Shell-wall thickness and breaking safety of mature trees

Frank Rinn

Abstract: The acceptable level of trunk hollowness with regard to the breaking safety of trees has been debated for decades but remains unresolved for most tree experts because of contradictory statements, theories, and publications. However, research and observations clearly demonstrate that mature (large diameter) trees require much less remaining shell-wall thickness for reasonable stability, than younger trees still growing in height. Furthermore, stability of mature trees is surprisingly independent of wood material properties such as fiber strength.

Keywords: shell-wall thickness, one-third-rule, breaking safety, tree safety

Introduction

Storm events often lead to breakage of conifer trees in forest stands, even those with intact cross sections. Breakage, though, is probably more likely to occur if decay is present. (**Fig. 1**). On the other hand, old trees are known for having surprisingly thin shell-walls, often for many decades (**Fig. 2**), yet many survive even strong storm events — even trees that are quite tall or have large, wide-spreading crowns. These observations seem contradictory, but can be explained as subsequently shown.

The uncertainty about potential stem breakage safety was one of the reasons for developing mobile testing methods to detect internal decay, and for measuring shell-wall thickness. In 1984, two retired German engineers (Kamm & Voss) tested a drilling device using a spring-driven scratch pin, and which recorded a 1:1-scaled profile of the thin needle's penetration resistance on a wax paper strip within the machine. These profiles allowed for the detection of large voids in trees, but were found to be systematically wrong in the more intact portion of the stem because of resonance and damping effects of the spring-loaded recording mechanism. Thus, evaluations of utility poles, trees, and timber products based on such profiles were also systematically wrong and unreliable. For example, decay was identified were the wood was just soft (by nature), but intact. Consequently, Kamm & Voss developed a resistance drill that recorded data electrically. With that improvement, they then tried to sell the corresponding patent application (Kamm & Voss 1985). A company interested in the intellectual property asked a German University whether the concept, based on measuring needle-penetration resistance, was practical. Starting in 1986, this idea became the

How hollow can a mature tree become, before the risk of stem breakage is unacceptable?

Figure 1. In forest stands, internally decayed stems show a significantly higher breaking probability, but even completely intact cross sections may break.

subject of a physics graduate research thesis (Rinn 1988). This research resulted in further technical developments and finally, patent applications describing high-resolution machines and drilling needles (Rinn 1990, 1991). The results clearly showed that regulation of the machine, acquisition of measurement values and recording of the profiles must be done electronically to ensure a distinct (linear) correlation between the obtained profiles and wood density— the major wood material property (Rinn et.al. 1989 & 1996). Only those profiles obtained in this manner, enable the user to correctly interpret results and reliably evaluate wood condition (Rinn

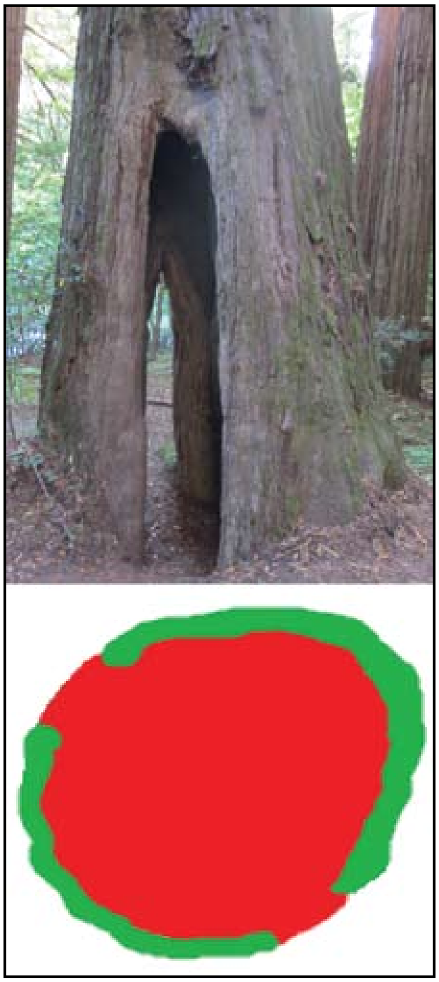


Figure 2. Large, old trees with very thin shell walls ($t/R<{}^1/_5$) often remain standing for decades despite the loss of much of their stem cross sections.

1996). Thereafter, wood samples from all over the world were tested with these improved devices. It's interesting to note that in stems of coconut palms (**Fig. 3**) it was found that approximately ⅓ of the trunk radius has a significantly higher density (and strength).

Some years later, Mattheck and Breloer published statistical data (1994) claiming that breaking safety of tree trunks is significantly lowered if the remaining intact outer shell wall (t) is thinner than ⅓ the radius (R). This finding was interpreted as confirmation of a potential natural mechanical design because the mechanical load characteristics of coconut palms are similar to slender conifers in forest stands.

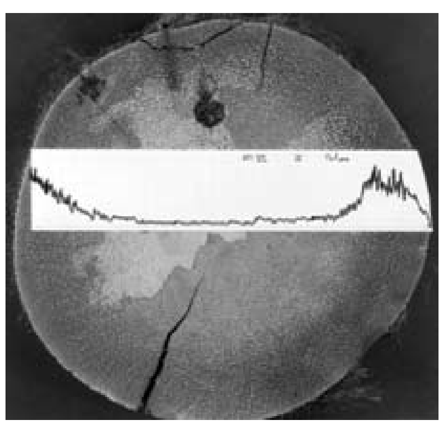
Eventually, new analytical and computational methods suggested that tangential tension stresses as a consequence of bending or torsional loads may explain the increase of breaking failures of trees with a t/R< ⅓ (Ledermann 2003). This result was expected because torsional and shear strength of wood are comparatively low (Blass und Schmidt 1998).

Years later, critics claimed that there is no scientific proof of the so-called 'Mattheck's ⅓ -rule' (Gruber 2007, 2008), and thus, no valid reason to fell trees if t/R< ⅓. Consequently, practitioners and experts became increasingly unsure about which method or 'rule' to apply for safety evaluation of trees.

Trunk and crown relations

The mechanical bending load of upright tree trunks is mainly determined by wind load (Spatz & Bruechert 2000). Because wind speed tends to increase with height above ground, and drag is dependent on wind speed to the power of two, tree height is the dominating allometric wind-load factor. Consequently, after a tree has reached maximum height, wind load does not increase any more (White 1998), although old branches may locally face higher drag due to higher wood stiffness (Fratzl 2002). While the crown does not grow any more, girth usually continues to increase due to annual radial growth increments. That means the trunks of aging trees continuously gain load-carrying capacity, while the load remains fairly constant. Consequently, the increasing girth of aging trees automatically leads to a steady increase in the trunk breakage safety factor (= load-carrying capacity / load). And this leads to the question: How hollow can a mature tree become, before the risk of stem breakage is unacceptable?

Figure 3. A resistance drilling profile of a coconut palm stem disk showing linear correlation to wood density, and that approximately ⅓ of the outer radius has significantly higher wood density.



Numerical estimation (based on Gere and Timoshenko 1997)

Mechanical stress (**S**) in a cross section is usually defined as the acting force (**F**) divided by the area (**A**):

$$\mathbf{S = F / A}$$

If a bending moment (**M**) is applied, stress can be calculated from

$$\mathbf{S = M / W}$$

W characterizes the section modulus that is usually determined by an integral over the cross sectional area. For cylinders of diameter (**D**) and a central void of diameter (**d**), **W** can be calculated in a simple form:

$$\mathbf{W = \pi * (D^4 - d^4)/(32*D)}$$

Strain in the material is usually defined by changes in length (Δ**L**) divided by the observed distance (**L**):

$$\mathbf{\varepsilon = \Delta L / L}$$

At the same time, strain is a consequence of external loading and strongly determined by the modulus of elasticity (**E**):

$$\mathbf{\varepsilon = \Delta L / L = S / E}$$

This helps to explain the influence of material strength (= maximum applicable stress = $\mathbf{S_{max}}$) on the maximum bending load that can be applied without causing damage:

$$\mathbf{M_{max} = W * S_{max}}$$

In an intact cylindrical cross section (**d=0**), the dependence of the load carrying capacity on diameter and material strength is obvious:

$$\mathbf{M_{max} \sim D^3\ S_{max}}$$

Therefore, a doubling of the material strength value of the wood ($\mathbf{S_{max}}$) in the whole cross-section leads to a double maximum applicable bending load ($\mathbf{M_{max}}$). A doubling of trunk diameter, however, leads to an eightfold increase in maximum applicable bending load:

$$(2*D)^3 = 8*D^3$$

Compared to the impact of diameter increase on total load carrying capacity, higher material strength within a newly formed tree ring is only of marginal relevance. The influence of radial growth of a stem cross section in terms of dimension is thus, far more important than changes in material properties. Therefore, we can characterize the load-carrying capacity of cylindrical cross sections in first order by its diameter.

Diameter growth with age

As already shown by Bräker (1981), ring width of mature trees usually stabilizes as a nearly constant value. If we assume that ring width, after the tree has reached maximum crown height (**time point y=0**), is a percentage (**p**) of the diameter at this time (**D_1**), we can estimate later diameters (**D_2**), years (**y**) after D_1 was reached:

$$D_2 = (1 + y * p) * D_1$$

The corresponding section modulus can then be written as:

$$W_2 = \pi * \frac{(D_2^4 - d_2^4)}{(32 * D_2)} = \pi * \frac{((1+y*p)^4 * D_1^4 - d_2^4)}{(32 * (1+y*p) * D_1)}$$

Now we can ask the most important question: at what point (level of hollowness) does a large old tree become unstable? For easier evaluation we transform diameter values into shell-wall thickness (**t**) and stem radius (**R**):

$$t/R = 1 - d/D$$

Once we set $W_2 \overset{!}{=} W_1$, we can calculate t/R-ratios equivalent to the ones at y=0:

$$\frac{t_2}{R_2} = 1 - \sqrt[4]{1 - \frac{(1 - (1 - \frac{t_1}{R_1})^4)}{(1 + y * p)^3}}$$

With this formula we can determine the t_2/R_2-ratio at any given point in time of maturity (y>0), which is equivalent to a certain t_1/R_1-value at y=0.

Practical application

If we assume an intact (**$d_1 = 0$**) tree trunk has a diameter of D_1= 60cm (about 24 inches) at the time when its crown reaches its maximum height (**y=0**), and then an annual ring width of 3mm (**p = 0.5% of D_1**), the diameter of the trunk after y = 20 years will be D_2 = 66cm. If this trunk cross section then (at y = 20) would have a central void of d_2 = 47cm, it would have the same load-carrying capacity as the completely intact cross section at y=0 (**Fig. 4**) That means, if we assume the tree at y=0 is "absolutely safe in bending" (because it is completely intact), we have to grant the same level of safety 20 years later to this tree with a diameter of 66cm if there is a central void leading to a t/R ratio less then ⅓: $t_2/R_2 = 9.5/33 \approx 0.29$, because these two cross-sections provide the same load-carrying capacity and thus, similar breaking safety.

If we assume a cylindrical trunk (D_1= 60cm) has a central void of d_1= 40 at y=0 (that means a t/R= ⅓), after y = 20 years and p = 0.5%, D_2 would be 66cm. If this trunk then has a central void of d_2= 52 (=>$t_2/R_2 \approx 1/5$), it would provide the same load carrying capacity as with a t_1/R_1= ⅓ at y=0 (**Fig 5**). What this means in terms of bending safety for such trees is that: a t/R= 1/5 at y = 20 is equivalent to a t/R= ⅓ about 20 years earlier (y=0). If we believe a t/R= ⅓ is a measure representing sufficient 'stability' of a tree at y=0, then we have to accept, that 20 years later, a t/R= 1/5 represents the same amount of 'stability' and relative safety.

Consequently, the critical t/R ratio is not a constant value, but strongly depends on trunk diameter and thus age (and crown size), as soon as the height does not increase any more.

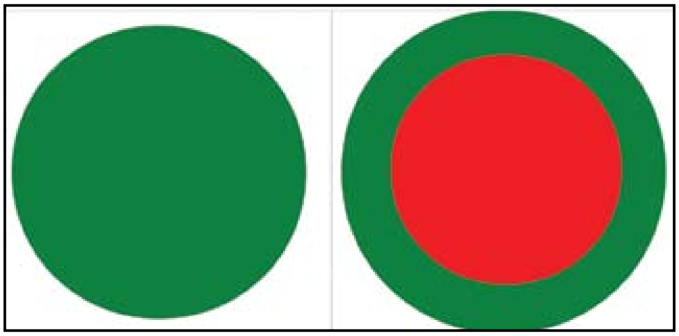
Consequences and limits

Especially in the urban landscape, risk of tree failures, resulting in injury to people or property damage, resulting from tree failures, increases with age. Therefore, most trees that require a thorough assessment are more or less mature. Consequently, the approach described here is relevant for the majority of urban tree inspections, especially for level 2 and 3 as defined and explained by the ISA tree risk assessment qualification (TRAQ).

The comparative shell-wall safety estimation method as described above, shows that the so-called '⅓-rule' may be correct for a certain kind and age class of trunks, but has no relevance for mature trees, and should not be used to justify felling or even extensive crown reduction to mitigate risk for such trees. In mature trees, a t/R= ⅓ is not even the starting point for being concerned about breaking safety, because, as shown above, in terms of breaking safety, a t/R= 1/5 or even less can be equivalent to a t/R= ⅓ at the time the tree reached maximum crown height. This explains why large, old, hollow trees with very thin shell walls often stand for decades, despite large crowns and exposure to strong wind.

When we assume the ⅓-rule as being correct in describing the point where the probability of breaking failures starts increasing significantly for centrally decayed, thin, and tall, slender forest trees (and coconut palms), we have to accept that this starting point for concern shifts down to thinner shell walls once maximum height growth is reached, because tree diameter continues to increase. In the second example described above, the starting point for concern would be a t/R= 1/5 (assuming that a t/R= ⅓ is the starting point of concern for younger trees as described above).

However, it has to be taken into account that this approach as presented here is valid only as long as t/R>1/10, approximately. Below this 'limit', and if big, open cavities are present, more complex approaches and estimations



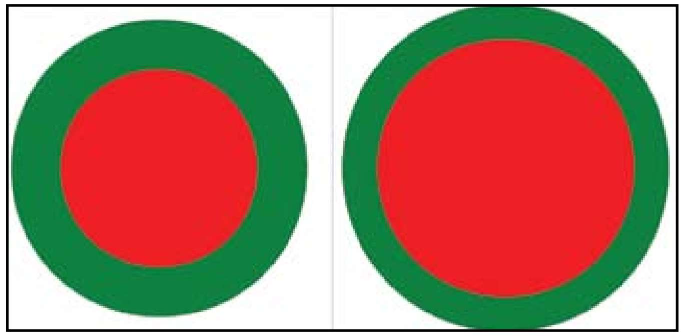


Figure 4. (Left) These two cross-sections (sketch to scale) provide the same load-carrying capacity and thus the same breaking safety provided the same wind load is applied.

Figure 5. (Right) The left cross section of a decayed tree stem at year=0 provides a $t/R \approx 1/3$. The image on the far right shows the same cross section after 20 years of annual increment growth and further decay progression with a $t/R \approx 1/5$. Assuming the same wind load, these two cross sections (sketch made to scale) provide approximately the same load-carrying capacity, therefore, if an expert evaluates the left cross section as acceptable ('safe enough') at the time of inspection (y=0), the same grade of safety has to be granted to the tree 20 years later despite a thinner shell wall.

have to be applied, because other failure modes may occur, and because longitudinal dimension of wood deterioration or other structural damages become more important (Niklas and Spatz 2012; 2013). This aspect shall be explained in future publications.

In addition, in terms of loss of load-carrying capacity (LCC), the location of decay (centered or uncentered) within the cross section, as well as cross-sectional shape, are more important than just the size of deteriorated parts (Rinn 2011). Comparatively small areas of decay in the outer sapwood of the stem, or on the upper side of a horizontal branch can lead to significantly greater losses of LCC and thus, have a greater impact on safety than large centrally located voids. Consequently, for assessing the stem breaking safety of mature trees, it is not enough to determine shell wall thickness by, for example, resistance drilling at just one point, or measuring fiber strain with only one elongation sensor during one pull-test. Both results are valid only for the point of measurement and cannot be extrapolated to the whole trunk. Results can be quite different in other areas of the same cross section, and even more so, up and down the trunk. If devices that can be calibrated are properly applied, both measurement methods (resistance drilling and pull test strain-assessment) can deliver valuable information, and significantly enhance tree risk evaluation compared to visual grading alone. But it has to be taken into account that each result is only valid for the point of measurement. In this sense, tomographic approaches deliver more information, but still have to be understood and interpreted correctly. (**Fig. 6**)

Without knowing the weakest point of the tree trunk under external loading, every localized measurement is just an approximation and cannot describe the mechanical behavior of the whole cross section, trunk or even tree. This limitation is valid for all technical methods and devices in a specific certain way, and has to be clearly understood, explained and communicated by the experts.

The shell-wall-to-radius-ratio (t/R) required for sufficient breaking safety is not a constant value over time, but decreases as trees mature

Figure 6. Two examples of decayed trunk cross sections of mature urban trees (left: *Ulmus*, right: *Tilia*). Decay columns are often asymmetric because they develop from trunk wounds or damaged roots. In addition, many mature urban trees do not have cylindrical cross sections. Thus, simple measurements of shell-wall-to-radius-ratios, or the local assessment of strain by pull-tests can hardly be applied correctly for evaluating breaking safety. In such situations, tomographic assessments are required for obtaining more precise results and more reliable evaluations.

and increase in girth. Understanding and applying this aspect of natural tree architecture while inspecting and evaluating mature urban trees can prevent unnecessary felling or crown reduction as compared to current standards - for the good of nature, people, and municipal budgets. In this manner, trees can be retained longer to provide social and environmental benefits that enhance quality of life in urban landscapes, without endangering people and their property.

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