Basic Aspects of Mechanical Stability of Tree Cross-Sections

By Frank Rinn

The mechanical stability of a tree trunk against bending loads caused by wind depends on the strength and condition of its wood as well as on the size and shape of its cross-section. A basic understanding of these aspects can help when evaluating tree strength loss due to decay within the scope of tree risk[3] assessments.

Diameter and Stability

When a tree is impacted by a wind force, its cells in the trunk on the windward (wind-exposed) side are stretched, while those on the leeward (wind-sheltered) side are compressed (Figure 1).

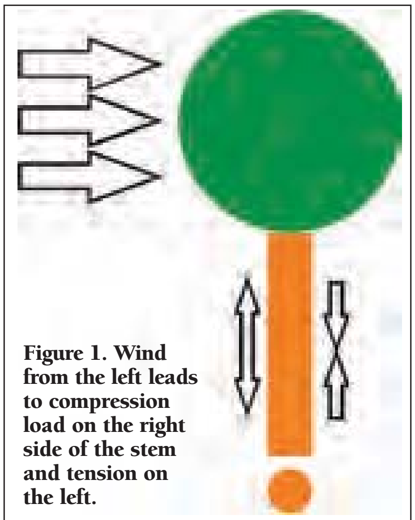

Figure 1. Wind from the left leads to compression load on the right side of the stem and tension on the left.

Furthermore, the tree crown's own weight has to be added as well, which results in an even higher compression load on the leeward cells and a correspondingly lower tension on the opposite side.

To describe the tree's ability to withstand such bending loads, the so called "moment of resistance," represented by the symbol "W" (for the German word *Widerstandsmoment*) is used. It characterizes the mechanical stability of a cross-section as far as it depends on size and geometrical shape. The resistance moment of a circular cross-section with a diameter D can be summarized with a simple formula:

$$W = Pi \cdot \frac{D^3}{32}$$

This formula helps us understand the effect of diameter on stability: if the diameter is doubled, for instance, the moment of resistance increases eightfold, since $(2D)^3 = 8D^3$. Likewise, if trunk diameter grows one percent, its moment of resistance rises by about three percent, since $(1.01D)^3 \approx 1.03D^3$. Therefore, an annual tree growth ring width of 0.2 in (5 mm) within a tree trunk cross-section of 20 in (500 mm) diameter (so one percent increase on each side) denotes a stabilization of a tree trunk cross-section of about 6 percent. In this manner, a sound tree gains stability by its annual ring growth on a yearly basis, ignoring potential changes in the tree crown's surface or wind load and internal damages.

Wrapped Curves Around Cross-Sections

To precisely calculate the load-carrying capacity of a tree trunk cross-section, often called its "strength" or "stability," one would have to know the individual characteristics of each cell and the stability of its compounds. This is hardly feasible, neither in terms of practical work with trees nor with scientific measurement. Therefore, it seems appropriate to adopt a simpler and more relative approach.

We can do this by calculating the moment of resistance for loading capacities from 1° to 360° (all wind directions), then dividing each result by the maximal value to produce a relative stability percentage. Those numbers would normally be represented as a linear graph, with the x-axis representing wind direction and the y-axis the percentage of maximum strength/stability. For better understanding, we can also wrap such a graph around the trunk cross-section to better visualize this effect. A circular trunk cross-section shows, therefore, a constant stability towards wind loads from all directions. Consequently, the curve of the calculated relative stability percentages (moment of resistance) runs along the 100 percent level, creating a perfect circle on the wrapped graph (Figure 2).

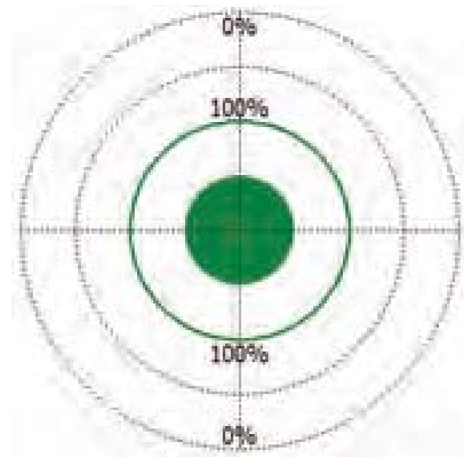

Figure 2. The green curve indicates relative strength of the cross-section against wind load as revealed by the moment of resistance.

Influence of Trunk Profile

This situation changes with different cross-sectional shapes. Trees growing between buildings that are located on their northern and southern side (so wind load is limited to the west or east), for example, mostly develop oval trunk cross-sections (Figure 3). In such a case, calculation of relative stability reveals the consequences of this mechanical impact on tree growth: a tree trunk with an E-W diameter of 40 in (1 m) and a N-S diameter of 28 in (0.7 m)

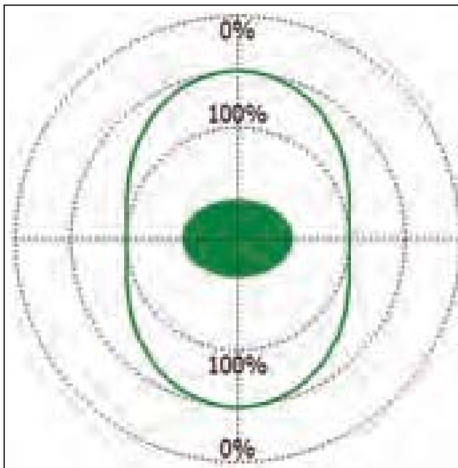

Figure 3. The weaker the cross section the more the green curve bulges into the direction of the corresponding wind flow.

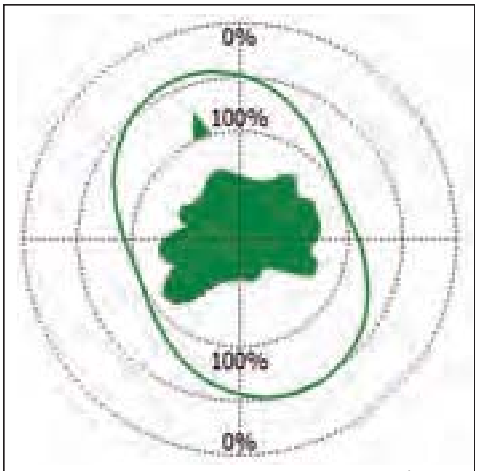

Figure 4. The arrow indicates the wind flow direction where the cross section is the weakest.

retains only approx. 50 percent of maximum stability when exposed to wind load from the north or south. The relative stability curve around the trunk "bulges" accordingly (Figure 3), where the bulges represent drops in strength. As a consequence, if the buildings south of the tree were demolished and the tree suddenly exposed to wind from that direction, the possibility of the tree's failure would be greatly increased.

Trunk flares at the lower trunk cannot only be used to estimate the primary wind-loading direction. In addition, they are critical for a tree's stability because of their influence on the profile of the cross-section.

For example, the cross-section in Figure 4 matches a tree growing at a location where the dominant wind exposure is to the south-west. Along the SW-NE axis of wind exposure, the resulting cross-section is approximately twice as strong along the opposing SE-NW axis.

The green arrow pointing SE on the diagram indicates that the cross-section displays the lowest stability against wind loading from the NW, as revealed by the large bulge (=drop in strength) on the opposite side. If the tree were exposed to wind loads from all directions, the highest possibility of a bending break would be expected in the direction of the arrow.

Defect Size and Strength Loss

In the simple case of a circular trunk cross-section with a cavity in its center, the internal diameter of this cavity will be included in calculating the moment of resistance:

$$W = Pi \cdot \frac{D^4 - d^4}{32 \cdot D}$$

For example, a trunk diameter of D=40 in (1 m) with a center cavity diameter d=20 in (0.5 m) has 50 percent of its radius missing. That corresponds to a loss of cross-section surface of 25 percent but a relative strength loss of a mere 6 percent. Following this equation, when about 70 percent of the radius is gone (i.e., $t/R \approx 0.3$), the cross-section lost about 50 percent of its area but only 25 percent of its strength (Figure 5).

Consequently, the actual strength loss is significantly lower than professionals as well as laymen might expect when observing the extent of internal damage. If this aspect is considered when making decisions about tree stability, it can often save the tree, especially if non-arborists have to decide what action has to be taken – be it neighbours in dispute or politicians.

As the cross-sectional residual wall ('shell wall') continues to thin out (Figure 6), the informational value of the formula we examined begins to reach the limits of its validity: it assumes that a cross-section stays firm and does not get deformed due to the loading force. But, the torsional and shear strength characteristics of wood are significantly lower compared to compression and tension strength in longitudinal direction. Skatter and Kucera (2000) showed that this is the reason why torsion is an important factor for tree failures.

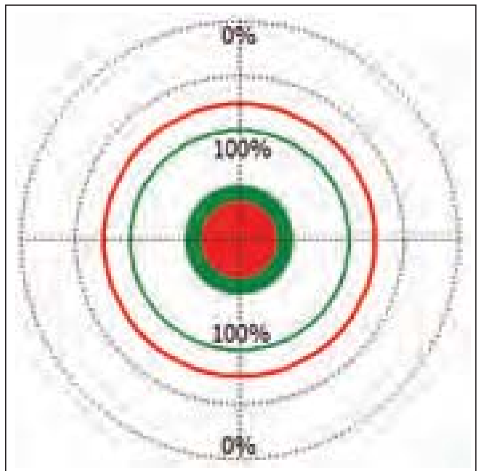

Figure 5. If a center cavity covers 70 percent of the diameter, 50 percent of the cross section is lost but only 25 percent of the moment of resistance.

For example, a tree trunk with a remaining shell wall thickness of only 10 percent of the radius (Figure 7), should theoretically still provide 35 percent of its strength. This cannot be true and needs to be corrected due to torsional effects, shear stresses and different failure modes than just bending.

Influence of Location of Decay

Up to this point we have assumed that the decay was located in the center of the cross-section. When it is not, different calculations must be used: mathematically speaking, an integral is calculated summarizing the contribution of each wooden cell regarding whether it is loaded under compression or tension.

When wood decay in a tree trunk is at the edge, the resistance moment towards the opposite side from the decay decreases to a greater degree because tension strength of wood is higher than compression strength (FPL 2010).

Figure 8 represents such an off-center situation, characterized in this example by a thin or missing shell wall on one side. As earlier, the red curve shows the relative value of resistance moment in the

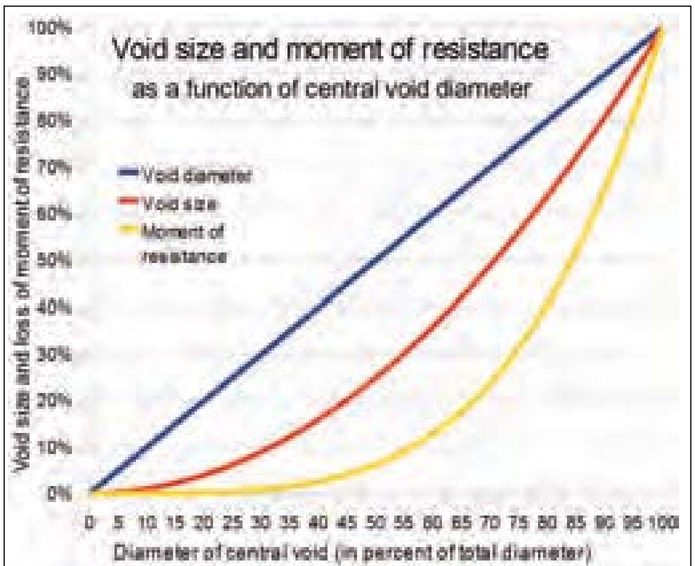

Figure 6. Size of a central cavity and the corresponding relative strength loss as a function of cavity diameter.

Basic Aspects of Mechanical Stability (continued)

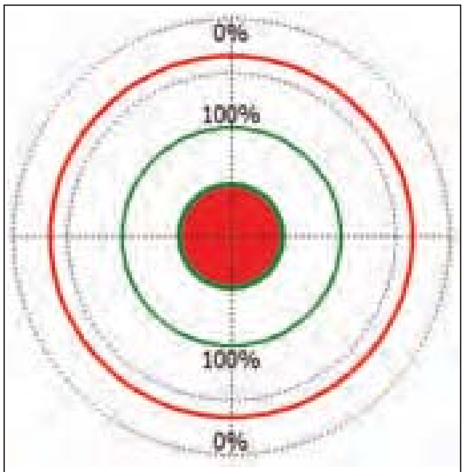

Figure 7. Theoretically, 90 percent loss of radius equals approximately 65 percent loss of moment of resistance.

damaged cross-section for all wind directions. The outward bulge (=relative decrease in stability) on the side opposite from the decay corresponds to the comparatively higher reduction of tensile strength for wind coming from the side where the decay is located.

Therefore, relative strength loss of a trunk cross-section depends not only on the extent of decay, but also – and above all – on its location. This is relevant for expert assessment of breaking resistance and critical when trying to communicate expert opinion to laymen.

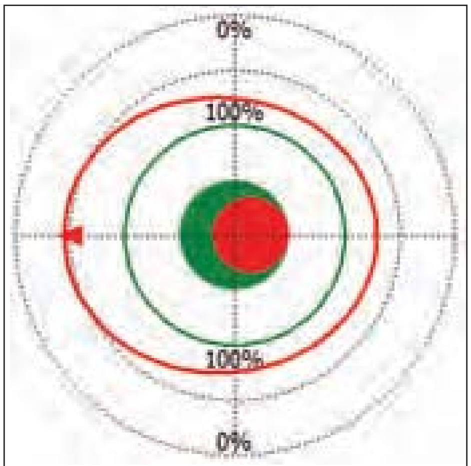

Figure 8. If a cavity covers 50 percent of the cross-section area and is located at the edge, the corresponding relative strength loss is doubled as compared to being located at the center.

Finally, for the real and mostly non-concentric cross-sections of urban trees that have to be inspected, a third curve is calculated in the moment of resistance graph: dividing the values of the red curve (representing the resistance moment of the decayed cross-section) by the green curve (representing the intact cross-section) delivers a curve (in blue) revealing the relative strength loss in percent for every wind direction. The more the blue curve bulges outward, the higher the strength loss due to wind blowing into this direction.

A typical result is shown in Figure 9, again indicating that decay location is more critical than extent: the blue curve shows that degradation strongly points towards the south of that trunk cross-section (or bottom of that branch). Even though only about 10 percent of the cross-section area is damaged, the moment of resistance for this direction has already decreased by about 50 percent.

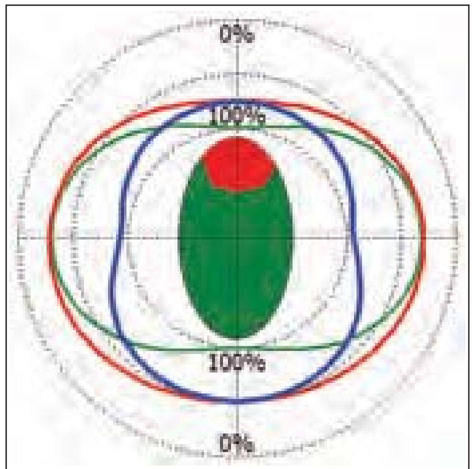

Figure 9. The blue curve reveals the relative strength loss for all load directions due to decay. It is used for evaluating failure potential and as a base for determining risk mitigation strategies, for example a corresponding wind load reduction by pruning.

Summary

The moment of resistance is used to characterize relative strength of cross-sections referring to different static wind loading directions as well as the influence of defects. The first major conclusion is, the cross-section diameter determines a mostly directional stability; the second, that the location of decay is of higher importance than extent. Relative strength loss due to decay can be higher or lower than corresponding loss in cross-section area, strongly depending on cross-sectional shape and defect location. For thin shell walls and dynamic loading, more complex approaches would be required.

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Frank Rinn received his physics diploma from Giessen and Heidelberg University, where his research was on the suitability of resistance drilling for tree-ring analysis in dendrochronology. He holds international patents and trademarks and received 5 innovation awards for developing resistance drilling and sonic tomography. Frank serves as voluntary executive director of ISA Germany and participated in the ISA Biomechanics Week, August 2010.

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January 2011

Aboveground Growth Response of *Platanus orientalis* to Porous Pavements

Justin Morgenroth and Rien Visser

Integrating healthy, mature trees into paved urban environments is a challenging task for

Wie hohl darf ein alter Baum sein?

Über die Frage, ab welchem Höhlungsgrad ein Baum als signifikant erhöht bruchgefährdet anzusehen ist, wird seit vielen Jahren nicht nur gerätselt und geforscht, sondern oft gestritten. Auch wenn diese Frage hier noch nicht für alle Bäume geklärt werden kann, so zeigt eine relativ einfache Analogieberechnung jedoch zumindest für alte Bäume, wie der jeweils akzeptable Höhlungsgrad ermittelt werden kann. **Von Frank Rinn**

Abb 1: Viele alte Bäume stehen seit Jahrzehnten, obwohl sie hohl sind und dünne Wandstärken aufweisen, oftmals sogar mit Stammöffnungen.

Für viele Fachleute ist das Ergebnis dieser Berechnung an sich schon erstaunlich. Es ist darüber hinaus aber auch überraschend unabhängig von den grundlegenden Annahmen, ab wann der Stamm eines Baumes nicht mehr stabil ist und mindestens ebenso unerwartet wenig beeinflusst von den Festigkeiten und Materialeigenschaften des Holzes.

Zur Geschichte

Nachdem die ursprünglichen Erfinder Kamm und Voß die ersten Nadel-Bohrwiderstandsmessgeräte mit federgetriebener Aufzeichnung über Kratzstift auf Wachspapierstreifen wegen systematisch falscher Kurven als untauglich erkannt hatten, entwickelten sie eine elektrische Aufzeichnung. Diese Idee wurde in und nach einer Physik-Diplomarbeit zu einer elektronisch messenden Methode weiter entwickelt (Rinn 1986-88; 1990), weil nur so verlässliche und hochauflösende Dichte-Profile zu erzielen waren.

Einige Jahre später wurde eine statistische Auswertung von Stammbrüchen publiziert (Mattheck & Breloer 1994) und postuliert, dass vollbekronte Bäume ab äußeren Restwandstärken von unter 1/3 des Radius eine deutlich ansteigende Bruchwahrscheinlichkeit aufwiesen. Da Kokospalmen zumindest hinsichtlich ihrer allometrischen Eigenschaften und mechanischen Belastungen schlanken Bestands-Nadelbäumen mit runden Stämmen und zentrischen Schäden nicht unähnlich sind, erschienen diese Ergebnisse kongruent und wurden interpretiert als Hinweis auf eine biomechanische Grundregel derartiger natürlicher Konstruktionen. Später zeigten Finite-Elemente-Berechnungen, dass nicht unbedingt direkt die Biegebeanspruchung, sondern eher andere Materialeigenschaften und Spannungen für das Ansteigen der Versagensrate verantwortlich sind, wenn Restwandstärken deutlich unter ein Drittel des Radius sinken (Ledermann 2003). Dies wiederum war nachvollziehbar, zumal die tangentialen Querzugfestigkeiten zu den schwächsten Materialeigenschaften von Holz gehören (Blass & Schmidt 1998).

Im Laufe der Jahre kam jedoch vermehrt Kritik an dem sogenannten 1/3-Kriterium auf, nicht nur, weil es angeblich schon zu oft missbraucht wurde, um unliebsame Bäume fällen zu lassen, sondern auch, weil es angeblich grundsätzlich keine verlässliche wissenschaftliche Begründung dafür gebe (Gruber 2007). Insofern stellt sich nicht nur Praktikern, sondern auch Sachverständigen und Wissenschaftlern die Frage, ob und wann das 1/3-Kriterium gültig sein kann. Hierzu nachfolgend einige grundlegende Erläuterungen wichtiger Hintergründe und einige auch in der Praxis hilfreiche Empfehlungen bezüglich alter Bäume.

Stamm und Krone

Die mechanische Biege-Belastung des Stammes von nicht schräg oder am Hang stehenden Bäumen wird vor allem vom Wind bestimmt. Da die Windlast von der Windgeschwindigkeit zum Quadrat abhängt und die Windgeschwindigkeit mit der Höhe über Boden ansteigt (Spatz & Bruechert 2000), bestimmt vor allem die Höhe eines Baumes die maximal auftretende Windlast. Wenn Bäume ihre maximale Höhe erreicht haben wächst demnach auch die Windlast nicht weiter an. Da alternde Bäume tendenziell eher noch Äste verlieren und die Krone kleiner wird (White 1998), nimmt die am Stammfuß ankommende Windlast insgesamt also tendenziell eher ab – auch wenn die zunehmende Versteifung der alternden Äste gegebenenfalls zu einer lokalen Erhöhung der Windbelastung führen kann (Fratzl 2002).

Mit jedem neuen Jahrring wird der Stamm aber dicker und stabiler, denn die Biege-Belastbarkeit eines Zylinders hängt vor allem von seinem Durchmesser ab. Und so stellt sich die Frage, welchen Einfluss dies auf die Bruchsicherheit des Baumes hat.

Rechnerische Abschätzung

Die mechanische Belastung im Querschnitt eines Zylinders ergibt sich aus der ▶

Abb 2: Besonders bei schlanken Bestands-Nadelbäumen sind Stammbrüche bekannt (links), insbesondere bei innerer Stockfäule (Bild rechts).

wirkenden Kraft F und der betroffenen Querschnittfläche A, wird meist als „Spannung“ bezeichnet und mit dem griechischen Buchstaben Sigma (σ) gekennzeichnet:

$$\sigma = \frac{F}{A}$$

Im Falle der Biegebelastung von Stämmen ergibt sich die Spannung aus dem Quotienten des angreifenden Biegemoments (M) geteilt durch das (axiale) Widerstandsmoment (W). Zum Zeitpunkt des Erreichens der maximalen Baumhöhe sei dies wie folgt definiert:

$$\sigma_1 = \frac{M_1}{W_1}$$

Das Widerstandsmoment kann für runde Querschnitte mit Außendurchmesser D und zentraler und runder Höhlung (d) durch eine einfache Formel beschrieben werden:

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

Für einen vollholzigen Stamm (d = 0) ergibt sich

$$W = \pi * \frac{D^3}{32}$$

Eine verdoppelte Festigkeit σ_{max} führt also zu einer ebenso verdoppelten maximalen Moment-Belastbarkeit M_{max}, die oft als Tragfähigkeit bezeichnet wird. Ein doppelter Durchmesser dagegen führt aufgrund der dritten Potenz bei gleicher Festigkeit zu einer achtfach höheren Belastbarkeit des Querschnitts. Die Abmessungen eines Querschnitts haben also einen vielfach höheren Einfluss auf seine Tragfähigkeit als Änderungen in der Festigkeit.

Alters-Tragfähigkeits-Zuwachs

Wie Bräker bereits bei der Erläuterung des sogenannten Alterstrends zeigte (1981), stagniert bei alternden Bäumen die Jahrringbreite typischerweise auf einem oftmals nahezu konstanten Niveau. Daher nehmen wir hier in konservativer Weise an, der Baum lege ab Erreichen seiner Maximalhöhe nur noch eine konstante kleine Jahrringbreite zu, die als Prozentanteil (p) des Durchmessers D_1 ausgedrückt wird. Damit ergibt sich der jeweils aktuelle Durchmesser D_2 nach y Jahren also zurückhaltend geschätzt zu:

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

Das Widerstandsmoment des Stammes nach y Jahren kann dann wie folgt beschrieben werden:

$$W_2 = \pi * \frac{(D_2^4 - d_2^4)}{(32 * D_2)}$$

Nun stellt sich die entscheidende Frage: wie hohl darf dieser Baum sein, damit sein äußerer intakter Stammrand noch ein Widerstandsmoment (W_2) aufweist, welches mindestens so groß ist, wie das seine Tragfähigkeit charakterisierende Widerstandsmoment (W_1) zum Zeitpunkt der Erreichung der maximalen Baumhöhe (y = 0).

Demnach setzen wir $W_2 ! = W_1$ und bestimmen das Restwandstärke–zu–Radius-Verhältnis t_2/R_2 nach y Jahren, indem die obigen Gleichungen verwendet werden:

$$\frac{t_2}{R_2} = 1 - \sqrt[4]{\frac{(1-\frac{t_1}{R_1})^4 + 3(yp + y^2p^2 + y^3p^3)}{(1+yp)^3}}$$

Mit dieser Formel kann also berechnet werden, welches Restwandstärke-zu-Radius-Verhältnis nach y Jahren die gleiche Stabilität gewährleistet wie es sich aus D_1 und d_1 beziehungsweise R_1 und t_1 zum Zeitpunkt der Erreichung der maximalen Baumhöhe ergab.

Beispiele

Zunächst nehmen wir an, ein Baum habe zum Zeitpunkt des Erreichens der maximalen Baumhöhe und damit der maximalen Wind-Biegebelastung des Stammes (y = 0) einen Durchmesser von D_1 = 60 Zentimeter und keinen inneren Schaden, also $d_1 = 0$, demnach t/R = 1 und Höhlungsgrad = 0. Nach 20 Jahren mit einem jährlichen Stammdickenzuwachs von sechs Millimeter (Jahrringbreite drei Meter), ist der Stamm-Durchmesser auf 66 Zentimeter angewachsen. Wenn ein solcher Stamm eine innere Höhlung von etwa 47 Zentimeter Durchmesser aufweisen würde, dann hätte er die gleiche Tragfähigkeit wie 20 Jahre vorher der vollholzige Stamm mit einem Durchmesser von 60 Zentimeter! (s. Abb. 3)

Ein jährlicher äußerer Durchmesserzuwachs von 1% führt zur Steigerung des Widerstandsmoments und damit der Tragfähigkeit von jeweils rund 3%, nach ca. 25 Jahren entspricht dies einer Verdopplung.

Wenn ein Stamm bei y = 0 eine Restwandstärke-zu-Radius-Verhältnis von etwa 1/3 (D_1 = 60 cm, d_1 = 40) hat und als noch ausreichend stabil eingeschätzt wird, dann hat er nach 20 Jahren Dicken-Wachstum (0,5% von D_1) einen Durchmesser von D_2 = 66 Zentimeter. Dieser Stamm hat die gleiche Biege-Belastbarkeit, wenn seine innere Schädigung einen Durchmesser von 52 Zentimeter aufweisen würde, das Restwandstärke-zu-Radius-Verhältnis also rund 1/5 beträgt (s. Abb. 4).

Grenzen

Die hier beschriebene Berechnung der Tragfähigkeit beziehungsweise Belastbarkeit eines (hohlen) Querschnitts basiert auf Jahrhunderte alten und ingenieurtechnisch tausendfach bewährten Konzepten, kommt jedoch auch an Grenzen: sobald die Restwandstärken im Bereich um und unter 1/10 des Radius liegen, wirkt sich die Anisotropie des Holzes signifikant stärker aus.

Wie nicht nur bei Ledermann (2002), sondern auch bei Niklas und Spatz zu lesen (2012, 2013), wirken sich ab spätestens t/R = 1/10 insbesondere die geringen Scher- und Querzugfestigkeiten aus und es kommt schneller zu Verformungen des Querschnitts. Die einfache Biegetheorie über die Betrachtung des axialen Widerstandsmoments verliert dann ihre theoretische Berechtigung und praktische Relevanz.

Die hier beschriebenen Sachverhalte sollen vor allem diesen einen grundlegenden Zusammenhang klar machen: ob man nun t/R = 1/3 oder eine andere t/R-Grenze als grobe Richtschnur oder Grenzwert betrachtet – an alte, in der Höhe nicht mehr wachsende Bäume sind auf jeden Fall andere Maßstäbe anzulegen. Das 1/3-Kriterium hat dort aus grundsätzlichen Überlegungen keine Gültigkeit und keine praktische Relevanz. Daher kann es nicht verwendet werden, um damit Fällungen zu begründen.

Grenz- oder Richtwerte zum mechanischen Versagen, die für junge und noch in die Höhe wachsende Bestandsbäume gelten mögen, wie anscheinend das 1/3-Kriterium, können also nicht einfach auf alte Bäume übertragen werden. Genau dies ist aber in den letzten Jahren tausendfach erfolgt und führte zu einem ebenso unwiderbringlichen wie auch bedauernswerten Verlust eines erheblichen Anteils unseres alten Baumbestands. In solchen Fehlentscheidungen liegt nicht nur nach meiner persönlichen Erfahrung eine der häufigsten Ursachen für Streit zwischen Sachverständigen um Bäume.

Außerdem ist zu bedenken, dass die Lage einer Schädigung im Querschnitt sich stärker auf seine Tragfähigkeit auswirkt (Rinn 2011) als ihre Ausdehnung und dass auch die vertikale Ausformung innerer Schäden einen Einfluss auf die Bruchfestigkeit hat (Niklas & Spatz 2012, 2013).

Schließlich ist zu beachten und auch hier nochmals zu betonen, dass die meisten bezüglich ihrer Verkehrssicherheit zu beurteilenden Straßen- und Parkbäume nicht nur alt sind, in Krone und Windlast nicht oder kaum noch wachsen, sondern in der Regel auch keine zentrisch geschädigten runden Stämme aufweisen. Alleine schon aufgrund dieser geometrischen Aspekte ist offenkundig, dass ein vermeintlich einfaches 1/3-Kriterium bei diesen Bäumen nicht anwendbar sein kann, auch nicht als grobe Richtschnur, ebenso wenig andere „Einfach-" Kriterien wie t/R > 1/10 oder das Höhe-zu-Durchmesser-Verhältnis.

Zusammenfassung und Schlussfolgerung

Die hier gezeigte, grob vereinfachende Darstellung belegt, dass an alte, nicht mehr in der Höhe wachsende Bäume spezifische baumstatische Anforderungen zu stellen sind. Das bei jungen, runden und zentrisch geschädigten Bestands-Nadelbäumen und Kokospalmen anscheinend relevante sogenannte 1/3-Kriterium kann bei alten Straßenbäumen weder als Grenzwert noch als Richtschnur angesehen werden. Im Vergleich zu jungen und noch in die Höhe wachsenden Bäumen brauchen alte auf jeden Fall geringere, oftmals erstaunlich dünne Restwandstärken, wobei die hier gezeigte Abschätzung nur für Restwandstärken oberhalb 1/10 des Radius gilt (Niklas & Spatz 2012). Materialeigenschaften wie Festigkeit und Elastizität wiederum sind im Vergleich zur mechanischen Auswirkung des äußeren Stammdicken-Zuwachses durch Jahrringe von deutlich geringerer Bedeutung, weil die Tragfähigkeit mit dem Durchmesser in der dritten Potenz steigt.

Literatur

Die Literaturliste finden Sie im Internet als Download unter www.baumzeitung.de.

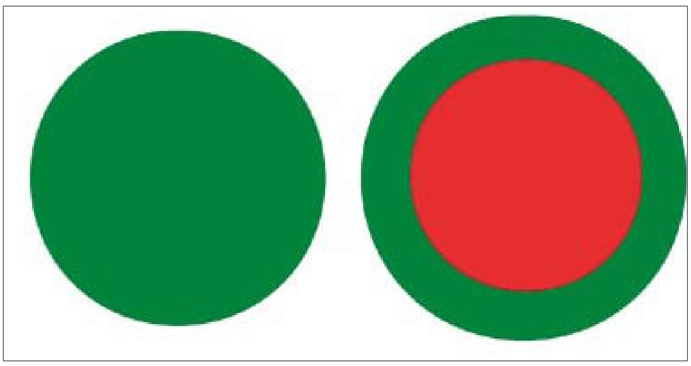


Abb. 3: Diese beiden Stamm-Zylinder-Querschnitte haben die gleiche Tragfähigkeit. Ein jährlicher äußerer Durchmesserzuwachs von 1% führt zur Steigerung des Widerstandsmoments von jeweils ca. 3%, nach ca. 25 Jahren entspricht dies einer Verdopplung. Deswegen sind Rohre bei gleicher Masse auch biegesteifer als Vollstäbe.

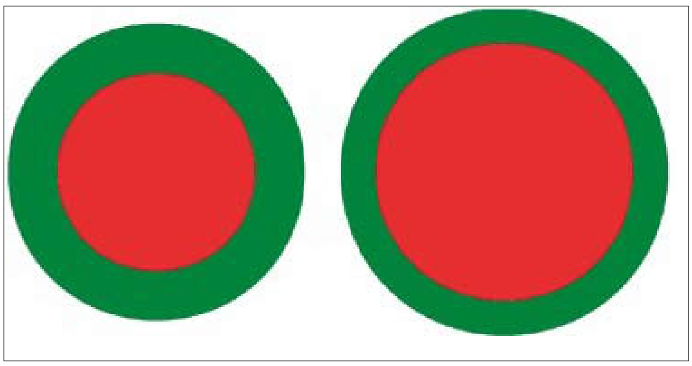


Abb 4: Auch diese beiden Stammquerschnitte weisen die gleiche Biegebelastungs-Tragfähigkeit auf. Beim linken Querschnitt beträgt t/R=1/3, beim rechten (nach 20 Jahren Stammwachstum) nur noch ca. 1/5 und dennoch haben beide Querschnitte das gleiche Widerstandsmoment und daher quasi auch die gleiche „Bruch-Sicherheit" (bei gleicher Windlast).

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

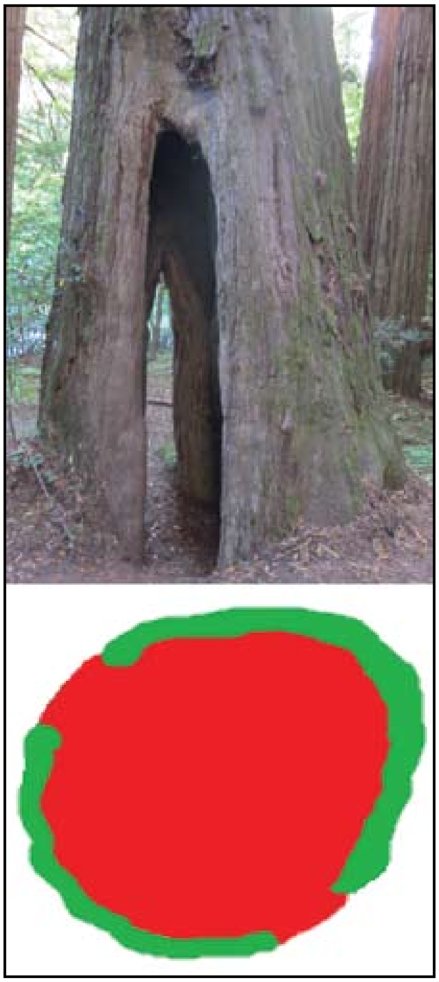


Figure 2. Large, old trees with very thin shell walls ($t/R<1/5$) often remain standing for decades despite the loss of much of their stem cross sections.

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.

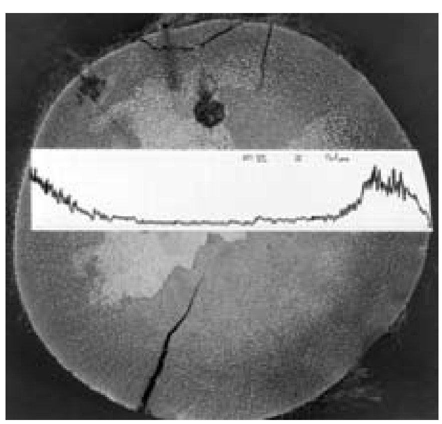
Eventually, new analytical and computational methods suggested that tangential tension stresses as a consequence of bending or torsional loads may explain the increase of breaking failures of trees with a $t/R<1/3$ (Ledermann 2003). This result was expected because torsional and shear strength of wood 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 $t/R<1/3$. 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**):

$$S = F / A$$

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

$$S = M / W$$

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:

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

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

$$\varepsilon = \Delta L / L$$

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

$$\varepsilon = \Delta L / L = S / E$$

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

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

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

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

Therefore, a doubling of the material strength value of the wood (S_{max}) in the whole cross-section leads to a double maximum applicable bending load (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 $W_2 ! = W_1$, 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.

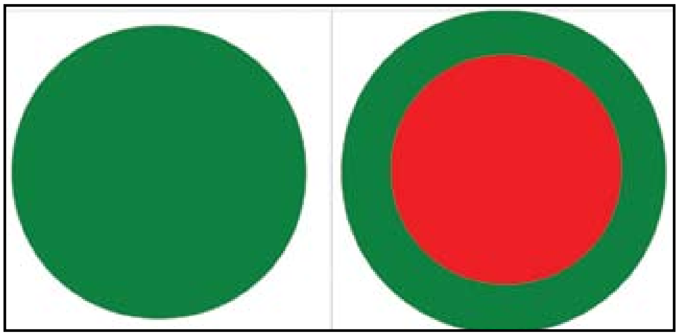
Consequences and limits

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



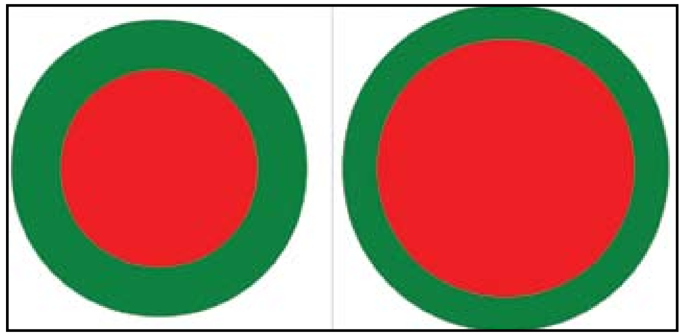


Figure 4. (Left) These two cross-sections (sketch to scale) provide the same load-carrying capacity and thus the same breaking safety provided the same wind load is applied.

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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How much crown pruning is needed for a specific wind-load reduction?

Frank Rinn

Abstract: Crown reduction is a standard procedure to reduce the risk of urban trees with structural defects near the trunk base. However, the recommended amount of pruning is usually based on a 'gut-feeling'. Understanding principles of tree wind-load as presented here will enable tree experts to more accurately determine how much of the crown to remove. In general, trees need to be pruned (their crowns reduced) much less than many arborists think to compensate for risk due to trunk or root defects. The advantages of less pruning and fewer and smaller pruning cuts include reduced impact on tree health and appearance, and environmental benefits, less pruning response, and cost-savings to the tree owner.

Keywords: wind load, crown reduction, pruning, and tree safety

Introduction

When significant trunk and root collar defects are identified in urban trees, crown reduction is one of the most common practices to reduce wind load and, as a consequence, to increase the so-called breaking and uprooting safety. Although this is a standard procedure in many countries, the amount of required reduction is mostly estimated by 'gut-feeling'. Many arborists use the percentage of trunk cross-sectional area loss determined or estimated at the trunk defect as a guide to the amount of height or crown sail area reduction needed to achieve reasonable safety. For example: if 50 percent of the trunk cross-section is decayed, the crown has to be reduced by 50 percent. In general, this is far more than actually needed.

The impact of a specific amount of height or wind-sail area reduction cannot be directly translated into a corresponding wind-load reduction because the functional dependencies are complex and not linear. To make decisions on crown reduction pruning more precise and reliable, a basic understanding of tree wind-load, as described below, is mandatory.

In this simplified approach, torsional aspects are left out, as they are much more complex and shall be described in another article. Thus, this text focuses on the bending moments at the stem base due to wind-loading.

Tree wind-load relations

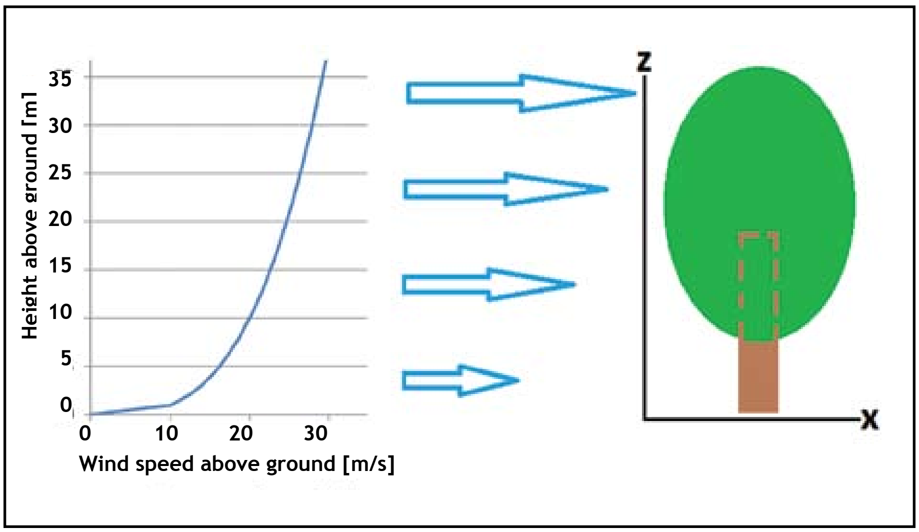
The discussion presented below regarding wind-load basics is a summary of concepts excerpted from published articles by Davenport, Ruck, Spatz, Brüchert, and Niklas. Following Davenport (**Fig. 1**), wind speed (v) increases with height above ground (z) and this is typically described by the following equation:

$$v(z) = v(z_{ref}) * \frac{z^a}{z_{ref}^a}$$

z_{ref} is defined as the height above ground where the wind is no longer disturbed by surface roughness, such

Tree height is the most important factor dominating trunk base bending-moment due to wind-loading of mature urban trees.

Figure 1. Assuming a 'roughness' parameter for typical suburban situations (a~0.3) and a wind speed of 40m/s on 100m above ground (=reference height), this is the resulting vertical increase of wind speed dragging the tree crown.



as trees or buildings. The exponent (a) describes the surface roughness and typically ranges from 0.1 to 0.5:

Surface type	Exponent
Town center	0.4
Suburbs	0.3
Forests	0.28
Agricultural land	0.25
Ocean	0.16

For the typical urban and suburban tree to be inspected in terms of traffic safety, the exponent (a) thus ranges between 0.3 and 0.4.

The drag on any part (i) of the crown 'sail area' as represented by the locally acting force (f_i) mainly depends on wind speed (v), air density (q) and the drag coefficient (c):

$f_i \sim ½ * q * c * v^2$

In a simplified approach, the total force (F) on a tree crown with a 'sail' area (A) is a sum of all (infinitesimal) forces (f_i):

$F = \sum f_i = ½ * q * c * v^2 * A$

This approach is a very rough approximation for several reasons, such as:

- Wind speed (v) changes with height above ground.
- The drag coefficient (c) of the crown changes with wind speed (v).
- The 'sail' area (A) changes with wind speed (v).

The dependencies, especially between wind-speed, height, drag coefficient, and sail area, are non-linear, and thus difficult to describe here comprehensively. However, a simple approach can be applied based on measurements published by Ruck that showed how the drag coefficient of trees drops from around 1 for low wind speeds to approximately 0.3 for high wind speeds in storms and gusts (>30m/s). This drop in drag-coefficient covers the effects of both crown re-configuration and smaller sail area in higher wind speeds.

Assuming constant air density and drag coefficient, the total force (F) acting on a tree crown is proportional to a wind speed integral over the surface area:

$$F \sim \iint \left(v(z)\right)^2 \, dx \, dz$$

Effective wind load

In terms of engineering, safety of a structure is mostly defined as the load-carrying capacity divided by the load. This value is often called the "safety factor". Consequently, stem breakage and uprooting safety of a tree are usually determined by the corresponding load-carrying capacity divided by the bending or tipping moment as representing the load. For calculating the bending moment, the force (f_i) acting on each part (i) of the crown sail area (A) has to be multiplied by the length of the acting lever arm (l_i), which, in this simplified case, is height (z) above ground:

$m_i = f_i * l_i = f_i * z_i$

The total bending moment (M) acting at the stem base is proportional to wind speed multiplied by height, integrated over the crown surface area:

$$M \sim \iint \left(v(z)\right)^2 * z \, dx \, dz$$

Replacing wind speed by its determining parameters, the total wind bending moment (representing the load on the tree) can be described by:

$$M \sim \frac{v\left(z_{ref}\right)^2}{z_{ref}^{2a}} \iint z^{1+2a} \, dx \, dz$$

The integral represents a sum of infinitesimal steps, running over the sail area (x from 0 to crown width W, and z from 0 at ground level to tree height H). Despite the importance of shape of the crown sail-area, the integration result reflects the dominating influence of tree height and crown width on bending moment as the major functional dependencies:

$M \sim W * H^{2+2a}$

Hasenauer showed in empirical studies (1997) that the crown diameter of solitary trees typically correlates with tree height: crown-width ~ tree-height^b, b>1, resulting in:

$M \sim H^{2 + 2a + b}$

Assuming the height exponent (a) is being approximately 0.3 to 0.4 for urban and suburban trees, the bending moment at trunk base depends on tree height to the power of more than 3.5:

$M \sim H^{3.5+\dots}$

That means that tree height is the most important factor dominating trunk base bending-moment due to wind-loading of mature urban trees.

Practical consequences

If two trees of similar crown architecture and site conditions are compared and one has a height twice that of the other, the wind-load bending moment at the stem base of the taller tree would be at least an eight times higher (2^3=8) than that of the shorter tree. However, due to the influence of width, shape, and height of the crown, a tree-height reduction of 10% (H*0.9) does not directly lead to a wind-load reduction of 27 percent ($0.9^3 \approx 0.73$) or 31% ($0.9^{3.5} \approx 0.69$). But, the resulting wind-load reduction percentage is commonly significantly greater than the reduction of the tree height and crown sail area.

If we assume, in a simplified approach, a tree resembling a circle on a pole (**Fig. 2**), the resulting wind-load reduction can be approximately twice as high as the reduction in height. That means, in this case, if tree height is reduced by 10 percent, wind-load is reduced by 20%, approximately.

In a more typical case of a common mature urban tree (**Fig. 3**), resulting wind-load reduction is more than twice the reduction in tree height. Although this amplification factor of 2 or more is very common, there is no

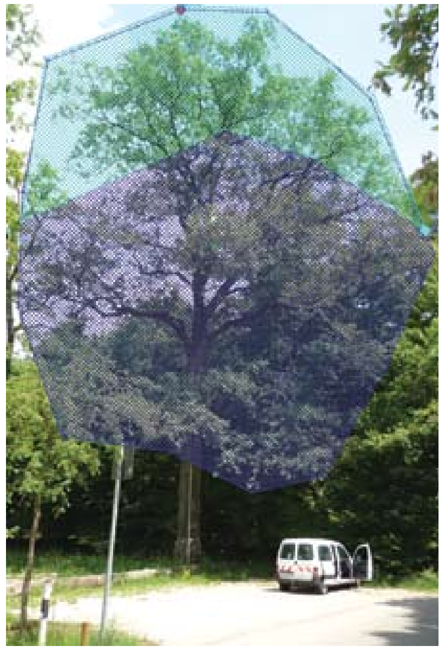


Figure 2. (Left) If this nearly circularly shaped crown would be reduced in height by about 10% this would lead to a reduction of the sail area by a little more than 10% and of the wind load by about 20%, approximately.

Figure 3. (Right) A reduction of the tree height by about 20%, in this case, leads to a reduction of the sail area by about 30% and squeezes down the wind load bending moment at the stem base by about approximately 50%.

simple rule for calculating the resulting wind-load reduction from the amount of height reduction because it depends on the ratio of crown height and width to overall tree height. As a rule of thumb, a factor of two is reasonable. That means, if a tree needs a strong reduction of wind load by about 50% (because of decay in the trunk base, or increased wind-load due to site changes), tree height has to be reduced most likely by less than 25 percent!

In addition, we have to take into account that the size of internal decay column does not equal the corresponding loss in load-carrying capacity (Rinn 2011) and that mature trees inherit much higher safety factors due to their natural allometric design (Rinn 2013).This commonly results in much lesser required wind-load reduction even when extensive defects are present as compared to many currently applied standard procedures.

If all these aspects are understood and applied in combination, the actual level of crown reduction required will often be much less than commonly practiced. Mature trees will remain healthier and survive longer when their crowns are reduced to the extent actually needed to achieve reasonable tree safety. In addition, less crown reduction leaves greater photosynthetic capacity, enabling trees to better defend themselves against insect pests, and fungal pathogens. Thus, when properly applied, crown reduction improves tree safety and, at the same time, has significantly less negative impacts on tree health and vitality, as well as esthetic and environmental benefits, while providing cost-saving to private and municipal tree owners. It also can minimize the chance of sunburn injury and resultant decay, particularly in species sensitive to extensive pruning.

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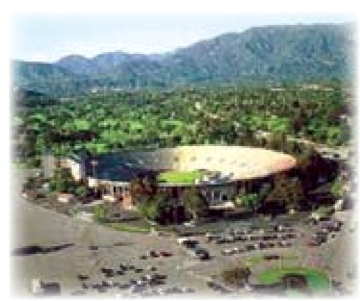

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