on a plan of action for gaining access to the tree e.g. employing a climber using rope & harness techniques, or using a mobile elevating work platform (MEWP);
2. deciding, in general terms, the method to be used in carrying out the work once access to the tree has been gained.

The flow chart in Figure 3.1 is organised under four main numbered headings which cover the main scenarios that generally arise, following an initial assessment, based on a Visual Tree Inspection (sometimes augmented by a more thorough examination), of whether or not:

- it appears to be possible for a climber to safely gain access to the tree using rope and harness
- it appears to be possible to safely carry out the work using rigging techniques
- the site appears to be compatible with the use of machinery (e.g. work platform or crane)

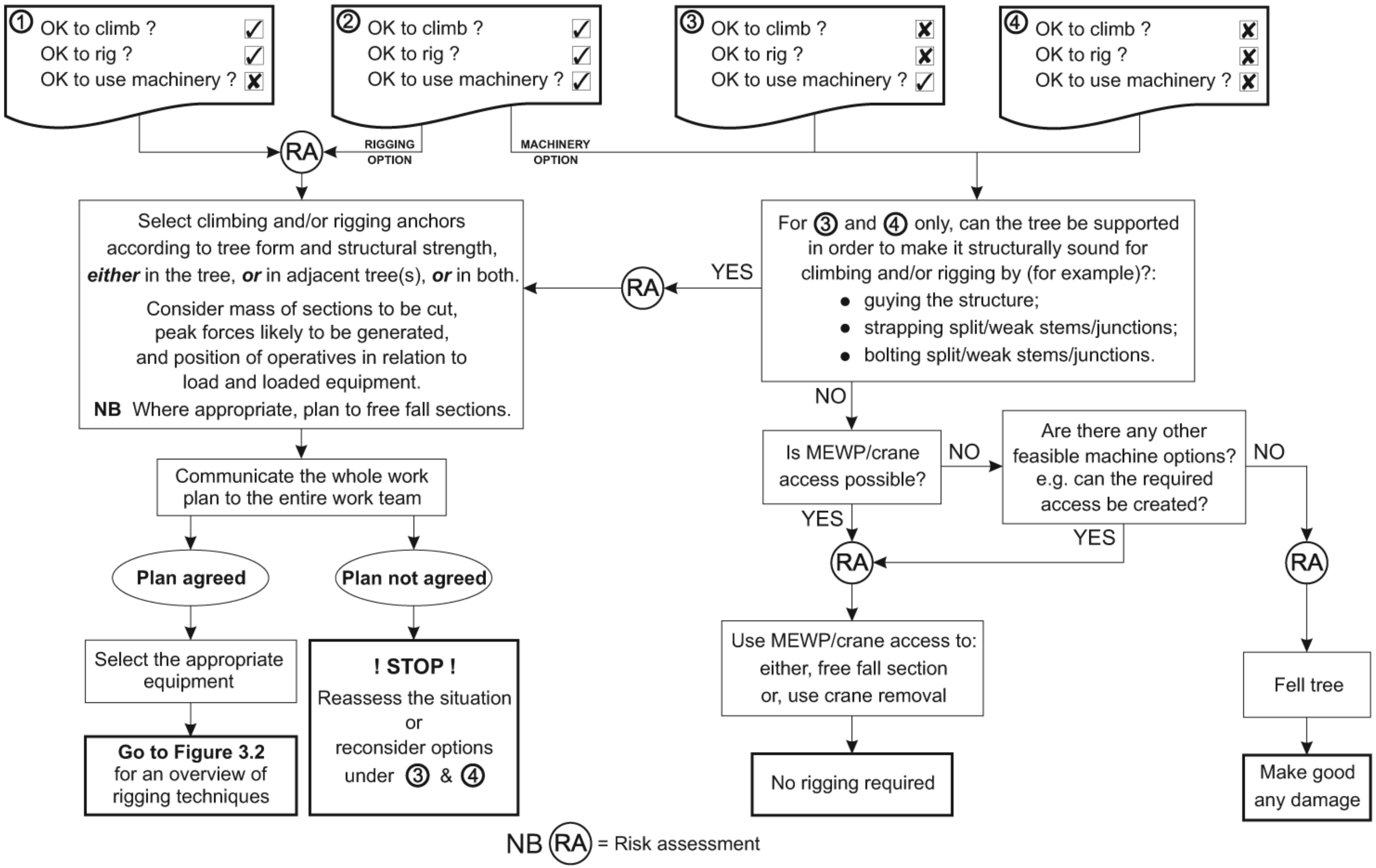

Figure 3.1 Establishing a safe strategy for carrying out a rigging operation

In many instances, more than one of the three options will present possibilities for carrying out the work. In such cases, it will be necessary for the person assessing the situation to use their professional experience in deciding which of the options to pursue. In making such a decision, other factors may well have a bearing on the final outcome e.g. the availability of equipment and/or the cost of pursuing a particular strategy. However, it is fundamental to the process of selecting an appropriate strategy that safety is regarded as paramount, and it is hoped that rigorous application of the flow chart in Figure 3.1 will ensure that this is so.

Bearing in mind that this report is primarily concerned with the application of rigging techniques, in Figure 3.1 the rigging options have been presented first, under headings (1) and (2). The options for using machinery are presented primarily under (3), but also under (4), subject to further considerations. However, this order of presentation should not be interpreted as implying any general preference for the use of rigging techniques over the use of machinery.

In some cases, when the option of rigging is being considered, inspection of the tree and its location can result in some uncertainty as to whether rigging techniques can be employed satisfactorily. In such scenarios, dealt with under heading (1) of Figure 3.1, or under the rigging option arising from heading (2), any doubt arising from working through the flow chart will lead to a reconsideration of the use of machinery. In a similar manner, when considering the options for using machinery, the flow chart also suggests that consideration be made of options for supporting, or otherwise strengthening, the tree to enable the use of rigging techniques which might initially have been thought to be inappropriate.

Carefully following through the flow chart of Figure 3.1 should ensure that all necessary considerations are made before finally deciding whether or not to use rigging techniques. The flow chart particularly emphasises those points in the decision process where a very careful assessment of the risks involved should be carried out (indicated by RA=Risk Assessment). It also emphasises the need for open communications between the various members of the work crew and for agreement from all parties to be arrived at before any plan of action is finally put into operation.

The outcome from working through the flow chart of Figure 3.1 should be agreement of all parties on a strategy for dealing with the dismantling work under consideration. This could well result in a decision to utilise machinery, or to not even attempt to undertake the dismantling work at all (i.e. to simply fell the tree and make good any damage). However, in those situations where careful application of the flow chart, underpinned by a thorough Visual Tree Inspection, results in a decision to utilise rigging techniques as the overall strategy, Figure 3.1 then directs those concerned to consider the method of rigging to be used by referring to Figure 3.2.

3.2 SELECTING A RIGGING TECHNIQUE

Once a decision has been taken to use rigging techniques in a particular dismantling operation, in order to progress the work the decision-making process must move on to deciding on the specific combination and configuration of equipment (hardware and cordage) to be used in removing each successive section of the tree. In other words, an appropriate rigging technique must be selected. This section deals with making that selection, while section 3.3 covers the selection of, and setting up of, the equipment required to put that technique into practice.

Figure 3.2 presents a flow chart that can be used to select an appropriate technique for removing a single section from a tree. The chart first specifies that, provided it can be done safely and with predictable results, free-falling a section is normally the best option. The chart then proceeds to list the most common rigging techniques used to remove sections where free fall (which is inherently unpredictable) is not an option.

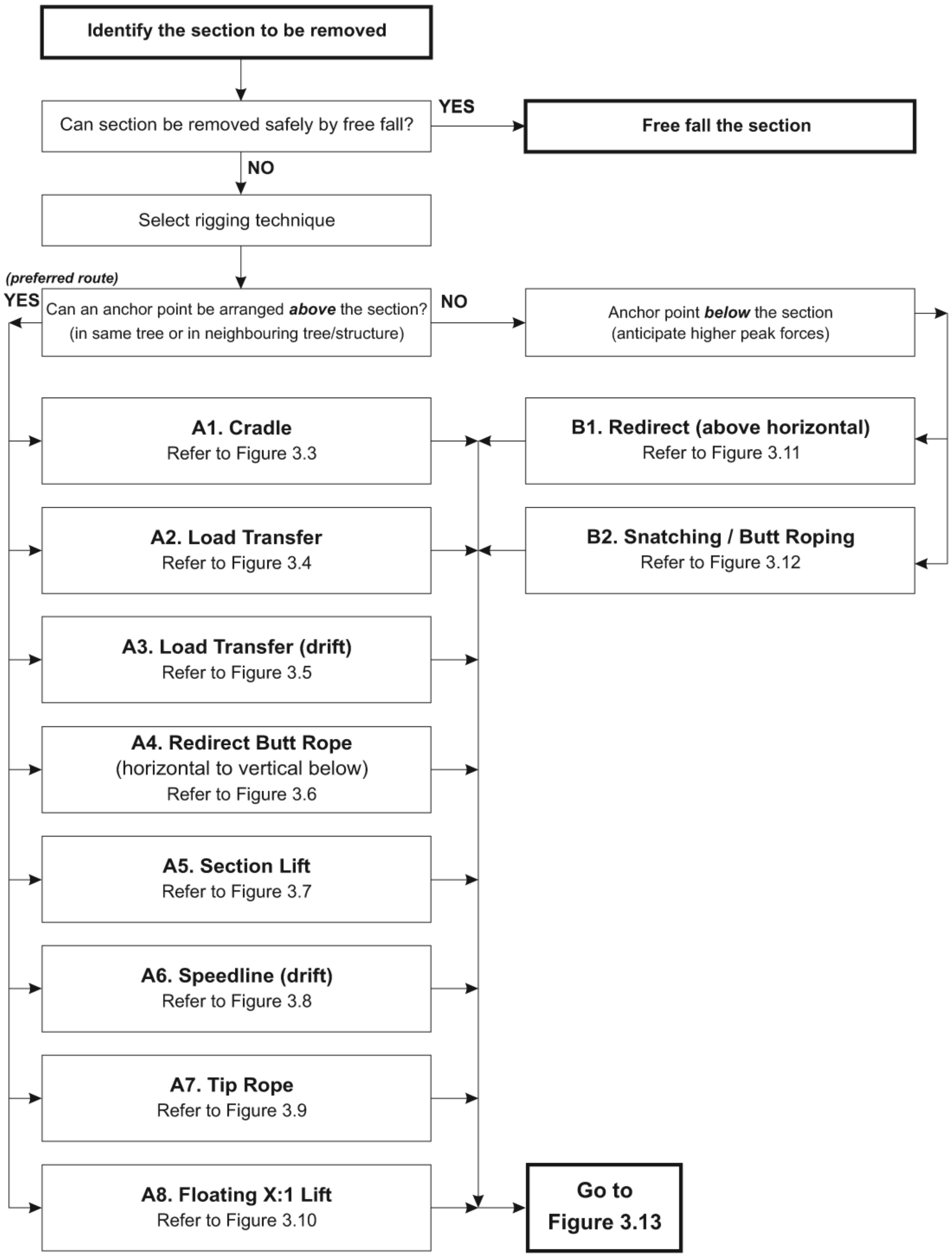

Figure 3.2 Selecting an appropriate rigging technique

Figure 3.2 lists the basic rigging techniques that are available for use in tree dismantling. Whenever possible, a technique should be selected that employs an anchor point arranged above the section to be removed. However, since such an anchor point is not always available, there will be times when it is necessary to use one of the techniques that employs an anchor point below the section, although every possible effort should first be taken to establish one above.

The basic techniques applying to a situation where an anchor point can be arranged above the section are listed as A1 to A8. The main techniques applying when the anchor point is below the section are similarly listed as B1 & B2. Corresponding to these techniques (A1 to A8, B1 & B2), schematic diagrams are presented in Figures 3.3 to 3.12. These latter figures illustrate, in general terms, the various elements of the rigging systems and how they are set up. They also include notes on important considerations, specific to each technique, that must be borne in mind when applying the techniques.

It should be noted that, in real situations in the field, modifications to these basic rigging systems will invariably be required to accommodate the actual circumstances and dimensions of the work being undertaken. When designing a particular system, variables such as line angles, distances and lateral forces can all be used to either advantage or disadvantage. Incorrect application of these techniques in particular circumstances may well result in the creation of unwanted hazards. It is therefore important that persons designing, installing and/or using these systems have the appropriate competencies.

It should also be noted that the techniques illustrated in the schematic diagrams, whilst summarising the common rigging configurations, are by no means the only possibilities. In the real world, complications caused by a particular location may require different elements of the basic configurations to be combined in order to produce an effective and safe technique.

3.3 SELECTING AND SETTING UP EQUIPMENT

A stated above, the set-up of a rigging system in a particular situation will invariably draw on elements of one or more of the techniques illustrated in Figures 3.3 to 3.12, and will certainly be constructed using components similar to those symbolised in these schematic diagrams.

In the diagrams, the separate components of the rigging systems are indicated by symbols, the complete set of which is shown below. The majority of the symbols refer to the hardware or cordage appropriate to the particular component. Where a symbol refers to hardware or cordage, the range of equipment to which it refers is illustrated in detail in Chapter 4, in which a series of tables is presented, with each separate table identified by both product type and symbol(s). However, the following brief descriptions should be sufficient to facilitate a basic understanding of the rigging systems as illustrated in Figures 3.3 to 3.12:

Impact block – a pulley block designed to take a dynamic shock load (normally attached to a structure with a rope sling).

Rescue pulley (single sheave) – a pulley block designed to accept a gradual loading (normally attached to a structure with an opening connector and rope or webbing sling).

Rescue pulley (double sheave) – a pulley designed to accept a gradual loading (normally attached to a structure with an opening connector and rope or webbing sling).

Trolley – a single component, or an assembly of components, with multiple sheaves that allow a load to be attached to a carriage.

An assembly of pulleys, ropes, connectors and a brake, designed to tension rope by applying a mechanical advantage (X:1); or a component specifically designed to be incorporated into such an assembly.

Anchor (closed) - rigging ring, used as a point of multiple attachment.

Anchor (closed) – swivel, used as a point of multiple attachment to avoid torsion build-up, particularly in hardware components.

Anchor (closed) – rigging plate, used as a point of multiple attachment.

Connector (opening) – karabiner, used to connect different components of the rigging system.

Connector (opening) – shackle and pin, used to connect different components of the rigging system.

Connector (opening) – quick link, used to connect different components of the rigging system.

Rope brake - a capstan tube with no moving parts which is normally attached to a tree with a rope sling.

Rope brake - a framed bollard with no moving parts which is normally attached to a tree with tensioned webbing straps.

Combined rope brake and tensioning device - a machine (sometimes modular) that can not only be used to hold and lower a load, but also to raise a defined load without the addition of further components.

Anchor - a load bearing structure of sufficient strength for the task in hand e.g. tree, branch, building, vehicle etc.

Rope – any rope suitable for the task in hand (e.g. single or multi-braid, selected from a range of diameters, material or construction).

Soft eye rope sling (single eye) - used to join rigging components to tree parts.

Soft eye rope sling (double eye) - used to join rigging components to tree parts.

Endless loop sling – an endless loop constructed from a range of materials, including rope, webbing and sleeved fibres, used to connect rigging components to tree parts.

Whoopie sling – a sling made from a hollow braid construction rope, with two spliced soft eyes, one of which is adjustable in length; used to connect rigging components to tree parts.

Loopie sling - a looped sling made from a hollow braid construction rope, spliced in a way that provides a loop which is adjustable in length; used to connect rigging components to tree parts.

Eye - a non-adjustable, looped rope termination of known strength e.g. spliced, stitched, swaged etc.

A knot or combinations of knots.

It should be emphasised that the information presented in the diagrams is not intended to be used as an instruction book, or as a substitute for appropriate training in applying the techniques illustrated. Any person wishing to employ any of these techniques should undertake a suitable course of certified training and develop their experience in using rigging techniques in an appropriate manner. It cannot be over-emphasised that inappropriate application of any of these techniques can lead to disastrous, even fatal, consequences.

Detailed consideration of the mechanics involved in these rigging techniques, and the loads that the equipment might be expected to bear, is to some extent included in subsequent chapters of this report, in particular in Chapter 8 which examines the forces generated in rigging operations.

3.4 CARRYING OUT THE OPERATION

Once a decision has been made to use rigging techniques in a dismantling operation, a particular technique/system has been decided upon, the equipment required and the details of the set-up have been determined, the next stage in the process is to remove the first section from the tree. Figure 3.13 presents a flow chart which details the considerations that need to be taken when removing such a single section.

It is important that all of the steps listed in Figure 3.13 are fully considered or acted upon with each successive section of the tree to be removed. Each section will be different from the previous one in a number of respects, and it cannot be assumed that the technique utilised in removing one section will be appropriate to the next. Indeed, it may well be necessary to change from one rigging technique to another in order to deal with the differences in weight, size and position of the different sections. Careful consideration of the issues raised in Figure 3.13, before the removal of each section, should ensure that any complicating factors are anticipated and appropriate changes to the rigging system are made.

As in the previous processes involved in deciding whether and/or which rigging techniques are appropriate in a particular dismantling operation, the flow chart in Figure 3.13 also emphasises the importance of communications between the different members of the work crew.

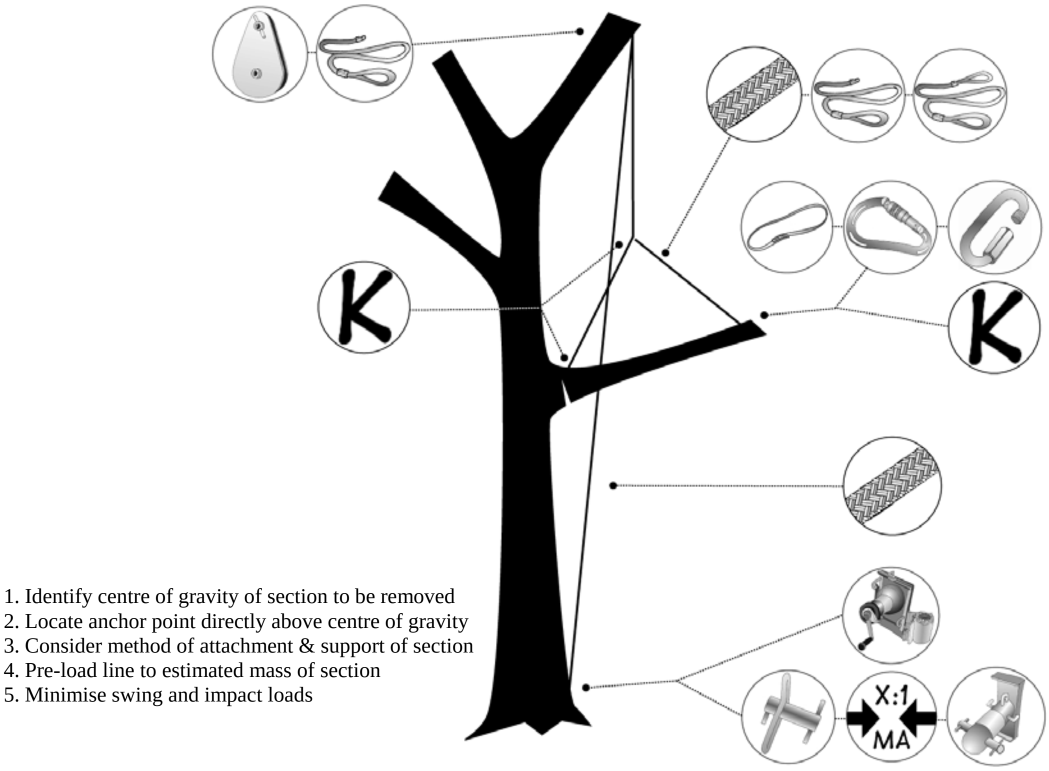

Figure 3.3 A1 Cradle*

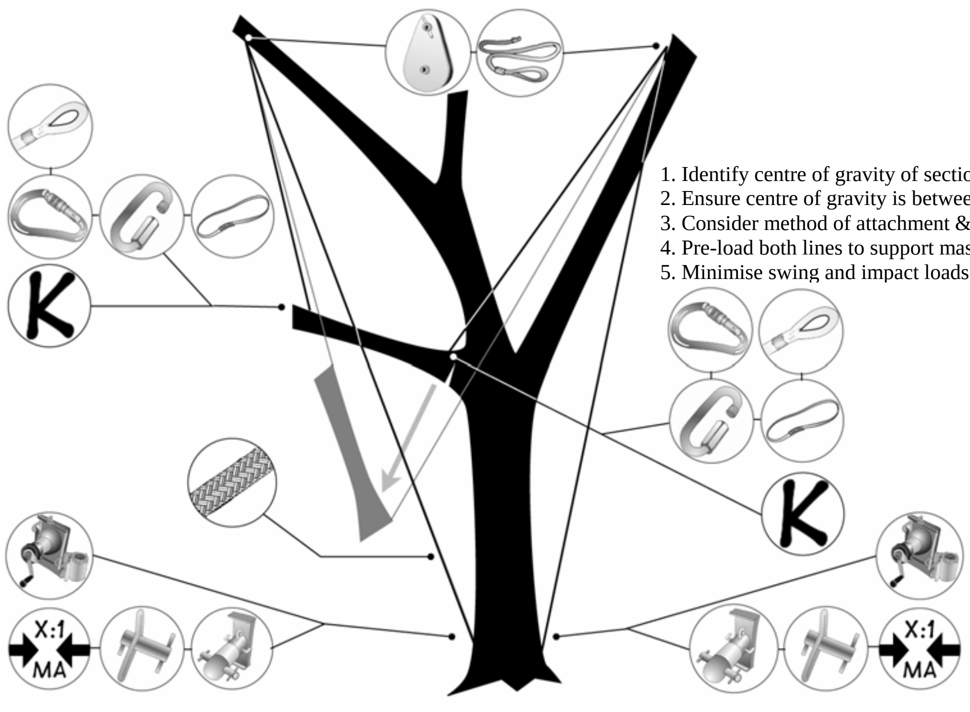

Figure 3.4 A2 Load Transfer*

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* *Illustrations prepared by Mark Bridge (2007)*

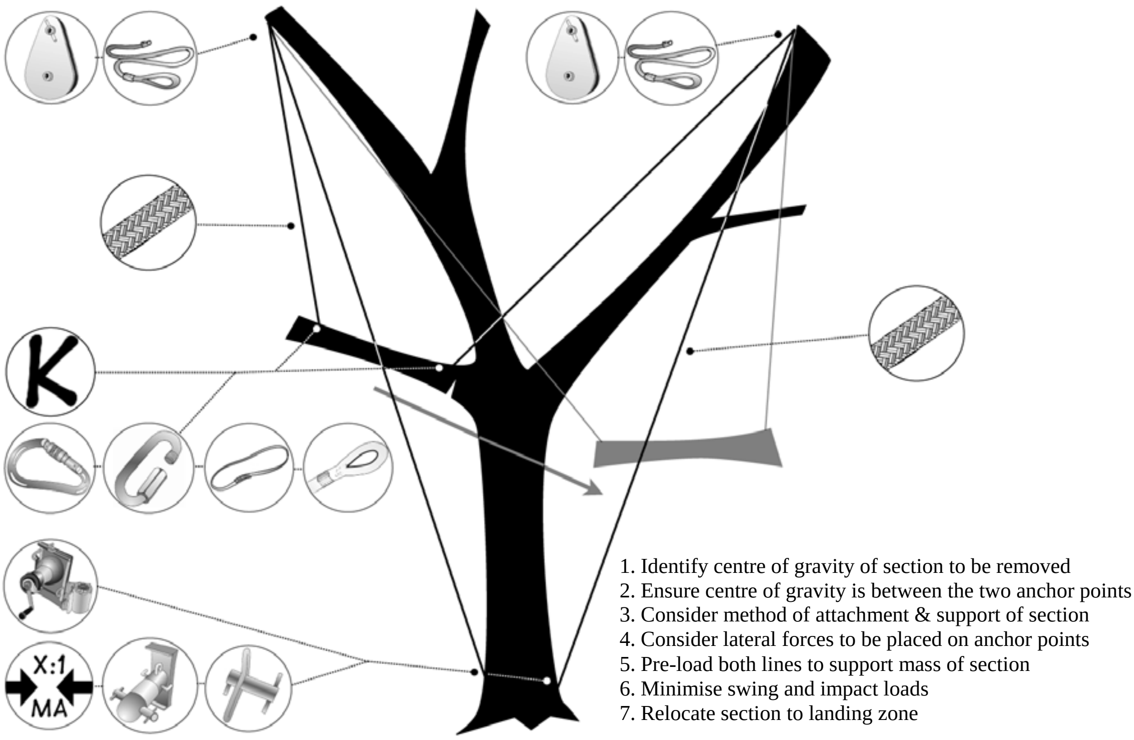


Figure 3.5 A3 Load Transfer (drift)*

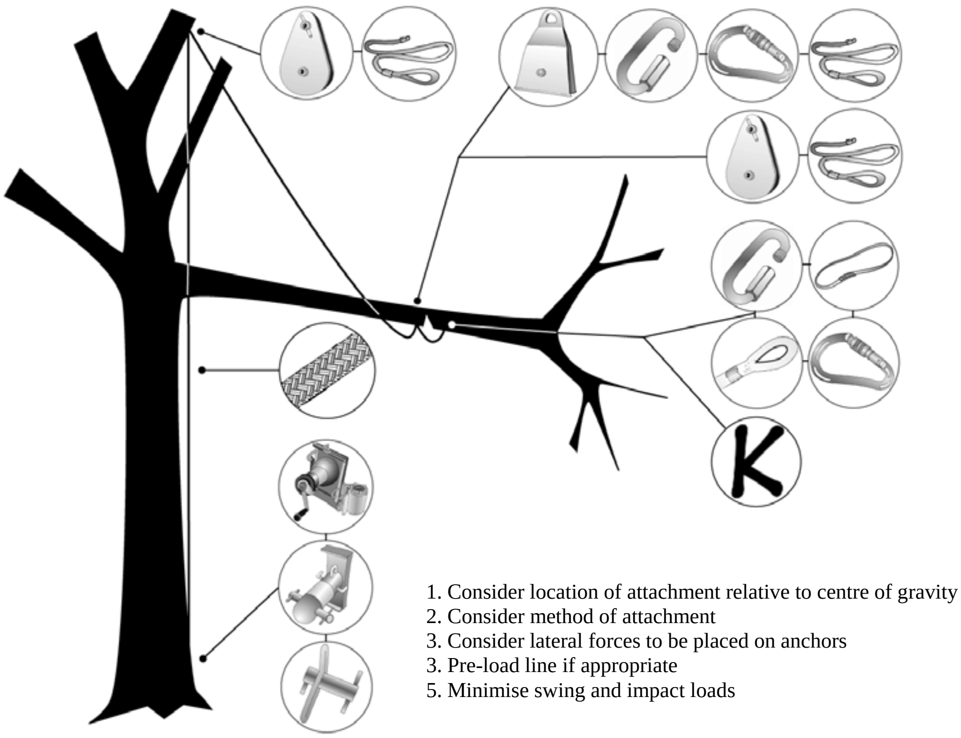


Figure 3.6 A4 Redirect Butt Rope (horizontal to vertical below)*

* *Illustrations prepared by Mark Bridge (2007)*

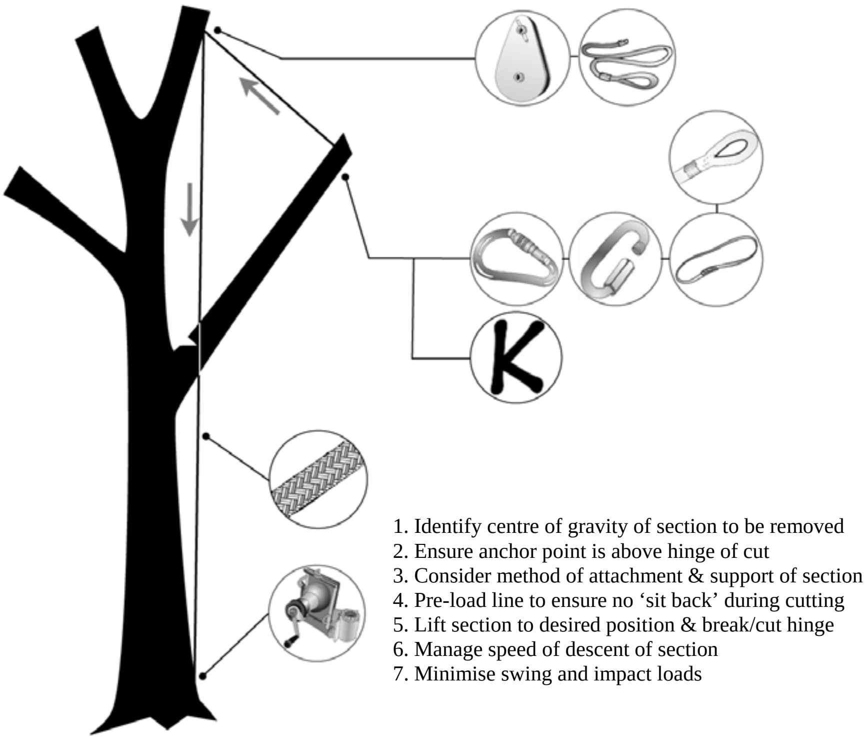


Figure 3.7 A5 Section Lift*

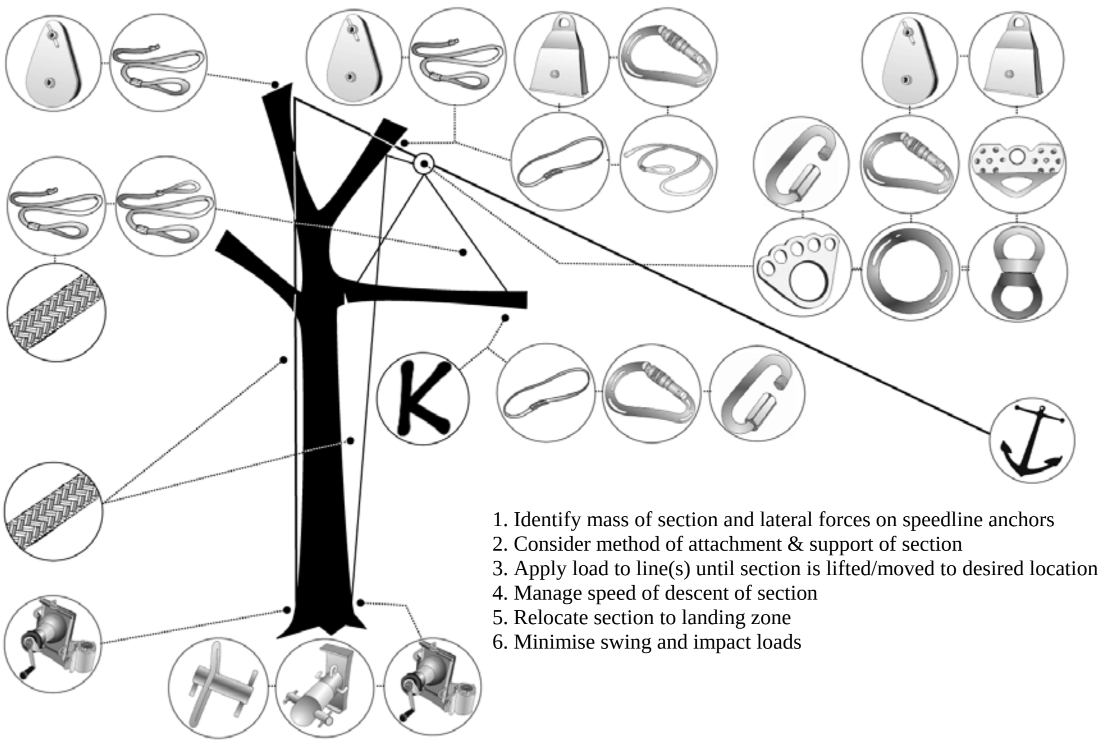
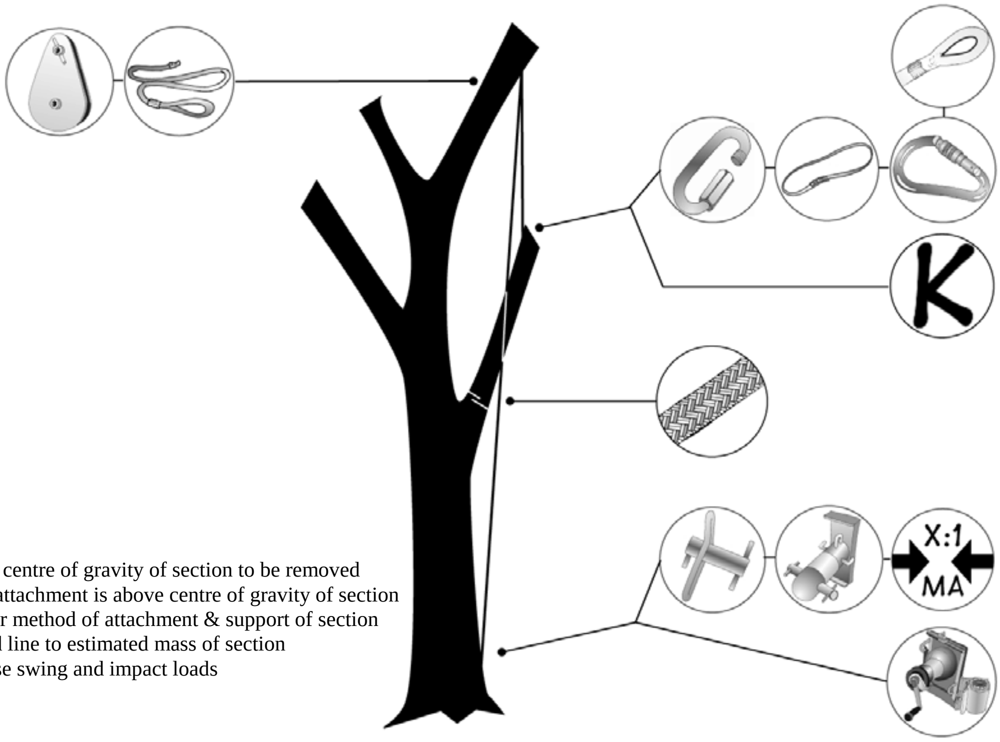


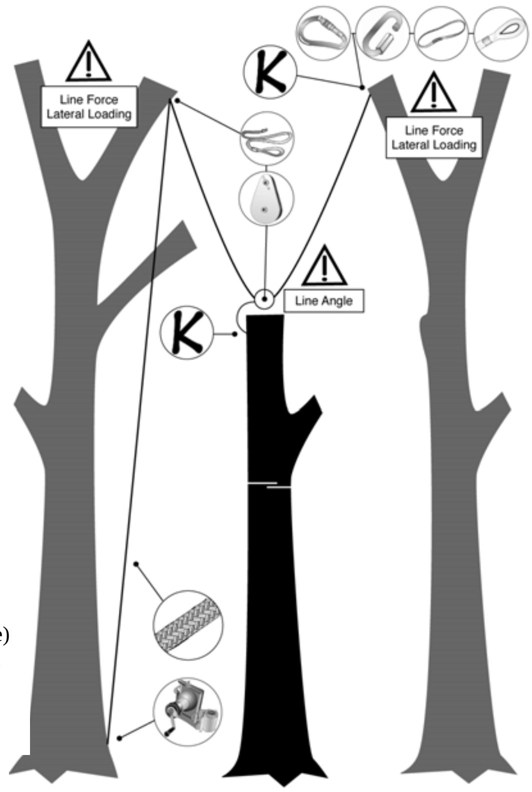
Figure 3.8 A6 Speedline (drift)*

* *Illustrations prepared by Mark Bridge (2007)*



1. Identify centre of gravity of section to be removed
2. Ensure attachment is above centre of gravity of section
3. Consider method of attachment & support of section
4. Pre-load line to estimated mass of section
5. Minimise swing and impact loads

Figure 3.9 A7 Tip Rope*



1. Identify mass of section and lateral forces on anchors
2. Consider method of attachment & support of section
   (beware high forces arising from large angles between legs of line)
3. Apply load to line until section is lifted/moved to desired location
4. Manage speed of descent of section
5. Relocate section to landing zone
6. Minimise swing and impact loads

Figure 3.10 A8 Floating X:1 Lift*

* *Illustrations prepared by Mark Bridge (2007)*

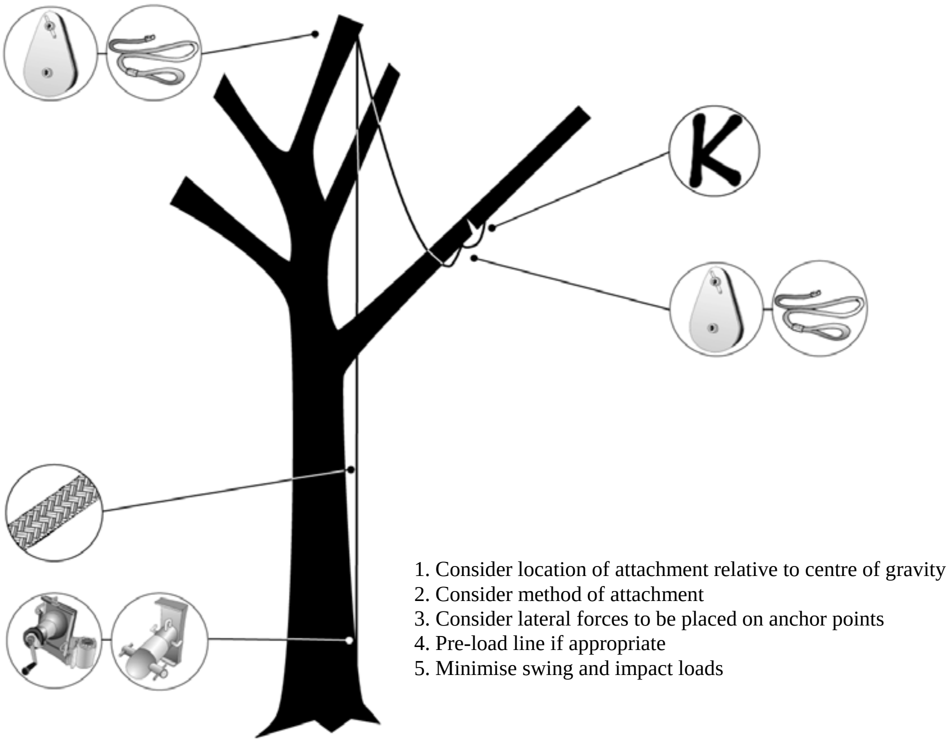


Figure 3.11 B1 Redirect (above horizontal)*

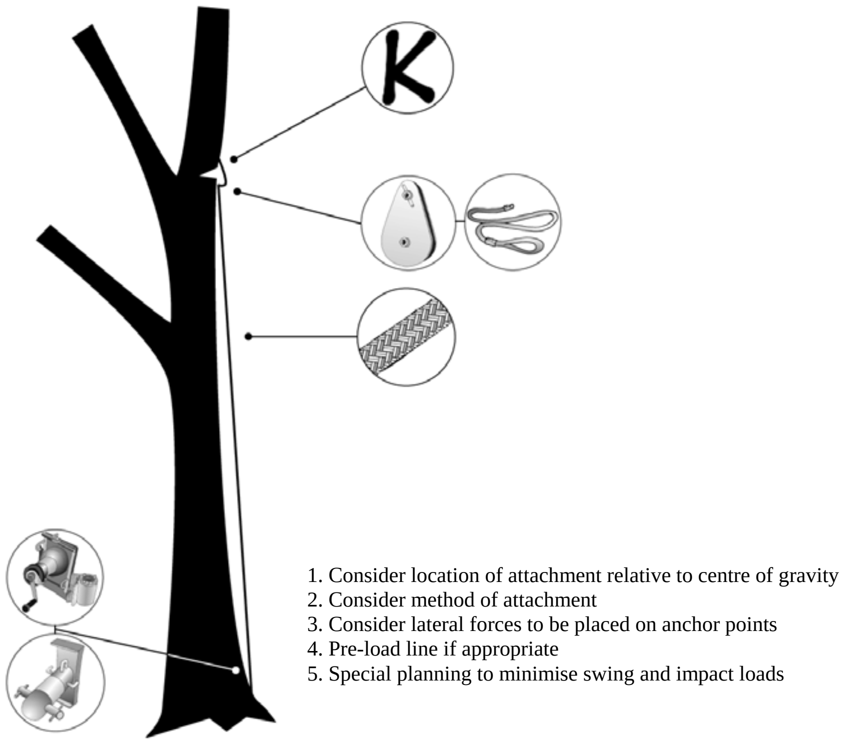


Figure 3.12 B2 Snatching / Butt Roping*

* *Illustrations prepared by Mark Bridge (2007)*

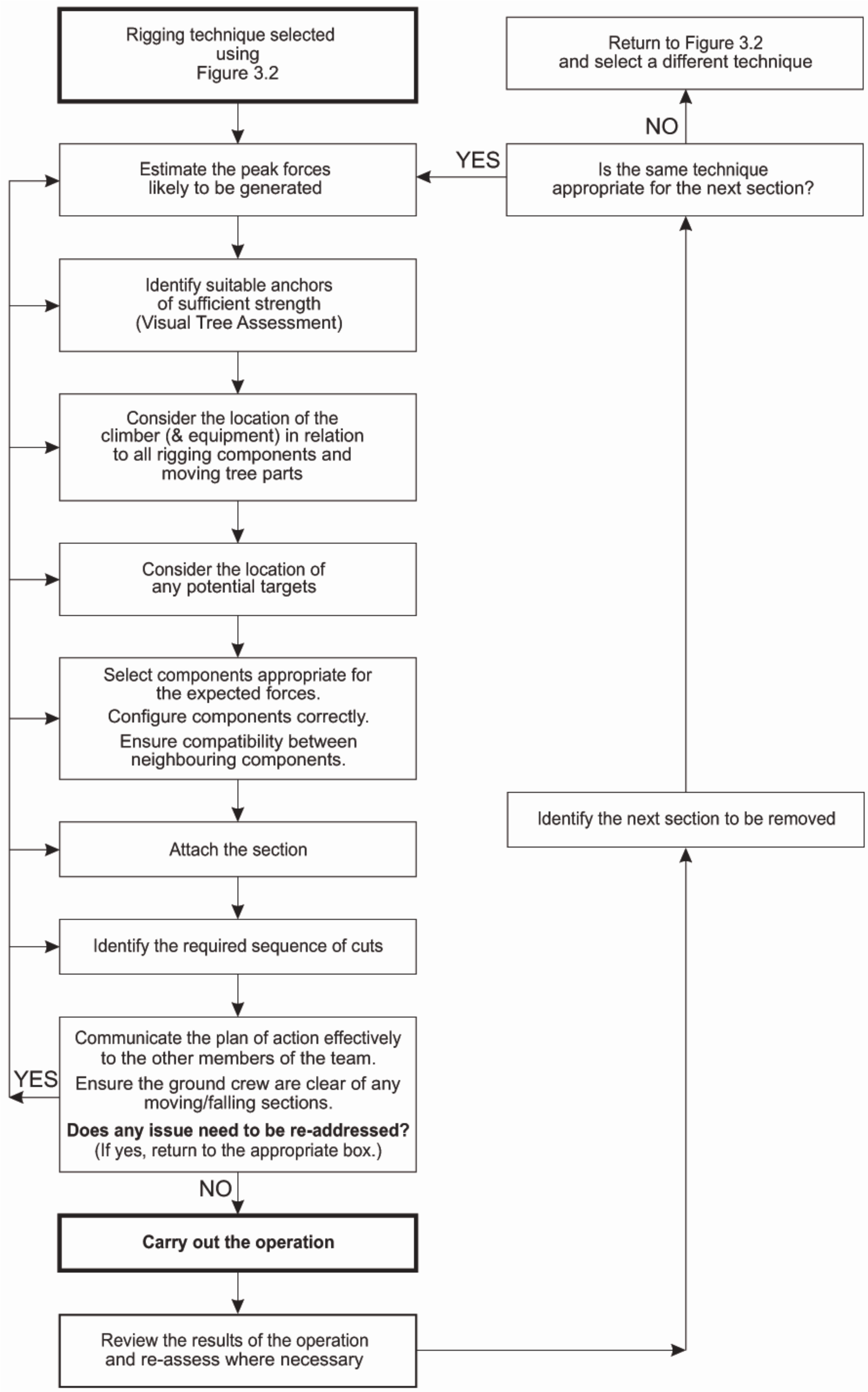


Figure 3.13 Carrying out an operation and reviewing the outcome

3.5 REVIEWING THE OPERATION

Part of the process incorporated in the flow chart of Figure 3.13 is the requirement to review the results of the removal of each section. The establishment of a rigging system in the first place requires a number of subjective assessments to be made, initially by Visual Tree Inspection, and subsequently at each stage of the operation, by the application of the experience and knowledge of the person responsible. An essential part of such operations must be that of learning from each successive part of the operation, so that each section is removed safely using a method that is based on the maximum amount of information available.

As with the process of deciding whether to use rigging techniques at all, safety considerations must be paramount at every stage of carrying out a dismantling operation. For this reason, as much thought and skill as possible must be brought to bear in the ongoing decision making. A responsible arborist should be fully prepared to modify the selected working method at any point, even to the extent of declaring any further application of a particular rigging system to be inappropriate (and therefore halting operations).

4 RIGGING HARDWARE, CORDAGE AND TEXTILE COMPONENTS

The previous chapter introduced the different categories of components available to arborists for designing and assembling rigging systems. In that chapter, the most common rigging techniques were presented in diagrammatic form, with the different categories of component being indicated by symbols first introduced in section 3.3. In the present chapter, a wide range of components is examined, together with the available information relating to the components. The appropriateness of that information to the arborist, in deciding how to use the components both successfully and safely, is also discussed.

A wide range of components is available, supplied by a variety of different manufacturers. Many of these components were originally designed for use in applications other than tree rigging (e.g. mountaineering or industrial rope access), and have subsequently been adapted for use in, or directly incorporated into, tree dismantling systems by arborists. Other components are bespoke products that have been developed specifically for a particular application, generally through the need for greater efficiency or flexibility in the tasks for which they were designed (e.g. arborist blocks and flying capstans).

A full understanding of the capabilities and limitations of the available components is one of the keys to designing successful (i.e. efficient and safe) rigging systems. As part of this research project, an attempt was made to survey many different components currently available on the market, and to record, for each component, as far as was possible, all the currently available product-related data that could be considered to be relevant to tree rigging operations. All data collected as a result of this exercise are presented in full in tables included at Appendices 1 & 2.

It must be emphasised that, whilst the items of equipment listed in the appendices may not cover the entire product market, the considerable range of items included provides some assurance that the information presented is representative of the equipment currently available. Furthermore, the inclusion in (or omission from) the appendices of any particular item of equipment cannot be regarded as implying or conferring any specific recommendation. The following paragraphs describe in detail the way in which the data for the items of equipment included in the appendices was obtained.

In compiling the data, information was first drawn from manufacturers' catalogues and websites. Draft tables were prepared corresponding to each product category. The draft tables listed all the products supplied by each manufacturer, and provided space for the inclusion of data under a number of headings. These headings corresponded to the information that the researchers considered to be required (i.e. necessary or desirable) for the successful design of tree rigging systems, and were derived both from the personal experiences of the researchers and from the results of research such as (and including) that described in subsequent chapters of this report. In most cases, therefore, further justification for inclusion of these parameters can be found elsewhere in this report, either by direct reference or by implication.

The next two sections describe in some detail the information that the researchers considered to be required (i.e. necessary or desirable). Section 4.1 lists the required information for hardware components; section 4.2 similarly lists the information for cordage and other textile components. To avoid repetition, an explanation of each parameter is only included (***in bold italics***) on the first occasion that it appears in each of the two main sections. Whilst some of the parameters are applicable to all the equipment categories (e.g. Minimum Breaking Strain and Working Load Limit), the requirements for their derivation can vary depending on the category. Other parameters are specific to one or only a number of the product categories.

4.1 HARDWARE COMPONENTS

4.1.1 Impact blocks, rescue pulleys and hauling sets

Impact blocks are pulley blocks designed to take a dynamic shock load, and they are normally attached to a structure with a rope sling. Rescue pulleys are available with either one or more sheaves, and are designed to accept a gradual loading. They are normally attached to a structure with a textile/rope sling via an opening connector. Hauling sets are assemblies of pulleys, ropes, connectors and a brake, and are designed for the purpose of tensioning a rope by the application of a mechanical advantage (X:1). Included in this latter category are single components specifically designed to be incorporated into such an assembly. These components are all identified in the tables by product description and image (where available). For these components, the following technical data were considered to be required for the successful design of tree rigging systems:

- ***Minimum Breaking Strength*** (MBS - sometimes written as Min.BS, also known as Minimum Breaking Load): The load above which an item of lifting equipment can be expected to fail when new.
- ***Working Load Limit*** (WLL): The maximum load an item of lifting equipment is designed to raise, lower or suspend, as guaranteed by the manufacturer at the point of sale, and not accounting for any particular service conditions that might otherwise affect the performance of the equipment.
- ***Design factor*** (or safety factor): The ratio of *Minimum Breaking Strength* (MBS) to *Working Load Limit* (WLL). (NB The relationship between these three parameters means that, provided any two of them are given, the third can be calculated.)
- ***Maximum rope diameter***: The maximum rope diameter specified by the manufacturer for use in the device – this normally means the diameter of the largest rope that can be fed through the pulley without affecting its efficient working.
- ***Tread diameter of sheave***: The diameter of the circle described by the inner points (i.e. nearest to the axis of the pulley) of the concave channel through which the rope moves round the sheave of the pulley.
- ***Bend ratio for maximum rope diameter***: The ratio of the *Tread diameter of sheave* to the *Maximum rope diameter* (NB The relationship between these three parameters means that, provided any two of them are given, the third can be calculated – *cf* Figure 7.21, page 180).
- ***Efficiency***: The rolling resistance of the sheave e.g. a 100% efficient pulley would allow a load to be transmitted with zero loss, whilst a 0% efficient pulley would not permit any movement to take place, whatever the loading (i.e. it would act as a brake).
- ***Weight***
- ***Approximate dimensions*** – L(ength) by W(idth) by D(epth)

4.1.2 Trolleys

These components can be in the form of either a single component or an assembly of components. They have multiple sheaves, mounted in a frame, that allow a load to be attached to a moveable carriage. They are identified in the table by product description and image (where available). For these components, the technical data considered to be required for the successful design of tree rigging systems is the same as for impact blocks and rescue pulleys (see above), but with the omission of *Bend ratio for maximum rope diameter*.

4.1.3 Anchors (closed)

These components generally take the form of one or more rings or ring-shaped devices, or a plate with a variety of attachment holes, and may or may not incorporate a swivel facility. They are used as points of multiple attachment, with the swivel facility (where available) being used to avoid torsion build-up, particularly between hardware components. They are identified in the table by product description and image (where available). For these components, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS)
- Design factor
- Working Load Limit (WLL)
- Weight
- Approximate dimensions

4.1.4 Connectors (opening)

These components take a number of different forms, but are generally either karabiners (snap-links/quick-links) or shackles and pins, with a single opening mechanism that is either hinged, threaded and spring-loaded or operated by the removal of a pin. They are used to connect different components of the rigging system, and are identified in the tables by product description, image (where available), shape and the type of locking mechanism. For these components, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS): Since these components can have loads applied to them in many different directions, MBS data is required for loads applied:
  - across the connector (outwards) in line with the major axis (***MBS Major axis***)
  - at the centre of the gate and across the connector (outwards) in line with the minor axis (***MBS Minor axis***)
  - across the connector (outwards) in line with the major axis with the gate open (***MBS Gate open***)
  - to the closed gate at right angles to the gate, in the same plane as both major and minor axes of the component, and in a direction towards the major axis (inwards) (***MBS Outside load on gate***)
  - to the closed gate at right angles to both the gate and the plane containing both the major and minor axes of the component (***MBS Side load on gate***)
- Design factor
- Working Load Limit (WLL): For loads applied in line with the major axis of the component (***WLL Major axis***)
- ***Gate opening***: A measurement across the opening of the component when it is in its fully opened state.
- Weight
- Approximate dimensions

4.1.5 Rope brakes


These components are generally either capstan tubes or framed bollards with no moving parts. When they are operated, friction is created by wrapping a rope around the tube, or bollard, a specified number of times. They are generally provided with a number of lugs around which bights of the rope can be passed in order to provide greater control or to 'lock off' the system. They are normally attached to a tree with either rope slings or tensioned webbing straps. They are identified in the tables by product description and image (where available). For these components, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS)
- Design factor
- Working Load Limit (WLL)
- ***Tread diameter of brake drum***: The diameter of the drum (i.e. tube or bollard) round which the rope turns.
- ***Maximum rope diameter***: The diameter of the largest rope that can be configured on the brake mechanism without affecting its efficient working.
- ***Bend ratio for maximum rope diameter***: The ratio of the *Tread diameter of brake drum* to the *Maximum rope diameter* (NB The relationship between these three parameters means that, provided any two of them are given, the third can be calculated – *cf* Figure 7.21, page 180, in which the inner diameter of the pulley can be regarded as analogous to a brake drum).
- Weight

4.1.6 Combined rope brakes and tensioning devices

These components are effectively machines (sometimes modular) that can be used not only for holding and/or lowering loads, but also for raising defined loads without the addition of further components. Some of them are supplied in different versions, or can be configured in different modes (e.g. as either a bollard mechanism or a winch), which are indicated by different data lines within the product lines of the tables. These components are identified in the tables by product description and image(s) (where available). For these components, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS)
- Design factor
- Working Load Limit (WLL)
- Tread diameter of brake drum
- Maximum rope diameter
- Bend ratio for maximum rope diameter
- Weight

4.2 CORDAGE AND TEXTILE COMPONENTS

Cordage and textile components include ropes and a variety of purpose-made slings specifically designed for use in rigging systems. They are made from a variety of different fibres and are generally flexible and have varying degrees of ability to absorb shock loading. Ropes are used throughout the rigging systems for connecting the different hardware components, and for transmitting loads from one point in the system to another. They have a circular cross-section and are available in a variety of different lengths.

In general, slings are pre-fabricated loops of either rope or flat-woven (textile) material. They are effectively tools that are designed primarily for use in connecting rigging hardware components to tree parts. Slings are commonly used in three different configurations: ‘singled’ (where the load is applied in a straight line along the full length of the sling); ‘choked’ (where the load is applied to one end, eye or bight of the sling after it has been passed around a tree part and through the other end, eye or bight of the sling i.e. effectively ‘choking’ the tree part); and ‘basket’ (where the sling is passed around a tree part and the load is applied equally to both ends, eyes or bights of the sling). Additionally, ‘soft eye slings’ can be used in a ‘knotted’ configuration (where the load is applied between the eye and a knot tied somewhere in the tail of the sling).

4.2.1 Rope

Rope comes in a variety of different forms/constructions. It can be single or multi-braid, made from a variety of different materials, and is generally available in a range of diameter sizes. Ropes are identified in the tables by product description, image (where available) and the material(s) from which they are constructed. For all rope types, the following technical data were considered to be required for the successful design of tree rigging systems:

- ***Mass***: The weight of the rope, expressed in grams per linear metre.
- ***Minimum Breaking Strength*** (MBS - sometimes written as Min.BS, also known as Minimum Breaking Load): The load above which an item of lifting equipment can be expected to fail in a specified configuration when new.
- ***Design factor*** (or safety factor): The ratio of *Minimum Breaking Strength* (MBS) to *Working Load Limit* (WLL). (NB The relationship between these three parameters means that, provided any two of them are given, the third can be calculated.)
- ***Working Load Limit*** (WLL): The maximum load an item of lifting equipment is designed to raise, lower or suspend, as guaranteed by the manufacturer at the point of sale, and not accounting for any particular service conditions that might otherwise affect the performance of the equipment.
- ***Extension at 10, 20 & 30% MBS***: The percentage by which a length of the rope extends (stretches) under the specified loads (i.e. 10, 20 & 30% of the rope’s MBS).
- ***Extension at break***: The percentage by which a length of rope extends (stretches) when loaded to its point of failure.
- ***Knotted strength***: The *Minimum Breaking Strength* (MBS) for the rope when it includes a knot in the tested length (normally quoted together with the particular knot used in the test e.g. bowline or figure-of-eight).
- ***Spliced strength***: The *Minimum Breaking Strength* (MBS) of the rope when it includes a factory-made splice in the tested length.

4.2.2 Soft eye slings

These rope tools are available with either a single eye or a double eye. They are identified in the tables by product description, image (where available) and construction i.e. the materials used in the kern (inner part of the rope) and the mantle (outer covering of the rope). Soft eye slings can be used in four different configurations: 'knotted', 'singled', 'choked' or 'basket'. However, single-eyed soft eye slings are most commonly used 'singled' or 'knotted', whilst double-eyed soft eye slings are most commonly used 'singled', 'choked' or 'basket'. For these rope tools, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS): For each of the commonly used configurations
- Design factor: For each of the commonly used configurations
- Working Load Limit (WLL): For each of the commonly used configurations
- ***Length(s)***: The range of lengths in which the component is available

4.2.3 Endless loop slings

These components are endless loops, constructed from a range of materials, including rope, webbing and sleeved fibres. They have one joint in their length, which is factory-made, usually by a process of either stitching or splicing. They are identified in the tables by product description, image (where available) and construction i.e. the materials used in the kern (inner part of the rope) and the mantle (outer covering of the rope). Endless loop slings are commonly used in three different configurations: 'singled', 'choked' or 'basket'. For all slings of this type, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS): For each of the commonly used configurations
- Design factor: For each of the commonly used configurations
- Working Load Limit (WLL): For each of the commonly used configurations
- ***Minimum length***: The shortest length in which the component is supplied.

4.2.4 Whoopie slings

Whoopie slings are made from rope that has a hollow braid construction. They have two spliced soft eyes, one of which is adjustable in length. They are identified in the tables by product description, image (where available) and construction i.e. the materials used in the kern (inner part of the rope) and the mantle (outer covering of the rope). Whoopie slings are commonly used in three different configurations: 'singled', 'choked' or 'basket'. For all slings of this type, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS): For each of the commonly used configurations
- Design factor: For each of the commonly used configurations
- Working Load Limit (WLL): For each of the commonly used configurations
- ***Length***: The effective shortest and longest lengths to which the sling can be adjusted

4.2.5 Loopie slings

Loopie slings are made from a hollow braid construction rope, spliced in a way that provides a loop which is adjustable in length. They are identified in the tables by product description, image (where available) and construction i.e. the materials used in the kern (inner part of the rope) and the mantle (outer covering of the rope). They are normally used in a ‘choked’ configuration. For slings of this type, the following technical data were considered to be required for the successful design of tree rigging systems:

- Minimum Breaking Strength (MBS)
- Design factor
- Working Load Limit (WLL)
- Length

4.3 SURVEY RESULTS

For each manufacturer, the draft tables of their products were e-mailed either to a general contact for the manufacturer, or to relevant personnel (where this information was known). Each manufacturer was invited to respond by commenting on the draft tables, and by providing additional information so that the tables could be completed as far as possible. Any additional information provided by the manufacturers was incorporated into the tables, together with any amendments to the initial information compiled by the researchers. Where no response was received from a particular manufacturer, two further e-mails were sent by way of reminders. Unfortunately, time and resource limitations precluded any further attempts to elicit information by other means.

The information presented in the final tables (included in Appendices 1 & 2) only represents information that was obtained through the processes described above. Other information may well be available to the manufacturers, but they may not have chosen to provide it to the researchers in this instance, or via this mechanism. Where information was not forthcoming, therefore, this can not be taken as indicating an actual lack of such information, or any general reluctance on the part of manufacturers to provide such information through other channels.

In this context, it should be noted that the reactions of manufacturers to the requests for further information and data on their products varied widely. Some manufacturers, perhaps understandably, gave the impression that they saw the requests as some sort of covert industrial espionage, whilst others replied to the effect that they did not consider the information to be necessary for the end user. Therefore, although a number of manufacturers did not respond at all, this cannot be taken as indicating that those manufacturers were not in possession of the requested information. At the other extreme, a number of manufacturers were happy to have discussions about their products and how they are used, and appeared to give their information both freely and willingly.

It is possible that some of the more reticent manufacturers are not fully aware of the uses being made of their equipment by some end users, and they may therefore not have a full understanding of what information could be of value to a user in a particular application (in this instance, for tree rigging operations).

The full results of the survey are presented as appendices to this report: Appendix 1 lists all the data obtained for rigging hardware components; whilst Appendix 2 similarly lists information for cordage (i.e. rope and rope products) and textile components (e.g. webbing slings). In both of these appendices, the components are listed by product category, each of which is further identified by the symbol used earlier in this chapter and first introduced in Chapter 3, section 3.3. (In considering the information presented in these appendices, the general qualifications expressed in paragraph 4 of page 87 should be borne in mind.)

Inspection of the data presented in Appendices 1 & 2 illustrates that for many products insufficient information is available to enable informed decisions to be taken on how best to use the products in tree rigging operations. However, the contents of the tables in the appendices appear to represent the total amount of information that could be readily available to an arborist prior to buying and/or using the products. Despite the comments made earlier, on behalf of those manufacturers who failed to respond, the researchers feel that the tables do in fact quite accurately illustrate the extent to which information is available to arborists for both hardware and cordage items. In particular, rigging products are often sold without any user instructions at all, let alone any instructions specific to their use in arborist rigging operations.

4.4 LEGISLATION CONSIDERATIONS

In the previous sections of this chapter, the discussion has been concerned with the requirements for technical information from the point of view of arborists engaged in setting up rigging systems using available rigging products. However, in the UK, the need for such information is, in many respects, already embodied in health and safety regulations. In fact, current legislation places obligations, on employers, the self-employed, employees and manufacturers, that can only be fully discharged by persons possessing all relevant technical information relating to items of equipment being used. Bearing this in mind, the apparent lack of information accompanying rigging products leaves both equipment manufacturers and users of arboricultural equipment in difficult positions. The references in the next three sub-sections should serve to illustrate the point.

4.4.1 Equipment

The Provision and Use of Work Equipment Regulations 1998 apply to all work equipment used in arboriculture, including ropes, harnesses, strops etc. The regulations require the selection of suitable work equipment, bearing in mind where it is to be used and the purpose for which it is to be used. The regulations also set out requirements for the instruction, training and supervision of those using the work equipment. In particular, they require employers to:

> *"… ensure that work equipment is so constructed or adapted as to be suitable for the purpose for which it is used or provided" [Regulation 4(1)]*

The Lifting Operations and Lifting Equipment Regulations 1998 apply to lifting and lowering operations carried out in arboriculture. The main aim of the regulations is to ensure that all such operations are properly planned, appropriately supervised and carried out in a safe manner. In particular, tree climbers' ropes and other rope access equipment are defined as lifting equipment. These regulations require that such matters as strength, stability and installation of equipment are properly addressed, and also set out how equipment should be marked and thoroughly examined at prescribed intervals. In particular, they require that lifting systems are designed by, and lifting operations overseen by, a competent person (see Chapter 1, section 1.1) who is required to have:

> *"… adequate practical and theoretical knowledge and experience of planning lifting operations" [Regulation 8(1)(a)]*

4.4.2 Personnel

The Management of Health and Safety at Work Regulations 1999 require risk assessments (see Chapter 1, section 1.2.1) to be carried out to identify the measures necessary to comply with health and safety legislation. In particular, the assessments should cover risks to the health and safety of employees, the self-employed and others who are not at work e.g. members of the public. The regulations also require arrangements to be put in place for managing the work. Throughout the regulations there are a number of references to the provision of relevant information, for example:

> *"Employers and the self employed are expected to take reasonable steps to help themselves identify risks, e.g. by looking at appropriate sources of information, such as … appropriate guidance, supplier manuals, and manufacturers instructions …" [Regulation 3(13)(b)]*

Elsewhere in these regulations, employers are charged with:

> *"Securing competence by the provision of adequate information, instruction and training and its evaluation, particularly for those who carry out risk assessment and make decisions about preventative and protective measures." [Regulation 5(34)(c)]*

Furthermore, the regulations require that:

> *"The employer should have adequate health and safety information and make sure it is communicated to employees and their representatives, so informed decisions can be made about the choice of preventative and protective measures." [Regulation 5(34)(b)]*

4.4.3 Manufacturers

The Supply of Machinery (Safety) Regulations 1992 require manufacturers of equipment originating in the EU to ensure that the machinery they supply is safe. Where the equipment originates from outside the EU, the importer/supplier is required to assume the manufacturer's responsibilities.

Machinery is often defined as a piece of equipment which has at least one moving part and, usually, some kind of drive unit. Under this definition, some individual components of lifting equipment can be considered to be a machine e.g. lifting and lowering devices. Also, a rigging system, including all its component parts, could be considered to fall within this definition of a machine. In fact, lifting equipment is specifically referred to in the regulations.

Discussion with HSE personnel revealed that some rigging system components should definitely be considered as machines e.g. winches. Others would only fall under the Machinery Regulations when forming part of a rigging or lifting system:

> *"The whole rigging system should be considered as a machine. Although many of the components would not be classed as a machine in themselves, the linking of the components together to enable the lifting or lowering of a load through directly applied manual effort classes that collection of components (rigging system) as a machine.*
>
> *When such a collection of parts is assembled into a machine, then the Essential Health and Safety Requirements (EHSR) of The Supply of Machinery (Safety) Regs (SMSR) will apply." (Jason Cole, pers. comm.)*

In discussing the scope of the Machinery Regulations, DTI guidance notes to the manufacturers of machinery also suggest that individual components may be included:

> *"Components which are supplied separately to fulfill a safety function when in use and the failure or malfunctioning of which endangers the safety of health of exposed persons" (DTI, 1995)*

The latter document carries on to describe the requirements for appropriate design procedures, product marking and user instructions for the components referred to.

Overall, therefore, there would appear to be very little difference in the information requirements for PPE (personal protective equipment) and non-PPE lifting equipment. Both types of lifting system would appear to fall within the scope of the Machinery Directive, and therefore be subject to the Machinery Regulations. Under these regulations, various obligations are placed on equipment manufacturers. These obligations can be summarised as:

- Design equipment for the intended task
- Identify health and safety hazards
- Assess the likely risks
- Eliminate risks (where possible) or provide information regarding residual risks
- Sign and guard the product to reduce risk
- Maintain a technical file on the product (drawings, design specifications, test information, technical reports and certificates etc.)
- Provide clear and comprehensive user instructions to ensure that the product is assembled, installed, commissioned, handled safely, used, adjusted and maintained correctly
- Provide a 'declaration of conformity' or a 'declaration of incorporation'
- CE mark where appropriate
- Be an information source to the end user

It is a common belief that manufacturers of PPE have more constraints and requirements placed on them by the regulations than manufacturers of non-PPE items (i.e. equipment that is not designed primarily for the personal protection of the end user). It is certainly the case that products sold as PPE, and certified under EN standards and CE marked, are required to be supplied with prescribed information. For example, karabiners that are supplied as connectors under the EN362 or EN12275 standards must be accompanied by the following information:

- The name or trademark of the manufacturer, importer or supplier
- The number of the European standard applying e.g. EN 12275
- The meaning of any marking on the product
- On the use of the product
- Whether or not the connector, when fitted with a device intended to lock the gate closed under load, can still be opened
- On how to choose other components for use in the system
- On the lifespan of the product or how to assess it
- On the effects of chemical reagents and temperature on the product
- On the effects of storage and ageing

Additionally, the EN 365 standard entitled ‘Personal protective equipment against falls from height – General requirements for instructions for use and for marking’ outlines the information that must be provided with each item of PPE equipment sold. The table of contents relating to this standard includes the following headings:

- Instructions for Use
- Instructions for Maintenance
- Instructions for Periodic Examinations
- Instructions for Repair
- Records
- Marking

4.5 GENERAL CONCLUSIONS

It is clear that both employers and employees can only discharge their obligations under the health and safety legislation to the extent that the relevant information is available. Where information is either absent or insufficient, as would generally appear to be the case with regards to rigging equipment, it could be argued that it is not possible for these obligations to be satisfactorily met. In particular, those employees who are charged with duties of competence (i.e. appointed as Competent Persons) in carrying out rigging operations, may very well not be in possession of sufficient information for them to be judged truly competent.

It became clear, during the gathering of information about rigging components, that information of sufficient depth was not generally readily available to allow competent persons and/or operatives to make informed decisions about, for example, system design. Many items of equipment lacked even basic information about compatibility with neighbouring components, or approved configurations e.g. the knotted or spliced strengths of ropes were rarely available. In some cases a Minimum Breaking Strength (MBS) was quoted for a component, but no Design Factor or Working Load Limit (WLL). In other cases, a WLL was provided without any information on Design Factors. In most cases, no limitations to product application were indicated e.g. the appropriateness or otherwise of certain rope fibre types to applications involving particular loading patterns. It is possible that the only information accompanying a critical component, such as a lowering device, could be the diameter of rope with which it is intended to be used, with no other indication of load capabilities. This is clearly insufficient.

During the course of this project, discussions, with both operatives and employers experienced in tree care operations, revealed some disquiet over the lack of relevant information. This led to the collation of a list of information required by employers, competent persons and/or site workers. Adherence to this list would, in most cases, also appear to cover the obligations of manufacturers under current UK legislation. In many instances, this data is already available, but it may not be routinely made available by manufacturers. In other instances, there is a need for manufacturers to ensure that the information is available in the first place, and subsequently supplied with their products at their point of sale.

The complete list of required/relevant information for hardware, cordage and textile components for use in rigging systems, as established through discussions with experienced operatives and employers, is as follows:

- Manufacturer contact details
- Construction and design information
- Materials used
- Corrosion resistance

- Markings and information
- Labelled diagrams and nomenclature
- Test results
- Who performed tests (independent or manufacturer)
- Test criteria and/or relevant standards (e.g. EN, ANSI)
- Requirement for risk assessment
- Requirement for rescue plan
- MBS, Design Factor, WLL (both dynamic strength and static strength, if different/relevant)
- Implications of different configurations (with images)
- Compatibility issues (with other possible links in chain, including recommendations, if any)
- Detailed user instructions
- Installation recommendations including ergonomic issues
- Appropriate usage including hazards and ergonomic issues
- Approved conditions of use
- Recommended usage
- Inappropriate usage
- Training/supervision requirements (possibly with the inclusion of relevant competencies)
- Lifespan
- Storage and transport
- Inspection, rejection, correction criteria (including location of wear ‘hotspots’)
- Maintenance techniques
- Record keeping (e.g. record of use, record of maintenance)

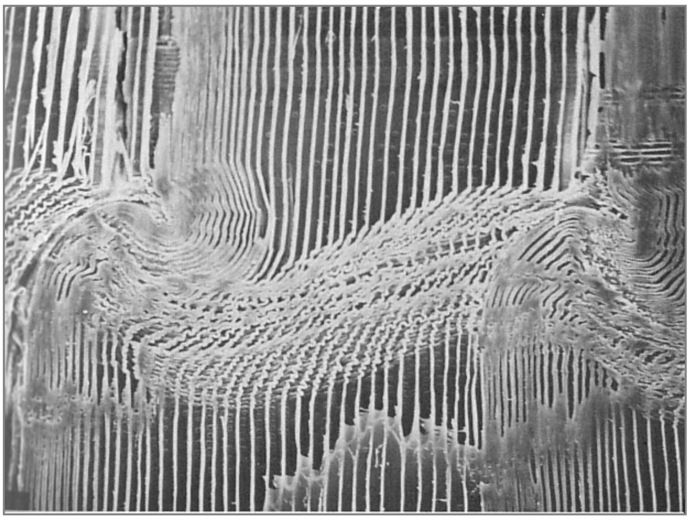
5 BEARING CAPACITY OF TREE SPECIES

The load-bearing capacity of a structure is usually defined as the maximum load it can sustain. Failure occurs as a result of overloading. The term strength is often used as if it was equivalent to the bearing capacity of a structure, although it actually refers to materials. With regard to metals, for example, engineers distinguish between ultimate strength and yield strength. The former is the maximum load required to fracture a specimen, whereas the latter is the load required to cause primary failure (*cf* Chapter 2).

5.1 METHODS OF ASSESSING THE LOAD-BEARING CAPACITY

In order to assess the bearing capacity of a living tree as a structure, a model derived from statics analysis is usually used. The tree is compared to a cantilever beam that undergoes unilateral bending. The root system is often assumed to be inflexible and static, forcing the stem to bend and concentrating bending stresses at the base of the tree. The cross-section of the stem is idealised to an elliptical or round shape, so the stem can be studied as the equivalent of a cylinder. Deflections are only incorporated in scientific studies (e.g. like Gaffrey *et al* 2002), but not in simplified approaches to assessing the load-bearing capacity of stems (e.g. the SIA-method by Wessolly, 1995).

The compressive strength of marginal fibres is decisive for load-bearing capacity in these models. On the scale of wood fibres, excessive compression causes permanent deformation that is referred to as primary failure. The ultimate load-bearing capacity may actually be greater than the compressive strength, but the tree would be damaged long before fracture. Green wood is reported to be about twice as strong in tension as in compression (Bodig *et al* 1982, Niemz 1993). Therefore, failure will occur on the compression side first, by the buckling of fibres (Vincent 1990). Even though the structure will not fail completely when the fibres kink, the tree may not withstand future loads, even if they are significantly lower (primary failure, *cf* Chapter 2). The compressive strength of fibres parallel to the grain should, therefore, be used as a threshold for strength (*cf* Wessolly, Erb 1998).



Crushing failure in Norway Spruce[*]

[*] *Picture reprinted from Bodig Jayne, 1982 courtesy of Krieger Publishing Company*

The 'modulus of rupture' is a measure describing the load at which a specimen fails e.g. in bending. Tests for determining bending strength are usually carried out on clear-cut specimens of wood suspended between two supports (three or four point bending). This test procedure is designed to assess the strength of wooden bars in construction. The structure of a stem or branch is much less homogeneous and the material properties of fibres may differ over the radius of a section. Furthermore, central loading of a supported specimen may produce considerably different strength properties than unilateral loading of a cantilever beam (Wessolly, pers. comm.). Therefore, the values derived from these tests should not be used without a caveat.

Models based on the compressive strength of marginal fibres seem more suitable for estimating the load-bearing capacity of stems and limbs in standing trees, and have been frequently used. The failure predicted by these models is generated from pure bending. They are also used in statics calculations for wood construction, and make the assumption that cross-sections are regular. They do not account for other modes of failure (see Chapter 2). In particular, if cross-sections show a great degree of hollowness (i.e. small residual walls), and if open cavities are present in stems of smaller diameters, allowance must be made for tendency to structural failure.

In order to assess the strength of trees against loads generated from rigging and dismantling operations, not only the maximum tolerable forces are of interest. Trees are not static structures, but are flexible and deformable under load. Therefore, dynamic properties should actually be taken into consideration. Trees that are more flexible can dissipate more energy than stiffer specimens. The energy transmitted by a specific impact (i.e. a log of mass A falling a distance B) will be absorbed more gradually if a branch bends further as the load is applied, thus reducing peak forces. Similarly, deflection of the stem will reduce peak forces under dynamic loading and thus increase its bearing capacity.

At a given strength of the marginal fibres, less stiff tree species can dissipate more energy and so can bear greater dynamic impact loads. Therefore, as well as the strength of wood fibres, the stiffness of wood fibres will also be covered in the following sections.

5.2 MECHANICAL PROPERTIES OF GREEN STEM TISSUE

5.2.1 Compressive strength

Values for the maximum compressive stress green wood fibres can sustain have been studied by only a few researchers in the past. The stiffness of the fibres was usually also tested in their research. Lavers (1983) published data on material properties for green timber of UK tree species; Jessome (1977), Winandy (1994) and Forest Products Laboratory (1999) (which appears to be a summary of the previous two) did likewise for North American trees. The application of these values to the safety assessment of trees is limited, due to the fact that they were derived from standard tests on small wooden specimens and boards. It is not known to the authors of the present report whether they have been used in practice to assess strength in a greater number of standing trees. Yet they do represent the strength of different species, relative to one another, and may serve as a basis for working out a specific tree's load-bearing capacity, taking into account the experience of other practitioners (*cf* Chapter 2).

Other data on the strength of green wood was derived from crushing tests on increment cores, using a device called 'Fractometer II' by Götz (2000). The small size of the wood samples extracted from tree stems (8 mm) and the potential distortions of the specimens, resulting from the extraction process itself, could eventually alter the findings of these experiments (*cf* Glos, Lesnino 1994) . The author of the study found significant deviations in his results compared with those in the above-mentioned study carried out by Lavers, but concluded that these were due to the natural variability of wood.

Statics-integrated methods, as developed at the University of Stuttgart, Germany (Sinn, Wessolly 1989), make use of material properties listed in the 'Stuttgart Strength Tables', which were derived from adapted standard tests (Wessolly 1989, 1992). The methods used for testing specimens, and the process of evaluating the data derived from the tests, were never published in a scientific journal. Yet the figures have been proved to be applicable to the assessment of fracture safety of trees, in pulling-tests successfully performed on the structural integrity of thousands of trees. The tables are constantly being expanded (e.g. Brudi 2001, Horacek 2003).

In the proposal on how to evaluate the strength of stems used as anchor points presented in 5.3, data contained in the Stuttgart Strength Tables was used for three major reasons. Firstly, as mentioned above, these values were widely used as a reference point for the safety assessment of thousands of hazard trees in Europe, and proved to be reliable.

Secondly, the tests were run at a greater speed than the usual testing standards would prescribe. Also, in a real rigging scenario, the load is not applied gradually, but quickly over a fraction of a second. Changes in the speed of deformation are known to affect the strength of fibres significantly, as shown by Ylinen (1959) for wood of *Pinus sylvatica*. Therefore, the test procedure used to compile the Stuttgart Strength Tables seems to be more than adequate for rigging applications.

Thirdly, if these figures are used, the calculations are most likely to err on the side of caution, as illustrated in Table 5.1 (overleaf). Only in some cases have other authors reported significantly lower values than Wessolly, Erb (1998). For these, the results of the calculations based on the Stuttgart tables may need to be further examined by practical tests on the strength of stems.

Rust *et al* (2007) recently criticised one aspect of the Stuttgart Tables: the dataset was not published in scientific journals, or by comparable means, thereby precluding critical review by other researchers. The tables, and statistical data to back them up, are contained in proceedings of conferences in Germany, dating back to the early 1990's. One of these publications indicates that the authors of the Stuttgart Strength Tables (Wessolly *et al* 1989) did not regard the arithmetic mean as an adequate figure for use in engineering calculations. It is stated, therefore, that the figures listed in the tables represent the arithmetic mean minus one standard deviation.

Other data is available on the mechanical properties of green wood (see references above), but this has not been tested to a similar degree in practical applications of tree stability assessment. It seems appropriate, therefore, to use the Stuttgart Strength Tables in evaluating the bearing capacity of prospective anchor points in a tree.

5.2.2 Modulus of elasticity

Some of the previously mentioned sources also list data on Young's modulus[*] in compression parallel to grain. Furthermore, Cannell, Morgan (1987) tested stiffness in young tree stems of four tree species of up to 17 cm diameter. They also list stiffness figures, published in other publications, based on over-bark diameters. Data found in literature has often been determined by three point bending tests. This information should not be used without amendment for assessing the stiffness of tree stems. Due to shear, curvature and hydraulic effects in green wood, three point bending may not correctly represent the critical load scenario in stem bending (which is actually unilateral bending). Coder (2005) uses a correction factor to account for shear deflection in specimens when determining Young's modulus of green wood tested in three point bending. By means of multiplying the stiffness found in three-point bending by a factor of 1.1, Coder derives a value for stiffness in compression and tension parallel to grain.

[*] *also referred to as stiffness or modulus of elasticity (MOE)*

Table 5.1a Compressive strength of green timber of common British tree species (Part 1)

Botanic name	***Stuttgart Strength Tables***	***Lavers***	***Götz***	***USDA***	***Jessome***
Abies alba	***15***	22.0	25.65		
Abies procera		***16.0***		20.8	
Acer campestre	***25.5***				
Acer platanoides	***27.3*** (Horacek 2003)		33.06		
Acer pseudoplatanus	***25***	27.5			
Acer saccharinum	20			17.2	***13.7***
Aesculus hippocastanum	***14***	17.4			
Alnus glutinosa	***20***	21.7			
Betula pendula	***22***	26.3	26.82		
Carpinus betulus	***16***	27.0			
Castanea sativa	25	***24.2***			
Fagus sylvatica	***22.5***	27.6	36.4		
Fraxinus americana				27.5	***16.4***
Fraxinus excelsior	***26***	27.2	31.23		
Gleditsia triacanthos				***30.5***	
Juglans nigra				29.6	***18.3***
Juglans regia	***22*** (C. Bader *nd*)				
Larix decidua	***17***	24.3	29.42		
Liriodendron tulipifera	***17***				
Nothofagus procera		***16.8***			
Picea abies	21	***17.0***	19.45		
Picea omorika	***16***	16.5			
Picea sitchensis		16.1		16.2	***14.3***
Pinus ponderosa		17.7		16.9	***14.8***
Pinus strobus	16.9 (Horacek 2003)	13.9			***13.4***
Pinus sylvestris	***17***	21.9	26.52		
Platanus x hispanica	27	***24.2***	30.55		
Populus x canadensis	20	***19.3***	21.38		
Populus x canescens		***20.1***			
Populus nigra	***20***				
Populus nigra 'Italica'	***16***				
Prunus avium		***27.8***			
Pseudotsuga menziesii	20	24.6	28.87	26.1	***19.4***
Quercus robur	28	27.6	***27.54***		
Quercus rubra	20	28.7			***16.8***
Robinia pseudoacacia	***20***		43.8	46.9	

(minimum values indicated in bold italic, all data in Mega Pascals [MPa])

Table 5.1b Compressive strength of green timber of common British tree species (Part 2)

Botanic name	***Stuttgart Strength Tables***	***Lavers***	***Götz***	***USDA***	***Jessome***
Salix alba	16	***14.7***	15.51		
Salix alba 'Tristis'	***16***				
Sequoiadendron giganteum	***18***				
Sequoia sempervirens				***21.4***	
Sophora japonica	***20***				
Thuja plicata		***18.3***		19.1	
Tilia americana				15.3	***7.7***
Tilia euchlora	***17.5***				
Tilia cordata	***19.7*** (Brudi 2001)				
Tilia platyphyllos	***20***				
Tilia vulgaris	***17***	26.1			
Tilia tomentosa	***20***				
Tsuga canadensis				21.2	***16.8***
Tsuga heterophylla		***19.7***		23.2	20.5
Ulmus americana				20.1	***12.1***
Ulmus glabra	***20***	30.4			
Ulmus x hollandica		***18.7***			
Ulmus procera		***16.9***			

(minimum value indicated in bold italic, all data in Mega Pascals [MPa])

Because lower values of stiffness allow branches to deflect further (thereby dissipating energy and reducing peak loads), higher values of stiffness are generally adverse in terms of bearing capacity against quickly applied (dynamic) loads. Therefore, to err on the side of caution, maximum values of stiffness should be considered the safer choice. On the other hand, greater flexibility of fibres may result in an increased susceptibility of a stem to swaying motion, which would enhance the adverse effects of harmonic excitation. Consequently, greater stiffness may be advantageous on slender stems without lateral branches, which are usually more prone to oscillation. In simple models for assessing bearing capacity, elasticity is usually not considered.

Considering the natural variety of Young's moduli for fibres in a stem (or branch), it does not seem adequate to refer to a figure representing the arithmetic mean of stiffness of all specimens taken from across its radius (as most sources do). Because the axial stresses are concentrated on the periphery of a stem, marginal fibres contribute more to resistance to flexing under a bending moment. Since fibres in the centre of a stem bear much smaller portions of the load, their stiffness should be weighted less when defining a representative stiffness for that stem.

Researchers at the University of Stuttgart developed, and used, an algorithm that considered the positions of specimens in the cross-section in relation to their contribution to a representative figure for overall stiffness. Also, the values have been successfully applied to numerous tree hazard assessments in Europe. Therefore, based on the authors' understanding, it may be appropriate to rely initially on these figures, but to augment them with further tests. Future studies should be evaluated according to the protocol used in determining the Stuttgart Tables.

Table 5.2a Stiffness of green wood parallel to grain (Part 1)

Botanic name	*Stuttgart Strength Tables*	*Lavers*	*USDA*	*Jessome*	*Cannell Morgan*
Abies alba	***9500***	8100			
Abies procera		5700	***9500***		
Acer campestre	***6000***				
Acer platanoides	***10540***				
Acer pseudoplatanus	***8500***	8400			
Acer saccharinum	6000			***10600***	
Aesculus hippocastanum	5250	***5300***			
Alnus glutinosa	***8000***	7600			
Betula pendula	7050				***8700***
Carpinus betulus	8800	***9700***			
Castanea sativa	6000	***7200***			
Fagus sylvatica	8500	***9800***			
Fraxinus americana			9900	***11000***	
Fraxinus excelsior	6250	***9500***			
Gleditsia triacanthos			***8900***		
Juglans nigra			9800	***10800***	
Juglans regia	***5000***				
Larix decidua	5035	***7900***			5950
Liriodendron tulipifera	***5000***				
Nothofagus procera		***5000***			
Picea abies	***9000***	6300			
Picea omorika	***9000***	6400			
Picea sitchensis		5900	7900	***10400***	7850
Pinus ponderosa		6000	6900	***8690***	
Pinus strobus	7330	4800		***8690***	
Pinus sylvestris	5800	***7300***			
Platanus x hispanica	6250	***6400***			
Populus x canadensis	6050	***6800***			
Populus x canescens		***7200***			
Populus nigra	***6520***				
Populus nigra 'Italica'	***6800***				
Prunus avium		***8300***			
Pseudotsuga menziesii	10000	8300	10800	***11500***	
Quercus robur	***6900***	8300			
Quercus rubra	7200	10500		***10800***	
Robinia pseudoacacia	7050		***12800***		

(maximum values indicated in bold italic, all values in Mega Pascals [MPa])

Table 5.2b Stiffness of green wood parallel to grain (Part 2)

Botanic name	*Stuttgart Strength Tables*	*Lavers*	*USDA*	*Jessome*	*Cannell Morgan*
Salix alba	***7750***	4800			
Salix alba 'Tristis'	***7000***				
Sequoiadendron gigantum	***4550***				
Sequoia sempervirens			***6600***		
Sophora japonica	***6450***				
Thuja plicata		5400	***6500***		
Tilia americana			7200	***8070***	
Tilia euchlora	***7000***				
Tilia cordata	***8300***				
Tilia platyphyllos	***8000***				
Tilia vulgaris	4500	***9200***			
Tilia tomentosa	***8350***				
Tsuga canadensis			7400	***9720***	
Tsuga heterophylla		6800	9000	***11200***	
Ulmus americana			7700	***8550***	
Ulmus glabra	5700	***9400***			
Ulmus x hollandica		***5400***			
Ulmus procera		***5200***			

(maximum values indicated in bold italic, all values in Mega Pascals [MPa])

5.3 LOAD-BEARING CHARTS FOR STEMS

The following is a proposal on how to derive an approximation for the strength of a stem, when it is being used as an anchor point during typical rigging operations. It is based on beam theory, and indicates the load-bearing capacity of a solid cross-section under bending, as a function of its diameter.

5.3.1 Equations

The compressive stress σ generated in the marginal fibres is determined by equation 5.1:

$$\sigma = \sigma_{bend} + \sigma_{axial} + \sigma_{weight} \quad \text{equation 5.1}$$

where
- σ_{bend} compressive stress generated from unilateral bending
- σ_{axial} compressive stress generated from axial component of the applied force
- σ_{weight} compressive stress generated from the weight of the stem

As a representative value, the magnitude of the total compressive stress at a height of one metre was chosen. At this specific height, the formation of buttress roots usually does not increase the diameter any more, whereas the taper of the stem has not yet begun to reduce the diameter significantly (*cf* SIA-method, Wessolly 1995).

The following equations determine the 3 summands of equation 5.1:

$$\sigma_{bend} = \frac{M(z_0)}{W(z_0)} = \frac{F_{lateral} \times l(z_0)}{W(z_0)} = \frac{32 \times F \times \sin\alpha \times (H - z_0)}{\pi \times d_1^3} \quad \text{equation 5.2}$$

where

M	bending moment at the height of the representative diameter
W	cross-section modulus of a cylindrical beam under unilateral bending
z_0	height of representative diameter (1 m)
$F_{lateral}$	component of the applied force perpendicular to the stem axis
$l(z_0)$	length of the lever arm at height z_0
H	height of the anchor point
d_1	representative diameter of the stem at 1 m height
F	applied force
α	the angle between load direction and stem axis

$$\sigma_{axial} = \frac{F_{axial}}{A} = \frac{4 \times F \times \cos\alpha}{\pi \times d_1^2} \quad \text{equation 5.3}$$

where

F_{axial}	component of the applied force parallel to the stem axis
A	area of cross-section of the stem at 1 m height

$$\sigma_{weight} = \frac{G}{A} = (H - z_0) \times \rho \times g \quad \text{equation 5.4}$$

where

G	weight of the stem, based on the area of the cross-section at 1 m height
ρ	density of green wood (species dependent)
g	acceleration due to gravity

From the equations above, the maximum tolerable load can be derived:

$$F_{\max} = \frac{\pi}{4} \times d_1^2 \times \frac{\sigma_{compr} - (H - z_0) \times \rho \times g}{\cos\alpha + 8 \times \sin\alpha \times \frac{H - z_0}{d_1}} \quad \text{equation 5.5}$$

where

F_{max}	maximum load tolerable at anchor height H under the angle α before primary compression failure of marginal fibres occurs
σ_{compr}	compressive strength of green fibres at the elastic limit (yield strength)

Due to the fact that the strength data was derived in more or less static tests, such calculations probably underestimate the actual factor of safety in a rigging scenario. Dynamic loads may cause a different reaction from living wood cells and may render greater load-bearing capacities. The mechanism of dynamic loading in living wood is not yet fully understood. Some researchers have been, and are currently, carrying out studies on the dynamic reaction of trees to wind (e.g. James *et al* 2006; Dirk Schindler, Freiburg, pers. comm. 2005).

French researchers recently studied the effect of rock fall impacts on the stems of living trees growing on a steep slope. The results indicate that the capacity of living wood to sustain short peak forces is considerably greater than the strength measured in static load tests (Dorren, Berger 2005). Calculations based on strength calculated against more or less static loads, therefore, will provide a conservative approach (*cf* Ylinen 1959).

5.3.2 Settings

The charts presented in Figures 5.1 & 5.2 (overleaf) were designed using specific settings: a straight, upright stem; a standard height; and a standard load angle between peak forces and vertical stem axis. The standard height of the anchor point was assumed to be at 10 metres. For other heights, the results must be divided by one-tenth of the actual height (i.e. the proportion of the actual height to the standard height of 10 metres). For a selected anchor point at 20 m height, the actual maximum load would be half of the figure in the chart. Similarly, for an anchor point set at only 5 m height (with a reduced lever arm), the maximum load listed in the load-bearing charts could safely be doubled.

These corrections for height generate a deviation from the actual calculation of the load-bearing capacity. Compressive stress generated by the axial component of the applied force does not vary with height. However, this component only adds marginally to the compressive stress in marginal fibres, compared to the bending moment generated, which correlates directly to the height of the anchor point. Although the corrections should actually be worked from the lever arm (anchor height minus one metre), considering the degree of exactness achievable in such estimations, this simplification seems to be adequate (if sufficient safety factors are included).

The angle of the loading direction was set at 20° from the vertical. This angle was derived from kinematic studies, both in the laboratory and in the evaluation of calibrated video-footage from on-site tests (*cf* Chapter 8). Recordings made at the moment when a log's vertical fall was being stopped by the rope, showed an average angle between the lead and fall of the rigging line at the arborist block of 37° from the vertical. Due to friction effects, the actual loading angle of the anchor point is not the bisection of that angle, but amounts to almost 20° (see Chapter 8, section 8.3.4). Therefore, the chosen angle is representative of a worst-case scenario.

The load-bearing charts were modified to depict the altered loading of the main anchor point when redirects are being used in rigging operations. In this case, the maximum potential loading of the stem was simulated by assuming that the load is applied perpendicular to the stem axis.

5.3.3 Load-bearing charts

The standard situation that the following charts refer to is snatching logs off a vertical stem. This scenario is defined by parameters derived from kinematic studies (*cf* Chapter 8). The maximum sustainable load is displayed in Figure 5.1 (overleaf) for five different groups of tree species, containing a range of 31 tree species common in the UK. For quick assessments, the values of the Stuttgart Strength Tables were grouped for tree species of similar compressive strength. By this means, the number of curves on the charts was limited to five.

It is, however, possible to use the yellow curve and the compressive strength of the genus Tilia (20 MPa) as a reference, and apply values for compressive strength from Table 5.1. In this way, estimates for other tree species are also possible. To assess tree species not listed in the Stuttgart Strength Tables, or to use data from other sources, the loads for specific stem diameters must be multiplied by a factor. This factor is derived by dividing the compression strength of the chosen species by the representative value used to determine the yellow line (20 MPa).

Example: The under-bark diameter of a Large Leafed Lime (*Tilia platyphyllos*) to be dismantled is determined to be 33 cm at 1 m height (e.g. diameter with bark 37 cm, minus 2 cm bark at each side). The peak force this stem could bear, when a section of the stem is snatched from an anchor point at 10 m height, would be the equivalent of approximately 2 tons mass (19.6 kN force). If the anchor point was at 5 m height, the maximum force would be doubled, i.e. the equivalent of 4 tons mass (39.2 kN).

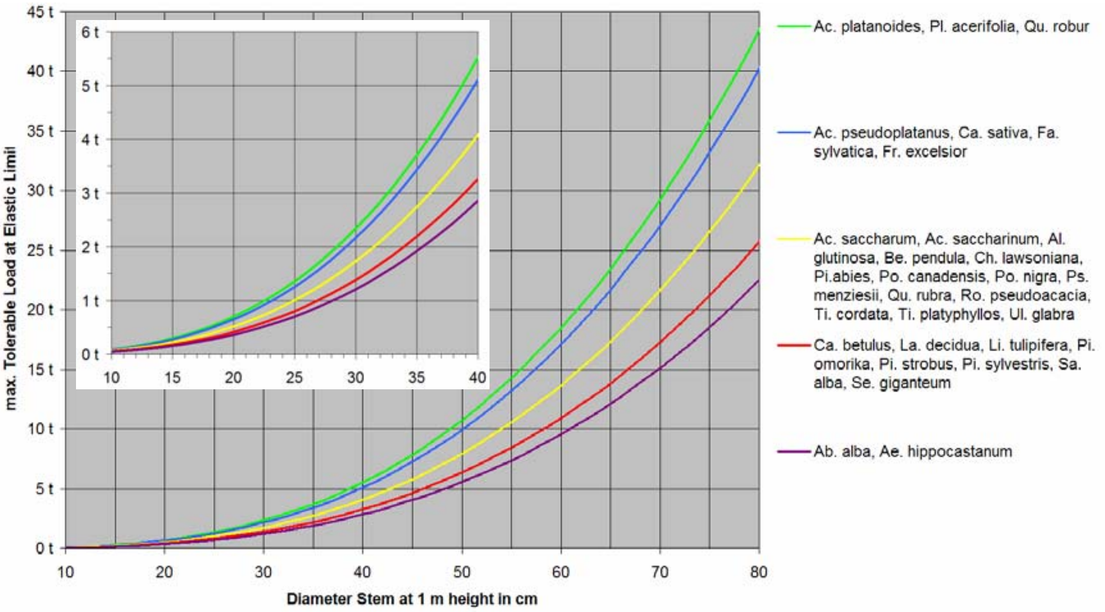


Figure 5.1 Load-bearing chart - single anchor points (insert: zoomed low range)

A Walnut (*Juglans regia*) of the same diameter could tolerate a greater load. According to Table 5.1, its compressive strength amounts to 22 MPa, i.e. 110% of the strength of Lime (which is listed as 20 MPa). Therefore, the load that could be supported from an anchor point at 10 m height would be equivalent to 2.2 tons (21.6 kN); for the anchor point at 5 m height it would increase to 4.4 tons or 43.2 kN. For dynamic loads, the significantly lower stiffness of Walnut (5 GPa as compared to 8 GPa for *T. platyphyllos*) also indicates a greater bearing capacity.

Using a redirect is common practice in dismantling trees, yet the load acting on the main anchor point is often underrated. Figure 5.2 depicts a worst-case scenario, where the usage of a redirecting pulley leads to a load direction perpendicular to the axis of the stem at the main anchor. In such a scenario, the maximum tolerable load will be significantly lower.

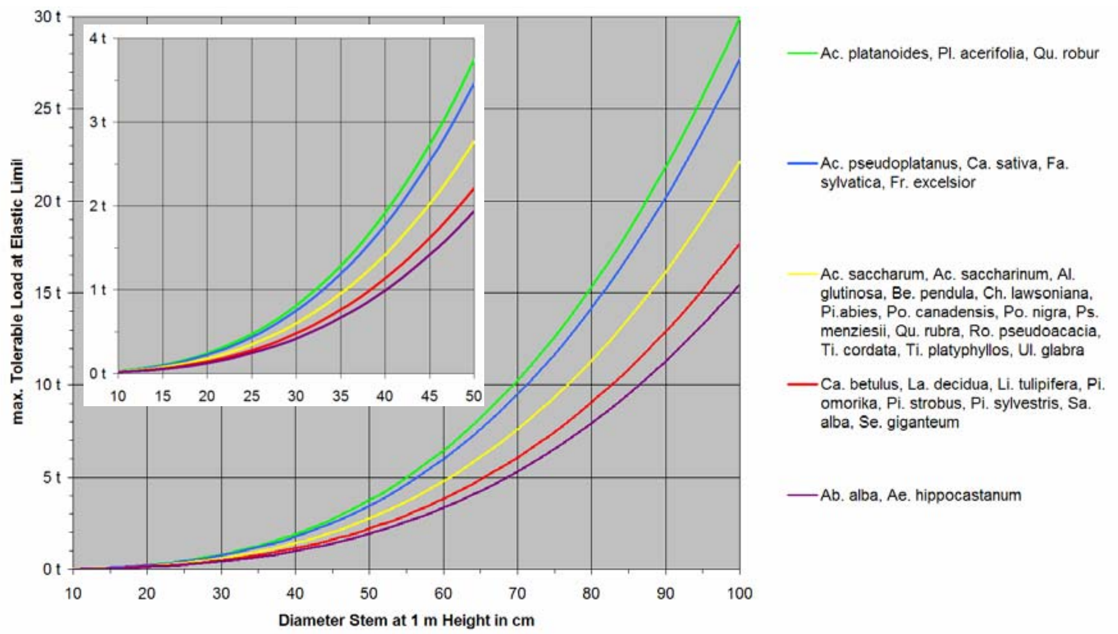


Figure 5.2 Load-bearing chart - main anchors in redirected rigging systems

For speedline or driftline scenarios, the angle of the line is decisive for the loading of the anchor point as well. Therefore, a correction for rope angles was developed in order to apply the values derived from Figure 5.2 to a specific rigging scenario. The coefficients used can be approximated by the formula:

$$cf = \frac{1}{\cos\alpha}$$

where cf the correction factor for loads from Figure 5.2 to actual bearing capacity
α the line angle measured from horizontal

The deviations from the actual strength of a stem are less than 5% and are well within the limited precision of such estimations. The formula applies only if the line is attached directly to the anchor point in the tree. As soon as a pulley is used, and the line is redirected to the bottom of the stem, the resultant force of the two legs of the line of the pulley has to be considered as the force acting on the anchor point (see Chapter 8, tables in section 8.7.1).

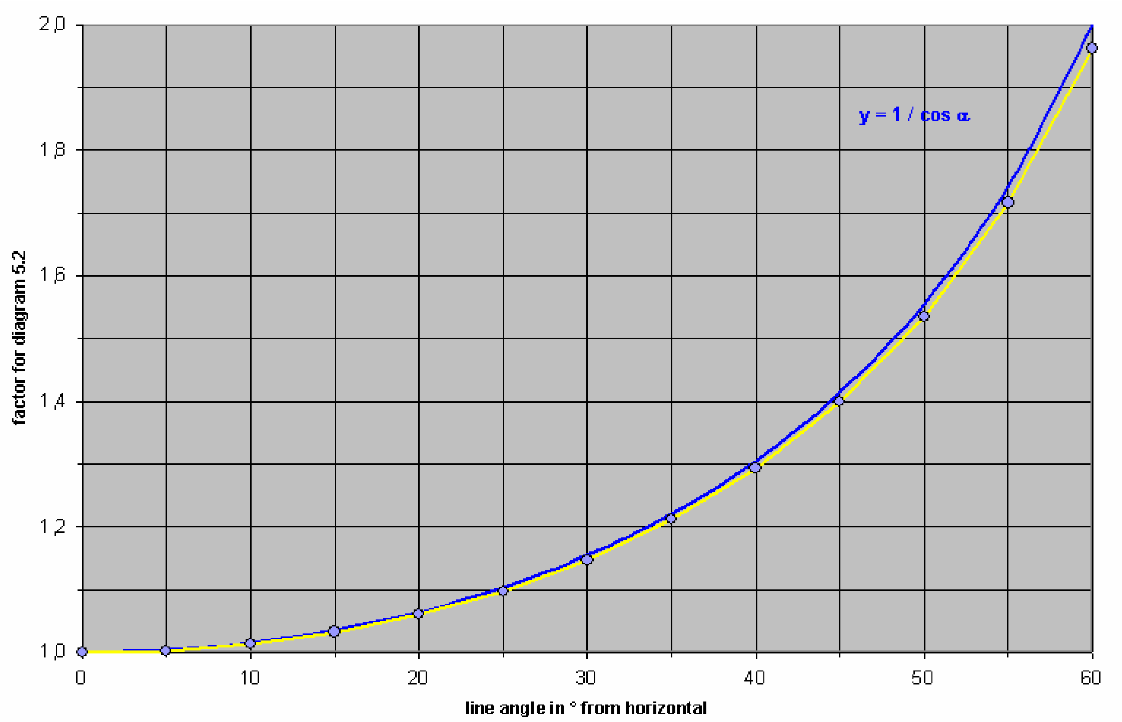


Figure 5.3 Correction factors for speedline angles

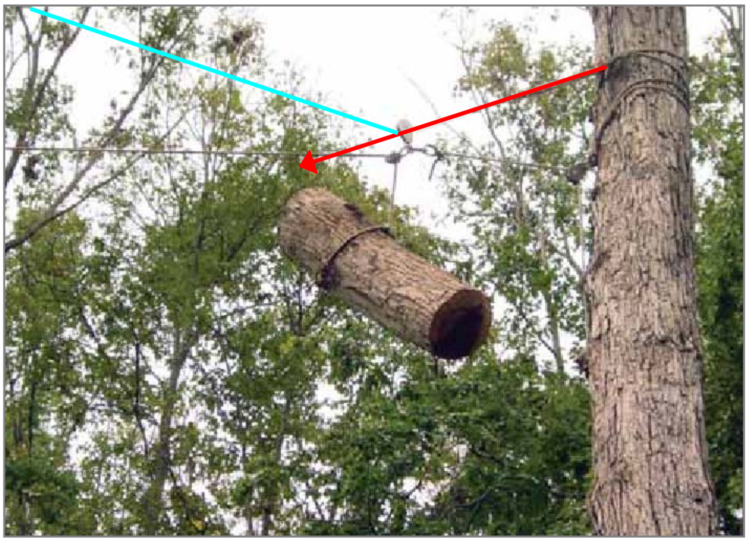
The line angle in a speedline set-up can be derived using optical clinometers, or by calculating the angle according to the following formula:

$$\alpha = \arctan\left(\frac{h_{anchortree} - h_{anchorground}}{l_{span}}\right)$$

where $h_{anchor\ tree}$ the height of the anchor point in the tree
$h_{anchor\ ground}$ the height of the ground anchor
l_{span} the horizontal length of the speedline span

The angle is distorted by slack in the speedline. A load applied at a point of the speedline, closer to the anchor point in the tree, will generate a steeper line angle, thus decreasing the bending moment applied to the stem. If the log slides further, the rope will run at a more horizontal angle and the bending moment will increase.

The maximum tension in the speedline can be expected to occur at about the middle of the speedline's length, when the angle between the two legs of the line is widest (*cf* Chapter 8). As the load always causes the rope to sag, the load angle at the anchor point will always be steeper than without the load. Therefore, a conservative approach for an assessment is to measure the gradient of the rope without the load.



Line angle in a speedline scenario[*]

5.4 STRENGTH LOSS DUE TO STRUCTURAL DEFECTS

Structural defects are not always visible to the eye. They may be hidden inside the trunk and still lead to failure if the structure is overloaded. Visual symptoms for structural defects and the means of assessing likelihood of failure were discussed in Chapter 2. The means of assessing strength loss in stems will be discussed in this section.

Kane (2006) indicates that stems are safe against fracture when they are less than 70% hollow – a criterion for proneness to wind breakage of conifers in the Western parts of the USA, published by Wagener in 1963. Wagener referred to 33% strength loss, which equals a degree of hollowness of 70% of a stem's diameter. Smiley, Fraedrich (1992) found that using a similar criterion (also based on 33% strength loss) would have predicted 50% of all tree failures in an Oak tree population during a hurricane that reached a wind-speed of 160 km/h. It would have led to the unnecessary removal of 13% of the trees that actually survived that exceptional storm.

As the authors state, incorporating exposure, height and density of the crown, as well as the strength of wood fibres (instead of using a fixed strength loss criterion regardless of other parameters), would have significantly reduced the number of false assessments (in fact, half of the trees that failed during this storm event would have been assessed as sufficiently strong, according to the threshold of 33% strength loss).

** Picture courtesy of Mark Adams, Downey Trees, USA, excerpted from (Adams 2006)*

Mattheck, Breloer (1994a) documented a field study of 800 trees that supported the validity of Wagener's criterion, later often referred to as the 'German 70% rule' (Mattheck *et al* 2006). The diagrams in that study do not show any broken trees with stems having a residual wall thickness equal to more than 32% of the stem radius (i.e. a degree of hollowness less than 68%). Yet data provided by Smiley, Fraedrich (1992) for Oaks contradicts such a clear threshold, as their data plot contained numerous broken trees that had experienced strength losses varying from 5% to 95%. Wagener also stated that his 33% limit merely represented an average value, not an absolute threshold. These authors advise that concessions had to be made in the strength of a tree's fibres, the density of the crown and site parameters.

Despite these earlier results, Mattheck *et al* postulated that the ratio t/R>30% criterion was valid, independent of the respective tree species and the height, shape and density of the crown (Mattheck *et al* 1994a) and was acquiring the rank of a constant in nature (Mattheck *et al* 1993). Only after strong crown reductions were the residual walls allowed to fall below the postulated threshold. This general applicability was doubted by a number of authors, such as Wessolly, Erb (1998), Kane, Ryan (2004), Detter *et al* (2005), and recently Bond (2006) and Gruber (2007).

Kane (2006) also indicates that the strength of wood fibres, and the actually applied load, should be considered when deciding whether climbing techniques can be used during the dismantling of a tree. He also advises taking into consideration the presence of cavities, according to their extent across the stem's circumference – in a similar way to the Bartlett criterion presented in Smiley, Fraedrich (1992). For an open cavity of 30% of the circumference, for example, Kane proposes that the required residual wall thickness should be doubled. Contrary to this, Mattheck *et al* (1994) published results of another field study carried out in Australia. The results of the latter study suggest that openings in the stem do not change the validity of their formerly postulated critical ratio t/R=0.3, provided the widths of all openings do not add up to more than 50% of the circumference.

A much smaller critical degree of hollowness was presented by Spatz (1994) for structural failure of thin-walled stems of an Elm (*Ulmus spp.*). According to biomechanical calculations, tangential fibre-splitting (delamination) would only have occurred at a residual wall thickness of one-tenth of the stem radius. These results indicate that only central cavities, of a degree greater than 90% of the radius, may lead to deformation of the cross-section sufficient to induce splitting of the thin residual wall, before the fibres fail in compression. During dynamic loading, or when forces acting in torsion are applied, these very thin-walled cross-sections show significantly decreased strength. Therefore, a similar threshold criterion may eventually also be applicable to rigging scenarios.

In drawing conclusions from the previously mentioned dataset based on a study of 800 trees, Mattheck *et al* (2006) argue that longitudinal splitting must occur before bending or kinking failure of marginal fibres occurs. This is said to be the case as a consequence of the increased shear forces occurring at the base of a hollow stem. However, they still do not provide proof for the validity of their data, whose clear threshold for critical residual wall thickness contradicts the findings of other authors (e.g. Gruber 2007). The discussion among arborists about the threshold for failure of hollow stems is still ongoing and has not yet reached a consensus (Lonsdale, 2003).

Based on safety considerations where rigging operations are concerned, the authors of the present report caution against the use of threshold criteria designed for assessing failure due to wind. It seems to be more appropriate to apply methods that are based on beam theory and to allow for the taking into account of specific loads generated by dismantling operations.

To achieve a comparative measure for strength loss of a decayed cross-section, relative to a solid stem, several means could be used. Coder proposed formulae for assessing strength loss in his ‘Tree Biomechanics Series’ (Coder 2000a). Coder's calculations are based on the reduction of the second moment of inertia for circular hollow cylinders, which works with the fourth power of the diameter:

$$I = \frac{\pi}{64}\left(D^4 - d^4\right) \qquad SL = \left(\frac{d}{D}\right)^4$$

where	*I*	the second moment of inertia
	D	the diameter of the stem
	d	the diameter of the central decay column
	SL	strength loss for a centred closed cavity

Wagener (1963) took a more conservative approach and derived strength loss from the difference in cross-section modulus between a solid stem and the decayed central column. Wagener's approach renders greater strength loss for a given degree of hollowness:

$$SL = \left(\frac{d}{D}\right)^3$$

This formula does not express the correct loss in resistance to static bending when applied, for example, to hollow cylinders in engineering, unlike Coder's formula. Yet Wagener states that this approach seemed to be appropriate, due to the irregularity of cross-sections and the heterogeneity of wood fibres in naturally-grown tree stems (*cf* Kane *et al* 2001).

Strength loss formulae are frequently being used internationally, by consulting arborists, for assessing tree hazards. In Germany, within the statics-integrated methods, a practitioner’s approach called the SIA-method (Statics Integrated Assessment) also uses formulae, based on the third power of the diameter ratio, for determining minimum residual wall thickness for closed, centred cavities (*cf* Wessolly, Erb 1998):

$$t = 0{,}5 \times D \times \left(1 - \sqrt[3]{SL}\right) \quad \Leftrightarrow \quad SL = \left(\frac{d}{D}\right)^3$$

where	t	the residual wall thickness of a closed centred cavity (equation from Wessolly, Erb 1998)

The SIA method assesses strength loss, due to open cavities and split sections, by considering standard forms of cross-sections. The underlying analysis is based on computer software that determines the cross-section modulus of any form, according to standard static definitions (as described for trees e.g. in Koizumi *et al* 2006).

In contrast to the above equation used to determine required residual wall thickness, the strength losses given in Figure 5.4 (*cf* Wessolly 1991; Wessolly, Erb 1998) are based on the difference between the moments of inertia of the sound and the defective cross-section, as computed from graphical analysis using specialist software. Two different load directions are evaluated, one along the direction of the cavity, and the other perpendicular to the opening. Also, examples for oval-shaped cross-sections and split trunks are given in order to account for the effect of adaptive growth in tree stems.

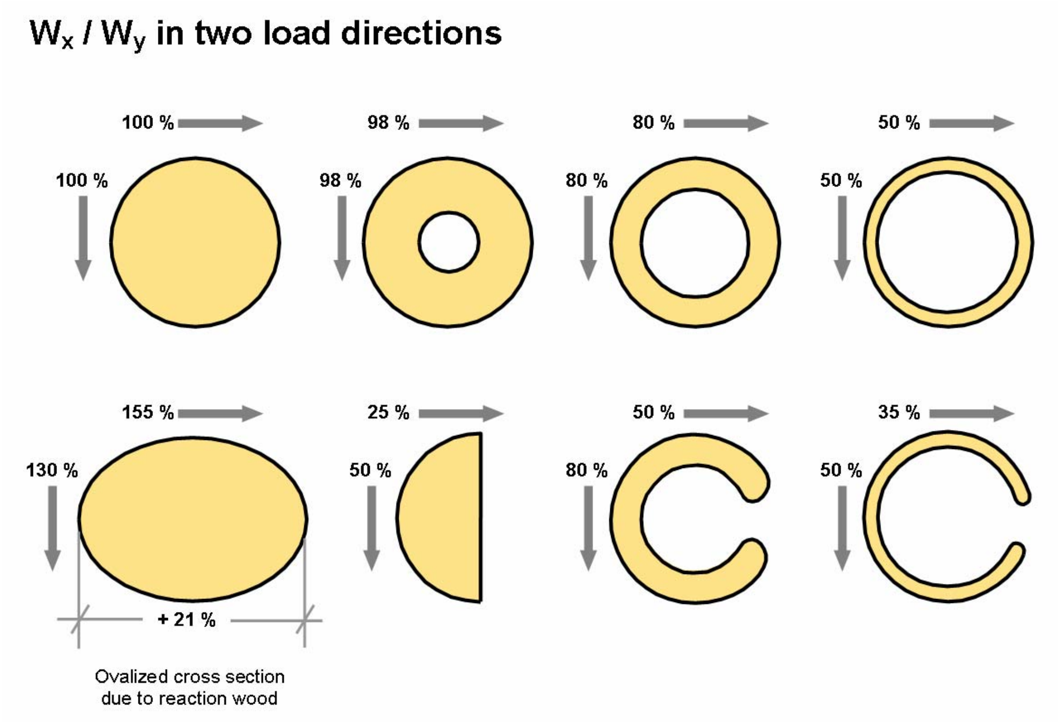


Figure 5.4 Strength loss for standard cross-sections (SIA-method)

The strength losses indicated in the above diagram, particularly for the more extreme cases, may not be as great as might be anticipated. This is because, under bending, stresses are concentrated in the marginal fibres, and a great loss of wood in the core section does not affect the residual strength as much as might be expected. However, where there is an opening in the marginal fibres, there is a much greater strength loss in the direction of the opening.

Unless wall thickness falls below a critical value of $1/10^{th}$ of the stem radius, the calculations based on bending failure are usually seen as a good approximation to strength loss (Spatz 1994). Mattheck *et al* (2006) use stress magnification factors to assess the strength loss in a hollow cylinder after a radial crack has split a stem in two halves. If the stem was previously 70% hollow, the stress in the marginal fibres increases by a factor of roughly 3.7 on the compression side after the section split.

Open cavities and eccentric decay columns can be taken into account in some of the formulae used to assess strength loss. Some of the calculations continue to work on beam theory (Coder 2000b); others adopt proportional factors in order to take into account openings within the circumference (Smiley, Fraedrich 1992). Mechanical defects in the neutral plane of stems are also evaluated by Coder's biomechanical calculations (Coder 2000c). The results are similar to the assumptions in Wessolly's SIA method: for example, for the co-dominant stem that is equivalent to a radially cracked stem (as described in Coder's work).

Practitioners might find difficulty in applying strength loss calculations to derive reliable figures on which to base a risk assessment. Simple diagrams, as used in the SIA-method, based on biomechanical calculations of acknowledged validity, may offer an option that enables practitioners to get a better understanding of the loads a compromised stem or limb can bear.

> *"Until better information is generated about the reliability and interpretation of the calculations, we caution against relying on strength loss calculations to quantify trunk failure potential" (Matheny, Clark 1994).*

Particularly in severely damaged structures, with open cracks or decayed wood tissue, there would be no value in advising a strength loss calculation. However, where visible symptoms indicate that the tree has reacted to structural defects, simple assumptions for strength loss could be made, according to the SIA-method (as depicted in Figure 5.4). At the very least, if the residual wall thickness falls below one-tenth of the radius, the weakened structure should be regarded as prone to failure, not due to bending stresses, but by the formation of delamination cracks and buckling of fibres.

*Structural failure of a thin-shelled cross-section**

5.5 STRENGTH OF LIMBS AND BRANCHES USED AS ANCHOR POINTS

The choice of anchor points in a tree is usually determined by the crown structure and limitations arising from targets on site, or the location of potential drop zones. For branches submitted to dynamic loads generated by rigging operations, a table of critical dimensions would enable arborists to detect rigging systems that are potentially prone to overloading.

According to regulations in many countries, as well as in the United Kingdom, prospective climbing anchor points must be inspected for structural defects and increased likelihood of failure. Weight tests are required to be carried out prior to using a natural anchor point in a tree for climbing (Arboricultural Association 2005). International standards and arborist training programmes also contain information on how to choose and test temporary anchor points for tree climbing. Yet recommendations on what diameter a branch needs to have for it to be used safely as an anchor point are rarely found.

One method of field testing branches in trees for structural integrity was recently presented by D. Neustaeter in an article in a Canadian magazine (Neustaeter 2007). The idea is to reveal hidden structural defects in limbs, by observing the pattern of sway when the branch is pulled and released rhythmically by two persons on the ground. The way the oscillation dissipates through the limb into the trunk is used as an indicator of weak or decayed sections. While this method may still have to prove its practical applicability on a wider basis, guidance on the selection of anchor points remains a vital issue for undertaking safe rigging operations.

** Picture courtesy of D. Neustaeter (Arboriculture Canada Training & Education Ltd)*

5.5.1 Required diameters of anchor points for climbing

Lilly (2005) proposes a diameter of 4 inches (approximately 10 cm) for a branch to be safe to use as an anchor point in tree climbing. Other sources (e.g. Hagen, Schwarze 1991) state that required diameters are species-dependent. In a report on 'Safe Work Practice in Arborist Fall Protection' (for the Canadian Ministry of Training, Colleges and Universities), practising arborists recommended a minimum diameter of 5 cm for branches used as climbing anchor points, and advised keeping the rope against the main stem while climbing, in order to minimise the effect of leverage (Anonymous 2005).

In another report, for the above-mentioned Ministry and the Canadian Ministry of Labour, an Arborist Industry Committee emphasises the individual characteristics of tree species, with regard to the strength of wood and the placement of anchor points within the tree (Arborist Industry Committee 2005).

A survey among 66 practising German arborists, carried out in the scope of this project, revealed that more than two-thirds would choose anchor points of diameters between 6 and 12 cm. Species-dependent variations were made within this range. Other parameters affecting the strength of anchor points were noted: more than 80% of the respondents named vigour of tree and branch, as well as branch form and attachment angle. About half of the respondents stated that season and the stem/branch diameter ratio had relevance to the strength of branches used as anchor points (Eberl, Höhne 2007).

In the UK, current best practice relating to the selection of anchor points in tree climbing operations is documented in Arboriculture and Forestry Advisory Group (AFAG) leaflet 401 *Tree-climbing operations*. In this document, which is currently under revision, no specific recommendation is given for anchor point sizes.

5.5.2 Mechanical properties of limbs and branches

Publications on the strength of living branches date back to the first half of the twentieth century (e.g. Opatowski 1944). Basic work on tree branch form, growth patterns and size dependent scaling in branches has been published since the 1970's (King & Loucks 1978, Bertram 1989, Castéra & Morlier 1991, Farnsworth & Van Gardingen 1995). Stresses around the base of a branch during bending were examined by Yoshioda *et al* (1992a).

The general behaviour of tree branches under a bending load was modelled by Gerhardt (1994) and Yang *et al* (2005) using finite element analysis. Alméras *et al* (2002) developed and tested a model that described the bending of branches of fruit trees. Several authors, e.g. Shigo (1989) and Mattheck & Breloer (1993), explained failure mechanisms for branches. Cannell & Morgan (1989) studied the mechanics of branch failure under gravitational load, and developed a useful means of examining the vulnerability of branches to breakage from measurements of their midpoint diameter.

It is commonly understood that material properties change over stem height, and that parameters derived from stem sections cannot be applied to the strength of branches and limbs without amendment (e.g. Niklas 1997, Brüchert *et al* 2000, Niklas 2002). Wessolly, Erb (1998) describe the change of material properties over height in a forked Beech tree that was probed when 85 years old. The strength of the fibres in the two scaffold branches was 75% greater compared to the stem fibres. At the same time, stiffness had also increased by roughly 85%. These values were derived from testing clear specimens of green wood extracted from the felled tree.

Furthermore, branches may not only break by fracturing at some point along their length, but also by failure of the fork or branch union. The latter mode of failure is quite different from the former. Fibre orientation in crotches (forks) differs strongly from that in the branch itself. Three failure modes for crotches are described in Farrell (2003). Calculations based on beam theory are not applicable to crotch strength without a caveat. This will be discussed in section 5.5.5.

Young's modulus of green branches

A number of researchers have determined Young's moduli of tree branches with regard to stability (e.g. Canell, Morgan 1987 for four different tree species). The stiffness of live branches attached to the tree, and the effect of reaction wood to strength, was investigated by Krämer (1998) in six broad-leaved tree species. Wood fibres on the topside of branches showed greater stiffness than those on the underside. Results derived from these tests are shown in Figure 5.5.

Niklas (1999) reports stiffness for the tree species Black Locust (*Robinia pseudoacacia*), derived from stem and branch wood. Older sections of the tree showed greater stiffness, whilst branches and limbs displayed significantly lower stiffness. Sections less than 15 years old had Young's moduli between 6 and 10 GPa, whereas older sections ranged from 9 to 13 GPa. In a more recent publication, Brian Kane determined the Young's modulus of samples of 2.5 x 2.5 x 35.6 cm freshly cut from branches of Bradford Pear (*Pyrus calleryana var. 'Bradford'*), using a universal testing machine and a three point bending procedure similar to ASTM 2000. He found an average modulus of elasticity of around 6 GPa.

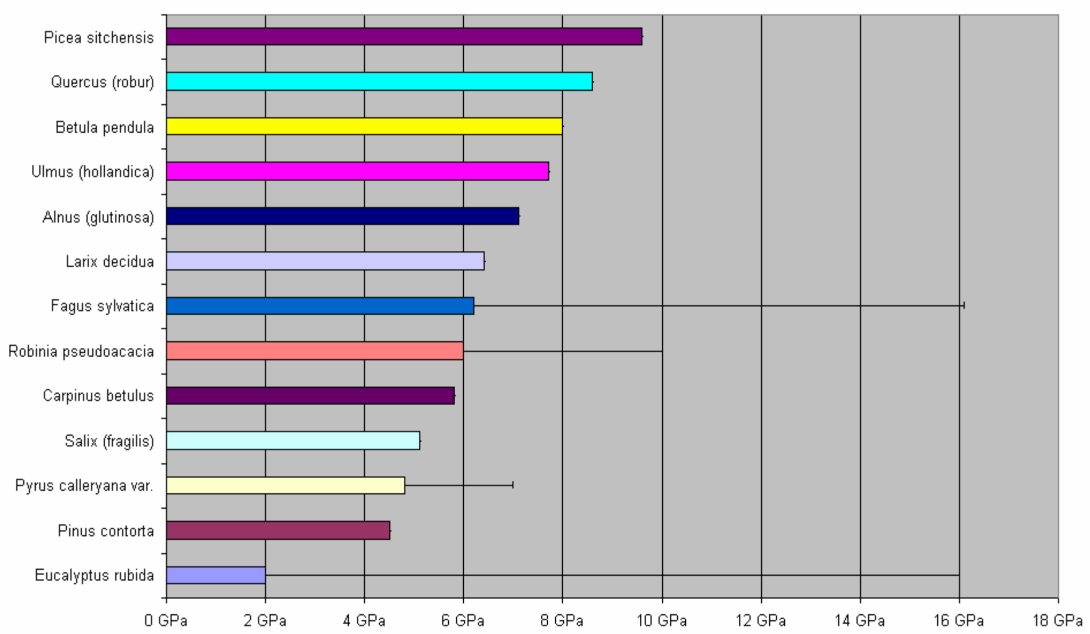


Figure 5.5 Young's modulus of living branches -minimum values found (range indicated for multiple sources)

Strength of green branches

Results of on-site tests studying branch strength of mature trees of species frequently dismantled using rigging techniques, were found in only three publications. Lilly, Sydnor (1995) compared the strength of branches for two species of Maple (*A. saccharinum* and *A. plataniodes*) under static loading, using a practical approach. They applied vertical force and broke 40 live branches ranging from 5 to 30 cm in diameter.

A practical study of the strength of limbs as anchor points was carried out in 1997 in Germany. The authors determined the critical forces required to break branches and limbs of from 5 to 13 cm in diameter, measured at their points of attachment. This study applied static loads, was carried out in summer on four Canadian Poplars (*P. canadensis*), and comprised 15 limbs taken from different parts of the crown hierarchy (Genenz *et al* 1998).

Water sprouts on trimmed trees were tested for stability against regular branches in Silver Maple (*A. saccharinum*) by Dahle *et al* (2006). The figures for unpruned branches were comparable with other data, while previous pruning was found to have significantly reduced the strength of both attachments and branches.

Strength properties for branches of other trees species could be derived from the published data, which usually lists the ultimate stress at fracture. Data for primary failure was contained in Niklas (1999) for Robinia (*R. pseudoacacia*) and in Wessolly, Erb (1998) for Beech (*F. sylvatica*). These tests were carried out on small specimens of geometrically-formed fresh specimens, with the load applied parallel to the grain. For the species European Linden (*Tilia vulgaris)*, data on compression strength parallel to grain was also obtained. Sinn tested samples cut from branches (Sinn 1985a) and, in another study, probes from branches of three other species were tested in three point bending (Sinn 1985b) using a standard protocol (DIN 52 186).

Other authors have referred to the bending moment required to break a branch, or to the compressive stress causing fracture on the compression side only. Some values were derived from tests on small specimens of wood crushed in a Fractometer III (Krämer 1998). Therefore, the suitability of the data for comparing one result with another is very limited. Sinn (2003), for example, states that the great strength of Honeylocust (*Gleditsia triacanthos*), as derived from static bending tests, is not confirmed by practical experience of the likelihood of branch failure in that species. Gleditsia is one of the trees that Sinn reports as being prone to shed branches, especially when growing on eutrophic soils. Sinn claims that short fibres, and slender branches that are susceptible to oscillation, are why this paradox occurs. He concludes that it is not adequate to rely on standard laboratory test data when assessing the strength of living branches.

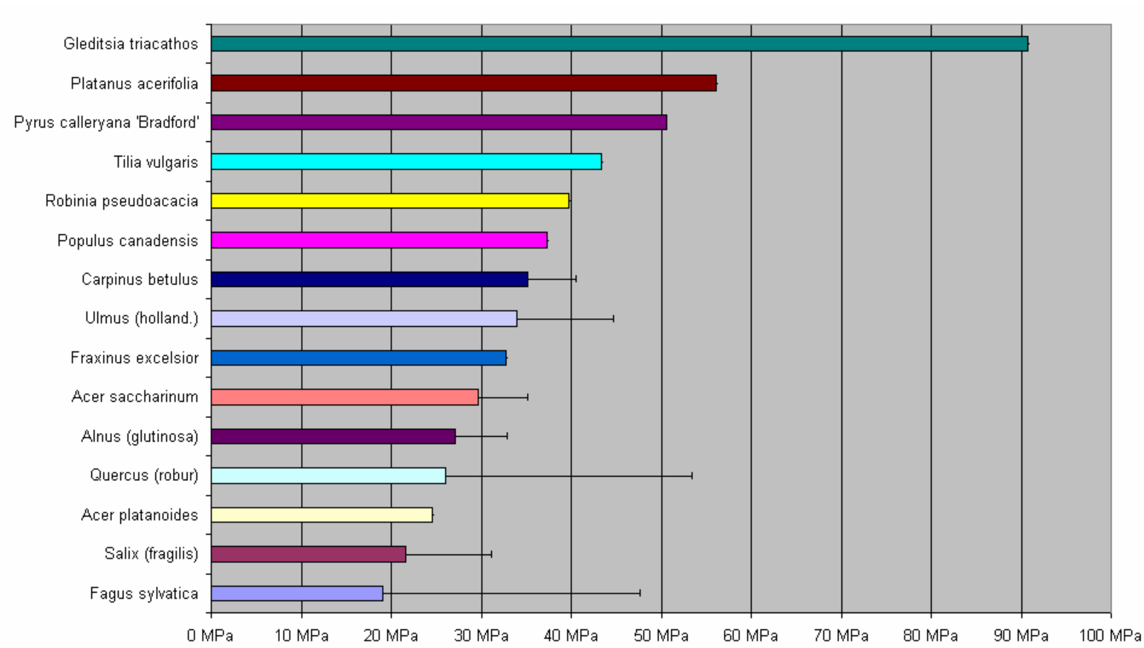


Figure 5.6 Average strength of branches and branch wood - (maximum range indicated for multiple sources)

It should be added that the actual testing procedures might significantly affect the results described above. Ultimate strength may be significantly greater than yield strength, so that overloading may occur at much smaller loads, eventually resulting in failure during the next load cycle. Bending strength derived from static tests on simply supported beams, differs considerably from strength in unilateral bending, which more closely reflects reality. Kane (2007) reports critical stresses, in marginal fibres of branches broken under unilateral bending, that were considerably lower than the modulus of rupture in three point bending for samples cut from the very same branches.

Many authors used branches in their test series that were well below the diameter of typical anchor points (as low as 0.5 cm). It is still unclear whether or not the figures so derived can reliably be applied to branches of greater diameter. Therefore, until a reliable correlation between strength in bending and actual bearing capacity in a standing tree can be derived, only results arising from practical tests in realistic loading scenarios can be considered valid for rigging operations without a caveat. Tests of this nature were carried out in the course of this project.

The results show significant deviations from the strength of fibres in stems of the respective tree species (*cf* Table 5.1). Inherent to the natural variability of mechanical properties of living wood, the bearing capacity of branches may also vary with season, fibre saturation and stiffness of fibres (Canell & Morgan 1987). Also, wind exposure has a significant influence on growth rates, and presumably also on material properties (Watt *et al* 2005). Other factors, such as wood density, spiral grain and the microfibril angle, may also affect the strength of wood tissue. The relationship between the ratio of trunk diameter *vs* branch diameter and branch strength was studied by Gilman (2003). However, the specimens used were taken from young trees, so the application of criteria derived from this study may be limited.

5.5.3 Parameters affecting the bearing capacity of branches

The study of trimmed Silver Maple carried out by Dahle *et al* (2006) revealed a strong influence of pruning history on the strength of branch attachments. Included bark, and restricted room for adaptive growth around the cuts, may have been the reasons for weak branch-trunk junctions, where these occurred subsequent to pruning. There is, of course, a readily apparent difference in the strength of old and new growth in pruned trees.

Structural defects such as cracks and decay may also significantly decrease the bearing capacity. Visual symptoms of structural defects were discussed in Chapter 2; means of assessing strength loss were presented in section 5.4 of this chapter. The influence of growth stresses that were described by Kübler (1959) might enhance the load-bearing capacity of branches significantly. The latter effect was studied by Yoshida *et al* (1992). Increases in bending strength may also result from the differences in stiffness of fibres on the compression and tension sides, a mechanism described in the previously mentioned studies by Krämer (1998) and Burgert *et al* (2003).

Shock loads, such as those generated by arresting a climber’s fall, or the accidental locking of a friction device during rigging operations, might have a different effect on a woody structure than static loads. The damping properties of limbs that restrict the effect of a dynamic load were studied by Hoag *et al* (1971), who determined the effect of moisture and leaves on the logarithmic decrement of wind-induced oscillation of branches. It may be justified to argue, therefore, that moisture and leaves will contribute to an increased ability to damp dynamic loads from rigging operations, and add to a branch's bearing capacity in such a scenario.

5.5.4 Practical tests

To overcome the limitations of pure literature review on this essential issue, a series of practical tests were carried out in the course of this project. Additional funds from the Hyland John's grant programme of the American TREE Fund enabled a widening of these labour and cost-intensive studies on standing trees. Within the next year, further studies will follow and add to a reliable database, which will be of value in determining the strength of branches used as temporary anchor points in trees.

Material and methods

Due to an underestimation of the effort required to achieve conclusive data when proposing this project, the data plot is still limited to a small number of tree species. To date, branches of four tree species were broken in a pilot study carried out by Brudi & Partner TreeConsult and in the course of this research project. Tests were carried out in cooperation with Paul Howard of ArBO, Germany, and Chris Cowell of Treepartner, UK. Two students of the College of Applied Sciences, Weihenstephan, Germany (namely Elisabeth Eberl and Christian Höhne), took part in the field tests on Acer in 2007 and evaluated data to complete their thesis for a Master of Science degree.

Forty branches of four different tree species were pulled until they fractured. Seven mature trees were dismantled in the course of the study, including three roadside and four park trees. Tests were carried out at two locations in three different seasons. The diameters of tested branches ranged from 7 to almost 30 cm at the trunk. The dataset contains 7 branches classified as re-growth and 10 leaders from the top of an unpruned crown. The other 23 branches were growing laterally from stems or main leaders rising from the bottom, or the middle third, of the crown.

Table 5.3 Tests details and tree species

Tree species	*No. of trees*	*No. of branches*	*Location*	*Diameter (cm)*	*Date*
Acer pseudoplatanus	2	13	Erding, Germany	8.2 - 26.0	Feb 07
Acer saccharinum	1	6	Erding, Germany	14.2 - 35.0	Feb 07
Fagus sylvatica	2	13	Erding, Germany	7.0 - 19.0	Aug 06
Tilia vulgaris	2	8	Starnberg, Germany	9.0 - 29.4	Apr 06

Loads were measured with two Dynafor load cells at resolutions of 2 and 5 kg units and a custom-built Dynamometer indicating 100 N units. Stiffness was derived from readings of Elastometers placed on the topside and/or downside of the branch during the load tests. The latter devices were developed at the University of Stuttgart and were custom-built by L. Wessolly. They indicate changes in length over a span of 200 mm, at an accuracy of 1 µm (0.001 mm), and are normally used for this purpose in pulling tests carried out to determine tree stability (in accordance with the Elasto-Inclinomethod).

Over-bark diameters were measured, as well as effective lever arms and line angles. Bark thickness was measured later, at several points along the fracture surface, after the destructive tests had been completed. By incrementally recording the applied force, stress in the marginal fibres was derived from the cross-section modulus and the applied bending moment. The test was interrupted at low loads, where recorded fibre deformation was well below the expected critical degree (usually less than 0.1% elongation). By correlating the generated stress to fibre elongation, measured at the marginal fibres (by placing Elastometers at the top and bottom side of the perimeter of the branch), values for fibre stiffness were derived.

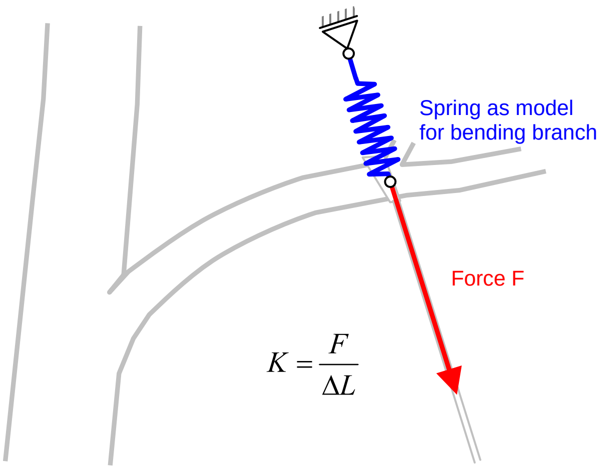
Elastometer used to determine branch stiffness

In the subsequent destructive part of the pull test, to avoid damaging the instruments, only load cells were set up, and the deformation of the branch was filmed with digital video. Deflection was recorded by counting the number of pulls and pushes of the cable winch, each shortening the cable by 22 mm in length. Loads were recorded after specific numbers of pulls and pushes of the cable winch. The load steps were selected in smaller increments as the presumed yield point was approached.

According to the method of Elastica, the deflection angle of a beam equals the bending moment divided by the flexural rigidity. However, if plastic deformations occur, i.e. beyond primary failure, the deflection angle will differ due to changes in flexural rigidity.

> *"The relation between the applied load and the deflection will be linear throughout the elastic range of a material's behaviour" (Niklas 1992).*

Therefore, the point of primary failure can be determined from the change in the linear relationship between applied force and the resulting deflection. Basically, the approach substitutes the branch by the theoretical model of a spring being pulled down by the winch. The greater the force (F) applied, the greater the stretch (ΔL) generated in the spring, with regard to its stiffness or 'spring rate' (K). Within the elastic range of any branch, that 'spring rate' is equivalent to the stiffness of that branch as an entire structure, but only if the load acts at the angle, and at the anchor point, chosen in the specific experimental design.



$$K = \frac{F}{\Delta L}$$

Figure 5.7 Spring model of branch/line set up

Nevertheless, at the limit of elasticity, a change in the gradient of the force *vs* deflection curve (i.e. an altered 'spring rate') will inevitably become visible. The fact that the branch no longer behaves like an elastic spring indicates that changes have taken place in the properties of its material (yield) and the structure has been permanently deformed (primary failure).

As the branches were gradually loaded, the length of rope pulled through the cable winch was measured in steps of approximately 20 to 100 mm. These measurements represent the deflection of the branch from its original position. At the same time, the forces generated at the anchor point were measured and plotted against the deflection to derive a force *vs* deflection curve.

The point of primary failure was determined, analogously to the definition of yield strength contained in Burgert *et al* (2003).

> *"The yield strength was defined as the point of the stress-strain curve where the deviation of the actual stress from the linear elastic behaviour exceeded 2%". (Burgert et al. 2003)*

Due to the fact that measurements in the field can never be as exact as under laboratory conditions, the 2% threshold proposed by Burgert *et al* was not a feasible measure for primary failure in the test series carried out in this project. The threshold for the deviation indicating primary failure was varied according to the specific course of each test run. As a rule, the last load measurement taken before a distinct deviation from the linear behaviour was defined as yield strength, and this value was used to derive the stress at primary failure.

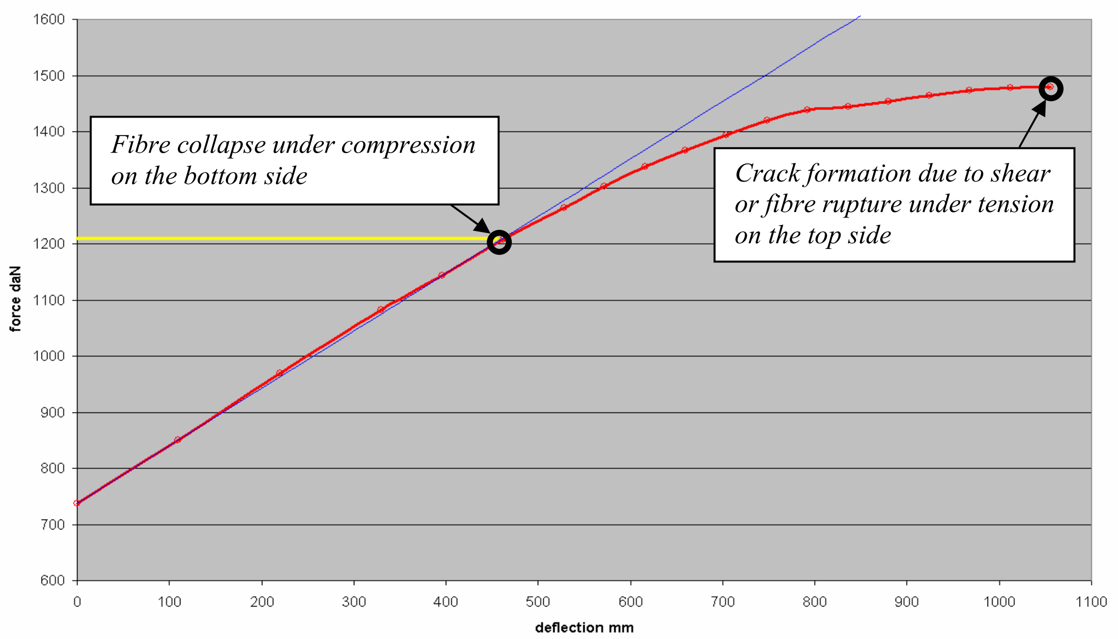


Figure 5.8 Determination of primary failure in a branch

From Figure 5.8, it also becomes obvious that living branches have a tolerance to further loading. By permanent fibre deformation, the branch can take up significantly more energy than within the linear range (energy is proportional to the area under the curve indicated in yellow and red colour). Even though this tolerance zone provides additional safety margins, it cannot add to the admissible load. The structure may be considerably damaged, and prone to failure, following loads that exceed the elastic range.

One branch was loaded beyond the elastic range. Due to recurring difficulties, the loading cycle had to be interrupted and was resumed with exactly the same set-up. The two load *vs* deflection curves show a significantly different spring constant. In the second phase, primary failure occurred at a considerably lower load.

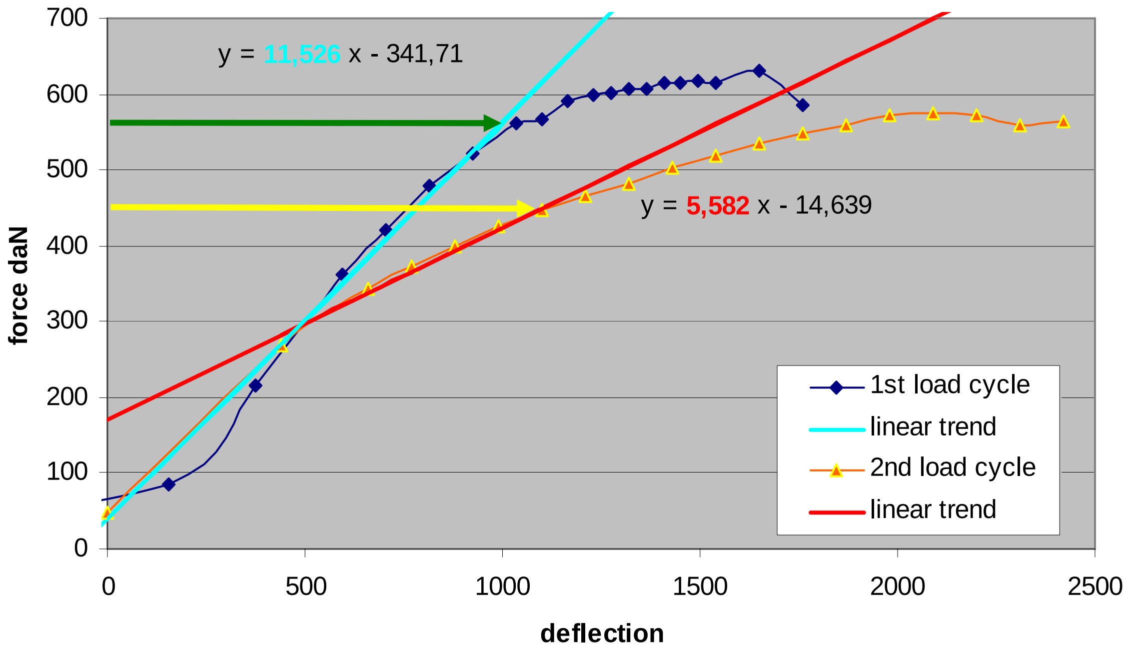


Figure 5.9 Branch loaded beyond the elastic range

For curved branches, the bending moment was calculated according to the formulae used in Genenz *et al* (1998) and Farrell (2003), who referred to Jensen, Chenoweth (1983). The force effectively causing bending stresses is the lateral component (acting perpendicular to the branch axis at the point of fracture) of the line force *F*. The line force acts at an angle α from the axis of the branch, at the fracture point. The effective lever arm *L* is the perpendicular distance of the fracture point to the line of action of the lateral force.

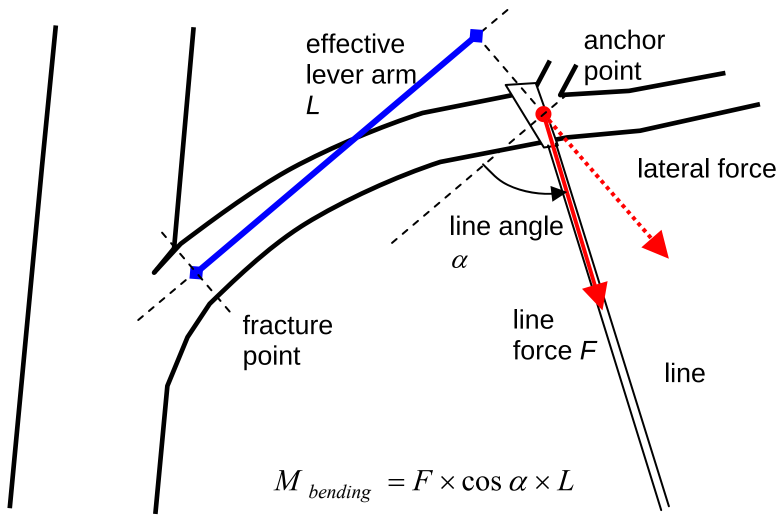


Figure 5.10 Parameters determined to derive the bending moment

Phased loading in discrete steps allowed for a determination of the point of time where primary failure occurred in the course of the load test. The lever arm *L* and the line angle α were measured, for each branch individually, in the recorded video footage at the time of primary failure (yield), as well as at the beginning of fracture. Specialist videogrammetry software 'Utilius® EasyInspect 2.0.1' was used, courtesy of Campus Computer Center GmbH, who provided a free licence for the period of data evaluation within this research project.

The segment of branch where fracture was going to take place was determined in the video footage. The location of compression failure was often visible from locally increasing curvature and could be determined from the actual process of fracture later in the video sequence. The video was played in half frames that were recorded by a digital camera, at a rate of 50 pictures per second. This allowed for a rather precise localisation of the point of primary failure. However, there was no objective way to determine its exact position on the branch's length. Cross-section modulus was derived from measurements of the fractured branch. According to the shape of the fractured parts, the relevant diameters were chosen along the fractured section.

For all tests on *Acer*, the branch to be tested was cut back to a stump just above the anchor point, before the destructive test was carried out. In most cases, weight and length of the cut-off section was measured, to derive the bending moment generated by the weight of the branch tip. Alternatively, the pre-tension of the branch induced by the weight of its outer parts was measured with Elastometers. These instruments recorded the deformation in the marginal fibres as the top was cut off from the branch, which indicated the release of compressive and tensile stresses on the bottom and top side of the branch respectively.

If branches were broken without length reduction (e.g. in Beech, *F. sylvatica*), the weight of the branch and its length were measured, in order to enable determination of the specific bending moment generated from the branch's weight. As a general rule, the centre of gravity of a branch was assumed to be at roughly one-third of its length, in accordance with the results of measurements carried out in branches throughout this research. For 22 branches of *Acer* and *Fagus*, which had been removed during the field tests, the distance from of the centre of gravity to the cut was determined and was correlated with total branch length. On average, the centre of mass was positioned at 37% (standard deviation 4%) of branch length (which ranged from 3.9 to 12.9 m).

Results

The strength of a branch can be described by the stress in fibres on the compression side, leading to primary failure (yield strength). Load tolerance of green wood fibres beyond the elastic limit (by plastic deformation, fibre kinking) usually results in considerably greater ultimate stress at the point of fracture. In order to assess the bearing capacity of an anchor point, primary failure was not admitted, having regard to safety. Therefore, the ultimate strength of fibres is only listed as additional information, and certainly not to suggest implicitly that branches can be loaded safely to that degree.

In most branches, ultimate failure obviously involved crack formation in a shear plane. The fracture pattern may support the description of bending failure in Niemz (1993). Due to compression failure on the bottom side, the neutral plane is shifted upwards, increasing the tensile and shear stresses in the remaining wooden body. If the tensile strength of the fibres is reached, cracks will start to propagate through the material from the topside, down. The release of tensile stresses results in a true explosion of the upper side of the branch, presumably causing great lateral stress and a splitting of the branch in the axial direction.

Typical fracture pattern for branches of Beech (branch no. 3)

This fracture pattern may be initiated by compression failures on the bottom side (red arrowhead), just under the crack on the top side.

As the fibres are kinking on the bottom side, tensile and shear stresses increase on the top side and cause longitudinal splitting and fracture of fibres in tension (red arrow).

Still picture from video of the instant after fracture (branch no. 3)

In *Fagus sylvatica,* fracture always occurred along the length of the branches, and not a single branch was pulled off from the crotch. In *Acer pseudoplatanus*, the distance of the anchor point from the crotch seemed to be the main determinant of where failure would occur. The closer to the stem, the more likely were branches to break immediately at the crotch and pull out fibres from the branch collar. In *Tilia vulgaris*, branches originating from regrowth after topping cuts usually failed along the length of the branch, and only one branch attachment was pulled out. In the latter case, the junction showed decayed wood fibres. In *Acer saccharinum*, almost all branches failed at the crotch, or at forks with lateral branches of similar diameter. One branch, which had a large pruning wound with decay, failed at the compromised part of its wooden body.

Kane (2007) indicated that branch failure on Bradford Pear occurred mainly on lateral branches, but he also states:

> *"It is difficult to predict the likelihood of lateral branch failing before the attachment between the main branch and the trunk".*

Fracture pattern, Silver Maple

For the same reasons as described in Farrell (2003), determining yield stress in crotches was beyond the scope of this research project. The failure mode in crotches implies that fibres are failing in delamination rather than in compression, i.e. the wood splits at the junction where fibres need to dissipate tension in a radial direction, whereas the fibre orientation is generally axial. However, the stress just before the crotch was derived from the measured diameters and the load applied. It has to be noted that these figures do not accurately describe fibre strength, but refer to the bending moment that living branches can tolerate. Therefore, figures for *Acer saccharinum* may not represent the actual stress required to fracture branches, but define a lower limit for the bearing capacity (which in this case is actually limited by crotch strength).

The yield stress derived from field tests is shown as a 'box plot[*]'in Figure 5.11. The arithmetic mean and standard errors were calculated from a dataset. Three branches were omitted that failed at the crotch, well below the figures for failure along the length of the branch. Only for Silver Maple, where failure almost exclusively occurred at junctions, was data from all specimens used. In order to derive a representative figure that allows for a safe determination of the strength of branches of different diameter, the mean value less one standard error was listed in Figure 5.12. This measure was chosen to take into account the natural variability of mechanical properties in wood fibres (as proposed in the Stuttgart Strength Tables, *cf* Wessolly 1989). More than 90% of the data exceeds this figure. When using this representative value as a basis for static calculations within the present dataset, the results will not exceed the actual strength by more than 10%.

As an alternative, a general factor of safety could be applied. It is evident that, if the mean values for critical stress are used (as listed in many other publications, *cf* Figure 5.5), branch strength may be overrated. Therefore, the difference between the minimum value found for each species, and its median and arithmetic mean respectively, was determined. The results indicate that, for the species evaluated in this study, a safety margin of 1.5 would not be sufficient for mean values. If the median value was used, this factor of safety would only underrate strength in one case by 2%. In other words, if the critical stress is set at two-thirds (67%) of the median value, the result would not fall significantly below the minimum figures found in the test series.

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[*] *In a box plot, the lines indicate the range between minimum and maximum values, the blocks/bars represent the range in which 50% of all data are found, and the dots indicate the median values (cf Chapter 6, section 6.1.3).*

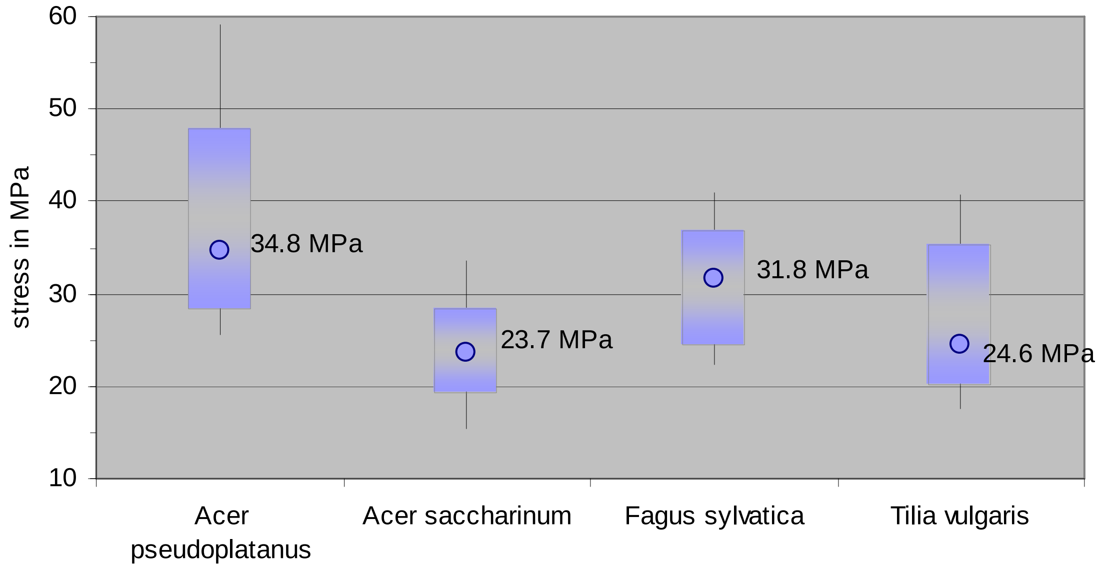


Figure 5.11 Yield stress (*median* indicated)

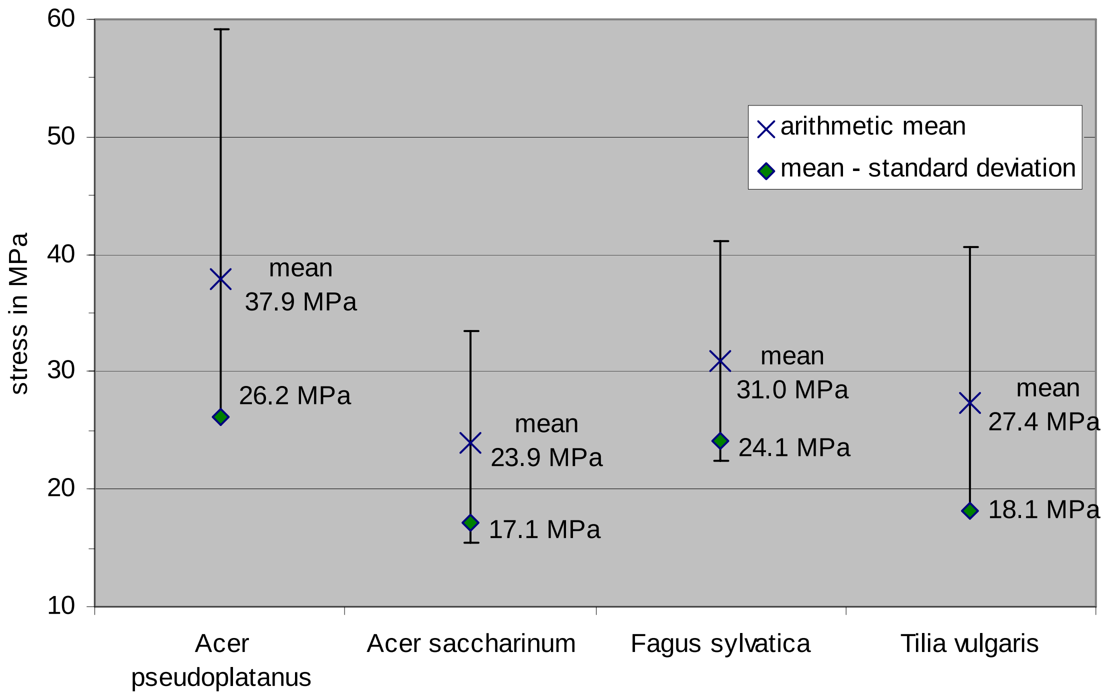


Figure 5.12 Yield stress: mean values and spread (*representative value* indicated)

As mentioned above, ultimate fracture stress could also be listed as additional information (Figure 5.13). In the long term, tests should be carried out to investigate the dynamic behaviour of branches under dynamic impact loads. It may very well turn out that strength properties derived from static load tests (i.e. loads increasing gradually over a long period of time) do not accurately represent the actual bearing capacity of trees. Thus, the diameter thresholds for suitable anchor points could possibly be adjusted, in order to conform more closely to practical experience in arboriculture.

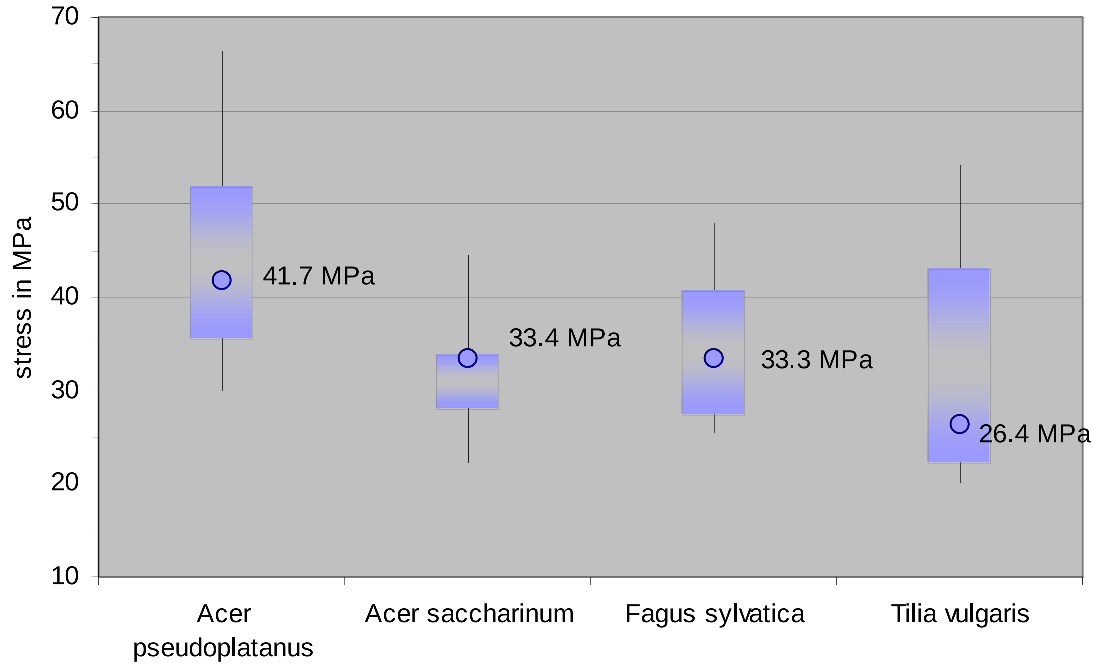


Figure 5.13 Ultimate strength (*median* indicated)

Some tree species are often classified as good-natured in terms of their tolerance to loads beyond the elastic range (*cf* Wessolly, Erb 1998). The capacity to absorb additional energy in the zone of plastic deformation (also referred to as yield zone) differs among species and obviously from branch to branch. However, the fact that some tree species may provide a greater 'safety cushion' to overloading is obscured by the large differences between individual branches (*cf* Figure 5.14).

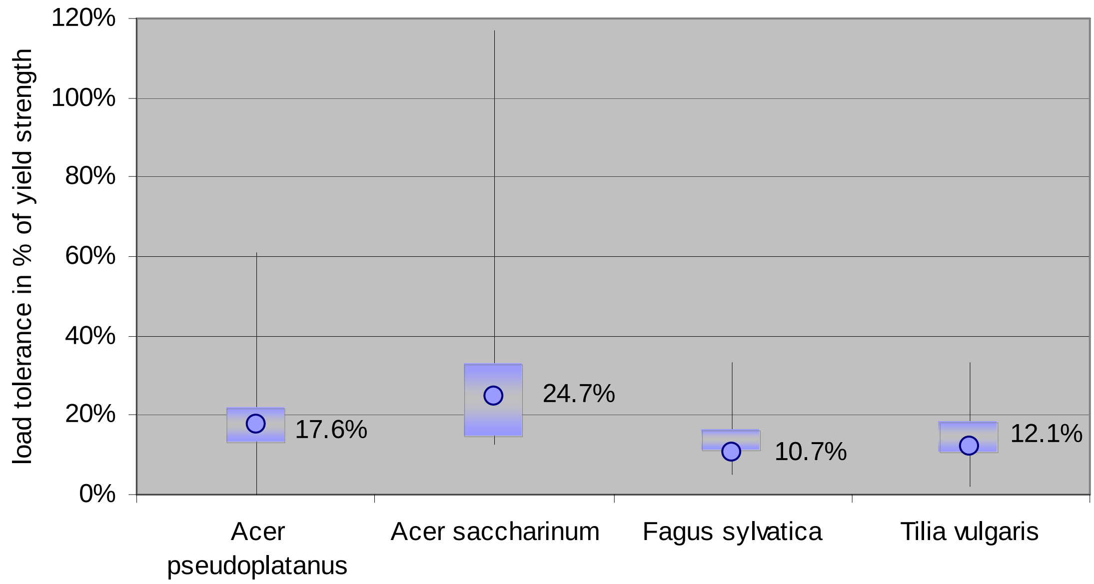


Figure 5.14 Load tolerance in the yield zone (*median* indicated)

Comparison of the values illustrated above for branch strength with sources in literature (as summarised in Figure 5.6), shows that the field tests carried out in this project, generally speaking, rendered values in the lower range. This may be due to the fact that some authors determined ultimate strength instead of yield strength. Also, parameters required to calculate stress in marginal fibres can be measured with much less precision in practice than under laboratory conditions. On the other hand, it may very well be possible that tests in standing trees reveal a closer picture of the true nature of the strength of branches, especially when used as anchor points in arboricultural rigging operations.

As the point of prospective fracture cannot be predicted prior to a rigging operation, the figure for yield strength does not allow for carrying out an absolute strength evaluation. However, it may still be useful as guidance for comparing the properties of tree species. Due to the great number of variables required to determine the strength of branches, it is not possible to derive a simple method based on graphs.

Genenz *et al* (1998) found that the lateral component of the failure load correlated with the diameter of the branch at the anchor point, regardless of the actual lever arm. In the studies carried out in the course of the present project, no correlations were found between force and cubic diameter. The best correlation existed between the bending moment at primary failure and the cubic mean diameter of the branch, measured at the anchor point (*cf* Figure 5.15). Thus, the bending moment that could be tolerated by a certain branch can be estimated from its diameter at the anchor point. Yet, as long as it is unclear where that branch is going to fail, only rough estimates are possible.

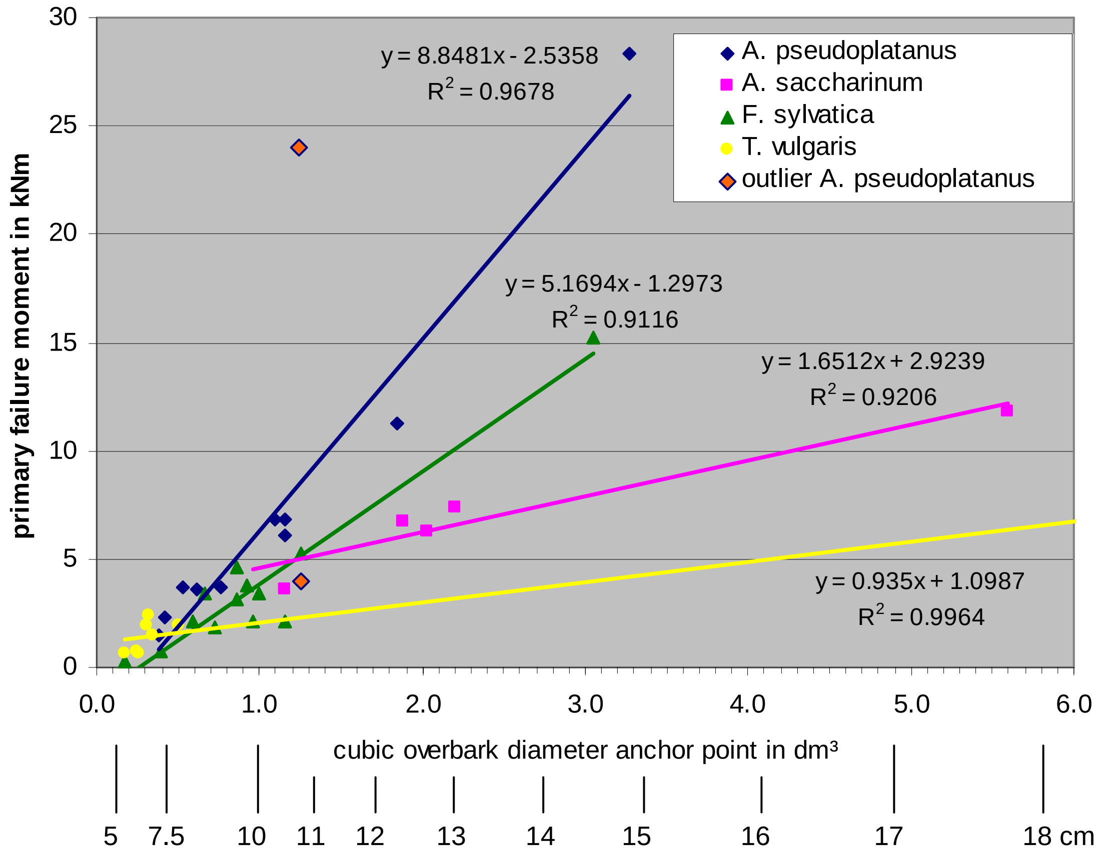


Figure 5.15 Correlation between primary failure load and branch diameter (diameters indicated in cm below the x-axis)

Two outlier values were dropped from the dataset for *A. pseudoplatanus*. One branch failed at about 50% of the expected load, obviously due to a weak crotch connection with included bark. Two other branches that also failed at the crotch fell well within the linear regression. One branch showed almost three times more bearing capacity than other branches of comparable diameter. Within the scope of this study, no plausible reason was found for this exceptional result.

The linear factor correlating bending moment and cubic diameter is a measure of species fibre strength, which may also be affected by season, moisture content and other variables. As this approximation has proved to work best when based on the diameter at the anchor point, the correlation factor actually incorporates some species specific properties, such as taper of branches and the typical point of fracture along the branch length (which may be a result of the former, *cf* Kane 2007).

Genenz *et al* (1998) showed that fracture occurred at local minima of branch diameter. Pfisterer (2004) reported that branches often failed just above a branch union, where the diameter abruptly increased due to the union. Using this information in anchor point selection, the lever arm to a prospective failure point may eventually be assessed. It may also be used to develop a diagram that allows for a quick determination of the bearing capacity of anchor points of branches. However, the length of the lever arm (from the anchor point to the next significant diameter change at a fork) would have to be estimated to define the maximum admissible force at the anchor point.

Eberl, Höhne (2007) indicate a correlation between moisture content and the yield strength for branches of *A. pseudoplatanus* (a species tested in the course of the present study). The fibres of the two trees comprised in this study showed different moisture contents. At the same time, yield strength varied from one tree to the other. The branches with less moisture content were considerably stronger, which indicates that wood parameters that change over a season may affect the bearing capacity of branches. However, further investigations would be required to distinguish genetic differences between individual trees (which may well be the cause for the divergence), and the effect of moisture content. In the scope of this project, it was not possible to study the strength of tree species in different seasons with a suitable sample size. Therefore, it is not yet possible to draw reliable conclusions with regard to this issue.

5.5.5 Strength of branch unions

Studies on crotch strength were published as early as the 1930's. MacDaniels evaluated the strength of Apple tree crotches and found that included bark affects strength significantly (MacDaniels 1923). In a similar approach, Miller (1959) tested whether the ratio of branch and stem diameter (branch aspect ratio) had an influence on the strength of Apple tree branches.

More recently, a number of studies have been published on the load-bearing capacity of branch junctions. Smiley (2001) reported a series of tests to determine the influence of included bark in co-dominant stems. He found that crotch strength was significantly reduced when included bark was present. Pfisterer *et al* (2003) described the effect of connecting tissue strength in U-shaped junctions on the load-bearing capacity, similar to an earlier publication by Tesari & Mattheck (1999) supporting the significance of included bark for crotch strength. The relation between aspect ratio and strength of attachment of branches was investigated by Gilman (2003) on small branches of Red Maple (diameter 0.5-2 cm). The results showed that there was a correlation between increasing differences between diameters of branch and stem and greater bearing capacity, i.e. the union between co-dominants of similar diameter was found to be weak.

Farrell (2003) gives a good overview of literature available on the strength of branches, with a focus on crotch strength. The author tested crotches cut from 78 trees of three different species, all of them about 15 years old. The author found a correlation between crotch strength and diameter ratio at the attachment, indicating that crotch strength was greatest if the ratio ranged below two-thirds. He reported that attachments of branches at the trunk were significantly stronger than forks between two branches. He also found a weak correlation of branch angle and crotch strength, as indicated in Lilly, Sydnor (1995).

The biomechanics of branch junctions was recorded with modern techniques, recently, by analysing the strain field in the area of a crotch (Müller *et al* 2006). Almost all these studies focus on stems and branches of less than 15 cm diameter and were not carried out in standing trees. It is still unclear whether or not the findings of these studies may be applied to branches of diameters used as anchor points in rigging operations. The quality of a branch stem junction was summarised from different research as follows:

> *"Strong branch attachment only occurs if the two components are unequal in size." (Matheny, Clark 1994)*

Farrell (2003) cites a study by Smiley *et al* (2000) which indicated that differences in crotch strength did not seem to be dependent on species. He makes the following statement:

> *"However, it is difficult to draw conclusions based on wood strength comparisons between species because the most common wood strength values are based on tests of clear- grained boards. Limb and crotch wood may vary significantly from these test conditions." (Farrell 2003)*

Choosing a suitable anchor point does include inspecting the crotch for signs of included bark and other weaknesses. Also, branch angle and diameter ratios should be considered. According to Farrell (2003), diameter ratio plays the most important role in branch strength. The lower threshold for significantly reduced strength was found by Farrell to be at a diameter ratio of 67%. Farrell, therefore, recommends regarding branches as insufficiently able to bear loads where their diameters are greater than two-thirds of the diameter of main stem or leader. This result could not be supported from the findings of the present study. In *Acer pseudoplatanus*, only a very weak correlation ($R^2<0.2$) was found (Eberl, Höhne 2007).

Another approach to crotch strength was presented by Wäldchen (2007). Visually detectable symptoms were described with regard to assessing the likelihood of failure of co-dominants. The author states that even narrow crotches (V-shaped) could be sufficiently safe against fracture, unless cracks or tissue protruding from the side of the union (formation of 'ears') indicate the presence of included bark.

Failures of V-shaped crotches with included bark are often the result of the lack of adaptive growth (Wessolly, Erb 1998). Due to the form of the crotch, the branches are not able to produce sufficient incremental growth inside the crotch, and are unable to compensate for this on the outside. Therefore, enhanced by strong apical growth in competition for light, co-dominants may not have a sufficient load-bearing capacity in the crotch. Decreased diameters result in locally increased bending stresses in marginal fibres if the crotch is pulled apart. In extreme cases, compression failure may occur at the base of the branch union, where diameters are smallest (*cf* Chapter 2, section 2.5.4).

If diameters of co-dominants do not change abruptly, but diminish gradually in the crotch area, the load-bearing capacity may not be considerably reduced. This is usually the case where solitary trees have formed V-shaped crotches, but compensated for the weak link by strong incremental growth on the outside of the union. Such specimens would seem to be well proportioned, and the attachment gives a balanced impression, with the bark ridge running almost straight down the stem. An inclined bark ridge indicates that one branch has outgrown the other. The weaker branch may not have had sufficient vigour to produce wood tissue on the outside of the crotch, and may be prone to failure.

5.5.6 Overview of fibre strength in branches and crotches

Experimental design and the size of branches included in a study may affect the results significantly. Also, two different failure modes – branch failure and crotch failure – may occur, which often result in different estimates for the load-bearing capacity of a branch. Therefore, it is difficult to compare values found in literature with the results of field tests. Kane (2007) summarises the results of former studies of branch strength in a table, the data in which had also been reviewed for this research study.

The difference in loading (static *vs* dynamic) will limit the applicability of the collected data to actual rigging operations, during which peak forces will load the branches only for a very short time. Therefore, inherent margins of safety may be expected if data from quasi-static load tests is used for safety considerations. The opposite is true where data was derived from three point bending tests. Kane (2007) states that the modulus of rupture, determined by testing fresh, clear-cut samples in accordance with standard protocols (ASTM 2000), was considerably greater than critical compressive stresses, measured in field tests carried out on the very same branches that the samples had been taken from. Therefore, such figures should not be used without a caveat.

Table 5.4 (at the end of this chapter) lists the relevant data on the species-dependent strength of branch fibres, as well as sample size and test procedure of the respective study. This would allow for a better evaluation of the data, with regard to its applicability to practical anchor point selection.

5.6 ANCHORING STRENGTH OF ROOTS

The bearing capacity of anchor points also includes the integrity of the tree's anchoring system. Under some site conditions, roots may not be able to develop properly and provide sufficient hold in the ground. Decay and other structural damage may weaken the strength of roots. In the urban environment, or along roads, roots may have been severed, leaving a tree unstable and in decline. By carrying out a proper visual inspection prior to carrying out a dismantling operation, and by investigating the history of construction activities in the vicinity of the root flare, the structural integrity of the root system may be evaluated.

However, not all defects are visible to the eye. Therefore, simple load tests of anchor points should include observation of the root flare and root crown, in order to detect a heaving of the root plate (*cf* Chapter 2). If the load-bearing capacity of the root system is in question, no mechanical model is available that would allow for calculations and estimations, as is the case for stem and branch strength. So far, only pulling tests such as those carried out in accordance with the Inclinomethod (*cf* Sinn, Wessolly 1989, Wessolly 1996) provide an established method for assessing the prospective failure load of root systems. Such assessments are based on empirical observations from monitored uprootings of hundreds of tress. The tipping process follows a specific pattern (the 'generalised root failure curve', *cf* Wessolly, 1996), that allows an extrapolation to be made, from inclination under small loads to a point where failure of the root system is initiated (primary root failure). The AfB-method (Sinn, 2003) uses the same principle, but with a refined algorithm, and uses stability classes in order to draw conclusions, from the results of load testing, about the risk of tipping at increasing wind speeds.

Also, the criterion used in the VTA-method, a ratio of stem radius and root plate radius, was developed from data relating to uprooting in the wind. Recently, a scientific review (Gruber 2007a) came to the conclusion that this criterion is inadequate and not scientifically 'understandable' (*Ger* nachvollziehbar). In any event, it could not be applied to risk assessments prior to dismantling a tree, without refinement, due to the different loads generated from wind and rigging operations. Nevertheless, even if root strength may not be quantifiable, strong movements under load, or cracks in the soil around the root collar, should be seen as indicators of insufficient stability of the root-soil matrix (primary failure).

In some cases, the root system will be unstable without visible signs of defects or primary failure. After extreme rains, entirely water-saturated soil may reduce the friction between roots and the surrounding soil. The root plate may start to slide and increase the bending stress in major roots. This effect will eventually lead to root failure and tipping of trees under relatively small loads (e.g. the recent failure of a mature tree in 35 mph wind speed in the Midlands, Paul Muir pers. comm. 2007). Therefore, exceptional climatic conditions in which water saturation may be a factor should also be considered when assessing the bearing capacity of trees.

5.7 GENERAL CONSIDERATION

In general, the strengths of trees and their branches, when being considered as part of a rigging system, may also be limited by structural weakness or defects in the living structure. Therefore, visual tree inspection and, in some cases, the use of diagnostic tools such as sound tomography, may be essential to ensure the structure has sufficient load-bearing capacity to sustain the planned rigging operation.

Table 5.4 Overview of strength of wood fibres in branches

Species	*Failure type branch(B) or crotch (C)*	*Stress range or mean (MPa)*	*Diameter range (cm) [no. Branches]*	*Test procedure in field (F) or in laboratory (L)*		*Study*
Acer platanoides	B/C fracture	24.5	5-30 [40]	unilateral bending	F	Lilly, Sydnor 1995
Acer pseudoplatanus	B/C yield	34.8	8.2-26 [13]	unilateral bending	F	present study
Acer rubrum	C fracture	22.4-60.6	1.8-7.8 [89]	unilateral bending	L	Farrell, 2003
Acer saccharinum	B/C fracture	35.2	4.5-14.2 [15]	unilateral bending	F	Dahle *et al* 2006
	B/C fracture	29.7	5-30 [40]	unilateral bending	F	Lilly, Sydnor 1995
	C yield	23.7	14.2-35 [6]	unilateral bending	F	present study
Alnus *spp*	B fracture	27.1-32.9	6.4 [1]	Fractometer III	F	Krämer 1998
Carpinus betulus	B fracture	35.2-40.5	3.7-6.8 [2]	Fractometer III	F	Krämer 1998
Fagus sylvatica	B fracture	40.3-47.6	3.1-5.5 [3]	Fractometer III	F	Krämer 1998
	B yield	31-44		axial compression	L	Wessolly, Erb 1998
	B fracture	19-25	15-20 [6]	axial compression	L	Burgert *et al* 2003
	B yield	31.8	7.0-19.0 [13]	unilateral bending	F	present study
Fraxinus excelsior	B	32.8		3-point bending	L	Sinn 1985b
Gleditsia triacathos	B	90.8		3-point bending	L	Sinn 1985a
	B	35.9		axial compression	L	Sinn 1985a
Platanus acerifolia	B	56.1		3-point bending	L	Sinn 1985a
	B	33		axial compression	L	Sinn 2003
Populus canadensis	B fracture	37.26	11-24 [15]	unilateral bending	F	Genenz *et al* 1998
Pyrus calleryana 'Bradford'	C fracture	71.3-32.1	2.3-8.4 [106]	unilateral bending	L	Farrell, 2003
	B fracture	69.9	7.1-17.8 [26]	3-point bending	L	Kane, 2007
	B fracture	50.7	7.1-17.8 [12]	unilateral bending	F	Kane, 2007
	C fracture	49.6	7.1-17.8 [14]	unilateral bending	F	Kane, 2007
Quercus acutissima	C fracture	36.7-103.9	2.3-6.9 [87]	unilateral bending	L	Farrell, 2003
Quercus *spp*	B fracture	26.1-53.4	5.2-9.1 [2]	Fractometer III	F	Krämer 1998
Robinia. pseudoacacia	B	20-40		axial compression	L	Sinn 2003
	B	39.7		3-point bending	L	Sinn 1985a
Salix *spp*	B fracture	21.6-31.1	8.2-8.7 [2]	Fractometer III	F	Krämer 1998
Tilia vulgaris	B	43.3		3-point bending	L	Sinn 1985a
	B/C yield	24.6	9.0-29.4 [8]	unilateral bending	F	present study
	B	18.9		axial compression	L	Sinn 2003
Ulmus *spp*	B fracture	33.9-44.7	4.8 [1]	Fractometer III	F	Krämer 1998

6 ESTIMATING THE WEIGHT OF SECTIONS

The weight of a body is defined as the force generated by gravity acting upon the body's mass. Weight is denoted by the unit Newton and can be derived from the mass by multiplication with the acceleration due to gravity (9.81 m/s^2). In common language, weight is expressed in kilograms, which is actually the SI unit of mass.

Specific gravity (SG) refers to both mass and weight. It is the proportion of a body's mass to the mass of an equivalent volume of water at 20°C. Specific gravity is therefore dimensionless and can be applied to both a body's weight and its mass. Due to the fact that water has a density of 1.0 g/cm^3 at 20°C, the specific gravity is also a measure of the density of the body's material (*cf* Bodig, Jayne 1982).

With these definitions in mind, in this project specific gravity was chosen as the parameter to be used in deriving the mass of a section. To work out the actual weight of a section, i.e. the force on the section generated by gravity, the mass so derived must then be multiplied by the constant 9.81 m/s^2.

6.1 SPECIFIC GRAVITY OF GREEN WOOD

6.1.1 Data evaluation

The dataset was analysed by standard statistical methods. To determine a representative figure for the specific gravity of a certain species from a range of figures, the median was calculated. This statistical technique is explained in Wikipedia.org as follows:

> *"In probability theory and statistics, a median is a number dividing the higher half of a sample […] from the lower half. The median of a finite list of numbers can be found by arranging all the observations from lowest value to highest value and picking the middle one. If there are an even number of observations, the median is not unique, so one often takes the mean of the two middle values.*
>
> *The median is primarily used for skewed distributions, which it represents differently than the arithmetic mean. Consider the multiset { 1, 2, 2, 2, 3, 9 }. The median is 2 in this case […] and it might be seen as a better indication of central tendency than the arithmetic mean of 3.166 […]*
>
> *Calculation of medians is a popular technique in summary statistics and summarizing statistical data, since it is […] giving a measure that is more robust in the presence of outlier values than is the mean."*

In analysing data taken from different sources in literature, it was important to take account of the range of figures found, as represented by the minimum and maximum values for specific gravity. Yet, when differing figures occurred, it was generally of more interest to see at what level the majority of sources actually rated the green weight of a particular species. In such cases, the average could be misleading, especially where outlier values existed. For this reason, the median was chosen as being the best measure for representing the middle of the range of figures under consideration.

6.1.2 Data basis

As a general rule, the specific gravity of green wood, as found in the available literature, was derived from laboratory tests using small samples of wood (Lavers 1983, Markwardt, Wilson 1935, USDA Forest Service 1999, Wagenführ 2000, Winandy 1994, Wessolly 1989, 1992, Sinn 1985a, b, Sell 1989, Lignum 2003, Eilers 2004). Whenever possible, the minimum, average and maximum figures cited in any one source were considered.

In three publications (Lavers 1983, USDA Forest Service 1999, Bodig, Jayne 1982) the specific weight listed was based on the weight of the sample when oven dry and on its volume when green (SG_{dry}). At the same time, two of the sources provided figures for moisture content of green specimens in percentages (MC_{green}), for some species. In these cases, the specific gravity of green wood (SG_{green}) was determined by equation 6.1:

$$SG_{green} = SG_{dry} \times \frac{(100 + MC_{green})}{100} \qquad \text{equation 6.1}$$

In most cases, USDA Forest Service (1999) indicates moisture content for core and sapwood separately. In order to derive practicable figures for inclusion in the log weight tables, a simplified assumption was made. In a first scenario, the diameter of the log was assumed to be 25 cm, containing a layer of sapwood 5 cm thick on both sides. Due to the fact that moisture content is generally greater in sapwood, this served as a worst-case scenario. Smaller diameters were not considered because correct weight estimation did not seem to be relevant. The minimum value for specific gravity was derived by assuming the diameter of the stem to be 100 cm and the width of the sapwood only 4 cm. In view of the lack of more detailed data, the specific gravity of dry wood had to be assumed constant over the radius. Due to the great amount of core wood in logs of greater diameter, the specific weight does not change significantly with increase in size.

The minimum and maximum specific gravity was derived according to equation 6.2:

$$SG_{\log} = SG_{core} + 4 \times (SG_{sap} - SG_{core}) \times \frac{D \times t_{sap} - t_{sap}^{2}}{D^2} \qquad \text{equation 6.2}$$

where

SG_{log}	*specific gravity of the log*
SG_{core}	*specific gravity of the core wood*
SG_{sap}	*specific gravity of sap wood*
D	*diameter of log (25 rsp. 100 cm)*
t_{sap}	*thickness of sap wood (5 rsp. 4 cm)*

Some sources of literature were omitted because of the large deviations from other consistent data (e.g. Höster 1993). It is very likely that some authors based their information on tests that were not carried out using fresh cut sections. Moisture content in green wood is a major factor in determining the weight of a section. It decreases significantly within the first days after cutting (Vogel 1995).

Figures published by Markwardt, Wilson (1935), for the weight of green logs, have been quoted in several publications (Blair 1999, Donzelli, Lilly 2001) over the years. Where other data was available, the figures available related, in most cases, to the bottom of the range being studied. Yet, especially with respect to many North American species, the latter data sources were the only ones found in this literature review.

In the course of this project, the weight of green logs was also measured directly from newly cut green logs. Data for 14 species was provided by U. Thomsen, an arborist located in Pinneberg, Northern Germany, who measured the weight of fresh cut sections with a scale. The volume of the sections was derived by immersing the log in water and determining the volume of water displaced.

Other figures were derived by estimating the volume of sections during on-site tests from their length and diameters, using calculations based on a cylindrical approximation. The weight was measured with a scale and the specific weight was determined. On this basis, the specific gravity of six species was assessed from tests carried out by the late P. Donzelli, K. Schöpe and the authors of this study.

6.1.3 Results

Data was collected for 126 species, although only 80 were included in the log weight charts (Table 6.2), for reasons of practicability. Among these are the species most common as garden, park and road trees in Britain. Specific gravity for a greater range of 95 species is displayed in three diagrams below, sorted into alphabetical order. Some were included because of their significance in Europe or in Northern America.

The following box plots (Figures 6.1, 6.2 and 6.3) display the range between minimum and maximum values, indicated by a black line, for each species. The white bars represent the range in which 50% of all data was found. The black dot indicates the median value. Where only one figure was available, a dot and the black line coincide. The number of citations found in literature for each species is shown along the top of each diagram.

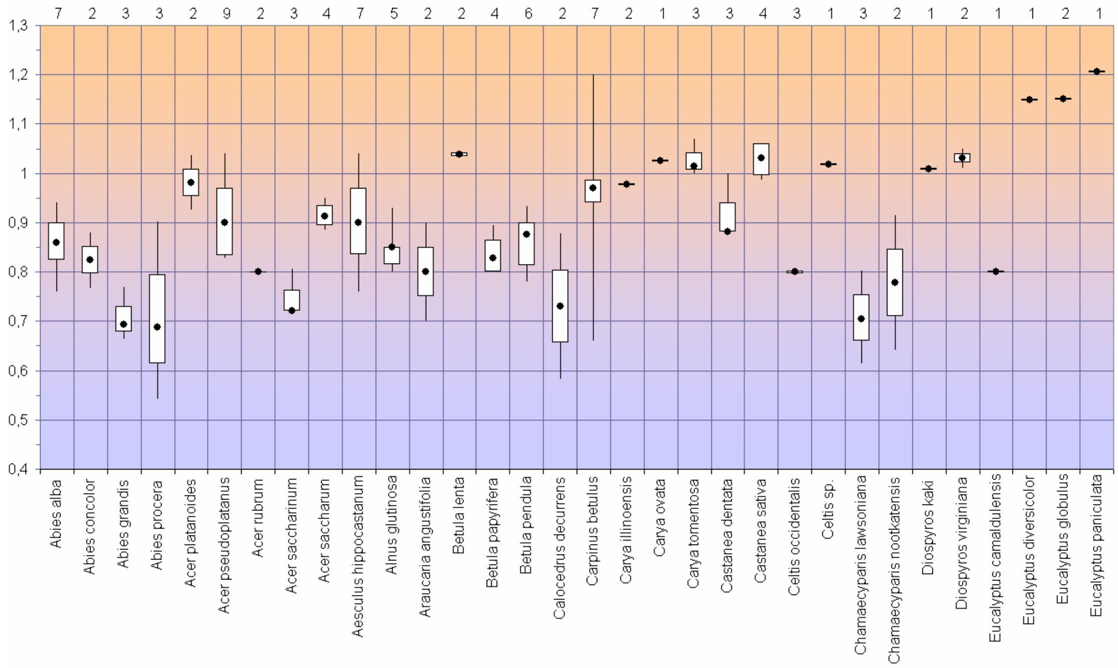


Figure 6.1 Specific gravity (part 1)

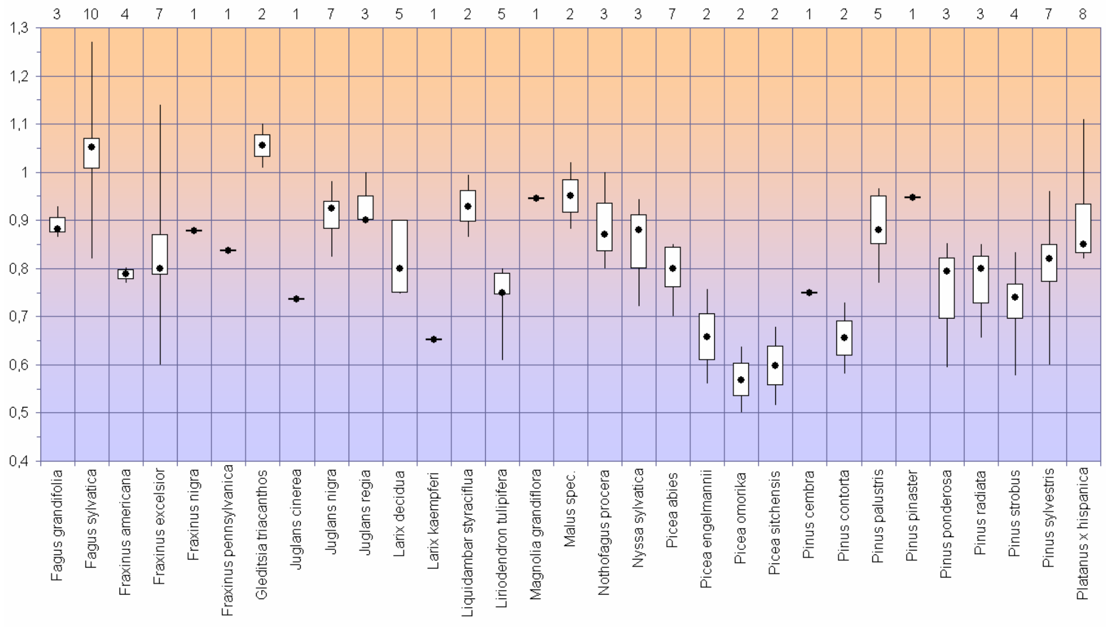


Figure 6.2 Specific gravity (part 2)

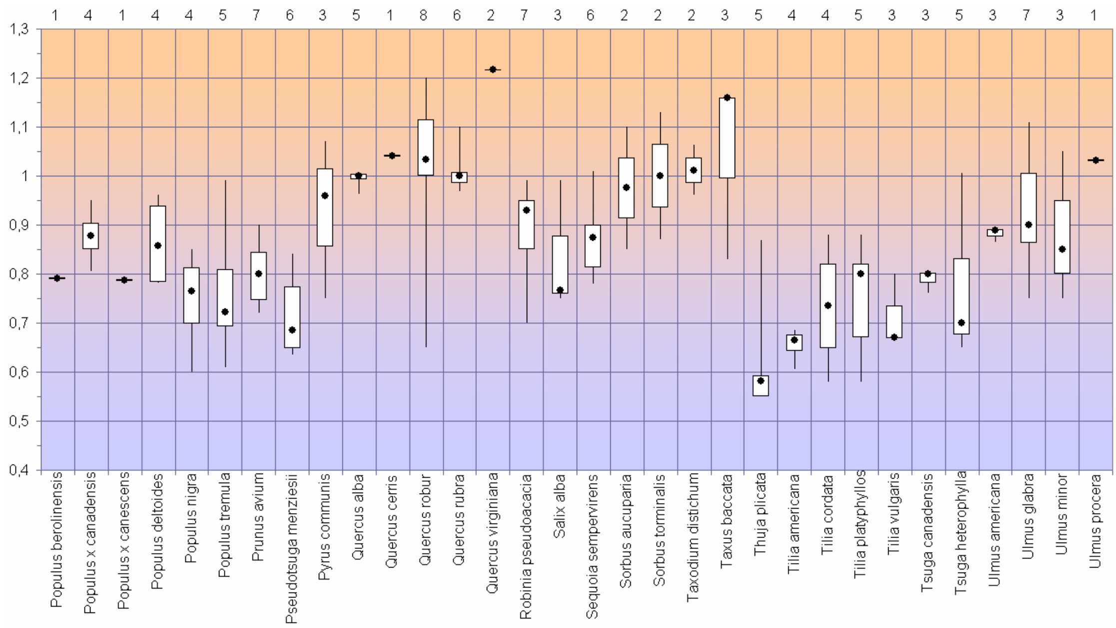


Figure 6.3 Specific gravity (part 3)

6.2 ESTIMATING LOG WEIGHT

Three different ways of estimating log weight are proposed, each of which works on a different level of accuracy. Complex calculations, as proposed e.g. in Coder (2000) or Wengert (2001), were avoided as far as possible. Instead, tables and graphs were used that require the measurement of simple reference parameters only**.**

6.2.1 Log weight curves

From the entire range of species-dependent values for specific gravity, a maximum value, an average value and a minimum value were chosen, regardless of species, and used to depict log weight curves in the graph presented at Figure 6.4. The curves in the graph indicate the mass of a cylindrical section of one metre length for a specific diameter.

For a very simple worst-case scenario, the upper green curve of Figure 6.4 represents the maximum weight to be expected, based on the chosen range of species and the sources included in the literature review. The lower red curve expresses the lowest possible weight of a cylindrical section that is to be expected, as a minimum, from the species included in the charts, based on the lowest figure found for the specific gravity of green wood in the literature reviewed. A blue curve is included to represent the average weight of a section, as derived from all species-dependent median values. The yellow curve is provided as a reference based on the specific gravity of Oak (see section 6.2.2).

Therefore, if the species of a tree is unknown, or if only a rather rough estimation of the load is considered to be adequate, Figure 6.4 can provide arborists with a quick means of performing an analysis of the range of potential weights of a log.

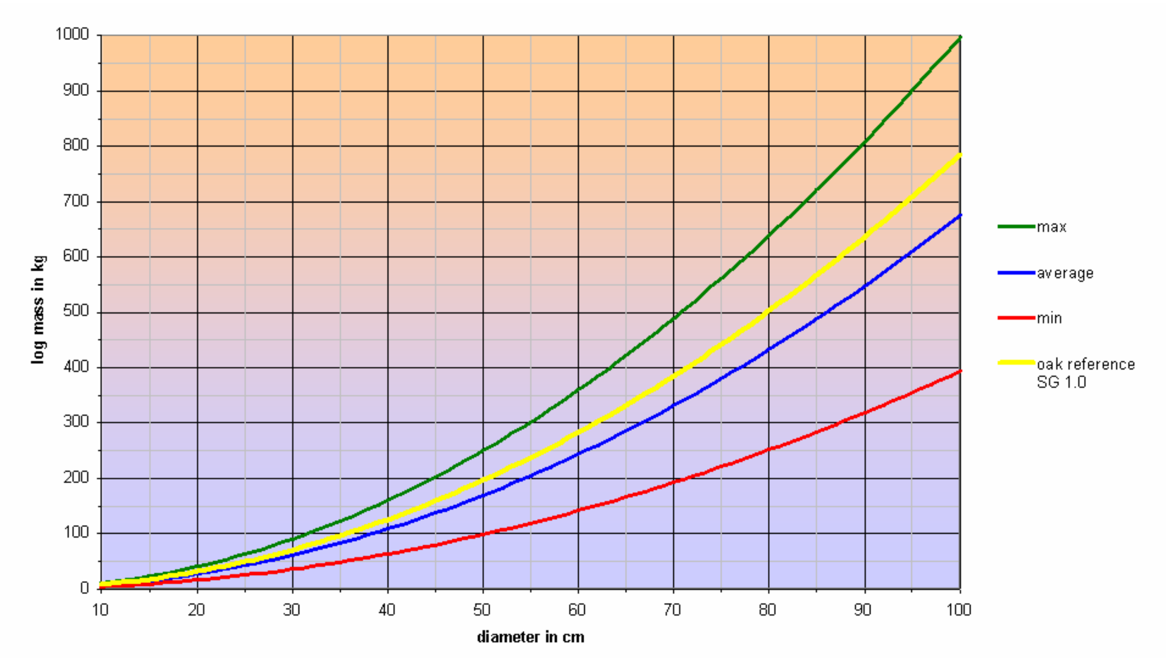


Figure 6.4 Log mass curves for 1 m sections of green wood

6.2.2 Reference log mass chart

Oak is a tree species often used as a reference for log mass. Brudi (2004) refers to a common understanding that green Oak logs do not sink in water, but float under the surface. The median value of the source data on specific gravity for Oak is roughly 1.0, which expresses the fact that the density of a green Oak log is equivalent to that of water. Therefore, this figure was chosen to define a reference for more exact log mass estimations.

The reference log mass, for a one metre long section of a specific diameter, can be determined using the yellow reference curve in Figure 6.4. For a quicker estimation, a reference log weight chart is provided in Table 6.1, including a variety of diameters *vs* a range of section lengths. The figures at the upper left corners may be unrealistically low and could be excluded. On the other hand, the values determined in the lower right section of the table may be too high to guarantee safe rigging practice, and therefore could also be omitted.

The reference values may offer a quick aid for arborists in estimating the mass of a section. By making a judgement based on their experience, they may be able to assess the weight of many different species, using Oak as a reference. When making such estimations, attention must also be paid to other factors influencing log weight, such as moisture content, reaction wood and decay.

To avoid underestimating the mass and to work on the safe side, the reference mass figures would have to be multiplied by a factor of at least 1.27, the highest recorded specific gravity in the scope of this research (*F. sylvatica*, Wagenführ 2000). Tree species grown outside Europe, e.g. in tropical regions, may show even greater density, resulting in increased log weight.

Table 6.1 Reference log mass chart (green Oak logs, SG 1.0) in kg units

	diameter of section in cm																	
length in cm	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	3,5	6	10	14	19	25	30	40	50	55	65	75	90	100	115	125	140	155
30	5	9	15	20	30	40	50	60	70	85	100	115	135	150	170	190	215	235
40	7	13	20	30	40	50	65	80	95	115	135	155	175	200	225	255	285	315
50	8,8	16	25	35	50	65	80	100	120	140	165	190	220	250	285	320	355	395
60	11	19	30	40	60	75	95	120	145	170	200	230	265	300	340	380	425	470
70	12	22	35	50	65	90	110	135	165	200	230	270	310	350	395	445	495	550
80	14	25	40	55	75	100	125	155	190	225	265	310	355	400	455	510	565	630
90	16	30	45	65	85	115	145	175	215	255	300	345	400	450	510	575	640	705
100	18	30	50	70	95	125	160	195	240	285	330	385	440	505	565	635	710	785
125	22	40	60	90	120	155	200	245	295	355	415	480	550	630	710	795	885	980
150	25	45	75	105	145	190	240	295	355	425	500	575	665	755	850	955	1065	1180
175	30	55	85	125	170	220	280	345	415	495	580	675	775	880	995	1115	1240	1375
200	35	65	100	140	190	250	320	395	475	565	665	770	885	1005	1135	1270	1420	1570
225	40	70	110	160	215	285	360	440	535	635	745	865	995	1130	1275	1430	1595	1765
250	45	80	125	175	240	315	400	490	595	705	830	960	1105	1255	1420	1590	1770	1965
275	50	85	135	195	265	345	435	540	655	780	915	1060	1215	1380	1560	1750	1950	2160
300	55	95	145	210	290	375	475	590	715	850	995	1155	1325	1510	1700	1910	2125	2355
350	60	110	170	245	335	440	555	685	830	990	1160	1345	1545	1760	1985	2225	2480	2750
400	70	125	195	285	385	505	635	785	950	1130	1325	1540	1765	2010	2270	2545	2835	3140
450	80	140	220	320	435	565	715	885	1070	1270	1495	1730	1990	2260	2555	2865	3190	3535
500	90	155	245	355	480	630	795	980	1190	1415	1660	1925	2210	2515	2835	3180	3545	3925

6.2.3 Using species-dependent correction factors

For the less experienced, or for those striving for greater accuracy, species dependent correction factors are provided in Table 6.2. These should enable the actual mass of a specific section to be calculated by application of the reference figures. In the tables, the minimum, median and maximum values found in this research are included. To be on the safe side, it is recommended that the maximum values are used.

The range could be expanded to include dead wood, extreme moisture conditions or degrees of rot. However, these figures are rarely found in literature sources and vary so greatly that, at this point in time, no reliable and practicable figures can be provided.

Table 6.2 Species-dependent log mass correction factors (part 1 of 3)

Botanic name	***English name***	***Min***	***Median***	***Max***
Abies alba	Fir, Silver	0.75	0.85	0.94
Abies concolor	Fir, White	0.77	0.82	0.88
Abies grandis	Fir, Grand	0.66	0.69	0.77
Abies procera	Fir, Noble	0.54	0.69	0.90
Acer platanoides	Maple, Norway	0.93	0.98	1.04
Acer pseudoplatanus	Sycamore	0.63	0.84	1.04
Acer rubrum	Maple, Red		0.80	
Acer saccharinum	Maple, Silver	0.72	0.72	0.81
Acer saccharum	Maple, Sugar	0.90	0.93	0.95
Aesculus hippocastanum	Horsechestnut	0.59	0.88	1.04
Alnus glutinosa	Alder, Common	0.64	0.81	0.85
Araucaria angustifolia	Pine, Parana Pine	0.70	0.75	0.80
Betula lenta	Birch, Sweet	1.03	1.04	1.05
Betula papyrifera	Birch, Paper	0.80	0.83	0.89
Betula pendula	Birch, European	0.78	0.84	0.93
Calocedrus decurrens	Cedar, Incense	0.58	0.73	0.88
Carpinus betulus	Hornbeam, European	0.66	0.95	1.00
Carya illinoensis	Pecan		0.98	
Carya tomentosa	Hickory, Mockernut	0.84	1.01	1.07
Castanea dentata	Chestnut, American	0.88	0.88	1.00
Castanea sativa	Chestnut, Sweet	0.66	1.00	1.06
Celtis occidentalis	Hackberry	0.79	0.80	0.80
Chamaecyparis lawsoniana	Cedar, Lawson's	0.61	0.70	0.80
Eucalyptus globulus	Gum, Blue	0.77	1.15	1.15
Eucalyptus paniculata	Ironbark		1.21	
Fagus grandifolia	Beech, American	0.86	0.88	0.93
Fagus sylvatica	Beech, European	0.82	1.03	1.27
Fraxinus americana	Ash, White	0.77	0.80	0.80
Fraxinus excelsior	Ash, European	0.60	0.80	0.89
Fraxinus pennsylvanica	Ash, Green		0.84	
Gleditsia triacanthos	Honeylocust	1.01	1.05	1.10
Juglans cinerea	Butternut		0.74	
Juglans nigra	Walnut, Black	0.81	0.91	0.95
Juglans regia	Walnut, English	0.81	0.90	0.95
Larix decidua	Larch, European	0.75	0.81	0.90
Larix kaempferi	Larch, Japanese		0.65	

Table 6.2 Species-dependent log mass correction factors (part 2 of 3)

Botanic name	***English name***	***Min***	***Median***	***Max***
Liquidambar styraciflua	Gum, Sweet	0.86	0.93	0.99
Liriodendron tulipifera	Poplar, Yellow	0.55	0.75	0.79
Magnolia grandiflora	Magnolia, Evergreen		0.95	
Nothofagus procera	Beech, South American	0.61	0.80	0.90
Picea abies	Spruce, Norway	0.68	0.80	0.85
Picea engelmannii	Spruce, Engelmann's	0.56	0.66	0.76
Picea omorika	Spruce, Serbian	0.50	0.57	0.64
Picea sitchensis	Spruce, Sitka	0.52	0.60	0.68
Pinus contorta	Pine, lodgepole	0.58	0.65	0.73
Pinus pinaster	Pine, Maritime		0.95	
Pinus ponderosa	Pine, Ponderosa	0.60	0.79	0.85
Pinus radiata	Pine, Radiata	0.58	0.73	0.83
Pinus strobus	Pine, Northern white	0.58	0.75	0.83
Pinus sylvestris	Pine, Scots	0.60	0.82	0.96
Platanus x hispanica	Plane, European	0.68	0.84	1.11
Populus deltoides	Cottonwood, Eastern	0.78	0.93	0.96
Populus nigra	Poplar, Black	0.56	0.67	0.85
Populus tremula	Aspen	0.60	0.69	0.81
Populus x canadensis	Poplar, Hybrid	0.78	0.85	0.95
Populus x canescens	Poplar, Grey		0.79	
Prunus avium	Cherry, Wild	0.69	0.78	0.89
Pseudotsuga menziesii	Fir, Douglas	0.63	0.67	0.84
Pyrus communis	Pear	0.75	0.88	1.02
Quercus alba	Oak, White	0.82	0.99	1.00
Quercus cerris	Oak, Turkey		1.04	
Quercus robur	Oak, European	0.65	1.01	1.20
Quercus rubra	Oak, Red	0.97	1.00	1.05
Quercus virginiana	Oak, Live		1.22	
Robinia pseudoacacia	Locust, Black	0.70	0.90	0.95
Salix alba	Willow, White	0.42	0.76	0.87
Sequoia sempervirens	Redwood	0.50	0.85	1.01
Sorbus torminalis	Wild Service Tree	0.87	0.90	1.00
Taxodium distichum	Baldcypress	0.96	1.01	1.06
Taxus baccata	Yew, Pacific	0.81	1.00	1.16
Thuja plicata	Cedar, Western red	0.46	0.57	0.87
Tilia americana	Basswood, American	0.60	0.67	0.69

Table 6.2 Species-dependent log mass correction factors (part 3 of 3)

Botanic name	*English name*	*Min*	*Median*	*Max*
Tilia cordata	Linden, Littleleaf	0.58	0.67	0.80
Tilia platyphyllos	Linden	0.58	0.70	0.82
Tilia vulgaris	Lime, European	0.67	0.67	0.80
Tsuga canadensis	Hemlock, Eastern	0.76	0.80	0.80
Ulmus americana	Elm, American	0.86	0.89	0.89
Ulmus glabra	Elm, Wych	0.75	0.88	1.11
Ulmus minor	Elm, European field	0.75	0.85	0.85
Ulmus procera	Elm, English		1.03	

6.3 DEVIATIONS AND CORRECTION FACTORS

6.3.1 Tapered logs

There are three practicable possibilities for assessing the volume of a tapered stem section:

1. determine the maximum diameter (usually at the bottom), calculate the volume of a cylinder with that diameter and multiply the volume by a ***form factor t*** with respect to taper (the form factor *t* here is proposed as the ratio of minimum diameter *vs* maximum diameter, *cf* equation 6.5*).
2. calculate the volume of a cylinder of constant diameter based on the ***average diameter*** of the log.
3. determine the volume of the ***frustum of a cone*** based on height and the maximum and minimum diameters of the log.

The third method allows for the best approximation of the volume of a regular log shape. However, it requires a more challenging calculation, or the use of another table containing volume correction factors. Therefore, the errors arising from choosing one of the other options were assessed using an estimation of volume based on a frustum of a regular cone as reference.

The volume of a frustum of a cone deviates by a linear factor from the volume of a cylinder with a radius equivalent to the frustum's basal radius. The volumes of the two geometric bodies are defined respectively by the following equations:

$$V_{cylinder} = \pi \cdot h \cdot R^2$$ equation 6.3

$$V_{frustum} = \frac{\pi}{3} h \cdot \left(R^2 + Rr + r^2\right)$$ equation 6.4

where

$V_{cylinder}$	volume of a cylindrical section
$V_{frustum}$	volume of a frustum of a cone
h	length of the section
R	maximum radius at the base of the section
r	minimum radius at the top of the section (*cf* wikipedia, 2007)

* *In general, taper is defined in literature as Δh/Δr. For practical reasons, in this context a form factor will be used that can be derived simply from the proportion of minimum and maximum diameter.*

The form factor for taper t is defined here as

$$t = \frac{r}{R}$$ equation 6.5

Substituting r in equation 6.4 gives

$$V_{frustum} = \pi \cdot h \cdot R^2 \cdot \frac{1 + t + t^2}{3}$$

and the factor $f_{frustum}$ for volume deviation due to conical shape as

$$f_{frustum} = \frac{V_{frustum}}{V_{cylinder}} = \frac{1 + t + t^2}{3}$$ equation 6.6

The first method mentioned above uses the ratio of maximum and minimum radius t (see equation 6.5) as a linear form factor in order to approximate the actual volume of the section. However, this form factor differs from the deviation factor $f_{frustum}$ that relates the volume of a cylinder with the actual volume of a frustum of a cone, as described by equation 6.6.

The second method determines the volume of a cylindrical section based on the average radius $r_{Ø}$ defined as

$$r_{Ø} = \frac{R + r}{2}$$ equation 6.7

Inserting in equation 6.3 and substituting r according to equation 6.5 gives

$$V_{Ø} = \pi \cdot h \cdot \frac{(R + r)^2}{4} = \pi \cdot h \cdot R^2 \cdot \frac{1 + 2t + t^2}{4}$$ equation 6.8

Thus the linear factor $f_{Ø}$ describes the deviation of the volume calculation (based on the average diameter of the section) from the volume of a cylinder with a basal radius R (according to equation 6.3), where

$$f_{Ø} = \frac{V_{Ø}}{V_{cylinder}} = \frac{1 + 2t + t^2}{4}$$ equation 6.9

Coder (2000) proposes another method of assessing the volume of a branch segment of conical shape. Coder uses the geometric average diameter of the frustum to determine the volume of a representative cylinder. He derives the geometric average diameter by calculating the mean ***area*** of the small and large ends. From the mean area, the geometric average diameter is derived as the diameter of a circle of that area. Again, a linear factor f_g can be derived to compare the volume of a cylinder of geometric average diameter (according to Coder 2000) V_g with the volume of a cylindrical section of diameter R (as in equation 6.3). These are given by the following two equations:

$$V_g = \pi \cdot h \cdot \frac{R^2 + r^2}{2} = \pi \cdot h \cdot R^2 \cdot \frac{1 + t^2}{2}$$ equation 6.10

$$f_g = \frac{1 + t^2}{2}$$ equation 6.11

Coder's geometric average diameter is always greater than the average diameter used above. Therefore, the volume estimation overestimates the actual volume of a conical section. Figure 6.5 shows the divergence of the volume estimations in accordance with the three methods for estimating the volume of a frustum of a cone with specific taper (expressed as the form factor *t*). The deviations are based on the results of the equations listed above and express the deviation of the calculated volume from that of a frustum of a cone.

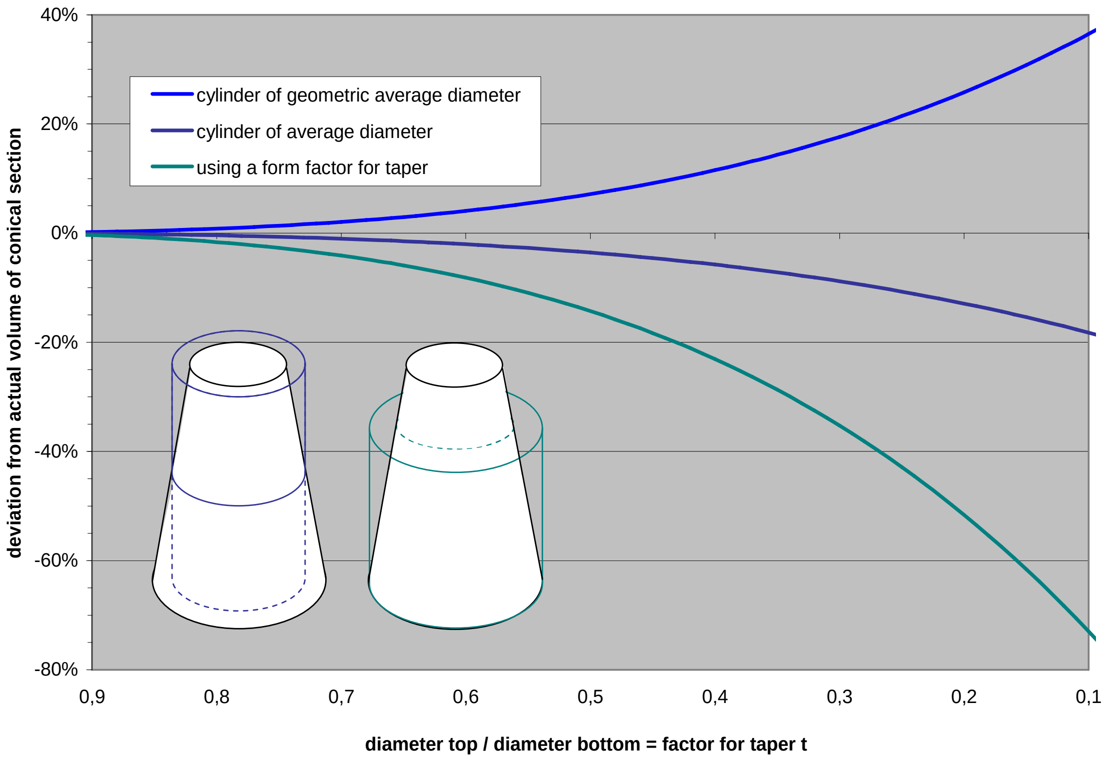


Figure 6.5 Errors in volume estimations

For a form factor of taper *t* greater than 0.5 (i.e. if the log's diameter at the top is not less than half the basal diameter), the error using the second method does not exceed 5%. Therefore, it seems reasonable for practitioners to estimate the mass of a regularly tapered log from the mass of a cylinder having a diameter equal to the average diameter of the log.

6.3.2 Irregularly shaped logs

In practice, it might not be possible to assess the average diameter, due to the irregular shape of the log. Results from on-site tests carried out in the scope of this research project were used to evaluate practicable methods for weight estimation.

Diameters of 7 beech logs and 12 sycamore logs were measured at the bottom, the top and the centre of gravity. The mass of each section was determined by weighing the logs on site, directly after cutting, using a scale (resolution 0.1 kg) for sections weighing less than, and a dynamometer (resolution 2 kg) for sections weighing more than, 200 kg.

The mass of each section was then assessed using the correction factors for specific gravity taken from Table 6.2 and three different methods of calculation. The first method of calculation consisted of measuring a representative diameter at the log's centre of gravity. The other two methods of calculation were those described in 6.3.1 (method 2 using the basal diameter and multiplying the volume of a cylinder of that diameter with the form factor for taper t = r/R; method 3 deriving an average diameter from the diameters at the top and bottom and determining the weight of a regular cylinder of that average diameter).

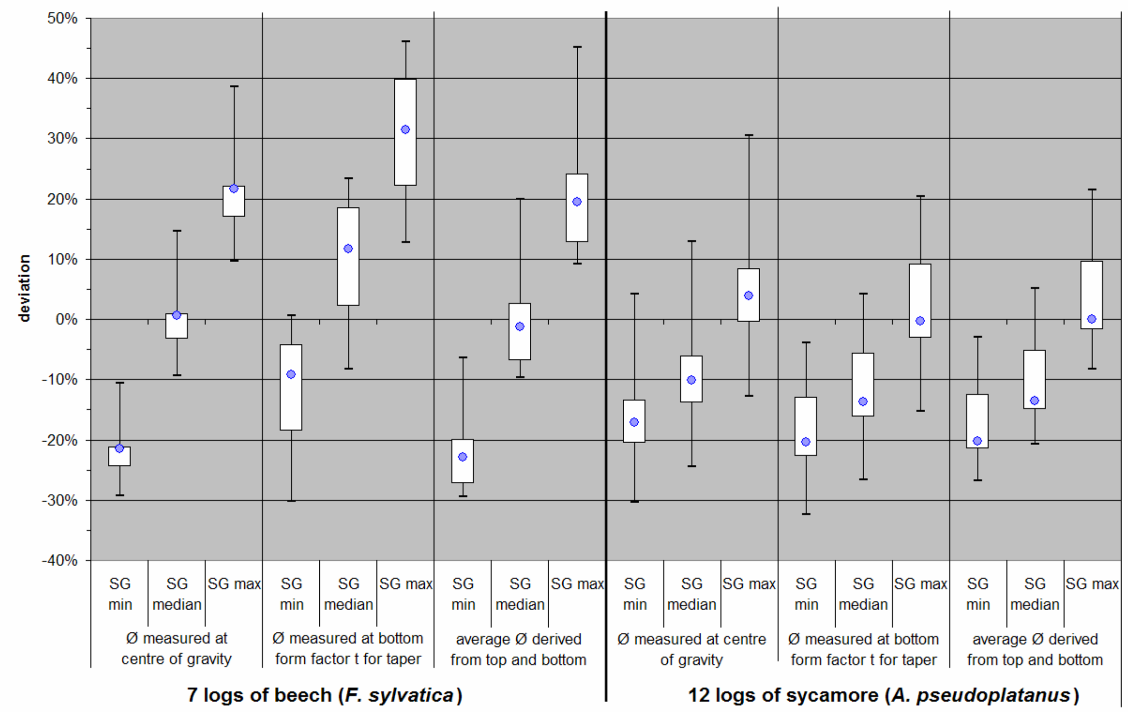


Figure 6.6 Deviations of estimated weight from actual weight

Figure 6.6 indicates that, for Beech logs, using the median value of SG for Beech logs, and measuring the diameter at the centre of gravity (or using the average diameter), produced the best fitting values for log mass (underestimating by not more than 10%). This may also be due to the fact that the logs were of a rather regular shape and gradual taper.

For Sycamore, the results indicated greater deviations. The logs measured included branch junctions where stem diameter changed abruptly. Therefore, the log weight estimation was more difficult and standard methods were less reliable. The study also shows that using the median SG from Table 6.2 underestimated log weight, by up to roughly 30%. Only using the maximum value listed in the SG correction factors (Table 6.2) and estimating the mass from an average diameter (right-hand column in Figure 6.6) resulted in acceptable deviations (not more than 10% less than the actual weight of the log).

For irregular sections, it is therefore recommended that practitioners either choose a representative diameter, or assess the position of the centre of gravity and measure the diameter at this position. To be on the safe side, it may be advisable to choose the maximum correction factors for species-dependent SG from Table 6.2, especially if the diameter of the log does not vary gradually over its length (i.e. sudden changes occur due, for example, to the presence of branch junctions).

Regular log shape, Beech

Irregular log shape, Sycamore

6.3.3 Decay and cavities

Decay generally results in a lower density of wood. Schwarze *et al* (1999) report a loss in weight, after three months incubation of wood blocks of different species with several wood-decaying fungi, of between 0.5 and 33%. At the same time, significant increases in moisture content were recorded for some specific fungus/tree combinations (almost 350% moisture content, for example, for *Ganoderma applanatum* and *Grifola frondosa* on *Tilia)*.

These results are derived from only a small zone in the wooden body of the tree where active fungal decomposition of the wooden fibres occurs. The major part of decayed wood consists of rotten material that has a significantly lower density and is often dry (e.g. brown rot). In the case of white (or soft) rot, the rotten material may be soaked with water, especially where the decay arises from the root zone, or where an open cavity is exposed to rain and/or intercepts water running down through the crown. However, as a starting point, the reduction in weight could be approximated by the degree of hollowness and the extent of decay.

The geometry of a decay column in the stem, although not visible at the tree diagnosis stage, becomes obvious during dismantling operations. The loss in weight can then be derived, either by assessing the thickness of residual walls, or by comparing the degree of cavity with standard shapes. Reduction factors that can be applied to decay and central cavities in the weight estimation are proposed, according to a geometric analysis of the loss in area in Figure 6.7.

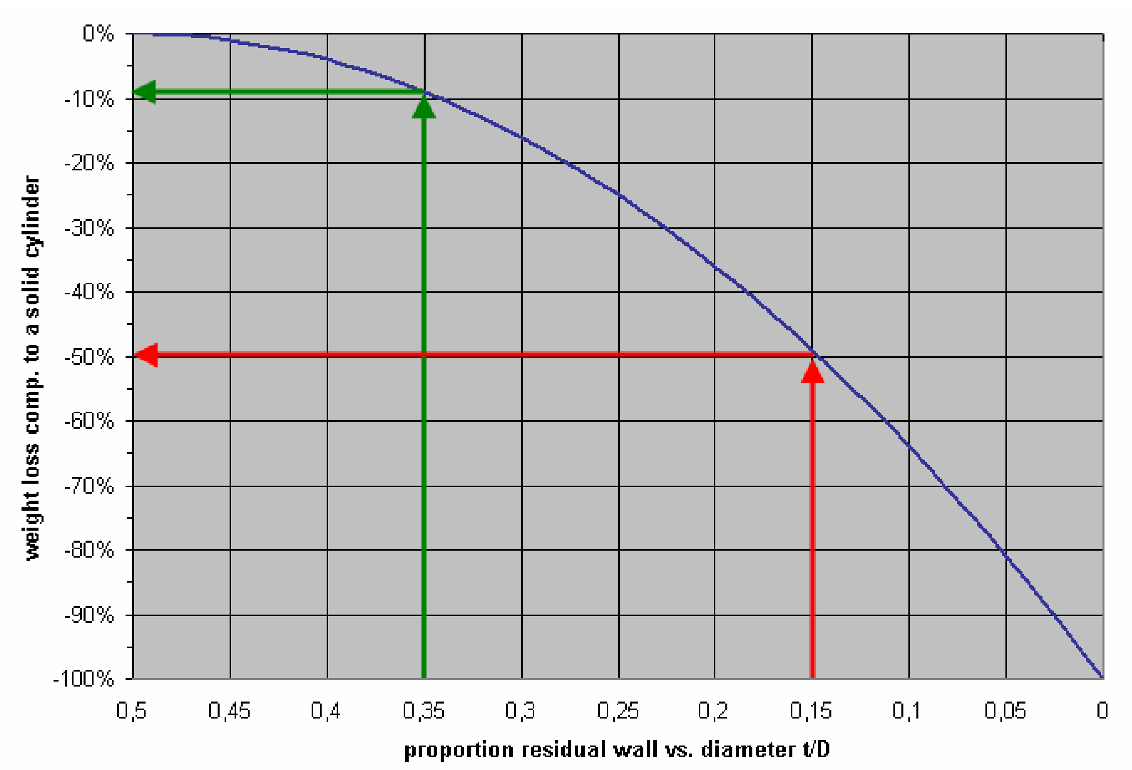


Figure 6.7 Reduction factors for central cavities

The Figure above shows that a concentric cavity, leaving a residual wall that is only 15% of the diameter (i.e. at a t/D ratio of 0.15), reduces the weight of the section by only half. Smaller central cavities, with residual walls greater than roughly a third of the diameter, do not affect the weight significantly (less than 10% weight loss at t/D > 0.35).

Rabe *at al* (2004) studied fresh density (immediately after cutting) of wood samples taken from stem sections of three different species, infected and decayed by three different fungi. The fresh density loss, due to decay, ranged from 35% for Beech wood infected by *Ganoderma adspersum*, to 40% for Norway Maple colonised by *Kretzschmaria deusta* and 70% for Horse-chestnut decayed by *Pleurotus ostreatus*.

Reduction factors should be incorporated with care. The actual extent of decay in the section to be lowered cannot be reliably predicted. The anatomy of wood fibres in the vicinity of structural defects may be altered due to the formation of ***reaction wood***. The diameter may also be locally greater where the tree has compensated for the loss of strength resulting from decay. The increase in density and diameter may very well balance the weight loss due to the initial stages of decay. The specific gravity of tension wood, for example is reported to be increased by up to 30% (Bodig, Jayne 1982). To be on the safe side, only small reduction factors for decay of unknown extent should be applied (up to 20%).

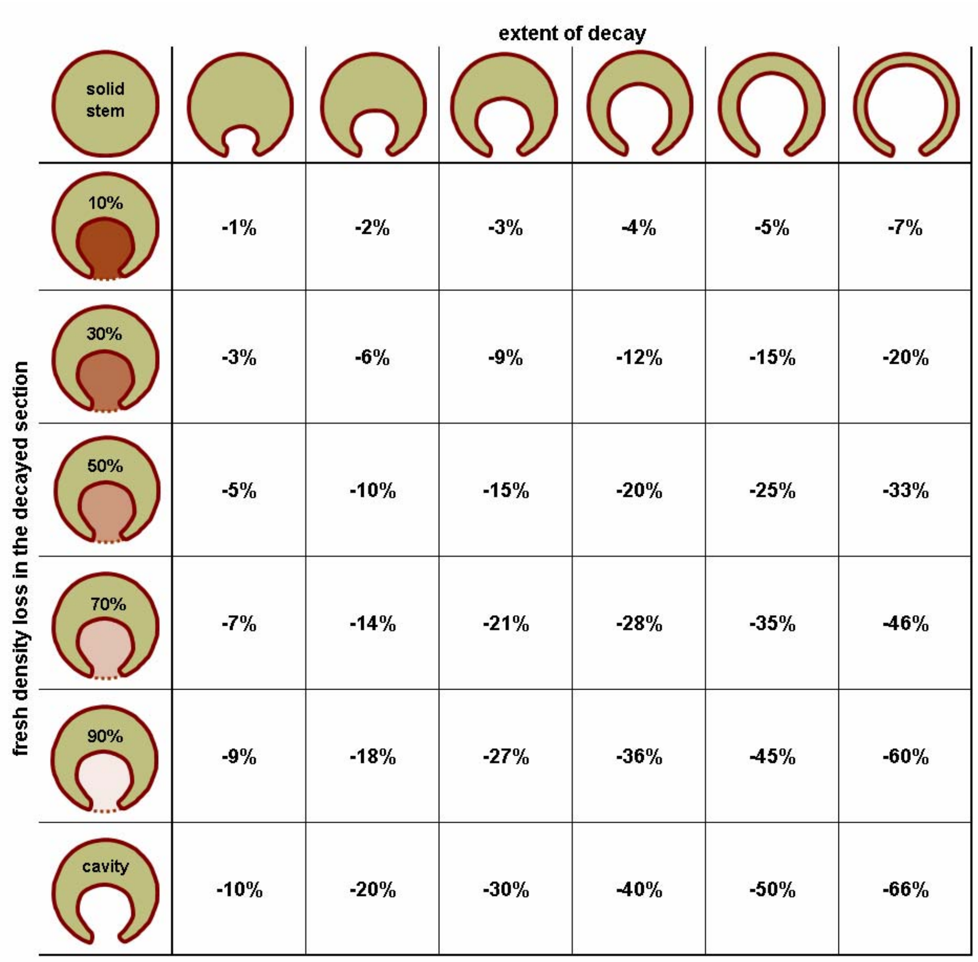


Figure 6.8 Weight reduction due to decay

6.3.4 Moisture content

Obvious changes in SG may also result from differing moisture content. The sapwood, especially, is prone to seasonal changes in moisture content. The water conducting vessels are filled with a surplus of water in early spring, due to water pressure generated from the root system (Zimmermann, Brown 1980). In summer, the vessels may contain less water due to negative pressure resulting from transpiration of water in the crown, and photosynthetic processes in the leaves. The changes in moisture content cause a diurnal swelling of the stem which were recorded as early as 1897 by Friedrich.

In the wet core of Poplar, the moisture content may reach 185% directly after felling (Wagenführ 2000). The Wood Handbook (Forest Products Laboratory 1999) lists a moisture content of over 160% for the heartwood. Among other tree species that can develop a wet core are *Fagus sylvatica* (Koch 2004), *Aesculus hippocastaneum* (Habermehl, Ridder nd.) and *Abies alba*. The wet core of Silver Fir is reported to contain up to 220% of moisture content, whereas regular heartwood only reaches 30 to 40% of moisture content (Grosser 1977). Depending on the extent of the wet core and the diameter of the stem, logs of Silver Fir may increase their weight significantly when they contain a wet core. However, data listed in Lavers (1983) indicates that an increase in moisture content of up to 220% will not render a log's SG greater than the maximum value given in Table 6.2.

The weight estimation of dry or dead wood in standing trees poses many difficulties. Dead wood is prone to rot when exposed to the natural environment. Therefore, it is virtually impossible to assess the weight of logs of dead wood. Decomposition by wood-decaying fungi causing white rot may be associated with increasing water absorption in delignified cellulose, counterbalancing the weight loss due to decay. Brown rot does not seem to be related to increasing moisture content (Schwarze *et al* 1997) and, therefore, weight loss may be more extensive for this type of decay.

Only laboratory data for wood at 12-15% moisture content (air dry) is available in literature sources. To the knowledge of the authors, no study has been undertaken to derive the specific gravity of dead wood in standing trees. Dismantling dead trees is often a great challenge for arborists, due to the many unknown parameters involved, one of them being the weight of the tree or logs to be lowered. Consequently, this may be an area worthy of further study in the future.

The differences in weight of green and air-dried samples of wood is listed for several species in Figure 6.9. These figures cannot be transferred directly to dead wood, due to the above-mentioned constraints, but they can serve as a basis for the evaluation of the weight of dead wood. As a rule of thumb, arborists can assume that, in practice, dead wood will be roughly 20 to 30% lighter than living green wood. Under exceptional conditions, the weight may be reduced much more (up to almost 60% weight loss).

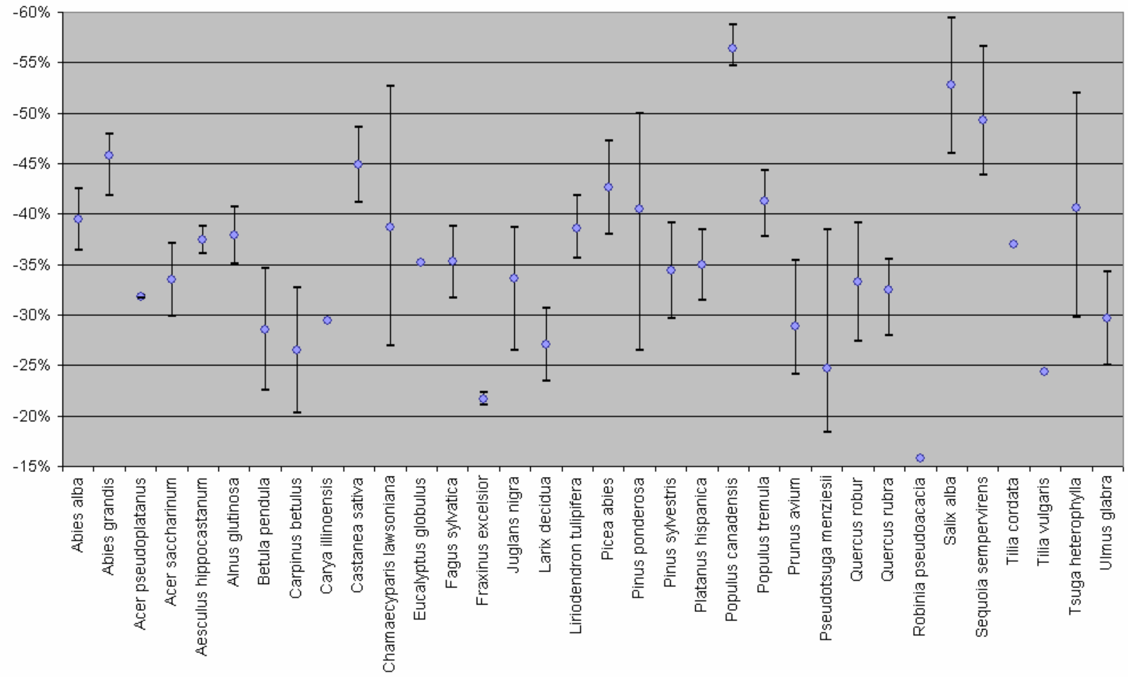


Figure 6.9 Weight loss of air dry wood *vs* green wood samples

6.4 ASSESSING THE WEIGHT OF LIMBS AND BRANCHES

6.4.1 Methods

Spatz (2003) uses a formula for assessing the weight of a branch. This is based on the volume of a cylindrical section, calculated from the diameter of the branch at its base and the length of the branch. To take into account the interference of taper (reducing wood volume) and crown spread (adding the weight of twigs and leaves), Spatz proposes a form factor of 0.8 to reduce the volume. The weight of the branch is determined by multiplying its assumed volume by its species-dependent density.

$$F_{weight} = f_{form} \times \pi \times r^2 \times L \times \rho \times g \qquad \text{equation 6.12}$$

where

F_{weight}	weight of the branch
f_{form}	form factor (here 0.8)
r	radius at the branch basis
L	length of the branch
ρ	species specific density of wood
g	acceleration due to gravity

Wessolly, Erb (1998) propose form factors for branches between 0.6 and 0.8 with regard to differing crown volumes. Both sources do not reveal a database to support their propositions.

6.4.2 Sources in literature

Lips (2005) compared three formulae for assessing the weight of branches, using measurements of sixteen branches of Horse Chestnut and Norway Maple with diameters between 4 and 16 cm at the base of the branch. Besides the form factor proposed by Spatz (2003), Lips also used both a conical and a parabolic model to assess the volume of a section. He based his weight estimations on a specific gravity of 0.84 for both species. The formula, using form factor 0.8 produced results closest to the real weight in all sixteen cases.

However, only three branches of more than 50 kg mass were included in this study. For two of them, the deviation from actual weight was between -5 and -10% when the formula used by Spatz (2003) was used. In one case, the estimated weight was too low by more than 30%. Using the specific gravity listed in Table 6.2, the weights of two branches would have been estimated to be by 5 to 10% too much, and the third one by more than 20% too little. If a form factor of 0.75 (instead of 0.8) had been used, the weights of two branches would have been estimated correctly (less than 2% deviation).

Choosing an adequate form factor may be crucial for achieving satisfactory quality of weight estimations of branches and crown sections. The specific gravity of wood in branches might also differ significantly from the green weight of logs, possibly due to the greater proportion of sapwood and therefore greater moisture content (*cf* Kane 2007, SG in branches of *Pyrus calleryana* only 0.68).

6.4.3 Results from practical tests

During on-site tests, the weights of tested branches, their diameters at their bases and their lengths were measured. Based on the data for specific gravity given in Table 6.2, suitable form factors for crown parts were derived by measuring four leaders from two of the tested tree species (Beech and Sycamore). These figures can serve as a guideline for adapting the weight estimations based on equation 6.12 for other species. The derived form factors are:

- Beech: form factor 0.50 – 0.65
- Sycamore: form factor 0.55 – 1.00

Data on branches of Poplar *(Populus canadensis)*, originally measured some 10 years ago, but recently retrieved, revised and provided by V.Genenz, reveal that a suitable form factor for this species would have ranged from 0.35 to 0.40. These numbers are significantly lower than those listed above, which further demonstrates the fact that form factors for branches are species-dependent, and more specific information would certainly be required to adequately assess the weights of crown sections. Furthermore, the variation in form factors for particular species indicates a great natural variability.

So that the weights of crown parts are not underestimated too much, a ***form factor of 0.8*** is therefore recommended, as a standard. Further research is required if more precise form factors are to be determined in the future.

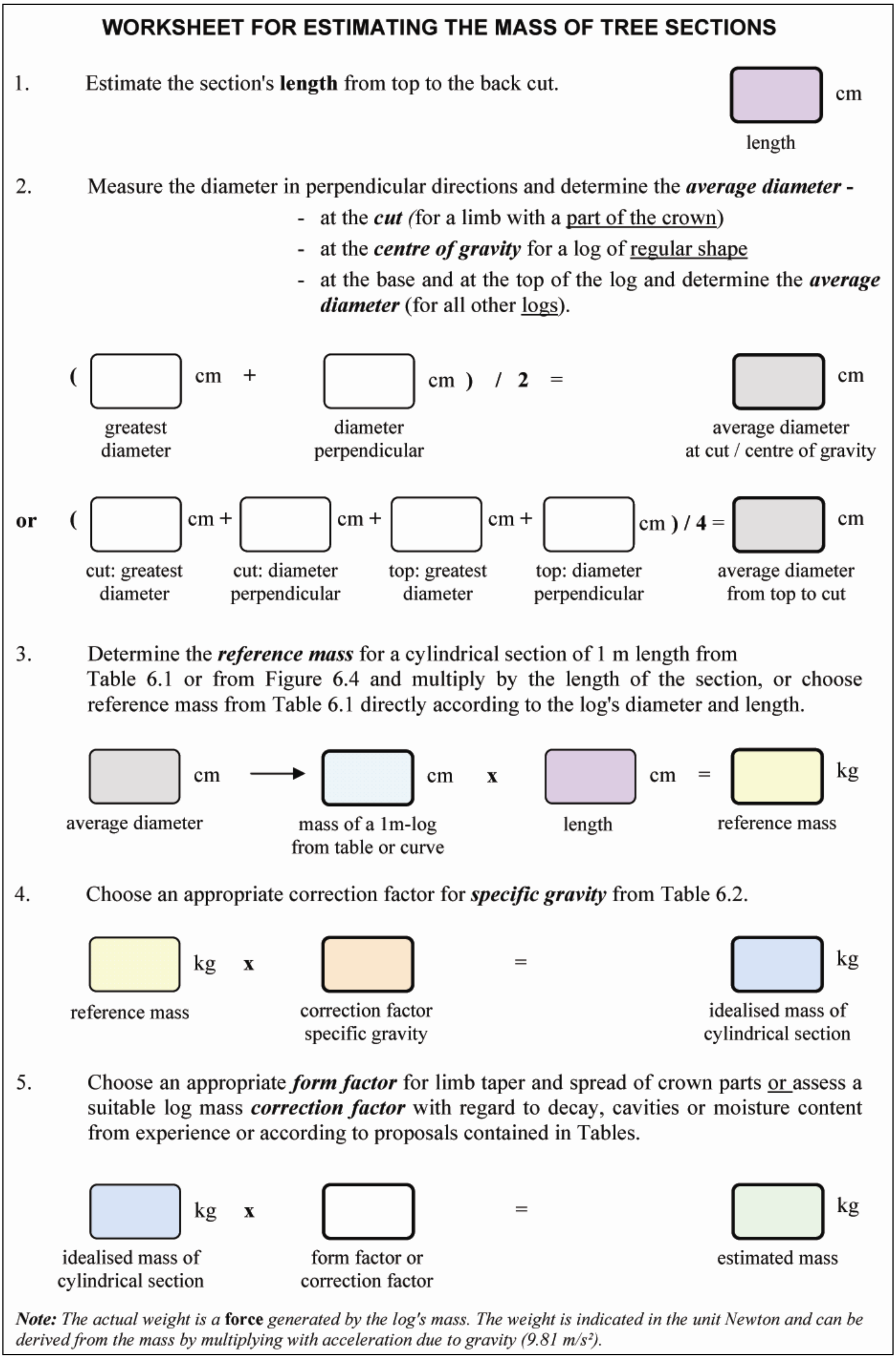
6.5 WORKSHEET

The actual weight of a section can be determined using a worksheet (a prototype of which is presented at Figure 6.10) that includes the following steps (bullet point numbers correspond to the different sections of the worksheet):

1. estimating the length of the section
2. measuring a representative diameter and calculating the average diameter
3. determining the reference mass by referring to Table 6.1 or Figure 6.4
4. multiplying the reference weight with a species-dependent correction factor for specific gravity taken from Table 6.2
5. multiplying with factors that take into account decay, wet core or dead wood and/or (eventually) a form factor for crown parts

6.6 WEIGHTS OF ENTIRE TREES

In Northern Germany, the Arborist Company of Uwe Thomsen recorded the weights of trees during crane-felling operations. On similar occasions, Chris Cowell and Paul Howard determined the weights of sections of trees during dismantling operations. The data from these different sources has been brought together in Table 6.3 (page 154). Due to the great variability in size and specific gravity, the data compiled in the table cannot serve as a representative basis for the estimation of the weights of trees and sections. However, it could serve as a pointer towards the range of weights that arborists might encounter during dismantling operations. Sources for Table 6.3 include Uwe Thomsen, Pinneberg, Germany, 2007; Sinn, 2003 (for data on *F. sylvatic Purpurea*).



WORKSHEET FOR ESTIMATING THE MASS OF TREE SECTIONS

1. Estimate the section's **length** from top to the back cut. [ ] cm
   length

2. Measure the diameter in perpendicular directions and determine the ***average diameter*** -
   - at the ***cut*** *(*for a limb with a part of the crown)
   - at the ***centre of gravity*** for a log of regular shape
   - at the base and at the top of the log and determine the ***average diameter*** (for all other logs).

([ ] cm + [ ] cm) / **2** = [ ] cm
greatest diameter; diameter perpendicular; average diameter at cut / centre of gravity

or ([ ] cm + [ ] cm + [ ] cm + [ ] cm) / **4** = [ ] cm
cut: greatest diameter; cut: diameter perpendicular; top: greatest diameter; top: diameter perpendicular; average diameter from top to cut

3. Determine the ***reference mass*** for a cylindrical section of 1 m length from Table 6.1 or from Figure 6.4 and multiply by the length of the section, or choose reference mass from Table 6.1 directly according to the log's diameter and length.

[ ] cm → [ ] cm **x** [ ] cm = [ ] kg
average diameter; mass of a 1m-log from table or curve; length; reference mass

4. Choose an appropriate correction factor for ***specific gravity*** from Table 6.2.

[ ] kg **x** [ ] = [ ] kg
reference mass; correction factor specific gravity; idealised mass of cylindrical section

5. Choose an appropriate ***form factor*** for limb taper and spread of crown parts or assess a suitable log mass ***correction factor*** with regard to decay, cavities or moisture content from experience or according to proposals contained in Tables.

[ ] kg **x** [ ] = [ ] kg
idealised mass of cylindrical section; form factor or correction factor; estimated mass

Note: *The actual weight is a* **force** *generated by the log's mass. The weight is indicated in the unit Newton and can be derived from the mass by multiplying with acceleration due to gravity (9.81 m/s²).*

Figure 6.10 Prototype worksheet for estimating the mass of sections

Table 6.3 Masses of entire trees

Tree species	***Tree height (metres)***	***Circumference (cm)***	***Stem diameter (cm)***	***Crown diameter (metres)***	***Total mass (tonnes)***
Abies alba	16			9	**2.9**
Abies alba	21			12	**7.9**
Acer plataniodes	22	260	83	17	**7.1**
Fagus sylvatica	28	320	102	24	**11.2**
F. sylvatica Purpurea	25	412	131	21	**23.0**
Platanus acerifolia	21	255	81	19	**6.8**
Populus canadensis	23			12	**4.7**
Populus canadensis	29			19	**13.2**
Populus canadensis	30	520	166	26	**22.0**
Quercus robur	23	285	91	19	**8.1**
Robinia pseudoacacia	19	235	75	16	**8.2**
Salix alba 'Tristis'	21	270	86		**5.5**
Salix alba 'Tristis'	20	215	68		**2.0**
Salix alba 'Tristis'	25	320	102		**6.45**
Tilia platyphyllos	24	230	73	17	**6.4**
Ulmus glabra	23	230	73	18	**7.1**

7 STRENGTH LOSS IN CORDAGE

7.1 STRENGTH LOSS DUE TO KNOTS

The mechanical properties of ropes are usually tested under standardised conditions, using testing procedures specified in industrial norms (e.g. EN 2307, CI 1801). These standards refer to an undisturbed, straight, section of new rope only. However, where a knot is concerned, bending of the fibres, and the effects of friction, cause a strength loss that varies with the type of rope and knot in question.

Publications on the strength of knots used in arboriculture are somewhat rare. Commonly used instruction books usually only refer to the fact that knots weaken the strength of rope (if they mention it at all), but do not specify strength loss for particular knots (e.g. Lilly 2005; Schütte 2007).

Specialised knot books refer to this issue from a general perspective:

> *"Knots weaken rope. The sharper the curve, the tighter the nip (the binding, frictional pressure within the knot that keeps it from slipping), the greater the chance that the rope will break. If it does, it separates immediately outside the knot." (Budworth 1985)*

Budworth (1985) lists typical strength reduction for two types of knot: an Overhand knot is reported to reduce the rope strength by 60% of its actual strength, while knots with several turns, like the Clove Hitch or Fisherman's Bend, are reported to leave the rope with 75% of its original strength (i.e. only a 25% strength loss). According to the Cordage Institute 1994, as cited in Blair (1999), a strength reduction of up to 50% should be anticipated for knotted ropes. For knots used by speleologists, strength reductions of from 30% to 60% are reported (Storage *et al* 1990).

HSE Research 364/2001 (Lyon Equipment, 2001) contains a detailed description of knots used in rock climbing, together with their strengths. Only one knot typically used as an attachment in rigging (the Clove Hitch) was tested whilst attached to an object. The testing was carried out on a standard testing rig, at an extension rate of 500 mm/min (in accordance with BS EN 566:1997 for slings used in mountaineering). The report lists strength reductions in low-stretch ropes of 10.5 mm to 11 mm diameter. The strength loss varied from 45% (Bowline and Overhand knot) to zero for the Double Fisherman's knot (where the knot did not fail before the rope). The Clove Hitch slipped without breaking at varying forces. On dynamic rope, the strength loss was always comparable to the Overhand knot on low-stretch rope, which showed more than 45% strength loss.

An overview of strength reduction of ropes due to knots is contained in Table 7.1 (overleaf). It should be noted that data on rope diameter was not provided in all publications. Where possible, strength loss data for ropes of at least 12.5 mm diameter was chosen. In particular, the results of the above-mentioned HSE Research have been included, despite the fact that the maximum rope size was 11 mm.

Beranek 1998 states that:

> *"the type of knot used or the way a line is fastened to the work is the weak link during dynamic loading; thus, it is also the cause of most broken lines."*

Table 7.1 Strength loss due to knots – data from literature

Source	**Budworth (1985)**	**Lyon (2001)**	**Richards (2005)**	**Allaboutknots (2005)**	**Samson (1996)**	**Ven *et al* (2006)**	**Gleistein (2004)**
Knot	reduction	reduction	reduction	reduction	reduction	reduction	reduction
Anchor Hitch						27%	
Barrel Knot		23 - 33%					
Bowline	40%	26 - 45%	27%	40%		28%	31 - 40%
Butterfly		28 - 39%	19%	25%			
Clove Hitch	25%	42 - 47%			40%	43%	
Figure-of-eight on the bight		23 - 34%	22%	20%		28%	20 - 24%
Fisherman's Knot (double)			21%	21%		26%	
Fisherman's Knot (single)	35%	23 - 33%	47%				
Overhand Knot (loop)		32 - 42%					
Sheet Bend	50%		49%		50%		
Timber Hitch	30%						14 - 30%

A study of knot strengths, published on the internet, tries to explain the differences in the strength of different knots by studying the results of various authors who looked at this issue, with regard to natural fibre ropes (Allaboutknots 2005):

> *"An excessive load on the first bend causes the knot to break."*

This may be true for rigging knots as well, especially with regard to a Half Hitch or Marline Hitch added to a primary knot for extra stability, when attaching a log to a lowering line. However, the author of this study also makes the following statement:

> *"Hitches around objects introduce an entirely different set of variables, particularly concerned with the effect of environment and conditions of use." (Allaboutknots 2005).*

All knots used as attachments to logs, or in setting up an anchor point on a stem, certainly fall into this category. Therefore, the published data on knot strength may not be applicable to use in arboriculture without caution.

High performance fibres are reported to lose a large amount of their strength when knotted. Pilkerton *et al* (2001) state that Amsteel ropes, when knotted, failed at loads 80 to 90% lower than their rated strength. Similarly, ropes made from Dyneema (a trade name of Beal Ropes applied to a high strength cord known as Spectra in North America, *cf* Moyer, 2000) lost almost 80% of their tensile strength when knotted with a Bowline, in tests carried out by the manufacturer (Gleistein Ropes 2004). Since knots are required in most rigging operations, these ropes must be used with care and should preferably be attached via a spliced eye (a method of attachment which would require the use of karabiners, and which, as such, is not recommended where dynamic loading is involved).

7.2 STRENGTH LOSS OF CORDAGE IN RIGGING APPLICATIONS

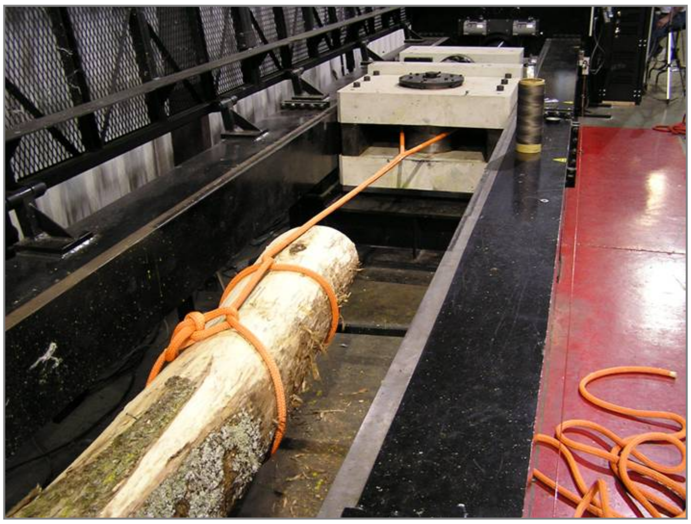
As no data was accessible on the strength loss of knots under conditions similar to those occurring in rigging applications, the results of a series of tests carried out previously, in the USA, by ArborMaster Training in cooperation with Samson Rope Technologies, were evaluated during the course of this project. The results are presented in the following paragraphs.

7.2.1 Material and methods

In order to assess the strength loss in a more realistic scenario, arborist ropes and slings attached to logs were studied. Destructive tests were carried out by Samson Rope, ArborMaster Inc. and Michael Tain in 2004. Data was generated from two series of tests, comprising a total number of 166 valid tests, on ten types of cordage in up to four different diameters. The dataset was evaluated with the kind permission of Samson Ropes Inc. and ArborMaster Inc.

A log, selected from a supply of logs 40 to 55 cm in diameter, was set up at the fixed part of the test rig. By drilling through the wood, and inserting solid round iron bolts, stable attachment points were formed. The log was then connected to the fixed end of the test rig by low stretch Amsteel slings of high tensile strength. Logs of similar diameter were cut from the species *Populus deltoides* and *Pseudotsuga menziesii*. As the bark was stripped off during the test procedure, new logs had to be provided in order to avoid rope slippage along the stem and retain a realistic situation.

The knot to be tested was tied around the log, and the other end of the cordage sample was fixed around a capstan-like bollard of 30 cm diameter. This connection was achieved either through a spliced eye, fashioned according to Samson standards, or by a Magnus Hitch, a knot known to not significantly reduce the strength of the cordage used.



Set-up test rig[*]

Some standard climbing knots, which are also used in rigging, for attaching karabiners or shackles, were tested on a smaller testing machine. In these tests, the shackles used for the testing procedure were chosen to fit the diameter and form of standard arborist karabiners. The load in the small test rig was applied in a vertical position.

[*] *Picture courtesy of Ken Palmer, ArborMaster, USA*

The following ropes and slings were tested in different configurations:

Table 7.2 Cordage used in tests

Sling/Rope Type	Construction	Material	Ø	Tests
Arbor-Plex	12-strand single braid	PES + Polyolefin	16 mm	3
Blue Streak	16-strand double braid	Nylon / PES	13 mm	12
Stable Braid	Double braid	PES / PES	13 mm 16 mm 19 mm 13 mm	19 13 12 6
Tenex	12-strand hollow braid	PES	16 mm	1
True-Blue	12-strand single braid	PES	13 mm 16 mm	3 10
Loopie	12-strand hollow braid	PES	13 mm 16 mm	12 7
Whoopie	12-strand hollow braid	PES	16 mm	9
Eye-sling (Stable Braid)	Double braid	PES / PES	16 mm 19 mm	2 2
Eye-sling (Tenex)	12-strand hollow braid	PES (Vectran)	13 mm 16 mm 19 mm 22 mm	12 16 12 12

Arbor-Plex is a 12-strand braided construction of polyester and polyolefin fibres, especially designed for rigging applications. Blue Streak is actually a climbing line of Samson's ArborMaster series, although the rope is reported to be used for rigging purposes as well. The Stable Braid series are classic double-braided rigging lines of 100% polyester with a special coating. Samson's Tenex is a 12-strand single hollow braid described as having 'sling construction', but which is also used for lowering lines. True-Blue is similar to the Arbor-Plex but made of polyester fibres only.

Four different types of slings were tested. Loopie and Whoopie consist of a Tenex sling hollow-braid construction, as mentioned above. Samson's eye-slings are called 'Treerig' slings and are available from Tenex and Stable Braid ropes, the latter being of a double-braided construction. Eyes were of standard length (20 cm for Tenex and 15 cm for Stable Braid). Splices on Tenex slings were secured with a Locked Brummel (*cf* Samson 2001), whereas Stable Braid splices were stitched.

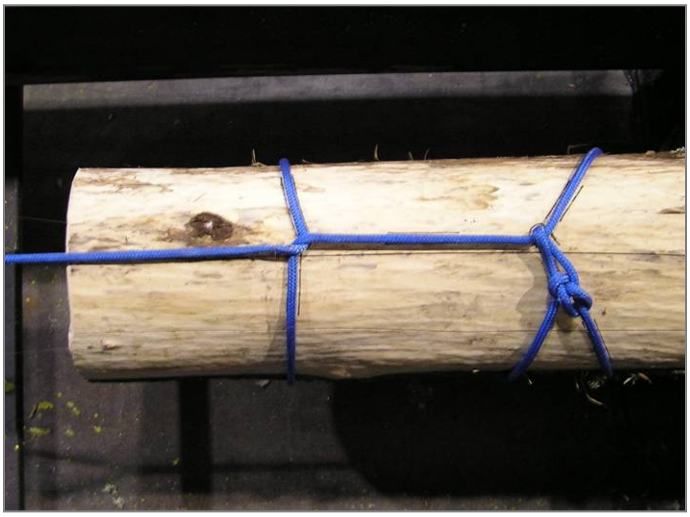
Cordage was supplied by Samson Inc. and was chosen from their range of arborist lowering ropes and slings. All samples were loaded to break in a test rig, in a quasi-static (i.e. forces increasing slowly over a period of time) pull test. In order to equate to the load application in actual rigging scenarios, ram speed was set to the maximum propulsion available at the test rig. If knots came undone, or if ropes failed before the knot, the respective test was not included in the dataset.

Knots were chosen according to their usual application during rigging operations. Some served as attachments for sections to be lowered; others were used to install temporary anchor points, either for arborist blocks, or for lowering devices such as the 'port-a-wrap'. For all configurations, logs of the same diameter were used in order to get comparable results.

Besides the use of different cordage for slings, the way the load is actually applied may also be decisive for strength loss. Therefore, eye-slings, Loopie and Whoopie slings were connected to either an arborist block with a bushing (ISC RP 050), or a single connecting link, or a shackle that fitted the diameter and curvature of a ‘port-a-wrap’. The direct attachment of a ‘port-a-wrap’ was rejected as a test configuration, because of the potential damage resulting from the high tensile forces applied (metal may yield to great quasi-static loads).

Girthed eye-splice[*]

To reduce the variation in knot strength as much as possible, the knots were all tied by the same person, using a standard procedure. The knots were all set and pre-tensioned, as is the usual practice. Lines drawn on the logs provided for standard attachment sites and similar spans between primary knots and supplementary hitches or hardware, respectively.



Knot set-up at log (Half Hitch with Running Bowline)[†]

[*] *Picture courtesy of Ken Palmer, ArborMaster, USA*
[†] *Picture courtesy of Michael Tain*

The following knot/sling configurations were tested:

Table 7.3 Knot/sling configurations

Primary knot / sling type	**Load applied at**	**No. of tests**
Ropes attached to logs		
Clove Hitch	exit next to load	9
	exit opposite to load	5
Cow Hitch		12
Running Bowline	directly	12
	Half Hitch	20
	Marline Hitch	6
Ropes attached to shackles		
Anchor Hitch		3
Buntline		3
Butterfly		3
Double Fishermen's Knot		3
Triple Bowline		3
Slings attached to logs		
Timber Hitch on eye-sling	block with bushing	12
	girth on shackle	11
Cow Hitch on eye-sling	block with bushing	20
	girth on shackle	12
	connecting link	1
Loopie	block with bushing	12
	girth on shackle	6
	connecting link	1
Whoopie	block with bushing	3
	girth on shackle	6

The study comprised only a ***small number of samples*** per cordage/knot combination. Generally, only three different samples were tested to breakage for each configuration. Therefore, it has to be clearly stated that the results of this study can only indicate a tendency, and cannot be represented as a rule generated from a statistically reliable database. Therefore, these results may not be fully suitable for use as a basis for proposing a technical standard.

However, the results of this study do provide information that was formerly not available and they do, therefore, appear to be of some value in the evaluation of current rigging and dismantling practice. Further studies could deepen and widen the understanding of how the strength of cordage may be altered by knots in realistic rigging scenarios.

7.2.2 Strength loss of ropes knotted to logs

Half Hitch with Running Bowline

One knot configuration used for attachment to logs of considerable size is a Running Bowline (primary knot) with an additional Half Hitch. The second (or supplementary) knot is added in order to achieve greater stability in the logs' movements, and to determine the direction of loading on the primary knot. Due to the fact that the first bend of the Half Hitch forms a 90° angle (unlike many other knots which cause a greater deflection of the rope), it is often assumed that adding a Half Hitch will actually strengthen the attachment.

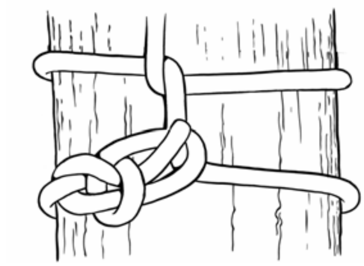


Figure 7.1 Half Hitch with Running Bowline*

In fact, the supplementary knot obviously takes most of the loading, and will fail first. In the series of tests, the primary knot (i.e. the Bowline) was never the weak spot. Ropes always failed at the first bend of the rope i.e. at the Half Hitch in this configuration.

Therefore, it may very well be that the strength loss will not differ much if other primary knots (e.g. the Timber Hitch, also called the 'Killick Hitch' by Budworth 1985) are used, although this would only be true if the primary knots offer similar stability, and also reliably prevent slippage of the rope through the Half Hitch. However, such alternative combinations were not tested in the course of this project.

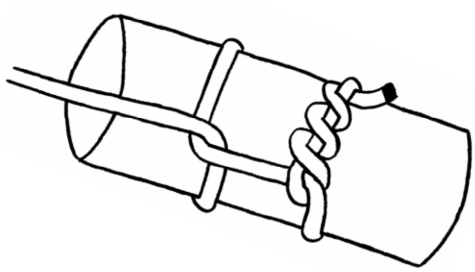


Figure 7.2 Half Hitch with Timber Hitch (Killick Hitch)†

Strength loss figures for the standard knot combination of Half Hitch with Running Bowline are shown in Figure 7.3 overleaf. Interestingly, the Half Hitch did not always make the attachment stronger. Compared to the strength loss due to the primary knot alone, the addition of a Half Hitch caused significantly greater strength reduction in the tested double-braid lines. Strength loss ranged from 28 to 33% for a Running Bowline alone, and increased to more than 40% for the combination of knots in a standard log attachment. The other rope that was tested in both combinations, a PES single braid, was only slightly stronger by the addition of the Half Hitch.

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* *Line drawing by Brian Kotwica, courtesy of the Intenational Society of Arboriculture, USA*
† *Line drawing from Lingens, 2006, courtesy of Dirk Lingens, Kletterdienste, Germany*

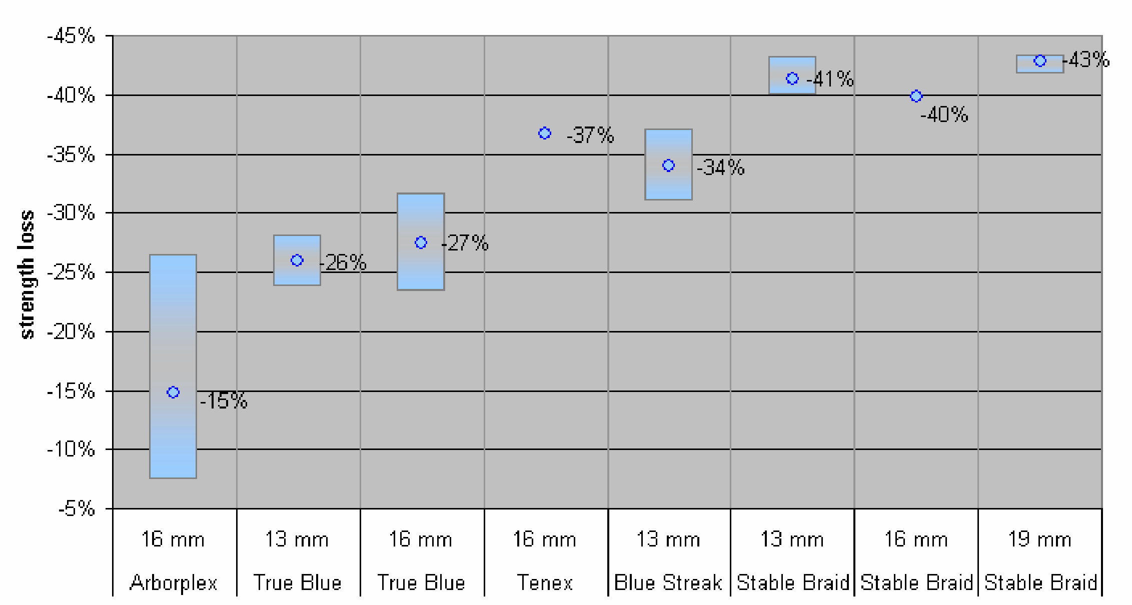

Figure 7.3 Half Hitch with Running Bowline (average strength loss indicated)

Studies of drop tests carried out in the course of this project (see Chapter 8) showed that a considerable length of rope (7 to 18 cm) slips through the Half Hitch when load is applied to the attachment. The greater the log's diameter, the more rope is wrapped in a loop around it, increasing the total stretch under a given force (despite the effect of friction). A larger diameter log may, therefore, result in more rope being pulled through the supplementary hitch. In some cases during the tests, as much as 30 cm of rope was found to have passed a Half Hitch during a worst-case shock loading.

The yellow-green marker identifies the original position of the rope's point of entry to the Half Hitch.

Note the visible abrasion of peripheral fibres on the left side of the rope after exiting the Half Hitch, indicating damage due to rope-on-rope friction under great load.

The rope used was a 14 mm double-braid PES line (Buccaneer Bullrope).

Slippage through a supplementary Half Hitch

Considering the fact that great peak forces may be acting on the rope in such scenarios, it is possible that rope-on-rope friction could severely damage the rope. Therefore, the negative effects of strength loss (due to abrasion) and heat (generated by friction) may very well exceed the positive effect of a greater bend angle in the supplementary hitch. This may explain why the supplementary hitch, generally speaking, weakens the attachment (but at the same time enhances its stability, which is the primary reason for its use in this situation).

The above discussion illustrates the importance of specific properties of knots. Other properties which may be of importance, such as stability, release and grip, were not studied in the course of the present project. Knots suitable for log attachments in rigging applications should not slip or unravel under load, should be easy to untie and, at the same time, should provide a strong and stable grip on the log. The strength reduction observed in supplementary hitches is the price paid for the benefits gained by using them: better control over log rotation; a tight and stable grip; steady loading of the primary knot; and protection against knot slippage or unravelling.

No significant differences were found between the two common options for supplementary knot i.e. the Half Hitch or the Marline Hitch. The Marline Hitch gave slightly smaller strength reductions on 13 mm rope, but the differences were not significant enough to indicate a real preference (see Figure 7.5). The difference in the two knots is described in Lilly *et al* (2003) and depicted in Figure 7.4 below.

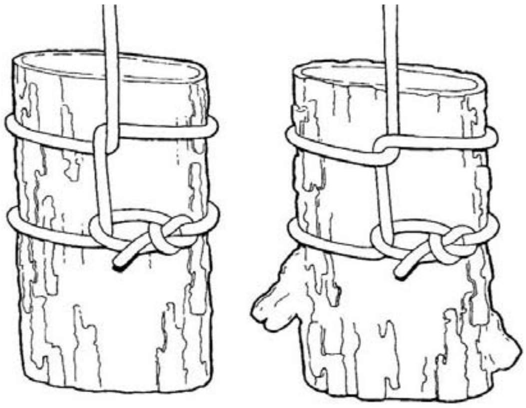

Figure 7.4 Half Hitch (left) and Marline Hitch (right)*

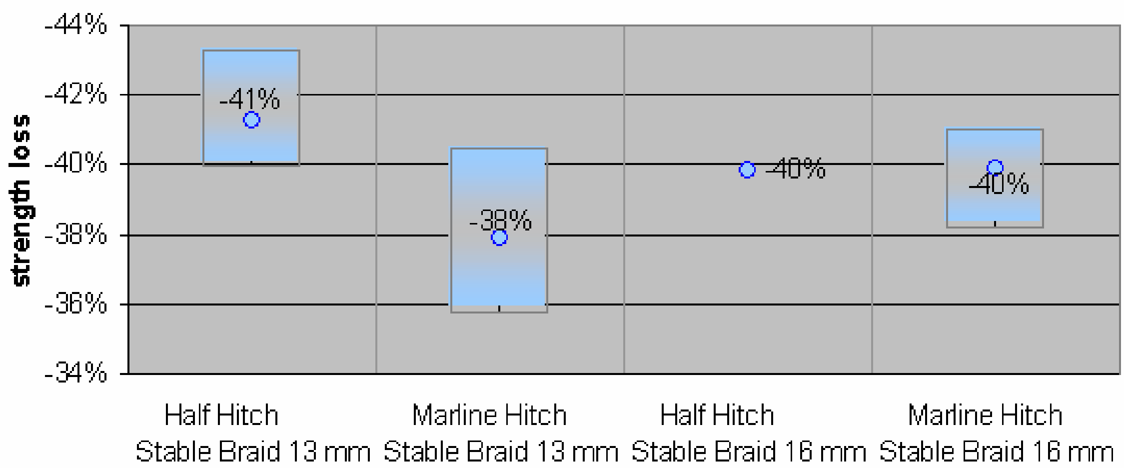

Figure 7.5 Half Hitch *vs* Marline Hitch with Running Bowline (average strength loss indicated)

* *Line drawing by Brian Kotwica, courtesy of the International Society of Arboriculture, USA*

Clove Hitch

The Clove Hitch is often used as a means of direct attachment to smaller logs and branches. It may also be used as a primary knot in the configuration referred to previously. Its tail must always be secured (e.g. with two Half Hitches in the standing end), in order to prevent unravelling and/or slippage through the knot (Beranek 1998; Lyon Equipment 2001; Lilly 2005; Schütte 2007).

If the Clove Hitch is loaded perpendicular to the branch it is securing, there would seem to be no preferred end to choose as the working end. If the knot is put under load laterally (i.e. along the long axis of the branch or log), the literature gives differing recommendations on which end should be used. Budworth (1985), Lilly *et al* (2003) and Jepson (2000) depict the 'American' version of the knot, where the working end of the rope exits the knot from the (upper) turn nearest to the load direction. In contrast, in the 'European' version of the Clove Hitch, the working part of the rope exits the knot from the bottom turn, i.e. on the opposite side to the load. This version is strongly recommended in Lingens (2006), for scenarios where the rigging is not placed at the log's centre of gravity. Michael Tain also reports its use, e.g. in Italy (Tain, pers. comm. 2006). However, according to practitioners, this version is more prone to unravelling and, therefore, needs to be secured with one, or even two, Half Hitches (e.g. Paul Howard, pers. comm.; Ken Palmer, pers. comm.). The two different configurations are shown below.

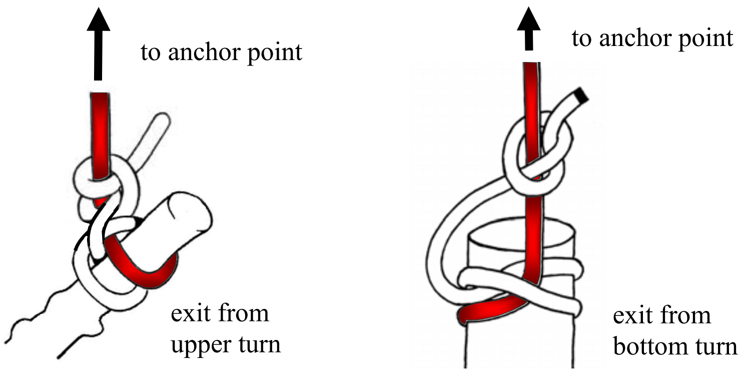

Figure 7.6 Clove Hitch, 'American' (left)[*] and 'European' (right)[†]

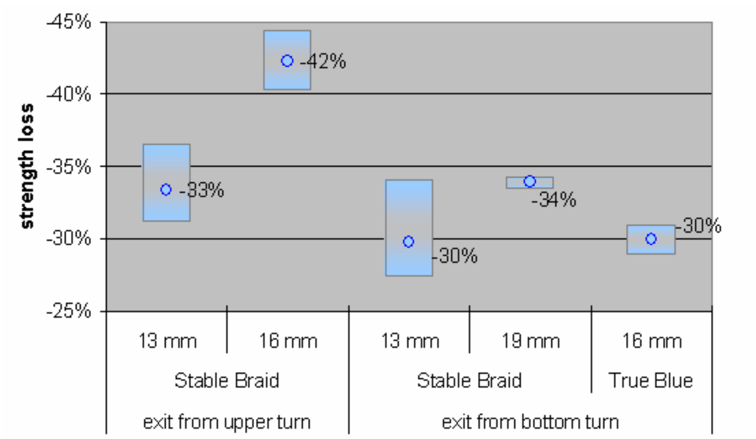

Figure 7.7 Strength loss in Clove Hitch in two versions (average indicated)

[*] *Modified, original line drawing by Brian Kotwica, courtesy of the International Society of Arboriculture, USA*
[†] *Line drawing from Lingens, 2006, courtesy of D. Lingens, Germany*

The difference in performance between the two configurations was noticeable, but not highly significant (see Figure 7.7). The 'European' version of the Clove Hitch was up to 12 % stronger on rigging lines of the same diameter. Therefore, this version only was included in the overview of primary attachment knots. The practicability of the 'European' Clove Hitch and the significance of differences in strength loss could be subject to further investigations.

Primary knots

Three widely used primary attachment knots were tested on ropes of different diameter and construction. Besides the Clove Hitch and the Running Bowline, the Cow Hitch was also tested, because, although its main application is in forming an anchor point with a sling, it can also be used to attach a log to a lowering line. The Timber Hitch was not included in the tests, because it is not suitable for use as a stand-alone attachment to logs that are to be lowered. The strength loss data for Clove Hitch, Cow Hitch and Running Bowline are presented in Figure 7.8.

It is a common belief that the greater the diameter of the rope, the less adverse will be the effect of knots on rope strength (i.e. that a thicker rope should experience less strength loss from a specific knot). This conclusion contradicts the fact that the bend ratios in a knot remain more or less constant for increasing rope diameters, and therefore more fibres are actually being loaded (for bend ratio *cf* e.g. Bacon, 2002). However, such a trend was not apparent from the results of this study of ropes attached to logs. By contrast, as a general trend, the strength loss was proportionately greater for greater diameters of rope.

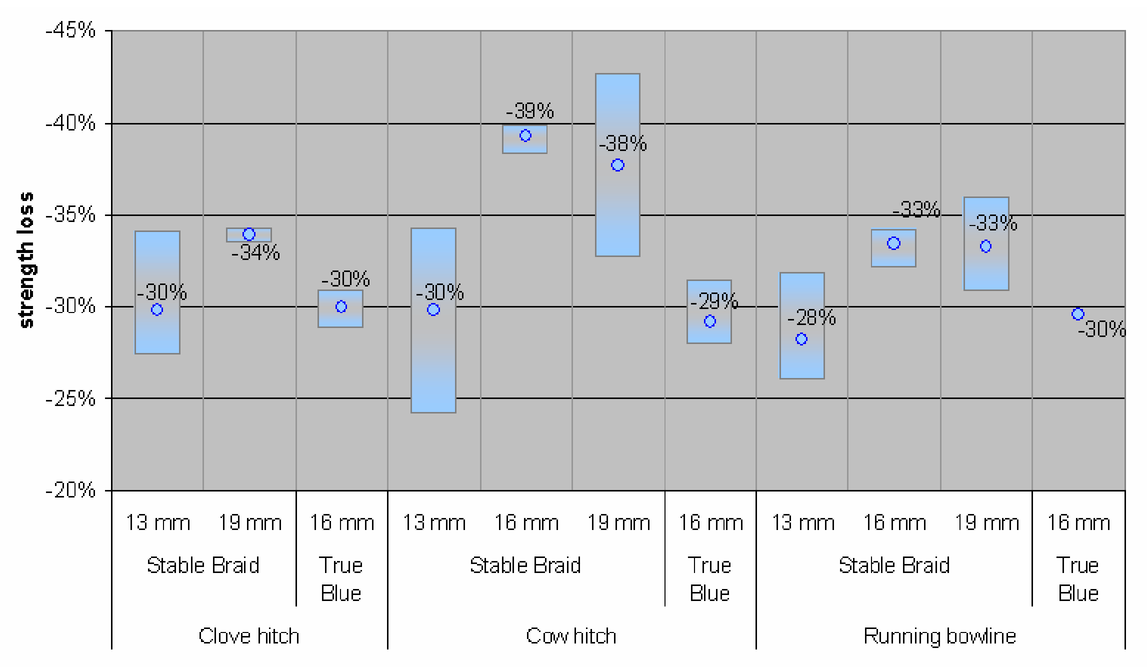

Figure 7.8 Strength loss in primary knots (average indicated)

An overview of the statistical test data for ropes is contained in Table 5 in Appendix 4. Table 7.4 (overleaf) summarises the percentage strength loss for each knot tested.

Table 7.4 Strength loss due to knots in ropes attached to a log

Knot	Clove Hitch	Cow Hitch	Half Hitch with Running Bowline	Marline Hitch with Running Bowline	Running Bowline
Number of tests	14	12	20	6	12
Strength loss (min - max)	27% - 44%	24% - 43%	7% - 43%	36% - 41%	32% - 36%

7.2.3 Strength loss of slings knotted to a stem

Eye-slings

Eye-slings are commonly used to configure anchor points in rigging. The present study included the testing of two different types of eye-sling, one made from a double-braided rope (PES) and another made from a 12-strand sling construction (Tenex). The two types of eye-sling were compared in a standard scenario consisting of a Cow Hitch connected to an arborist block (see Figure 7.11). A load was applied to the block with an Amsteel rope of adequate strength.

The Tenex eye-slings experienced a lower strength loss at the same diameter of cordage than the Stable Braid slings. As an exception, the strength loss in the ½ inch (13 mm) Tenex eye-sling was significantly greater than all other results for this material. It was observed that the slings of this small diameter failed at the entry to the Cow Hitch, i.e. at the first Half Hitch. For the slings of 16 and 19 mm diameter, the weak spot was either at the Locked Brummel, or at the exit point of the bury, or along the circumference of the log. The 22 mm eye-sling failed at the entry point into the knot, in common with the 13 mm sling.

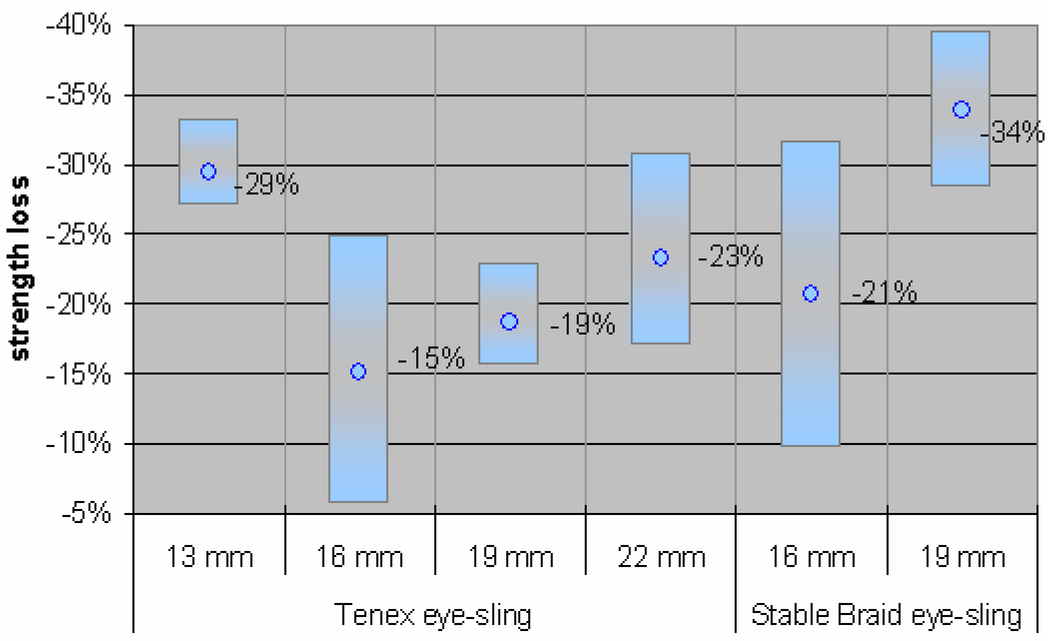

Figure 7.9 Strength loss in eye-slings tied to a log with a Cow Hitch – load applied through an arborists block (average indicated)

Two different knots, the Timber Hitch and the Cow Hitch, were tested against each other in two standard rigging scenarios, using Tenex eye-slings which provided better strength loss properties. In the first scenario, the knots were combined with an arborist block through which the load was applied. In the second scenario, the 'dead-eye' was girthed to a steel shackle to simulate the use of a 'port-a-wrap' lowering device. In both scenarios, the Timber Hitch generated significantly less strength reduction when compared to the rated strength of the sling.

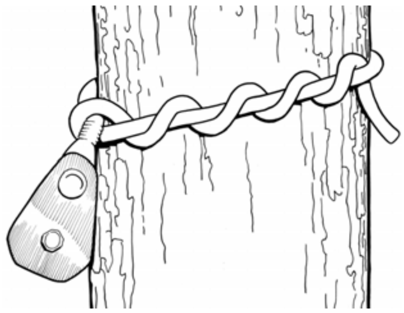

Figure 7.10 Eye-sling with arborist block attached to log by a Timber Hitch*

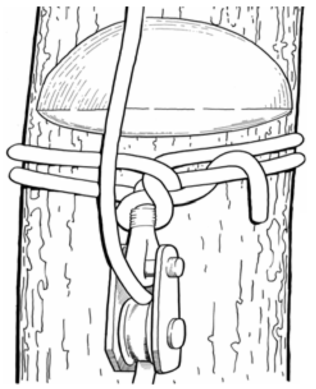

Figure 7.11 Cow Hitch with arborist block*

The following illustrations seem to indicate that strength loss was lower, for the slings tested, when the eye was attached to an arborist block, rather than to a shackle simulating a 'port-a-wrap'. As recorded in the tests, the slings broke at the splice, the Half Hitch or the first bend of the knot, rather than at the eye-sling (Palmer, pers. comm. 2007). It is difficult to explain the obvious trend towards greater strength when a block with a bushing was used, because the actual failure point was only once in the eye of the sling (which may have been affected by adverse bend ratios). However, this trend may be misleading, and may have occurred merely as a result of the small number of samples contained in the test. Again, further studies would be enlightening and may affect potential recommendations for safe rigging practice.

* *Line drawings by Brian Kotwica, courtesy of the International Society of Arboriculture, USA*

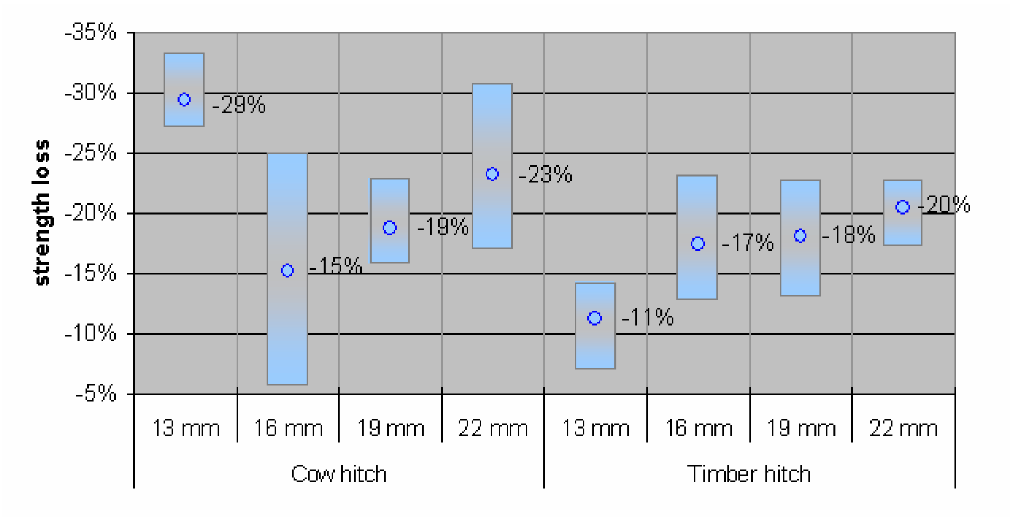

Figure 7.12 Strength loss in Tenex eye-slings tied to a log (load applied through an arborist block)

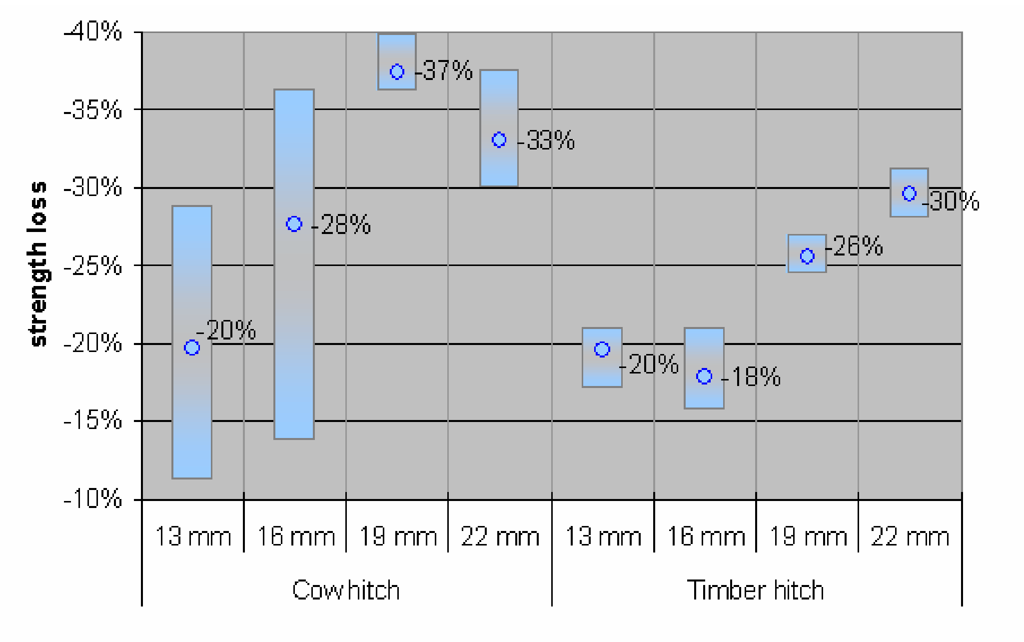

Figure 7.13 Strength loss in Tenex eye-slings tied to a log (load applied through a girthed shackle)

An overview of the statistical test data for slings is contained in Tables 6 & 7 in Appendix 4. Table 7.5 summarises the specific data generated in this test series.

Table 7.5 Strength loss in eye-slings knotted to a log

Eye-sling type	**Stable Braid**		**Tenex**			
Rope diameter	**16 mm**	**19 mm**	**13 mm**	**16 mm**	**19 mm**	**22 mm**
Number of tests	2	2	12	16	12	12
Timber Hitch			7% - 21%	13% - 23%	13% - 27%	17% - 31%
Cow Hitch	10% - 32%	28% - 40%	11% - 33%	6% - 36%	16% - 40%	17% - 38%

The Munter Hitch, not tested in the present research, was recently proposed by Lingens (2006) (also in Schütte 2007) as an alternative that can be used instead of a Cow or Timber Hitch, in order to attach a friction device to the base of a tree. According to Lingens, the strength loss with the Munter Hitch is not significantly greater than with the Cow/Timber Hitch (approximately 20% observed in one field test). The Munter Hitch can be tied without passing the end of the rope through the knot (unlike the Cow Hitch) and is stable in all directions (unlike the Timber Hitch, D. Lingens pers. comm. 2007).

In the present study, the sling eyes were formed as specified in Samson's technical standards, producing eye lengths of 15 or 20 cm respectively. However, Lingens (2006) (and in Schütte *et al* 2007) recommends the formation of longer eyes (30 to 40-times the rope diameter). Although the use of longer eyes has not yet been studied sufficiently, during one test (at Edelmann & Ridder, Germany, by Münchner Baumkletterschule) two Tenex slings were attached to a 45 cm diameter log, using a Timber Hitch, and pulled to break. A long eye (in which the splice was positioned in the rope running around the log) resulted in a tensile strength of 49 kN, whereas a standard length eye (with the bury of the splice falling inside the turn of the knot) resulted in a tensile strength of around 41 kN. In other words, the longer soft eye appeared to be 15% stronger than a standard short eye (Münchener Baumkletterschule, 2007). Until sufficient statistically approved data is available, this result can only serve as an indication.

Loopie and Whoopie slings

Adjustable loops used for attaching hardware in rigging are called Loopie slings. The Loopie sling is choked around the stem, with the spliced section (bite) forming a bend. The Whoopie sling is an eye-sling with a large adjustable second eye at the other end. The fixed eye is passed through the adjustable eye, which extends around the circumference of the stem, thus forming a Girth Hitch.

The Loopie sling was tested in position around a stem, firstly tied correctly (i.e. with the bight formed from the spliced section), and secondly tied incorrectly (i.e. with the spliced part passed through a bight formed from the unspliced section). Loads were applied through an arborist block with a bushing, and through a connector (a shackle) as a substitute for a 'port-a-wrap'.

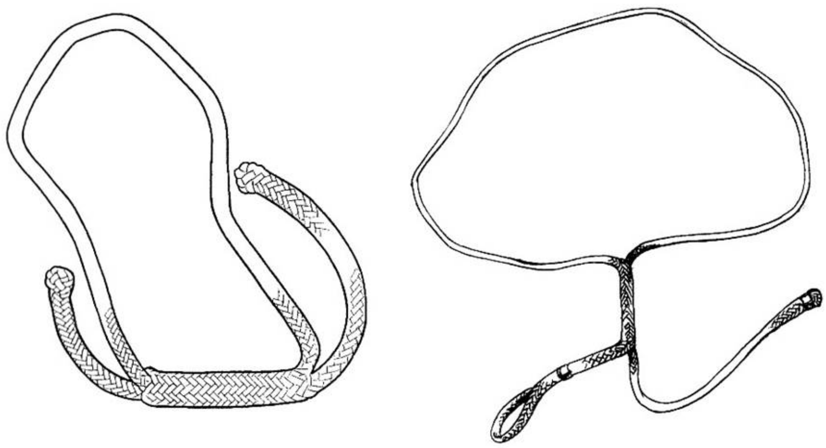

Figure 7.14 Loopie sling (left)* and Whoopie sling (right)†

* *Drawing by B. Kotwica, from Donzelli, Lilly 2001, courtesy of the International Society of Arboriculture, USA*
† *Drawing by R. Shetterly, from Blair 1995, courtesy of Don Blair & the International Society of Arboriculture, USA*

*Loopie sling with arborist block (correct configuration)**

By using an arborist block, the strength of a ½" (13 mm) Loopie sling was not greatly reduced, on average, relative to its rated breaking strength. Nevertheless, the maximum strength loss amounted to more than 15% for this diameter. Installing the sling incorrectly generated slightly increased average and maximum strength losses. Applying the load through a girthed shackle reduced the strength further. Again, the recommended configuration (with the bight in the spliced part) proved to be slightly stronger.

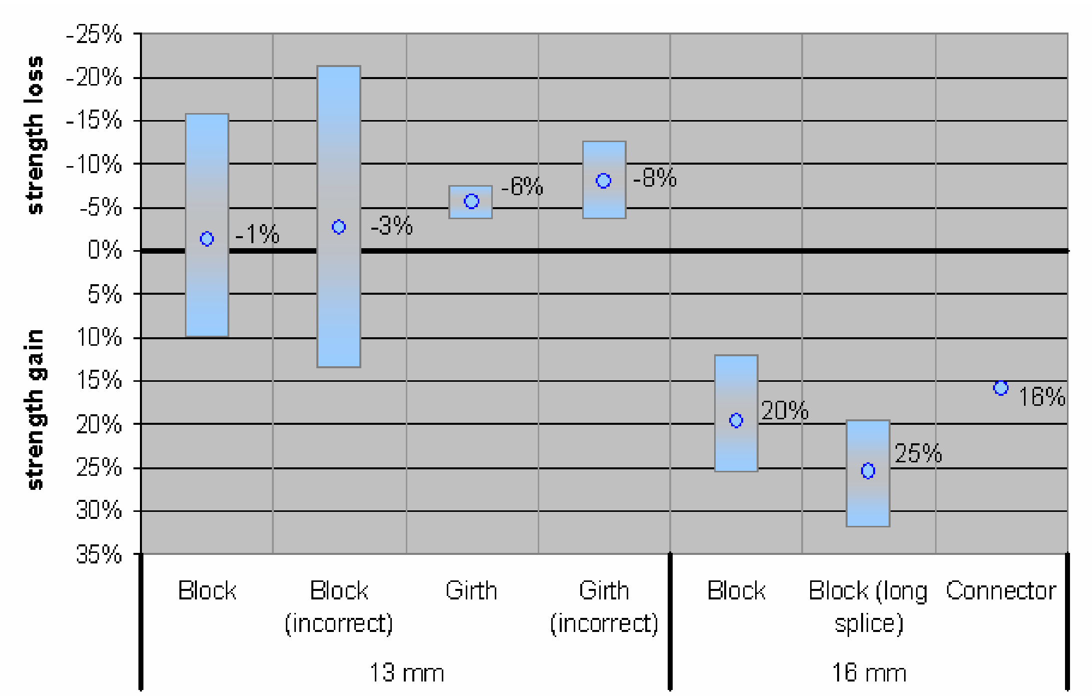

Figure 7.15 Strength alteration (loss or gain) in Loopie slings attached to a log

Slings of greater diameter (16 mm) did not show strength loss when attached to a stem and loaded through an arborist block bushing. In fact, they were actually stronger than their rated tensile strength. In practice, manufacturers could increase the strength of their slings by extending the splice (2 fid lengths instead of 1⅓ fid lengths). The strength was slightly reduced when a connector was used instead of the arborist block (presumably due to the adverse bend ratio).

* *Photograph courtesy of Ken Palmer, ArborMaster Training Inc, USA*

Whoopie slings of 16 mm diameter were tested in two configurations: either an arborist block was attached, or the load was applied through a suitable shackle. Tests were carried out with the sling installed correctly (i.e. according to the manufacturer's instructions), and also with the sling installed incorrectly (as described for the Loopie sling).

*Whoopie sling (correct configuration)**

For the Whoopie sling, the incorrect (non-standard) set-up actually showed greater tensile strength in one test, although this result may need to be confirmed by further testing. A possible explanation for the strength gain in this instance may be the limited length of the fixed eye. In the standard configuration, the fixed eye of 15 cm length is pulled through the bight formed by the adjustable eye, thus bending the splice and causing it to be weakened by abrasion. In the incorrect configuration, the two legs of the adjustable loop share the load, and are both exposed to abrasion to the same degree. However, at this stage this result can only serve as an indication and would need further testing for confirmation. Even if it is confirmed, there are practical disadvantages of using the sling in this way that would probably make its use undesirable.

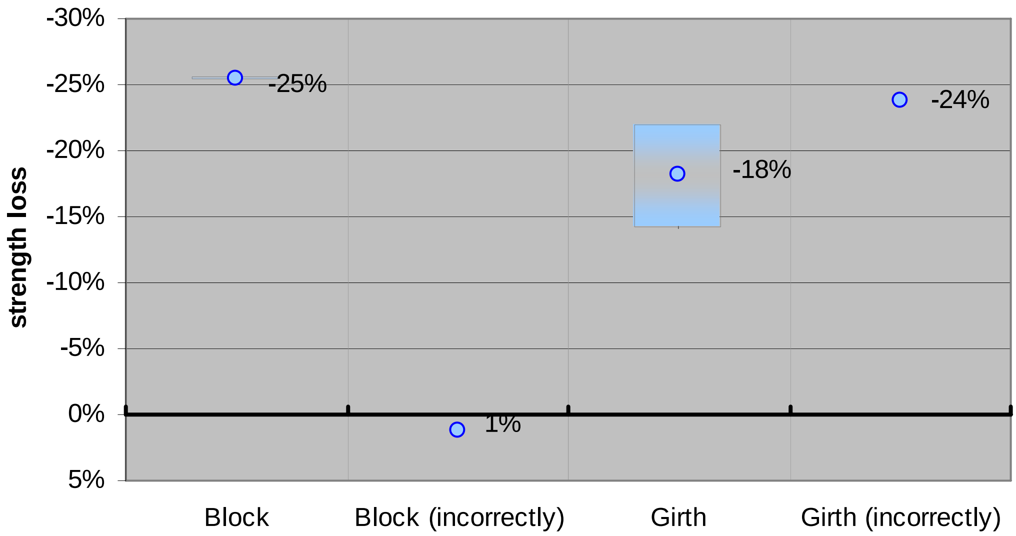

Figure 7.16 Strength alteration in Whoopie slings (average indicated)

* *Picture courtesy of Johannes Bilharz, Freeworker oHG, Germany*

An overview of the statistical test data for slings is contained in Tables 6 & 7 in Appendix 4. Table 7.6 summarises data on adjustable sling strength from this test series. Strength loss relative to the rated tensile strength is shown as negative numbers, whilst strength gain is indicated by positive numbers.

Table 7.6 Strength changes in adjustable slings attached to a log

Sling type	Loopie 13mm	Loopie 16mm	Whoopie 16mm
Number of tests	12	7	9
Negative strength gain (effective strength loss)	up to -16%	-	-14% to -26%
Positive strength gain	up to 10%	12% to 26%	-

7.2.4 Strength loss of ropes due to knots used in rigging

Table 7.1 (in section 7.1) lists strength loss for some knots used in rigging. In the tests carried out during the current research, five knots were tested on two different 13 mm ropes that are commonly used to attach karabiners or shackles. Four of these knots are shown in Figures 7.18 and 7.19, and the results of the tests are presented in Figure 7.17.

The better results for Blue Streak , which is actually a climbing line, indicate that some features of standard rigging lines may adversely affect their knot strength. This may also explain the differences arising from comparing data in Table 7.1 with that in Figure 7.17. In particular, Table 7.1 shows significantly lower figures for strength loss in the Butterfly Knot (up to 40%). Also in Table 7.1, the simple Bowline Knot shows less strength reduction (up to 45 %) than (what might be expected to be) the stronger Triple Bowline in Figure 7.17.

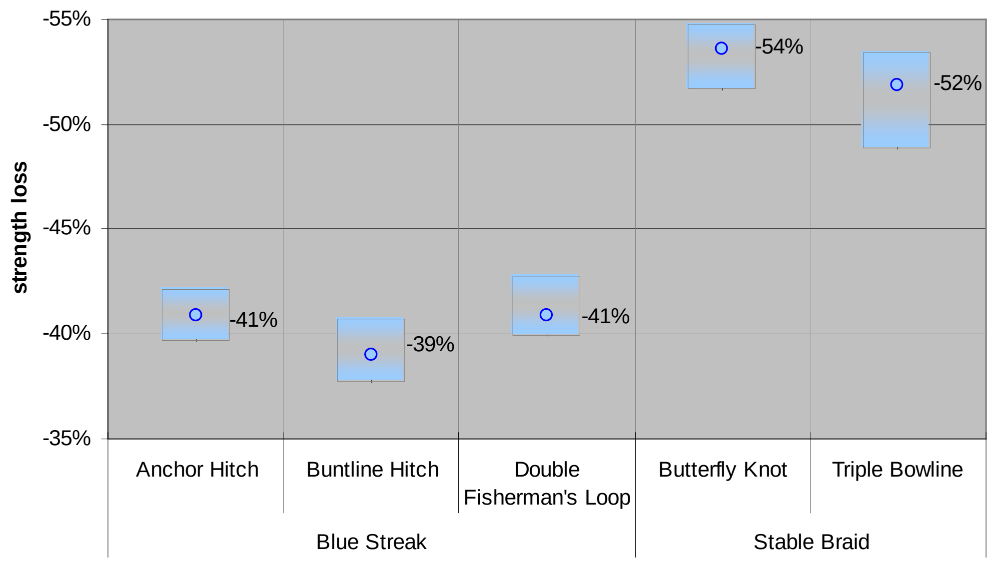

Figure 7.17 Strength loss in standard knots on 13 mm rigging lines

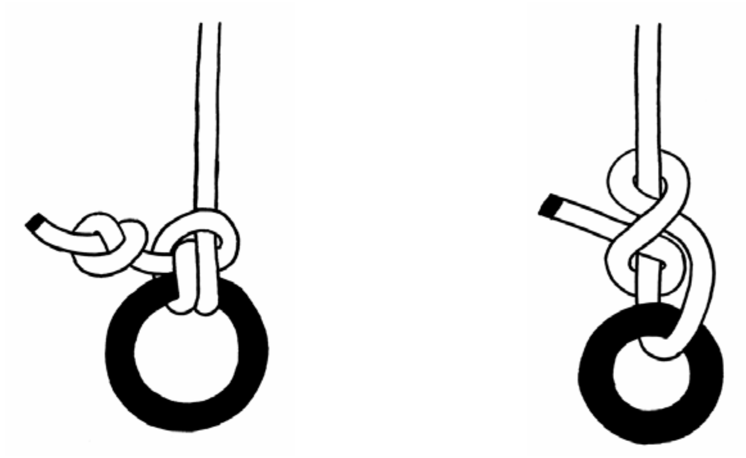

Figure 7.18 Anchor Hitch (left) and Buntline Hitch (right)[*]

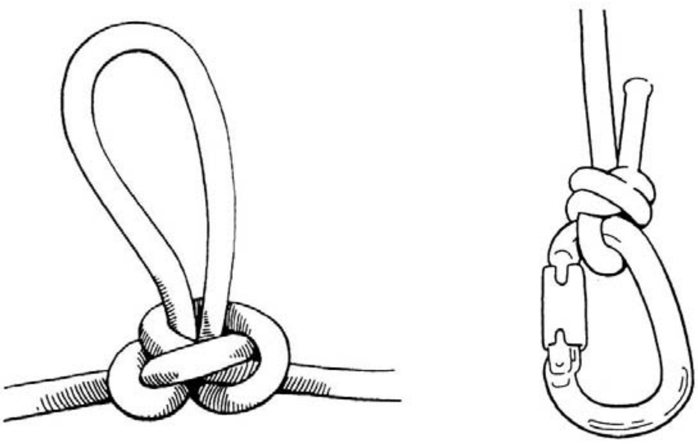

Figure 7.19 Butterfly Knot (left)[†] and Double Fisherman's Loop (right)[‡]

An overview of the statistical test data for knots in rigging lines is contained in Table 5 in Appendix 4. Table 7.7 summarises the percentage strength loss for each of the five knots tested.

Table 7.7 Strength loss in knots tied with a rigging rope

Knot	Anchor Hitch	Buntline Hitch	Butterfly Knot	Double Fisherman's Knot	Triple Bowline
Number of tests	3	3	3	3	3
Strength loss (min to max)	40% to 42%	38% to 41%	52% to 55%	40% to 43%	49% to 53%

[*] *Line drawings from Lingens, 2006, courtesy of Dirk Lingens, Kletterdienste, Germany*
[†] *Line drawing by B. Kotwica, reprinted from Jepson, 2000, courtesy of J. Jepson, USA*
[‡] *Line drawing by B. Kotwica from Donzelli, Lilly, 2001, courtesy of the International Society of Arboriculture, USA*

7.3 CHANGES IN BEARING CAPACITY ARISING FROM USE

7.3.1 Ageing, wear and tear

The Cordage Institute lists types and effects of damage on fibre rope (Cordage Institute 1994). External abrasion, heat generated from friction, cuts and pulled strands/yarn are more or less obvious signs of wear that alter the strength of rope. Dirt and grit may also affect the load-bearing capacity, as they generate internal abrasion. Additionally, temperature, moisture and the use of detergents and softeners are reported to change stiffness and strength parameters:

> *"Tests by Smikmator (1986) and Kipp (1979) clearly show that old rope is stiffer and produces higher loads than a new rope subject to the same fall. Testing by Stibranyi (1986) on Czechoslovakian climbing ropes produced the opposite results. Theory would tend to support the former conclusions, though. Testing by the German Alpine Club (Microys, 1977) showed a significant increase in stiffness of new climbing ropes that were cold and wet.*
>
> *"Tests conducted in a study by Smith (1988) indicate that treatment with concentrated fabric softener reduced the strength of a new rope. Frank (1989) showed that certain ropes treated with dilute softener (per manufacturer's recommendations) were stronger than the same rope without softening, after ageing and washing. Frank reported that the likely mechanism at work explaining these results is that the fibre lubricants contained in new rope are lost with age, allowing the fibres to cut one another. Fabric softener replaces some of the lubricants. Excess softening leaves the rope effectively wet, with the corresponding loss in strength.*
>
> *"With this mechanism in mind, a further argument for treatment with fabric softener would be its effect on spring rate. Since a rope's spring rate is determined by both nylon material properties and fibre weave, it is likely that fabric softener will help prevent stiffening, due to loss of internal lubrication. In dynamic situations, the underlying physics shows that preserving the spring rate is as important as preserving its strength, toward the goal of avoiding rope breakage" (Storage et al 1990).*

Heat caused by friction will rapidly alter the properties of fibres. The melting point of a particular material does not give a reliable indication as to what temperatures can be safely tolerated. Damage will occur well before the melting point (Parrino 2005), and be indicated by glossy or glazed marks, or streaks (often stiffer than the undamaged rope), and melting or bonding of fibres (*cf* Blair 1999, Cordage Institute International Guideline CI 2001-04).

Due to the fact that ropes used in rigging operations are generally exposed to environmental influences and mechanical distortion, strength loss due to wear and other influences must be considered. Manufacturers, therefore, recommend the application of sufficient design factors, as reflected in guidelines produced, for example, by the Cordage Institute (1994). With regard to arborist operations, some authors propose increased safety factors to make up for the special features of environment and use. Blair (1999), for example, doubles the manufacturers' design factor of 5:1 when applied to arborist applications.

In general, ropes showing significant signs of wear should be taken out of service. The Guide to Good Climbing Practice (Arboricultural Association 2005) prescribes an inspection of ropes, prior to climbing, in order to detect cuts, frays, glazing, poor condition of eye splices, contamination and other defects. Similarly, the American ANSI Z 133.1 Safety Standard states:

> *"Arborists shall inspect climbing lines, worklines, lanyards, and other climbing equipment for damage, cuts, abrasion, and/or deterioration before each use and shall remove them from service if signs of excessive wear or damage are found" (ANSI Z133.1).*

Unfortunately, precise data on gradual strength loss of arborist rigging lines, due to increasing age, degrees of wear or damage to a particular extent, is not available at the present time. The only publication relating to used arborist climbing lines focuses on the friction coefficient, which was found to increase with wear (Kane 2007). In the present study, the residual strength of the lowering line was also measured, in order to determine strength loss (see 7.3.3).

When considering the use of webbing in arboricultural rigging, the potential for abrasion and other mechanical or chemical damage must also be taken into account:

> *"Looking at the data, the one thing that stands out as blindingly obvious is that webbing is awful! For a round rope, only a few fibers at a time are exposed to the rock edge, and the rope wears a few fibers at a time. For webbing, almost all the fibers are abraded on every cycle, and it fails very quickly" (Moyer 1999).*

Since cordage used in arboricultural rigging applications will usually be exposed to the effects of abrasion, cuts, weather, sunlight etc., rope should generally be preferred to webbing slings.

7.3.2 Cycling and fatigue

'Rope remembers' – this phrase expresses the fact that previous loading may reduce the tensile strength of any rope. The greater the cycled load, relative to the maximum tensile strength of unused rope, the greater the adverse effect on strength.

> *"Ropes that are cycled for long periods of time within a normal working load range will gradually lose strength. This loss of strength is accelerated, if the rope is unloaded to a slack condition or near zero tension between load cycles. The subsequent damage is commonly referred to as fatigue." (Cordage Institute International Guideline CI 2001-04).*

Blair 1999 (also Blair 2000) cites a publication by Samson Oceans Systems that illustrates the effect of repeated loading on the strength of a rope comparable to a 22 mm double-braid polyester line. It is unclear whether the load applied in the described tests was applied gradually, or as a dynamic load, such as would be generated from drops or lifts. The fact that data was derived from tables on winch line maintenance implies that the load was probably static rather than dynamic. Thus, if applied to rigging applications, these figures may only have relevance subject to the exercise of caution.

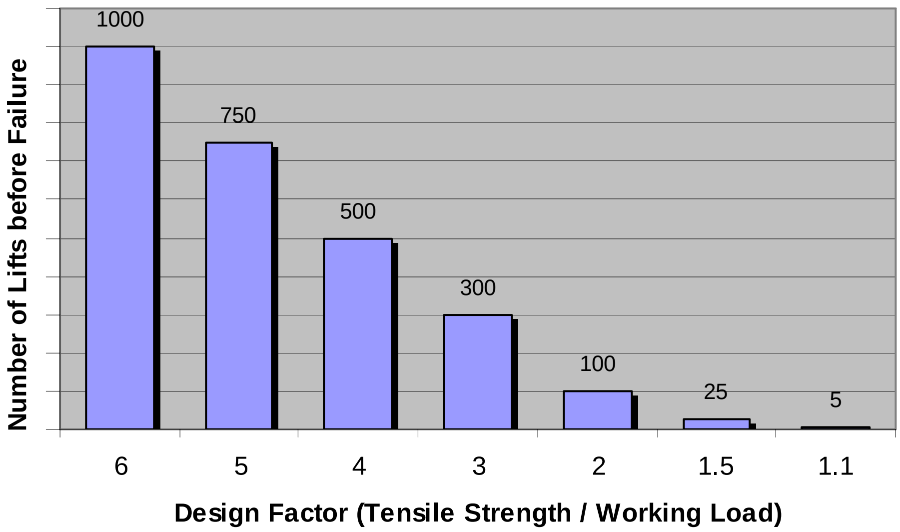

Figure 7.20 Cycles of failure (data taken from Blair 2000)

From data extracted from the Samson Catalogue, it becomes clear that previous loading also causes an increase in rope stiffness (also referred to as 'rope modulus' or as a rope's 'spring rate' in Storage *et al* 1990). Again, the design factor is decisive for the grade up to which the material properties change. Samson provides data on elastic elongation after 50 cycles, at loads equivalent to a proportion of the rated strength. The higher the cycled load, the greater the stiffness of the rope for most forms of rope construction. In Table 7.8, the values were derived from elastic elongation data in the Samson Rope Catalogue (Samson Rope 2005) and represent the dimensionless factor stiffness *vs* rated strength.

Table 7.8 Stiffness linear fit after 50 load cycles at % rated strength

Load (% rated strength)	Stiffness linear fit for rope type				
	Tenex-TEC	Stable Braid	Arbor-Plex	Pro-Master	Tree-Master
10%	7.1	9.1	3.3	5.0	3.4
20%	8.7	11.8	6.1	6.3	3.6
30%	10.0	11.1	7.1	7.7	3.7

In a series of tests carried out in 2002, in the course of developing the educational software Rigging 1.0, three different double-braided ropes were studied. Tests were carried out at Samson Rope Technologies, USA, and by Brudi & Partner TreeConsult at the test lab of Edelmann & Ridder, Germany. The ropes were cycled to a specified proportion of their rated strength, without allowing time for hysteresis recovery (as mandatory in technical standards like EN 892). The applied load was recorded against the resulting elongation, and figures for stiffness were derived as the best linear fit to the curve ($R^2 > 0.98$).

Table 7.9 Stiffness linear fit after load cycles in double-braid ropes

	Stiffness linear fit after load cycles			
Rope type	1st load	10 load cycles at 10:1 (10%)	10 load cycles at 5:1 (20%)	10 load cycles at 2:1 (50%)
13 mm Samson	218.11 kN	-	334.09 kN	429.63 kN
14 mm Buccaneer	324.43 kN	341.54 kN	364.11 kN	448.43 kN
19 mm Samson	420.88 kN	-	621.73 kN	663.66 kN

The stiffening of a rope results in greater peak forces under dynamic loading. Therefore, the more often a rope is exposed to loads, the more the peak forces will increase. Thus, the two effects described above interact when a rope is being used in real working situations. As a result, while peak forces increase with cycling, greater loads will reduce the prospective number of cycles to failure.

Similar effects were observed in tests carried out following the same protocol at Teufelberger, Austria, in 2007. Five different types of rope (double-braid and kernmantel, 12 to 14 mm in diameter) were subjected to 10 load cycles at 10% of their tensile strength. Other samples of the same ropes were then tested according to EN 2307, which prescribes three load cycles to 50% of the rated tensile strength. In the second set of tests, the rope modulus was significantly greater than in the first. The increases in stiffness ranged from 10% to more than 115% (in one case), averaging around 45%. These results seem to reflect a property of the elastic behaviour of ropes that engineers are aware of (T. Reuschel, pers. comm. 2007), but arborists often are not.

Further information could be obtained by studying the characteristic effects of repeated loading on arborist lowering ropes that have been frequently exposed to dynamic loads. Such studies could be implemented by requesting arborists to record the use of specific lowering lines, and testing the mechanical properties of these ropes (strength and stiffness) after a defined number of load cycles in practical arborist operations. However, if tests of this nature are carried out, it will be necessary to take account of the degradation due to wear and tear, which will distort the influence of cycling.

7.3.3 Shock loading

Dynamic loads that arise when a fall is stopped are often called 'shock loads'.

> *"Any sudden change in tension – from a state of relaxation or low load to one of high load – may also be described as shock-loading […]. Instantaneous changes in load up or down, in excess of 10 percent of the line's rated working load constitutes hazardous shock loads that would void normal working loads." (Blair 1999).*

The Cordage Institute defines shock loading as follows:

> *"A sudden application of force at such a rate of speed that the rope can be seen to react violently. The dynamic effects can be estimated to be well in excess of the WLL. Arresting a falling weight is the most common example." (Cordage Institute International Guideline CI 2001-04).*

According to the latter publication, shock loading may cause internal melting of fibres. In dismantling operations, severe shock loading can be experienced, especially when falling logs are not gradually decelerated. Changes in tension can be applied suddenly and at a level that far exceeds 10% of the Working Load Limit of the ropes (*cf* Chapter 8 on the kinematics of rigging operations).

> *"The working load ratings listed contain provision for very modest dynamic loads. This means, however, that when the working load has been used to select a rope, the load must be handled slowly and smoothly to minimise effect and avoid exceeding provision for them." (Yale Cordage Arborist Division).*

When choosing a lowering rope, allowances should be made for the effect that previous shock loads have on the stiffness and strength of the lowering line. However, so far no data is available on the strength reduction of arborist ropes due to shock loading.

> *"Overloading or shock loading a rope above a reasonable working load limit can cause significant loss of strength and/or durability. However, the damage may not be detectable by visual or tactile inspection. The usage history of a rope is the best method to determine if excessive tension or shock loading has occurred." (Cordage Institute International Guideline CI 2001-04).*

Repeated overloading, or shock loading, may result in visible damage similar to that caused by fatigue (cyclic tension wear). Signs of such damage may be:

- breakdown of yarns in the outer braid of a double-braided rope.
- internal compaction of broken fibres, causing rope to become extremely hard.
- many broken filaments at the crossover points of strands in the braid, caused by fibre-on-fibre abrasion.
- fuzzy appearance on the outside, over the entire length subjected to loading, that may even obscure the underlying braid structure.

- for braided ropes, broken filaments within the rope can also mat, entangle and/or leave a powdery residue.
- melted fibre and fusion may be observed in the core of the rope, or between core and cover (according to Cordage Institute International Guideline CI 2001-04).

In the course of both this project and the earlier pilot study, two ropes of the same type (14 mm double-braid Buccaneer Bullrope) were tested, after being used for drop tests. The extent to which they were exposed to shock loads was recorded in the course of the tests.

The first rope was subjected to five drop tests with logs of approximately 65 kg mass, each generating a peak force ranging from 4 to 6 kN. The second rope was shock loaded 21 times with forces between 6.7 and 13.7 kN by snubbing-off sections of 135 to 340 kg. Between each drop test, the rope was allowed to recover for at least one hour, often much more.

After the drop tests, the ropes were tested, at Edelmann & Ridder, Germany, for stiffness and tensile strength at both ends. In the case of the second rope, the middle section, that had not been shock loaded at all, was tested as a control specimen. The rated tensile strength of 55 kN had been significantly reduced to roughly 40 kN on all samples i.e. the rope had undergone a strength loss of approximately 25%. Surprisingly, the unloaded middle part showed the same strength loss as the rope ends.

This alteration in strength, occurring after a rather small extent of shock loading, was, in most cases, within the recommended Working Load Limit, and, with little to moderate wear, does not exceed the strength loss expected from ropes when exposed to a rough environment, abrasion and loading. A technical engineer at Edelmann & Ridder stated that a strength loss of 10 to 20% may very well occur within the first period of using a rope (Reuschel, Th., pers. comm. 2007). This is accounted for by applying a design factor when deriving safe working loads.

Stiffness was only slightly increased in the used ends of the second rope, and had decreased in the first rope to roughly 75% of a representative figure (new rope cycled 10 times to 20% of the rated strength). Drop tests with a weight of 55kg mass were carried out to compare the peak forces generated in rope previously exposed to shock loads, with forces generated in a new rope sample. The distance of fall was chosen at 2 m on a 3 m length of rope. Drops were repeated 6 times on the second rope and on new rope (control).

The first peak force generated reached approximately 10 kN within 1/15th of a second (0.065 sec) and was 5% lower in the new rope, presumably due to the effect of constructional deformation and the setting of strands. The second drop immediately increased the peak forces to about 12 kN. No significant difference was found between the used ropes and the new sample. The maximum peak force was recorded in the sixth drop at about 13 kN, with only small incremental increases in the last three drops. These results may indicate that the dynamic characteristics of the double-braid rope had not been altered by the amount of shock loading it had been exposed to during the field tests.

The same effect (of peak forces initially increasing, then becoming more or less constant) was observed in drop tests carried out by the authors at Edelmann & Ridder, Germany, in 2003. In these tests, which utilised a similar fall arrest scenario, peak forces increased during the first load cycles but remained more or less constant after 5 to 7 drops. When the same test procedures were later applied to both kernmantel and high-strength rope (Vectran), at Teufelberger Seile, Austria, in 2007, the same behaviour was observed.

Drop test on double-braid ropes

The line was attached to the test rig by an Overhand knot on the bight. Failure did not occur, so strength reduction did not play a role.

Slippage in the knot may have occurred in the first drop test as the knot set. Subsequently, after the first test run, the knots were set hard and could not be opened. Friction or abrasion damage on the rope, that would have indicated significant rope slippage, were not detected at the entrance to the knots.

Eventually, shock loading will speed up the decline of a rope's strength more than loads generated by lifting and winching operations, which avoid the abrupt changes in tension that are typical for dynamic shock loads (Lilly, 2005). In operations that involve fall arrest, failure under shock loading may occur after relatively few load cycles. In a test carried out at Teufelberger, Austria, a 14 mm kernmantel rope (48 kN tensile strength) failed after 14 impact load cycles that generated forces of less than 40% of its rated strength (design factor 2.5). As shown in Figure 7.20, some ropes would have been able to sustain more than 100 load cycles when lifting at the same load level.

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The number of cycles to failure under shock loading may also be affected by the fall factor, the mass of the falling object and other parameters that have not been considered here. Although the study of such factors was beyond the scope of the present research, this is an issue that may be worth exploring in the future. In any further investigation, it would be important to determine the change in mechanical properties of arborist lowering ropes, after they have been exposed to shock loads in real rigging scenarios. Recommendations might then be developed, on a reliable basis, on how far to downgrade the working load limit of a rope that has undergone shock loading during dismantling operations, and on when to remove the rope from service.

7.3.4 Rope bend ratio

When rope passes over an object (e.g. a branch or a pulley) the bend generated in the rope will result in uneven loading of the threads of the rope. The fibres on the inside of the bend will be compressed, and therefore they cannot participate in carrying the load in the same way as they would if the rope were straight. As a result, the load must be carried by fewer fibres (in simple terms, those on the outside of the bend only), which increases the relative stress on those fibres, and may result in failure at loads far below the rope's rated tensile strength.

> *"Working rope over too small a sheave or tying off to an undersized bollard, for example, can cause both internal and external fibre fatigue and abrasion, creating potential for failure." (Blair, 1999)*

The smaller the diameter of the object, the more unevenly are the stresses distributed in the rope. Therefore, a suitable measure for this effect on rope strength is the 'bend ratio', which is defined as the diameter of the object *vs* the diameter of the rope. Donzelli, Lilly (2001) recommend a ratio of 4:1, as a rule of thumb, for the diameter of sheaves and bollards, and rate the strength loss in such a configuration at 15% of the tensile strength. If the recommended ratio of 4:1 cannot be achieved, allowances should be made for greater strength loss due to a smaller bend ratio. The Cordage Institute (1994) recommends a downgrading of the 'working load limit' of a rope where bend ratios of less than 3:1 are involved.

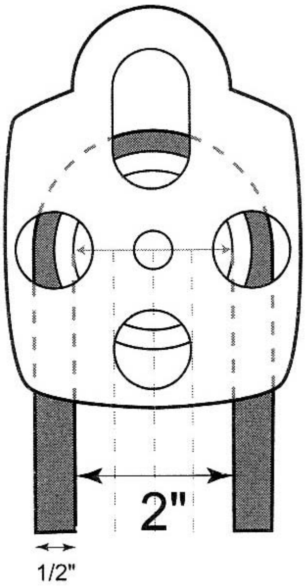


Figure 7.21 Bend ratio in a pulley*

7.3.5 Rope and sling angle

When ropes or slings are attached to an object and not loaded directly in line, but at an angle, their load-bearing capacities will be reduced. Strictly speaking, sling angles do not alter the strength of cordage, but lead to an increase in the tension applied to it, which in turn can lead to failure at lower loads. In a similar way to that in which blocks and pulleys share a load, the angles involved are the main determinants of the forces generated.

This subject has been covered in manuals and user instructions for workers in industry (e.g. as described in ANSI B30.9) as well as in catalogues, handbooks and other literature designated specifically for arborists. A formula for determining the stresses and force magnifications during lifts, when using slings attached to an object, is contained in Herkommer (2006). Blair (1999) provides two illustrations demonstrating these effects, one of which is concerned with lifting an object in configurations similar to cradle-rigging scenarios (see Figure 7.22).

As long as the two legs of a line run more or less parallel to each other, they will share the load equally. That is the basic principal of mechanical advantage, where each leg of the line at the running block (or pulley) carries half the load – which is why it can be lifted with a force equivalent to half the load (assuming friction is neglected).

* *Reprinted from Donzelli, Lilly 2001, courtesy of the International Society of Arboriculture, USA*

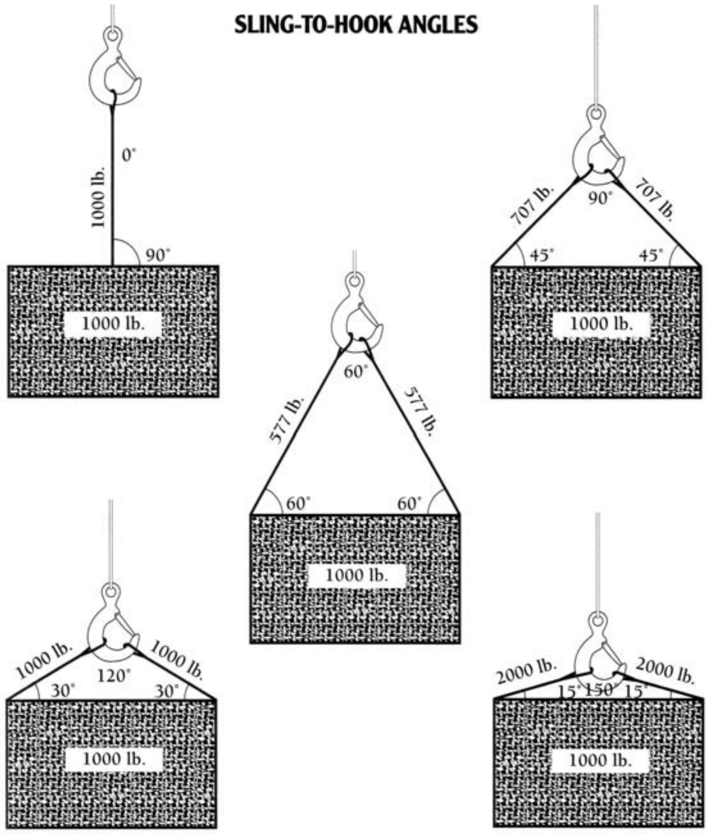


Figure 7.22 Sling angles*

Increasing the angles will result in greater tension in the line (see Figure 7.22). At an angle of 120° between the two legs of the line, the force in each of the two legs is equal to the weight being lifted (Figure 7.22, bottom left). Any further increase in the angle will actually magnify the forces in the line beyond the weight to be lifted. The greater the angle between the two legs of a line from which an object is suspended, the more rapidly will the tension in the lines increase with further increases in angle. Due to this effect, taut lines may break when comparably small loads are suspended from them.

Table 7.10 Force magnification due to sling and rope angles

Sling/rope angle (equally loaded)	**0° (parallel)**	**30°**	**60°**	**90°**	**120°**	**150°**	**160°**	**170°**
Force factor for tension in each leg	0.500	0.518	0.577	0.707	1.000	1.931	2.879	5.737

If two slings are being used to lift a load, and if both slings are equal in length, the force magnification is equivalent to that for forces in a line where the load is being applied through a running block or pulley. However, if slings of different length are being used, the calculation is more complex (see Figure 7.23 overleaf).

* *From Blair (1999), courtesy of D. Blair and the International Society of Arboriculture, USA*

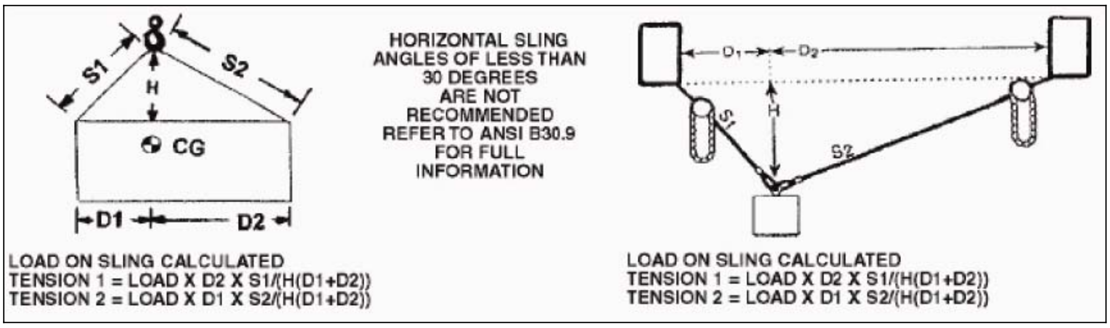


Figure 7.23 Tension in slings of unequal length*

Due to the often unexpected effects of magnified tensions in taut lines, and in lines that share a load, sling and rope angles must be considered when determining a suitable strength for cordage used in rigging. Especially in speedline, driftline or cradle scenarios, there is a good chance that arborists will underestimate the loads that cordage will be exposed to. At the same time, those forces will also be acting on the anchor points chosen for a specific rigging setup, and may sometimes have a great lateral component. Therefore, a proper analysis of the mechanics and dynamics involved in more complex rigging scenarios is essential.

* *From The Crosby Group, 2006*

8 FORCES GENERATED IN RIGGING OPERATIONS

If arborists could estimate the peak loads generated in rigging operations in worst-case scenarios, rope failure and other potentially catastrophic consequences might be avoided. As in any other engineering approach to safety, when assessing safety factors for a rigging system, the load is one of the major factors to be considered. Even if the rope does not break, it could be essential to detect when safe working loads are exceeded. Due to permanent elongation of synthetic fibres, the number of load cycles to failure will decrease significantly where ropes are constantly being overloaded (*cf* Chapter 7). Metal is less prone to fatigue failure than cordage, and deformation is often easy to detect long before fracture occurs. Even so, if loads cannot be assessed precisely enough, it will not be possible to determine when the safe working load limit of rigging equipment has been exceeded.

The mechanical properties of ropes and slings, rigging blocks and friction devices (as well as the stem of the tree), may have a considerable influence on the dynamic process of rigging. Their flexibility determines the peak force generated. Their load-bearing capacity under shock loading is a measure of the maximum load the rigging should be exposed to, in order to avoid failure of any part of the equipment and to prevent rapid fatigue of cordage. Last but not least, the tree is also part of the rigging system. Its participation in dissipating energy and damping shock loads has not yet been investigated.

Three basic questions need to be answered when attempting to gain more information about forces generated in rigging and dismantling operations:

1. What are the actual movements of log, rigging and stem, that take place when a log breaks off from the hinge and subsequently falls onto a rope?
2. How is the energy dissipated in the rigging system, and by what means and to what degree do the different components absorb the energy?
3. What are the peak forces and maximum deformations that components must bear, and what factors of safety are required to allow for safe working?

Furthermore, the effects on the climber during a rigging operation, and his reactions to the movements and forces, need to be investigated.

8.1 SOURCES IN LITERATURE

8.1.1 Engineering principles in rigging

The mechanics behind rigging operations are not fully understood and have only partially been described. A first attempt to apply simple mechanics to arboricultural operations dates back to 1989 (Redden *et al).* The author described forces and moments generated by climbing and dismantling operations, and the presumed reactions of trees involved. The late Peter Donzelli successfully introduced engineering principles to tree care. In his publication (Donzelli 1998), he elaborated the reaction force on a tree stem as the log pivots over the hinge. He also described how the dynamic load-bearing capacity of equipment is related to its static strength. The next two paragraphs paraphrase and summarise Donzelli's explanations.

Force is defined as mass times acceleration. Under static conditions, i.e. when a mass is suspended from rigging and at rest, only acceleration due to gravity works on the log's mass and exerts a force in the line. Thus, the mass that can be supported is derived by dividing the tensile strength of the rope (a unit of force measured in kN) by the factor for acceleration due to gravity on earth (9.81 m/s²).

Under dynamic conditions, when a log is being stopped by a rigging line, for example, increasing acceleration works on the mass as it is brought to rest (the same acceleration we feel on our body when we hit the brakes in a car). Therefore, the rated strength has to be divided by the increased figure for acceleration, with the result that the mass the equipment can support under dynamic loading decreases significantly. This description is a simplification with regard to dynamic strength properties of materials, but it does provide a comprehensible picture of how acceleration is the clue to understanding the effects of dynamics on arborist safety.

Blair (1995) described the result of dynamic loads generated by a dropped log as dependent on:

> *"shock and energy absorbing properties of the rope involved, and the length of rope available to absorb the shock, as well as the obvious factors of the weight of the log and the distance of fall before it stops." (Blair 1995)*

The influence of the distance a log falls was described in detail in another of Peter Donzelli's publications (Donzelli 1999a). The significance of the position of the centre of gravity along the length of the log was pointed out. Contrary to common understanding, Donzelli showed that changing the point of attachment along the length of a log does not alter the distance of fall (unless the knot is placed above the log's centre of gravity).

Donzelli also investigated friction in several arborist blocks (Donzelli 1999b). Static friction coefficients were derived for lifting and lowering masses up to 200 kg. Chisholm (2000) analysed force magnification in pulleys and arborist blocks, and how forces could best be dissipated, along the axis of branches and stems, by choosing a suitable rigging set-up. In the present research, Peter Donzelli's results were used to modify Chisholm's account that neglects friction, and to determine how pulleys share loads in real rigging scenarios, where friction is actually a major factor.

In a series of articles that began in 2000 and were subsequently put into book form, Donzelli and his co-authors described what was called 'The Art and Science of Practical Rigging' (Donzelli, Lilly 2001). The energy transfers and kinematics of a worst-case rigging scenario, i.e. blocking a log on a vertical stem with the rigging point (arborist block) under the log, were explained by mechanical models. Also, some peak forces measured during drop tests were published to illustrate the advantage of letting the log run.

Further information on forces generated by rigging operations was contained in the last article of the series, published after Peter Donzelli's death (Donzelli 2000). Drop tests had been carried out in collaboration with ArborMaster Training Inc as part of a research project funded by the Tree Research and Education Endowment Fund (TREE Fund). Some of the measurements and findings were contained in this final article. Additional results and comparisons with the forces predicted by a simplified mechanical model had already been listed on a poster that was published in 1998 for the International Society of Arboriculture (Donzelli *et al* 1998). The dataset showed strong deviations between the predicted forces and the actual measurements in the tests.

In the UK, Bavaresco (2001a) compared traditional methods of rigging and modern techniques as described in Blair (1995) and Donzelli's work. The author listed factors of safety, as recommended in these publications, by rope and hardware manufacturer.

8.1.2 Rigging Scenarios

There are many scenarios in rigging and dismantling of trees that could generate considerable forces. Dropping logs in a tensioned speedline, for example, may lead to failure of both rigging and anchoring trees, due to the great forces involved. This scenario was described as hazardous, already in Donzelli (2000), Donzelli *et al* (2001) and again by Bavaresco (2001). It would seem obvious, therefore, that this technique should be abandoned, due to the inevitable risk of causing severe damage and injury. For this reason, this scenario was not studied in greater detail.

However, speedlines may very well be used in situations where the load is rigged into a block first, and then attached to and slid down a tensioned speed-line. As to how much tension should be applied and where the maximum forces should be expected, there is little information available. It would be beyond the scope of this report to comprehensively study speed-line forces. Furthermore, if speed-lines are applied according to common practice (as described above), forces in the rigging will be significantly reduced, even though a great bending moment may work on the stem (*cf* strength of stems in speed-line scenarios in Chapter 5). An overview of what is known about forces in speed-lines is outlined in Section 8.7, sub-section 8.7.3.

The computer software Rigging 1.0 (see 8.1.4) lists five different rigging scenarios. For logs of a specific mass, the greatest amount of kinetic energy will be set free when ‘snatching’ a stem with the rigging point below the log (also referred to as topping-down, butt-hitching or pole-rigging). During such operations, the friction device may become locked and not let the log run (snubbing off). This could occur either intentionally (due to limited space below the rigging), or accidentally (if wraps on the friction device fall over each other, or if ground persons either overestimate the log’s weight or underestimate the friction generated by a number of wraps on a lowering device).

The fact that great forces are generated in this scenario, which therefore represents the worst case, is also reported by other authors (Donzelli 2000, Donzelli, Lilly 2001 and Bavaresco 2007). The deceleration of the log takes place abruptly and only a small part of the energy can be transformed directly via friction into heat (according to Donzelli, Lilly 2001). Therefore, the rigging, the tree, and, last but not least, the climber, are all exposed to great forces. The following paragraphs focus on this rigging scenario, while others are mentioned only briefly, either by way of comparison, or to describe particular effects that can help to minimise the forces generated.

8.1.3 Assessing peak forces

To date, only a few rules of thumb for assessing peak forces generated by rigging operations have been made widely known and/or published by practical arborists. These tend to mirror the experience gained from a great number of rigging operations, and their application does not generally seem to pose any risks for standard dismantling operations. However, their validity could be compromised when applied to certain situations, including working with heavy sections and/or limited rope length. In such circumstances, they might not appropriately accommodate a worst-case scenario in which a section has to be blocked and cannot be gradually decelerated.

The peak force is usually assumed to be a fixed multiple of the log’s weight. This would presume a linear relationship between mass and peak force. One rather widely-held belief, for example, is that the peak force could reach about 10-times the log’s weight in a snubbing off operation (as compared to the log being gradually lowered by a running rope). According to some opinions, even a magnification factor of 20 is to be expected for forces generated by a log fall arrest in a topping-down scenario.

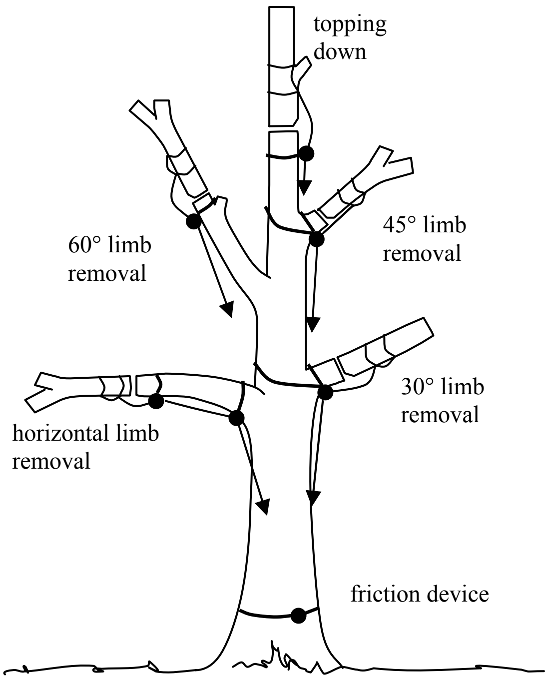


Figure 8.1 Rigging scenarios, modified from Rigging 1.0

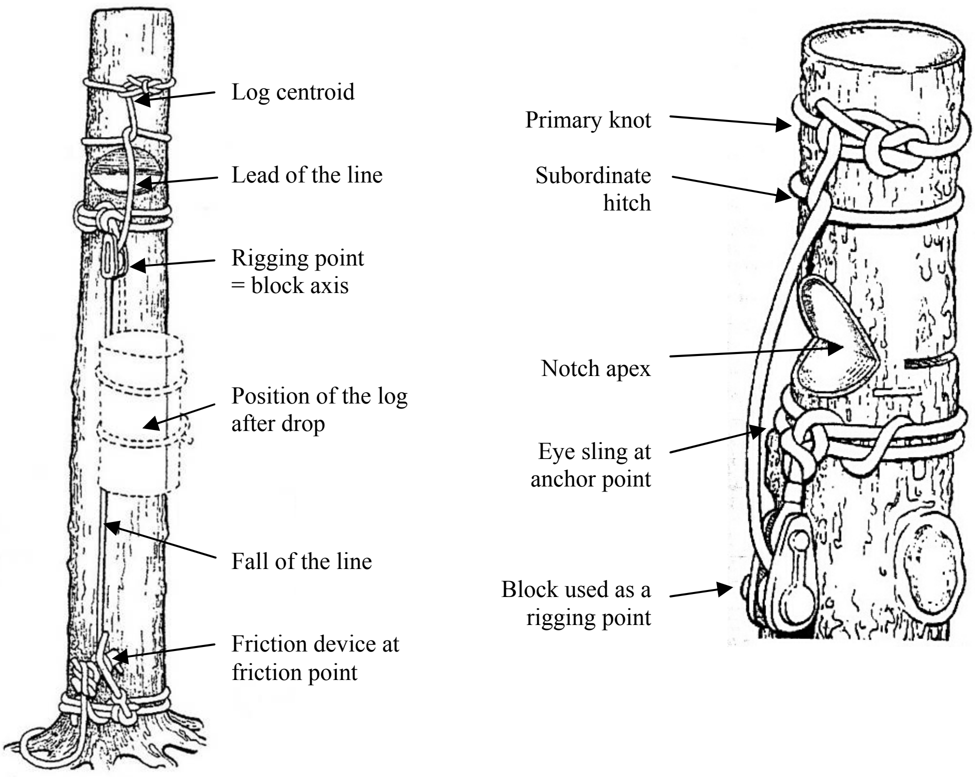


Figure 8.2 Topping down: rigging set-up and terms*

* *Drawings by B. Kotwica, reprinted from Donzelli, 2000 and Donzelli, Lilly 2001, courtesy of International Society of Arboriculture, Il, USA*

More recently, the study guide of Münchner Baumkletterschule (a German arborist school) advises applying a linear safety factor to rigging operations (Schütte *et al* 2007). The authors recommend that a force magnification factor of 5 should be applied, in addition to the standard design factor for ropes (usually 5:1, i.e. a working load limit 20% of tensile strength) and an assumed strength reduction for rope of 50% due to knots. The factor of 5 was proposed to take into account the building up of peak forces during a lowering operation. It was derived from drop tests carried out by Dirk Lingens, Kletterdienste, Germany and also from tests to determine the forces built up by a single climber on an access rope as he jerks the line when ascending (pers. comm. Bernhard Schütte, 2007).

Blair (1995) used a method of assessing dynamic forces resulting from a mass being suddenly stopped by rigging, in relation to short fall distances. He subsequently explained that the peak force is not a linear function of the weight, but depends on the distance of fall:

> *"A rough rule of thumb that probably does more good than harm is: For every foot a falling object falls it gains a unit of weight plus one.*
>
> > *EXAMPLE: 500 pounds falling four feet will hit the rigging at about 2,500 pounds." (Blair 1995)*

The origin of this rule is not stated, and Blair warns that it does not mirror the actual physics equations that are required to assess peak loads. It is also unclear from what point the distance of fall is to be measured. In physics, the fall distance always starts at the initial position of the log's centroid (centre of gravity) before the fall, and extends to its lowest position in the course of the fall (Donzelli 1999a). This fall distance includes elongation in the length of rope, and slippage in the slings that provide anchor points for both the block at the top of the stem and the friction device at its base. This actual fall distance cannot be determined prior to an operation.

Blair's rule was quoted in a recent publication and used to confirm another rule of thumb called 'Rule of Thumb for Riggers' (Bavaresco 2007). Uncertainty about how to measure distance of fall may have led to the assumption that a log of four feet in length would fall a distance of four feet, thus generating a peak force five times its weight (according to Blair's rule of thumb). This may be an underestimation, as the distance, from the initial position of the centroid to its position after the fall, is likely to be significantly greater than the length of a typical log. The distance from the cut to the axis of the block adds twice to the fall distance, extending it another two feet approximately in a standard set-up. Furthermore, stretch in the rigging accounts for at least another foot length when standard rigging slings and ropes are being used. Thus, the actual length the 4 ft log falls could be as much as seven feet.

However, this rule of thumb incorporates more parameters than any of the previously mentioned rules. As it refers to a standard log length (1.2 m) and specific rope length (12 m), two factors are being taken into account that are in fact essential for assessing the peak force generated. With regard to the diameter of a section, it recommends using a certain diameter of double braid rope, namely the same diameter in mm as is the bar length (measured in inches) required to cut the log. As log weight increases with the square of the diameter (*cf* Chapter 6), the tensile strength of rope also increases with greater diameters.

The limitations of such rules of thumb become obvious when they are applied to safety assessments in scenarios that do not necessarily match those from which the rules were derived. Shock loading may result in greater force magnification than letting a log run. Stronger rope will have greater stiffness, and its use will increase peak forces when a log is snatched (i.e. not slowly decelerated). Shorter rope length, as the stem is topped down, may also result in greater peak forces if it is not compensated for by shorter sections. At the same time, a short, thick stem will damp the peak force less than a high, slender one.

Advice on how to adapt any of the above-mentioned rules of thumb to a specific rigging scenario is not provided, which would seem to imply an assumption that they fit a wide range of situations. This is certainly not the case, because the underlying mechanics are far too complicated to be summed up in a simple rule of thumb, that errs on the side of caution yet still allows for cutting practicable sizes of wood. There are many parameters that cannot even be determined by arborists in the field (e.g. rope stiffness or a tree's damping effect), but which significantly affect the magnitude of forces during rigging operations.

8.1.4 Mechanical models for rigging operations

Educational software developed by Brudi & Partner TreeConsult, in cooperation with ArborMaster Training Inc, USA, allows arborists to input parameters that are determinable and adjustable in a specific rigging scenario. Rigging 1.0 (see Figure 8.3) can then show the effects on the peak force in a worst-case scenario that result from making changes to the following four parameters:

- log weight
- rope length
- rope types of various stiffness
- distance of fall

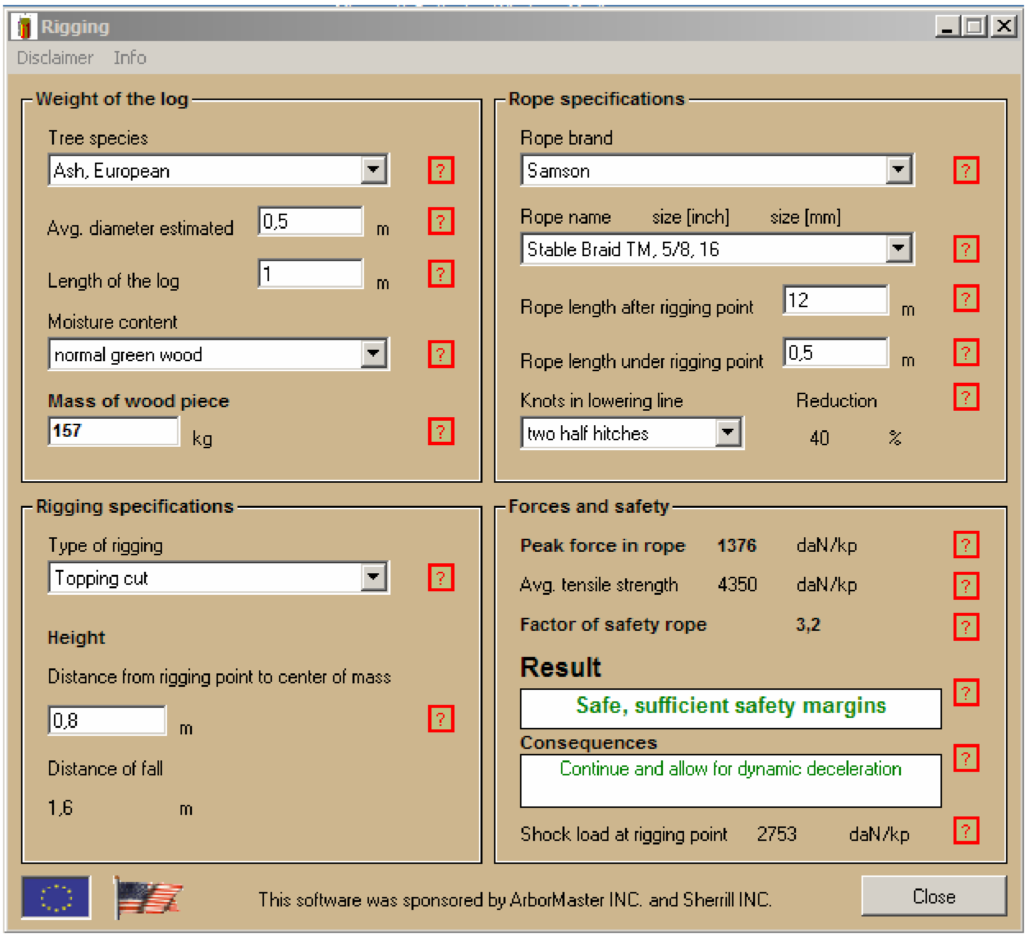


Figure 8.3 Rigging 1.0

The mechanical model behind the calculations in Rigging 1.0 is the same as that used by Peter Donzelli to estimate line forces in his research. The basic assumption is a full energy transfer into the rope. As the log falls from its initial position, until it begins to be slowed down, its potential energy is transformed into kinetic energy (speed). As the log is being stopped by the rope, this model assumes that the full amount of potential energy is being transferred into, and stored in the rope in the form of, strain energy (Donzelli 2000). Therefore, the energy transfer in this simplified model can be expressed by the assumptions made in the following equations:

$$E_{pot} = E_{elastic} \qquad \text{equation 8.1}$$

$$m \times g \times (h + \Delta L_{\max}) = \frac{1}{2} \times F_{peak} \times \Delta L_{\max} \qquad \text{equation 8.2}$$

where

E_{pot}	potential energy of the log
$E_{elastic}$	strain energy stored in the line when stretched
m	mass of the log being lowered
g	acceleration due to gravity
h	distance of fall without rope stretch
ΔL_{max}	maximum stretch in the rope
F_{peak}	peak force occurring when the log is being stopped by the rope

As stretch in a rope is a linear function of the force applied (as long as the rope is not loaded beyond the elastic range), the force F can be expressed via the relation defining rope stiffness:

$$F = M \times \varepsilon = M \times \frac{\Delta L}{L}$$

$$\Delta L = \frac{F \times L}{M} \qquad \text{equation 8.3}$$

where

F	force applied to stretch the rope
M	rope modulus (also called rope stiffness)
ε	elongation in % of initial rope length
ΔL	rope stretch
L	initial rope length

Inserting equation 8.3 in equation 8.2 and solving for F_{peak} renders

$$F_{peak} = m \times g \times \left(1 + \sqrt{1 + \frac{2 \times M \times h}{m \times g \times L}}\right) \qquad \text{equation 8.4}$$

In both Peter Donzelli's work and Rigging 1.0, the fact that rope stretch adds to the distance of fall was neglected. Therefore, peak forces are predicted from the less complex equation 8.5 that gives lower results than equation 8.4:

$$F_{peak} = \sqrt{\frac{2 \times m \times g \times M \times h}{L}} \qquad \text{equation 8.5}$$

While these simplifications allow for an easy calculation of prospective peak forces, the model neglects a number of important factors. The stem, the anchor slings and the knots are all assumed to be absolutely static and not moving, when in fact they provide a certain amount of flexibility. Friction in the rigging system, slippage of rope and slings, and aerodynamic resistance during the fall, are all neglected, despite the fact that energy is dissipated by these effects. Also the tree, being more or less flexible depending on its slenderness, will damp the forces generated. Therefore, the calculations will always err on the side of caution.

Comparisons of peak forces calculated by Rigging 1.0 with loads measured in drop tests in a realistic rigging scenario, have shown that the load is overrated by a factor ranging from 2 to 3, when using the simple equation above. The same is true for comparisons of drop tests carried out by Donzelli *et al* (1998) when similar deviations were noted. Such considerable deviations can hardly be accounted for by the factors that are neglected in this simple energy transfer model (some of which are listed in the previous paragraph). Obviously, the mechanical model used by both Peter Donzelli and Rigging 1.0 does not sufficiently match the real kinematical process in rigging operations.

Evaluation of video footage of drop tests carried out by Peter Donzelli and ArborMaster Inc showed significant variations in motion and trajectory (flight path) of logs, as well as a different energy transfer to that presumed by the simple mechanical model. Therefore, Brudi & Partner TreeConsult carried out a pilot study in 2005 to record the kinematics of a standard rigging scenario, and to determine the peak forces and line angles under realistic conditions. Drop tests carried out in the course of the present study were also recorded on video, to enable kinematical studies of actual on-site rigging operations.

8.2 PRACTICAL STUDIES: MATERIAL AND METHODS

8.2.1 Laboratory studies

In February 2005, Brudi & Partner TreeConsult, with the support of Paul Howard and Oriol Campaña of ArBO Treecare, evaluated the simulation of a worst-case scenario in arboricultural rigging under laboratory conditions. Prof. Dr. Klaus Schneider, lecturer in Sports Science at the Universität der Bundeswehr (University of the Federal Army) in Neubiberg, provided the laboratory facilities and personnel required for determining the kinematics of topping down a vertical stem, which serves as a worst-case scenario for common rigging operations.

A 5.5 m long stem and several 2 m long logs were freshly cut from four approximately 40 year old Norway Spruce trees (*Picea abies*), that were felled on a forest site in Munich, three days prior to beginning the test series. The stem and the logs were of similar diameter, between 26 and 34 cm. Due to the below 0°C temperatures occurring at that time of the year, the wood was considered to be fresh at the time of testing.

The stem was set up in a vertical position, by attaching it to four wooden beams laid out on the floor (see illustrations overleaf). Custom-made U-shaped steel profiles were partially inserted in and bolted to the stem with four threaded steel rods. The steel bars were then screwed to T-profile steel legs and bends which provided attachment to the wooden beams. Thus, the stem was fixed in a steel-wood anchoring structure of up to 90 cm height above ground. Prior to the drop tests, the flexibility of the anchoring structure was tested in a load test.

The top of the stem was replaced after every drop test, in order to retain an unchanged section of wood for setting the notch and back cut. The top was cut off at 3.5 m height and a 2 m section of wood was fixed to the stem. The attachment was formed by inserting two U-shaped steel profiles into the wood of both the stem and the new section and bolting them with two threaded steel rods, to ensure a stiff connection.

Nine markers were placed on both the stem and the log, five on one side and four on the opposite side. These spherical reflecting markers could automatically be traced in video footage recorded by eight high speed cameras, in motion capture technique at a speed of 240 frames per second.

Base attachment of the stem

Attachment of a new top section

"Motion tracking or motion capture started as a photogrammetric analysis tool in biomechanics research in the 1970s and 1980s, and expanded into education, training, sports and recently computer animation for cinema and video games as the technology matured. A performer wears markers near each joint to identify the motion by the positions or angles between the markers. […] The motion capture computer software records the positions, angles, velocities, accelerations and impulses, providing an accurate digital representation of the motion. […]" (www.wikipedia.org)

A rigging system was set up to simulate a worst-case scenario: that of a log being snatched into the rigging line with the rigging point under the cut, and without letting the log run (snubbed off). A ‘port-a-wrap’ friction device was attached to the base of the trunk and a CMI arborist block was installed just below 4 m height, using a used 16 mm stable-braid eye-sling forming a Timber Hitch. The logs were cut at roughly 4 m height above ground, with lengths between 1.45 and 1.50 m. They were of regular, slightly tapered shape and had diameters between 27 and 29 cm at mid-length. Their masses ranged from 56 to 67 kg.

Two different notch types were used; a conventional notch and a Humbolt notch, both with 45° opening angles and a depth of one-third of the stem diameter. Angle and depth of the notch were kept constant by using a stencil made from rubber foam to mark its position on the bark, prior to making the cuts. The back cut was placed at about 1 to 1.5 cm above the apex of the notch. Its depth was kept constant, as much as possible, in order to produce comparable hinges.

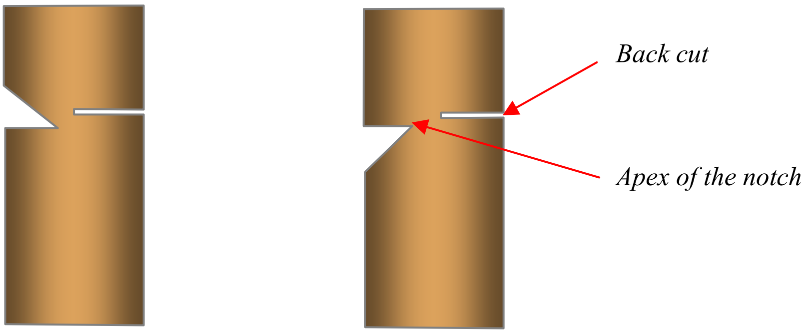
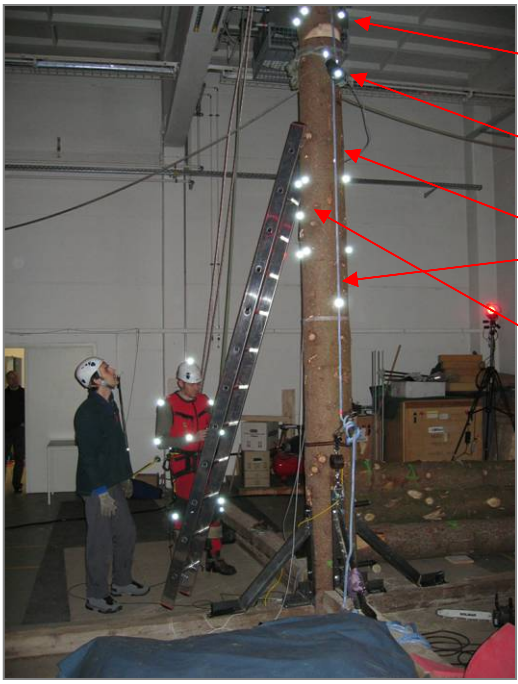


Figure 8.4 Conventional (left) and Humbolt notch 45°

Typical hinge, Humbolt notch

A new 14 mm double-braid rope (Buccaneer Bullrope) was pre-tensioned to its working load limit (10 kN), passed through the block and attached to the log, using a Half Hitch followed by a Timber Hitch as the primary knot. The rope was tensioned by hand, wrapped around the friction device and tied off. The two legs of the rigging rope were each marked with two markers and the distances between the two markers on each leg of the line were measured. The block axis was marked on both sides, and the eye-sling was marked at the exit of the Timber Hitch.



Markers:
- on the log

- at the rigging point

- in the standing part of the line (fall)

- on the stem

In the background:
- red LED light at one of the high-speed cameras

Markers on stem and rigging

A climber was equipped with markers on his joints and head to record his reaction to the forces and movements generated by the rigging operation. A 3D-acceleration sensor was placed on the back of his harness to record the change in momentum during the dismantling process, especially when the stem was being pulled forward by the log, and when it oscillated after being hit by the log.

Markers indicate the position of joints on the climber's body and enable the creation of a 'matchstick man' in the motion capture software.

The load cell placed under the friction device was mounted to a ring-nut on one of the through bolts.

Climber with markers

In order to precisely record the stem's reaction during the dismantling operation, high resolution strain gauges were placed on the stem. These devices were originally developed at the University of Stuttgart, and are used in Tree-Statics to determine structural defects in living trees by the application of the Elasto-Inclinomethod, also known as SIM or pulling test (*cf* Sinn, Wessolly 1989). The strain gauges record fibre elongation at a level of 1/1000 mm over the base length of 20 cm.

Inclinometers, also used in Tree-Statics, were placed at the base of the stem to reveal changes in inclination resulting not from bending, but from flexibility in the anchoring structure. These instruments can display inclinations to an accuracy of 0.01°. A load cell was placed under the friction device and attached to a ring-nut on one of the through-bolts. A CMI Arbor Pulley was equipped with DMS strain sensors, and calibrated in order to enable force measurements at the rigging point.

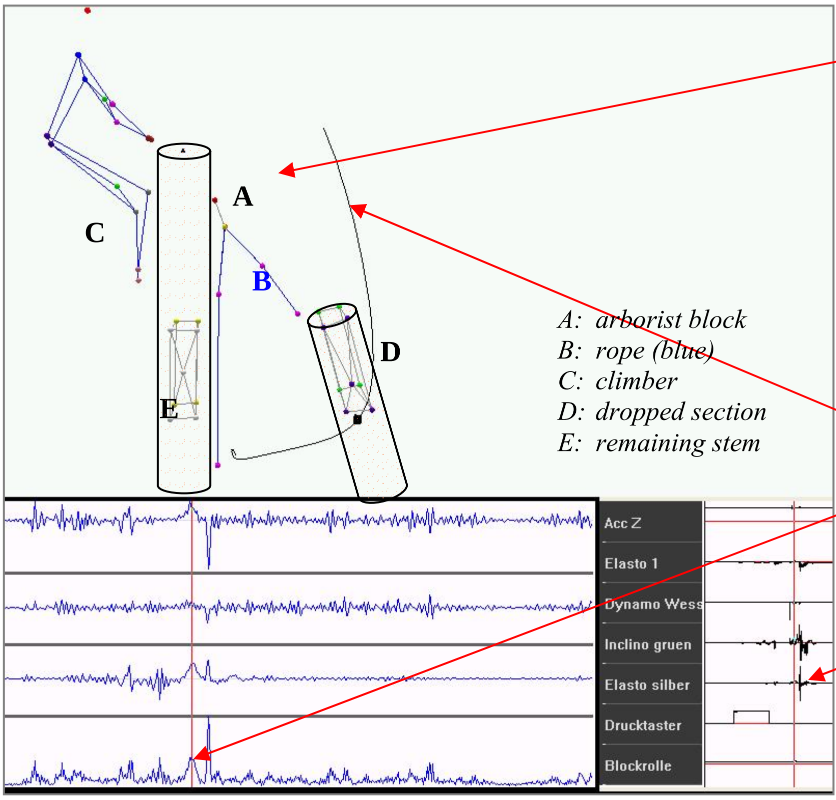
Two strain gauges (Elastometers) measure deformation of marginal fibres as the stem bends under load.

Two Inclinometers at the base of the trunk detect movements in the anchoring structure that the stem is mounted on.

Set up of Tree-Statics instruments

Data from the acceleration sensor, load sensors, strain gauges and clinometers were recorded at a speed of 960 samples per second, which was the maximum sampling rate of a 32-channel data logger that was triggered by the video and motion capture recording. The video camera system was calibrated using a one metre reference grid, in an automatic procedure provided by the evaluation software, until sufficient accuracy was reached.

The position of the centre of gravity of the log, and the height of the cut, were extrapolated from measurements taken on the log and the stem, based on the known position of the markers. They appear as 'virtual markers' in the software. The position, speed and acceleration of the markers were calculated using specialised software. Due to the large area covered by the dismantling operation being carried out, the differing perspectives from the 8 cameras resulted in small inconsistencies in the data points. Therefore, the dataset required the application of low pass filters of high order (of Butterworth characteristics) to smooth the movements**.** The positions and movements of the markers were successfully recorded in four separate drop tests.



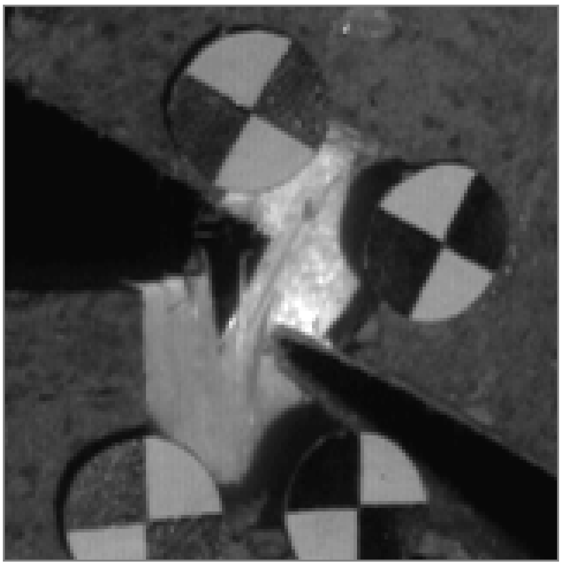
Motion of the dropped section, the remaining stem, the rope and the climber were recorded at a rate of 240 frames per second.

The centroid of the section followed a distinct trajectory (black curve). From the centroid's deceleration, forces acting on the log were derived.

The strain in marginal stem fibres was recorded with high resolution strain gauges.

Figure 8.5 Motion capture recording of topping-down a stem

In addition, two breaking hinges were filmed with a high speed digital camera at 2,500 frames per second, in order to study the effect of the closing notch and the breaking hinge on the log's rotation and trajectory. The logs were cut at lengths of one metre from the top of the trunk and were pulled over, using a line attached to the top of the log. They had diameters of 27.5 cm and were dumped on a cushion instead of being rigged. The video footage only shows a small section of the stem around the hinge, where four markers were placed to track the movement.



Still picture from high-speed video footage of breaking hinge of Spruce (Humbolt notch)

8.2.2 On-site drop tests

The experiments in the laboratory provided the basis for practical on-site tests carried out in the course of the present research. The fieldwork took place in August 2006 and February/March 2007 in Erding, Germany. Two Beech (*Fagus sylvatica*) and two Sycamore trees (*Acer pseudoplatanus*) were dismantled. Some of the trees had lost several branches during tests to determine branch strength (*cf* Chapter 5). The trees were provided courtesy of Deutsche Bundeswehr, Standortverwaltung Fliegerhorst Erding, and Staatliches Hochbauamt Freising.

The Beeches were between 60 and 65 years old, with a diameter of 52 and 62 cm at 1 m height, and were roughly 22 m high. The first Beech that was dismantled had two co-dominant stems, joined in a V-shaped crotch at approximately 5 m height. The second Beech had a single leader, but an asymmetric crown due to the vicinity of the dominant first Beech tree. Only the top section of the second tree was rigged in the course of the research. The Sycamores were about the same age, with diameters of roughly 80 cm at 1 m height, and were 18.5 and 24.5 m high. These trees were both multi-stemmed, each with two major codominant leaders. The main fork was at roughly 2.2 m in the first tree and at about 3.5 m in the second. Due to a lack of time, only one of the leaders in the second tree was dismantled during the test series.

Again, the worst-case scenario was studied. Standard sized logs and tops were cut with the rigging point below the cut (topping down). The lowering line was tied off at a bollard fixed to the base of the trunk. Tree-Statics instruments were set up at the stem to record the trees' reaction to loading: one inclinometer was placed at the base of the trunk, two Elastometers at the stem between 0.25 and 1.80 m height (*cf* 8.2.1). DMS strain gauges were mounted on an ISC arborist block (RP 051), and calibrated to facilitate the recording of forces generated at the rigging point. The signal was amplified using an HBM MC 55 amplifier. Data from the four instruments was logged, at a sampling rate of 2,400 samples per second, to a laptop, using a Dataq DI-158 data logger and WinDAQ data acquisition and evaluation software.

Since the pilot study had shown problems in achieving greater accuracy, even under laboratoy conditions, the drops in the field tests were recorded with one standard camcorder only. This was placed on an aerial platform, perpendicular to the plane of fall, roughly at the height of the block axis. To facilitate extraction of measurements from the video footage, a three dimensional calibration frame of known dimensions was set up in the direction of fall before each drop. Markers placed on the stem and the log enabled their positions and movements to be tracked.

The position of the hinge, the Half Hitch at the log and the axis of the block were all measured both before and after the rigging operation. The exact dimensions of the section (length and diameters), the distance of markers on the log, the position of its centre of gravity and its mass, were all measured after the log had been lowered. The log was either lifted using an aerial platform, or winched on a line suspended between two adjacent trees. The mass of the log was determined using a scale having an accuracy of 0.1 kg for logs up to 200 kg mass, or a dynamometer with a 2 kg resolution where larger logs exceeded this limit.

Fifteen logs and six top sections were snatched with the friction device locked (snubbed off). Two logs were let run to determine the minimum forces involved in regular rigging scenarios. Two top sections of co-dominants were rigged with the anchor point above the load, to derive additional information about other rigging scenarios. In the latter tests, the peak forces generated in lowering the sections were recorded by using the peak-hold function of a Dynafor 2.5 tons dynamometer. The instrument was placed between two Butterfly knots in the fall of the lowering line, just above the friction device. The rope between the knots was kept slack to divert the tension into the dynamometer. At the same time, the force on the arborist block was recorded but, unlike in the other drop tests, in this case the results were not studied in detail.

The video sequences recorded during the other 23 drop tests were evaluated using the 50 half-frames per second that the PAL system provides. For every 0.02 seconds, one picture was available at a resolution of 720 x 290 pixels. Specialised software (Utilius EasyInspect 2.01) was provided courtesy of Campus Computer Centre, Germany, for analysing positions of markers in the video footage, determining angles and distances, and depicting the motion of objects.

The trajectory of the log was tracked and the speed of the log's centre of gravity derived for a number of representative drop tests. The angle formed by the lowering line at the block and the speed of the log's rotation were determined. Furthermore, the stem's reaction and the effect on the climber were studied as shock loads from lowering operations occurred.

8.3 KINEMATICS OF BLOCKING WOOD ON A VERTICAL STEM

The kinematical studies were made comparatively, analogous to a qualitative investigation. Due to the variety of factors involved in a rigging operation, and the lack of knowledge of the mechanics involved, the study set out to provide a basic understanding of the process and to formulate hypotheses. Verification with statistically approved data was beyond its scope.

8.3.1 Trajectory of a section

The initial laboratory studies showed a distinct trajectory that was very similar for all four logs dropped in this test series. The log's centre of gravity follows a path resulting from increasing inclination (as the log pivots over the hinge), forward thrust and rotation (generated as the notch closes and the log jumps off the hinge) and acceleration due to gravity (causing a vertical fall). It should be noted that not all the parameters affecting the trajectory and the forces generated could be standardised. The aim of this part of the study was to gain qualitative data on the kinematics of rigging operations, rather than to quantify the forces involved. Due to the small sample size, the following results can only serve as an indication, or trend, and do not represent statistically approved data.

In Figure 8.6, the trajectories of the logs' centres of gravity have been normalised by adjusting the height of the notch apex to 4 m (on the vertical axis) and displaying the horizontal displacement on the other axis. The horizontal displacement was derived from the centroid's two horizontal coordinates using trigonometric calculations. The height was taken from the height data as recorded by the motion capture software, and corrected to match the standardised notch apex position of 4 m. The trajectories differ with regard to the notch form and the weight of the section.

When the Humbolt notch was used, the horizontal displacement was in both cases greater than with a conventional notch, although the increase was very small and may not be significant. Also, the total distance of fall was greater when the Humbolt notch was chosen. Distance of fall also varied with mass: for logs of greater mass it was considerably longer, although again, due to the low number of tests, this may eventually be found to be caused by other factors involved. For the logs of 1.5 m in length, the distance from the highest to the lowest position of the centre of gravity ranged from roughly 2.5 to 2.8 m. For the logs of 64 and 67 kg mass, the maximum distance of fall was 7 to 8% greater than for the logs of 56 and 58 kg mass.

The observation of differing trajectories, depending on the form of the notch, is also supported by the results of the high-speed video footage of the breaking hinges. With the conventional notch, the hinge seemed to hold longer and slowed down the log's rotation. The log received less forward thrust and rotated closer to the stem. In the case of the Humbolt notch, the log jumped off in a horizontal direction, at greater speed, after separating from the hinge.

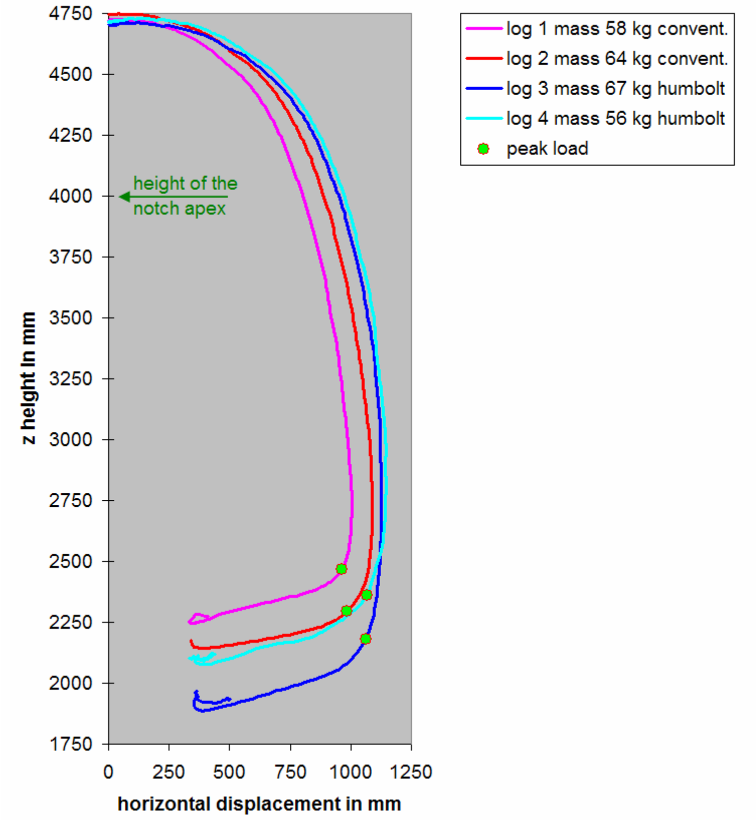
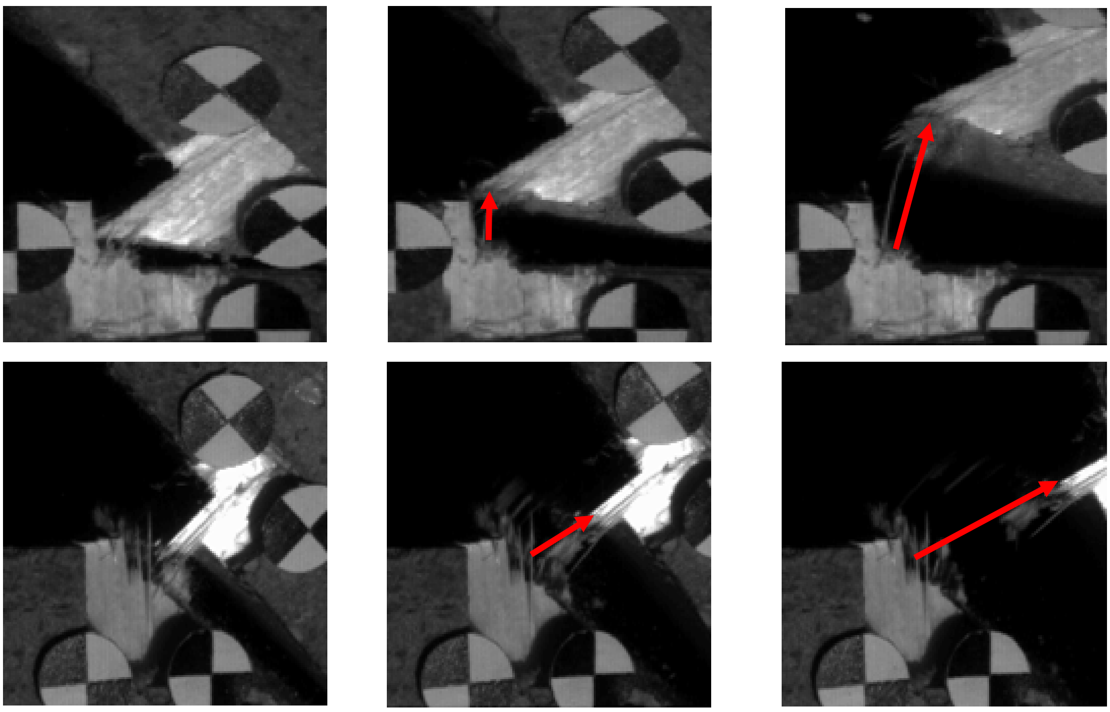


Figure 8.6 Trajectories of 4 logs from lab tests*



Top row: conventional notch 36, 72 and 120 ms after hinge fracture
Bottom row: Humbolt notch 36, 72 and 120 ms after hinge fracture†

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* *Illustration created from motion capture data, recorded and evaluated at Universität der Bundeswehr, Neubiberg, courtesy of Prof. Schneider*
† *High-speed video sequences filmed at Universität der Bundeswehr, Neubiberg, courtesy of Prof. Schneider*

The axis of the block moved down the trunk while the rope was gradually tensioned. Also, the stem bent under full load, and then swung back over the point of zero displacement as the log moved beyond the point where the peak force was generated. The speed of fall was greatest just before the rope stopped the log's fall, and was not significantly reduced when the block was pulled down.

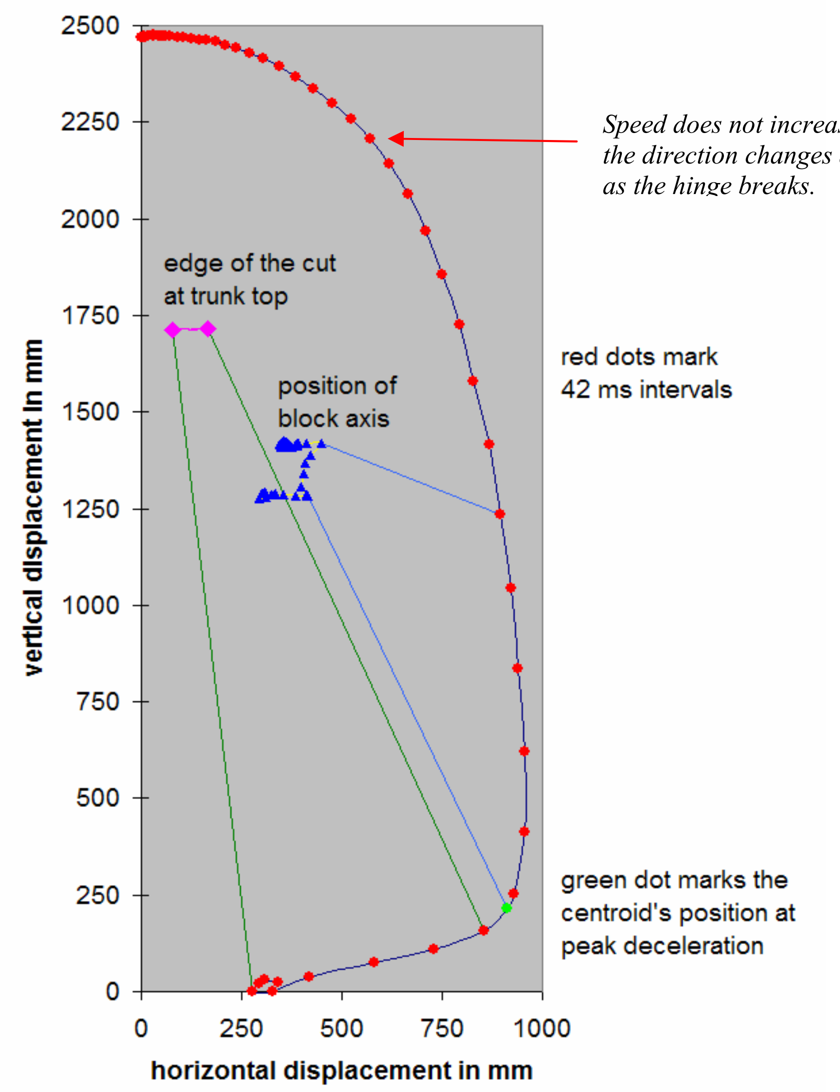
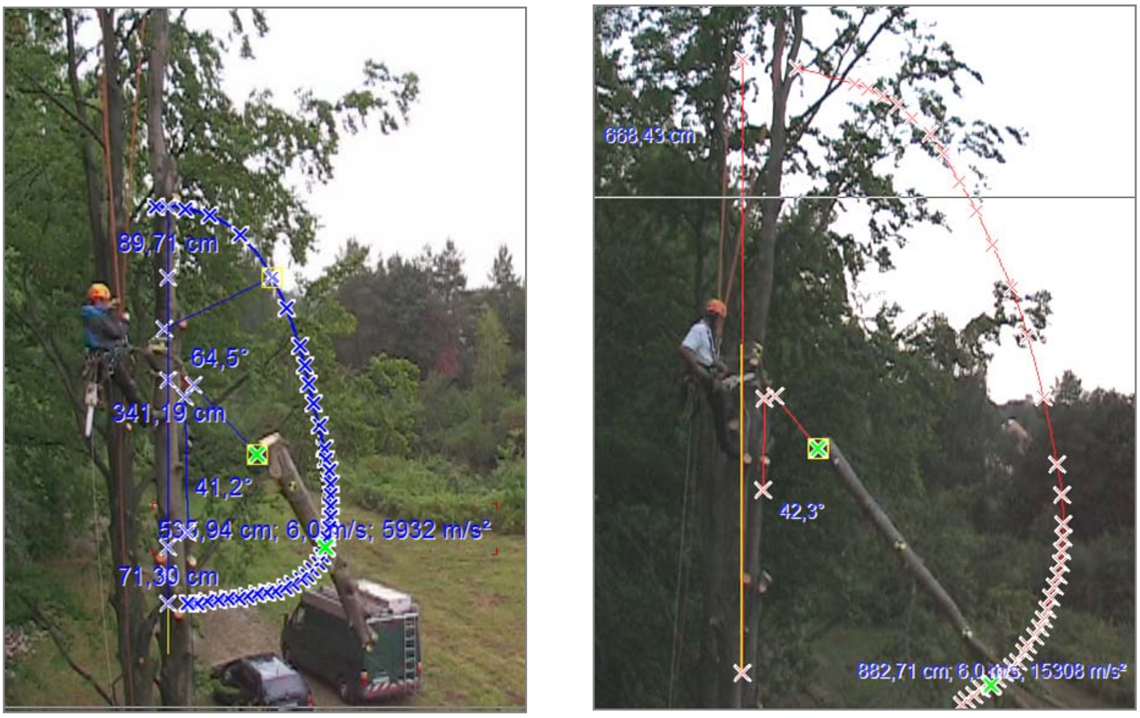


Figure 8.7 Trajectory of log 1, mass 58 kg (conventional notch)*

Similar trajectories were found in on-site tests for logs of different dimensions. In fact, the length of a log seems to be the main decisive factor for the path of the centroid during the lowering operation. In contrast to this, considerable differences occurred when sections of the crown with branches and leaves were lowered. These differences seem to be mainly due to the greater aerodynamic drag in the upper parts of such sections.

* *Illustration created from motion capture data, recorded and evaluated by the authors at Universität der Bundeswehr, Neubiberg, courtesy of Prof. Schneider*

The on-site tests were carried out using a 70° open-face notch with an attack angle of roughly 15 to 20° in the bottom cut. Two arborists, Chris Cowell and Paul Howard, carried out the dismantling operations. A variance in the cutting technique was unavoidable, but not disadvantageous. The objective of this qualitative study was not to single out all factors that may eventually influence the trajectory, but rather to study the variation in different runs of similar rigging operations, and to understand the kinematics behind it. It is to be hoped that further studies can be undertaken in the future, in order to describe, in detail, the effects of single parameters in rigging operations.



Trajectories of a log and a crown section[*]

8.3.2 Stages of topping down logs

The kinematical process of blocking wood in a rigging system under load was also studied in field tests. By this means, the information gained from the laboratory tests could be verified. In the following paragraphs, the worst-case scenario for dismantling operations is described, in five stages, in terms of its kinematics. The sequence is similar to the phases described in Peter Donzelli's work.

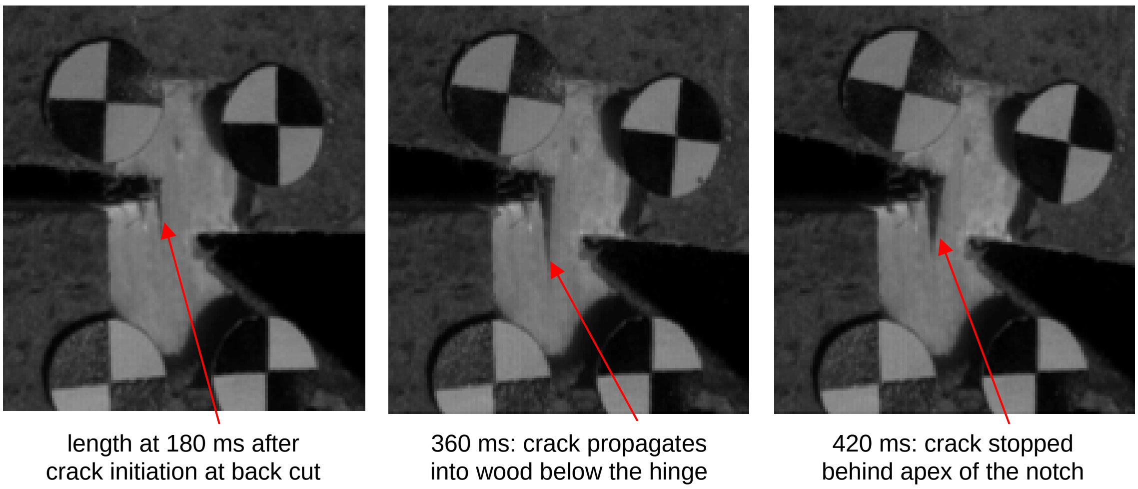
Stage 1 the log is pivoting over the hinge and the notch closes

In order to bend the hinge, a bending moment must be provided by the log's lean, the climber's push or a ground person's pull. As soon as the log's centre of gravity is positioned beyond the hinge, the log itself contributes to the motion with its weight. As the centre of gravity moves further beyond the hinge, the bending moment on the hinge increases. If there is sufficient torque from the log's weight, it starts to rotate by itself. At the same time, the log's weight pushes against the stem, eventually bending it backwards, as described by Donzelli, (1998). This phenomenon is only significant for slender stems and treetops, or very long, heavy logs.

[*] *Trajectories tracked with Utilius EasyInspect 2.0.1*

Stage 1, drop test no. 7

Primary failure of the hinge may be initiated by crack formation along the longitudinal axis, i.e. by fibre delamination. This effect was observed in a high-speed recording of a breaking Humbolt notch. (The form of the notch may have an effect on crack formation, as a crack did not occur behind a conventional hinge.) The crack closed again under the weight of the section, as the fibres on the compression side of the hinge failed by buckling. However, in a compromised stem with, for example, old hidden cracks inside, the initial fissure in the wood may propagate through the trunk and cause a serious hazard for the climber.



Crack formation behind the hinge (Humbolt notch)[*]

[*] *High-speed video sequence filmed at Universität der Bundeswehr, Neubiberg, courtesy of Prof. Schneider*

Stage 2 the hinge breaks and the log freefalls

As the mouth of the notch closes and the hinge breaks, the support for the log's weight shifts from the hinge to the outer margin of the stem. Whether the induced momentum acts more horizontally, or in a rather more vertical direction, seems to depend on the geometry of the notch. Donzelli, Lilly (2001) state that it is essential that the fracture of the notch and the maximum rear push of the log do not occur at the same time, which is the case if 45° notches are being used on a vertical stem.

During the fall, the log rotates around its centre of gravity, while its motion follows a trajectory, as described in the previous chapter. Velocity in the vertical direction increases quickly, as only aerodynamic drag counteracts the force of gravity and the rotational momentum, until the log starts to bear on the line.

Start of stage 2 (drop no. 7)

Stage 3 the log falls into and is being stopped by the line

Even beyond the point where the rope catches, the speed of the log increases. At the beginning of the process of fall arrest, the rope offers little resistance to the log's pull, and can only limit its horizontal displacement. As the anchor point sling stretches, it opens its grip on the front side of the girth. As a result, the block slides downwards on the stem axis if no stub or branch of sufficient length is present. This increases the log's distance of fall and adds rope to the lead[*]. In this stage, friction has to be overcome in the arborist block, and at points where the rope eventually touches the stem. The effect of friction prevents the rope from being loaded equally along its length.

[*] *The part of the rope between the block and the knot that attaches it to the log is referred to as the 'lead', the other end running down to the friction device as the 'fall' (cf Donzelli, Lilly, 2001).*

As the load on the line increases, the stem starts to bend forward under the load applied to the anchor point. When parts of the crown are still intact, this movement may be restrained by the damping effect of side branches and foliage. In such cases, more energy can be transferred into aerodynamic drag and structural damping, thus slowing down the loading process and reducing the peak forces being generated.

Maximum stretch is reached when the rope connects the block axis and the centroid of the log in a straight line. At this point, the rotation is in significant decrease and the peak force in the line occurs. Just after the maximum bending moment is generated in the stem, it starts to sway backwards. At maximum stretch, the two legs of rope, lead and fall, form an angle of around 32° to 42° from the vertical. Due to friction in the arborist block, the resulting load at the anchor point has a direction of roughly 20°, on average, from the vertical.

Beginning and end of stage 3 (drop no. 7)

Significant differences were noted between the lowering of logs and tree tops bearing branches and leaves. When a log is being lowered, it constantly rotates around its centre of gravity from Stage 2 to Stage 3. When falling free, a tree top rotates more slowly due to aerodynamic resistance and mass damping, but continues to rotate at the end of Stage 3 when the line is more or less at rest. For tree tops, the peak load lasts for a longer period of time (up to 1/5 of a second), especially if there are other branches or co-dominants damping the stem's movement. Also, the angle between the two parts of the line at the block is usually slightly greater, regularly reaching more than 40° from the vertical. Thus the load direction on the anchor point can be assumed to be around 25°, on average, from the vertical, which also enhances the bending moment applied to the stem.

Stage 4   the log rotates around the block towards the stem

In this phase, the rotation around the log's centre of gravity has stopped. At the end of Stage 3, while maximum deceleration is in the direction of the line, the vertical speed is greatly reduced. A great part of the momentum is diverted into a direction perpendicular to the line, resulting in a pendulum-like swing, with the block axis being the pivot point. While the tension in the rope is gradually released, the log rushes towards the stem at a more or less constant angular speed. In some cases, a vertical lifting of the centroid was observed during Stage 4. This results in a small gain in height, returning a small portion of potential energy to the log again.

Stage 3 - lowering a tree top, final phase, interval 0.2 sec (drop no. 1)

Stage 5 the log hits the stem and causes oscillation

At the moment of impact, the remaining kinetic energy is transferred into the stem in a very short interval of time, resulting in a high-frequency vibration of the stem. Depending on its mass, the log may bounce back from the stem. The intensity and frequency of the oscillations induced in the stem depend on the mass ratio of log to stem, the slenderness, stiffness and height of the trunk and the location of the impact. The forces involved can be great enough to push the climber’s spikes off the stem, with the potential risk of injury, or even a fall.

Again, this stage is very different when a tree top is being lowered. Branches may break when hitting the stem, their fracture energy consuming a great proportion of the remaining kinetic energy, and considerably damping the impact.

Stage 5 (drop no. 7)

8.3.3 Rotation of the log

The rotation of a representative log was studied in detail. The log was cut at 8 m height from the first Beech tree and had a length of 2.4 m, a mean diameter of 32 cm and a mass of 223 kg. The total rope length was 7.6 m and the distance of fall measured on site was 3.6 m. The peak load at the anchor point was 22.5 kN, which means that the impact force at the anchor point (where the line force is almost doubled) was about 10 times the weight of the section.

In Stage 1, the log is pivoting over the hinge and not rotating around its centre of mass. The angular speed increases more or less linearly as gravity acts on the log and its centroid moves further beyond the hinge. To allow for the hinge to break, fracture energy is consumed, thereby limiting the increase in speed (i.e. kinetic energy). As the mouth of the notch closes, the angular speed remains constant for fractions of a second. As soon as the log is free falling, rotation around the centroid starts and the speed increases. The support for the log's weight is abruptly shifted from the hinge to the outer margin of the stem, adding further rotational momentum.

A flat, horizontal undercut will give the end of the log a vertical push, as the notch closes and the hinge breaks. With a Humbolt notch, the surface of the undercut points in a direction of 45° from the vertical, and so the stem will push the log more in that direction. In an open face notch, the angle of attack will provide more or less forward thrust. Obviously, the thickness of the hinge, the height of the back cut and the properties of the tree's fibres may all affect the log's motion, as well as (and, in some cases, even more than) the form of the notch.

With regard to short logs and long-fibred tree species in particular, the fact that an inclined bottom cut keeps the pivot point further from the centroid as the notch closes, may help in generating sufficient torque to break the hinge (torque is the product of weight and the lateral distance to the pivot point). At the same time, the lever between hinge and pivot point at the margin of a stem is greatest in a 90° open face notch, increasing the lever arm against the resisting force of the hinge. A lower angle of attack for the undercut could reduce this effect.

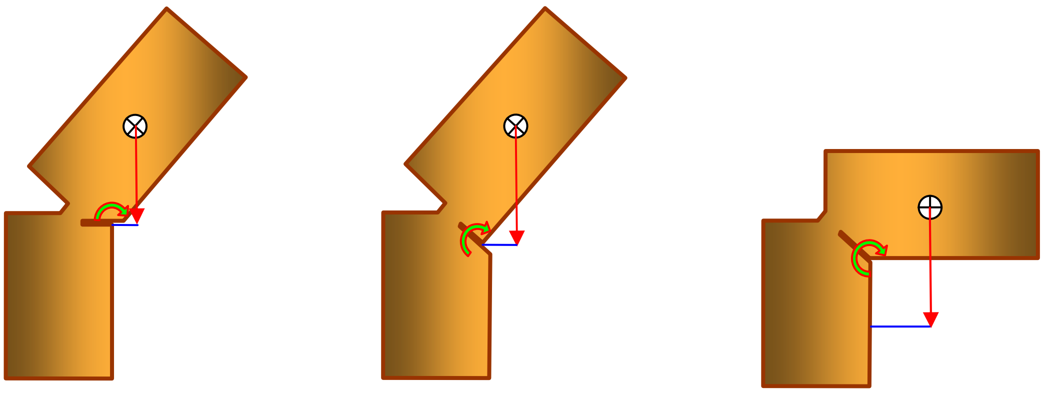


Figure 8.8 (L to R) conventional, Humbolt, open face: torque as the notch closes

Until the hinge breaks, the speed of rotation increases. During the free fall phase, the speed of rotation remains constant, because gravity is the major force of acceleration acting on the log, until the rope tension begins to slow it down. The point of maximum rope stretch falls within a phase of decreasing rotation around the centroid. Rotation in Stage 4 occurs mainly due to the pendulum swing towards the stem. The dip in the graph (Figure 8.9 overleaf) at the middle of this phase may result from interference between rotation and swing.

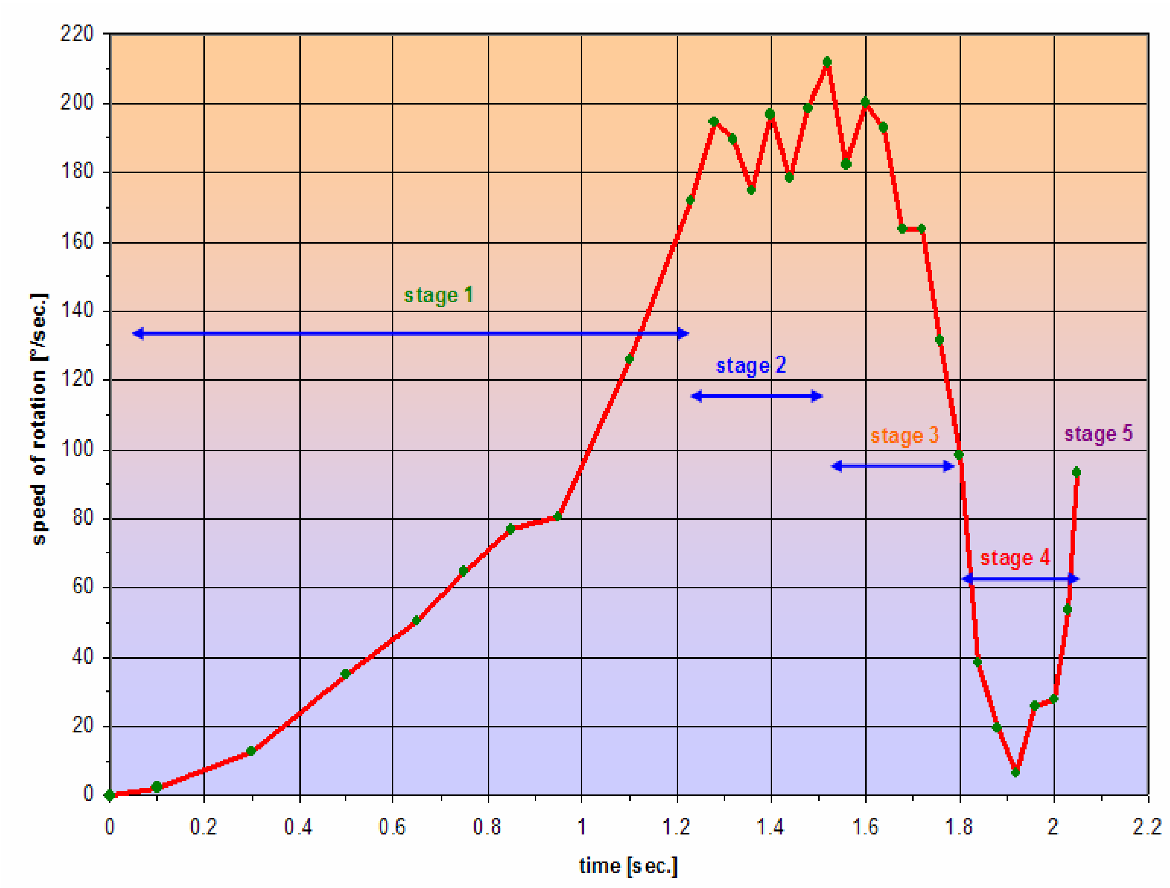


Figure 8.9 Log rotation, 70° open face notch (drop no. 7)

8.3.4 Load angles

The effect that a peak force generated in the line will have on the rigging and tree, depends considerably on the angle at which the load acts. In the tests carried out during the present study, the angle formed by the two legs of the lowering line was fairly constant. It ranged between 32 and 42° from the vertical. Due to the effect of friction in the block, the force is not disseminated evenly between the lead and the fall of the line. The actual resultant force acting on the anchor point also depends on the friction in the block.

Donzelli studied the friction properties of four arborist rigging blocks (Donzelli 1999b). He determined that static friction (the force required to start movement) is always significantly greater than the dynamic friction (the force resisting the moving load). For loads greater than 100 kg, the friction effort* ranged between 5 and 20% for the blocks studied. Donzelli stated that the friction properties depended on the diameter of the sheave, with greater diameters generating less friction.

From data for other pulleys (Sheehan 2004), and given the fact that the rope wraps around the sheave by less than 180° (i.e. not an entire half turn) at the time the peak force occurs, it seems reasonable to assume that dynamic friction in a typical arborist block amounts to roughly 10%. This leads to a reaction force of 1.8 times the tension in the lead end of the line, acting at an angle that is slightly greater than the bisector (i.e. 19.5° from vertical for a rope angle of 37°).

* *Friction effort: the excess force required to overcome friction i.e. proportion of the weight required to start motion.*

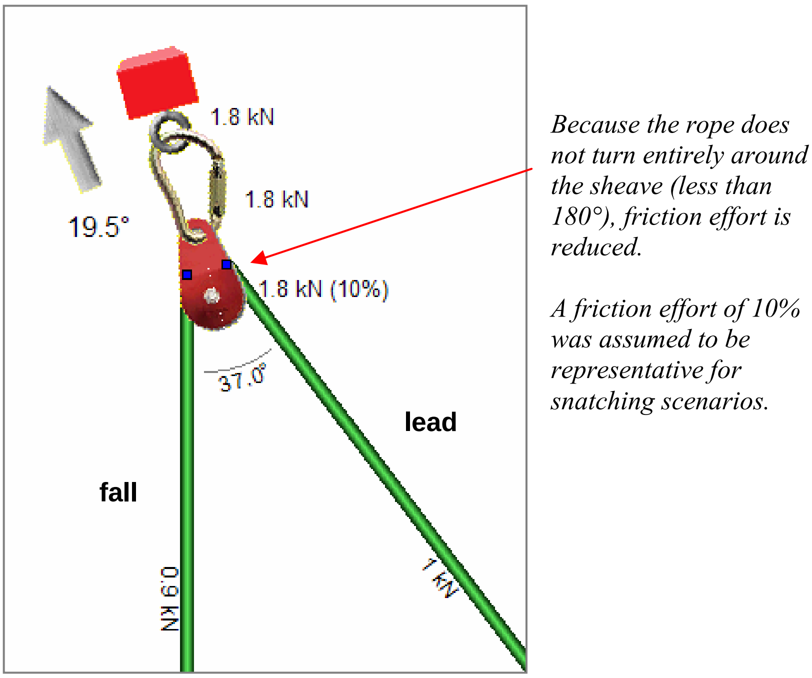


Figure 8.10 Line force shared at a block*

During the laboratory tests, greater friction effort (roughly 14%) was derived from the differing degrees of stretch in the two ends of the rope. As the mass of the rigged sections was comparatively low (less than 67 kg), this may not be representative of a worst-case scenario. According to Donzelli (1999b), static friction coefficients for arborist blocks are significantly greater at low loads.

8.3.5 Reaction of the stem

The fact that the peak force occurs when the log is some distance away from the stem has two major implications for the stem's reaction. Firstly, the peak force generates a considerably greater bending moment on the stem. If both legs of the line are running more or less parallel to the stem (as is the case when the log is finally at rest), this force will be applied almost in line with the stem axis. As wood fibres are most resistant in this direction, the load-bearing capacity of stems used as anchor points should be very high (*cf* Chapter 5). However, rigging operations will always generate considerable bending moments on stems, due to the angle of 32 to 42° at which the peak force occurs in the lead of the rigging line.

Secondly, the log still has considerable speed when the peak load occurs and will gain even more as it accelerates during the pendulum swing towards the stem. The further away from the stem the log's centre of gravity is, the greater is the speed it may reach during its pendulum swing. Velocity will determine the momentum transferred to the stem when the log impacts and forces the stem to oscillate.

The loading of the rigging line generates a swaying to and fro of the stem. The impact of the log has a different reaction and results in a high-frequency vibration that runs up and down the stem, similar to vibrations in a tuning fork. Just below the top of the stem, where the climber is standing, the amplitude of oscillation may eventually be great enough to cause the considerable shake that all climbers have experienced when dismantling trees.

* *Illustration created with RescueRigger 6.0*

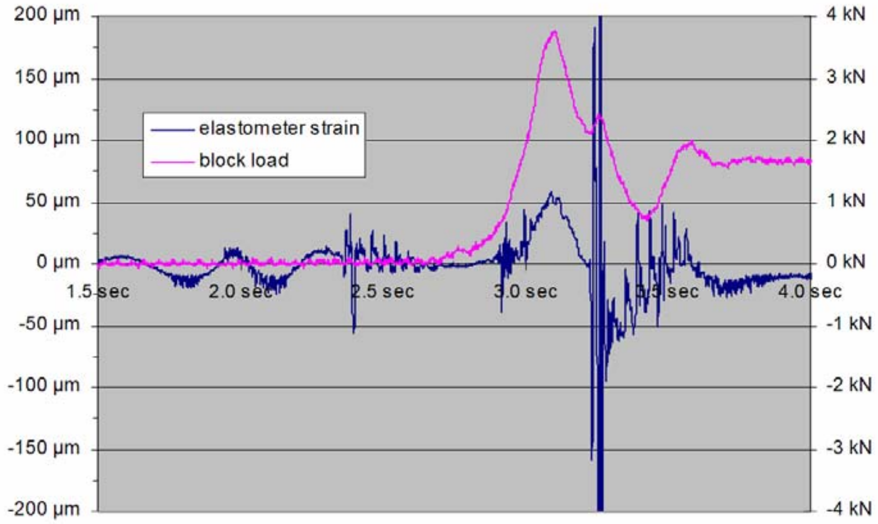
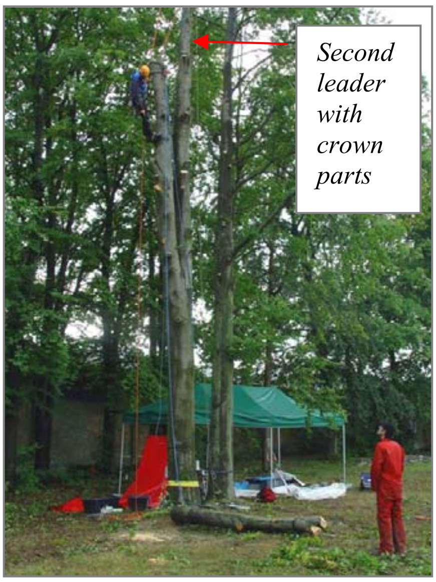
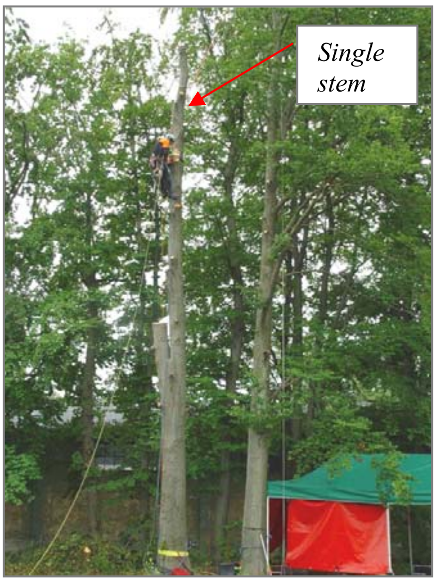


Figure 8.11 Stem reaction in laboratory (drop no. 2)

The high resolution instruments attached to the stem were able to pick up this vibration, which generated enormous peaks (see Figure 8.11) that do not represent the actual strain, but rather the oscillation of the mechanical components of the sensor. This oscillation allowed the precise time of impact to be determined. The reading of the peak strain generated by the pull of the rigging line was not unduly influenced by the latter effect of the impact of the log. After a short period, the sensors displayed the elastometer strain again and the oscillation of the stem was recorded.

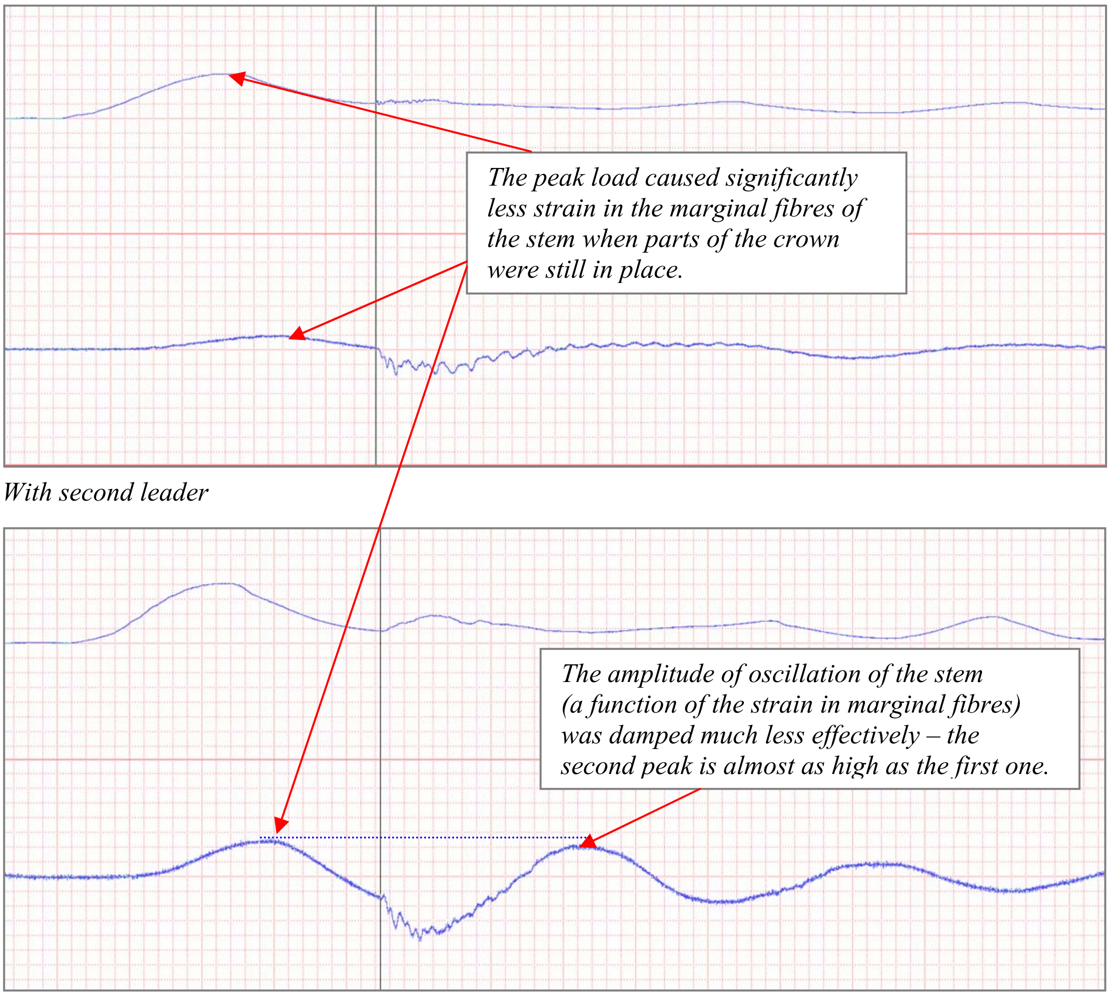
Significant differences were noticed in the trees' reactions depending on the remaining crown parts. Two logs were rigged from approximately 10 m height in the first Beech. In the first topping down operation, a second co-dominant stem was still in place (see illustrations below), whereas when the second log was subsequently lowered the other stem had already been removed. In the first case, the remaining crown structure resulted in significantly less strain in the fibres, a lower vibration frequency and a more effective damping of oscillation in the stem.





The curves shown in Figure 8.13 were generated when dropping the sections shown in these photographs.

Set-up, first Beech (drops nos. 2 and 6)



Without second leader

Figure 8.12 Load and fibre strain curves for two logs lowered from approx. 10 m height in field tests (drops nos 2 and 6)

Differences were also noted as a result of the height and slenderness of the stem (i.e. the height of the anchor point *vs* the stem diameter) and the mass of the log. When a much heavier log was lowered from a rigging point on the short and thick stem of the first Sycamore, the vibration subsequent to the log impact caused greater fibre deformation than the bending of the stem under the peak load in the rigging line. At the same time, the oscillation had a higher frequency, but damping seemed to be equally effective when compared to that of the longer stem with no remaining crown parts (bottom curve in Figure 8.12).

Figure 8.13 (overleaf) illustrates the tree's reaction in this drop test. As the time scale in Figure 8.13 is identical to that in Figure 8.12, the curves in this second illustration reveal a much greater peak force (indicated by the peak in the upper curve), less strain in the fibres and a considerably greater frequency of oscillation in the shorter stem. As a result of low damping effects, the second strain peak (indicated by the shorter red arrow) is almost as high as the first one.

Figure 8.13 Load and fibre strain curves for log dropped from approx. 5 m height in field tests (drop no. 20)

Set-up for first Sycamore (drop no. 20)

The differences in the oscillation frequencies are a result of the natural frequencies of the trunks. For tree stems in the form of an ideal cylindrical beam (taper and form irregularities not taken into account), the natural frequency of damped bending oscillations is given by an equation derived from Mayer 1987:

$$f_n = \frac{1}{l_b{}^2} \times \frac{\lambda^2}{2\pi} \times \sqrt{\frac{EI}{\rho A}} = \frac{r}{l_b{}^2} \times \frac{\lambda^2}{4\pi} \times \sqrt{\frac{E}{\rho}} \qquad \text{equation 8.6}$$

where

where	f_n	natural frequency of a one-sided fixed cantilever beam
	λ	a constant determined by the order of harmonic vibration, e.g. λ_1= 1,875
	l_b	beam length
	E	stiffness
	I	moment of inertia, derived from the fourth power of the stem radius
	ρ	density of wood
	A	cross-sectional area, derived from the second power of the stem radius
	R	radius of the stem

The formula shows that the natural frequency of a stem depends strongly on its slenderness (height *vs* diameter), height and material properties (density and stiffness). Stiffer fibres with lower density in less slender, shorter stems result in a greater frequency of oscillation.

The inclination of the root plate was also monitored during the drop tests. However, in the laboratory tests the flexibility of the anchoring construction was greater than would occur in naturally grown trees. Therefore, this data could not be used in kinematical studies. On the other hand, because of the greater movement at the base of the trunk, it may be assumed that the laboratory simulation was analogous to a rigging operation on a stem of greater length than that actually used, or that the deflection of the anchoring structure was equivalent to that of a stem at a point some distance above the ground.

8.4 DISSIPATION OF ENERGY IN A WORST-CASE SCENARIO

The concept of energy conservation in rigging operations was described by Donzelli *et al* (2001) and applied to snatching logs on a stem. According to the first law of thermodynamics, energy is never lost, but only transformed into work or heat. Generally speaking, the potential energy of the log, defined by its mass and the distance of fall, is absorbed by the rigging system and transferred to other forms of energy. One way to reduce the potential of a log to do work (i.e. to deform or to accelerate other objects) is to convert its energy, via friction, into heat. Energy can also be dissipated by damping effects in the material and structure of the rigging system. Some work is also done when the falling log has to overcome aerodynamic resistance.

The energy transfer described in Donzelli *et al* (2001) includes potential energy, kinetic energy, elastic energy and heat generated from friction. This simplified approach allows for a fairly easy estimate of forces generated by rigging operations, but does not match the actual complexity of the process. The flow chart in Figure 8.14 tries to depict the dissipation of energy in a rigging operation, as it is now understood to occur, as a result of the kinematical studies carried out during this research.

The energy of the initial push/pull of the arborists dismantling the tree may be almost entirely counterbalanced by energy used up when the hinge breaks and a splintering sound is heard. At the point where the rope is stretched to its maximum, the log still has considerable speed. Therefore, it can be concluded that not all the potential energy is transformed into elastic energy. Great parts of the total potential energy are transferred to the stem when, at the end of its trajectory, the log impacts with a loud, hammering sound.

Where parts of the crown are involved, the fracture of branches as they hit the stem absorbs much of the remaining kinetic energy and generates noise. In such cases, aerodynamic drag also plays an important role in reducing the amount of energy actually dissipated within the rigging system. The elastic energy that a slender stem is able to store, when bending under the tension of a lowering line, also reduces the residual fraction of the total potential energy that must be transferred into stretch in the rope.

The effects of friction in the system cannot be disregarded, even when a log is snubbed off. Being under great tension, the sling at the rigging point slides down the stem and the stretching rope passes over the block. Therefore, friction comes into play and transforms energy into heat. When letting a log run, even greater amounts of energy are converted in this manner. Figure 8.14 sums up some of the major components acting during the energy transformation process in a worst-case rigging scenario (snatching a log). In the next paragraphs, some forms of energy involved in this rigging operation will be described in more detail.

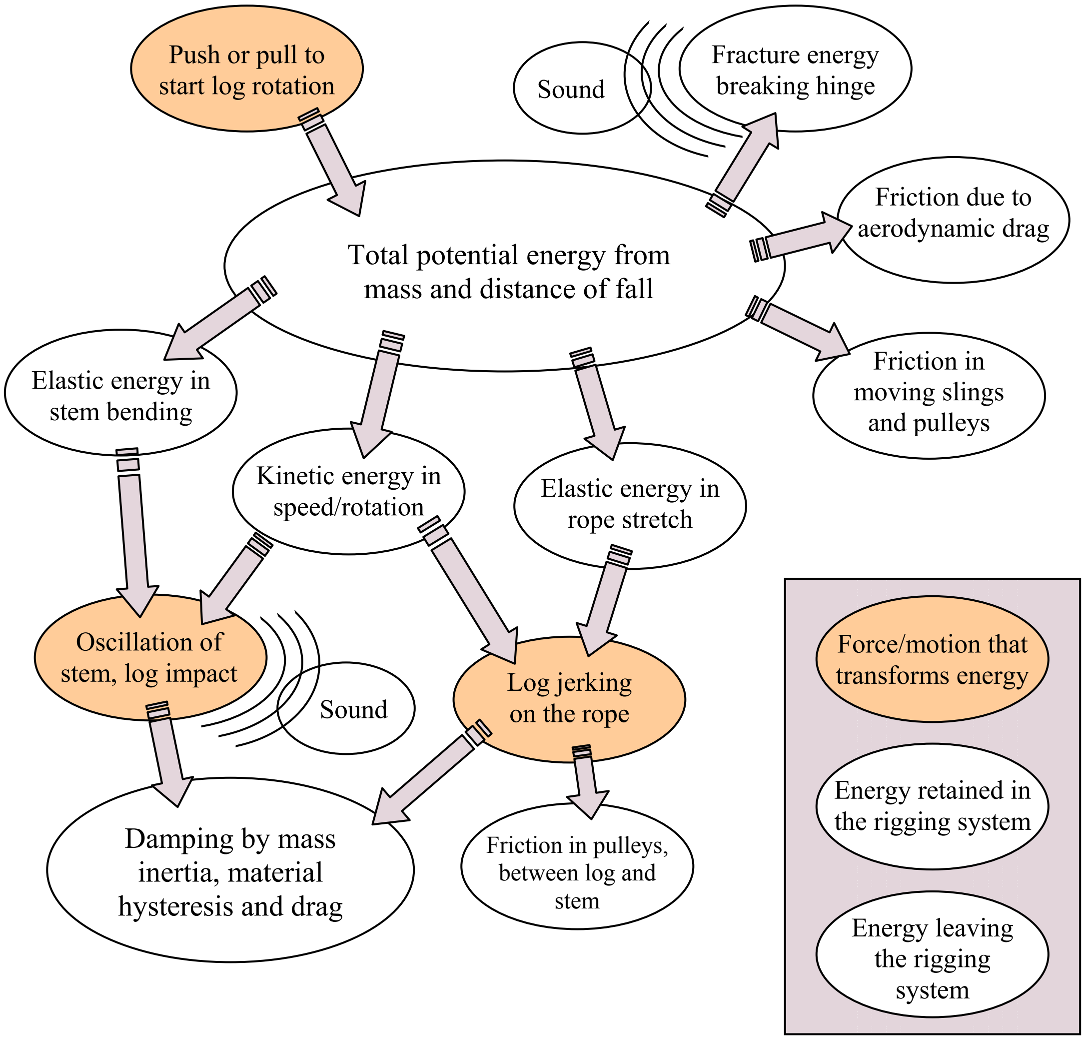


Figure 8.14 Dissipation of energy in a rigging operation

8.4.1 Potential energy

The potential energy set free when a log falls a certain distance, is defined as its mass multiplied by both the distance of fall and the acceleration due to gravity. This means that more and more potential energy is released as the log loses height during its trajectory. This amount of energy has to be continuously dissipated into other forms of energy, including transformation into heat. At different stages of the fall, different amounts of potential energy are set free.

At the lowest point of the trajectory, the maximum energy turnover takes place. The total distance of fall at this point is the sum of the following four items:

- twice the distance of the log's centroid from the initial position of the block axis;
- twice the slippage of the block and the sling along the stem (twice because the same length of rope passes through the block as it slides down);
- rope slippage in knots and at the friction device;
- stretch in the rope.

Donzelli (1998) incorporated the first component of the fall distance into models for rigging operations. He assumed that the peak force occurs as the two legs of the line are both more or less vertical, and that, therefore, at this stage the total distance of fall has been covered. However, according to the tests in the present study, the lead of the line is not vertical when the peak force occurs, but is loaded at an angle. At this point, only a proportion of the total fall distance has been covered. The correct fall distance consists of the drop height of the log (if all other elements are stiff), slip in the rigging (sling, block, rope knots and friction device) and the elastic stretch of the line. Not all of these motions directly cause a vertical shift of the log's centroid, as the legs of the line form an angle at the time the peak force occurs in the line.

The resultant vertical displacement can be determined by the following equation:

$$\Delta z_{peak} = \Delta z_{drop} + \Delta z_{slip} + \Delta z_{stretch}$$

$$\Delta z_{drop} = l_c + z_b + \cos\alpha \times (l_c + z_b)$$
$$\Delta z_{slip} = s_b + \cos\alpha \times (s_b + s_r)$$
$$\Delta z_{stretch} = \cos\alpha \times \Delta L_{\max}$$

$$\Delta z_{peak} = l_c + \Delta z_b + s_b + \cos\alpha \times (l_c + \Delta z_b + s_b + s_r + \Delta L_{\max}) \qquad \text{equation 8.7}$$

where

Δz_{peak}	total vertical displacement of the centroid at peak load
Δz_{drop}	vertical displacement if rope and structure were absolutely inflexible
Δz_{slip}	vertical displacement resulting from slippage
$\Delta z_{stretch}$	vertical displacement resulting from rope stretch
l_c	position of centroid on the log's length from the base
z_b	vertical position of block axis under the hinge
α	angle of the two legs of the line at the block
s_b	slippage of the block on the stem
s_r	slippage of rope in knots and on friction device

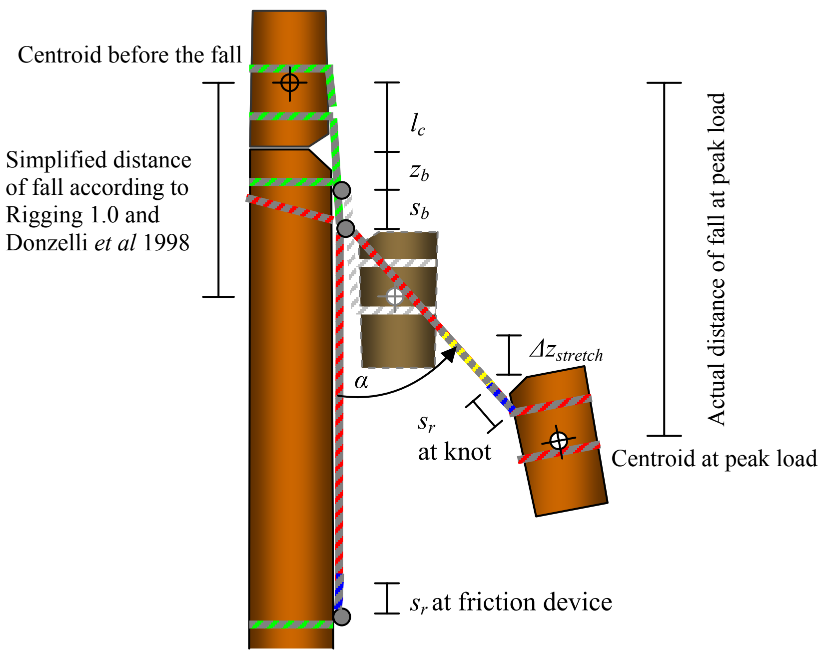


Figure 8.15 Parameters affecting distance of fall

It is not possible to measure rigging displacement or rope elongation prior to carrying out dismantling operations. Only elastic rope stretch, in accordance with equation 8.2, can be added to the distance of fall, provided that data for rope stiffness and line angle are available. Information derived from the tests carried out in the course of the Rigging Research can offer guidance on how to assess the other elements of vertical displacement in a standard scenario. Yet there are still some areas of uncertainty, as, for example, the slippage of sling and rope, that may depend strongly on surface roughness and moisture, as well as on the load applied.

The 'box plot' in Figure 8.16 illustrates how three different parameters, all of which affect the distance of fall, varied in the tests. These parameters are the distance from block to hinge, rope slippage and block slippage. In the box plot, the lines indicate the range between minimum and maximum values, the blocks/bars represent the range in which 50% of all data are found, and the dots indicate the median values (*cf* Chapter 6, section 6.1.3).

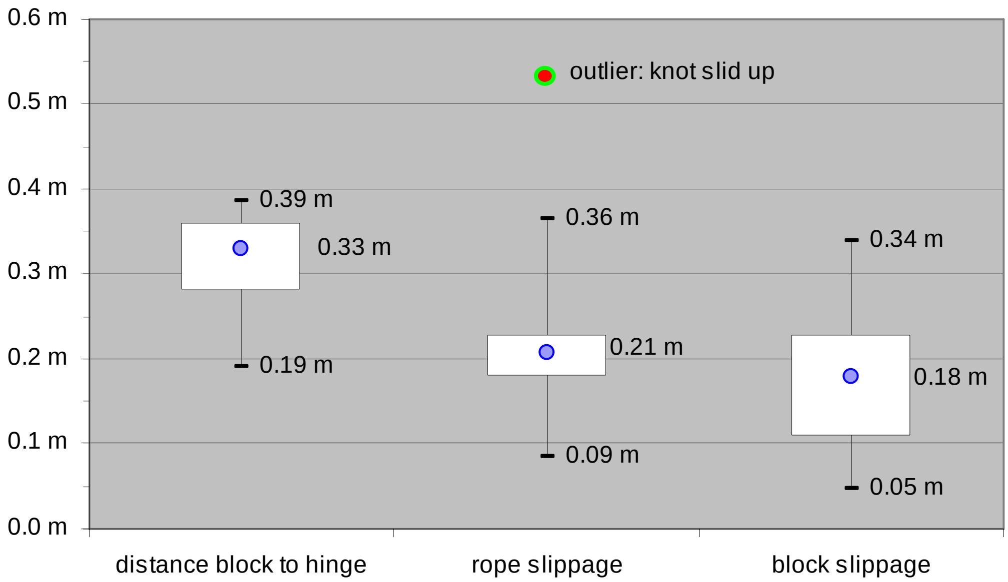


Figure 8.16 Box plot of parameters affecting distance of fall (median indicated)

The ratio of total distance of fall to rope length (fall factor) is used as a measure of the severity of shock load occurring in a fall arrest scenario. In rigging operations, fall factors are generally low, whilst the ropes used are primarily of semi-static, low-stretch construction. Therefore, fall factors are not suitable measures for estimating peak forces generated by dismantling operations. No reliable relationship was found between log length (which determines the height of the centre of gravity above the hinge) and distance of fall. The data obtained during the field tests varies greatly, even when logs only are considered (and crown sections are excluded).

Cutting smaller sections of wood is a very efficient way of reducing the peak forces generated in a worst-case scenario. Detter *et al* (2005) described the centre of gravity as being closer to the pivot point in shorter logs (i.e. the distance to the block's axis is smaller). Therefore, besides the obvious reduction in weight, the distance of fall also decreases. Cutting a log to half the length of another will reduce the eventual peak force to much less than half, usually to about one-third.

The distance of fall is not measured from the attachment of the rope, but from the log's centre of gravity (centroid). In a mostly cylindrical section, the centroid is located in the middle of the log's length. Therefore, it does not matter where the rope is attached, as long as it is located below the centre of gravity so that the log does not flip over (*cf* Donzelli 1999a).

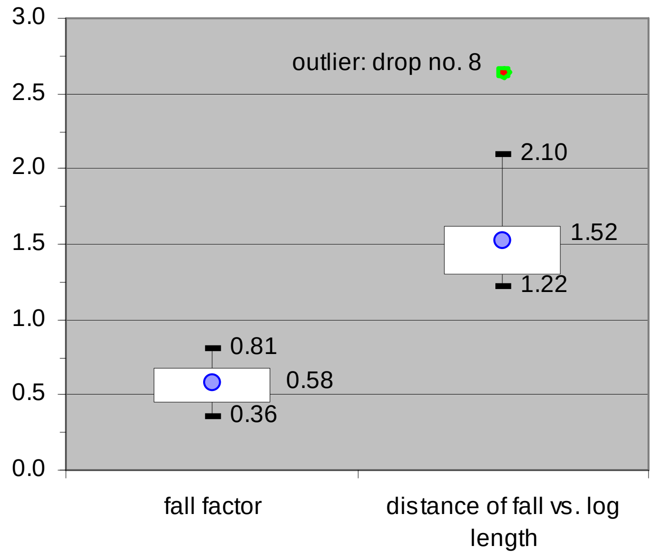


Figure 8.17 Box plot of fall factor and fall distance *vs* log length (median indicated)

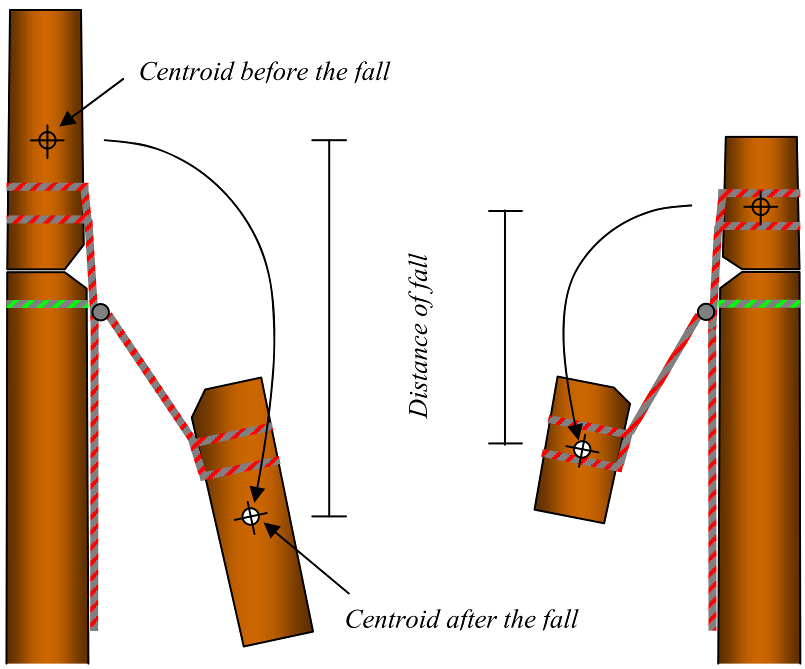


Figure 8.18 How section length affects distance of fall

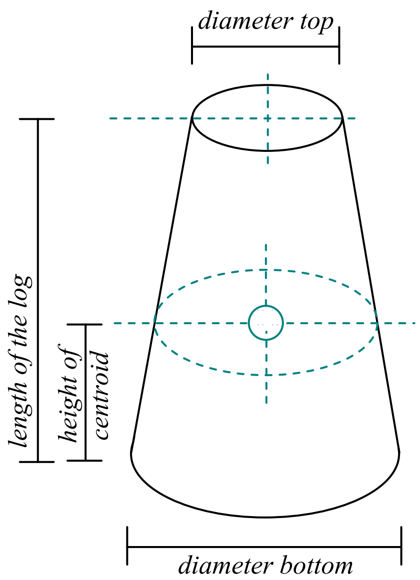
In a conical log, the position of the centre of gravity is not at half length. With increasing taper, the centroid shifts down the log. If logs are approximated by a frustum of a cone, the position l_c of the centroid is derived as a function of the log's length l_{log} and the factor t for taper (*cf* 6.3.1):

$$l_c = \frac{l_{\log}}{4} \times \frac{3t^2 + 2t + 1}{t^2 + t + 1} \qquad \text{equation 8.8}$$

Table 8.1 gives examples of the height position of the centroid for vertical tapered logs in proportion to their length, as derived from equation 8.8.

Table 8.1 Position of centroid in regularly tapered logs

***Taper* (*diameter top / diameter bottom*)**		***Height of centroid* (*x length of tapered log*)**
1.00	cylinder	0.50
0.95		0.49
0.90		0.48
0.85		0.47
0.80		0.46
0.75		0.45
0.70		0.44
0.65		0.43
0.60		0.42
0.55		0.41
0.50		0.39
0.45		0.38
0.40		0.37
0.35		0.35
0.30		0.34
0.25		0.32
0.20		0.31
0.15		0.29
0.10		0.28
0.05		0.26
0.00	cone	0.25



The position of the centroid in crown sections is hard to determine because of many variables like crown spread, changing wood density and the presence of leaves or needles, fruits or cones. Often it is observed that some species seem to accumulate mass at the tips of branches or leader, due to high density, water saturated fibres, dense branching and/or strong fructification (e.g. Spruce, Eucalyptus, Poplar).

As loads generated from rigging crown sections are generally much lower, the potential risk of accidentally overloading a rigging system is comparatively low. With regard to arborist safety, it is essential to realise that treetops can cause significant sway in, and a hard impact on, the stem, due to the great distance between the centroid and the pivot point at the hinge or block axis respectively.

8.4.2 Kinetic energy

Kinetic energy is contained in all bodies in motion. It is dependent on the mass of the body and its velocity. Since velocity works with the second power, changes in speed result in relatively large changes in the amount of kinetic energy. For some forms, the type of motion and the geometry of the body also play an important role. Three different movements of the log generate kinetic energy in a rigging operation:

- rotation around the hinge or the centroid (rotational speed)
- translation* (velocity)
- pendulum swing (angular speed)

* *Translation: uniform motion of a body along a straight line*

In the kinematical studies, the resultant velocity of the log's centre of gravity was derived by motion capture or videogrammetric techniques. At most stages of the rigging process, the recorded velocity represents a combination of the three above-mentioned motions.

In rotation, the kinetic energy depends on the inertia of the log and the position of the rotation axis. As the log is pushed over the hinge, the pivot point is at one end of the log, and, at its full length, the log effectively becomes the rotating arm, and equation 8.9 applies:

$$E_{rot} = \frac{1}{2} \times I \times \omega^2$$

$$I_{cyl} = \frac{m}{4} \times \left(r^2 + \frac{l^2}{3} \right)$$

$$E_{rot} = \frac{m}{8} \times \left(r^2 + \frac{l^2}{3} \right) \times \omega^2 \qquad \text{equation 8.9}$$

where	E_{rot}	rotation energy
	ω	speed of rotation
	I_{cyl}	moment of inertia of a regular cylinder rotating around one end
	r	radius of the cylinder
	l	length of the cylinder

As the notch closes and the hinge breaks, the log starts to rotate around its centre of gravity. The rotating arm is now only half the length of a cylindrical log and the moment of inertia changes. Due to the fact that only a small portion of the energy is actually transformed into rotation, and rotational speed is rather low when the peak force in the line is generated, this form of energy does not seem to play a major role in understanding forces generated by rigging operations.

During the freefall phase, and as the log starts to bear on the line, the log's major displacement is caused by the vertical fall accelerated by gravity. The energy that is transformed into kinetic energy is determined by the velocity of the log and its mass, and described by the formula:

$$E_{kinetic} = \frac{1}{2} \times m \times v^2 \qquad \text{equation 8.10}$$

where	$E_{kinetic}$	kinetic energy
	v	velocity

As the peak force in the line occurs, rotation around the centroid almost stops, and the vertical translation decreases dramatically. The log's motion turns into a pendulum swing and its speed increases again as it follows an almost circular path round the block axis (ignoring decreasing rope stretch). The kinetic energy is now given by the product of angular speed and path radius:

$$E_{angular} = \frac{1}{2} \times m \times (R \times \omega)^2 \qquad \text{equation 8.11}$$

where	$E_{angular}$	kinetic energy in an angular motion
	R	radius of the circular path around the block axis, which is determined by the length of the lead under stretch

While the log is rotating on the line around the block axis, a centripetal force acts on the line. This force, resulting from the angular speed of the log's mass, adds to the stretch in the rope (storing energy in the rope after the peak force has occurred), and is given by equation 8.12:

$$F_R = m \times R \times \omega^2 \qquad \text{equation 8.12}$$

where	F_R	centripetal force acting in the direction of the rope

8.4.3 Elastic energy

Any object that can be deformed under a force is able to store energy due to its elasticity. Springs or rubber bands are good examples of elasticity that can serve to illustrate the concept of elastic energy and energy conservation. In rigging operations, potential energy is dissipated into elastic energy in ropes and slings, as well as in the tree.

Stretch in the rope

The fact that ropes can store energy if they are elastic can be demonstrated by a simple comparison. No harm will result from cutting a cord that is tensioned between a person's hands, but if this was a tensioned rubber band instead, which was cut, the great amount of elastic energy stored in strain will suddenly be set free, and provide a painful experience.

The stiffer a rope, the less energy it will be able to absorb in the form of strain. Modern ultra-high-modulus, static ropes, like Vectran (Spectra, Dyneema) or aramids, offer strength and great stiffness at low diameters and weight. However, their dynamic properties are very different to materials like polyethylene, polyamide or polyester, from which most standard rigging ropes are made. Due to their high modulus, they only deform under very high loads and, therefore, store very little elastic energy. In that respect, they behave more like steel cables. Flexible ropes, like bungee cords, are able to absorb a lot of energy at low loads. At these load levels, hardly any elastic energy can be stored in a static rope.

Static rope has a high rope modulus, expressed by a steep gradient of the load *vs* elongation curve and illustrated in purple in the graph below. Dynamic ropes show a flatter line (blue in the graph). The elastic energy stored in the ropes is depicted by the coloured triangles. At low force levels, little energy is stored in the rigid rope (yellow triangle). To take up as much energy as the flexible rope at the same load (green and red triangle having the same area), the rigid rope must be loaded with much greater force.

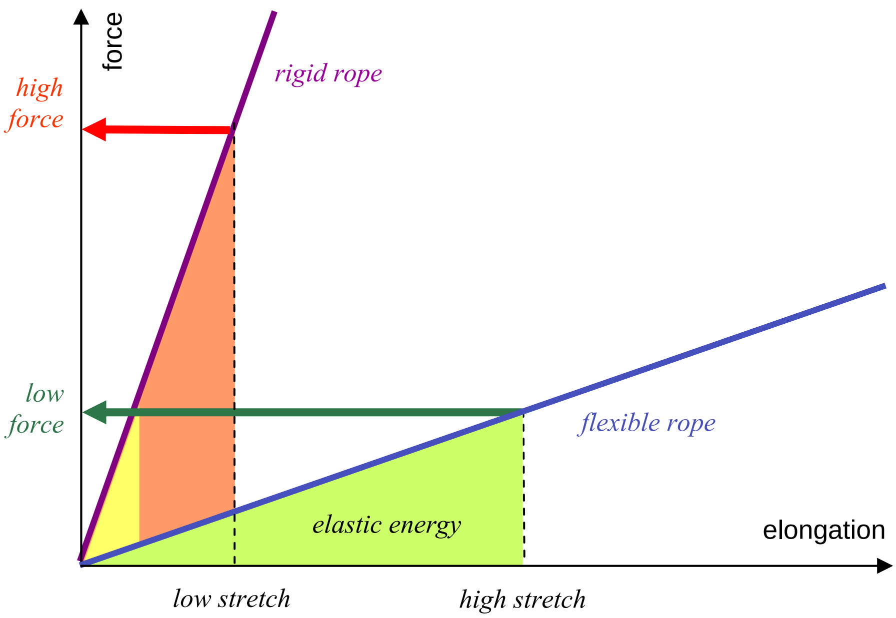


Figure 8.19 Elastic energy

Elastic energy is defined as (*cf* equation 8.2):

$$E_{elastic} = \frac{1}{2} \times F \times \Delta L \qquad \text{equation 8.13}$$

Introducing a rope modulus M that correlates the elastic elongation ε to the force applied according to equation 8.3, solving for ΔL and inserting in equation 8.13 produces:

$$E_{elastic} = \frac{1}{2} \times F^2 \times \frac{L}{M} \qquad \text{equation 8.14}$$

Stronger ropes of the same material are thicker in diameter because they consist of more fibres but, at the same time, more fibres offer greater resistance to stretch under a given force and, therefore, the elongation of the rope is less. This is expressed in a higher rope modulus M and results in greater peak forces when the rope is exposed to dynamic shock loading in drop scenarios.

> *"Thicker ropes, while more abrasion resistant, will produce higher dynamic loads than thin ropes." (Storage et al 1990)*

Increased stiffness is also the reason why high modulus ropes and steel cables are not suitable for dynamic rigging operations. Lower peak forces result from the greater amounts of stretch that dynamic ropes undergo as they stop the fall of a load. The peak load in the ropes depicted in Figure 8.20 is determined by equation 8.4 referred to earlier in this chapter.

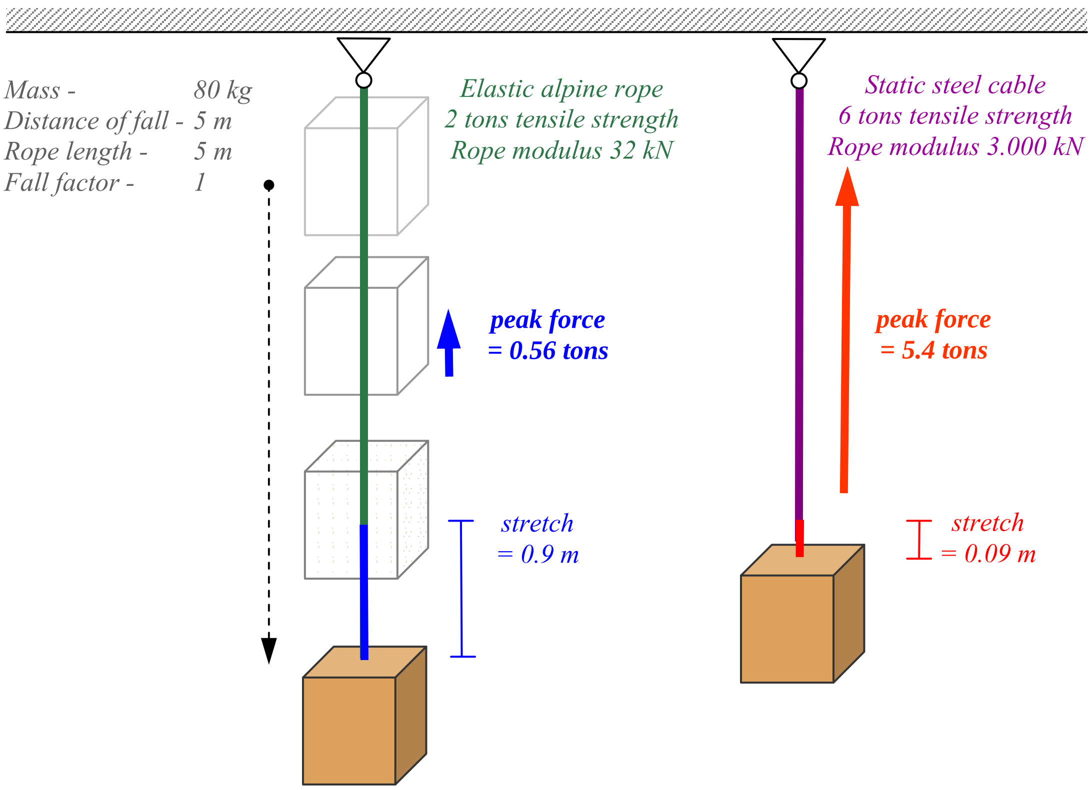


Figure 8.20 Shock load, rope modulus and peak force

Stem deflection

If load-bearing structures other than ropes deform elastically under load, they will also transform work into elastic energy. This is true for a tree as the stem bends and the root plate inclines. The amount of energy stored in a tree can be derived by using a spring model as a mechanical substitute (as described in Chapter 5, Figure 5.5).

In the spring model of a tree trunk, the horizontal deflection Δx is proportional to the horizontal component of the applied force. The proportional factor is called the 'spring rate' (K), which is dependent on the length of the spring (unlike rope modulus which is derived from elongation in proportion to rope length). This constant was determined in load tests prior to the drop tests carried out in the laboratory. The trunk was pulled at the prospective rigging point with a 'griphoist' (Greifzug 1.6 tons) and a steel cable. The tensile force in the steel cable was measured using a load cell. A plumb line and ruler were used to measure the horizontal deflection of the anchor point. Strain in marginal fibres of the trunk was monitored by high sensitivity strain gauges (Elastometers), while inclination of the stem base was recorded with Inclinometers (see laboratory test set-up, 8.2.1). Readings were taken at distinct load increments in a lower load range up to 3 kN. The force was corrected by the cosine of the rope angle.

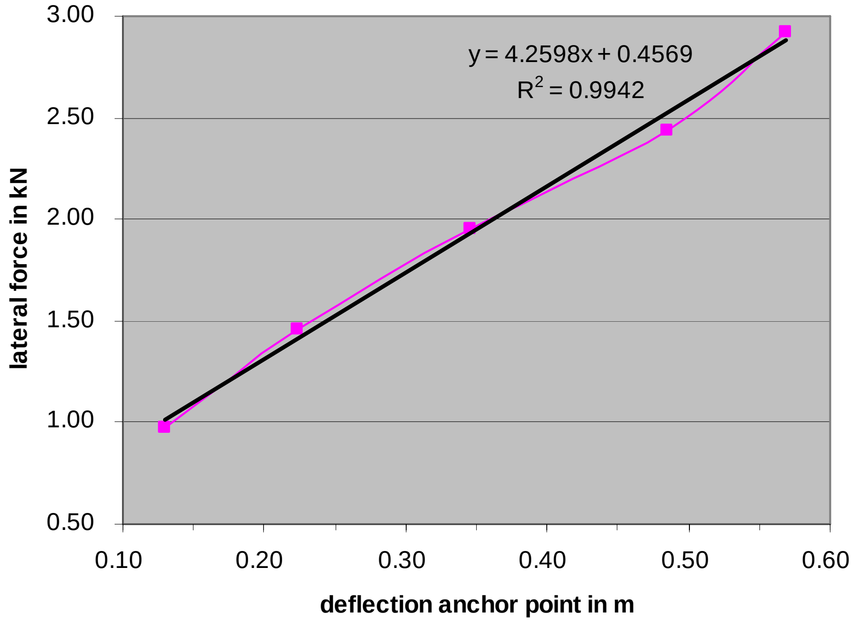


Figure 8.21 Spring rate for laboratory tree structure

When the 'spring rate' of the stem structure had been determined, it was then used to assess the elastic energy transferred into the stem by the force acting on the block. The energy required to deflect the stem from its initial position is given by equation 8.13. In this case, the energy can be determined using the stem's spring rate (K) and the load angle from the vertical:

$$F_{lateral} = K \times \Delta x$$

$$E_{elastic} = \frac{1}{2} \times \frac{F_{lateral}{}^2}{K} = \frac{(F \times \sin \beta)^2}{2K} \qquad \text{equation 8.15}$$

where
- $F_{lateral}$ lateral component of the force with regard to the stem axis
- K spring rate of the stem structure
- β angle from vertical under which the load acts on the block

In a regular wooden beam of cylindrical shape and length l_b, fixed on one side in a vertical position, the horizontal deflection Δx of the free end under a lateral force $F_{lateral}$ applied at the free end is:

$$\Delta x = F_{lateral} \times \frac{l_b{}^3}{3 \times EI} \qquad \text{equation 8.16}$$

During the entire drop test series, the strain in the marginal fibres was determined using high resolution strain gauges (Elastometers). Inclination of the root plate was only monitored with inclinometers in the laboratory tests and when dismantling the Beech trees on site. The elastic deformation of the structure was correlated to the bending moment applied in the pulling tests that were carried out to derive the modulus of elasticity of the stems.

The Elastometer readings were used to simulate the dissipation of energy into stem bending by application of a different method. The strains in the marginal fibres are indicators for both the lateral force applied and the horizontal displacement (provided that the dimensions of the lever arm are considered and the stiffness of the material is known). Therefore, it is possible to determine the elastic energy stored in a bent cylindrical stem by the following equation:

$$F_{lateral} = \frac{EI \times \varepsilon}{(l_b - z_\varepsilon) \times r}$$

$$E_{elastic} = \frac{1}{2} \times F_{lateral} \times \Delta x = \frac{E \times \varepsilon^2 \times V}{24 \times \left(1 - \frac{z_\varepsilon}{l_b}\right)^2} \qquad \text{equation 8.17}$$

where ε measured strain in the marginal fibres
z_ε height of strain measurement
V volume of the cylindrical stem

It should be noted that the inclination of the roots adds to the horizontal displacement of the anchor point and is usually fully recoverable below an inclination of 2.5° (according to Wessolly, Erb 1998). The quantity of energy dissipated into elastic deformation of the roots was not taken into account because it was impossible to simulate this effect under laboratory conditions. This aspect could well be the subject for more detailed study in the future.

Bending also occurs in the hinge at the very beginning of the rigging operation. In this case, elastic energy is also being stored in the wood fibres. This energy is then transformed into permanent deformation as fibres kink, and into fracture energy as the hinge breaks apart. According to Griffith's explanation of fracture mechanisms (see Gordon 1984), as the fibres rip apart, the energy is being used to form new surfaces. However, for the estimation of peak forces in the rigging system, this energy transformation is not really relevant.

8.4.4 Friction

Friction between solid surfaces and/or fluids (drag) generates forces. To overcome those forces, work is required and heat is generated. In this way, energy formerly contained in the rigging system is transferred into heat and is able to leave the system in that form. In other words, the total quantity of potential energy, set free as the log is lowered, is reduced by friction effects.

Three major forms of friction will be described in the following paragraphs:

- rope-on-block friction
- sling-on-stem friction and
- aerodynamic drag

Friction in a rigging system

A study by Peter Donzelli (Donzelli 1999b) describes the mechanical principle behind friction in arborist blocks. Lately, Kane (2007) has elaborated on the friction coefficients of arborist ropes passing over a branch or a cambium saver. Due to the effect of friction, the energy is dissipated unevenly to the two parts of the rope (‘lead’ and ‘fall’). In a snatching scenario, the fall line will experience less tension, because the friction in the block inhibits the rotation of the wheel, an effect which can be compared to the action of the brake shown in Figure 8.22. As a result there is an uneven dissipation of tension between the lead and fall line. Less tension in the fall line also means less elongation in this part of the line. Therefore, the total stretch in a rope in a rigging scenario is less than might be expected from the actual rope stiffness.

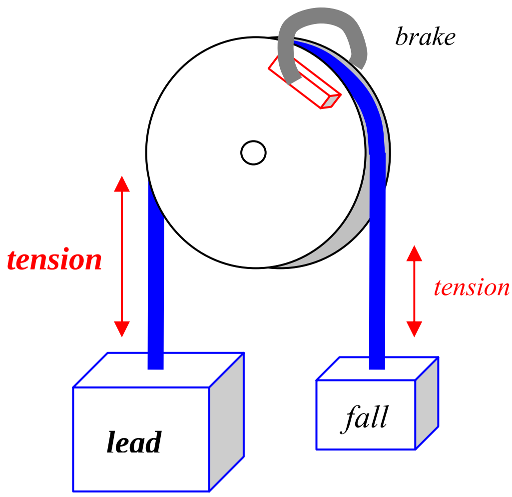


Figure 8.22 Model of friction in a rigging block in a snatching scenario

At the same time, the generation of friction by the rope passing over a block or a branch effectively reduces the energy in the rigging system. The determining factor for energy dissipation is the work that has to be done to overcome the friction. Friction generates a force that resists movement. It acts in the opposite direction to the force accelerating a moving body. The surface, its geometry and load-specific friction coefficient μ determine the friction effort, and, therefore, the energy used in overcoming the friction in a rigging scenario.

Generation of friction at a rigging point has other disadvantages, besides the fact that the length of rope effectively damping the shock loads is reduced. Natural crotch rigging also results in greater friction, thus transforming more energy into heat, but friction is always accompanied by abrasion and heat, and this may wear or burn ropes and eventually damage bark. Furthermore, a rough surface like bark does not generate steady friction as the two materials slide over each other. Irregular sliding can result in small peak forces as the force resisting motion varies. Under such circumstances, the speed of a log, as it falls into a rope, can vary within short periods of time, causing jerking on the line and thereby increasing peak forces (see 8.5.1).

Steel or alloys have smoother surfaces, but much greater friction coefficients than pulleys. Karabiners cause roughly 50% friction effort, according to tests carried out by Sheehan (2004). The friction effort in steel karabiners is only a few percent less than in those made of alloys, still close to 50%. The adverse bend radius of rope in a karabiner, or on a shackle, disqualifies them from being used as rigging points (see 7.3.4). However, the greater friction alone will only affect safety in topping-down rigging operations where the fall does not run parallel to the stem axis.

The loading angle at the anchor point changes if the difference in tension in the two legs of the lowering line increases. At the same time, the anchor force is reduced by the friction in the karabiner, by the same proportion as the new load angle magnifies the lateral force. In the end, the bending moment acting on the stem remains the same, no matter how much friction is applied at the block, as long as the fall of the rope runs more or less parallel to the stem. Providing this is the case, the resultant force always has the same lateral component as the tension in the lead part of the line. However, due to the effect of friction, the eye-sling at the anchor point is loaded to a significantly lower degree than in systems that have less friction at the rigging point.

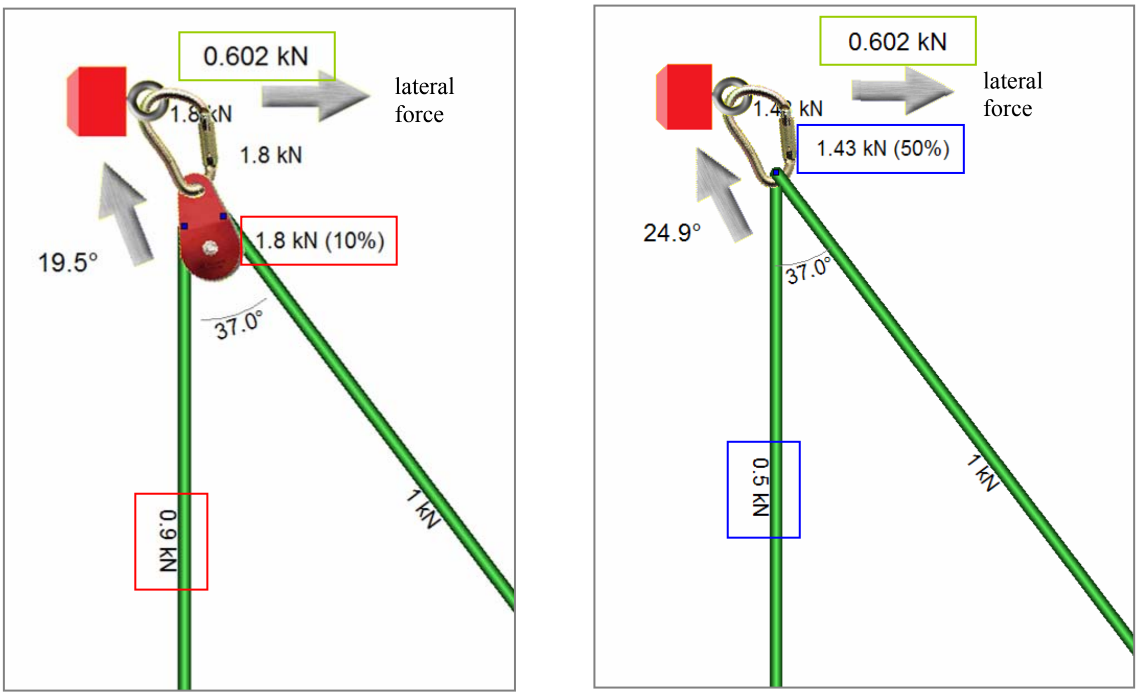


Figure 8.23 Load reduction from increased friction at the rigging point*

Practical implications may neutralise the potential benefits of generating more friction at the rigging point. Peak forces in the lead of the line will increase due to the shorter effective rope length. The risk of the line getting locked in a friction device at the rigging point poses questions of practicability. Also, there is an inherent danger that ropes may be damaged by abrasion and heat, if greater friction is applied to the rope at this point in the rigging system. On the upside of a block's sheave, the rope presses on metal with a force resulting from both legs of the line, whereas at the friction point at the base of the trunk only one line applies tensile force. Therefore, similar friction coefficients may cause greater damage on the cordage at the former point of the rigging system.

From pure mechanics, friction at the rigging point will reduce loads at the anchor point, without generating greater stress in the stem, only if the fall of the rope runs parallel to the axis of the stem. Otherwise, increased friction will cause the angle between the resultant force at the anchor point and the stem axis to increase. The bending moment in the stem will also be magnified, but only at a low level. In this scenario, the direction of the resultant force runs almost parallel to the stem, so the bending stresses applied to the tree are rather low in any event.

* *Illustrations created with RescueRigger 6.0*

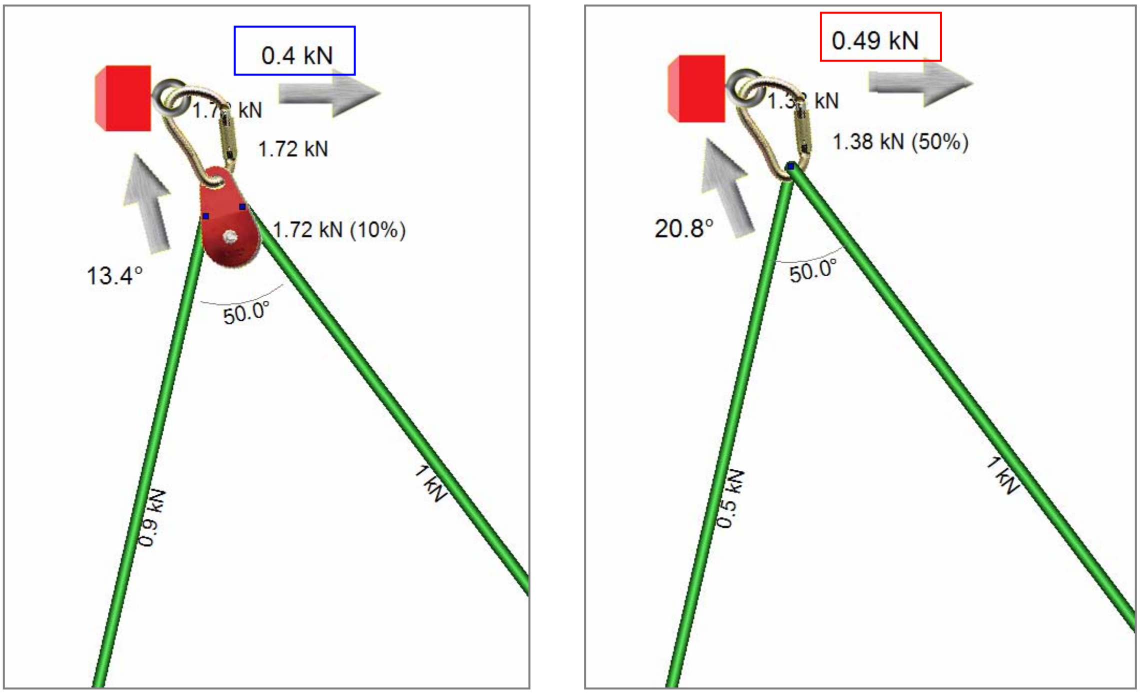


Figure 8.24 Increased stem bending due to friction at the rigging point*

Chisholm (2000) pointed out that positioning the friction device at the rigging point up in the tree would be the optimum set-up. From a mechanical point of view this may be correct, but Chisholm also stresses the impracticability of this approach. Any means of generating increased friction at the rigging point would, therefore, require further detailed studies, in order to exclude any adverse implications, before making recommendations for common dismantling practice.

The friction properties of the block may differ significantly if the force is applied statically (at low speed) or under dynamic shock loading. The friction effort to start movement (static friction) is always significantly greater than the kinetic friction that resists the propulsion of an already moving body. The question of whether static friction may be more easily overcome when loads are applied quickly, has not yet been studied, as far as the authors are aware.

Friction is also involved in slippage of slings along the stem, rope slippage on the friction device, and in knots as they set and tighten. The quantity of energy absorbed by friction in these components of the rigging system has not yet been studied. As slippage of the block along the stem adds almost twice to the distance of fall, it is possible that any effect of friction will be counteracted by an increased turnover in potential energy, eventually increasing the peak force.

Some degrees of slippage at the anchor point may even lead to conflicts with arborists' personal protective equipment. If the chosen anchor points are directly beneath the initial position of the sling, the ropes may eventually become pinched. The implications of slings moving down the stem suggest a recommendation that anchor points should be chosen so that the slings pass over small stubs or branches. However, branch stubs will only stop slippage if they are located on the back and at the sides of the stem. Under the load of the tensioning line, the slings loosen their grip at the front side (where the pulley is attached), and may eventually be shifted over small stubs, as was observed in one of the drop tests carried out during this study.

* *Illustrations created with RescueRigger 6.0*

A sling may be shifted over a small stub when put under tension

Aerodynamic drag

In the evaluation of kinematical data from the laboratory tests, the aerodynamic drag was derived from the formula for drag resistance, which indicates a drag force counteracting the acceleration of the section at a certain speed:

$$F_{drag} = -\frac{1}{2} \times \rho \times c_d \times A \times v^2 \qquad \text{equation 8.18}$$

where
- ρ air density
- c_d aerodynamic drag factor
- A the surface area exposed to the air
- v measured velocity along the trajectory

For stem sections, Tree-Statics use an aerodynamic drag factor of 0.7 (Sinn 2003). For parts of the crown, a lower drag factor of between 0.12 and 0.35 is recommended for greater wind speeds (*cf* Wessolly *et al* 1998). At the same time, the aerodynamic drag on crown sections that expose greater sail areas to the air, is much greater. The drag force derived from equation 8.18 was multiplied by the distance covered by the log's centroid along its trajectory, in time intervals at a rate of 240 Hz. The energy increments (force multiplied by length of path travelled) were summed to determine the total work done by aerodynamic drag. While the effect of drag may be great when lowering crown sections, it was very small on the logs dropped in the laboratory tests.

Another approach to assessing the energy dissipation to drag may be to compare the potential speed that would be gained from gravity in a vacuum with the actual recorded speed. However, such considerations were beyond the scope of the present research project.

8.4.5 Hysteresis, reconfiguration and damping effects

During the entire rigging process, energy is dissipated by reactions to and damping of motions. For example, when rope stretches at the beginning of a load cycle, the strands and filaments move against each other, as they set to their perfect alignment, causing friction and generating heat. Eventually, internal damage may occur in a rope from excessive abrasion between fibres and dirt particles, or from friction-generated temperatures beyond the rope's melting point. The energy used to reconfigure the fibres is not retained in the rigging system, but transformed into permanent deformation and heat.

After each load cycle, there will also be some additional permanent elongation of the rope. This is due to the fact that loading changes the structure of synthetic fibres. It may also provide an explanation as to why ropes can only experience a certain number of load cycles before they fail. Since each load cycle irreversibly stretches the fibres a bit more, the amount of permanent elongation in a rope will also increase with each cycle. Assuming the synthetic fibres can only tolerate so much permanent deformation before they fail, this capacity will, at some point in the rope's life, become exhausted, and result in rope breakage (T. Reuschel, pers. comm. 2007).

Some part of the deformation occurring during a load cycle recovers after a short period of time. This behaviour is called viscoelastic* and the energy lost as the rope stretches and recovers is called hysteresis. Of course, the energy is not really lost but transformed into work and heat. Reconfiguration, permanent elongation and viscoelastic behaviour all add to the shock damping properties of rope, and will contribute to reducing peak forces in fall arrest (see Samson Catalogue, 2005, for a comprehensive description of rope stretch).

However, other components of a rigging system also exhibit similar behaviour. The slings and knots will be set at the beginning of a load cycle, and so will reconfigure and experience permanent deformation. Girthed slings will usually behave in a viscoelastic way as they return from the state of maximum grip to the relaxed state, but only after some time. Last but not least, the tree also has a damping effect, which depends considerably on its structure.

The behaviour of plants under dynamic loads has been studied by several authors. The damping effects of grasses are described by Speck *et al* (2004), who carried out tests to determine both aerodynamic and structural damping. Kerzenmacher *et al* 1998, Moore *et al* 2004, James *et al* 2006, and others, have all studied the effects of crown structure on the dynamic reaction of trees.

Three types of damping may be differentiated in trees:

- aerodynamic damping
- tuned-mass damping
- structural damping in the material

The study of these effects was beyond the scope of this research. It should be noted, however, that slenderness and height of the stem, the amount of leaves, and the distribution and structure of branches, all have significant effects on a tree's reactions to load and its ability to dissipate energy in a dynamic loading scenario (see 8.3.5).

A considerable quantity of energy may also be dissipated by the root system. The root-soil matrix may contribute to damping of both a tree's bending under peak force and the high frequency vibrations exerted in the stem by the impact of a log. Few authors have studied how a tree's root system reacts to dynamic loading (e.g. O'Sullivan *et al* 1992). In models for windthrow, root systems are often simulated using mechanical substitutes, without reference to any reliable data on their actual dynamic properties (e.g. Coutts 1983, Ruck *et al* 2003).

After a log has hit the stem, the oscillation of the trunk is responsible for dissipating most of the energy. Ultimately, when the log, tree and rigging are at rest again, the total potential energy must have been transformed into work and heat (First Law of Thermodynamics). Therefore, the mechanisms for transforming energy into heat are the key to understanding how the potential energy of a log actually leaves the rigging system.

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* *Viscoelastic materials have both elastic and viscous components. Elasticity gives material the potential to store energy, while viscosity enables material to dissipate energy into heat as it is loaded and unloaded.*

8.4.6 Energy dissipation in a worst-case scenario

Based on the kinematical studies carried out in the laboratory at the Universität der Bundeswehr (University of the German Federal Army) in Neubiberg, the energy dissipation in snubbing off logs from a vertical stem was described. The potential energy of a log was determined by its mass and its potential vertical fall distance (i.e. its height above the lowest possible position of its centre of gravity). Potential energy is at its maximum before cutting, which is shown at (1) in Figure 8.25. The initial push or pull to start the pivoting of the log was neglected, despite the fact that it adds to the total energy turnover in the process. This initial input may well be counterbalanced by the bending work and fracture energy of the hinge, which could not be quantified within the present study. This assertion is supported by Figure 8.25, which at (2) indicates that all the energy was transformed into kinetic energy, although this cannot actually be the case, since the bending of the hinge also consumes energy. It may well be the case that this equates to the initial energy input.

As the log starts to lose height, potential energy is set free. Because energy is never lost, it is progressively transformed into other forms of energy during the dropping sequence, while the sum of all forms of energy remains constant (vertical line on the right side of Figure 8.25). Because kinetic energy varies with the square of speed, this form of energy shows a big variation and amplitude, e.g. that between (3) and (4) in Figure 8.25. The kinetic energy of the log was calculated from the resultant speed of the log's centre of gravity, as derived from the kinematical study. Energy due to rotation around the log's centroid was not covered, but it may be assumed that this rotation would only increase the displayed kinetic energy to a small extent (see (5) in Figure 8.25).

Data obtained for the elongation in the two legs of the lowering rope was used to determine rope stretch at all stages of the drop. The amount of elastic energy stored in the rope was calculated with regard to its known rope modulus, and added cumulatively to the kinetic energy (see (6) in Figure 8.25). Bending of the stem was measured by recording the strain in the marginal fibres using high resolution strain gauges (Elastometers). Using the results of the load tests carried out prior to the drop test, the elastic energy in the bending stem (see (7) in Figure 8.25) was derived from equation 8.17, and added cumulatively to the previous two forms of energy. Due to poor data output, inclination of the stem base under load (which also is a form of elastic energy) could not be used in quantifying the energy transfer during this rigging operation.

Quantifying the different forms of energy leaving the rigging system, as illustrated in Figure 8.14, was beyond the scope of the present study. Only aerodynamic drag during the log's fall was estimated, using equation 8.18, and subtracted from the potential energy set free (see (8) in Figure 8.25). Much more energy would be lost due to air resistance when dismantling crown sections rather than logs. There was a difference between the sum of the forms of energy that were quantified (shown in Figure 8.14), and the potential energy actually released. This difference indicates the amount of energy leaving the system (area (9) in Figure 8.25). However, only assumptions could be made of how friction in the rigging system, reconfiguration of cordage, permanent deformation and hysteresis in ropes, slings and the stem structure dissipate that energy.

The instant when the peak force is generated in the rope is marked by the horizontal red-dashed line at (10) in Figure 8.25. At this stage, which is depicted, for example, in Figure 8.5 or in the pictures on page 200, elastic energy in both the rope and stem is at a maximum (see (6) and (7)), while kinetic energy is at a local minimum (see (4) in Figure 8.25). The calculated quantities of energy, and the losses (presumed to be dissipated by reconfiguration, friction, and hysteresis in rigging and tree), are displayed in Figure 8.26 as fractions of the released potential energy at peak load (red-dashed line at (10) in Figure 8.25).

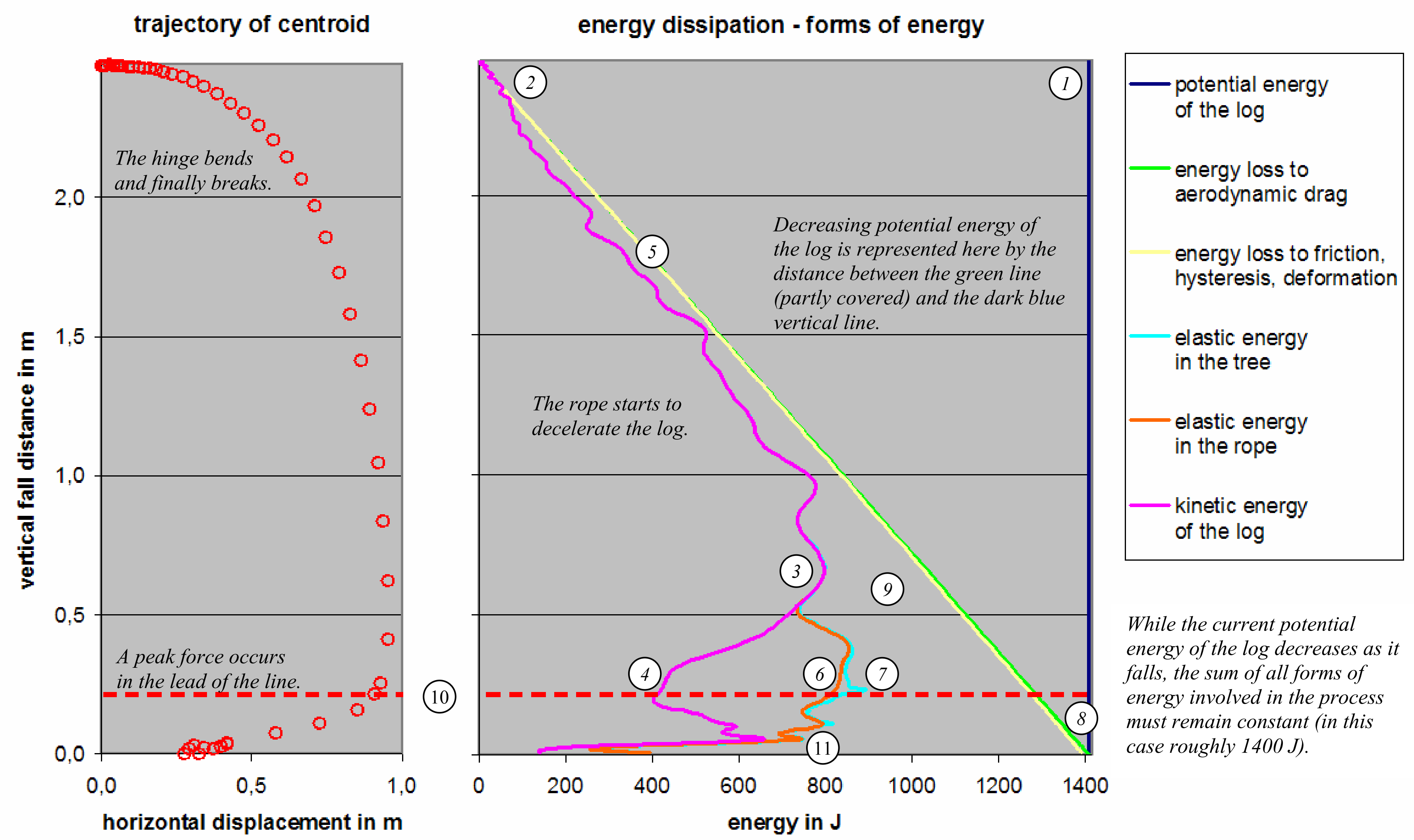

Figure 8.25 Energy dissipation in snubbing off a 58 kg log into a 14 mm rope (evaluation of lab test no. 1)

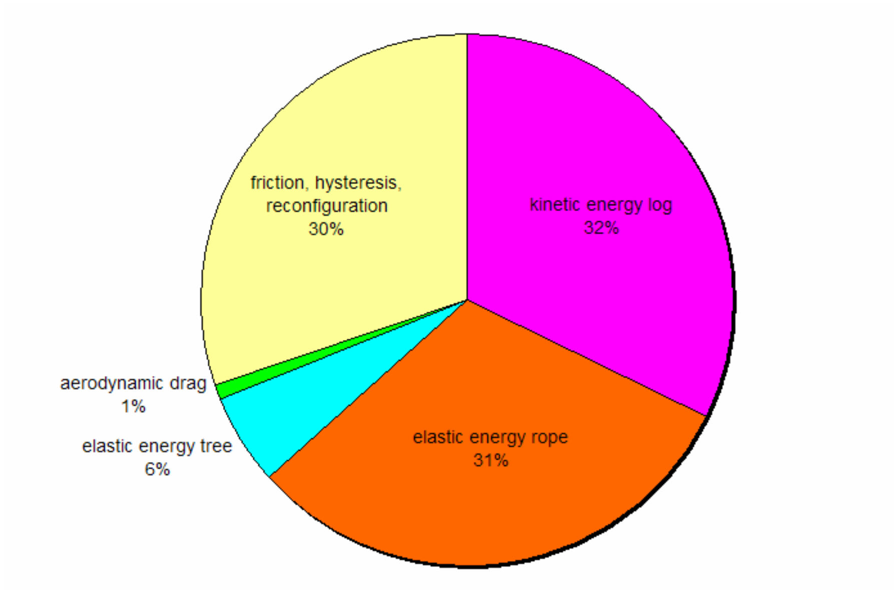

Figure 8.26 Distribution of forms of energy at peak load when snatching logs

In phases other than at peak load, the dissipation of energy may be very different. Just before the log hits the stem, for example, kinetic energy is much greater and covers almost half of the energy dissipation. Elastic energy in the rope is significantly decreased and bending of the stem is negligible (area 11 in Figure 8.25). As a matter of fact, elastic energy stored in the rope and the stem is only partially recovered as kinetic energy, while a great part of it is used to overcome friction or dissipated by hysteresis.

In other rigging scenarios, for trees or sections with lateral branches, for logs of greater length, longer stems and greater amounts of rope in the system, the distribution of energy dissipation will very likely be different. However, the conclusion that roughly one-third of the potential energy is dissipated by the rope into elastic energy, matches the observed deviations of earlier test results from estimations based on simplified mechanical models (*cf* 8.1.4). One-third of the potential energy is retained in the log in the form of kinetic energy, due to its residual speed at the instant when the peak force in the rope occurs. This is also in accordance with the observations made in the kinematical studies carried out in the course of this study.

The proportion of energy dissipated by the tree may seem surprisingly low. Yet, due to the steep angle of loading at the anchor point (roughly 20° from the vertical at peak force), only very little force effectively generates bending in the trunk and inclination in the root plate. Additionally, the short stem tested under laboratory conditions experienced significantly less deflection than some of its natural counterparts in the field. The tree as a load-bearing structure may play a much more important role in dissipating energy in the last stage of the rigging operation – when the log impacts on, and transfers most of its momentum into, the stem. Therefore, this event may be of as much interest, with regard to arborist safety, as the peak force generated in the lowering line.

Whether or not it is realistic to presume that 30% of the energy turnover is dissipated into friction, damping and permanent deformation, would have to be investigated in future studies. From other studies on damping effects in natural structures and the shock absorbing features of cordage, it does seem to be a reasonable assumption to make (e.g. Spatz *et al* 2004, Detter 2003, James 2003).

8.5 ESTIMATING PEAK FORCES

8.5.1 Change in momentum

It is widely understood that letting a log run significantly decreases the forces in the rigging system. Yet, adding more rope to the system results in more energy being set free, due to the fact that the distance of fall increases dramatically. It is often claimed that the energy of the fallen log is transformed into heat generated from friction between rope and the lowering device, in a similar way to friction occurring in climbing hitches that could eventually burn the rope (e.g. Donzelli *et al* 1998).

For example, snubbing off a 1 m length of wood of 204 kg mass to a drop height of 2 m will set free a potential energy of 4 kJ (a weight of 2 kN is falling 2 m distance, 4 kNm = 4 kJ). By comparison, cutting the same log at a stem height of 12 m, letting it run and bringing it to a halt by dynamic deceleration at 2 m height, involves a total energy turnover of 20 kJ, that is five times as much (fall distance 10 m). A small version of Port-a-Wrap III consists of 0.772 kg massive steel. If the total amount of energy is transferred into the steel (which has a heat coefficient of 0.5 kJ/kg K) the temperature of the Port-a-Wrap should increase from 20°C to 72°C (assuming the heat is distributed evenly and none is lost to the surrounding air).

But, in fact, energy is also dissipated through structural damping in the rope (due to hysteresis), permanent shifting and setting of attachments (slings and knots), and damping by the swaying tree (as described earlier). The further the section falls, the more significant becomes the effect of aerodynamic drag, which absorbs energy when the section offers resistance to the air (crown parts in leaf). Also, friction in the arborist block becomes more relevant when a greater length of rope runs through it. But these effects are hard to quantify, and cannot alone provide a comprehensive explanation for the distinctly lower peak forces generated by dynamic deceleration, even though much greater quantities of energy are released.

This phenomenon is more easily described by the gradual deceleration of the log. The rate at which the speed decreases is responsible for the lower forces generated when letting the log run. Remember, force is defined as mass times acceleration. Acceleration is the change of momentum of an object, or the change in its speed over time. Acceleration is great if the speed changes quickly. It is low if the speed alters more slowly and the change happens over a longer period of time (*cf* Bacon 2002). Since mass remains constant at the speeds being considered, it becomes clear that the forces generated are lower when a body is decelerated more slowly, even though the total energy turnover may be greater.

This is also the reason why the traditional methods of natural crotch rigging, and taking turns around the stem to provide friction, are not an adequate solution for lowering logs of large mass. Even though more energy may be converted into friction on the bark of the tree, greater peak forces must be anticipated. Due to the usually occurring uneven application of friction, the rope 'stutters' when sliding over the bark, causing rapid changes in log speed and corresponding, significant increases in peak forces. When a generally more smooth friction device is used, the deceleration of the log can take place more consistently and gradually.

The process of gradual deceleration takes place over a much longer period of time than shock loading. Therefore, as discussed earlier, the combined damping effects of the rigging and tree structure can play a much more significant role in dissipating energy and extracting it from the rigging system. This may also be the reason why longer fall distances, using longer ropes, will generally speaking (and all else being equal), generate lower loads in drop scenarios.

8.5.2 Energy equation

In estimating forces in a worst-case scenario (i.e. snubbing off a log from a vertical stem), the transformation of energy provides a viable approach to determining the dynamic peak force generated in the line. In order to accommodate the energy dissipation shown in Figure 8.26, equation 8.2 needs to be modified to the form:

$$\frac{1}{3}E_{pot} = E_{elastic}$$

According to equation 8.7, the vertical displacement of the centroid at peak load Δz_{peak} incorporates the fact that the lead of the rope runs at an angle from the block and is, therefore, not adding directly to the fall distance (see Figure 8.15). Taking into account the mean load angle, as found in the kinematical studies, the potential energy side of equation 8.2 needs to be changed as follows:

$$\frac{m \times g}{3} \times \Delta z_{peak} = \frac{1}{2} \times F_{peak} \times \Delta L_{\max}$$

$$\frac{m \times g}{3} \times (\Delta z_{drop} + \Delta z_{slip} + \cos\alpha \times \Delta L_{\max}) = \frac{1}{2} \times F_{peak} \times \Delta L_{\max} \qquad \text{equation 8.19}$$

Additionally, the force is not applied evenly on the full length of the rope because of the friction in the arborist block. In a simplified way, this can be accounted for by reducing the actual length of the rope by a factor determined by the friction effort and the length of the fall:

$$\Delta L = \frac{F}{M} \times \left(L - \nu \times L_f\right) \qquad \text{equation 8.20}$$

where ν a factor for friction effort in the block
L_f length of the fall of the line

Applying equation 8.20 to equation 8.19, and solving for F_{peak}, renders a new equation for determining the peak force in the line:

$$F_{peak} = \frac{\cos\alpha}{3} m \times g \times \left(1 + \sqrt{1 + \frac{6}{\cos^2\alpha} \times \frac{M \times (\Delta z_{drop} + \Delta z_{slip})}{m \times g \times \left(L - \nu \times L_f\right)}}\right) \qquad \text{equation 8.21}$$

The force generated at the anchor point results from the two forces exerted in the two legs of the line and the angle between them at the block. If friction effort is assumed to be 10% and the line angle to be 37° from the vertical, the anchor force will be roughly 1.8 times the peak force (*cf* Figure 8.10). For all other friction efforts and line angles, the resultant force at the anchor point can be determined by referring to the tables in 8.7.2, or by application of the following equation:

$$F_{anchor} = F_{peak} \times \sqrt{(1-\nu)^2 + 2\cos\alpha \times (1-\nu) + 1} \qquad \text{equation 8.22}$$

8.5.3 Test results

Loads generated in drop tests were expressed in the form of an anchor force factor δ, defined as the peak load generated at the anchor point in a worst-case scenario divided by the weight of the lowered section:

$$\delta = \frac{F_{anchor}}{G_{\log}} \qquad \text{equation 8.23}$$

where	F_{anchor}	dynamic force generated at the anchor point by shock loading
	G_{log}	weight of the log, or mass x 9.81 (m/s^2 acceleration due to gravity)

If both the force and the weight are expressed in kilograms or tons (which would be incorrect from a physics point of view because they are both units of mass, not weight), the same anchor force factor applies. The same factor also works for imperial units, using pounds-weight and pounds-force. Therefore, this measure is very easy to understand and could be used by practitioners without confusion over choice of units.

The actual tensile force in the lead of the rigging line (which is the part of the rope that experiences the greatest stress) varies from that in the fall of the line because of the effects of friction, both in the arborist block and along the fall as the line occasionally rubs on the stem. It can be assessed by using a constant factor for friction effort (v) in conjunction with a mean angle (α) between fall and lead and solving equation 8.22 for F_{peak}.

Evaluation of Peter Donzelli's drop test notes

Data from drop tests carried out by Peter Donzelli and ArborMaster Training Inc was provided and used by kind permission of S. Lilly, USA. In these tests, loads generated at the rigging point were measured by means of a dynamometer mounted between the arborist block and the eye-sling at the anchor point. The logs were not cut from an intact stem, but dropped from a point in the crown of the tree and winched up again, in order to be able to repeat the tests and obtain more quantifiable results. This set-up led to the following two differences in the simulation as compared to a realistic rigging scenario.

Firstly, the trajectory of the log may be different if a real cut is not performed. Comparative studies of video footage on a small number of drops from the test series (provided by and used by courtesy of ArborMaster Training Inc) did not show distinct deviations from the typical trajectory recorded in the kinematical studies of this research. However, because the video sequences were not filmed at an angle convenient for easy analysis, there is no reliable confirmation for this assumption.

Secondly, a load cell was added to the rigging system between the anchor and the rigging point This difference may have caused considerable deviations between the test results and those relating to real rigging operations. An increase in distance at this point in the rigging affects the generated peak loads considerably, because, although the length of the rope is not altered, the distance of fall increases by twice the length of the load cell and its attachments. Therefore, the actual distance of fall in these drop tests was artificially increased by roughly 0.60 m. Any conclusions on how to estimate forces in rigging operations would presumably err on the side of caution if they are derived from these tests. Also, comparative studies on how the type and diameter of a lowering line affects the peak forces are certainly possible in the set-up chosen by Peter Donzelli and his co-workers.

Drop test on Green Ash, carried out by P. Donzelli and ArborMaster Training[*]

Peter Donzelli also recorded the line force at the friction device. Combined information about the tension in the fall of the lowering line and the force at the rigging point will indicate the forces acting on the lead of the rope. To achieve this, the previously-mentioned angle between the two legs of the line, and the friction in the arborist block, must both be taken into account.

Data from Peter Donzelli's drop tests were analysed, particularly with regards to differing rope types. Some tests involved the friction device being mounted to an adjacent tree and the fall of the rigging line running at an angle of 45° from the vertical. However, this set-up was not regarded as representative and was excluded from the presented results (this decision also reflected the fact that reputable instructors strongly advise against its use) (*cf* K. Palmer cited in Chapter 2). In general, forces measured with the fall of the line running at an angle of 45° were always significantly lower when compared to those recorded in a standard set-up.

In light of the kinematical studies of this research, intentional diversion of the fall of the line from the axis of the tree does not seem to be at all unnatural. As the tension in the lead of the line acts under an angle of roughly 37° from the vertical, this angle may also be recommended for the fall of the line, but on the opposite side of the stem axis. In this case, more rope is added to the system providing greater shock redemption. At the same time, the resultant force at the anchor point will be considerably lower due to the increased deflection of the rope in the pulley. Additionally, the force will act more or less parallel to the vertical stem axis, where the strength of the tree stem is greatest.

Nevertheless, the potential implications of this method on arborist safety should be carefully considered and studied in more detail, before the practice can be generally recommended. In this respect, it is worth recalling the tragic death of Peter Donzelli, who died when a tree broke beneath him, in a dismantling operation which apparently involved a similar rigging set-up that may, in the event, have contributed to the tree failure (K. Palmer, pers. comm. 2004).

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[*] *Video footage courtesy of ArborMaster Training Inc, USA; flight curve tracked with DAVID Videogrammetry*

The drop tests were carried out on two different tree species, Green Ash (*Fraxinus pennsylvanicana*) and Northern White Pine (*Pinus strobus*). Rope length varied between 8.15 and 15.11 m, with the length of the fall ranging from 7.26 to 13.72 m. Three different logs were used: the first was 81 cm long, 29 cm average diameter and of 45 kg mass; the second 91 cm long, 31 cm in diameter and 68 kg in mass; and the third 1.6 m long, 34 cm in diameter and roughly 90 kg in mass. Due to the dynamometer installed at the anchor point, the distance from the cut to the block axis ranged between 0.81 and 1.14 m, with one exception in which the distance was 74 cm.

Block slippage was recorded and ranged from 3 to 15 cm, while 50% of all values ranged from 5 to 8 cm. One outlier was recorded where the vertical block displacement was noted as 56 cm, which could neither be explained nor falsified and excluded from the dataset. At least for those trees where video footage is available, the tested scenario was quite different to a real topping down operation. The block was not fixed on a vertical stem, but on a scaffold branch near one of the leaders (see photograph on page 233). Although this may not affect the trajectory of the log, it certainly does limit the ability of the block to slip down during the course of the rigging operation.

An overview of the variation in anchor force factors, relative to the type and diameter of rope used, is contained in Figure 8.27 (in which the lines are the best linear fit for data relating to the specific rope types used). Having regard for the differences in the test procedures, these results were not correlated with data obtained during the current research.

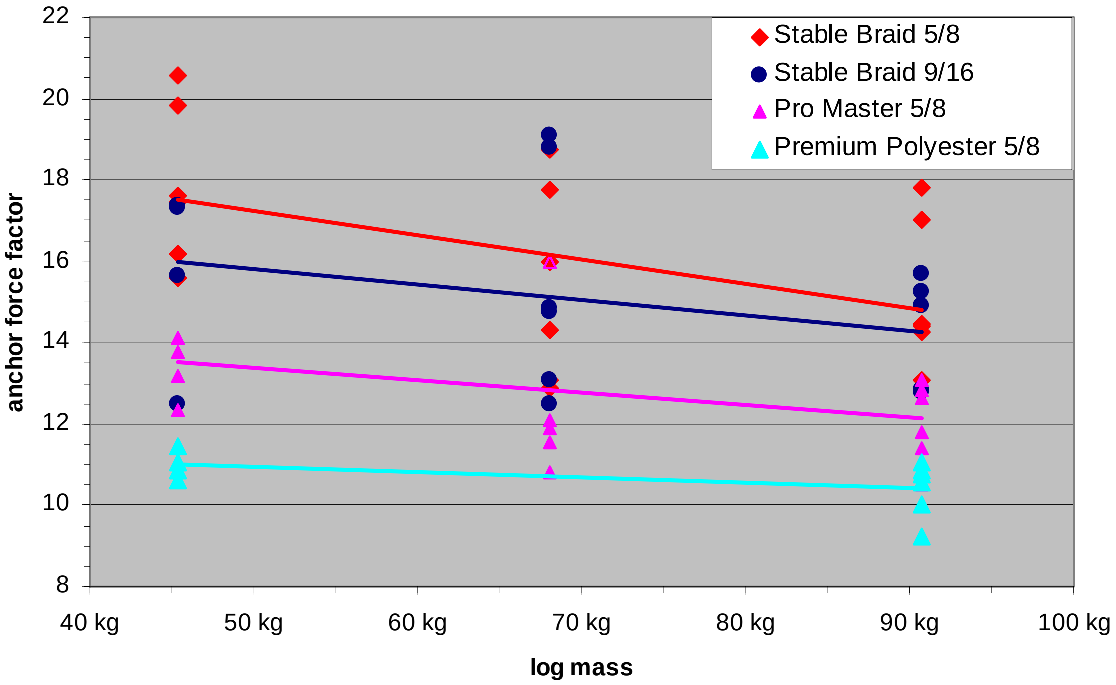

Figure 8.27 Effect of rope characteristics on anchor force factor

Figure 8.27 indicates that the rope construction has a greater influence on the peak load than the diameter of the rope. Double-braided rope, like the Stable Braid, generated the greatest anchor force factors. Notwithstanding the differing friction parameters of the different rope types, the trend in the data still indicates greater peak forces in the lead of the line. The other double-braid rope, one class of size smaller, resulted in peak loads that were to some degree lower.

The difference in anchor force factors is much more significant when the double-braid line is replaced by a three-strand line of the same diameter (which offers greater elongation by means of a lower rope modulus). The third rope tested by Peter Donzelli was obviously even more flexible, thereby providing even better energy absorbing properties.

Besides variations in log size (length, diameter and mass), the length of rope used in the rigging system was varied. No reliable correlation was found between rope length and the anchor force factor. Yet from Figure 8.28, a trend towards lower anchor force factors is visible for greater log mass and length (where all other parameters remain constant).

The data is displayed using different colours for the four ropes used in the drop tests, and different symbols (circle, triangle and square) for the respective log masses. On some occasions, the anchor force factor was quite closely reproduced in subsequent tests using the same parameters (indicated by markers of the same form and colour close together); at other times, the variation was found to be great.

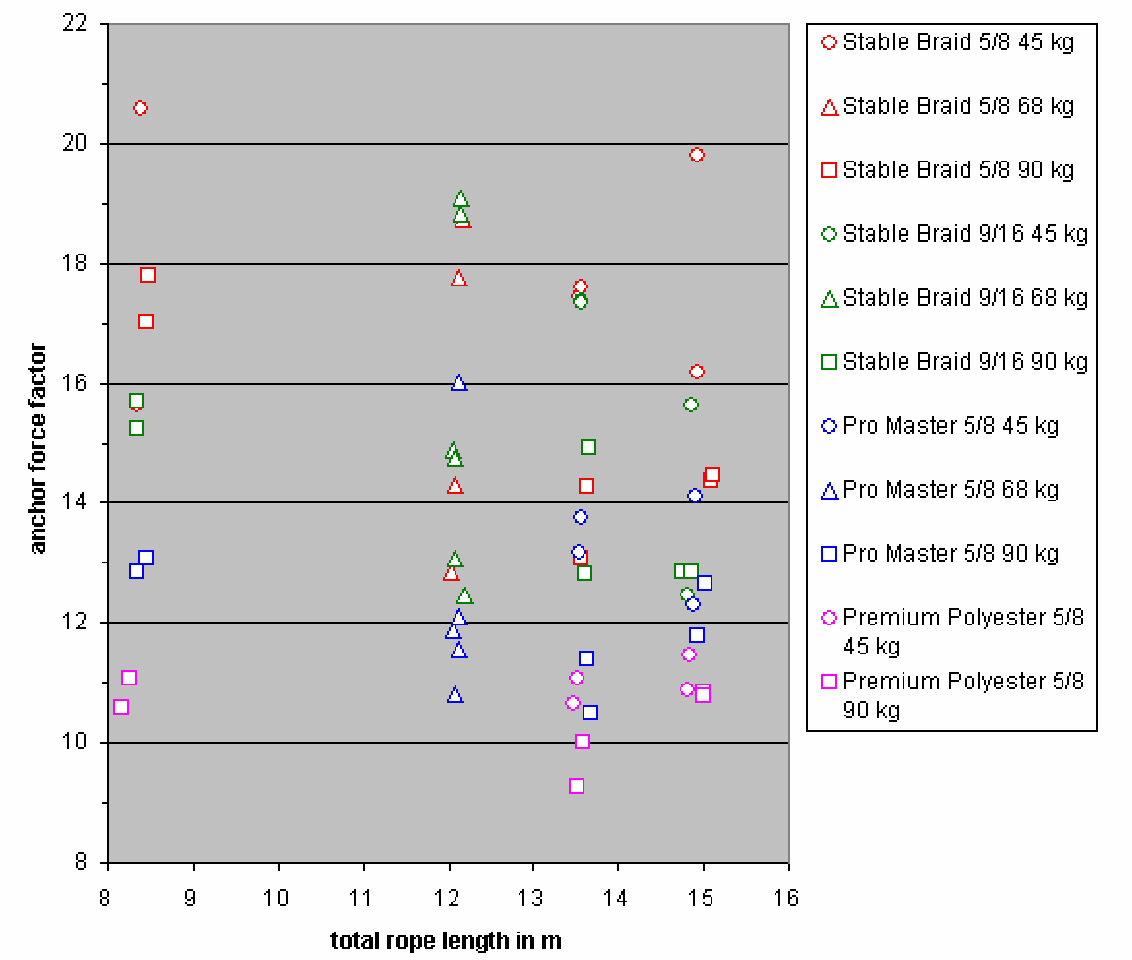

Figure 8.28 Variations in anchor force by rope length and log weight

Due to uncertainties in some of the handwritten notes reviewed in the course of the present research, not all anchor force data could be reliably attributed to specific rigging set-ups. Increased force factors occurring in similar rigging scenarios, for example, may be the result of repeated drop tests carried out on the same rigging, with gradual decreases in the flexibility of slings and ropes leading to a reduced damping effect on the peak force.

Evaluation of drop tests carried out in the present study

On-site tests on two tree species, *F. sylvatica* and *A. pseudoplatanus,* were carried out in the course of this research project. The anchor force factor δ was derived from a strain gauge placed at the axis of an arborist block, instead of a dynamometer placed between block and anchor sling, in order to avoid the additional fall distance introduced by a dynamometer.

The lowered sections were tied off at the friction device to simulate a worst-case scenario. Two logs were gradually decelerated (let run) to determine the difference between a regular rigging operation and the chosen worst-case scenario. A weak linear trend was found, indicating a decreasing anchor force factor for logs of greater mass. The variation in the results is depicted in Figure 8.29, which also shows the linear trend.

When identifying the linear trend, one value was not considered because it was classified as an outlier (or maverick). In this case, a log of only 136 kg mass generated a peak force of 17.2 kN at the anchor point, i.e. roughly 1.75 tons. The anchor force factor (almost 13) that this represented was exceptional and was never reproduced in the course of the present study. The log concerned was the lightest log used in the test series, and it may very well be that its low mass caused other side effects to have a greater influence on the forces being measured. When the total energy turnover and associated forces are relatively small, even small additional forces (such as those occurring when a sling is suddenly stopped from slipping) can have a relatively large effect, since they may represent a greater proportion of the maximum forces generated. Since the actual forces generated in lowering this section were still among the smallest found, it would seem to be appropriate to exclude this outlier from the following discussion.

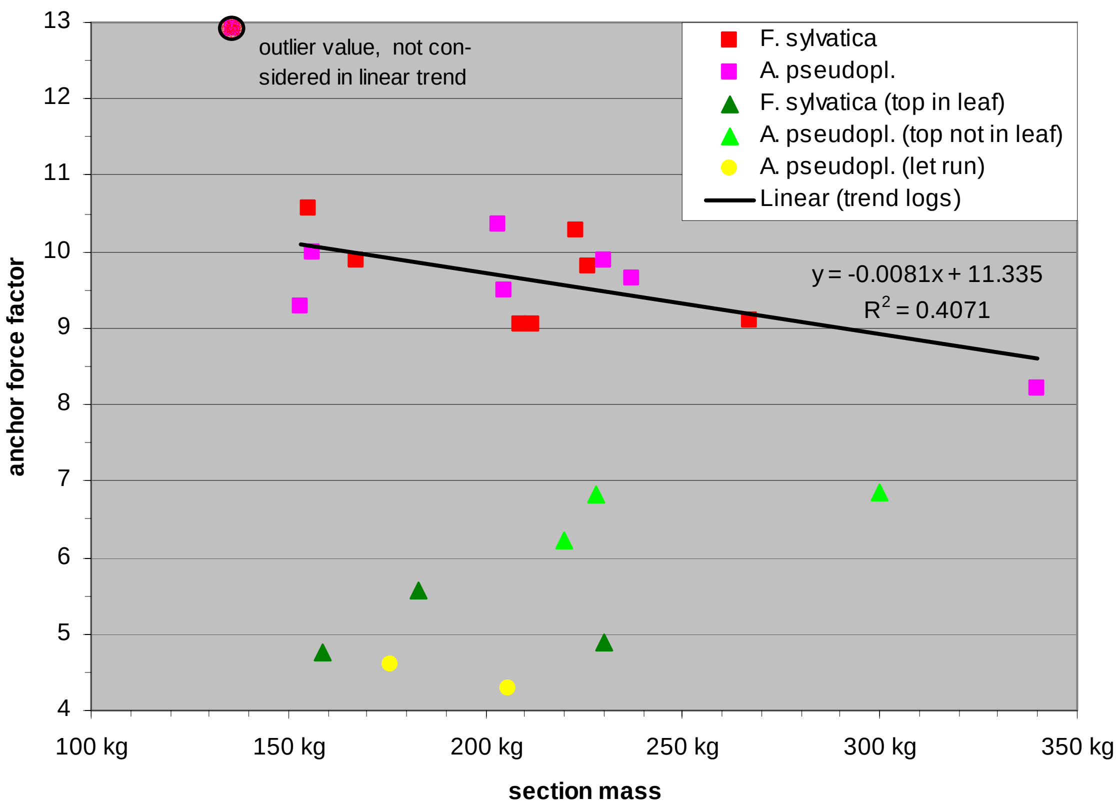

Figure 8.29 Anchor force factors for logs lowered with a 9/16” double-braid rope (Buccaneer)

The tests also showed significant differences between anchor force factors for logs and crown sections. Presumably due to greater aerodynamic resistance, peak forces at the anchor point for crown sections were only 4 to 7 times the weight of the section, whereas logs generated peak forces from 8 to 11 times their weight. Furthermore, crown sections in leaf generated smaller forces than crown sections without leaves. In fact, crown sections with leaves generated forces almost as small as those produced by logs that were let run. The differences are most likely due to aerodynamic resistance, and to speed when hitting the rigging. However, effects of variations in material properties of wood and root system cannot be excluded, as only two species were tested, one with leaves and the other without. These species-related factors may also affect energy dissipation and resultant peak loads generated. Whether or not these effects are significant, and the extent to which they account for the observed differences, needs further detailed study.

From consideration of alpine climbing and roped access work, it might also be expected that the peak force in a rigging system would depend on the fall factor, i.e. the ratio of fall distance to rope length. If a correlation could be found between these parameters, this might provide a means of estimating forces prior to rigging operations. Accordingly, the field data on anchor force factors was checked against the fall factors in the specific set-ups.

Distance of fall was measured as the distance between the log's centroid before and after the drop. The rope length was estimated by measuring the maximum rope length at the end of the drop test (assuming low stretch under the weight of the log at rest). Although these values do not perfectly match the geometry of the set-up at the time when the peak force occurs, it would have been possible to estimate them prior to carrying out the operation. Although no correlation could be found, a trend similar to that with log mass was observed. With increasing fall factor, the anchor force factor decreased slightly. However, this result was derived from logs only, as crown sections were not included.

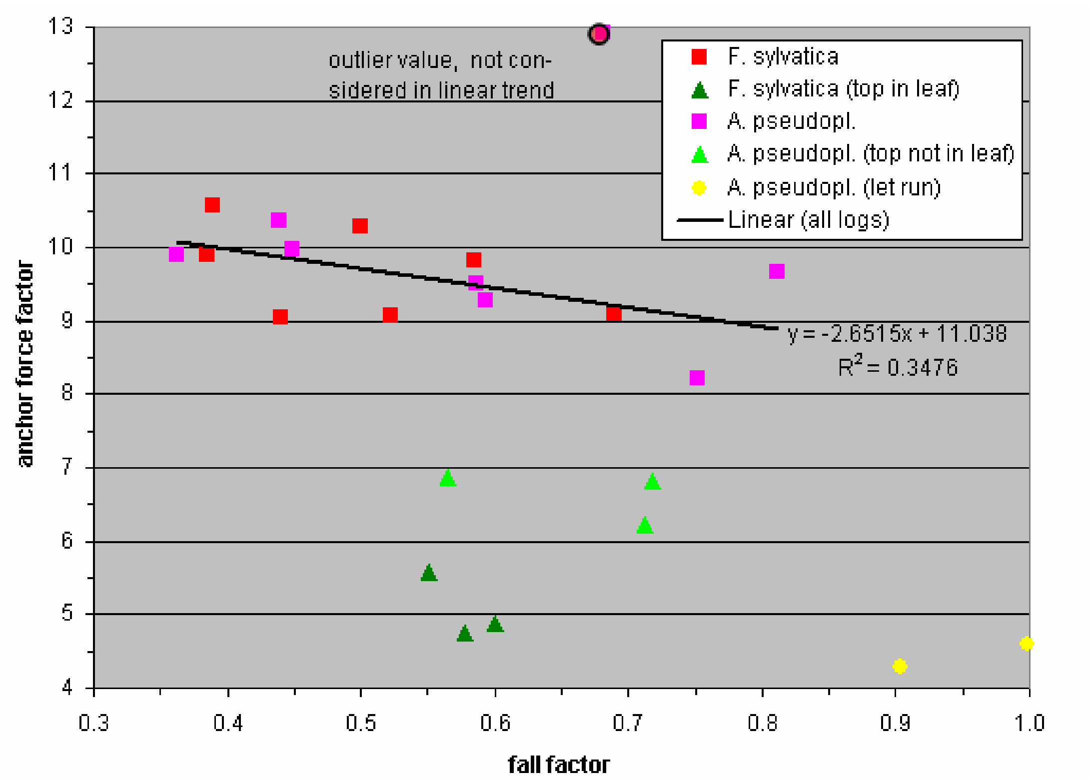

Figure 8.30 Anchor force factor *vs* fall factor

Considering the distance of fall alone, no significant correlation was found between this parameter and the anchor force factor, even when crown sections and the outlier value were excluded from the correlation test (least squares method). Only a weak decreasing trend was observed. Despite the assumption made in Blair's rule of thumb (Blair 1995), force magnification did not occur with distance of fall.

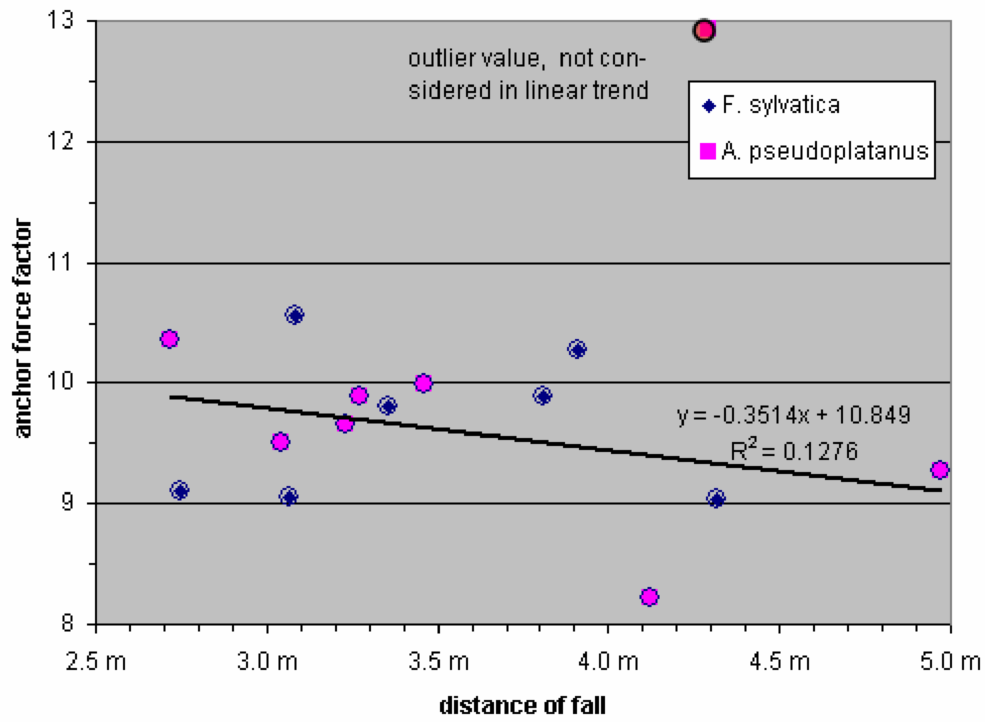

Figure 8.31 Anchor force factor *vs* distance of fall (logs only)

No correlation was found between anchor force factor and rope length. In fact, none of the major parameters, rope length, fall distance, or their ratios (including fall factor), had any direct influence on the anchor force factor. Only decreasing trends were observed in those parameters already discussed. Indeed, the field tests included in the study were not able to identify the relevance of any specific factor involved in generating forces. To achieve successful results in this area, a much greater number of standardised test runs would be required, before any correlation between these parameters and anchor forces could be established. As an alternative approach, in the present, qualitative study, experienced arborists were given the task of choosing suitable anchor points and log sizes, reflecting the way they would proceed in real dismantling operations. This approach allowed for a better understanding of the effects of worst-case scenarios in regular working situations.

This part of the research focused on studying the interaction of all factors in regular rigging scenarios. When arborists choose log sizes and rigging configurations, different conditions can affect the crucial parameters. For example, when the lower part of a stem is rigged, the shorter rope length in the system is usually related to shorter fall distances and greater strength in the tree's structure. On the other hand, when rigging the upper parts of the crown, long sections may be chosen, resulting in greater fall distances, counteracted by greater amounts of rope in the system and smaller diameter sections. In these situations, the tree can also contribute to damping the peak forces to a greater degree, resulting in reduced energy transfer into the rope.

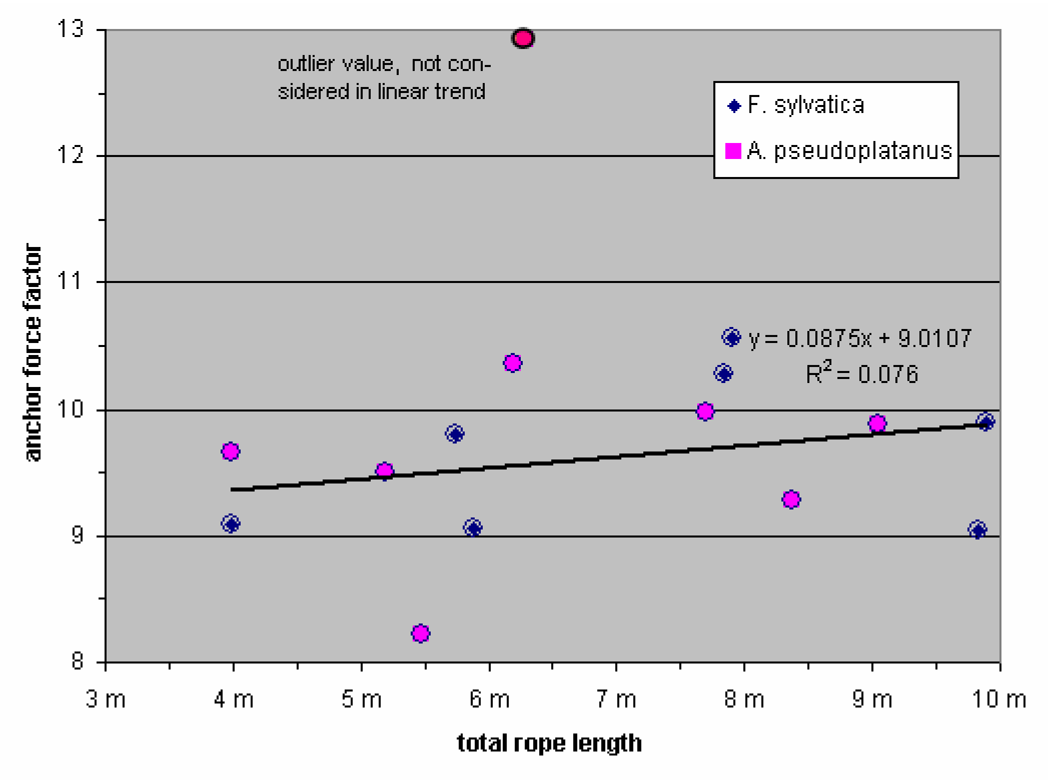

Figure 8.32 Anchor force factor *vs* length of rope in the system

The fact that anchor force factors were surprisingly constant throughout the field tests may be due to the way the study was carried out. If less experienced arborists had chosen the parameters, with less careful consideration of log length, rope type and diameter, and less concern for safety, greater peak forces may have been generated. The dissipation of energy in the rigging system, and the influence of log mass, rope length and rope modulus cannot be disregarded. For this reason, a more complex approach to estimating peak forces, in worst-case rigging scenarios, is required than might seem necessary from the rather constant force factors found in this study.

8.5.4 Comparison of estimated and measured forces

Forces derived from energy equations

In order to test the validity of equation 8.21, the field tests results were checked against force estimates based on the theoretical calculation. Rope length and drop distance Δz_{drop} (see equation 8.7, page 213) were measured prior to the rigging operation. Log dimensions were recorded on the ground, where more exact measurements were possible. The angle between the two legs of the line was assumed at 37° and friction effort at 10%, in accordance with section 8.3.4. Block slippage on the stem, and rope slip in knots and friction device, were estimated in accordance with the median values in Figure 8.16. The peak force at the anchor point was derived from equation 8.22.

The force estimate was based on variables that could be derived by arborists, prior to cutting a section, in real rigging scenarios. Only log mass and rope modulus was determined more precisely than would be possible before an actual dismantling operation. This procedure was chosen to ensure a reliable test of the equation's validity, and its practicability in estimating forces prior to carrying out rigging operations.

The rope modulus for the double-braid rope (Buccaneer Bullrope, 14 mm) was established in a test carried out at Edelmann + Ridder, Isny, Germany, immediately following the previous series of test drops. The strength and rope modulus of the rope were tested on a Zwick testing device. Three parts of the rope were included in the test series: the first two were the ends of the rope that had been utilised as the lead in the drop tests; the third was a middle section that had not been loaded at all. Elongation was measured by optical tracking of markers on the rope and correlated with the applied tensile force. In the calculations, the mean rope modulus in the lead part of the rope (258.21 kN*) was used. It should be noted that rope modulus and residual strength would not be available at this accuracy for ropes used in the field.

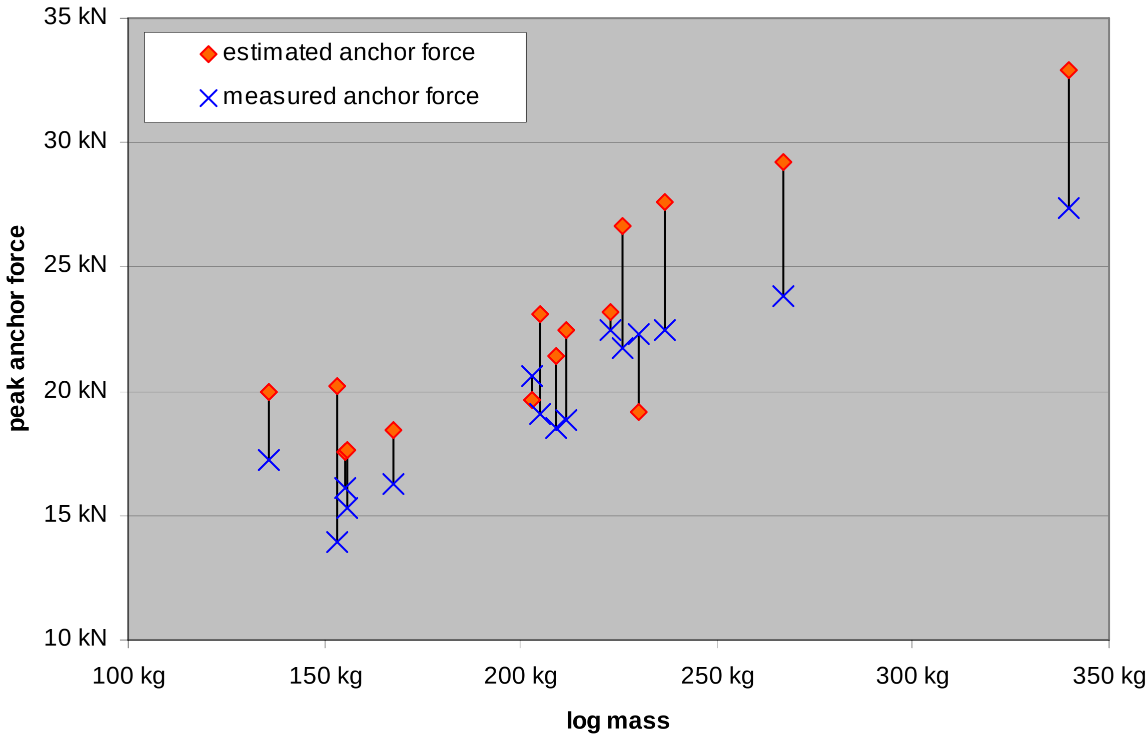

Figure 8.33 Errors in force estimation using energy equation

Equation 8.21 underestimated the anchor force for two of the 15 logs (errors of 5 and 14% respectively). In both cases, the actual distance of fall was considerably further than the estimates would have suggested, and the fall factors (distance of fall *vs* rope length) were among the lowest in the study.

Overestimates ranged from 1.4 to 45%, with only one exception exceeding 25%. The latter result occurred when an exceptionally long log (roughly 4 m) was snatched at 8.6 m, after the other leader of a forked Sycamore had been removed. Overestimates in excess of 20% only occurred where the ratio of fall distance to log length was greater than 1.5, but the reverse did not always hold true (for example, in the case of the two underestimated logs this ratio was also greater than 1.5).

* *Rope modulus is represented as a force (SI-unit Newton). It is defined as the ratio of tensile force to elongation (Gordon 1984). It may be imagined as the force that would be required, in theory, to double the length of a rope (elongation 100%), In reality, the rope would, of course, break before such a great force could be applied.*

To compensate for the two recorded underestimates, a safety factor of at least 1.2 must be applied to the output of the energy equation. The same safety factor would increase a 25% overestimate to 50%. In the exceptional case mentioned in the previous paragraph, where the estimated force was 1.45 times the actual measurement, the overestimation would increase to 75% (or a factor of 1.75). However, taking everything into consideration, equation 8.21 does seem to predict the forces generated by rigging much more precisely than other proposed models, which typically produced errors ranging from almost 175% to more than 380% (e.g. Donzelli *et al* 1998).

The best linear fit to the estimated anchor forces was derived ($R^2 = 0.76$), as was the best linear fit to the measured forces (R^2=0.88) whose y-values were multiplied by a safety factor of 1.2. The best linear fit to the estimated forces was almost identical to the best fit to the modified measured forces, differing only by a slightly different slope. Although this could be interpreted as meaning that the energy equation incorporates an average factor of safety of around 1.2, it could also be a result that only applies to the rigging system and trees used in the field tests. Due to the variance in the data, greater safety margins are essential to ensure its safe application in the field.

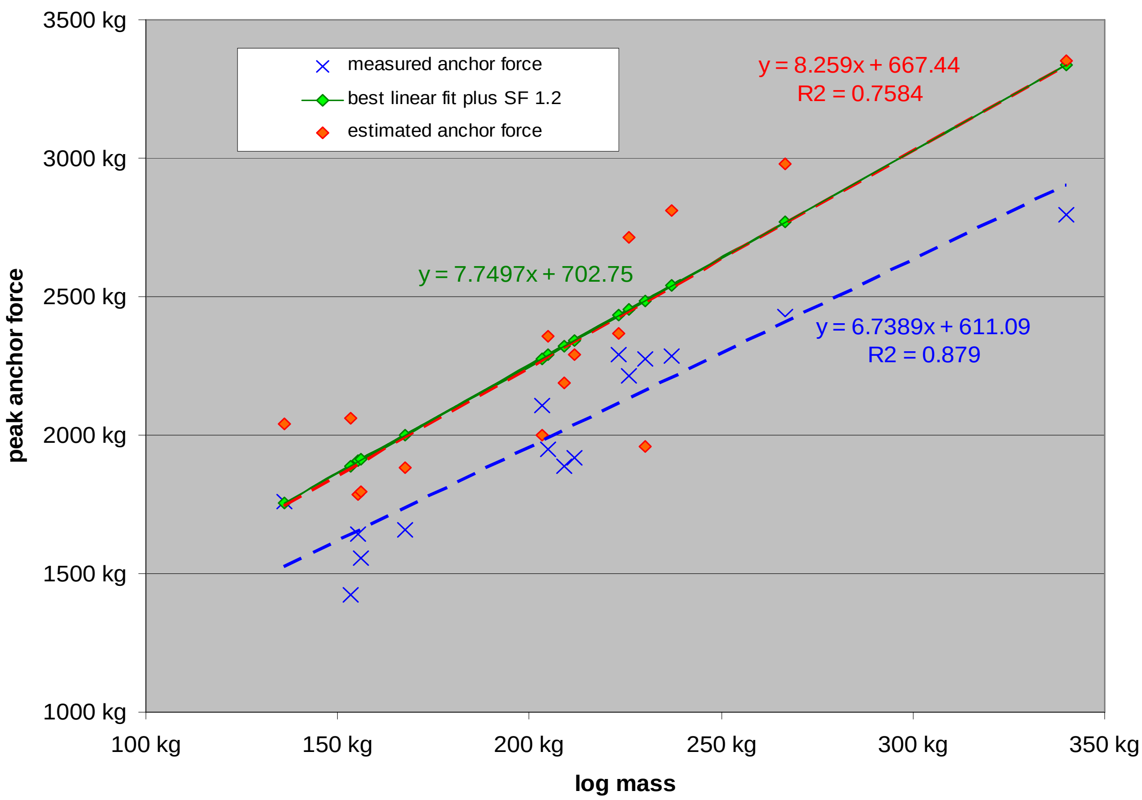

Figure 8.34 Best linear fits to measured and estimated forces

Where the lowering of crown sections is concerned, in order to predict the peak forces different values must be used for the proportion of the potential energy dissipated into strain, and for the angle between the legs of the rigging line. It was found that, estimating the potential energy dissipated by the rope at peak load as 10% of the total, and changing the line angle to 42° from the vertical, would not have underestimated the anchor forces generated when lowering crown sections in leaf (3 drop tests on Beech). In fact, overestimates of from 10 to 42% would have occurred.

With crown sections that are not in leaf (three tests run on Sycamores), it is clear that the portion of the potential energy dissipated into rope stretch is significantly greater. In these cases, assuming that 20% of the log's energy was dissipated into the rope would not have led to an underestimate of the anchor force. In fact, overestimates of up to 45% occurred. However, the small number of tests for this scenario cannot reliably confirm these energy dissipation assumptions. Whereas, for logs, only one out of 15 anchor forces was overestimated by more than 25%, the forces generated by 3 out of 6 crown sections were overestimated by more than 30%. For crown sections, the assumed ratios may be too high, or may need to be more varied than is the case for logs. These are issues that would be worth future study.

For the two logs that were let run, assuming only 2.5% of the potential energy was dissipated into rope stretch, and changing the line angle to 30° from the vertical, would have predicted the anchor forces much more accurately (giving 2% and 7.5% overestimates respectively). The actual fall distance is not measurable under real conditions, and forces involved in such rigging scenarios are so low that they are not normally the object of safety considerations. Nevertheless, by definition, when logs are let run, shock loads that could be a source of risk are avoided.

For the rope used in the tests, load *vs* elongation data (for unused rope) was provided by the manufacturer. According to this data, the rope modulus had decreased, by 10% of its original stiffness, after the drop tests (i.e. the rope became more flexible). Therefore, if the peak force estimates had been made using the rope modulus for unused rope, the generated forces would have been overestimated. In particular, the overestimates for logs would have reached almost 53%, but the underestimates would have been limited to below 10%. For this type of rigging rope construction, this suggests that it may be safer to use the rope modulus for unused rope.

Whether ropes of other constructions and diameters show a similar effect, or show an increase in stiffness after use, are questions that need further investigation. In drop tests carried out by the author and some rope manufacturers, a trend towards stiffening of ropes during repeated shock loads generated from drop tests was observed (see Chapter 7). Should data gained from testing new ropes be used in attempts to estimate peak forces in rigging operations, sufficient factors of safety must be included to allow for any errors due to rope modulus assumptions.

Forces estimated by rules of thumb

A linear correlation between weight and line force, based on a force factor of 5 (Schütte *et al*, 2007) was found to be reasonable at predicting peak forces (for the particular range of rigging operations and rope included in the present study), but it mostly underestimated the forces (by up to 30% in one extreme case). For stiffer ropes or other fall factors, the deviations from the linear behaviour would make this rule of thumb less reliable than it was observed to be in the present field studies. A force factor of 10, as recommended by Blair (1995), would have exaggerated the forces by a factor of between 40 and 120% (see Figure 8.35).

The rule of thumb proposed by Blair (1995) for peak forces in rigging, is that, for each foot the log flies, it gains a unit of weight plus one (*cf* section 8.1.3). This rule of thumb produced force estimations way beyond those actually recorded when the true distance of fall was considered. Where the length of the log was used as the distance of fall, as suggested in Bavaresco (2007), the peak forces, measured at the anchor point and in the line, were underestimated for all logs up to 1.4 m in length. For longer sections, forces were considerably overestimated (see Figure 8.36). In the calculations, the anchor force was assumed to be 1.8 times the line force, with a mean rope angle of 37° and an assumed friction effort of 10% at the pulley.

Evidently, neither the distance of fall, the dimensions of the log, nor its mass alone, can serve as a basis for reliable force estimation.

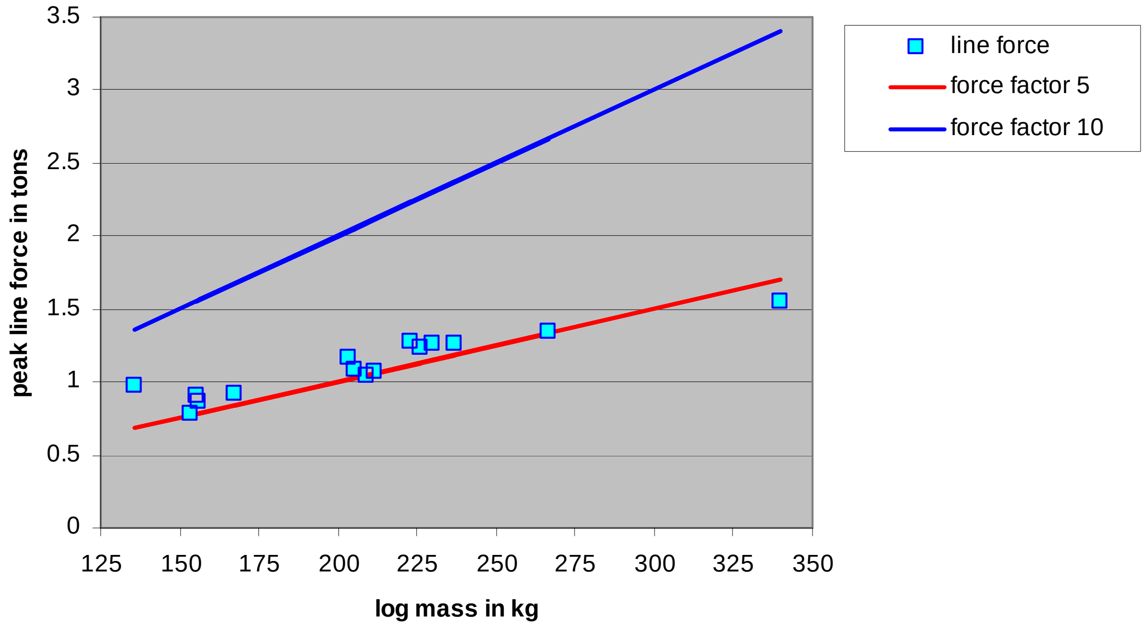

Figure 8.35 Peak line force *vs* log mass

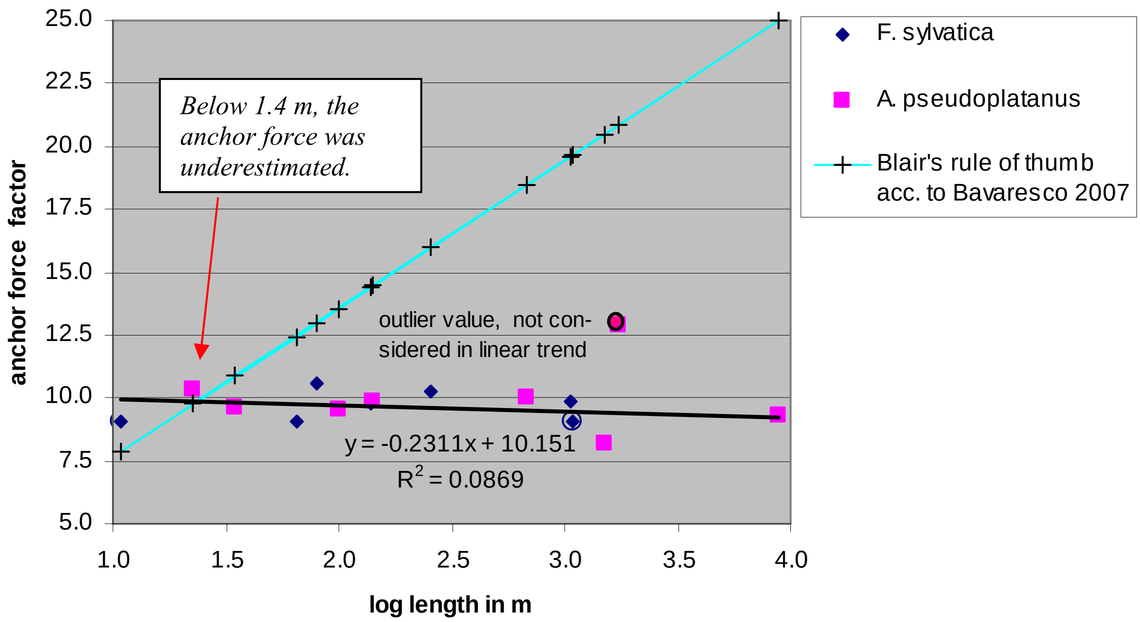

Figure 8.36 Anchor force *vs* log length

The fact that rules of thumb are generally only applicable to certain scenarios should be carefully considered by those advocating their use by arborists. They may well serve as useful means of visualising safe working conditions for training purposes, but they should always be qualified with guidance on how to deal with the variety of changing parameters in real rigging operations. Although the educational software Rigging 1.0 also overestimates the forces generated by rigging operations, software of this type does have the capacity to incorporate different parameters, and to illustrate their effects on peak forces more reliably than rules of thumb. By their very nature, rules of thumb make simplifications in order to be practicable.

8.5.5 Safety margins in rigging operations

The answer as to whether or not a certain rigging system can be regarded as adequate for lowering sections of a certain size, does not depend only on the forces generated. Yet, in a worst case, the material and equipment used must be capable of sustaining the peak loads with sufficient safety margins to prevent failure. As to the question of what magnitude of safety factor is adequate, if most of the variables like dynamic peak forces in shock loading, strength loss of cordage due to wear and knots etc. are properly considered, there is an ongoing discussion in the arborist industry, with different points of view being expressed (Blair 1995, Bavaresco 2001a, Rigging 1.0, Lilly 2005, Schütte *et al* 2007), and as yet no definite answer.

Scenario recommended by the 'Rule of Thumb for Riggers'

The 'Rule of Thumb for Riggers' does not directly aim at estimating peak forces, but is presented as just one part of a wider recommendation detailing how to build a safe rigging system (*cf* Bavaresco, 2007). The rule was developed from practice and based on mathematical calculations for specific constant factors like rope, log length, specific gravity and the rated tensile strength of certain double-braid rope. No guidance is given on the extent to which the method is applicable to set-ups other than those on which it was based, and no guidance is provided on how the recommendation for rope diameter might change in the face of shorter lengths of rope in the system or logs of different length.

In order to judge whether the 'Rule of Thumb for Riggers' is consistent with the findings from the kinematical studies, the peak forces generated from the described standard scenario were estimated by application of equation 8.21. The log's dimensions and the rope length were taken from Bavaresco (2007). The mass of the section was estimated in accordance with the recommendations made in Chapter 5, presuming cylindrical form and a specific gravity for Oak of 1.0. The distance from hinge to the block axis, slippage of the block and rope, and the line angles at peak force, were all assessed according to the methods recommended in previous chapters. Rope modulus was taken from a comparable double-braid (Buccaneer Bullrope). Strength loss due to the attachment knot was assumed to be 45% (which is roughly the maximum figure found in the tests run at Samson Ropes on double-braid ropes of different diameters). The tensile strength of the rope was reduced by 25% to account for strength loss due to previous usage (*cf* Chapter 7).

Results were calculated for four different scenarios of log and rope diameter. A factor of safety of 1.2 was added to the calculated force, to compensate for uncertainties and eventual variations in the parameters involved. The estimated peak force in the lead of the line was compared to the rated tensile strength of the rope, as quoted in Bavaresco (2007), in order to derive the actual safety margins. Bavaresco's assumption, that a working load limit of 10% (derived from a design factor 10) is maintained by this rule of thumb, was not supported by the results (see Figure 8.37). The actual safety margin, under realistic working conditions, was reduced to between 2.3 and 3.2 when reasonable assumptions relating to strength loss for knots and wear were taken into account.

Safety margins in field tests

The rigging operations carried out in the field tests were also checked for inherent safety margins. For this purpose, the actual peak forces measured in the anchor point were utilised. Assuming a standard angle of 37° for the legs of the line at the pulley, and a friction effort of 10%, the line force in the lead was derived. Strength loss due to a Cow Hitch in the 19 mm double-braid eye-sling used at the anchor point was estimated at 40%, in accordance with the findings in Chapter 7.

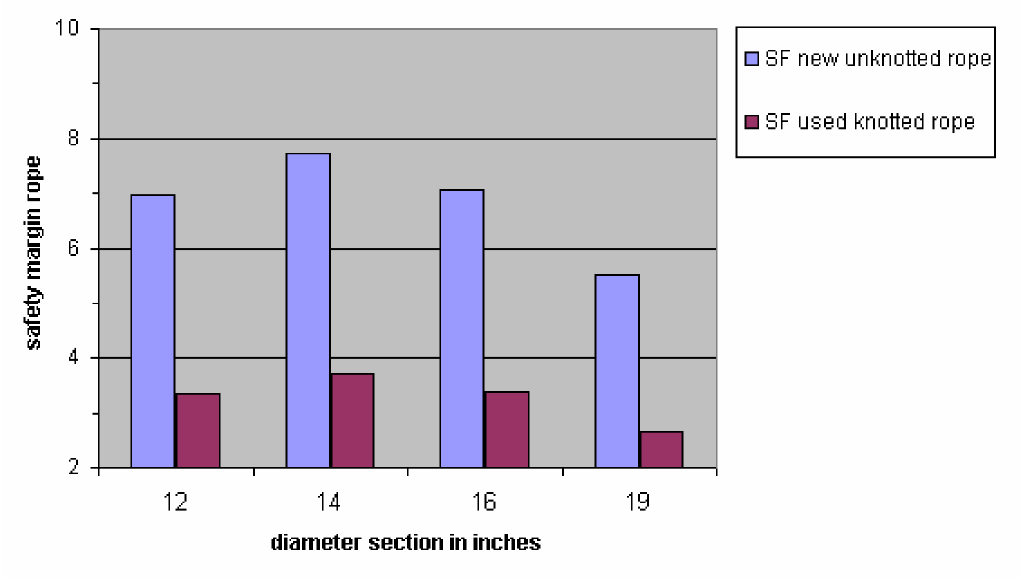

Figure 8.37 Safety margins estimated 'Rule of Thumb for Riggers' scenarios

Strength loss resulting from the Half Hitch in the lead of the 14 mm lowering line was estimated to be 45%, based on conclusions arrived at from the data presented in Chapter 7. Three potential changes to the rigging system were also checked for their effects on the safety margins: firstly, changing the lowering line for one at the next diameter size (i.e. 16 instead of 14 mm); secondly, using a smaller eye-sling only one size greater than the rigging rope (i.e. 16 instead of 19 mm); and thirdly, using a 19 mm Tenex Eye-sling of higher tensile strength. The results are presented in Figure 8.38.

The safety margins were similar for both slings (used at the anchor point) and ropes (used in the rigging system). A larger diameter rope would have increased safety margins in the rope, far beyond those in the sling, so that the eye-sling would have become the weak link. Using a smaller diameter eye-sling would have significantly decreased safety margins for the sling, again making it the weakest link in the system. If a tenex sling is used, the safety margins for the sling are considerably greater than for the lowering line.

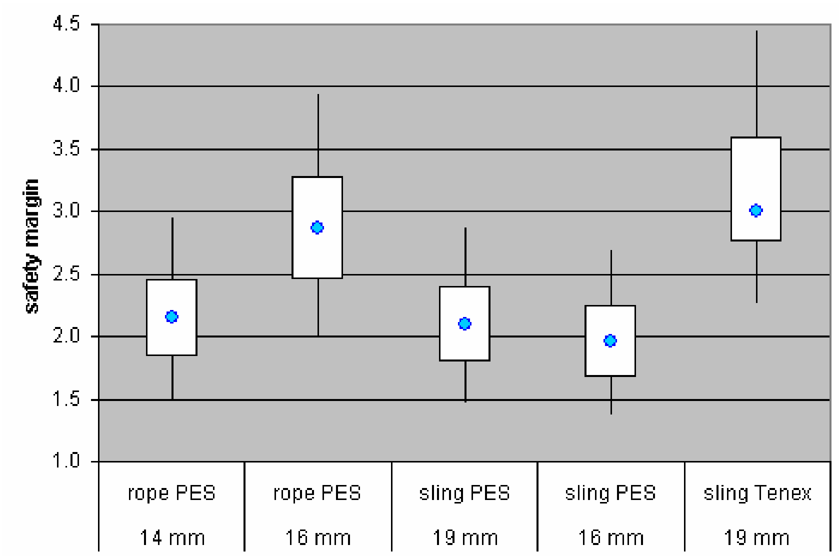

Figure 8.38 Safety margins for field tests and potential changes in components

These considerations indicate that recommended safe working loads for arborists' ropes cannot always be guaranteed in worst-case scenarios. Therefore, it is essential to safety that working practices are utilised that can enable the snubbing-off of logs to be avoided, and the potential loads to be minimised by letting the logs run. It is also essential that the effects of shock loading (where such loading cannot be avoided), on the potential safe-use periods and strengths of rigging lines, are carefully considered.

The effects of shock loading may well necessitate downgrading the safe working load of ropes and/or slings, or may require the most stressed section of a rope (the lead) to be removed, particularly if it is not otherwise possible to completely withdraw the rope from use. Until further investigations can reliably quantify the effects that shock loads have on cordage, no recommendations can be made as to when ropes should be withdrawn from use. In alpine climbing, manufacturers often recommend that climbers should stop using a line after just one standard fall-arrest scenario.

8.5.6 Minimising forces when blocking wood

Arborists have a variety of methods at their disposal with which to minimise the forces generated by dismantling operations. Considering the low safety margins inherent in a worst-case scenario, it would seem to be essential that all means available are used, in technical development, training and education, to ensure that arborists are made aware of the potential hazards involved when logs are eventually snubbed off (either intentionally or accidentally). Donzelli, Lilly (2001) list the following possible actions that can be taken:

"As a rule, forces can be minimized by

- *Cutting smaller pieces*
- *Using a rope with more stretch*
- *Putting more rope in the system*
- *Reducing the distance of fall*
- *Letting the piece run and slowing it gradually." (Donzelli, Lilly 2001)*

Additionally, the following options could possibly reduce peak loads in rigging operations (although they have not yet been subject to rigorous evaluation):

- Retain branches and co-dominant leaders on the stem for as long as possible
- Use shock absorbers that do not significantly lengthen the rope
- Tension the lowering line, at best with a winch, as the line is slack during the log's freefall
- Avoid sling slippage at the anchor point
- Leave side branches on sections to increase air resistance and cushion impact on the trunk

Before such measures can be recommended for general use, further studies may be required to verify their benefits, and to exclude any adverse implications for safety issues.

8.6 IMPLICATIONS FOR CLIMBER'S SAFETY

Keeping forces to a minimum will enhance a climber's safety, because stem bending will be reduced, as a result of which the climber will experience less sway. But, more importantly, some measures that can be taken may also help in minimising the effects of a log's impact on the stem. The impact of a log on the stem may well be the most critical stage for a climber's safety on solid, sound stems. Video footage from drop tests carried out in the course of this research revealed potentially hazardous situations when lowering both logs and top sections. Slender stems generated great amounts of sway, and the impact of a large section could even lift a climber off his spikes. Log dimensions should therefore be kept as small as practicable.

If a log is gradually decelerated, less energy is transferred into the stem. A small log is more likely to bounce back from a stem, because of the greater difference in their relative masses. Momentum is best transferred between bodies when they are of similar mass. If the point of impact lies further down a stem (by letting a log run), the momentum is applied with a shorter lever to the stem base. At lower heights, the log's capacity to cause deflection and oscillation in the stem is correspondingly lower. It was also observed that working on leaning stems adversely affects the outcome for a climber when snubbing off logs. It seems that the impact of a log on a stem is harder when its lean causes the impact to occur earlier in the dropping sequence.

Long and slender stems swayed as a result of a log's weight pulling on the rigging line. The coincidence of a stem swaying back towards a log at the instant of impact could amplify the effects on a climber through the effects of inertia. However, in all of the drop tests studied, the stem was hit by the section either as it was swaying away from the log, or when it was close to the point of maximum deflection, and such a coincidence never occurred.

The forces acting on the climber in the worst-case scenarios did cause spikes to come loose, and did result in flexing of the climber's body. As these effects only occur in the worst-case scenarios that are usually prevented by letting the log run, there is no current concern for long-term health implications. Nevertheless, proper work positioning and belaying is essential in any regular dismantling operation, so that the climber is suitably prepared to deal with any unexpected shock loading of the rigging system, and able to minimise any consequent effects.

Video sequence of log mass 167. 5 kg, length 3 m, sequence interval 460 ms (drop no. 6)

Generally speaking, a second anchor point attached above the climber (e.g. in an adjacent tree) would be the best safety backup. This would also help to minimise body vibration and prevent loss of grip with climbing spikes. Positioning the climber directly behind the log seemed to induce more severe shaking in the climber than positioning at an angle to one side. Pressing the climber's hands against the stem, in anticipation of sway, seemed to transfer more of the vibration to the climber's body, especially when the climber was directly behind the log. Yet letting the stem move freely runs the risk of a climber's chest being slammed against the trunk. However, if the climber's weight can be supported from an anchor point above, and a position about 45° to the side can be adopted, the stem's sway can be easily dissipated.

Deadwood present in the crown of co-dominant leaders was observed to be a potential hazard. Oscillation of the stem could eventually cause small branches to break loose. Although failure of larger diameter branches was not observed, this cannot be excluded, particularly in view of the potentially large oscillations induced by shock loads in the rigging.

Climber in a lateral position to the rigging point, belayed from a second anchor point above

8.7 ADVANCED RIGGING SCENARIOS

8.7.1 Lifting techniques

Generally speaking, loads being lifted are under much greater control than falling loads. When topping down the trunk of a tree, the rigging point is under load and the logs are inevitably allowed to free fall for a certain distance, thus generating considerable shock loads in the rigging system as they are stopped by the rope. The adverse effects of this process can be avoided if it is possible to lift the log from an anchor point above.

As part of the research, tests were carried out to determine the forces generated, in a worst-case scenario, for lifting operations. A 420 kg top was allowed to slide sideways with a small amount of pre-tension (roughly 90 kg) applied. The section slid down by about 1.2 m, before it was caught by the rope, and generated a dynamic force factor at the anchor point of 3.25 (implying a peak anchor force of roughly 1.35 tons).

In a more controlled situation, a 170 kg top was properly cut and winched up from a suitable anchor point. Still the dynamic load factor measured at the anchor point amounted to roughly 2.7 (implying a force of approximately 460 kg). These forces will usually not overload a properly configured rigging system. Yet, the way the pulleys share the load in such a system may be misunderstood, due to the significant role played by friction, especially in lifting operations. Chisholm (2000) provided a table on how pulleys share loads and Bavaresco (2003) presented examples of resultant forces in redirecting pulleys. However, neither of these papers considered the effects of friction on the magnitudes and directions of the resultant forces.

The results of Peter Donzelli's study on the friction properties of arborist blocks can be considered in this context (Donzelli 1999b). Donzelli measured the friction effort involved in lifting loads, and derived static friction coefficients. Sheehan (2004) listed friction properties for pulleys used in vertical rescue scenarios. According to both these authors, the force required to lift a load is significantly greater than the actual weight of the load. Tables provided by Donzelli show that friction is more effective at low weights. To lift a mass of 50 kg (i.e. 490 N), a friction effort of almost 25% is required, increasing the force to more than 600 N. At greater loads, the friction effort is considerably less, up to 17% for a mass of 225 kg.

In lifting operations, the friction in a pulley may result in greater forces in the winching side (fall) of the rope. While friction reduces the resultant forces at the anchor point in a topping down operation, it adds to the load in a lifting operation, because the friction has to be overcome (i.e. more force has to be applied to lift a load). The resultant angle at the pulley is closer to the direction of the fall, just the opposite of what is the case in a topping down scenario.

The data provided by Chisholm (2000) was corrected for equipment of different friction parameters, ranging from an arborist pulley (10% friction effort) to a karabiner or steel link (50% friction effort). In Table 8.2, the rope angle is the angle between the two legs of the line, as used elsewhere in this research report. (Chisholm listed the angle of deflection, which he defined as 180° minus the angle between the legs of the rope.) Friction effort was corrected by the ratio of the line angle to a straight line (180°). Due to the lower resultant force and reduced area of contact, the friction in a pulley decreases as the lines form greater angles. Reference values for friction coefficients are only available for lines exiting pulleys in a more or less parallel way (line angle 0°). In Table 8.2 the 'force angle' columns list the deviation of the resultant force from the direction of the line at which the winch is pulling (fall).

Table 8.2 How pulleys with friction share loads in lifting

Friction	*0%*		*10%*		*25%*		*50%*	
rope angle at pulley	***force factor***	***force angle***	***force factor***	***force angle***	***force factor***	***force angle***	***force factor***	***force angle***
0 °	2.00	0.0 °	2.10	0.0 °	2.25	0.0 °	2.50	0.0 °
20 °	1.97	10.0 °	2.06	9.6 °	2.19	9.0 °	2.41	8.2 °
30 °	1.93	15.0 °	2.01	14.4 °	2.13	13.6 °	2.34	12.4 °
45 °	1.85	22.5 °	1.92	21.6 °	2.02	20.5 °	2.20	18.8 °
60 °	1.73	30.0 °	1.79	28.9 °	1.88	27.5 °	2.03	25.3 °
75 °	1.59	37.5 °	1.63	36.3 °	1.70	34.5 °	1.83	31.9 °
90 °	1.41	45.0 °	1.45	43.6 °	1.51	41.6 °	1.60	38.7 °
105 °	1.22	52.5 °	1.24	51.0 °	1.28	48.8 °	1.35	45.5 °
120 °	1.00	60.0 °	1.02	58.4 °	1.04	56.0 °	1.09	52.4 °
135 °	0.77	67.5 °	0.78	65.8 °	0.79	63.3 °	0.82	59.4 °
150 °	0.52	75.0 °	0.52	73.2 °	0.53	70.6 °	0.55	66.5 °
160 °	0.35	80.0 °	0.35	78.2 °	0.35	75.6 °	0.36	71.3 °
180 °	0.00	90.0 °	0.00	90.0 °	0.00	90.0 °	0.00	90.0 °

Since friction works in an opposite way in lowering scenarios, the effects of friction should always be considered, particularly in scenarios involving the use of redirects. For pulleys used in lowering, the data in Table 8.2 was modified to account for the fact that friction reduces the load in the fall of the line, with regard to a weight suspended from the other end. The revised data is presented in Table 8.3 (overleaf).

In Table 8.3, the force angle is again the angle between the resultant force and the rope at the side where the winch or, in this case, any lowering device is attached. To derive the angle from the other leg of the line, where the load is attached, the given angle must be subtracted from the respective rope angle, as listed in the first column.

Table 8.3 How pulleys with friction share loads in lowering

Friction	0%		10%		25%		50%	
rope angle at pulley	***force factor***	***force angle***	***force factor***	***force angle***	***force factor***	***force angle***	***force factor***	***force angle***
0 °	2.00	0.0 °	1.90	0.0 °	1.75	0.0 °	1.50	0.0 °
20 °	1.97	10.0 °	1.88	10.5 °	1.75	11.3 °	1.53	12.9 °
30 °	1.93	15.0 °	1.85	15.7 °	1.73	16.8 °	1.53	19.0 °
45 °	1.85	22.5 °	1.78	23.4 °	1.68	25.0 °	1.51	28.0 °
60 °	1.73	30.0 °	1.67	31.1 °	1.59	33.0 °	1.45	36.6 °
75 °	1.59	37.5 °	1.54	38.8 °	1.47	41.0 °	1.37	45.0 °
90 °	1.41	45.0 °	1.38	46.5 °	1.33	48.8 °	1.25	53.1 °
105 °	1.22	52.5 °	1.19	54.1 °	1.16	56.6 °	1.10	61.1 °
120 °	1.00	60.0 °	0.98	61.7 °	0.96	64.3 °	0.93	68.9 °
135 °	0.77	67.5 °	0.76	69.3 °	0.74	72.0 °	0.73	76.6 °
150 °	0.52	75.0 °	0.51	76.8 °	0.51	79.5 °	0.50	84.2 °
160 °	0.35	80.0 °	0.35	81.8 °	0.34	84.6 °	0.34	89.2 °
180 °	0.00	90.0 °	0.00	90.0 °	0.00	90.0 °	0.00	90.0 °

8.7.2 Redirects

A common rigging set-up was simulated using specialist software (RescueRigger 6.0), in order to visualise the effects of friction and how pulleys share loads in lifting. Some common load angles in lifting and lowering scenarios were chosen. Friction in the pulley was assumed to be 10%, as expected for kinetic friction in a moving block (although it must be noted that static friction, acting as the motion is about to start, can amount to significantly greater factors of up to 25%).

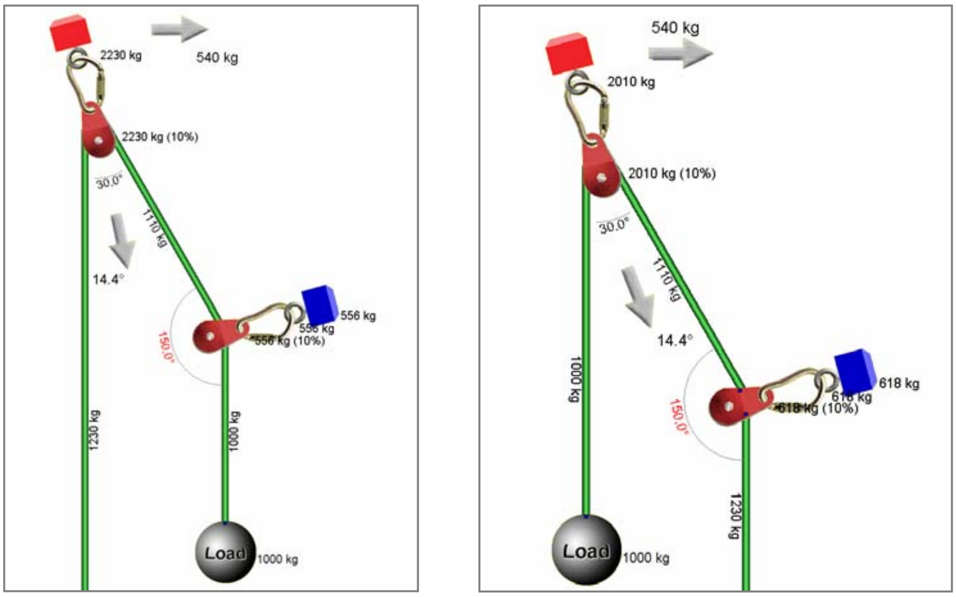

Figure 8.39 Redirect system 30° & 150°, load at bottom & top positions (lifting)*

* *Illustrations created with RescueRigger 6.0*

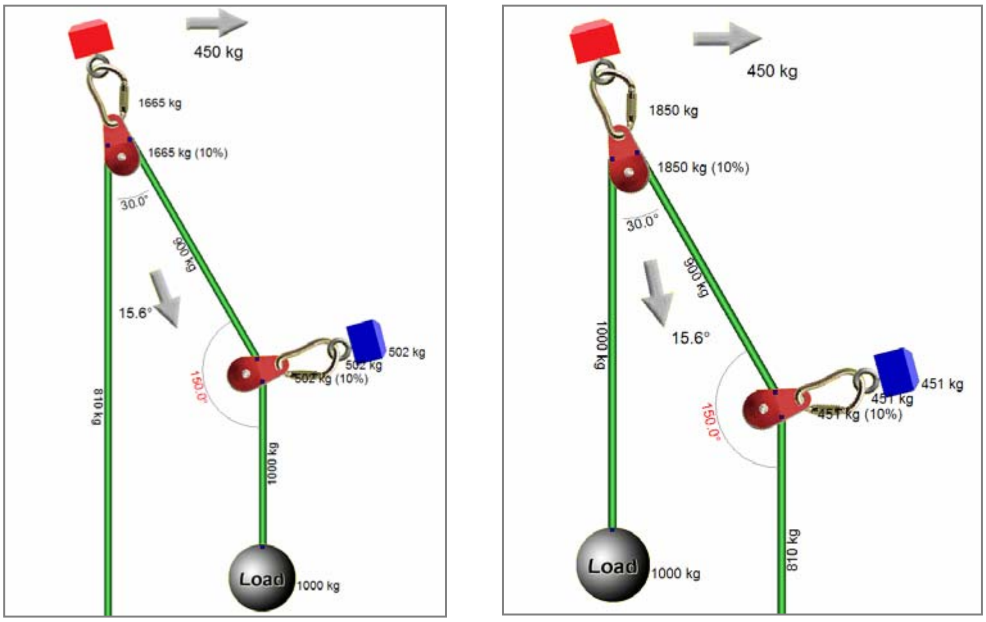

Figure 8.40 Redirect system 30° & 150°, load at bottom & top positions (lowering)*

When redirects are being used, both the load on the main anchor point and the load on the redirect should be considered. In dismantling operations, the maximum tension in the rigging line is expected to occur at an angle of from 32° to 42° from the vertical. Therefore, the bending moment resulting from a redirect in a branch should be estimated in relation to this angle, not to the vertical.

8.7.3 Speedlines

Speedlines provide valuable means of facilitating transport of sections on-site and speeding up the dismantling of large trees (Adams 2006). In a standard scenario, the load is always applied gradually to the speedline, and the eventual peak force generated by dropping the load (section) is taken by a separate rigging system mounted in the tree being dismantled. In order to completely avoid force magnification in the speedline due to dynamic effects, the load would have to be applied so slowly that no sudden change in the tension in the line occurs. In practice, however, some dynamic forces are inevitable, yet they are much smaller than they would be if a load were dropped into a tensioned speedline.

Tensioned speedlines (commonly called zip-lines) are often included in ropes courses set up in living trees for 'outdoor adventure' purposes. Measurements carried out by the author on such installations have shown increases in rope tension of roughly two to three times the attached weight. When a person entered the speedline with a sudden drop, the maximum force was recorded at the very beginning. During a more gentle slide, with the weight of the person being applied gradually, a similar peak force was recorded somewhere in the middle of the slide.

In forest trees, harmonic effects have been observed in speedline scenarios. The maximum force did not occur when the load (a person) was caught by the line, but a little afterwards in a second peak (V. Genenz, pers. comm. 2007). This might have been caused by opposed harmonic frequencies occurring in the zip-line (oscillating with the load) and the trees used as anchor points (oscillating more slowly as a result of bending caused by the initial loading).

* *Illustrations created with RescueRigger 6.0*

The mechanics behind speedlines are complex and beyond the scope of this research. In the course of the literature review, no publication was found that described the kinematics and forces of speedline operations in arboriculture.

> *"... [T]he initial rope tension and stretch (engineers would talk about rope stiffness, the ability to resist stretch)... is the key to solving for the forces in a speedline. Problem is that it now becomes more complicated than just vector diagrams; there are differential equations involved. Just as important, though are some experiments to validate the equations." (Peter Donzelli, cited in (Adams 2006)*

Figure 8.40 Speedline set-up*

From static geometry considerations (see Figure 8.41), it becomes clear that the maximum tension in the speedline will be exerted when the angle between the two legs of the line is greatest. A worst case would be a totally rigid, straight rope that does not sag under an attached load, in which case the tension would be infinite. But, in the real world, ropes always stretch under load, and, at the instant of loading, the angle between the legs of the line quickly increases until the load is suspended by rope tension at a certain height, and then runs down the slope of the line.

At the beginning of the forward motion on the speedline, the log's weight generates a strong forward thrust. As the log moves further away from the stem, the line angle becomes flatter and the tension in the line increases. The implications of friction in the pulleys involved will affect the energy dissipation in the whole process. Until further information is available, it should be noted that speedlines pose specific hazards:

- In order to overcome stretch, a large amount of work may be required (and stored in the rope as elastic energy), unless high-modulus ropes are used.
- Over-tensioning the speedline may increase the forces occurring during the lowering operation, eventually overloading the rope.
- High tensile forces in the speedline will cause great bending moments on the tree used as the upper anchor point, which may need to be guyed or otherwise backed up.
- A steeper gradient in the line will generate a greater forward thrust of the load, and the eventual speed that it gains may be underestimated.

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* *Drawing by B. Kotwica, reprinted from Donzelli, Lilly (2001) courtesy of International Society of Arboriculture, USA*

Before utilising speedlines, arborists must be confident that they can handle the implications and potential hazards involved. At the present time, no guidance is available, only the experience of arborists in finding the right balance, between the slack required to minimise forces and the tension needed to carry the weight of a log over the length of the speedline. Many variables are involved in assessing the load-bearing capacity of living trees under lateral forces such as those generated by speedlines. Speedlines may therefore be regarded as valuable tools that need to be handled with caution.

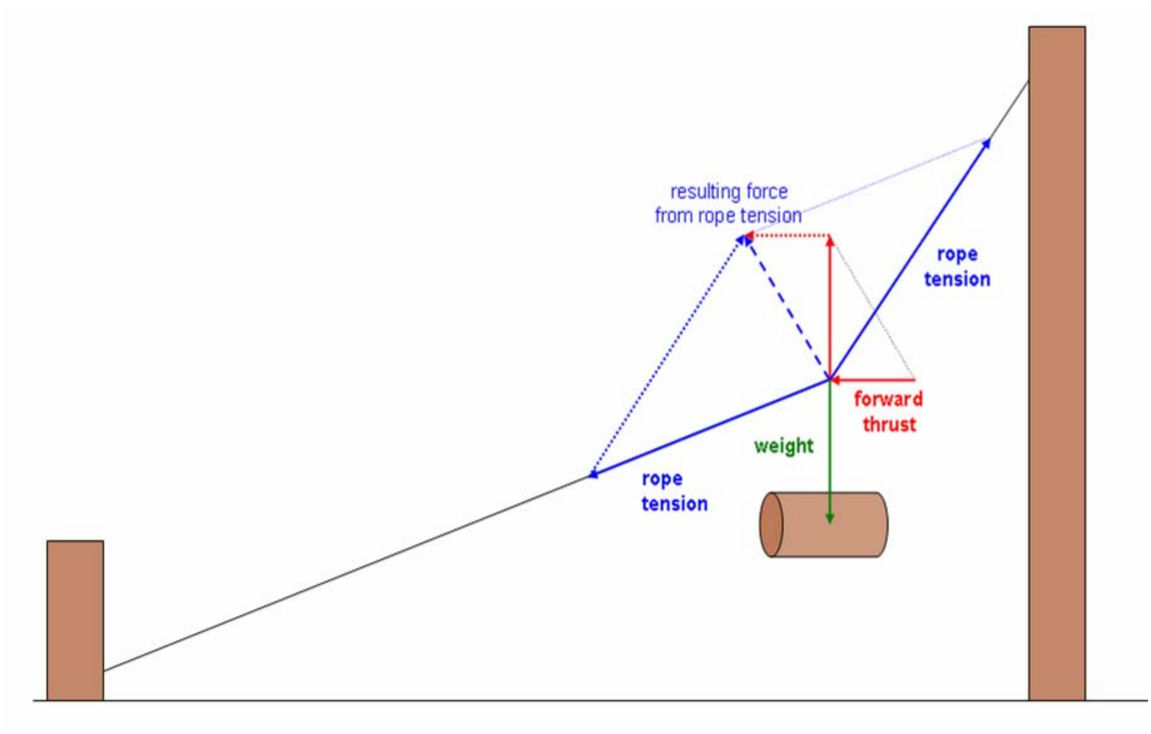


Figure 8.41 Speedline forces

9 CONCLUSIONS

9.1 RISK MITIGATION IN CARRYING OUT RIGGING OPERATIONS

The use of rigging techniques, as described in this report, is one strategy for dismantling trees. It differs from other techniques insofar as it combines the use of synthetic ropes and pulleys, together with the stem of a tree as a natural structure, in dynamic systems that are designed to be loaded with falling logs, which can often be of considerable mass. The different components of a rigging system interact with each other in ways that are complex and not fully understood. Rigging may expose the rigging equipment, the tree, and the climbing arborist, to loads that are great in magnitude and difficult to predict. The hazards involved in rigging, and the potential consequences for the climber, are significantly greater in number, and higher in risk, than those arising in most other arboricultural operations. Therefore, in order to undertake operations safely, a different level of experience, training and individual work planning is also required.

9.1.1 Managing a rigging operation

Procedures need to be established whereby arborists can be reminded of essential precautions to take, and considerations to make, prior to carrying out any dismantling operations involving rigging techniques. By standardising procedures, and thereby directing climbers to reflect upon potential hazards, it should be possible to mitigate against the risk of accidents occurring.

Chapter 1 of this report discusses the essential requirements for managing rigging operations. It emphasises the importance of correct work planning and management. In particular, it describes the essential roles of ‘Responsible Person’ and ‘Competent Person’ in the management of rigging operations. Chapter 1 also presents, in draft form, a ‘checklist’ which, subject to further evaluation and development, could be used to progress rigging work from the initial planning stage through to its completion. Checklists are not new to arboriculture, and are starting to become standard procedures for ensuring that work is planned appropriately and undertaken safely. They currently form part of the educational programme operating in arborist schools worldwide. Subject to checklists being carefully designed, and revised appropriately as practices and procedures change, they can be powerful aids to practising arborists, and should be welcomed by the industry.

9.1.2 Visual tree inspection

Visual inspection of the tree forms an essential part of safety considerations and work planning. Even though loads generated in rigging operations may be high in worst-case scenarios, they are considerably lower than loads acting on tree crowns in normally occurring storms. Extensive structural defects, or previous failure in the load-bearing parts of a tree, have the greatest potential for causing failure during a dismantling operation.

Correctly assessing the severity of visible damage with regard to rigging loads, or detecting hidden weaknesses in trees, requires both experience and specialist knowledge. Specialist training is necessary to develop the skills of arborists in visual tree inspection. In particular, guidance is required on which symptoms may indicate that a tree really does have the potential to fail during a prospective rigging operation.

In many cases, arborists are called in to remove trees, precisely because defects have been detected and the trees have been deemed to be hazardous. The ability to differentiate between the following three types of damaged trees requires profound knowledge and training, but is essential for arborist safety:

- a tree that is still safe to climb and safe to rig
- a tree that is safe to climb (considering the forces likely to arise in an arrested fall or slip), but not safe to be rigged (taking into account the forces generated in a worst-case loading scenario)
- a tree that is not safe to either climb or rig

Red flag indicators (as discussed in Chapter 2) that hint at symptoms for immediate hazard, may be useful in the form of a checklist designed to assist in this differentiation. Often it is not a single symptom, but a combination of observations, that leads an experienced arborist to the conclusion that a tree is not safe to climb. Reliable information on how structural defects affect the bearing capacity of trees is always complex. However, even though simple rules may not be at hand, effective training of arborists in how they perceive and diagnose tree hazards will undoubtedly assist in preventing accidents. Chapter 2 presents a comprehensive description of current knowledge relating to visual tree inspection, and can form a factual basis for designing appropriate training regimes.

Understanding the interaction of trees and wood-decaying fungi, and how physiological symptoms of trees can indicate extensive decay, is an important addition to the identification of mechanical defects. Also, data on species-dependent proneness to failure, and the mechanical properties of wood, can bring additional benefits in making a worthwhile assessment of a tree's condition. Some severe defects may require remedial action and/or additional precautions, both of which should be included in arborist training in rigging techniques. These topics are also covered in Chapter 2.

9.1.3 Safe rigging systems

Chapter 3 describes the processes involved in establishing a safe strategy for undertaking rigging work. It also describes the procedures for selecting appropriate rigging systems (or techniques), and gives a comprehensive description of the equipment (hardware and cordage) available to arborists for this purpose. The basic rigging techniques used in tree rigging operations are also depicted in diagrammatic form. The information provided in the various lists, flow charts and diagrams in Chapter 3 could be developed and represented in suitable formats as *aides-mémoire* that can be made available to practising arborists to assist them in making appropriate selections.

Besides considering the tree itself, and the issues described in Chapter 3, the development of a safe rigging strategy should also include consideration of the strengths and properties of the equipment used, such as ropes, slings, pulleys and friction devices. The condition of the equipment (age, wear and damage), and the specific way it is intended to be used in a rigging system, can alter its load-bearing capacity (e.g. knots tied in a lowering rope). At the same time, the specific configuration of a rigging system will determine the load its components will be exposed to (e.g. the angle that the two legs of the rope form at a pulley block; or the total length of rope used in a rigging system). Safety considerations should always be based on a worst-case scenario.

Safety margins, factors of safety and design factors

The definitions presented on the next page are used in the discussion that follows with regard to specific 'safety factors':

Safety margin the fraction of a rigging component's rated strength that exceeds the load actually experienced, having regard to its application in a certain configuration and state. Example: a 'safety margin' of 2 implies that the rated strength of the equipment is twice the load applied.

Factor of safety the factor incorporated in any safety assessment, especially in engineering calculations, that is applied in order to compensate for uncertainties in any assumptions and deviations from the theoretical model used. Example: a 'factor of safety' of 150% implies that the bearing capacity is calculated to be 1.5 times the estimated peak load.

Design factor the fraction of the ultimate strength of a new, unconfigured, rigging component that is recommended by the manufacturer as the Working Load Limit. In other words, the proportion of the failure load that can be safely tolerated in a rigging application. Example: a 'design factor' of 5 implies that the recommended Working Load Limit is 20% of the ultimate strength (e.g. 10 kN for a 50 kN rope).

The assessment of safety margins, prior to carrying out a rigging operation, involves estimations of, and assumptions about, a variety of different parameters. In order to ensure that any assessment errs on the side of caution, sufficient factors of safety must be incorporated in any calculations. In general, whenever any considerations relating to safety are being made based on assumptions, such factors of safety should always be incorporated to compensate for uncertainties.

Design factors are commonly applied by equipment manufacturers. The recommended Working Load Limit (WLL) of rated hardware components, and the 'design factor' proposed for cordage used in rigging operations are intended to provide sufficient safety margins. Design factors are chosen with regard to several unknown parameters, in terms of both the actual strength of the material in a certain configuration (e.g. knots in a rope, with a certain bend ratio) and its condition at a certain state (e.g. age, wear, abrasion). Furthermore, prospective impact loading is also considered when choosing a design factor (*cf* Cordage Institute, as quoted in Blair, 1999). However, especially with regard to impact loading, manufacturers have stated that standard design factors do not apply.

The term 'design factor' is often used as equivalent to 'safety factor', implying that any rigging system that adheres to recommended design factors will actually produce an equivalent safety margin. In actual fact, a design factor of 5 for a rope (resulting in a recommended Working Load Limit of 20% of the rope's tensile strength) does not guarantee that, in a given rigging scenario, the rope will be able to carry 5-times the load it is exposed to. Simply by forming a knot in the rope, it may lose 50% of its original strength (thus reducing the effective factor of safety to 2.5). Taking into account a typical degree of wear, another reduction of at least 20% might be expected, which would render the rope's actual strength as being only twice the recommended Working Load Limit. Should such a loading actually occur, the safety margin in this scenario would be 2, and not 5 as initially indicated by the design factor.

If it is possible to assess the effects of knots, wear and ageing on rope, as well as to estimate satisfactorily the loads they will be exposed to in rigging scenarios, safety margins might be adequately assessed. Nevertheless, each consideration will bear a degree of uncertainty, which further emphasises the need to incorporate appropriate factors of safety in any calculation. These may be significantly lower than normal design factors, which do not reflect the numerous parameters involved in rigging operations.

Adequate factors of safety

Consideration of factors of safety may start with the weight of a log (or section), a topic which is covered extensively in Chapter 6. If a standard value for specific gravity is used, the weight of a log may well be underestimated by 25%, especially where logs of irregular shape are concerned. Therefore, a factor of safety of no less than 1.3 should be used in calculations.

When estimating the load-bearing capacity of stems and branches used as anchor points (a topic covered in Chapter 5), it is also necessary to use a factor of safety that can accommodate the variations that must be anticipated. In Tree-Statics, a factor of safety of 1.5 has been established as being appropriate for calculations based on standard material properties. This safety factor has been thoroughly tested, and shown to be suitable, in several thousand tests and hazard assessments, and is therefore recommended here as well.

Detailed studies of the residual strength of used ropes, especially where knots are involved, are not yet available. Nevertheless, and for the time being, the tensile strength of new rope may be estimated using factors found in the present research, including a factor of safety of 1.5 (which implies an assumption that actual rope strength may in some cases only reach two-thirds of its expected value). Detailed consideration of strength loss in rope is covered in Chapter 7.

Where ropes are expected to be exposed to dynamic loading, the factor of safety should be at least doubled. Force estimations using the complex formula developed from the results of this study were found to underestimate peak forces generated in a worst-case scenario by up to 20%. This figure may well be exceeded if the rope modulus, and several other parameters in the equation, cannot be assessed as exactly as was possible in this study. A greater factor of safety would account for any additional variation and could reasonably be assumed to be covered by a value of 1.5.

In engineering, only aircraft construction is carried out with lower safety factors (since the application of greater factors could well result in machines that are no longer able to fly). When additional mass is not a problem (e.g. in standard architecture), safety factors of 3 are regularly incorporated in calculations in order to ensure the stability of constructions. Only lightweight designs, such as modern membranes, and other forms of natural construction, are usually calculated with safety factors as low as 1.5 (*cf* Wessolly, Erb 1998). In rigging, increased strength of ropes would have the negative effect of increasing peak forces in shock loading scenarios. Therefore, a factor of safety of 1.5 seems to be adequate for use at this stage, but may need to be reviewed following further investigations.

Appendix 5 contains a worked example, using a factor of safety of 1.5, that demonstrates the principles involved in examining components of rigging systems, with regard to potential forces generated and associated strength requirements. This worked example demonstrates how the results of this study can be used, with regard to the loads: firstly, to perform a risk assessment of a rigging scenario; and secondly, to inform the choice of components to be used in the rigging system, with regard to the loads expected in a worst-case scenario.

Amongst other things, the worked example in Appendix 5 demonstrates that the size of log that can be rigged using such a safe system is quite small. In the worked example, the safety factor that was applied to obtain the estimated knotted strength of the rope is already lower than that frequently recommended by manufacturers (design factor 5, *cf* Samson Catalogue 2005). If the working load limit implied by a design factor of 5 (20% of the knotted tensile strength) had been used in the worked example, the admissible log mass would have been reduced even further.

Some authors recommend applying even greater design factors to arborist ropes, which would result in almost impracticably small log sizes (e.g. Blair recommends a working load limit of 5% of the rated tensile strength of ropes – but it is unclear whether this figure refers to the weight of a section or to the peak force occurring in the line in a shock load scenario, *cf* Blair 1989). As a logical consequence, the application of such rules may lead to an undesirable state where arborists might feel forced to choose between adhering to best practice and working effectively in a competitive context. To avoid this scenario, further considerations should be made as to what design factors are adequate for use in determining the working load limits of used and knotted arborist ropes.

9.1.4 Rigging components selection

In developing a safe rigging system, components must be selected such that their bearing capacities match the peak loads that they might be exposed to in a worst-case scenario. However, increased strength in a component may well affect its performance in a rigging system (e.g. choosing a rope of greater diameter often results in the generation of greater peak forces). With regard to components other than ropes, greater strength can also bear negative implications with regard to the ease of installation and handling (e.g. bulky slings, heavy blocks etc), but may positively increase the factors of safety involved.

It is still unclear whether or not some rigging components are optimised for their intended purpose in rigging systems. An important issue is the reaction and tolerance of a component to shock loading. It is also unclear whether some products increase or reduce the probability of unintentionally shock loading the system. There would be value in investigating this topic in future studies. At the same time, there is a lack of proper user instructions and load ratings for many rigging components commonly used in arboriculture. With regard to regulations like the European Machinery Directive, it is essential that users are equipped with the required instructions and load ratings, in order to ensure that the products concerned can continue to be deployed safely in arboricultural rigging operations in the future. Detailed consideration of rigging components is given in Chapter 4, while Appendices 1 & 2 provide a comprehensive listing of currently available hardware, cordage and textile components, together with information relating to the availability of associated user instructions and load ratings.

Other than ensuring that the equipment to be used has appropriate strength properties, an arborist can also increase safety margins by altering some other factors involved in a rigging operation. Above all, the size of log or tree section to be removed should be subject to careful consideration. When considering the strength of the supporting tree stem, although its structural integrity can reasonably be evaluated through careful examination, its actual load-bearing capacity can only be estimated using standard material properties and the visible extent of defects. The development of more accurate means of determining load-bearing capacities of compromised trees, if possible, would require considerable time and cost-intensive pulling tests with high resolution sensors.

The selection of rigging strategies should always strive to avoid shock loading of the rigging components. Ropes currently used in arboriculture, which have relatively low elongation properties, may not be designed specifically to accept shock loading. Yet it seems to be impossible to completely exclude the occurrence of shock loads in standard rigging operations, or impracticable to deploy ropes that are specifically designed to tolerate shock loading (‘bungee’ type ropes). Therefore, it is necessary for working plans to be used that strive to minimise any peak forces generated by shock loading, and incorporate the minimum acceptable factors of safety in a worst-case scenario.

Where unexpected shock loadings of a rigging system occur, the standard recommendations of Working Load Limits for cordage may well be exceeded in common rigging operations, such as snatching logs or operating speedlines. Shock loads recorded in the field tests reached up to 65% of the knotted tensile strength of the lowering rope being used. Whilst ropes of greater strength may bring increased factors of safety for the rope, they would also, as a result of their greater stiffness, result in increased peak forces being generated. This latter effect would correspondingly increase the loads experienced by other components in the rigging system, e.g. the anchor sling and the block. If ropes of greater strength, but without the increased stiffness, were available for use, safety margins in worst-case scenarios could be improved.

9.1.5 Anchor point selection

The selection of an appropriate anchor point in a tree requires not only a good work plan, but also an ability to correctly assess the load-bearing capacities of tree stems and branches. Experience is the main determinant of the way in which the majority of practising arborists, in their day-to-day work, manage to choose anchor points that are usually capable of supporting the loads generated in standard rigging scenarios. Yet, many arborists underestimate the force that may be generated at an anchor point in the case of an unexpected shock loading. In general, when arborists undertake any tree climbing activities (many of which are for purposes other than rigging operations), anchor points are frequently chosen based on experience gained only in carrying out routine climbing operations under normal conditions. Such choices do not necessarily take into account the potential forces that could be generated as a result of an unexpected slip or an arrested fall.

The intentional snatching of great masses is usually only required when removing the lower portions of a tree’s trunk, or sections of scaffold branches that originate from the bottom of the crown. The load bearing capacity of a solid stem is usually not critical in a tree of relatively large diameter, because the strength of a tree increases with the third power of the diameter. If the force generated in a rigging operation acts with a lever of less than 10 m, the strength of any stem above 60 cm (2 ft) in diameter will generally exceed the strength of any slings used at the rigging point. Therefore, failure of a sound tree trunk is rather unlikely when snatching large diameter logs.

In contrast to the situation relating to normal arborist climbing activities, it is not possible to provide arborists with charts or tables of minimum diameters of branches required to sustain rigging operations. The considerable range of loads generated, branch angles, and lengths of lever arms, is far too wide to be incorporated in simple diagrams or rules. However, the information on the specific strengths of branches of individual species (as presented in Chapter 5) may assist practitioners in making better assessments of the bearing capacities of potential anchor points. Additionally, an understanding of how diameter, load angle and form of a branch union affect the strength of branches should certainly improve the assessment of temporary anchor points.

The strengths of stems can be satisfactorily assessed using simplified models and standard figures for material properties. This approach has been successfully applied in Tree-Statics, and may very well be suitable for arborists to use in assessing safety margins of rigging operations. Simple approximations for strength loss due to decay can be applied in order to further refine an evaluation. With suitable development, it should be possible to make these methods accessible to arborists undertaking tree rigging operations.

9.1.6 Log weight estimation

Weight estimations for more or less regularly shaped logs (conical or cylindrical) can be performed by using reference charts, diagrams and/or worksheets, as illustrated in Figure 6.10 at the end of Chapter 6. The mass of a log can be determined from simple measurements, which can be made using a calliper or any other reference length (e.g. a handsaw). Species-dependent factors for specific gravity, subtractions for taper, and eventually corrections for decay, reaction wood, moisture content etc. can be used to refine the resulting estimate. Suitable reference values are available in currently existing literature.

Weight estimations for irregularly shaped logs, and crown sections, are more difficult to make, due to the lack of adequate models. In the case of logs, tests have indicated that measuring the diameter at a representative point (e.g. at the position of the centre of gravity), produces the best fit for making estimates of weight. Similarly, with regard to branches and crown sections, the centre of gravity can provide some guidance. Many arborists are able to determine the position of the centre of gravity of a branch from experience alone. Despite this, consistently accurate weight estimates are not possible for irregularly shaped logs or crown sections, if only because of the variable nature of both the wood itself and irregularities that occur in living trees. Sufficient safety margins should, therefore, always be included in any safety assessment based on weight estimates prior to carrying out rigging operations.

9.1.7 Forces generated in rigging operations

The shock loading of standard rigging systems with logs of great mass will increase the likelihood of damage to the rigging components, and inevitably shorten their potential working life (through a reduced number of loading cycles to eventual failure through permanent deformation). If it is necessary to snatch logs right down to the final sections of a large stem, the equipment used is likely to suffer to a greater extent, even though any damage may not be visible, or in any other way apparent. As a precaution, cordage that has been shock loaded significantly by heavy loads during a snubbing-off process, may very well need to be removed from service immediately afterwards. Metal components should be inspected for signs of primary failure (e.g. any deformation such as bent cheek plates on a block). Any method of monitoring the loads actually being generated by a rigging operation, or any method of detecting the extent to which a rope suffers from strength loss during use, would assist arborists in deciding whether or not the safe working load has been exceeded, and which part of a rope, if any, should be removed from service.

Shock loading may result in failure of rigging components, because it can reduce safety margins considerably (and catastrophically). At the same time, it is difficult for simple rules of thumb to be produced that can cover the whole variety and complexity of rigging scenarios. Establishing accurate peak force estimates can involve detailed calculations that are best carried out by computers. It would seem to be impracticable for arborists to take exact measurements of the geometry of stem and log, and subsequently to use portable computing devices to estimate potential peak forces, before making each and every cut. But, in training and education, the use of specialised software (such as Rigging 1.0 and RescueRigger 6.0, both of which are referred to in Chapter 8) may be a valuable way of making arborists sensitive to these issues. By such means, it may be possible to develop arborists' awareness of the forces, and their perception of the risks, involved in rigging operations. In the longer term, it can only be hoped that the assimilation of results of future investigations of shock loading may result in the development of more appropriate and comprehensive rules of thumb.

Arborists should always include the possibility of unexpected shock loading, and its potential consequences, in any work plan that they develop for a rigging operation. This can be done, for example, in the following ways:

- by careful system design, incorporating appropriate correctly configured components (in order to minimise the likelihood of accidental shock loading occurring).
- by cutting shorter sections, and using appropriate cutting techniques (in order to reduce the magnitude of the forces that equipment, tree and climber are exposed to).
- by proper work positioning, communication and site organisation (in order to prevent injuries and other consequential incidents arising from an unexpected failure).

Furthermore, it would seem to be essential to ensure that the rope is the weakest link in a rigging system, as recommended by a number of authors. In the case of failure of an item of equipment other than the rope, the energy stored in the intact rope could otherwise turn any failed hardware component into a deadly projectile. That is not to say that the recoil of a failed rope is without risk, but it may well be the lesser of two evils.

A study of forces in rigging aimed at developing means and techniques for reducing peak loads could be an interesting and worthwhile objective for a future research project. Potential for reducing shock loads may lie in the selection of cutting techniques, in utilising the damping properties of rigging systems, or in the development of new items of rigging equipment. However, the full range of possibilities would need to be studied and assessed with regard to the forces generated.

9.2 PROPOSALS FOR PUBLICATIONS

At the present time, a starting point for providing practising arborists with a rigorous means of assessing and mitigating risks in rigging operations, including the prevention of accidental shock loading, could be the promotion of information collected during the course of this research project, via a written ‘code of practice’. This is further discussed in Appendix 6, in which an initial listing of the material that might usefully be included in such a ‘Guide to Good Rigging Practice’ is also presented.

However, in addition to a need for a publication relating specifically to arboricultural rigging operations, discussion with practising arborists has indicated a need for a further publication that incorporates all of the available arboricultural dismantling techniques, in a way that indicates fully, and without bias, their relative merits, and places them in the context of current requirements arising from legislation. A publication of this type is also discussed in Appendix 6, together with a listing of topics for inclusion.

9.3 POTENTIAL FOR IMPROVEMENTS AND INNOVATION

A number of issues were raised during the course of this research project that seemed to offer opportunities for improving the performance of rigging equipment, or for mitigating the risks involved in rigging operations. Some of these indicate the possibility of developing new items of equipment, whilst others are concerned with effecting improvements to techniques that are currently being used.

Even though the following questions may seem to be of a largely theoretical nature, they are presented here, together with the next two paragraphs, as a possible source of inspiration for manufacturers, as well as for arborists and trainers who are concerned to develop their industry:

- Is it possible to develop shock absorbing components that can be added to a rigging system without significantly increasing the distance that logs fall?
- Can ropes be constructed with better shock absorbing properties when placed under greater loads (i.e. with more elasticity at this extreme), whilst still having properties that enable sufficient control to be maintained under low loads (i.e. with relatively little stretch at this extreme)?
- Abrasion damage caused by large forces can be mitigated by incorporating sleeves of appropriate material around contact points that have greater failure potential (e.g. eyes in slings). When large diameter logs are lowered, a substantial amount of rope may pass through the supplementary knot on the log. Is it possible, therefore, to design sleeves that could protect the rope from abrasion and heat damage in the supplementary knot?
- Is it possible to design load indicators, suitable for use under normal working conditions, that can be used to monitor the peak loads experienced by rigging equipment, so that reliable judgements can be made concerning when cordage should be removed from service?
- Can a standard testing protocol be established for arborist ropes (climbing and rigging)?

In consideration of arboricultural techniques that are currently being used within the industry, there was an expressed need for a total review of the complete range of rope access and positioning systems (including working on a pole, using multiple anchor points, static and running rope systems, backup lines etc). Such a review could also be concerned with updating current rope access guidelines, not only with specific regard to rigging operations, but also as part of the development of a prospective ‘code of practice’ for ‘working in a tree from a rope and harness’. In just one example of currently unsatisfactory information, the existing guidelines provide a general recommendation for the use of two tie-in points (or anchor points). Where the removal of hazard trees using climbing techniques is concerned, such a recommendation may not be sufficiently specific. It might be appropriate in such circumstances to recommend that the anchor points be located in two different structures.

In consideration of educational and training materials, a desire was also expressed for the development of methods of visualising the kinematics of rigging operations, the influence of different cutting notches on the flight path of a falling log, and the effects of a log’s impact on various parts of a tree’s stem, including the consequential effects on a climbing arborist. There was also an expressed desire for the use of computer software that can simulate rigging operations (e.g. RescueRigger 6.0, Rigging 1.0) to be incorporated into training programmes for ‘competent persons’, to illustrate different standard scenarios and as an aid in the planning of complex rigging operations.

Methods that provide alternatives to current rigging techniques are already being used in some quarters to avoid high risk scenarios. For example, in the US, Ken Johnson has introduced a rigging system that involves installing lag-bolts and allows shorter stem sections to be lowered. Also, the free falling of logs onto shock absorbing material is being used as an alternative to rigging large stem sections. Particularly for the dismantling of large sections of the lower part of a tree stem, load transfer techniques, drift-lines and floating X:1 lifts (see illustrations in Chapter 3) can be viable alternatives to snatching logs, provided that they are subject to correct design and configuration.

9.4 FURTHER INVESTIGATIONS

Besides illuminating some issues that were previously unclear, this research project also raised a number of questions that could be worthy of further investigation. These questions generally concern essential, yet more specific, elements of the processes involved in carrying out proper risk assessments of rigging operations. The authors hope that other arborists or interested professionals may be encouraged to undertake such studies, and thereby make further contributions towards the full evaluation of rigging practices. By carrying out small studies on any of the following issues, either independently or in coordination with others (including the authors of this report), remaining gaps in the available information may in time be filled:

Characteristics of rigging equipment

- What are the mechanical properties (tensile strength and rope modulus) of used arborist rigging ropes?
- How and to what extent does damage like abrasion, cut strands or melted fibres influence the tensile strength and stiffness of arborist rigging lines?
- What constitutes an adequate test for simulating the loading of arborist ropes in a worst-case scenario?
- Can reference values be determined for ‘cycles to failure’ of different arborist rigging ropes exposed to shock loads typical of a worst-case rigging scenario?
- What are the dynamic (not static) friction coefficients of different arborist blocks, at different levels of load and speed of rotation?
- Can the figures for strength of knotted lowering lines be statistically verified, eventually adding other knot configurations and an evaluation of knot stability in different loading directions?

Properties of trees and tree sections

- What are the strength characteristics of branches, used as anchor points, in other tree species than those so far tested?
- Are the figures for the strength of branch unions/crotches suitable for application to branches that are equivalent in size to those typically selected as anchor points? (Only one recent study actually tested samples of a size typical of potential anchor points i.e. greater than 8 cm diameter.)
- Are there differences in the bearing capacities of living branches between quasi-static loading and the rapid (shock) loading such as occurs in a worst-case rigging scenario (snubbing-off logs)?
- What are the masses of major branches and crown sections; what are suitable form factors for estimating such masses; and how can the positions of the centres of gravity of such structures be effectively determined (e.g. in top sections of conifers, with or without cones)?

Rigging and dismantling techniques

- What are the advantages and disadvantages of different rope access systems that might be used during rigging operations? Specifically, what is the best position for an arborist to adopt whilst cutting a section? How can movement in rigging and climbing anchor points best be accommodated? How can multiple tie-in points be achieved most effectively?
- Are there differences in the stability and strength of typical log attachment knots (e.g. Half Hitch with Running Bowline) where, either 1: the rope is wrapped around the log in the same direction in both knots (C/U/n-shaped), or 2: the direction of the rope alternates from primary to subordinate knot (S/Z-shaped)? (See Figure 9.1)

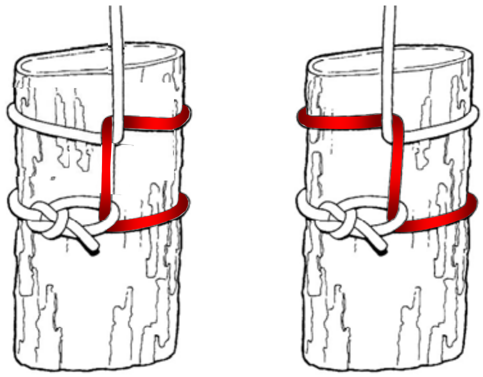


Figure 9.1 C/U/n-shaped (left) and S/Z-shaped (right) formation of log attachment knots*

Kinematics of, and forces generated in, dismantling operations

- Does the cutting technique (e.g. notch form and depth, hinge height and thickness) affect the rotation and flight path of a log?
- How does the damping effect of retained branches on conifers and broad-leaved trees affect tree sway during rigging operations, and does it also effectively reduce peak loads generated in a worst-case scenario?
- Can the positioning of the friction device at an adjacent tree opposite to the drop zone effectively reduce peak loads? Are there any other safety implications arising from such a scenario? (If the rope angle on the tension side [fall] matches the angle on the load side [lead] of the rope when peak loading occurs, the stem may not experience any bending force. It may only be loaded in compression, because its axis would be parallel to a line bisecting the angle between the two legs of the line.)
- How great is the influence of the rope modulus and rope length on peak loads generated in a worst-case scenario (continuing Peter Donzelli's studies)?
- What is the effect of other parameters such as log size, aerodynamic resistance, stem dimension etc. on the kinematics of, and forces generated in, snatching logs?

* *Modified, original drawing by B. Kotwica, reprinted from Donzelli, Lilly 2001, courtesy of International Society of Arboriculture, Il, USA*

- What are the kinematics of, and how great are the forces generated in, other rigging scenarios (including speedlines)? Is there a rigging technique that effectively reduces forces in snatching? Is there a rigging scenario that generates even greater forces than snubbing logs off (e.g. letting a section run and then suddenly stopping it)?
- How does applying friction at the rigging point affect peak forces and the reactions of the tree (as occurs when using a ‘Distel’ block, a device that does not involve a running sheave on an axis, but works like a small bollard)? How much does friction reduce the damping effect of the rope?

9.5 LIMITATIONS AND RISKS

The objective of the present research was to determine best practice in undertaking arboricultural rigging operations. The work undertaken in this study will provide the arboricultural industry with a review of currently used rigging practice and the available means for assessing the major parameters affecting the safety of a rigging strategy. The authors were required to collect data on different issues involved in rigging operations, and to carry out detailed investigations into other aspects. The findings of this project were required to be processed into easily accessible, practicable and yet reliable forms. While these objectives may have been achieved in some parts, they proved to be not achievable in other parts.

Unfortunately, the budget for this comprehensive research did not allow for the scientific studies to be carried out on sufficient samples to produce statistically approvable data, that could finally answer some questions that still remain open to debate. Therefore, with regard to the practical tests carried out in the present study, a rather more qualitative approach was chosen. Such methods attempt to describe the processes taking place, to detect eventual correlations and to derive hypotheses that may serve as a basis for future research projects (that may or may not verify the findings of the present study in the future).

Some issues, such as estimating the forces generated in rigging operations, are simply too complicated to be described in simple models, tables and graphs. Only computer software would be able to provide a quick, reliable estimate of forces, in a way suitable for application prior to carrying out a rigging operation. Means of simplifying the calculations that did not significantly change the reliability of the results were not found in the present research.

For other points considered in this project (such as the strength of branches used as anchor points), the great variability in the mechanical properties of the natural wood material, and in the loading scenarios applicable to anchor points, did not allow for precise recommendations to be formulated. For the specific case of branch anchor point strengths, it did not prove possible to devise a chart that could assist in determining minimum branch diameters.

As far as tree section weights are concerned, significant changes in weight can result from geometrical, physiological, anatomical or structural variations. The available data has usually been derived under standardised laboratory conditions. It shows strong deviations and variability within species. Therefore, any simple means of assessing the weight of a section is likely to be prone to wide deviations, and any such assessment will require safety margins of some degree to be built in to the calculations.

The characteristics of a number of components of current rigging systems are not yet known. As long as manufacturers do not provide the required data, it is not possible to obtain the respective factors of safety applicable to rigging operations using these components. Consequently, if a list of approved components were to be prepared, it would not be possible to include these products in it. Yet, some of them are already being used by many arborists, possibly worldwide.

Too little information is available on the strength of used ropes. Ropes undergo changes in strength as a result of wear, changes in condition, and degradation (e.g. due to abrasion, dirt, moisture, UV light exposure etc.). Manufacturers only determine material properties for new and unused rope. As long as reliable data on strength loss in arborist ropes remains unavailable, the required factors of safety to determine safe working loads can only be derived from experience.

Within the scope of this study, it was not possible to definitively determine best practice. This is due to the lack of statistically approved data, the great natural variation in a range of parameters, the complexity of the structures involved, and the absence of reference data that could be drawn upon. At the present state of development, essential parameters, that require evaluation in rigging scenarios for safety reasons, have to be assessed from the limited, qualitative, base data now established. Yet, confirmation of the information being used in this way by quantitative testing, and of statistical significance, is still lacking.

Therefore, it was not possible to determine entirely definitive factors of safety. If factors of safety are chosen that are too high to accommodate all the variables, they may produce unrealistic results in terms of practicability and efficiency, and may therefore not gain industry acceptance. If factors of safety are chosen that are too low, the resulting levels of risk might be too high, and dangerous situations could result. Although definitive factors of safety cannot be prescribed, sufficient information has been gained for guidance to be provided, for issues requiring further study to be highlighted, and for improved training and hazard awareness to be promoted among arborists.

Full and effective presentation of the results of this study is not possible in a printed format, although it is hoped that this document, as it stands, will serve to inform the industry in a generally beneficial manner. However, there is considerable scope for the information to be communicated to the industry in the form of separate articles or via other educational material or media. For example, to enable a working arborist to fully appreciate the concepts of energy dissipation, tree dynamics and the effects of shock loads on a climbing arborist, media such as interactive presentations or video displays may be more suitable. Certainly, the breadth and volume of information contained in this report might be more palatable if presented via a number of publications specific to different subject/target groups. In any event, the authors hope that the knowledge gained through this project will be successfully communicated to the various target audiences concerned, and may perhaps even inspire other researchers to pick up on some of the questions posed in this chapter (or suggested by the contents of the report in general).

APPENDICES

APPENDIX 1 RIGGING HARDWARE COMPONENTS*

* *The contents of the tables presented in this appendix are not intended to be an exhaustive listing of the entire product market. Furthermore, the inclusion (or omission) of any particular item of equipment cannot be regarded as implying or conferring any specific recommendation.*

TABLE 1 (part 1) Rigging Hardware – Impact Blocks

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMI RP130	125			16				1030		Steel cheekplates. Threaded anchor pin location. No User Instructions.
	CMI RP131	178									Steel cheekplates. Threaded anchor pin location. No User Instructions.
	Hobbs Block	350	10:1	35	25	107	4.25		2840	254x150x49	Sheet aluminium cheekplates. Threaded anchor pin location. No User Instructions.
	ISC RP050	100	5:1	20	13				1479	182x100x65	Cast aluminium cheekplates. Spring-loaded anchor pin. No User Instructions.

TABLE 1 (part 2) Rigging Hardware – Impact Blocks

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	ISC RP051	100	5:1	20	16				1565	182x100x65	Cast aluminium cheekplates. Spring-loaded anchor pin. No User Instructions.
	ISC RP054	150	5:1	30	16				2222	227x127x72	Cast aluminium cheekplates. Spring-loaded anchor pin. No User Instructions.
	ISC RP055	150	5:1	30	20				2310	227x127x72	Cast aluminium cheekplates. Spring-loaded anchor pin. No User Instructions.
	ISC RP057	225	5:1	45	20				3432	258x160x70	Cast aluminium cheekplates. Spring-loaded anchor pin. No User Instructions.
	ISC RP056	100	5:1	20	20				1550	182x199x37	Steel cheekplates. Threaded anchor pin location. No User Instructions. Stainless steel cheekplate option.

TABLE 2 (part 1) Rigging Hardware – Rescue Pulleys (single sheave)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMI RP112 Double-ended pulley	38			16			96.6	318	146x76x	Bearing
	CMI RP129NFPA 3" Prusik pulley	71			13			91.7	750	171x133x	Bushing
	CMI RP 106 3" Pulley	71			16			94.1	613	240x108x	Bushing
	CMI RP108 4" Pulley	71			16			95.6	818	190x127x	Bearing
	CMI RP123 4" Pulley	89			16			94.6	1000	127x121x	Bearing

TABLE 2 (part 2) Rigging Hardware – Rescue Pulleys (single sheave)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMI High Line Pulley	66			19			91.4	1590	267x132x	PVC sheave
	CMC Pro Series Red Pulley	76			13	95	7.3		850	198x143x34	Bearing
	CMC Rescue Pulley	47			13	38.1	2.93		145	89x63x23	Bearing
	CMC Pro Series Hi-Line Pulley	36							1500	250x122x84	Aluminium sheave. Bearing
	ISC RP021 Small Prusik Pulley	40			13				218	104x70x28	Bushing
	ISC RP017 Medium Prusik Pulley	45			13				369	130x88x28	Bushing

TABLE 2 (part 3) Rigging Hardware – Rescue Pulleys (single sheave)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	ISC RP018 Large Prusik Pulley	50			16				446	156x106x30	Bushing
	Kong Alby	50			26				1150	237L	
	Petzl Minder P60	36	4.5:1	8	13			97	310		
	Petzl Kootenay Knot Passing Pulley P67	40	4:1	10	8-19	76	4		1390	260L	

TABLE 3 (part 1) Rigging Hardware – Rescue Pulleys (double sheave)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMI RP133NFPA Double 2" Sheave Prusik pulley	58			13			186	704		
	CMI RP106D Double 3" sheave pulley	89			16				1045	190.5x102x	Bearing
	CMI RP125 Double 4" sheave pulley	111			16				1818	229x121x	Bearing
	CMC Rescue Swivel Pulley	32.7			13	38	2.93		320	135L	
	CMC Pro Series CSR Swivel Double Pulley	52.5			13	70	5.4		1000	196x102x51	Swivel eye

TABLE 3 (part 2) Rigging Hardware – Rescue Pulleys (double sheave)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMC Pro Series Double pulley Gold	62			13	57	4.38		595	173x109x51	MBS Becket 24.5kN
	Kong Twin	50			16				490	142L	
	Petzl Twin P65	44	3.66	12	13			97	580		

TABLE 4 Rigging Hardware – Trolleys

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Efficiency (%)	Weight (g)	Approx Dimensions LxWxD (mm)	Notes
	CMI Velocity Micro Trolley	62.6			13			341	127x 6.2x	
	CMI Trolley HD and Maxi rigging plate	62.5			19			1704	240x238x	
	ISC RP036 Tandem Pulley	40			13			1500	190x143x70	
	Petzl Tandem P21	24	2.4	10	13		71	195		Bushing
	Petzl Tandem Speed P21SPE	24	2.4	10	13		95	270		Bearing

TABLE 5 (part 1) Rigging Hardware – Hauling Sets

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMC CSR Pulley Kit										
	CMI MicroS	31.2			13				205	159x57x	
	CMI MicroD	31.2			13				250	159x57x	
	CMI RP110D Double Micro	31.2			13			133	113	89x44x	
	CMI UpliftNFPA	53.5			13			184	1091	254x101x	

TABLE 5 (part 2) Rigging Hardware – Hauling Sets

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Max rope diameter (mm)	Tread diameter of sheave (mm)	Bend ratio for max rope diameter	Efficiency (%)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	CMI UP101	53.5			13			184	750	184x95.3x	
	ISC RP702 Single Rescue Hauler	45			13				634	220x80x	
	ISC RP703 Double Rescue Hauler	45			13				856	220x80x	
	ISC RP701 Double Pulley	45			13				543	150x75x	
	ISC RP700 One-way friction double pulley	45			13				734	170x84x60	

TABLE 6 (part 1) Rigging Hardware – Anchors (closed)

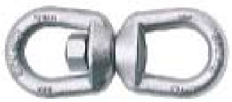
Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	Crosby S-643 7/8” x 4” Weldless Steel Ring	192	6:1	32	1236	146x146x23	
	Crosby A-341 Weldless Steel Pear Link	186	6:1	31	250	100x75x	WLL valid for load on multiple legs <120^o
	CMC Pro Series Aluminium Swivel	45.9			184	114L	
	Crosby G402 5/8 Steel Swivel	115	5:1	23	1130	197x75x38	

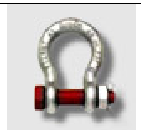
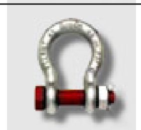
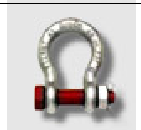
TABLE 6 (part 2) Rigging Hardware – Anchors (closed)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	Petzl P58L Aluminium Swivel	36	7.2:1	5	167	107x50x37	
	CMC Aluminium Micro Anchor plate	40.6			57		
	CMC Aluminium Anchor Plate	50.4			170		
	CMI SS Bearpaw	62.6			245	170x127x	
	CMI Aluminium Maxi Rigging Plate	62.6			500	240x120x	

TABLE 6 (part 3) Rigging Hardware – Anchors (closed)

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Weight (g)	Approx dimensions LxWxD (mm)	Notes
	ISC RP300 Aluminium Rigging Plate	55			58	91x84x5	
	ISC RP310 Aluminium Rigging Plate	55			262	166x108x9	
	ISC RP320 Aluminium Rigging Plate	55			471	249x150x9	
	ISC Steel Rigging Plate						

TABLE 7 (part 1) Rigging Hardware – Connectors (opening)

Product image	Product description	* Shape	MBS Major axis (kN)	Design factor	WLL Major axis (kN)	MBS Minor axis (kN)	MBS Gate open (kN)	MBS Out-side load on gate (kN)	MBS Side load on gate (kN)	Gate open-ing (mm)	* Locking mechanism	Weight (g)	Approx dimensions LxW (mm)	* Notes
	CMC Rescue XL	H	41								SL, 2A	663-683	218(L)	CP
	CMC Rescue karabiner	B	40								SL, 3A	283-308		
	Crosby 2130 3/8" Bow Shackles		54	6:1	9		N/A			16.5	Nut & pin security	150	63x45	
	Crosby 2130 ½" Bow Shackles		107	6:1	17.8		N/A			20.5	Nut & pin security	360	83x59	
	Crosby 2130 5/8" Bow Shackles		174	6:1	29		N/A			43	Nut & pin security	764	106x75	

***** *See key below part 5 of this table.*

TABLE 7 (part 2) Rigging Hardware – Connectors (opening)

Product image	Product description	* Shape	MBS Major axis (kN)	Design factor	WLL Major axis (kN)	MBS Minor axis (kN)	MBS Gate open (kN)	MBS Out-side load on gate (kN)	MBS Side load on gate (kN)	Gate open-ing (mm)	* Locking mechanism	Weight (g)	Approx dimensions LxW (mm)	* Notes
	DMM Oval	X	30	4:1	7.5 (765kg)	9	10			18	SL, 2A, 3A	150-167	106x56	CP
	DMM Offset D	B	45	4:1	11.25 (1147kg)	9	10	22	16	18	SL, 2A, 3A	226-270	109x63	CP
	DMM BOA	H	40	4:1	10 (1019kg)	10	12	22	16	24	SL, 2A, 3A	258-300	123x76	
	DMM Captive eye	D	45	4:1	11.25 (1147kg)	10	12	22	16	16	SL, 2A, 3A	250-306	131x70	
	DMM Scaffold hook	H	45	4:1	11.25 (1147kg)	12	12	22	16	38	2A	652	195x115	CP
	DMM Side-opening Kwiklock	H	40	4:1	10	12	12	22	16	52	2A	442	194x113	CP

***** *See key below part 5 of this table.*

TABLE 7 (part 3) Rigging Hardware – Connectors (opening)

Product image	Product description	* Shape	MBS Major axis (kN)	Design factor	WLL Major axis (kN)	MBS Minor axis (kN)	MBS Gate open (kN)	MBS Out-side load on gate (kN)	MBS Side load on gate (kN)	Gate open-ing (mm)	* Locking mechanism	Weight (g)	Approx dimensions LxW (mm)	Notes
	ISC KH311 Oval	X	22							18	SL, 2A	90	107x58	
	ISC KH200 Offset D	B	50							20	SL, 2A, 3A	220	112x64	
	ISC KH212 HMS	H	40							23	SL, 2A, 3A	263	120x80	
	ISC KH301 Captive eye	D	50							18	SL, 2A, 3A	240	130x73	
	ISC KH251 Captive Swivel	D	35							18	SL, 2A, 3A	330	166x73	
	ISC KH307 Fireman	H	40							50	SL, 2A, 3A	389	170x97	
	ISC KH400 Atlas	H	45							57	2A	740	211x142	
	ISC KH450 Big Dan	H	50							25	SL, 2A, 3A	278	123x90	

***** *See key below part 5 of this table.*

TABLE 7 (part 4) Rigging Hardware – Connectors (opening)

Product image	**Product description**	*** Shape**	**MBS Major axis (kN)**	**Design factor**	**WLL Major axis (kN)**	**MBS Minor axis (kN)**	**MBS Gate open (kN)**	**MBS Out-side load on gate (kN)**	**MBS Side load on gate (kN)**	**Gate open-ing (mm)**	*** Locking mechanism**	**Weight (g)**	**Approx dimensions LxW (mm)**	**Notes**
	ISC KH415TL	H	70							33		535		
	Kong Oval	X	24			10	6			16	SL	143	106L	
	Kong XL Carbon steel	B	50			13	20			27	SL, 2A, 3A	245-255	114L	
	Maillon Rapide Oval Standard MRNZ20.0	Q(X)	200	5:1	40					26	SL	1100	178L	
	Maillon Rapide Oval Long MRGOZ20.0	Q(X)	180	5:1	36					35.5	SL	1.220	200L	
	Maillon Rapide Delta MRDZ20.0	Q	150	5:1	30					24	SL	1185	176x112	
	Maillon Rapide Pear MRPZ16.0	Q(H)	100	5:1	20					29.5	SL	717	177x96	

***** *See key below part 5 of this table.*

TABLE 7 (part 5) Rigging Hardware – Connectors (opening)

Product image	Product description	* Shape	MBS Major axis (kN)	Design factor	WLL Major axis (kN)	MBS Minor axis (kN)	MBS Gate open (kN)	MBS Out-side load on gate (kN)	MBS Side load on gate (kN)	Gate open-ing (mm)	* Locking mechanism	Weight (g)	Approx dimensions LxW (mm)	Notes
	Maillon Rapide Square MRCZ18.0	Q	130	5:1	26					23	SL	875	153x107	
	Omega Pacific ½" Modified D NFPA	B	56			11	18			38	SL	363	152x93	
	Omega Pacific ½" Modified D	B	65			12	24			22	SL	269	113x69	
	Omega Pacific Ladder Hook OPLH8L	H	41				11			60	SL	683	223x111	
	Stubai Super 5000	B	50			10	35			16	SL	245		
	Stubai Oval	X	40			20	15			28	SL	305	130x75	

**** Shapes:*** *B – Basic e.g. offset D karabiner*
D – Directional e.g. captive eye karabiner
H – HMS e.g. pear-shaped karabiner or Maillon Rapide
K – Klettersteig
Q – Screw closure connector (Maillon Rapide)
X – Oval connector

Locking mechanisms: *SL – Screw lock*
2A – Two action autolock
3A – Three action autolock
4A – Four action autolock

Notes: CP – Captive pin option

TABLE 8 (part 1) Rigging Hardware – Rope Brakes

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Tread diameter of brake drum (mm)	Maximum rope diameter (mm)	Bend ratio for max rope diameter	Weight (g)	Notes
	Buckingham Port A Wrap III Small (Steel)	30.8	7:1	4.4	33.5	12.7	2.6	635	
	Buckingham Port A Wrap III Standard (Steel)	52.8	6:1	8.8	47.6	15.8	3.0	1837	
	Buckingham Port A Wrap III Large (Steel)	79.2	9:1	8.8	60.3	19	3.1	3311	
	Drayer Port-a-wrap III B30			3.5	60	14		3500	Nach dem belegen des Bremsgerätes immer auf eine Vorspannung des Seiles achten. (Das Bremsgerät hängt vor dem belegen unter dem Anschlagpunkt. Bei Belastung wird es über den Anschlagpunkt nach oben gezogen.)
	Drayer Poller B60			5.0	100	18		7800	Montage immer mit 2 Spanngurten durchführen. Spanngurte immer durch die dafür vorgesehenen Halterungen am Kopf und am Fuß des Pollers führen.

TABLE 8 (part 2) Rigging Hardware – Rope Brakes

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Tread diameter of brake drum (mm)	Maximum rope diameter (mm)	Bend ratio for max rope diameter	Weight (g)	Notes
	Freeworker Port A Wrap – small GT53A					13			
	Freeworker Port A Wrap GT533					18			
	Freeworker Rigging Poller GT56								
	Grube Abseil-Poller/Bremse 71-818								
	Hobbs Rope Brake								

TABLE 8 (part 3) Rigging Hardware – Rope Brakes

Product image	Product description	MBS (kN)	Design factor	WLL (kN)	Tread diameter of brake drum (mm)	Maximum rope diameter (mm)	Bend ratio for max rope diameter	Weight (g)	Notes
	ISC AE150 Porta Wrap			10.0	76.5			2500	
	Petzl Tuba D12	22			50.5	13	3.88	1240	Allows passage of knots around brake drum.

TABLE 9 (part 1) Rigging Hardware – Combined Rope Brakes and Tensioning Devices

Product image(s)	Product description	MBS (kN)	Design factor	WLL (kN)	Tread diameter of brake drum (mm)	Maximum rope diameter (mm)	Bend ratio for max rope diameter	Weight (kg)	Notes
 	The Good Rigging Control System (GRCS)	Bollard 177.9 Winch 91.6	10:1	Bollard 17 Winch 9	Bollard 101.6 Winch 92.1 (Harken 46)	Bollard 22.2 Winch 19.1	Bollard 4.6:1 Winch 4.9:1	Frame 19 Bollard 2.9 Winch 13.2	
	Hobbs H2. Lowering and Lifting Device			Preservation Mount 4.5 Standard Mount 8.9 Cut in Mount 13.4					
	Kong Baobab					12-16			

TABLE 9 (part 2) Rigging Hardware – Combined Rope Brakes and Tensioning Devices

Product image(s)	Product description	MBS (kN)	Design factor	WLL (kN)	Tread diameter of brake drum (mm)	Maximum rope diameter (mm)	Bend ratio for max rope diameter	Weight (kg)	Notes
	Borsky Spezial Winch	75	3:1	25	110	20	5.5	30	Winching ability 5kN
	Tree Runner Harken self-tailing winch 71-825					8-14			Winching ability 310-1000daN
	Tree Runner Bremswinde 71-820					20			

APPENDIX 2 CORDAGE AND TEXTILE COMPONENTS*

In the tables presented in this appendix, the following abbreviations are used:

Abbreviation	**Material**	**Also known as**
VEC	High Modulus Polyester	Vectran Liquid Crystal Polymer
PES	Polyester	
ARA	High Modulus Polyamid	Aramid group, including Technora, Twaron, Kevlar
PA	Polyamid	Nylon, Perlon
DYN	High Modulus Polyethylene	Dyneema, Spectra
PP	Poly-propylene	PP Multifilament
PE	Polyethylene	Polythene

* *The contents of the tables presented in this appendix are not intended to be an exhaustive listing of the entire product market. Furthermore, the inclusion (or omission) of any particular item of equipment cannot be regarded as implying or conferring any specific recommendation.*

TABLE 1 (part 1) Arborist cordage – Rope (single braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Liros D-Pro 12mm	12 Strand Hollow braid (Dyneema)	61	85	7	12.2	0.9 1.3 1.6	3.2	48	73	
	Mamutec Baracuda 12mm	Parallel braid (PES)	112	40							
	Mamutec Baracuda 14mm	Parallel braid (PES)	146	50							
	Mamutec Hake 12mm	Parallel braid (PES)	112	29							
	Mamutec Hake 12mm	Parallel braid (PES)	146	38							
	Mamutec Piranha 12mm	Parallel braid (DYN/PES)	105	73							
	Mamutec Shark 12mm	Parallel braid (VEC/Technora)									

TABLE 1 (part 2) Arborist cordage – Rope (single braid)

Product image	**Product description**	**Construction (material)**	**Mass (g/m)**	**MBS (kN)**	**Design factor**	**WLL**	**Extension at 10, 20 & 30% MBS (%)**	**Extension at break (%)**	**Knotted strength (kN)**	**Spliced strength (kN)**	**Notes**
	New England V12 12mm	12 Strand Hollow braid (Vectran)	125	125							
	New England T12 12mm	12 Strand Hollow braid (Technora)	124								
	New England Endura 12 12mm	12 Strand Hollow braid (Dyneema)	77								
	New England Nerex 12.7mm	12 Strand Hollow braid (PES)	132								
	New England Nerex 14.3mm	12 Strand Hollow braid (PES)	156								
	New England Nerex 15.9mm	12 Strand Hollow braid (PES)	177								
	New England Nerex 19.1mm	12 Strand Hollow braid (PES)	267								
	New England Nerex 22.2mm	12 Strand Hollow braid (PES)	379								

TABLE 1 (part 3) Arborist cordage – Rope (single braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	New England Nerex 25.4mm	12 Strand Hollow braid (PES)	482								
	New England Treeline 15.9mm	12 strand (PES)	164	38.4							
	New England Treeline 19.1mm	12 strand (PES)	223	54.6							
	New England Treeline 22.2mm	12 strand (PES)	342	78.6							
	New England Treeline 25.4mm	12 strand (PES)									
	Samson Validator 12 12.7mm	12 Strand Hollow braid (Vectran)	131	143							
	Samson Tech 12 12.7mm	12 Strand Hollow braid (Technora)	119		10:1	13.5 (spliced)	0.63 0.96 1.20			135	Elastic elongation figures are for stabilised rope
	Samson Amsteel 12.7mm	12 Strand Hollow braid (Dyneema)	95	112							

TABLE 1 (part 4) Arborist cordage – Rope (single braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Samson Tenex TEC 9.5mm	12 Strand Hollow braid (PES)	64		5:1	5.0 (spliced)	1.4 2.3 3.0			25	Elastic elongation figures are for stabilised rope
	Samson Tenex TEC 12.7mm	12 Strand Hollow braid (PES)	149		5:1	10.6 (spliced)	1.4 2.3 3.0			53	Elastic elongation figures are for stabilised rope
	Samson Tenex TEC 15.9mm	12 Strand Hollow braid (PES)	220		5:1	15.3 (spliced)	1.4 2.3 3.0			77	Elastic elongation figures are for stabilised rope
	Samson Tenex TEC 19.1mm	12 Strand Hollow braid (PES)	285		5:1	20 (spliced)	1.4 2.3 3.0			101	Elastic elongation figures are for stabilised rope
	Samson Tenex TEC 22.2mm	12 Strand Hollow braid (PES)	397		5:1	27.9 (spliced)	1.4 2.3 3.0			140	Elastic elongation figures are for stabilised rope
	Samson Tenex TEC 25.4mm	12 Strand Hollow braid (PES)	516		5:1	36 (spliced)	1.4 2.3 3.0			182	Elastic elongation figures are for stabilised rope
	Samson Arborplex 12.7mm	12 Strand (PES+Polyolefin)	101	24.3	4.5:1	5.4	3.0 3.3 4.2				Elastic elongation figures are for stabilised rope
	Samson Arborplex 15.9mm	12 Strand (PES+Polyolefin)	179	37	4.5:1	8.2	3.0 3.3 4.2				Elastic elongation figures are for stabilised rope

TABLE 1 (part 5) Arborist cordage – Rope (single braid)

Product image	**Product description**	**Construction (material)**	**Mass (g/m)**	**MBS (kN)**	**Design factor**	**WLL**	**Extension at 10, 20 & 30% MBS (%)**	**Extension at break (%)**	**Knotted strength (kN)**	**Spliced strength (kN)**	**Notes**
	Samson Arborplex 19.1mm	12 Strand (PES+Polyolefin)	241	54	4.5:1	11	3.0 3.3 4.2				Elastic elongation figures are for stabilised rope
	Teufelberger Vectran 3000 12mm	12 Strand Hollow braid (Vectran)	92	102	≥5:1	use dependent	0.3/0.7/1.1	3.5		95	
	Teufelberger Ocean 3000 12mm	12 Strand Hollow braid (Dyneema)	54	90	≥5:1	use dependent	0.3/0.7/1.1	3.4		80	
	Yale Vectrus 12.7mm	12 strand Hollow braid (Vectran)	119	104.4	3.6	2.9					
	Yale Aracom 100 12.7mm	12 strand Hollow braid (Technora)	115								
	Yale Maxibraid 12.7mm	12 strand Hollow braid (Spectra)	102	106.4	4.5	23.7					
	Yale Yalex 9.5mm	12 strand Hollow braid (PES)	59	24.1	4.5	5.4					
	Yale Yalex 12.7mm	12 strand Hollow braid (PES)	134	50.2	4.5	11.2					

TABLE 1 (part 6) Arborist cordage – Rope (single braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Yale Yalex 15.9mm	12 strand Hollow braid (PES)	189	73.1	4.5	16.3					
	Yale Yalex 19.1mm	12 strand Hollow braid (PES)	253	96.4	4.5	21.4					
	Yale Yalex 22.2mm	12 strand Hollow braid (PES)	381	142.6	4.5	31.7					
	Yale Yalex 25.4mm	12 strand Hollow braid (PES)	481	172.3	4.5	38.4					
	Yale PE12 12.7mm	12 strand (PES)	126	42.7	4.25	10					
	Yale PE12 14.3mm	12 strand (PES)	156	56.3	4.25	13.3					
	Yale PE12 15.9mm	12 strand (PES)	176	62.2	4.25	14.6					
	Yale PE12 19.1mm	12 strand (PES)	235	82	4.25	19.3					

TABLE 1 (part 7) Arborist cordage – Rope (single braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Yale PE12 22.2mm	12 strand (PES)	351	121.2	4.25	28.5					
	Yale PE12 25.4mm	12 strand (PES)	424	146.9	4.25	34.6					
	Yale XTC12 12.7mm	12 Strand (PES+Polyolefin)	100	24.1	4.5	5.36					
	Yale XTC12 15.9mm	12 Strand (PES+Polyolefin)	150	39.4	4.5	8.75					

TABLE 2 (part 1) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Buccaneer Power Pull 12.7mm	Double braid (PES/PES)	119	43.8	5-10		1.8/3.6/4.7	12			
	Buccaneer Power Pull 14.3mm	Double braid (PES/PES)	150	44.6	5-10		1.8/3.6/4.7	12.1			
	Buccaneer Power Pull 15.9mm	Double braid (PES/PES)	193	74.1	5-10		1.8/3.6/4.7	12.5			
	Buccaneer Power Pull 19.1mm	Double braid (PES/PES)	267	82.6	5-10		1.5/3.0/3.6	12.9			
	English Braids Braid on Braid 12mm	Double braid (PES/PES)		33.5							
	English Braids Braid on Braid 14mm	Double braid (PES/PES)		51							
	English Braids Braid on Braid 16mm	Double braid (PES/PES)		62							

TABLE 2 (part 2) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	English Braids Braid on Braid 18mm	Double braid (PES/PES)		75							
	English Braids Braid on Braid 24mm	Double braid (PES/PES)		140							
	Gleistein Heavy Green 16mm	Double braid (PES/PES)	174	67							
	Liros Vectran Olympic 12mm	Triple braid (VEC/PES/PES)	105	54	7	7.7	0.8 1.2 1.4	3.0	20	46	
	Liros Aramid 12mm	Triple braid (ARA/PES/PES)	163	34	7	4.9	0.9 1.3 1.6	3.5	12	29	
	Liros Runner 12mm	Triple braid (ARA+PES/ PES/PES)	104	66	7	9.4	1.0 1.4 1.7	3.6	10	56	
	Liros Regatta 2000 12mm	Triple braid (DYN/PES)	87	82	7	11.7	1.1 1.4 1.8	3.4	30	68	
	Liros Drayer 12mm	Double braid (PES/PES)	125	47	7	6.7	3.0 4.4 5.9	9.0	23	41	

TABLE 2 (part 3) Arborist cordage – Rope (multi-braid)

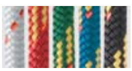
Product image	**Product description**	**Construction (material)**	**Mass (g/m)**	**MBS (kN)**	**Design factor**	**WLL**	**Extension at 10, 20 & 30% MBS (%)**	**Extension at break (%)**	**Knotted strength (kN)**	**Spliced strength (kN)**	**Notes**
	Liros Drayer 14mm	Double braid (PES/PES)	177	56	7	8	3.1 4.6 6.1	9.1	27	48	
	Liros Drayer 16mm	Double braid (PES/PES)	219	67	7	9.6	2.9 4.3 6.0	8.9	38	66	
	Liros Drayer 18mm	Double braid (PES/PES)	324	77	7	11	3.0 4.8 6.3	9.0	38	66	
	Marlow Marlowbraid 12mm	Braided Cover, 3 strand core (PES/PES)	100	40.2		Use Dependent			~24.1 Bowline or Fig 8 knots	~36.2	
	Marlow Marlowbraid 14mm	Braided Cover, 3 strand core (PES/PES)	145	49.3		Use Dependent			~29.6 Bowline or Fig 8 knots	~44.4	
	Marlow Marlowbraid 16mm	Braided Cover, 3 strand core (PES/PES)	190	65.2		Use Dependent			~39.1 Bowline or Fig 8 knots	~58.7	
	Marlow Marlowbraid 20mm	Braided Cover, 3 strand core (PES/PES)	285	102.3		Use Dependent			~61.4 Bowline or Fig 8 knots	~92.1	
	New England V-100 12mm	Double braid (Vectran/PES)	113	82.6							

TABLE 2 (part 4) Arborist cordage – Rope (multi-braid)

Product image	**Product description**	**Construction (material)**	**Mass (g/m)**	**MBS (kN)**	**Design factor**	**WLL**	**Extension at 10, 20 & 30% MBS (%)**	**Extension at break (%)**	**Knotted strength (kN)**	**Spliced strength (kN)**	**Notes**
	New England T-100 12mm	Double braid (Technora/PES)	121	95.3							
	New England Endura Braid 12mm	Double braid (Dyneema/PES)	100	84.8							
	New England IPDB 12.7mm	Double braid (PES/PES)	104	31.7							
	New England IPDB 15.9mm	Double braid (PES/PES)	185	65.8							
	New England IPDB 19.1mm	Double braid (PES/PES)	260	89.9							
	New England IPDB 22.2mm	Double braid (PES/PES)	353	11.4							
	New England IPDB 25.4mm	Double braid (PES/PES)	457	13.7							
	New England Sta Set 12.7mm	Double Braid (PES/PES)	122	38.6							

TABLE 2 (part 5) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	New England Sta Set 14.3mm	Double Braid (PES/PES)	158	53.1							
	New England Sta Set 15.9mm	Double Braid (PES/PES)	186	65.4							
	New England Sta Set 19.1mm	Double Braid (PES/PES)	260	90.8							
	New England Sta Set 22.2mm	Double Braid (PES/PES)	353	135.8							
	New England Sta Set 25.4mm	Double Braid (PES/PES)	491	172.5							
	New England Poly/Nylon 12.7mm	Double braid (Nylon/PES)	112	45							
	New England Poly/Nylon 14.3mm	Double braid (Nylon/PES)	140	56.8							
	New England Poly/Nylon 15.9mm	Double braid (Nylon/PES)	171	70.4							

TABLE 2 (part 6) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	New England Poly/Nylon 19.1mm	Double braid (Nylon/PES)	235	10.2							
	New England Poly/Nylon 22.2mm	Double braid (Nylon/PES)	348	13.8							
	New England Poly/Nylon 25.4mm	Double braid (Nylon/PES)	452	18.2							
	Samson Validator II 12.7mm	Double braid (Vectran/PES)	134	77							
	Samson Ultra-Tech 12.7mm	Double braid (Technora/PES)	146	77							
	Samson Warpspeed 12.7mm	Double braid (DYN/PES)	122	81							
	Samson Stable Braid 12.7mm	Double braid (PES/PES)	122		4.5:1	9.4 (spliced)	1.10 1.70 2.70			42.3	Elastic elongation figures are for stabilised rope
	Samson Stable Braid 14.3mm	Double braid (PES/PES)	164		4.5:1	12 (spliced)	1.10 1.70 2.70			54	Elastic elongation figures are for stabilised rope

TABLE 2 (part 7) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Samson Stable Braid 15.9mm	Double braid (PES/PES)	208		4.5:1	15 (spliced)	1.10 1.70 2.70			67	Elastic elongation figures are for stabilised rope
	Samson Stable Braid 19.1mm	Double braid (PES/PES)	268		4.5:1	19 (spliced)	1.10 1.70 2.70			84	Elastic elongation figures are for stabilised rope
	Samson Stable Braid 22.2mm	Double braid (PES/PES)	403		4.5:1	27 (spliced)	1.10 1.70 2.70			122	Elastic elongation figures are for stabilised rope
	Samson Nystron Coated 12.7mm	Double braid (Nylon/PES)	115	40							
	Samson Nystron Coated 14.3mm	Double braid (Nylon/PES)	149	51							
	Samson Nystron Coated 15.9mm	Double braid (Nylon/PES)	187	63							
	Samson Nystron Coated 19.1mm	Double braid (Nylon/PES)	257	89							
	Samson Nystron Coated 22.2mm	Double braid (Nylon/PES)	283	104							

TABLE 2 (part 8) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Samson Nystron Coated 25.4mm	Double braid (Nylon/PES)	506	143							
	Teufelberger Admiral Vectran 12mm	Double Braid (VEC/PES)	98	62	≥5:1	use dependent	0.4 0.8 1.3	4.0		49	
	Teufelberger Ocean Dyneema 12mm	Triple braid (DYN/PES/ ARA+PES)	87	63	≥5:1	use dependent	0.4 0.8 1.4	4.5		50	
	Teufelberger Globe 5000 12mm	Triple braid (DYN/PES/PES)	89	57	≥5:1	use dependent	0.5 1.0 1.5	4.5		45	
	Teufelberger Sirius 500 12mm	Double braid (PES/PES)	103	36	≥5:1	use dependent	1.9 3.0 4.5	15.0		28	
	Teufelberger Sirius 500 14mm	Double braid (PES/PES)	140	48	≥5:1	use dependent	1.9 3.0 4.5	15.0		38	
	Teufelberger Sirius 500 16mm	Double braid (PES/PES)	178	65	≥5:1	use dependent	1.9 3.0 4.5	15.0		52	
	Teufelberger Rio 18mm	Double braid (PES/PES)	196	55	≥5:1	use dependent	3.8 6.8 7.8	20.0		41	

TABLE 2 (part 9) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Teufelberger Rio 20mm	Double braid (PES/PES)	260	66	≥5:1	use dependent	3.8 6.8 7.8	20.0		52	
	Teufelberger Rio 24mm	Double braid (PES/PES)	384	100	≥5:1	use dependent	3.8 6.8 7.8	20.0		72	
	Teufelberger Monte Carlo 18mm	Double braid (PP/PES)	155	48	≥5:1	use dependent	6.5 10.5 13.2	30.0		36	
	Yale Crystalyne 12.7mm	Double braid (VEC/PES)	126	80.4	3.6	22.3					
	Yale Aracom T 12.7mm	Double braid (Technora/PES)	129								
	Yale Ultrex Plus 12.7mm	Double briad (DYN/PES)	109	80.4	4.5	17.9					
	Yale Double Esterlon 12.7mm	Double braid (PES/PES)	121	42.2	3.6	11.7					
	Yale Double Esterlon 14.3mm	Double braid (PES/PES)	143	52.6	3.6	14.6					

TABLE 2 (part 10) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Yale Double Esterlon 15.9mm	Double braid (PES/PES)	204	67.5	3.6	18.8					
	Yale Double Esterlon 19.1mm	Double braid (PES/PES)	243	80.4	3.6	22.3					
	Yale Double Esterlon 22.2mm	Double braid (PES/PES)	353	124.6	3.6	34.6					
	Yale Double Esterlon 25.4mm	Double braid (PES/PES)	524	176.8	3.6	49.1					
	Yale Polydyne 12.7mm	Double braid (PA/PES)	113	42.2	3.6	11.7					
	Yale Polydyne 14.3mm	Double braid (PA/PES)	144	60.3	3.6	16.7					
	Yale Polydyne 15.9mm	Double braid (PA/PES)	198	72.3	3.6	20					
	Yale Polydyne 19.1mm	Double braid (PA/PES)	250	92.4	3.6	25.7					

TABLE 2 (part 11) Arborist cordage – Rope (multi-braid)

Product image	Product description	Construction (material)	Mass (g/m)	MBS (kN)	Design factor	WLL	Extension at 10, 20 & 30% MBS (%)	Extension at break (%)	Knotted strength (kN)	Spliced strength (kN)	Notes
	Yale Polydyne 22.2mm	Double braid (PA/PES)	350	128.6	3.6	35.7					
	Yal Polydyne 25.4mm	Double braid (PA/PES)	489	168.8	3.6	46.9					

TABLE 3 (part 1) Rope tools – Soft Eye Slings (single eye)

Product image	Product description	Construction (kern/mantle)	Singled			Knotted			Lengths (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Samson Stable Braid Treerig Sling 14.3mm (200mm eye)	Double braid (PES/PES)	54	5:1	10.8				180-600	
	Samson Stable Braid Treerig Sling 15.9mm (200mm eye)	Double braid (PES/PES)	67	5:1	13.7				180-600	
	Samson Stable Braid Treerig Sling 19.1mm (200mm eye)	Double braid (PES/PES)	84	5:1	16.8				180-600	
	Samson Stable Braid Treerig Sling 22.2mm (200mm eye)	Double braid (PES/PES)	122	5:1	24.4				180-600	
	Samson Tenex Treerig Sling 12.7mm (150mm eye)	12 strand single hollow braid (PES)	53	5:1	10.6				300-450	Blue
	Samson Tenex Treerig Sling 15.9mm (150mm eye)	12 strand single hollow braid (PES)	77	5:1	15.3				180-600	Red

TABLE 3 (part 2) Rope tools – Soft Eye Slings (single eye)

Product image	Product description	Construction (kern/mantle)	Singled			Knotted			Lengths (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Samson Tenex Treerig Sling 19.1mm (150mm eye)	12 strand single hollow braid (PES)	101	5:1	20				240-600	Orange
	Samson Tenex Treerig Sling 22.2mm (150mm eye)	12 strand single Hollow braid (PES)	140	5:1	27.9				300-600	Green
	Samson Tenex Treerig Sling 25.4mm (150mm eye)	12 strand single hollow braid (PES)	182	5:1	36				360-600	Yellow

TABLE 4 (part 1) Rope tools – Soft Eye Slings (double eye)

Product image	Product description	Construction (kern/mantle)	Singled			Choked			Basket			Length (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Yale Double Esterlon Spliced Eye/Eye Sling 12.7mm	Double braid (PES/PES)			11.7			9.4			23.4	107	
	Yale Double Esterlon Spliced Eye/Eye Sling 15.9mm	Double braid (PES/PES)			18.8			15			37.5	135	
	Yale Double Esterlon Spliced Eye/Eye Sling 19.1mm	Double braid (PES/PES)			22.3			17.9			44.6	152	
	Yale Double Esterlon Spliced Eye/Eye Sling 22.2mm	Double braid (PES/PES)			34.6			27.7			69.2	173	
	Yale Double Esterlon Spliced Eye/Eye Sling 25.4mm	Double braid (PES/PES)			49.1			39.3			98.2	198	
	Yale Polydyne Spliced Eye/Eye Sling 12.7mm	Double braid (PA/PES)			11.7			9.4			23.4	107	
	Yale Polydyne Spliced Eye/Eye Sling 15.9mm	Double braid (PA/PES)			20			16.1			40.2	135	

TABLE 4 (part 2) Rope tools – Soft Eye Slings (double eye)

Product image	Product description	Construction (kern/mantle)	Singled			Choked			Basket			Length (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Yale Polydyne Spliced Eye/Eye Sling 19.1mm	Double braid (PA/PES)			25.7			20.5			51.3	152	
	Yale Polydyne Spliced Eye/Eye Sling 22.2mm	Double braid (PA/PES)			35.7			28.6			71.4	173	
	Yale Polydyne Spliced Eye/Eye Sling 25.4mm	Double braid (PA/PES)			46.9			37.5			93.8	198	
	Yale Vectrus Spliced Eye/Eye Sling 12.7mm	12 strand single hollow braid (Vectran)			29			23.2			58	102	
	Yale Vectrus Spliced Eye/Eye Sling 15.9mm	12 strand single hollow braid (Vectran)			39.1			31.3			78.1	112	
	Yale Vectrus Spliced Eye/Eye Sling 19.1mm	12 strand single hollow braid (Vectran)			54.1			43.3			108.3	122	
	Yale Vectrus Spliced Eye/Eye Sling 22.2mm	12 strand single hollow braid (Vectran)			69.8			55.8			139.5	140	
	Yale Vectrus Spliced Eye/Eye Sling 25.4mm	12 strand single hollow braid (Vectran)			94.9			75.9			189.7	157	

TABLE 4 (part 3) Rope tools – Soft Eye Slings (double eye)

Product image	Product description	Construction (kern/mantle)	Singled			Choked			Basket			Length (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Yale Yalex Spliced Eye/Eye Sling 12.7mm	12 strand single hollow braid (PES)			11.2			8.9			22.3	102	
	Yale Yalex Spliced Eye/Eye Sling 15.9mm	12 strand single hollow braid (PES)			16.3			13			32.5	122	
	Yale Yalex pliced Eye/Eye Sling 19.1mm	12 strand single hollow braid (PES)			21.4			17.1			42.9	140	
	Yale Yalex Spliced Eye/Eye Sling 22.2mm	12 strand single hollow braid (PES)			31.7			25.4			63.4	157	
	Yale Yalex pliced Eye/Eye Sling 25.4mm	12 strand single hollow braid (PES)			38.4			30.7			76.8	178	

TABLE 5 (part 1) Rope tools – Endless Loop Slings

Product image	Product description	Construction (kern/mantle)	Singled			Choked			Basket			Minimum length (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Yale Double Esterlon Spliced Eye/Eye Sling 12.7mm	Double braid (PES/PES)			19			15.2			38	117	
	Yale Double Esterlon Spliced Eye/Eye Sling 15.9mm	Double braid (PES/PES)			30.4			24.3			60.7	147	
	Yale Double Esterlon Spliced Eye/Eye Sling 19.1mm	Double braid (PES/PES)			36.1			28.8			72.1	173	
	Yale Double Esterlon Spliced Eye/Eye Sling 22.2mm	Double braid (PES/PES)			54.1			43.3			108.1	206	
	Yale Double Esterlon Spliced Eye/Eye Sling 25.4mm	Double braid (PES/PES)			76.3			61.3			152.5	234	
	Yale Loups Endless Sling 10mm	Coiled braid inside cover sleeve (Dyneema/PE)	95.5		19.1			15.3			37.9		
	Yale Loups Endless Sling 12mm	Coiled braid inside cover sleeve (Dyneema/PE)	159.4		31.9			25.5			63.9		

TABLE 5 (part 2) Rope tools – Endless Loop Slings

Product image	**Product description**	**Construction (kern/mantle)**	**Singled**			**Choked**			**Basket**			**Minimum length (cm)**	**Notes**
			MBS (kN)	**Design factor**	**WLL**	**MBS (kN)**	**Design factor**	**WLL**	**MBS (kN)**	**Design factor**	**WLL**		
	Yale Loups Endless Sling 14mm	Coiled braid inside cover sleeve (Dyneema/PE)	222.8		44.6			35.6			88.4		
	Yale Loups Endless Sling 19mm	Coiled braid inside cover sleeve (Dyneema/PE)	375		75			60			150		
	Yale Polydyne Spliced Eye/Eye Sling 12.7mm	12 strand single hollow braid (PES)			19			15.2			38	66	
	Yale Polydyne Spliced Eye/Eye Sling 15.9mm	12 strand single hollow braid (PES)			27.6			22.1			55.3	81	
	Yale Polydyne Spliced Eye/Eye Sling 19.1mm	12 strand single hollow braid (PES)			36.4			29.1			73.9	99	
	Yale Vectrus Endless Sling 12.7mm	12 strand single hollow braid (Vectran)			47.9			38.3			95.8	130	
	Yale Vectrus Endless Sling 14.3mm	12 strand single hollow braid (Vectran)			64.5			51.6			128.9	145	
	Yale Vectrus Endless Sling 15.9mm	12 strand single hollow braid (Vectran)			89.3			71.4			178.6	163	

TABLE 5 (part 3) Rope tools – Endless Loop Slings

Product image	Product description	Construction (kern/mantle)	Singled			Choked			Basket			Minimum length (cm)	Notes
			MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL	MBS (kN)	Design factor	WLL		
	Yale Vectrus Endless Sling 19.1mm	12 strand single hollow braid (Vectran)			115.1			92.1			230.2	183	
	Yale Vectrus Endless Sling 22.2mm	12 strand single hollow braid (Vectran)			156.5			125.2			313.1	218	
	Yale Yalex Endless Sling 22.2mm	12 strand single hollow braid (PES)			53.9			43.1			107.8	114	
	Yale Yalex Endless Sling 25.4mm	12 strands single hollow braid (PES)			65.3			52.2			130.5	132	

TABLE 6 (part 1) Rope tools – Whoopie Slings (adjustable)

Product image	**Product description**	**Construction (kern/mantle)**	**Singled**			**Choked**			**Basket**			**Length (cm)**	**Notes**
			MBS (kN)	**Design factor**	**WLL**	**MBS (kN)**	**Design factor**	**WLL**	**MBS (kN)**	**Design factor**	**WLL**		
	Samson Tenex TEC Whoopie sling 12.7mm	12 strand single hollow braid (PES)			9.8			7.9				76-122	Blue
	Samson Tenex TEC Whoopie sling 15.9mm	12 strand single hollow braid (PES)			14.3			11.4				91-152	Red
	Samson Tenex TEC Whoopie sling 19.1mm	12 strand single hollow braid (PES)			18.8			15.1				104-178	Orange
	Yale Vectrus Whoopie sling 12.7mm	12 strand single hollow braid (Vectran)			25.5			20.4			51.1	109-?	
	Yale Vectrus Whoopie sling 14.3mm	12 strand single hollow braid (Vectran)			34.4			27.5			68.8	122-?	
	Yale Vectrus Whoopie sling 15.9mm	12 strand single hollow braid (Vectran)			47.6			38.1			95.3	165-?	

TABLE 6 (part 2) Rope tools – Whoopie Slings (adjustable)

Product image	Product description	Construction (kern/mantle)	Singled			Choked			Basket			Length (cm)	Notes
			Min.BS (kN)	Design factor	WLL	Min.BS (kN)	Design factor	WLL	Min.BS (kN)	Design factor	WLL		
	Yale Vectrus Whoopie sling 19.1mm	12 strand single hollow braid (Vectran)			61.4			49.1			122.8	191-?	
	Yale Vectrus Whoopie sling 22.2mm	12 strand single hollow braid (Vectran)			83.5			66.8			167	221-?	
	Yale Yalex Whoopie sling 12.7mm	12 strand single hollow braid (PES)			9.9			7.9			19.6	71-?	
	Yale Yalex Whoopie sling 15.9mm	12 strand single hollow braid (PES)			14.3			11.4			28.6	81-?	
	Yale Yalex Whoopie sling 19.1mm	12 strand single hollow braid (PES)			18.9			15.1			37.7	97-?	
	Yale Yalex Whoopie sling 22.2mm	12 strand single hollow braid (PES)			27.9			22.3			55.8	117-?	
	Yale Yalex Whoopie sling 25.4mm	12 strand single hollow braid (PES)			33.8			27			67.6	137-?	

TABLE 7 Rope tools – Loopie Slings (adjustable)

Product image	Product description	Construction (kern/mantle)	Choked MBS (kN)	Design factor	WLL (kN)	Length (cm)	Notes
	Sherrill Tenex TEC Loopie Sling 9.5mm	12 strand single hollow braid (PES)			4.45	45-90	
	Sherrill Tenex TEC Loopie Sling 12.7mm	12 strand single hollow braid (PES)			8.9	60-120 60-180	
	Sherrill Tenex TEC Loopie Sling 15.9mm	12 strand single hollow braid (PES)			13.4	60-180	

APPENDIX 3 REFERENCES

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APPENDIX 4 DATA FROM LABORATORY AND FIELD TESTS

TABLE 1 Data from destructive tests on branches used as anchor points – part 1 (Chapter 5)

sp.	test no.	tree no.	failure	F (in N)	l (in cm)	α (in °)	Ø ∥ (cm) anchor	Ø ∥ (cm) fork	Ø ∥ (cm) fracture	Ø ⊥ (cm) anchor	Ø ⊥ (cm) fork	Ø ⊥ (cm) fracture	bark (in cm)
Acer pseudoplatanus	1	1	yield fracture	9,476 9,928	- -	- -	11.3	14.0	22.0	12.0	12.5	17.8	0.36
	2	1	yield fracture	13,734 17,717	263 254	51.8 48.9	15.2	26.0	19.5	14.5	25.0	19.0	0.53
	3	1	yield fracture	7,063 8,044	112 103	50.1 58.0	11.5	12.0	11.0	9.5	14.0	12.0	0.40
	4	1	yield fracture	3,728 4,238	157 150	39.1 44.7	9.0	12.0	12.0	9.3	11.5	11.0	0.40
	5	1	yield fracture	5,376 5,533	284 265	26.4 29.5	10.8	16.5	15.0	9.8	16.0	14.0	0.50
	6	1	yield fracture	12,027 11,850	127 127	47.8 47.8	13.0	15.0	15.0	11.5	14.6	16.5	0.45
	7	1	yield fracture	6,749 6,847	37 36	67.6 71.8	17.9	9.0	9.0	7.0	8.2	8.2	0.45
	8	1	yield fracture	14,303 16,128	292 294	35.1 38.4	10.5	21.0	21.0	11.0	18.5	18.5	0.69
	9	1	yield fracture	12,400 14,793	- -	- -	15.0	23.0	19.5	15.0	25.0	22.0	0.62
	10	2	yield fracture	3,198 4,513	120 95	73.6 74.5	8.0	10.5	9.5	8.2	10.0	9.5	0.45
	11	2	yield fracture	4,101 4,827	190 184	60.5 64.1	10.0	13.5	15.0	11.0	14.0	12.5	0.53
	12	2	yield fracture	2,963 3,434	137 132	61.3 62.7	8.8	11.5	12.0	8.2	12.0	11.0	0.45
	13	2	yield fracture	1,432 2,551	119 95	57.1 72.4	7.5	9.0	9.0	7.0	9.0	8.0	0.31
	14	2	yield fracture	5,513 6,278	257 253	48.1 51.4	-	17.8	17.3	-	17.8	17.3	0.56
	15	2	yield fracture	6,004 7,456	271 270	14.1 16.6	10.8	13.2	18.0	10.8	14.2	14.0	1.02

TABLE 2 Data from destructive tests on branches used as anchor points – part 2 (Chapter 5)

sp.	test no.	tree no.	failure	F (in N)	l (in cm)	α (in °)	Ø ∥ (cm)			Ø ⊥ (cm)			bark (in cm)
							anchor	fork	fracture	anchor	fork	fracture	
Acer saccharinum	**16**	3	yield fracture	3,139 6,121	271 236	47.5 71.2	12.5	22.0	18.7	12.8	22.2	17.0	1.00
	17	3	yield fracture	5,886 6,612	- -	- -	10.2	17.2	15.0	9.5	19.0	14.0	1.38
	18	3	yield fracture	2,708 3,100	291 287	69.2 68.2	11.0	14.2	16.0	15.0	15.0	16.5	0.84
	19	3	yield fracture	8,495 22,543	314 302	26.4 27.4	18.0	31.5	26.0	17.5	35.0	26.0	1.83
	20	3	yield fracture	3,885 5,278	320 300	33.0 34.2	12.2	23.8	16.0	12.5	23.8	15.0	1.45
	21	3	yield fracture	2,963 3,473	358 334	19.8 22.7	10.5	18.8	14.5	10.5	16.0	14.2	0.82

TABLE 3 Data from destructive tests on branches used as anchor points – part3 (Chapter 5)

sp.	test no.	tree no.	failure	F (in N)	l (in cm)	α (in °)	Ø ІІ (cm) anchor	Ø ІІ (cm) fork	Ø ІІ (cm) fracture	Ø ⊥ (cm) anchor	Ø ⊥ (cm) fork	Ø ⊥ (cm) fracture	bark (in cm)
Fagus sylvatica	**22**	4	yield fracture	3,609 4,099	98 97	74.8 76.7	8.5	12.8	11.5	8.9	11.5	11.0	0.34
	23	4	yield fracture	3,432 4,001	162 158	57.1 58.4	9.4	15.0	13.2	9.6	14.5	12.9	0.40
	24	4	yield fracture	2,530 2,726	84 85	85.8 86.7	10.0	13.8	10.4	9.8	14.0	11.0	0.36
	25	4	yield fracture	1,942 2,157	132 129	57.8 62.2	8.3	13.0	10.2	8.5	11.5	10.5	0.32
	26	4	yield fracture	1,432 1,530	25 25	60.2 63.3	5.5	7.0	6.3	5.5	7.0	6.0	0.24
	27	4	yield fracture	1,393 1,824	310 297	51.8 51.4	9.5	15.1	13.4	10.5	15.5	13.7	0.35
	28	4	yield fracture	2,667 2,785	85 85	56.6 57.8	8.9	11.3	9.6	9.1	11.2	9.7	0.26
	29	4	yield fracture	2,295 2,628	123 122	50.0 51.0	10.4	14.1	11.5	10.6	14.9	12.0	0.25
	30	4	yield fracture	2,275 2,805	318 313	46.7 46.4	11.3	16.8	15.2	10.3	19.0	15.4	0.38
	31	4	yield fracture	1,177 1,716	90 88	44.6 48.6	7.2	10.6	8.5	7.5	10.3	8.6	0.30
	32	5	yield fracture	2,275 2,746	169 169	85.7 83.0	9.7	12.5	11.1	9.8	13.9	11.6	0.42
	33	5	yield fracture	3,589 4,119	87 90	84.2 71.2	9.8	18.0	12.3	9.2	16.5	12.8	0.40
	34	5	yield fracture	8,120 -	108 -	65.6 -	15.2	18.0	16.6	13.8	16.5	14.3	0.42
	35	5	yield fracture	11,690 12,533	133 147	78.8 73.9	15.2	18.0	17.7	13.8	16.5	15.7	0.42

TABLE 4 Data from destructive tests on branches used as anchor points –part 4 (Chapter 5)

sp.	test no.	tree no.	failure	F (in N)	l (in cm)	α (in °)	Ø ‖ (cm)			Ø ⊥ (cm)			bark (in cm)
							anchor	fork	fracture	anchor	fork	fracture	
Tilia vulgaris	**36**	6	yield fracture	1,600 1,765	125	72.7	7.2	11.0	17.3	6.4	11.0	15.4	0.40
	37	6	yield fracture	2,950 3,236	85	50.3	7.7	10.8	10.8	8.2	10.5	10.5	0.40
	38	6	yield fracture	8,450 8,630	383	68.8	31.9	29.2	25.7	31.0	29.4	30.9	1.80
	39	7	yield fracture	2,100 2,354	80	64.6	6.9	9.9	7.6	7.2	10.9	8.4	0.25
	40	7	yield fracture	700 785	126	61.1	6.2	9.0	7.0	6.3	11.0	7.8	0.25
	41	7	yield fracture	850 981	80	62.3	5.8	9.9	7.4	6.9	10.9	8.0	0.25
	42	7	yield fracture	700 932	98	62.8	5.3	9.9	6.6	5.9	9.0	6.7	0.63
	43	7	yield fracture	1,250 1,569	210	65.0	6.6	13.0	9.5	7.1	13.1	9.6	0.30

TABLE 5 Statistical data from tests on strength loss of ropes due to knots (Chapter 7)

min max **arithmetic mean** st. dev. no.	**Arborplex**	**Blue Streak**	**Stable Braid**			**Tenex**	**True Blue**	
	16 mm	**13 mm**	**13 mm**	**16 mm**	**19 mm**	**16 mm**	**13 mm**	**16 mm**
Anchor Hitch		-39.6% -42.1% **-40.9%** 1.2% 3						
Buntline Hitch		-37.7% -40.7% **-39.0%** 1.5% 3						
Butterfly Knot			-51.6% -54.7% **-53.6%** 1.7% 3					
Double Fisherman's Knot		-39.9% -42.8% **-40.9%** 1.7% 3						
Triple Bowline			-48.8% -53.4% **-51.9%** 2.7% 3					
Clove Hitch (exit next to load)			-27.3% -34.1% **-29.8%** 3.7% 3		-33.4% -34.3% **-33.9%** 0.4% 3			-28.8% -30.9% **-30.0%** 1.1% 3
Clove Hitch (exit opposite load)			-31.2% -36.5% **-33.4%** 2.8% 3	-40.2% -44.4% **-42.3%** 2				
Cow Hitch			-24.2% -34.3% **-29.8%** 5.2% 3	-38.3% -39.9% **-39.3%** 0.9% 3	-32.7% -42.7% **-37.7%** 5.0% 3			-28.0% -31.5% **-29.2%** 2.0% 3
Running Bowline			-26.0% -31.9% **-28.2%** 2.7% 4	-32.1% -34.2% **-33.4%** 1.4% 4	-30.8% -35.9% **-33.3%** 2.6% 3			**-29.6%** 1
Half Hitch (with Running Bowline)	-7.5% -26.4% **-14.9%** 10.2% 3	-30.9% -37.1% **-34.0%** 3.1% 3	-39.9% -43.2% **-41.3%** 1.7% 3	**-39.8%** 1	-41.8% -43.4% **-42.8%** 0.9% 3	**-36.8%** 1	-23.8% -28.2% **-25.9%** 2.2% 3	-23.3% -31.7% **-27.4%** 4.2% 3
Marline Hitch (with Running Bowline)			-35.7% -40.5% **-37.9%** 2.4% 3	-38.1% -41.0% **-39.9%** 1.5% 3				

TABLE 6 Statistical data from tests on strength loss in slings due to knots – part 1 (Chapter 7)

min max **arithmetic mean** st. dev. no.	**Eye-sling Stable Braid**		**Eye-sling Tenex**					
	16 mm	**19 mm**	**13 mm**	**16 mm**		**19 mm**	**22 mm**	
				standard	**class 1 bury ***		**standard**	**full bury**
Timber Hitch arborist block			-14.2% -7.0% **-11.2%** 3.8% 3	-23.1% -12.8% **-17.4%** 5.2% 3		-22.7% -13.0% **-18.0%** 4.9% 3	-22.7% -17.1% **-20.4%** 2.9% 3	
Timber Hitch girth at shackle			-21.0% -17.1% **-19.6%** 2.1% 3	-21.0% -15.6% **-17.8%** 2.8% 3		-27.0% -24.4% **-25.6%** 1.3% 3	-31.2% -28.0% **-29.6%** 2	
Cow Hitch arborist block	-31.6% -9.7% **-20.7%** 15.5% 2	-39.5% -28.3% **-33.9%** 7.9% 2	-33.3% -27.1% **-29.4%** 3.4% 3	-24.9% -5.6% **-15.1%** 9.7% 3	-16.9% -13.7% **-14.8%** 1.8% 3	-22.9% -15.7% **-18.7%** 3.7% 3	-30.8% -16.9% **-23.2%** 7.0% 3	**-10.1%** 1
Cow Hitch girth at shackle			-28.8% -11.2% **-19.7%** 8.8% 3	-36.3% -13.7% **-27.6%** 12.1% 3		-39.9% -36.1% **-37.4%** 2.1% 3	-37.5% -30.0% **-33.0%** 4.0% 3	
Cow Hitch connecting link				**-13.2%** 1				

** class 1 bury as specified in Samson splicing standards*

TABLE 7 Statistical data from tests on strength loss in slings due to knots – part 2 (Chapter 7)

min max **arithmetic mean** st. dev. no.	**Loopie**			**Whoopie**
	13 mm	**16 mm**		**16 mm**
		short bury *	**long bury ****	
Choked arborist block	-15.7% 10.1% **-1.3%** 13.2% 3	12.1% 25.7% **19.5%** 6.9% 3	19.6% 32.0% **25.5%** 6.2% 3	-25.5% -25.2% **-25.4%** 2
Choked (incorrectly) arborist block	-21.3% 13.7% **-2.7%** 17.6% 3			**1.2%** 1
Choked girth at shackle	-7.6% -3.6% **-5.6%** 2.0% 3			-22.0% -14.1% **-18.1%** 3.1% 5
Choked (incorrectly) girth at shackle	-12.7% -3.5% **-8.1%** 4.6% 3			**-23.8%** 1
Choked connecting link		**15.8%** 1		

** short bury = 1⅓ fid length bury* *** long bury = 2 fid length bury*

TABLE 8 Data from drop tests to study peak forces (Chapter 8)

test no.	species	tree no.	type of section	mass of section	position centroid section	length of section	peak force block	position Half Hitch	position notch apex	block axis before drop	block axis after drop	friction device	slip Half Htch	slip friction device
1	**Fagus sylvatica**	**1**	top	158.8 kg	3.23 m	9.65 m	7.4 kN	13.72 m	12.90 m	12.57 m	12.46 m	0.75 m	0.08 m	0.10 m
2			log	209.0 kg	1.46 m	3.04 m	18.5 kN	10.35 m	9.85 m	9.50 m	9.30 m	0.75 m	0.14 m	0.09 m
3			log	155.3 kg	0.97 m	1.90 m	16.1 kN	8.45 m	7.98 m	7.70 m	7.54 m	0.75 m	0.12 m	0.09 m
4			log	226.0 kg	1.16 m	2.14 m	21.7 kN	6.20 m	5.82 m	5.52 m	5.47 m	0.75 m	0.15 m	0.13 m
5			top	183.0 kg	2.92 m	8.30 m	10.0 kN	13.35 m	13.26 m	12.90 m	12.80 m	0.75 m	0.08 m	0.13 m
6			log	167.5 kg	1.33 m	3.03 m	16.3 kN	10.43 m	10.24 m	9.88 m	9.80 m	0.75 m	0.09 m	0.12 m
7			log	223.2 kg	1.18 m	2.41 m	22.5 kN	8.33 m	7.92 m	7.55 m	7.30 m	0.75 m	0.11 m	0.14 m
8			log	211.8 kg	0.81 m	1.81 m	18.8 kN	6.42 m	6.10 m	5.82 m	5.50 m	0.75 m	0.08 m	0.13 m
9			log	266.8 kg	0.48 m	1.04 m	23.8 kN	4.20 m	3.91 m	3.53 m	3.31 m	0.75 m	0.39 m	0.15 m
10		**2**	top	230.0 kg	3.17 m	10.40 m	11.0 kN	12.97 m	12.60 m	12.30 m	12.20 m	0.76 m	0.07 m	0.15 m
13	**Acer pseudoplatanus**	**3**	top	228.0 kg	3.22 m	8.45 m	15.2 kN	11.10 m	10.85 m	10.48 m	10.25 m	0.89 m	0.06 m	0.08 m
14			log	156.0 kg	1.21 m	2.83 m	15.3 kN	8.43 m	7.97 m	7.78 m	7.58 m	0.89 m	0.11 m	0.06 m
15			log	205.0 kg	0.88 m	2.00 m	19.1 kN	5.93 m	5.93 m	5.60 m	5.41 m	0.89 m	0.11 m	0.04 m
16			log	237.0 kg	0.75 m	1.54 m	22.4 kN	4.68 m	4.42 m	4.05 m	3.78 m	0.89 m	0.12 m	0.08 m
17			log	136.0 kg	1.52 m	3.24 m	17.2 kN	7.00 m	6.60 m	6.34 m	6.20 m	0.89 m	0.15 m	0.04 m
18			top	220.0 kg	3.70 m	8.35 m	13.4 kN	12.93 m	12.50 m	12.15 m	11.88 m	0.89 m	0.05 m	0.04 m
19			log	153.2 kg	1.86 m	3.95 m	13.9 kN	9.00 m	8.62 m	8.32 m	7.98 m	0.89 m	0.08 m	0.18 m
20			log	340.0 kg	1.27 m	3.18 m	27.4 kN	6.00 m	5.46 m	5.20 m	5.03 m	0.89 m	0.30 m	0.07 m
21		**4**	top	300.0 kg	3.12 m	10.02 m	20.2 kN	13.92 m	13.55 m	13.22 m	13.13 m	0.70 m	0.10 m	0.11 m
22			log let run	176.0 kg	1.05 m	2.26 m	7.9 kN	11.60 m	11.30 m	11.08 m	10.85 m	0.70 m	0.06 m	0.08 m
23			log	230.0 kg	0.99 m	2.15 m	22.3 kN	9.56 m	9.20 m	8.94 m	8.72 m	0.70 m	0.12 m	0.06 m
24			log let run	206.0 kg	0.67 m	1.56 m	8.6 kN	7.95 m	7.68 m	7.41 m	7.15 m	0.70 m	0.12 m	0.04 m
25			log	203.2 kg	0.66 m	1.35 m	20.6 kN	6.64 m	6.35 m	6.04 m	5.88 m	0.70 m	0.18 m	0.07 m

APPENDIX 5 A WORKED EXAMPLE

1 INTRODUCTION

This worked example (illustrated in Figure 1 on page 353) demonstrates how the study results can be used: firstly, to perform a risk assessment of a rigging scenario; and secondly, to inform the choice of components to be used in the rigging system, with regard to the loads expected in a worst-case scenario. Calculations are made for a log which is to be removed from the stem of a Norway Spruce tree, that shows signs of decay and has an open wound on one side.

1.1 Mass of the section

The mass of a section can be estimated from its dimensions and its species-dependent specific gravity. In this example, the log is 100 cm long and has a diameter of 40 cm, and its corresponding reference mass is 125 kg, as derived from Table 6.1 on page 140. Since the log is Norway Spruce (*Picea abies*), the appropriate species-dependent log mass correction factor is 0.8 (median value taken from Table 6.2 on page 142), the application of which reduces the estimated mass of the log to 100 kg (125 kg $\times$ 0.8 = 100 kg). Due to uncertainties in both the specific gravity and the dimension measurements, a Factor of Safety of 130% must now be incorporated. Therefore, the assumed mass of the log is 130 kg (100 kg $\times$ 1.3 = 130 kg). This result can be summarised as follows:

	Estimate	Factor of Safety	Assumption
Mass of the log	100 kg	1.3	130 kg

1.2 Bearing capacity of the anchor point

If the log is snatched, the anchor point will be positioned directly below the cut. For this example, it is assumed that the anchor sling is positioned on the stem of the tree at 13 m above the ground. It is also assumed that, due to taper, the trunk has gained a diameter of 65 cm at 1 m height above ground. Subtracting 2.5 cm for bark thickness on both sides of the trunk, the under-bark diameter is assumed as 60 cm (65 cm – 2 $\times$ 2.5 cm = 60 cm). Using the yellow curve in Figure 5.1 on page 108 (for *Picea abies*), the bearing capacity of an anchor point at a height of 10 m is assessed as roughly 13.5 tons or 132 kN (13.5 t $\times$ 9.81 Nm/s² $=$ 132 kN).

Because, in this example, the stem shows signs of decay, and has an open cavity on one side, this figure is reduced by 50%, in accordance with Figure 5.4 on page 113 (bottom row, third cross-section from the left), and assessed as 65 kN (132 kN $\times$ 0.5 = 65 kN). Due to the fact that the anchor point is actually located at a height of 13 m height (rather than 10 m), the bearing capacity must be divided by 1.3 (i.e. by the proportion of the actual height to the reference height (13 m $\div$ 10 m $=$ 1.3). Therefore, the final estimate for the bearing capacity of the anchor point is 50 kN (65 kN $\div$ 1.3 $=$ 50 kN), or roughly 5 tons, in a topping-down scenario (i.e. with the peak force acting at 20° from the vertical, *cf* section 5.3.3).

In order to take account of variations in material strength, in addition to deviations in height and diameter measurements, a Factor of Safety of 1.5 must now be incorporated into the estimate, in accordance with the principles of Tree-Statics. Therefore, the assumed strength of the anchor point in a snatching scenario will be 33.3 kN (50 kN $\div$ 1.5 = 33.3 kN). This result can be summarised as follows:

	Estimate	Factor of Safety	Assumption
Bearing capacity of anchor point	50 kN	1.5	33.3 kN

1.3 Strength of rope

In real rigging operations, new ropes are used only as an exception. To account for the effects of ageing, wear and minor damage (e.g. from abrasion), a design factor is usually recommended by the rope manufacturer, to be applied when defining working load limits. It is normally recommended that the frequently proposed design factor of 5 should be doubled for rope use in arboricultural operations, due to the great number of unknown variables. However, in this example, the parameters that have been more rigorously determined through this study will be incorporated in the detailed risk assessment.

In this example, it is assumed that the rope employed is a used 14 mm double-braid polyester rope, with a listed tensile strength of 55 kN (roughly 5 tons). If the rope was new, using a Half Hitch and a Timber Hitch in the log attachment would reduce the strength of the rope by roughly 40%, as shown in the results presented in section 7.2.2. Therefore, the knotted strength of the rope when new would be estimated as 33 kN (reduced strength $=$ initial strength $-$ strength reduction $=$ 55 kN $-$ 55 kN $\times$ 0.4 = 55 kN $\times$ (1 $-$ 0.4) $=$ 55 kN $\times$ 0.6 $=$ 33 kN).

However, for a used rope that has not been exposed to dynamic loads, a strength reduction of up to 20% due to wear and ageing should at least be considered (*cf* section 7.3.3). Therefore, the knotted strength of a used 14 mm rope as used in this example could be estimated at 26.4 kN (33 kN $\times$ 0.8 $=$ 26.4 kN). Finally, applying the standard safety factor of 1.5 to the latter result would lead to a safe assumption for rope strength of 17.6 kN (26.4 kN $\div$ 1.5 $=$ 17.6 kN).

Furthermore, in a dynamic loading scenario, and in a traumatic working environment, this strength may not be sufficient. Based on recommendations made by the Cordage Institute (1994) and Blair (1999), adequate compensation for such working conditions might be achieved by doubling the safety margins (i.e. by using a safety factor of 3 rather than 1.5 - *cf* the proposed safety factors used in the specialist software Rigging 1.0). For such a situation, therefore, the maximum peak force tolerable by the 14 mm rope used in this example would be 8.8 kN (a peak force which is equivalent to the tension in the rope when a mass of roughly 900 kg is suspended). This result can be summarised as:

	Estimate	Factor of Safety	Assumption
Rope strength (used/knotted)	26.4 kN	3	8.8 kN

1.4 Strength of slings

For slings, the same considerations apply as for ropes. Attaching a 19 mm eye-sling made of double-braid polyester rope with a Cow Hitch would reduce its rated strength of 90 kN by roughly 35% (*cf* section 7.2.3). To account for wear, ageing and damage, a strength reduction of at least 20% would have to be considered. Via calculations carried out as for the rope, but using the values of 35% and 20 %, respectively, and by applying the increased Factor of Safety of 3, as in the previous paragraph, the maximum tolerable peak force would be assumed to be 15.6 kN, i.e. a load equivalent to roughly 1.6 tons. This result can be summarised as:

	Estimate	Factor of Safety	Assumption
Sling strength (used/knotted)	46.8 kN	3	15.6 kN

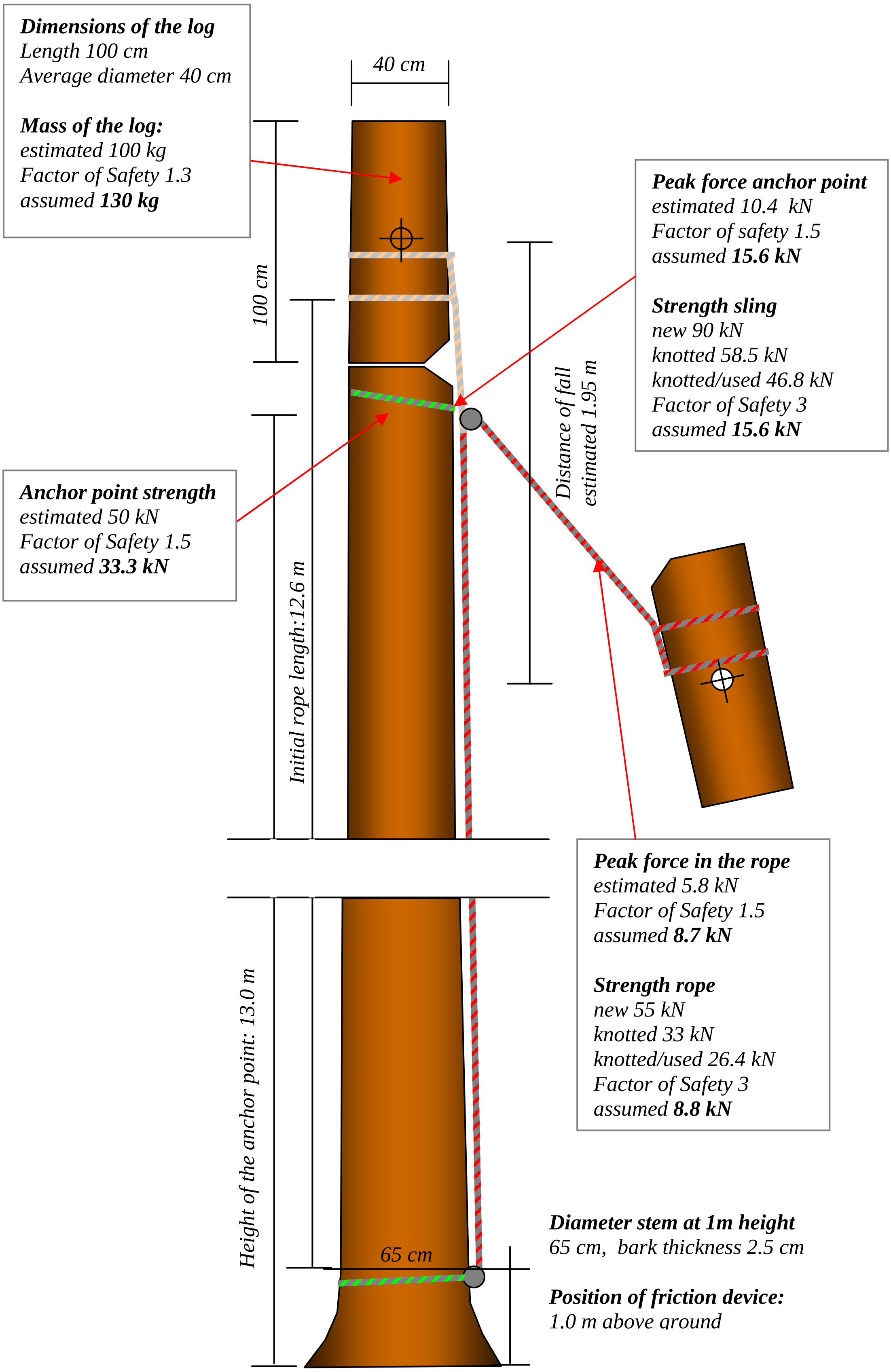

Figure 1 Worked example of a rigging system

1.5 Peak forces generated

According to equation 8.21 (page 231), the peak force generated in the rope can be estimated from certain characteristics of the rigging set-up, by making a number of assumptions with regard to variable angles and distances (such as rope and sling slippage). In the present example, the rope length is assumed to be 12.6 m, measured from the friction device located at a height of 1 m to the attachment knot located at a height of 13.6 m, 60 cm above the anchor sling. The rope modulus for a 14 mm double-braid polyester rope is assumed to be 250 kN, in accordance with the samples tested in the present study (*cf* section 8.5.4, page 239 *et seq*).

The distance from the block axis to the hinge, and the rope and block slippage, are assumed to be in accordance with the mean values given in Fig. 8.16 on page 214. The angle of the two legs of the line are assumed to be 37°, in accordance with the findings in the kinematical studies (*cf* section 8.3.4, page 206 *et seq*). Log mass is taken from the assumption derived in section 1.1 on page 351 (130 kg). The centre of gravity is assumed to be midway along the log's length, i.e. at a point 50 cm above the hinge. Taking all these assumptions together, the vertical distance of fall adds up to roughly 1.95 m at the point of maximum force in the rope. Taking into account friction effort in the block with a value of 10% (*cf* section 8.3.4, page 206 *et seq*), the peak force, as derived from equation 8.21, can be calculated to be 5.8 kN, and the reaction force at the anchor point can be estimated as 10.4 kN, in accordance with equation 8.22 on page 231 (the latter value being roughly 1.8 times the line force for the chosen angle and friction effort).

Due to the deviations from the estimated force, as observed in the present study (-20%), and variability in rope modulus, a safety factor of at least 1.5 should be applied. Therefore, the line force and anchor force would be assumed to be 8.7 kN and 15.6 kN respectively. These results can be summarised as:

	Estimate	Factor of Safety	Assumption
Peak force - rope	5.8 kN	1.5	8.7 kN
Peak force - anchor	10.4 kN	1.5	15.6 kN

1.6 Safety assessment

Ultimately, the estimates of the strength of components in the configured rigging system (including the bearing capacity of the anchor point) match the peak forces likely to be generated in a worst-case scenario, i.e. in case of accidental shock loading. At the anchor point there is actually a factor of safety of 3, even though the recommended safety margin was chosen as a minimum of only 1.5. Thus, in this example, the described rigging system could be considered to be sufficiently safe, because all the components match the loads they are expected to be exposed to, and sufficient factors of safety have been incorporated in the calculations.

It should be noted that changes to the rigging set-up could change the situation arising in this example, where the components have been calculated to match the expected loads. Changes in the dimension of the log could also change this situation. If, for example, a 16 mm sling is specified instead of the above-mentioned 19 mm sling, the resultant force at the anchor point would have reduced the safety margins (in a worst-case scenario) to less than 3. In this way, the sling could have been identified as being insufficiently strong, with the result that a stronger sling would have then been selected.

APPENDIX 6 PROPOSALS FOR PUBLICATIONS

As part of the overall study of arboricultural rigging described in this report, consideration has been taken of the need for information that can be readily available to practising arborists. Certainly, in view of the extent to which the awareness of rigging techniques, and the body of knowledge relating to them, is developing, there would seem to be a pressing need for a mechanism whereby arborists can be updated with regard to best practice. Those arborists who have been involved in discussions relating to this topic have come to the broad conclusion that there is a need for two different publications to be made available throughout the industry.

Firstly, there is a need for a publication that incorporates all of the available arboricultural dismantling techniques, in a way that indicates fully, and without bias, their relative merits, and places them in the context of current requirements arising from legislation. Such a document would include information on at least the free falling of sections, rigging operations, use of cranes and mobile elevated work platforms (MEWPs), and on any other dismantling techniques that might be considered to be appropriate for use by the industry. Such a document, or book, would only deal with the techniques in a general way, and, as a minimum, might contain the following information :

- general descriptions of the different techniques
- how to select an appropriate technique (see Chapter 3)
- risk assessment requirements and procedures (see Chapter 1)
- legislation applying to the different techniques
- safety requirements arising from legislation
- required competencies
- issues relating to arborist safety
- glossary of terms used in the different techniques

Secondly, there is a need for a publication relating specifically to arboricultural rigging that can serve as an operational manual for practising arborists. Such a publication might be entitled *A Guide to Good Rigging Practice* and published alongside the currently existing A *Guide to Climbing Practice* (published by the Arboricultural Association), which already serves as an operational manual for arborists engaged in general tree climbing activities. The following list of items is put forward as a starting point for developing a publication of this type:

1 RISK ASSESSMENT

1.1 Site planning

Traffic management, weather conditions, allocation of drop and processing zones, emergency contingencies (including rescue plan) etc.

1.2 Visual Tree Inspection

This section to be based initially on the information presented in Chapter 2.

1.2.1 List of tree-related hazards

- Strength loss in load-bearing parts of the tree due to visible damage (e.g. decay, cracks, old pruning wounds, split crotches, severed roots, boring insects)
- Poor structural development (e.g. V-shaped crotches with included bark, poor grafts, girdling roots, underdeveloped root system, re-growth after topping, susceptibility to oscillation)
- Primary failure (inclined root plate, over-bent branches, internal cracks)
- Climatic conditions (slippery of bark in rain, water saturated soil, sudden limb drop, heavy pre-loading generated from wind, ice or snow)
- Hazards resulting from objects in the tree (electric conductors, major deadwood, overgrown objects, stinging insects, extraneous vegetation)

1.2.2 List of red flag indicators

A checklist of red flag indicators as indicated in Chapter 2, possibly including illustrations.

1.2.3 Guidance on how to rate the severity of structural defects

- Strength loss tables
- List of fungus/tree species combinations known to be hazardous to climbing/rigging
- List of tree species reported to be more susceptible to failure than the average

1.3 Planned work sequence

Example of a checklist of things to be considered when planning a work sequence.

2 ESTIMATING THE MASS OF SECTIONS

2.1 Estimating log mass

This section to include an example worksheet, together with reference data, including:

- Tables and graphs of volume and reference weight estimates
- Species-dependent correction factors for specific gravity
- Proposals for correction factors for taper, irregular form, decay and moisture content

2.2 Estimating the mass of crown sections

Techniques appropriate for crown sections, suitable form factors, reference values based on experience etc.

3 RIGGING SYSTEM COMPONENTS

3.1 Hardware components and selection tables

Tables listing suitable hardware and appropriate known properties (rated strength, working load limit), together with links to sources of manufacturers' product information and user instructions, to include:

- Pulleys and arborist blocks
- Friction and lowering devices
- Fiddle blocks and lifting devices
- Karabiners and connectors

3.2 Cordage and webbing components

Rope selection tables detailing rope constructions, manufacturers and properties of rigging ropes, e.g. tensile strength, working load limit, rope modulus or elongation at fixed load levels, together with links to source of manufacturers' information.

Sling selection tables, analogous to rope selection tables, without elongation/stiffness data, but with recommended methods of installation, together with links to sources of manufacturers' information.

3.3 Proper use and inspection of cordage and webbing

- Bend ratios, friction
- Abrasion, kinking and fibre breaks
- Cycles to failure, ageing, fatigue
- Dynamic loads (shock loading)

3.4 Rigging knots

3.4.1 Knots for log attachment

- Primary knots: Clove Hitch, Running Bowline, Cow Hitch
- Supplementary hitches: Half Hitch, Marline Hitch

3.4.2 Knots and configurations for sling attachment

- Hardware attachment: Spliced eye with Girth Hitch, Bowline
- Attachment at anchor point: Timber Hitch, Cow Hitch, Munter Hitch

3.4.3 Knots for attachment to a rope

- Termination Knots: Anchor Hitch, Buntline Hitch, Double Fisherman's Knot
- Knots for mid-line attachment: Butterfly Knot, friction hitches

3.4.4 Strength loss due to knots

Tables listing strength loss for commonly used rigging ropes when tied in the following configurations:

- Rope to log
- Sling to log
- Rope to hardware

3.5 Compatibility and configuration

- Definition and review of the meanings of compatibility, incompatibility and good/bad configuration
- Generic guidelines for designing rigging systems, i.e. examples of correct subassemblies of rigging components
- Indications of potential conflict areas and situations, e.g. abraded webbing in a tight bend, rope on rope, picking from sharp-edged karabiner gates

3.6 Inspection and maintenance

- Generic points to be considered when carrying out inspections
- Considers conflict areas highlighted above
- Follows manufacturers' guidance on rejection, correction and maintenance criteria

4 ANCHOR SELECTION AND EVALUATION OF LOAD-BEARING CAPACITY

4.1 Strength of living trees

- Failure modes of living fibres, branches and stems
- Strength parameters and their influence on bearing capacity in rigging applications (including the effect of increased stiffness under dynamic loading)
- Natural variation of material properties in green wood, influence of defects

Tables listing species-dependent parameters for green stems and branches:

- Yield strength
- Ultimate strength
- Stiffness

Factors of safety in engineering calculations with regard to trees (Tree-Statics)

4.2 Bearing capacities of natural anchor points in trees

Parameters determining the bearing capacity of an anchor point:

- Diameter of the anchor point and all load bearing parts of the tree
- Structural integrity of wood and strength of branch unions/crotches
- Branch attachment angle and stem/branch diameter ratio
- Load angle and length of lever arm
- Moisture content of fibres
- Pre-stress on a branch (crown weight and length, additional loads such as ice and snow, branch angle, position of centre of gravity)
- Speed and duration of load application

Examples of load-bearing capacities of branches.

Guidance on variations due to a number of the parameters such as diameter, fibre compression strength, branch angle and pre-stress on branches in living trees

5 PEAK LOAD ASSESSMENT IN A WORST-CASE SCENARIO

5.1 Worst-case scenario

- Explanation of why safety consideration should start with determining the worst-case scenario
- Explanation of when and how maximum peak forces are generated
- Explanation of the kinematics of snatching
- Consequences of the log's impact on the stem for tree and climber

5.2 Parameters affecting peak loads

- Mass of the section (potential energy)
- Distance of fall (including log length and the actual flight curve)
- Rope length and rope modulus (how elasticity determines the deceleration rate when the log is being stopped by the rope)
- Elasticity, height and slenderness of the trunk (how flexibility cushions deceleration of the log, but enhances the amplitudes of sway)
- Aerodynamics and dampening (affects of retained branches on section and trunk)
- Friction and rope angles at the rigging point (how the affect the anchor force)

The consequences of high peak loads.

How peak forces and amplitudes of sway can be minimised.

5.3 Estimating peak loads generated in a rigging operation

Reference charts listing a range of anchor force factors for a number of specific rigging scenarios, determined from field tests and defined at least by:

- Rope type, diameter and length
- Section length and mass, section type: log or crown section
- Stem height and slenderness, tree species
- Stage of dismantling - single stem (pole) or parts of the crown retained

Guidance for variations in peak force expected for differing parameters such as rope length, rope modulus, section length, trunk height and slenderness

5.4 Parameters defining the effect on the climber

- Log mass in relation to trunk mass, position of log impact on stem
- Distance of fall, length of the section, aerodynamic drag
- Elasticity, height and slenderness of the stem (how this enhances sway and affects frequency and amplitude of vibration)
- Aerodynamics and damping effect of retained branches on section and trunk)
- Position of the climber

6 TECHNIQUE SELECTION

6.1 Rigging scenarios

- Presentation of detailed and comprehensive descriptions (with illustrations) of the different rigging techniques listed in Figure 3.2 (Chapter 3)
- A ranked list of the range of forces generated by each of the different rigging techniques
- Review of supplementary techniques, e.g. tag lines, control lines, mechanical aids.

6.2 Cutting techniques

Review of commonly used notches and cutting sequences, and the effects they create

6.3 Work positioning

Review of the full range of rope access and positioning systems (including working on a pole, multiple anchor points, static and running rope systems, backup lines, etc).

Reference to the prospective Code of Practice for working in a tree from a rope and harness

6.4 How to minimise peak loads

- Avoiding shock loads
- Keeping the anchor point above the cut as long as possible
- Cutting shorter sections
- Minimising the distance between cut and block positions
- Pre-tensioning the installed lowering line
- Adding rope to the system without increasing the bending moment acting upon the stem
- Letting the log run and decelerate gradually
- Retaining branches and leaves on the section where possible
- Using advanced techniques such as re-directs, fish-pole technique, or lifting where adequate

6.5 How to prevent failure of compromised trees

- Examining defects thoroughly and evaluating their severity (with caution)
- Minimising peak forces (see above), avoiding snatching
- Retaining branches and codominant leaders as long as possible
- Keeping the fall of the rope in the opposite direction to the direction of fall
- Guying the weak structure to the ground or adjacent trees
- Strapping split/weak stems or junctions
- Bolting split/weak junctions and cabling unstable crowns
- Using diagnostic tools, if required, to detect the extent of defects, and/or consulting an expert who has the skills needed to assess the load-bearing capacity of a severely compromised tree

6.6 Avoiding personal injuries

- Using aerial lifts, MEPWs/cranes where feasible
- Belaying from adjacent trees or retained second leaders
- Installing two separate anchoring systems
- Providing a climbing system suitable for a direct descent to the ground
- Cutting precisely
- Installing a tag-line, withdrawing from a stem after finishing the hinge, and employing a groundperson to pull off the section, if the stability of the trunk is in question
- Standing clear of the drop zone
- Establishing and maintaining good communication between climber and groundperson

Published by the Health and Safety Executive 12/08

HSE

Health and Safety
Executive

Evaluation of current rigging and dismantling practices used in arboriculture

This report presents the results of a comprehensive study into a number of topics related to rigging operations used in the dismantling of trees in the UK. The information it contains should enable the arboricultural industry to determine good practice in:

- carrying out risk assessments prior to dismantling a tree;
- planning and organising rigging operations; and
- selecting measures to mitigate against risks and accidents.

The project received additional funds from the Hyland John's Grant Programme of the TREE Fund (Grant No 06-HJ-05), in order to extend the investigation on the load-bearing capacity of branches beyond the scope of the original project plan.

RR668

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