When is a bottleneck dangerous?

Frank Rinn

FOR MATURE TREES WHERE canopy growth has all but stopped, there is no fixed shell-wall-to-radius-ratio (t/R) that can be used to identify a significantly higher breaking risk (Rinn 2013). The key is to understand that the ratio t/R is not the one-and-only critical measure, but more appropriately the safety-factor, representing the relation between load and load-carrying capacity. When the load no longer increases but load-carrying capacity does, the safety factor increases, thus the required t/R ratio drops. As a result, mature and over-mature trees can tolerate thinner shell-walls, yet remain stable: first, wind-load is no longer increasing, and second, stem diameter is continuing to increase with the addition of each new annual radial increment. Thus, there is a corresponding increase in load-carrying capacity in excess of what is needed in terms of breakage safety. However, when shell walls become extremely thin, for example 1/10 of the radius, the situation becomes much more risky because the cross sections tend to deform under load, and common calculation methods do not apply any more. In such cases, the longitudinal size of the defects, as well as shear stresses have to be taken into account (Niklas and Spatz 2013). The calculation method becomes far more complex. However, even this aspect can be analysed and much better understood using a new software (TuboCalc™) based on the papers of Niklas and Spatz, mentioned above.

For young trees, still growing in height, the situation is different because wind-load is largely proportional to tree height (Rinn 2014), and thus, continually changes with it (Spatz & Bruechert 2000). When young trees have obvious defects near their stem bases (**Fig. 1**), breaking safety may no longer be sufficient. In court cases regarding failed trees, judges typically ask if it was foreseeable that the tree in question had a significantly higher probability of breaking or uprooting due to one or more defects that should be obvious to a tree expert.

Basics of the calculation

A bottleneck is mostly seen as an obvious defect-symptom - but not always dangerous as explained below.

For trees with round stems and central defects, the probability of breakage strongly depends on the ratio t/R, the shell wall thickness t divided by the radius R (Ledermann 2003; Spatz & Niklas 2013). The critical t/R-threshold for hollow or centrally decayed trees has been hotly debated for years (Gruber 2007, 2008; Fink 2009). This question will not be discussed here because it is not relevant in the context of this method using "self-referencing" as subsequently described.

A surprisingly simple solution for a common and quite obvious problem frequently encountered by tree-risk assessors, foresters, and municipal arborists.

Figure 1. Typical example of an urban tree with a 'bottleneck' due to cars bumping against the stem.

This article does not refer to any potentially critical t/R-threshold, but introduces a completely different approach to assessing tree stability. This new method of self-referencing can be applied on young and old trees and enables the risk assessor to evaluate the safety of a tree with a surprisingly simple assessment and reference comparison directly while observing the tree.

The reference-calculation

In a simplified model, we assume a total height **H** of the tree (**Fig. 2**). The lower crown edge starts at **C**. **Hi** is the approximate height of the lowest intact cross section of the stem with an average diameter **Di**. **Hd** is the height above ground where the defect is and **Dd** the average stem diameter at this height.

The total wind drag is described

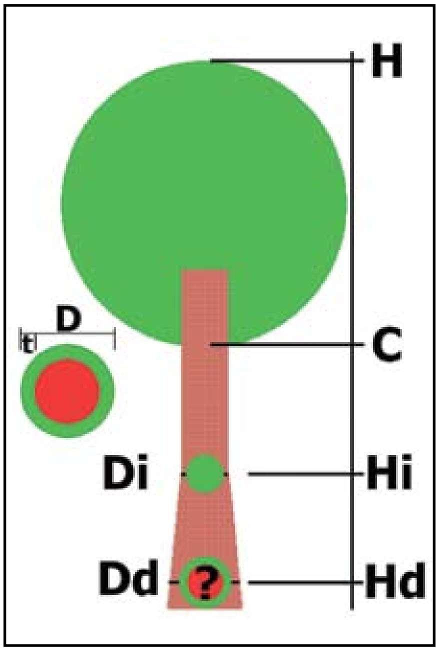


Figure 2. Sketch describing the major parameters used in this calculation concept of 'self-referencing'. Hi is the height above the bottleneck where the stem cross section is intact. Its diameter is Di. Hd is the height of the lower internal stem defect, and its stem diameter is Dd. For the relative wind-load estimation, tree height H and the height of the lower edge of the crown C are required.

by the force **F** acting on the crown center at height **Hf**. For simplification and with an implemented additional safety factor, the lever arm length is calculated by referring to the geometric central point between lower edge of the crown (**C**) and tree height (**H**):

$$\mathbf{Hf = (H+C)/2}$$

Thus, the bending moment (M) created by the wind load on the height of the intact cross section is:

$$\mathbf{Mi = F * (Hf - Hi)},$$

and at the height of the defect cross section:

$$\mathbf{Md = F\ (Hf - Hd)}$$

According to Gere & Timoshenko (1997), the maximum bending-load a circular stem cross section can carry depends largely on strength of the material **σ** and diameter **D**:

$$\mathrm{Mmax} = \boldsymbol{\sigma} * \mathrm{W}$$

W is the section modulus of a circular cross section with outer diameter (**D)** and, if centric defects are present, inner diameter (**d)**:

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

For an intact cross section:

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

As long as a tree is vital enough and responds to changing environmental factors, the radial increment growth along the stem is strongly influenced by mechanical load, and the resulting local stresses and strains (Jaffe & Telewski 1984; Telewski 2006). With this kind of adaptive growth, trees achieve a 'normal' or 'natural' level of breaking safety, mostly described by a 'safety factor' (Niklas 1990; Niklas & Speck 2001).

If the tree is intact at height **Hi** and able to provide the 'normal' or 'natural' safety factor, we can use this cross section as a reference for evaluating other sections of the same stem. This comparison enables the tree risk assessor to determine if there is a significantly higher breaking probability in the area of the observed or obvious defect, and thus, an obvious 'foreseeability' in the legal sense, too.

For this comparison, we assume that the diameter of the stem at the height of the defect **(Hd)** is greater than at the height of the intact cross section (**Hi**): **Dd > Di**. The inner diameter of the defect is **dd**. Consequently, the section modulus is:

$$\mathbf{Wd} = \pi * (\mathbf{Dd}^4\text{-}\mathbf{dd}^4) / (32\ \mathbf{Dd})$$

Because the thickness (**t**) of the outer intact shell wall is more easily determined than any internal diameter, we can use **t** rather than **dd**:

$$\mathbf{dd = Dd - 2 * t}$$

If both cross sections, the intact and the decayed one, have the same breaking safety, the following equation has to be fulfilled:

$$\mathbf{Mi / Wi = Md / Wd}$$

This equation assumes that the wood quality (strength properties) is similar at both height levels. In reality, wood in the area of defects often has higher strength properties (Ledermann 2003), resulting in another safety reserve in the method described here.

If the bending moment is written in its components, the equation changes to:

$$\mathbf{(Hf - Hi) / Wi = (Hf - Hd) / Wd}$$

The most important aspect

If the lever arm of the wind bending-moment at the height of the defect is 10% longer than for the intact cross section, the section modulus of the defect cross section must be 10% greater to provide the same breaking safety. This sounds plausible, but it's much more interesting when we realize that the section modulus depends on the diameter of the cross section raised to the power of three. Because of this, a diameter 3% larger than the intact one is sufficient to compensate for the 10% longer lever arm. This explains why the stems of slender forest trees in dense stands do not need strong taper to provide similar breaking safety along the stem. Even tiny increments in diameter lead to a significantly higher load-carrying capacity due to increasing cross-sectional diameter, providing over-proportionally higher breaking safety.

Now, we put in the individual dimensions into the formula of the section modulus of the two cross sections to be compared and solve the equations to determine the minimum required thickness of the intact shell wall (**t**) at the height **Hd** with the defect cross section required to provide the same breaking safety as the intact reference cross section at height **Hi.** (**Fig. 3**) **[Equation]**

$$t = \frac{1}{2}[D_d - \{(D_d^4 - D_i^3 D_d)(H_f - H_d)/(H_f - H_i)\}^{\frac{1}{4}}]$$

Applying the formula

Let's assume we are doing a risk assessment on a tree with a lower stem defect. Tree height (**H**) is 25m (~82ft), and the lower edge of the crown (**C**) starts at 15m (~49ft). The height of the defect (**Hd**) is at 10cm (~5 inches) above ground and its diameter (**Dd**) is 70cm (~28"). The intact stem cross section (**Hi**) is at a height of 1m (~40 inches) above the ground and its diameter (**Di**) is 60cm (~24inches).

The calculation shows that at the height of the defect (**Hd**) [10cm or ~5 inches above ground], this tree needs a minimum intact shell wall thickness (**t**) of approximately 7cm (~3 inches) to provide the same breaking safety in the area of the defect (**Hd**) as compared to the intact cross section at height **Hi** (1m) and with a diameter of 60cm (**Fig. 4**).

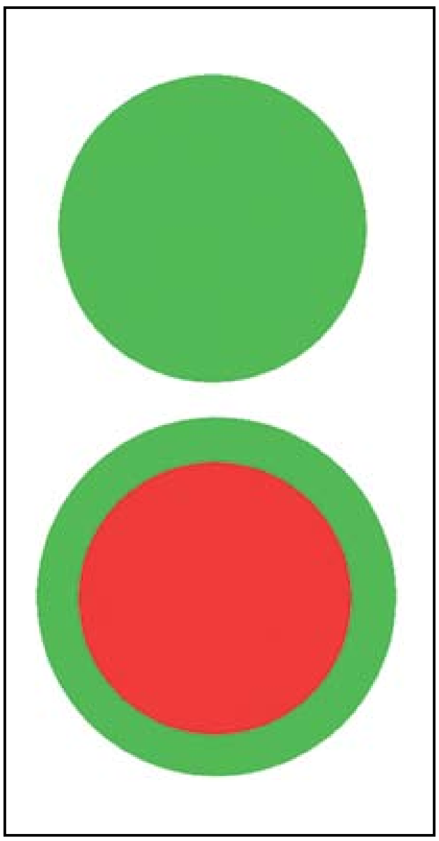
This estimation is conservative and thus safe in many ways, especially for mature trees (no longer growing in height): because wood quality in the area of defects is often significantly higher than in other, undisturbed parts of the stem. In addition, trees can tolerate a certain amount of internal defects without becoming significantly more hazardous (Niklas & Spatz 2013). This is a consequence of the fact that the load-carrying capacity strongly depends on the diameter, and, thus, on the outer parts of a cross section. The contribution of internal areas of a cross-section to the load carrying capacity are comparatively small.

Therefore, safety evaluation based on the reference comparison as described here is a conservative estimation with several implemented safety reserves and far away from critical values.

Possible further steps

If tree risk assessors want to determine and evaluate breaking safety of tree stems under wind load more precisely than the relatively simple approach described here, many other factors have to be taken into account. One aspect is that, in terms of strength loss of the cross section, location of defects is more important than size of the defects (Rinn 2011). This is important for urban trees because their stem base defects often are the result of root loss or cars bumping against the lower stem – and thus the defects are not central. The impact of such defects on stability is often more difficult to assess and to determine. This cannot be done by gut feeling any more. However, there are more and more tools available to assist experts in evaluating such cases, even by using mobile computers for instant evaluation of the tree.

Figure 4. Even though it may seem illogical, these two cross sections (shown to scale here) of the tree used in the example described above represent similar breaking safety. This is largely due to the fact that diameter is the dominating factor determining load-carrying capacity, thus the outermost parts of the cross section carry most of the load. Consequently, if the remaining intact shell wall (t) of the decayed cross section is approx. 7cm (~3"), this cross-section provides for the same breaking safety as the intact (but thinner) cross-section. The point here is that the minimum required shell wall thickness cannot be estimated by gut feeling. It can, however, be determined on the spot with an application for smartphones by comparing with an intact cross section of the same tree by the method of self-referencing as described here.



Practical application

If a (young or old) tree shows a bottleneck and has a central defect in the lower stem but is intact above that point, the procedure described above allows tree risk assessors to quickly determine what shell-wall-thickness is required at the height of the defect to provide the same breaking safety as at the height of the intact cross section. As long as this shell-wall thickness is adequate, the probability of a stem failure remains low despite the defect – otherwise, even the intact cross-section would have to be identified as being dangerous. Consequently, this would mean that all trees, even intact ones, would not be safe enough.

The simple calculation described here is a conservative estimation and allows experts to evaluate the defect on the spot (without worrying about the formula): there is a simple application available (ArboRef™) in the major APP-Stores for mobile phones and tablets as well as for different operating systems of desktop computers for calculating the required shell-wall thickness within seconds.

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