How stem cross-sectional shape and size determine load-carrying capacity of trees

Frank Rinn

Introduction

Jaffe and Telewski (1986) described how locally-acting stresses in response with mechanical loading determines the radial growth rates of tree stems. This information later became the basis for the more comprehensive theory of "thigmomorphogenesis" (Telewski 2006). When increased cambial growth rates are a result of mechanical stresses, the cross-sectional shape and size reflects the influence of the cumulative mechanical loading over time. Recognizing that local radial growth rates are influenced by mechanical stresses, implies that a tree's load-carrying capacity is determined by its shape and size. Understanding how this basic bio-mechanic principle works is a central key to evaluating risk potential, particularly for trees with defective cross sections.

Mechanics

Strength of the material (**σ**) and size (diameter **D**) are the two major factors determining the load-carrying capacity (**LCC**) of any cross section. Interestingly, diameter is significantly more important in this context than material strength. This can be easily shown for the simple example of circular cross-sections where load-carrying capacity is proportional to strength multiplied by the diameter (to the power of three):

$$LCC \sim \sigma * D^3 \; (= \sigma * D * D * D)$$

When comparing the cross sections of two trees with the same diameter, for example an oak with a poplar, the oak has double the strength of the poplar and thus, double the load-carrying capacity. If two cross sections have the same material quality and strength, but one is twice the diameter (**D**) its load–carrying capacity is eight times greater than the smaller cross section (because diameter is taken to the third power). Consequently, when the load-carrying capacity of a specific cross section has to be evaluated, determining size and shape are far more important than material strength values. This is even more obvious, considering that strength or other relevant material properties of wood are commonly measured at only one point. Due to great variability in wood density (Rinn 2013), the result obtained at one point does not characterize the whole cross-section. Furthermore, Kibblewhite (et.al. 2004) showed that the changes in wood material properties along the stem can be even greater than within a cross-section (Fig 1). Local measurements of wood material properties, thus, cannot provide a reliable estimation of the material properties for other parts of the stem. When, for example, modulus of elasticity is locally measured with pull-tests, wood density is obtained locally by resistance drilling, or strength properties are determined by cracking increment cores, the results are valid only for the point of measurement and can usually not be extrapolated to other parts of the same tree.

Understanding how this basic bio-mechanic principle works is a central key to evaluating risk potential.

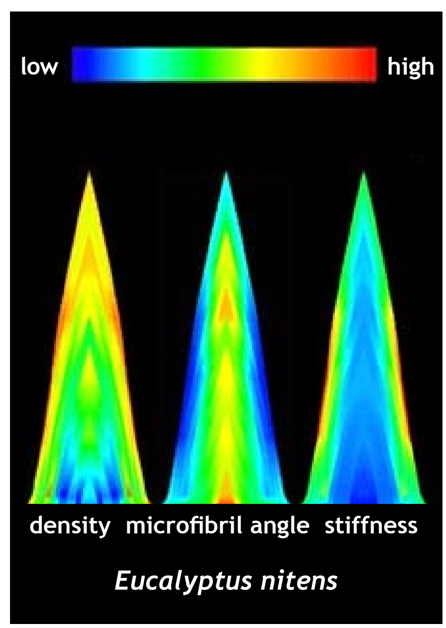


Figure 1. Vertical length plot of material properties of a complete stem, measured by Robert Evans at CSIRO (Melbourne; Australia): density, microfibril angle, and stiffness (modulus of elasticity) change strongly not only within a cross-section but further along the stem. These changes depend on many factors, such as genetics, site/stand structure, crown-architecture, and wind conditions. Consequently, material properties locally measured at one point along a tree stem (by increment coring and fracturing, resistance drilling, or pull-tests), are not representative for the whole tree. "Stiffness", for example, changes dramatically going up the outer perimeter of the stem as shown here in colors.

Table 1:					
Diameter			Relative load-carrying capacity for wind from ... to ...:		
West-East	South-North		West-East		South-North
[cm]	[cm]	[+%]	[%]	[-%]	[%]
100	100	-	100	-	100
100	110	10	83	17	100
100	120	20	70	30	100
100	130	30	59	41	100
100	141	41	50	50	100

Consequently, assessing size and shape of the load-carrying parts of a cross-section is significantly more important and more relevant for determining load-carrying capacity than measuring local strength values.

Basic relationships

The relationship between cross-sectional diameter and relative load-carrying capacity is not linear (Table 1). Thus, gut feeling is not an option for estimating the results for non-circular cross-sections, especially when the circumference is irregularly shaped as commonly found in mature urban trees (to be inspected in terms of safety).

For easier understanding of basic tree-biomechanics principles, it helps to look at circular and elliptically shaped cross-sections (**Figs. 2, 3**). They illustrate what is shown numerically in Table 1.

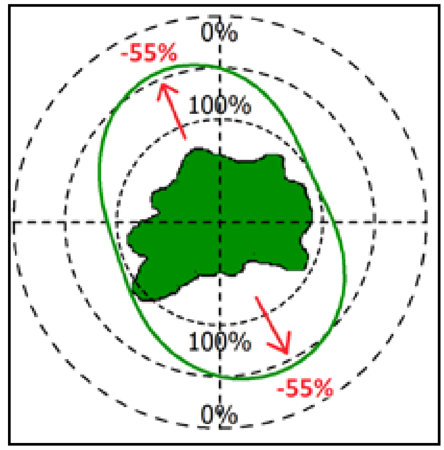
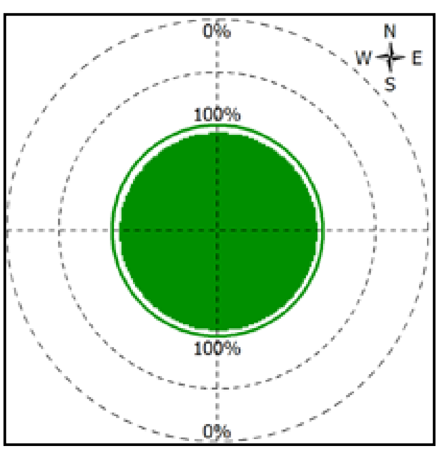
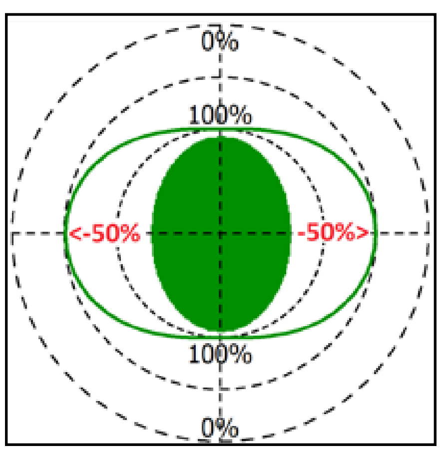


Figure 4. Sketch of a cross-section of a mature urban tree with a shape typical for this region. The green curve has its maximum value (always 100%) to the North-East direction, indicating that this cross-section is the strongest against bending by wind-loading from South-West. This is typical for trees of this region because the wind mostly comes from South-West. Due to the much smaller diameter, even though it is intact, this cross-section can carry approximately 55% less load when the wind is coming from South-East or North-West. This is a typical adaption to the local wind pattern at urban sites, influenced by nearby buildings. The safety of such trees may be significantly reduced when nearby buildings are removed and wind load comes from a different direction. The cross-section shown here could potentially be too weak when the building south of it was removed allowing wind to come from this direction - because the load-carrying capacity for this wind direction is more than 50% less. Even intact trees can then tip over or break.

Figure 2. (Left) If the cross section of a stem is circular (and the material homogenous), the load-carrying capacity is the same for all load directions. Consequently, the solid green curve, representing relative load-carrying capacity for all wind directions, is a circle. For this and the following graphs and examples, the wood is assumed to be intact and homogenous. As soon as defects are present, the situation becomes more complex. This will be explained in a later article.

Figure 3. (Right) If the stem cross sectional diameter is 1m (~40") in West-East and ~1.4m (55") in North-South direction, the load carrying capacity for wind from South or North is nearly twice as high as for wind from West or East. The solid green curve, representing the relative load-carrying capacity for all wind directions, bulges out the most where the cross section is the weakest under bending loads. Such cross-sections are often found where the wind has a dominant direction.





Urban trees

Because diameter has such a great impact on the load-carrying capacity, stem diameters must be accurately measured when assessing tree risk. Measuring tree diameters is relatively simple for smaller trees, particularly forest trees with circular or elliptical cross sections. It is, however, more difficult to measure for most mature urban trees due to greater irregularity in cross-sectional shape of the lower stem (**Fig. 4**) where defects to be assessed are commonly present. In most cases, this requires the use of specialized tools. Fortunately, there are some options to solve these measurement challenges in the field quickly and efficiently.

A quick and 'dirty' approach involves measuring the minimum and maximum diameter of a cross-section. This can be done on the spot with a caliper. But then arborists will need a more technical means to evaluate the relative load-carrying capacity for different wind/load directions (as shown in the figure 4). Software that can perform this function is now available for smart-phones and tablets.

Reaction wood

Conifers, as we know, produce compression wood on the lower side of branches and leaning stems. Broad-leave trees, on the other hand, produce tension wood on the upper sides of branches and leaning stems (Niklas and Spatz 2012). Both types of wood serve to direct branch growth, maintain branch position and return leaning stems to a more upright position. In this manner, static loads lead to higher material properties (density/strength) in the reaction wood zone. In contrast, increased radial (increment) growth rates appear to compensate for additional dynamic loading due to changing wind direction and intensity, or exposure to wind: when wind-load increases significantly, thicker annual rings and sometimes even spirally-arranged wood is formed rather than higher strength wood (Neumann and Rössler 2006).

This concept makes sense because the size of a cross-section is far more important in terms of load-carrying capacity than increasing wood strength. Increasing tree ring width is, thus, a more efficient way to adapt to increasing (dynamic) loads than making high-strength wood. This is, as explained above, because load-carrying capacity of a cross section increases with diameter to the power of three, but changes linearly (to the power of one) with increasing wood strength.

Furthermore, this helps to explain why we find similar cross-sectional shape properties at the same locations for both broad-leave trees and conifers. Most trees we inspected produce and built up (strengthen) their major roots in the prevailing wind direction, and we found the stem to be the thickest in this direction as well. This may be due to the fact that the wood of most tree species is significantly stronger under tension than under compression (USDA FPL Wood Handbook, 2010). Generating wood in the direction of the prevailing wind is a more efficient use of growth resources for tree stabilization than generating wood on the opposite side, loaded in compression. A similar effect we find on slopes, where all tree species try to build up the major roots along their top sides. Obviously, the tree growth concept 'recognizes' that wood can be loaded more under tension than compression and that increasing the size of a cross-section is a more efficient use of energy and material than creating wood with higher strength values in order to compensate for dynamic loads.

Practical consequences

If the shape of a cross-section is non-symmetric and the result of wind-shading by trees and/or buildings, it is important to understand that such cross-sections can be significantly weaker in directions with the smaller diameter – even if the wood is completely intact. As can be seen in Figure 4, the load carrying-capacity of this cross-section was approx. 55 percent less for winds coming perpendicular to the prevailing direction. If such a cross-sectional shape is the consequence of wind-shading, changes in the wind pattern have to be carefully evaluated. The reason is that when wind speed is doubled, wind-load is quadrupled (Rinn 2014). Removing buildings or trees can lead to over-loading and failure of the remaining trees, even those that are intact.

Consequently, if changes in the wind pattern are likely to result in increasing wind load for a particular tree, pruning (crown reduction) to reduce its wind load should be considered. The most efficient way to reduce wind load is by reducing tree height (Rinn 2014). As a rule of thumb, reducing height of mature urban trees by 20 percent, mostly leads to at least 40 percent reduction of wind load.

However, before reducing tree height, the crown should be checked for symmetry because torsional strength of wood is approximately 5 times smaller than its bending strength, and often nearly 10 times less than its strength under tension (USDA FPL Wood Handbook 2010). Avoiding torsional loads, by making sure the crown is symmetric, thus, has a bigger impact on tree-safety than just reducing wind load.

When there are internal defects, it is practically impossible to determine the load-carrying capacity of the stem's cross-section for different wind directions without using advanced technology. The impact of location and size of defects on structural safety shall be described in a further paper.

Summary, conclusion and recommendation

Before taking down buildings or neighboring trees, the remaining trees and their loading characteristics should be checked. This involves measuring tree-height and the maximum and minimum stem diameter at breast height and at the root collar, even when the trees appear intact (defect free). The relative load-carrying capacity can then be determined for all wind (loading) directions with simple tools. Tree risk assessment experts can then determine if changes in wind load could potentially lead to a significantly higher probability of failure.

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