Rigging Research

Article two in the series by Treevolution, in conjunction with Brudi & Partner TreeConsult (Germany), promoting the findings of the recent research project: An evaluation of current rigging and dismantling practices used in arboriculture. The research was published in 2008 and is available on the HSE website (www.hse.gov.uk/research/rrhtm/RR668.htm).

Inspecting trees and anchor points prior to rigging

The objective of this section of the series is to introduce the concept of red flag indicators in the form of pictures and descriptions, and to illustrate the required competence to carry out a risk assessment on the strength of anchor points used in rigging.

Introduction

Arborists are often called on to dismantle trees which show significant defects and are presumed to be likely to fail. Yet in regular climbing and rigging operations, those very trees may be used as anchor points to belay the climber or lower sections of wood. However, it is difficult to provide a clear answer on whether a certain defect makes a tree unsuitable for climbing and rigging loads, as the forces generated vary a lot and are usually much lower than the wind load a tree would experience in a storm.

The HSE Rigging Report lists some definitions which are essential in this context:

- 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)
- Risk – the chance of something adverse happening (Lonsdale 1999)
- Risk assessment – combines magnitude of hazard, probability of occurrence and the likelihood of damage to result from such incident

In essence, a risk assessment may very well conclude that a certain defect does not pose any risk for a climber during a dismantling scenario, even though the tree may be seen as a hazard in a storm event. In order to enable arborists to carry out such risk assessments, a proper understanding of the probability of failure is required which takes into account the severity of the defect and the loads imposed on the compromised part of the tree.

Methods

The Rigging Report provides a number of common symptoms for defects in the load-bearing parts of trees and made the attempt to tag them with indicators for increased and great likelihood of failure during rigging operations. The system of yellow and red flag indicators was used by Dwayne Neustaeter, a Canadian arborist, in his study guide.

There are a number of potential reasons for failure of structural parts of a tree which also apply to arborist safety. Among them are:

- strength loss due to biotic effects (e.g. fungal decay, wood-boring insects)
- abiotic damage (lightning strike, sunscald, severed roots)
- poor structural development (included bark, poor grafts, weak anchorage)
- previous failure (tilted root plate, over-bent branches, cracks)
- insufficient load-bearing capacity (inappropriate diameter, long lever arms, dead branches)

Besides this, there are other hazards in trees that are not related to failure of the anchor point, but should just as well be considered in a risk assessment, like dead major branches that could come loose, overgrown objects in the stem, stinging insects, harmful animals, vines and other objects suspended from the tree as well as electrical conductors running through, or in the vicinity of, the crown.

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. The Rigging Report provides a list of species that are regarded as structurally weak.
- 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.

Symptoms for risk of failure ...

In the following, a number of symptoms are presented as an example of situations arborists may encounter during a visual inspection prior to climbing or dismantling a tree. The choice is not random, because it focuses on severe defects, but the possible range is definitely not limited to the selection made for this paper.

... in the root zone

A tree's anchoring strength may be severely compromised for example by previous failure of the root-soil-matrix. The fact that the anchoring roots have already failed makes it very hard to assess the remaining load-bearing capacity of the root system. Generally, if failure has occurred in major parts of the load-bearing structure, the tree should be neither climbed nor rigged without appropriate measures to minimise the risk. Determining which measures could be taken requires a high level of competence. Any inherent risk of failure during dismantling should be avoided by rather choosing an appropriate working technique (see part 1 of this series).

Decay in structural roots or root severance close to the stem may also destabilise trees to a degree that the risk of failure is not tolerable. With regard to stability in wind, the distance of the damage to the stem base and the tree's reaction to the damage are important factors that allow for an assessment of the likelihood of failure. The area around the stem up to a distance equivalent of 1 to 1.5 times the stem diameter is regarded as a critical zone by some authors. Root severance in that area or

Tilted root flare of a spruce tree – A raised root flare and cracks in the soil indicate primary tipping failure. These trees may be very unstable.

root decay that was not compensated for by the tree should be regarded critical to stability and a thorough risk assessment is required.

There are a number of decay fungi which should be considered to indicate a great risk of failure when attempting to dismantle the infected tree. The Giant Polypore *(Meripilus giganteus)* for example is a frequent pathogen on beech and has often resulted in whole tree failure. A poor state of the crown and the absence of strong buttress roots underline that the infected tree was unable to compensate decay by putting on additional wood in compromised

Meripilus giganteus at roots of beech – 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.

areas. The likelihood of those trees to fail is much greater than if the formation of reaction wood has taken place.

Fruiting bodies that are formed right at the base of the stem are usually more significant than further away from the stem. Some species are more susceptible for decay generated by specific fungi – and may be compartmentalised for a much longer time by another tree species. It is understood that Ustulina *(Kretzschmaria deusta)* is able to cause a quickly progressing rot in Linden trees, where it has caused failures during

Kretzschmaria deusta on birch – 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.

rigging operations, whereas it appears to affect stability to a lesser degree in beech trees for example.

... along the stem

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), 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. If pathogens are able to break wound-wood barriers and to infect adjacent areas of the stem this will usually indicate a greater failure potential due to an advanced destabilisation.

Hidden cracks may be indicated by rib-like protrusions 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. 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.

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. However, crack propagation and reopening can present significant hazards.

Especially in the advanced stages of decay, some fungi species are able to cause a significant degradation of wood strength in limbs and stems. 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.

... in branches and branch unions

Cracks in a junction indicate that failure has occurred when the fork has been

Conks and bark damage around a cavity in Celtis – 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.

Fresh crack through the stem of beech – 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.)

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. Included bark acts like internal cracks, because notch stresses are concentrated when the fork is loaded in tension.

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).

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 on oak – 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 focusing on the integrity of anchor points is required to identify hazard branches. For this purpose, the use of binoculars may sometimes be necessary. 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 potential anchor points in the crown.

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). Similarly, horizontal cracks in solid cross-sections, arising from radial delamination of fibres in an upward bent branch (hazard beam), are associated with a reduction in strength greater than 50%.

Split branch ('hazard beam') – 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.

Assessing the strength of natural anchor points in trees

If the visual inspection does not indicate symptoms for structural damage in a potential anchor point, the question remains if it is adequately strong to sustain the load it will be exposed to during the dismantling operation. In order to address this need, a model derived from statics analysis may be used. The tree or a branch is compared to a cantilever beam that undergoes unilateral bending. In that model, the compressive strength of marginal fibres is decisive for load-bearing capacity.

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. Therefore, failure will occur on the compression side first, by the buckling of fibres. 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. Therefore the compressive strength of fibres parallel to the grain should be used as a threshold for strength.

The Rigging Report presents charts for the bearing capacity of tree stems that 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. The rigging operation that the charts refer to is snatching logs off a vertical stem. This scenario is defined by parameters derived from kinematic studies which will be discussed in the following part of this series.

The maximum sustainable load is displayed in Figure 1 (below) for five different groups of tree species, containing a range of 31 tree species common in the UK. They are based on values listed in the 'Stuttgart Strength Tables' which are commonly used in tree statics and were grouped for tree species of similar compressive strength. The under-bark diameter of a lime *(Tilia)* to be dismantled is determined as 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).

Open cavities and decay columns can be taken into account in some of the formulae used to assess strength loss. Practitioners might find difficulty in applying strength loss calculations to derive reliable figures on which to base a risk assessment. 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.

In order to assess the strength of limbs and branches, tests were conducted in the course of the Rigging Research (with additional finances provided by the TREE Fund). Forty branches of four different tree species were pulled to failure. Seven mature trees were dismantled in the course of the study, including three roadside and four park trees.

The diameters of tested branches ranged from 7 to almost 30 cm at the trunk. During the destructive tests, the stress at primary failure was determined. The results show that living branches have a tolerance to further loading. By permanent fibre deformation, the branch can take up significantly more energy even though the structure may be considerably damaged. During the next loading it may be prone to failure at much lower forces.

Structural failure of a thin-shelled cross-section – A collapse of the load-bearing geometry is called structural failure. It is usually much easier to identify, as significant delamination cracks are often visible. It occurs only on trees that show severe structural defects like extensive decay when residual walls are reduced to a very thin shell, as it is the case in this picture.

The yield stress derived from field tests is shown in Table 1. During another series of tests that followed the field study, yield stress values were derived for another 6 tree species. Values found in literature for other species were also included in the table if the test set-up and the diameter range included in the dataset seemed appropriate.

The unit Megapascal (MPa) can be visualised in an example. A horizontal branch of 10 cm diameter at its base is sustaining a mass at 90 cm distance. The stress in the marginal fibres will be critical, if the mass in kg is 10 times the yield stress value indicated in MPa, i.e. for lime (yield stress 25 MPa) the critical mass would be 250 kg.

Species	Mean Yield Stress (MPa)	Diameter Range (cm)
Acer platanoides	24.5 / 33	5 - 30
Acer pseudoplatanus	35	8 - 26
Acer saccharinum	24	14 - 35
Betula pendula	27	5 - 12
Fagus sylvatica	32	7 - 19
Fraxinus excelsior	33 / 36	6 - 12
Gleditsia triacathos	36	-
Platanus acerifolia	33 / 56	-
Populus canadensis	37	11 - 24
Quercus robur	27	5 - 19
Robinia pseudoacacia	40	-
Salix alba	29	12 - 16
Tilia vulgaris	25 / 29	9 - 30

Table 1 Strength of wood fibres in branches.

Figure 2 Example visualising the stress unit MPa for branches.

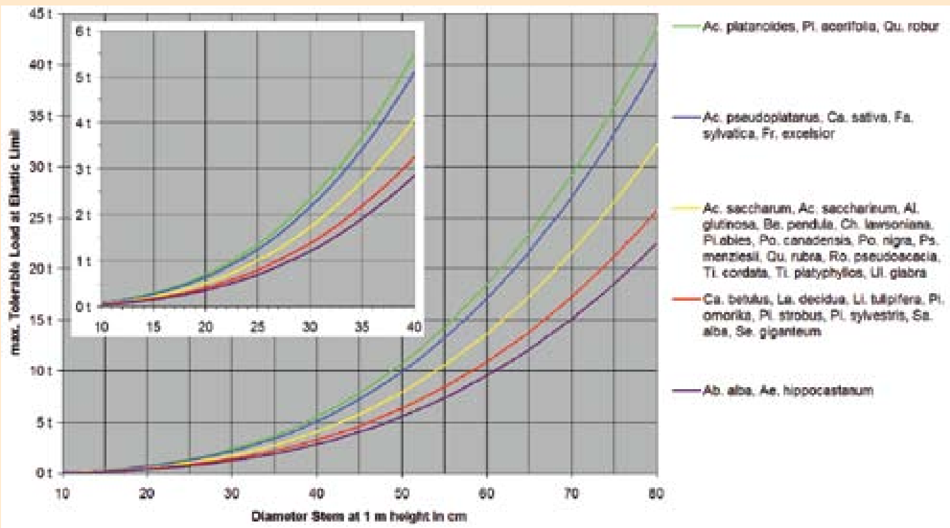

Figure 1 Load-bearing chart – single anchor points (insert: zoomed low range).

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