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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 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). 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.

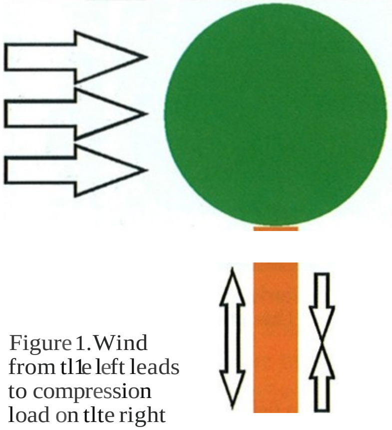

Figure 1. Wind from the left leads to compression load on the right side of the stem and tension on the left.

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:

$$W = Pt\ x\ \frac{D3}{32}$$

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 $(2D)^3 = 8D^1$ Likewise, if trunk diameter grows one percent, its moment of resistance rises by about three percent, since $(l.01D)3\text{-}l.03D^3$. 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

RI LWV FRPSRXQGV
SUDFWL FDO ZRUN ZL
7KHUHIRUH LW VHHPV
UHODWLYH DSSURDFK
:H FDQ GR WKLV E\ F
LQJ FDSDFLWLHV IURP
HDFK UHVXOW E\ WKH
SHU FHQWDJH 7KRVH
OLQHDU JUDSK ZLWK
D[LV WKH SHUFHQWDJH
XQGHUVWDQGLQJ ZH
FURVV VHFWLRQ WR E
VHFWLRQ VKRZV WKH
D FRQVWDQW
VWDELOLW\ WRZDUGV
ZLQG ORDGV IURP
DOO GLUHFWLRQV
&RQVHTXHQWO\
WKH FXLYH RI WKH
FDOFXODWHG UHOD
WLYH VWDELOLW\
SHUFHQWDJHV
PRPHQW RI
UHVLVWDQFH UXQV
DORQJ WKH
SHUFHQW OHYHO
FUHDWLQJ D SHU
IHFW FLUFOH RQ
WKH ZUDSSHG
JUDSK)LJXUH

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)

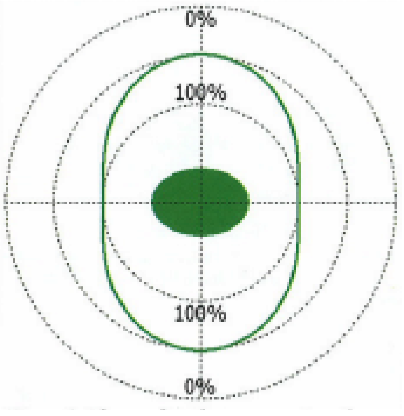

Figure 3. The weaker the cross section the more the green curve bulges into the direction of the corresponding wind flow.

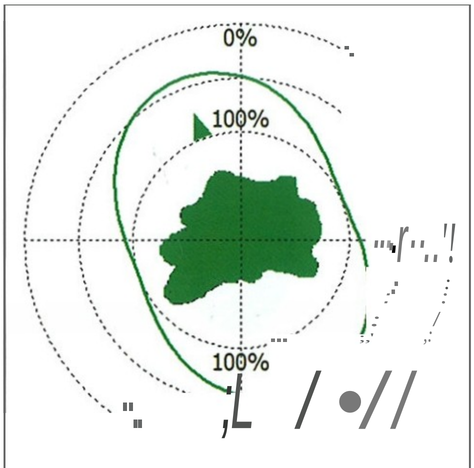

Figure *4*. The arrow indicates the wind flow direction where the cross section is the weakest.

retains only approx. 50 percent or maximum stability when exposed to wind load rrom the no11h or south. The relative stability curve around the trunk "bulges" accordingly (Figure 3), where the bulges represent drops in strength. As a consequence, ir the buildings south or the tree were demolished and the tree suddenly exposed to wind from that direction, the possibility or the tree's failure would be greatly increased.

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

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

The green atTow pointing SE on the diagram indicates that the cross-section displays the lowest stability against wind loading from the N'vY, as revealed by the large bulge (=drop in strength) on the opposite side. If the tree were exposed Lo wind loads from all directions, the highest possibility or a bending break would be expected in the direction or 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 vvill be included in calculating the moment of resistance:

$$W = Pi\, x\, \frac{D4 - d4}{32\, x\, D}$$

For example, a trunk diameter of 0=40 in (1 m) with a center cavity diameter d=20 in (0.5 m) has 50 percent of its radius missing. That con-esponds 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"" 0.3), the cross-section lost about 50 percent of its area but only 25 percent or 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. Ir this aspect is considered when making decisions about tree stability, it can often save the tree, especially if non-arborisls 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 or the fonnula we examined begins to reach the limits or its validity: it assumes that a cross-section stays finn and does not get defonned 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.

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

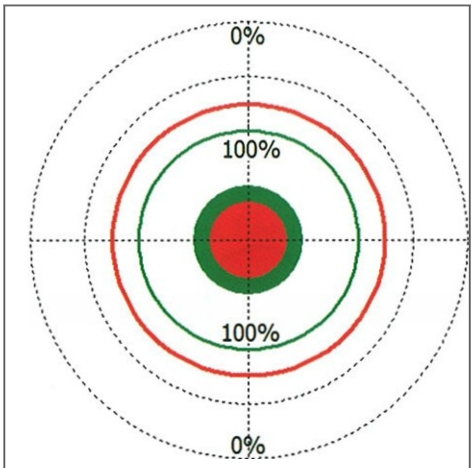

Figure S. If a center cavity covers 70 percent of the diameter, SO percent of the cross section is lost but only 25 percent of the moment of resistance.

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 or 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 or resistance moment in the

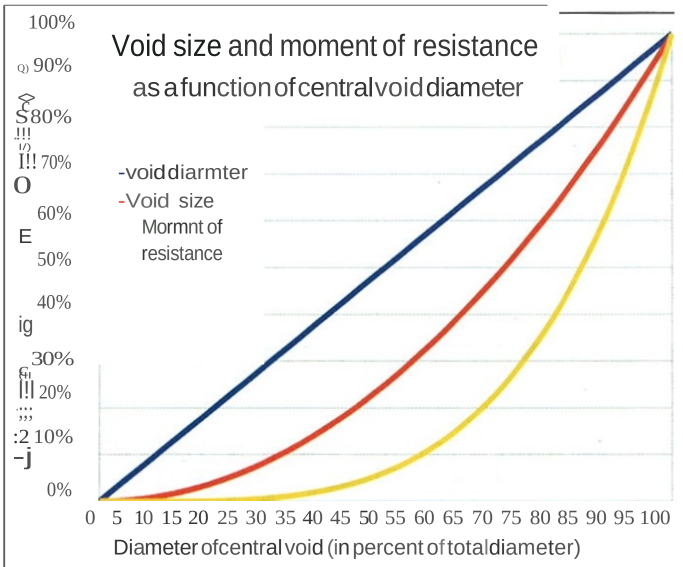

Figure 6. Size of a central cavity and the corresponding relative strength loss as a function of cavity diameter.

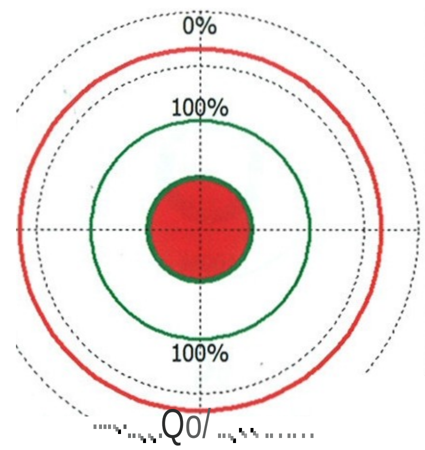

Figure 7. Theoretically, 90 percent loss of radius equals approximately 65 percent loss of moment of resistance.

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.

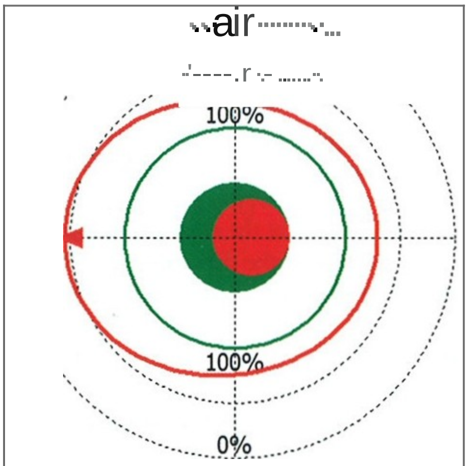

Figure 8. If a cavity covers 50 percent of the cross-section area and is located at the edge, the corresponding relative strength loss is doubled as compared to being located at the center.

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.

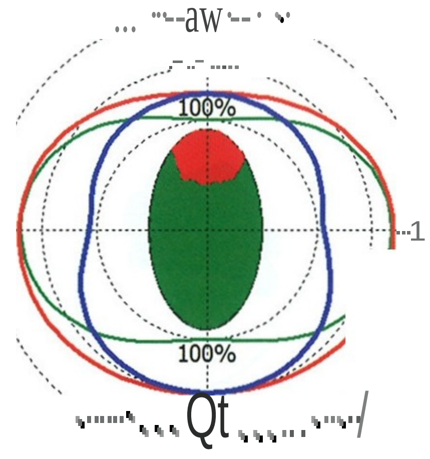

Figure 9. The blue curve reveals the relative strength loss for all load directions due to decay. It is used for evaluating failure potential and as a base for determining risk mitigation strategies, for example a corresponding wind load reduction by pruning.

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