Hollow stem stability: scaling diameter and crown height

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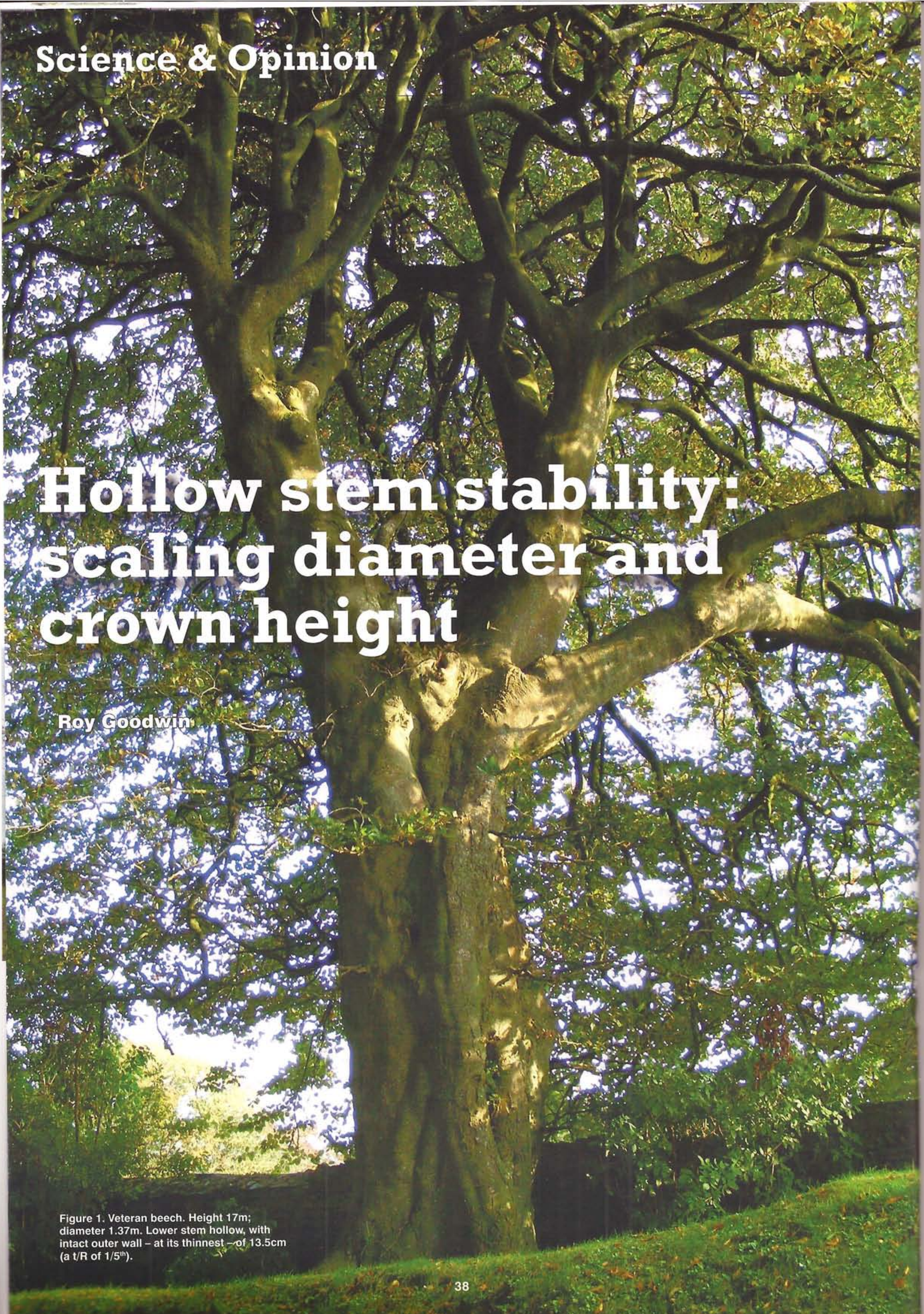

Figure 1. Veteran beech. Height 17m; diameter 1.37m. Lower stem hollow, with intact outer wall – at its thinnest – of 13.5cm (a t/R of 1/5th).

Many of the old landscape trees that arboriculturists assess have lower stem decay, often with the lower stem (trunk) being hollow.

The thickness of the remaining outer stem wall (t) divided by the radius (R) of the stem gives the ratio t/R. Previous research, including that by Waegner, Smiley & Fraedrich and, of course, Mattheck (Mattheck & Breloer, 1994) proposed an approximate safety limit or threshold for the bending safety of hollow stems of t/R = 0.3 (meaning the outer 1/3rd of the stem radius, or that a circular stem can be hollow in the centre for up to c. 70% of its radius).

Qualified arboriculturists have of course never applied this 'rule of thumb' blindly; stem decay is just one factor, and often not the most critical one as regards failure potential. But its current wide acceptance in arboriculture can present problems when dealing with large, often magnificent, specimens with hollow stems. Such trees have withstood countless severe storms with often full live crowns, yet can have thin outer stem walls often far below a t/R of 1/3rd. Faced with such trees, many arboriculturists, given the t/R ≥ 0.3 'rule', may often feel bound to recommend crown reduction, or worse still, removal (felling).

At the Association's national conference in September 2014, Frank Rinn gave a presentation on the stability of hollow stems (Rinn, 5). He said that the postulated minimum safe t/R of 1/3rd sounds plausible to him for younger, slender trees with circular stem cross-sections in dense forest stands, as long as they are still growing in height. But, he asked, is it valid for older, open grown trees, with often larger diameters and non-circular stem cross-sections? Rinn argued that the typical mature urban tree to be inspected differs strongly in many ways from young slender forest trees and that hollow stem stability depends not only on t/R. Most importantly, perhaps, Rinn stated that the situation changes with age, when the tree no longer significantly increases in height, but continues to increase in diameter. Let's briefly review the evidence.

Mature crown size

Notionally, trees reach a (more-or-less) maximum height and crown size at maturity. For many of our common species, this occurs long before 'senescence' and death (King, 2011; Bond et al., 2007). So at maturity, crown height may not significantly increase any further. The stem diameter, of course, continues to increase each year that the tree is alive. Of course, whilst the outer rings may appear to get narrower, the actual cross-sectional area of wood produced annually is often equal to or greater than that of the wider rings of a smaller diameter stem.

Within whatever location/setting the tree stands, its crown height is the principal factor as regards wind loading, and wind loading is the principal factor as regards the mechanical stress on the tree stem. As Rinn states in another presentation, 'tree height is the most dominant factor determining stem base bending moment and thus wind load' (Rinn, 4).

Diameter

If the crown size (and specifically height) is no longer increasing, the wind loading on that tree and its stem (trunk) will no longer increase significantly. But at the same time, the load-carrying capacity of the stem cross-section increases steadily due to the annual radial incremental growth. The section modulus, characterising the load-carrying capacity, increases with diameter to the power of three. Thus even small radial increments lead to an over-proportional increase in load-carrying capacity. So after maturity, the scaling between stem diameter and crown size/height becomes allometric. As a consequence, Rinn states, stability increases significantly with age; due to their diameter in comparison to tree height, the stems of old trees even 80% hollow can provide more structural safety than a young tree stem without any decay.

Applications

It may be difficult to say when and at what diameter a tree ceased to increase in height. But Rinn's concept is simple: once the height and thus the wind loading remain largely the same, the shell-wall thickness required for guaranteeing a constant safety decreases with increasing diameter, because the load-carrying capacity is proportional to the diameter to the power of three.

This means that if the tree's stem diameter increases per year by, for example, approximately 1%, its load-carrying capacity increases by more than 3%. Accordingly, its fracture safety increases by more than 3% because the height-related wind load does not significantly change. After 10 years, with an annual diameter increase/growth of 1%, the safety is increased by more than 30%. Hence the tree needs a lesser thickness of intact outer shell wall than 10 years previously to guarantee the same safety against stem fracture from wind-induced bending stress. So, decades later, when the stem diameter of a tree has, for example, increased from 75cm to 120cm, it may be as stable with a t/R of 0.2 (1/5th) as it was previously with a t/R of 0.3 (1/3rd).

There are of course limits. Rinn rightly warns that below a t/R of 1/10th effectively 'all bets are off' as regards stability, not least as the risks of fracture failure from torsional or shear stresses increase dramatically. Mattheck himself clearly stated that the risk of failure of a hollow stem is from cross-sectional flattening, and in particular, hosepipe kinking; and that, of course, is initiated at the hollow/solid transition, albeit that the fracture generally occurs in the lower hollowed section. Lastly, please note here that we are discussing the hollowness of a stem and its resistance to bending fracture; compounding features such as open cavities, necrosis, co-dominant forks, etc. will all need to be taken carefully into consideration in any actual assessment. Obviously, when internal stem decay is in combination with root decay or stem cracks, the risk of fracture failure can increase dramatically.

Rinn's equation is reproduced in Figure 2. Unfortunately there is no simple rule, such as t/R <0.3, for estimating what might be a reasonably safe t/R, but Frank Rinn is providing an Android App that calculates this.

Carefully and expertly applied, this revised model could allow old hollow trees with

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

Figure 2. t1/R1 represents the shell wall to stem radius when the tree has reached maximum height. This can be given a conservative 'safe' value such as t/R 1/3rd. The t2/R2 represents the shell wall to radius ratio in future years that would provide the same load-carrying capacity (stability).

large stem diameters and little or no increase in crown height to be deemed still relatively safe with a t/R of 0.2 ($1/5^{th}$) or even $1/7^{th}$ – that is, they may, under certain circumstances, be at least as safe as a younger more slender tree with a t/R of up to $1/3^{rd}$.

Rinn's model does not discount Mattheck's t/R < 0.3 model, but it may refine and expand it. From a rule for hollow stem stability for slender stems with circular cross-sections and concentric decay, it attempts to address aspects of ageing and stem diameter so as to be more applicable to the trees that arborists typically evaluate. We should remember that before Mattheck's published research into this subject (from the early 1990s), any decay hollow could be considered grounds for removal or inappropriate crown reduction.

Crown height and stem diameter scaling

Mattheck's concept of H/D (height to diameter ratio) is highly relevant here (Mattheck, 2002). Trees with a low (<30:1) H/D may perhaps be likely to be those that can remain stable with a t/R below 0.3 ($1/3^{rd}$), whilst more slender trees will not. As a reminder example, a 20m high tree with a stem diameter of 1m has an H/D of 20:1. The beech in Figure 1 has an H/D ratio approaching 12:1!

As Mattheck has always stated, crown reduction pruning is effective in reducing the wind loading/bending stress on a hollow stem; it is effective also, of course, simply because reducing the crown height lowers the H/D. In a different presentation, Rinn offers a simple, albeit rough, rule of thumb: that wind load reduction is roughly twice the % height reduction (e.g. a 2m reduction of a 20m height tree can result in c. 20% wind load reduction).

Related thoughts – crown size and root system scaling

The concept or notion that tree height and crown size level off and effectively cease to increase after maturity may surely have implications also for the assessment of mature root systems. There is increasing, though not yet conclusive, evidence to suggest that tree root systems similarly expand to a mature maximum spread, and in later maturity little further radial root expansion may occur. Indeed, the root system of an old tree may even retrench, as the crown may, as previously modelled by Raimbault (Raimbault, 1995).

The only reliable dimension known to correlate with root spread is stem diameter; but that research is based upon younger, smaller trees (Day et al., 2010). As stem and root mass are thought to have a near isometric scaling relationship (Niklas & Spatz, 2006), we can ask: if the mature crown size remains roughly the same, why then would the mature tree's root system keep increasing? In maturity, the tree's stem diameter cannot help but keep increasing; its crown height and root spread may often not need to. So, both for effective stability and for vascular physiology, the root system could also notionally remain the same size/extent, once mature crown height is reached.

The question is, do trees reach a maximum mature root spread, and do they reach this at approximately the same time as they achieve maximum crown size? If the answer to that is yes, they do, then we must accept that after reaching maximum root spread, stem diameter may continue to slowly increase. On that basis, therefore, root-spread area has a non-linear relationship to stem diameter. We might expect, then, that relative to increasing stem diameter the increase in root spread is greater in young trees and less for older trees.

Further research is needed to allow a more refined model to be applied in assessing root systems, just as the work of Mattheck and Rinn and others continues to improve how we assess and manage old hollow trees.

Summing up

For now, as regards mature hollow trees, Rinn's model is worthy of consideration. Links to several of Rinn's presentations are listed in the references (right). What Mattheck and Rinn are saying is not I think at odds with each other; in effect, what they both point to is Mattheck's concept of height to diameter ratio (H/D). The difference is simply that Mattheck did not incorporate hollowness into his H/D concept, whilst Rinn is saying a tree more hollow than t/R 0.3 may not necessarily need to be shortened to be 'safe' if it is in otherwise good condition, its diameter is sufficiently large and its height is not increasing. The conclusion is that the lower the H/D of the tree, the lower the t/R may need to be for stability; the higher the H/D of the tree, the higher the t/R needs to be. It should perhaps be clear that the deciding factor – the key variable – is the stem diameter, not the height.

My thanks go to Frank Rinn for reviewing and assisting in earlier drafts of this article; I hope it's of some help in explaining his work and promoting critical thinking in these things. As Rinn himself says: *'Question everything and everyone (even me).'*

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Frank Rinn presentations:

1. www.download.rinntech.com/RINN_TreeWindLoad_WesternArborist_Spring_2014.pdf

2. www.download.rinntech.com/RINN_MatureShellWalls_ISA_WesternArborist_Fall_2013.pdf

3. www.download.rinntech.com/RINN_ArboristNews_Feb2011.pdf

4. www.trees.org.uk/aa/documents/aarc-presentation/rinn/RINN_WindLoadReductionPruning_d.pdf

5. www.trees.org.uk/aa/documents/amenitydocs/amconf14/tue/T_7_Frank_Rinn-1.pdf