Limits of the SIA method & online application for tree-breakage safety evaluation

Frank Rinn

Introdction

Wessolly and Erb developed the "Static-Integrated-Assessment" (SIA) method for assessing tree risk (Wessolly & Erb 1998, 2016), to move beyond the VTA (Visual tree Assessment) method (Mattheck et al. 1993). According to SIA, the major parameter for characterizing tree safety is called Basic Stability, based primarily on wind-load, tree-height, breast-height diameter, and material properties (elasticity and critical strain). A free SIA-online application is available for estimating tree-safety: **http://sia.simgruppe.de/sia.php**.

The SIA-method and use of the free online application has gained broad acceptance because most tree risk specialists presenting at Universities, educational seminars and conferences, particularly in Germany and Europe, favour SIA over VTA and promote the application of SIA.

Basic Stability as provided by the SIA online application is valuable and important for preventing trees from being cut down or topped unnecessarily, because still too many tree-risk assessments of mature trees are based solely on locally determined shell-wall thickness. Although shell-wall thickness is an important value for understanding basic biomechanical properties of hollow plant organs (Spatz & Niklas 2013), locally measured shell wall thicknesses are mostly irrelevant in terms of breaking safety of typical mature urban trees (Rinn 2013).

Despite some benefits of using the SIA online application, there are some significant shortcomings. The following discussion will identify some of them.

Ideas behind the SIA online-application and consequences

Tree wind-load depends on tree-height (Rinn 2014a), in much the same way that load-carrying capacity of stems depends on the diameter of the cross-section (Rinn 2013). This explains why many trees maintain a relatively constant ratio of tree-height (H) to diameter (dbh=D). Height to diameter (H/D) remains relatively constant for decades after the juvenile growth phase (Kahle et al. 2008). This allometric behavior of tree growth emphasizes the importance of H/D as a measure for breaking safety and clearly defines the pre-mature exploration-growth phase.

> *…these parameters are dependent on the conditions of the individual tree, e.g., crown size, tree height, wind speed, air density.*

This underscores the basis for the dispute regarding the VTA-threshold which sets the H/D ratio at less than 50 for sufficient breaking safety of intact solitary trees (Mattheck et al. 2002). Gruber (2007) criticized the VTA thresholds for H/D as scientifically unproven. Rust claimed (2013): "Our experiments and the scientific literature do not support the use of a threshold value of slenderness [H/D] in tree-risk assessment". Interestingly, Gruber and Rust promote the application of SIA in tree-risk assessment instead of VTA, despite the fact that the SIA method and SIA online application uses the H/D ratio for evaluating tree-safety. Gruber's statements were criticized as non-scientific by Fink (2009) who claimed that Mattheck's hypothesis is confirmed by the data. Gruber (2008) responded that Fink's claims are incorrect. The confusion of tree-risk assessors around the world about what is right and what is wrong is a logical consequence of this situation. Arborists, however, are currently more inclined to favour the SIA approach because of the publicity it has received by the many supporters.

Research published by the few independent biomechanical scientists with no apparent economic interests in tree-risk assessment, for example, Niklas and Spatz, and from related scientific fields, such as Kahle and Hasenauer, (for more sources see: Rinn 2015), clearly indicates that the absolute value of H/D of trees primarily is a consequence of local site/growth conditions and differs correspondingly. Thus, H/D is primarily a consequence of mechanoperceptional adaptation, confirming the hypothesis of thigmomorphogenesis (Telewski 2006): the distribution of radial cambial growth rates along the surface of the trunk is strongly determined by the acting mechanical stresses. Thigmomorphogenesis can be defined as the response of a plant's growth rate or morphology to mechanical stimulation such as touch, wind or gravity. As one of the results, the absolute value of H/D is not a relevant measure of breaking safety for urban trees, as long as site and wind-load conditions and/or structural integrity of the trees do not change. As soon as wind-load increases significantly, for whatever reason, even intact trees can become unsafe. In the same way, defects can lead to an increasing likelihood of failure, particularly in combination with an increase in wind-load. Then, H/D becomes an important criterion for determining the basic breaking safety for evaluating the likelihood of failure and fortunately, this is addressed by the SIA-online application.

However, the most important aspect regarding H/D in urban tree-risk evaluation is the fact that basic stability, a measure of the safety factor of intact mature urban trees, begins to increase automatically and annually after height growth stops. This is a simple consequence of the ongoing annual radial increments (of all living trees) leading to an over-proportional increase of load-carrying capacity of the corresponding cross-sections (Rinn 2013). Thus, H/D is indeed a very important property of the typical urban tree in terms of safety, particularly of those with stem defects. Because the SIA-method and online application uses H/D as one aspect of breaking safety, it's important to understand the limitations of this approach.

Basics of the SIA calculation

In the SIA online application, the theoretical breaking safety factor of the tree is called Basic stability and expressed as a percentage. However, in reality it is not a percentage but just a safety factor:

Basic stability = Safety factor = load-carrying capacity/load

When the Basic Stability of the SIA online application is given as 317%, for example, the safety factor was determined to be 3.17, meaning, the tree stem is 3.17 times stronger than the expected load (due to wind based on the assumptions for wind speed and site conditions as well as on the assumed drag coefficient for the selected tree species).

Failure obviously occurs when load exceeds load-carrying capacity (Safety < 1 = SIA basic stability < 100%). Consequently, Wessolly suggested to always require a safety factor of at least 1.5 (in SIA given as 150%) in order to guarantee sufficient tree safety. That means, when "basic stability" of a tree is determined to be between 1 and 1.5, action must be taken to reduce the likelihood of failure.

To understand the precision and reliability of the safety factor ("Basic Stability") as determined by the SIA application, it is important to identify the main contributing factors to the load-carrying capacity as well as for the wind load. The possibilities and limitations of these methods will then automatically become clearer.

Precision of calculations

If a calculation results in a final value, the impreciseness of the variables and parameters used for the calculation are cumulative and add up to the total imprecision (Rinn 2014b). Assuming, for example, the simple case:

$$\mathbf{A = B * C^3}$$

The uncertainties (Δ) in A build up from the uncertainties of B and C:

$$\mathbf{\Delta A = \Delta B + 3{*}\Delta C}$$

Following international standards (ISO 5725-1), this kind of error analysis has to be applied to all kinds of calculations, not only, but as well in tree-risk assessment.

From load-carrying capacity and wind load to "basic stability"

According to Gere & Timoshenko (1997), the maximum bending moment (M_{max}) that can be applied to a cantilever beam of homogeneous material can be calculated by multiplying the strength (σ) with the section modulus (W), characterizing its cross-section:

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

For a solid cylindrical rod with a cross sectional diameter D, the section modulus is given by:

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

Taking into account how strength, modulus of elasticity (E), and strain (ε) are related.

$$\mathbf{\sigma = E * \varepsilon}$$

the maximum applicable bending moment depends on elasticity, critical strain (ε_{crit}), and diameter:

$$\mathbf{M_{max} = E * \varepsilon_{crit} * \pi * D^3 / 32}$$

That means, the error in estimating the maximum applicable bending moment (equalling the load carrying capacity) based on determination of the included variables is:

$$\mathbf{\Delta M_{max} = \Delta E + \Delta\varepsilon_{crit} + 3\Delta D}$$

In a simplified model (Rinn 2014a) focussing on the major dependencies, the wind-load (WL) of a tree, largely depends on crown size (A), tree height (H), wind speed (v), air density (q), and the (species specific) drag coefficient c_w:

$$\mathbf{WL \sim q * A * c_w * v^2 * H}$$

This means, the estimation error is:

$$\mathbf{\Delta WL \sim \Delta A + \Delta c_w + 2\Delta v + \Delta q + \Delta H}$$

The major result of the SIA calculation, called "basic stability" ("S"), comes from dividing the load carrying capacity by the (estimated) load:

$$\mathbf{S = M_{max} / WL}$$

Thus, the safety is proportional to these major determining factors:

$$\mathbf{S \sim E * \varepsilon_{crit} * D^3 / (q * A * c_w * v^2 * H)}$$

This leads to an estimation error of:

$$\mathbf{\Delta S \sim \Delta E + \Delta\varepsilon_{crit} + 3\Delta D + \Delta A + \Delta c_w + 2\Delta v + \Delta q + \Delta H}$$

What all this demonstrates, is that there are many parameters influencing the precision and reliability of the result. And these parameters are dependent on the conditions of the individual tree, e.g., crown size, tree height, wind speed, air density. Similarly important are the species specific reference values (E, ε_{crit} c_w). Understanding what this means in detail is beyond the scope of this paper, but is well covered in current literature (Niklas & Spatz 2012). Here, the meaning of this kind of estimation-error in the real world shall be explained with two application examples.

Intact poplar trees

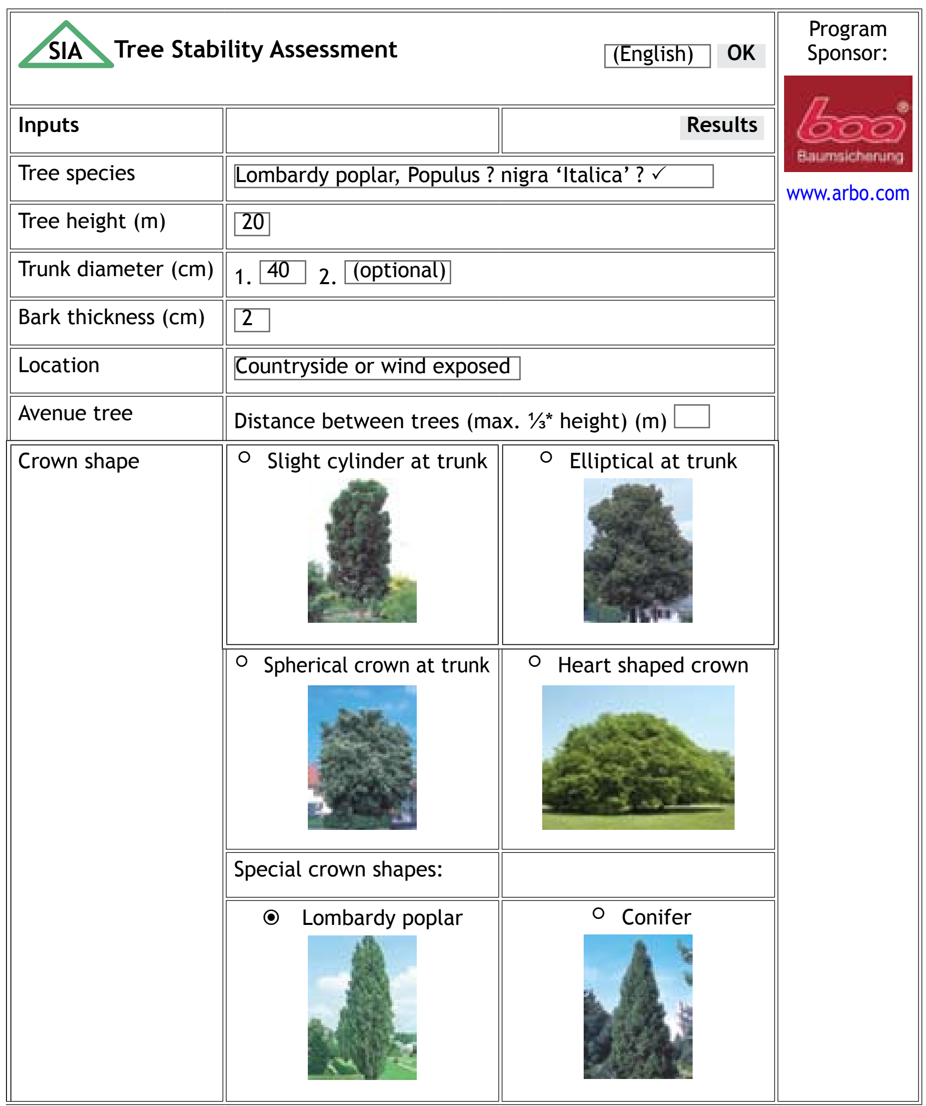
We inspected 9 poplar trees (Populus spp.), standing in a row (from South-West to North-East) on a hill in Southern Germany, always fully exposed to prevailing winds (**Fig. 1**). Tree height was above 20m (>60ft), while diameter at breast height was just under 40cm (<18 inches), and bark thickness was approximately 2cm. According to the H/D<50 criterion of VTA mentioned above, these trees would not be considered safe enough. When assuming a conservative height of 20m and a diameter of 40cm (**Fig. 2**), the SIA calculation results in a "basic stability" of 27% (**Fig. 3**) - meaning, the load-carrying capacity of the trunk cross section is approximately only one fourth of the wind load. Thus, these trees should not be standing. The trees in this row greater than 20 meters in height and with stem diameters less than 40cm in diameter have an even lower basic stability value and a higher H/D and are thus even more unsafe when following the two methods (VTA, SIA).

But, the poplar trees have developed and grown in response to strong winds without any protection for decades and survived several storms with extreme wind speeds. Clearly, nature shows that both methods obviously are not appropriate for this kind of tree and thus, should not be applied. When assuming that a tree needs a safety factor of at least 1.5 to remain safe, and considering that these trees have withstood strong winds for decades, it is fairly obvious that they are sufficiently safe. Consequently, the SIA-result for these poplar trees was wrong by at least a factor of 5. That means, the SIA method obviously does not correctly take into account the ability of trees to adapt to local loads and growth conditions and underestimates load-carrying capacity as a consequence of correspondingly inappropriate reference values (E, ε_{crit}, c_w) of such kinds of trees.

How well these intact poplar trees adapt to the acting wind load can be clearly seen by the increase in tree height measured from South-West

Figure 1. (Above) A row of 9 poplar trees (*Populus* spp.), standing on a hill in Southern Germany. The picture was taken from Northwest. The prevailing wind direction in this region is Southwest. The trees have always been freely exposed to the winds.

Figure 2. (Below) Input form of the freely available SIA-online tool for evaluating breaking safety of trees, filled out for the smaller poplar of the row shown in figure 1.



SIA Tree Stability Assessment	(English) OK		Program Sponsor: boo Baumsicherung www.arbo.com
Inputs		Results	
Tree species	Lombardy poplar, Populus ? nigra 'Italica' ? ✓		
Tree height (m)	20		
Trunk diameter (cm)	1. 40 2. (optional)		
Bark thickness (cm)	2		
Location	Countryside or wind exposed		
Avenue tree	Distance between trees (max. ⅓* height) (m)		
Crown shape	○ Slight cylinder at trunk	○ Elliptical at trunk	
	○ Spherical crown at trunk	○ Heart shaped crown	
	Special crown shapes:		
	◉ Lombardy poplar	○ Conifer	

SIA Tree Stability Assessment	Inputs	Chart: A B C D Bearing strength
Tree species	Lombardy poplar, Populus nigra 'Italica'	
Tree height	20 m	
Trunk diameter	40 cm	
Bark thickness	2 cm	
Location	Countryside or wind exposed	
Crown shape	Lombardy Poplar	
Avenue tree	no	
Net trunk diameter	36 cm	
Required diameter acc. to chart A	56 cm	
Basic stability acc. to chart B	27%	
Percentage of required residual wall acc. to chart C		
Medium required residual wall		

If withal SIA there are doubts about die tree stability,
we do recommend (in accordance to the directive of the FLL 'Baumkontrolle 2004')
a detailed analysis with the statical integrated method 'elasto/inclino'.

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Programmierung: Brehm & Fritsch GmbH, Bachstraße 14, 15741 Bestensee, Deutschland

Figure 3. According to SIA, the poplar trees should not be standing anymore because the "basic stability" is only 27 %, meaning the wind load is at least 4 times higher than the load carrying capacity.

to North East: the tree, directly facing the prevailing wind (from Southwest) is significantly shorter than the ones at the other end of the row. This clearly shows that these trees obviously have adapted their allometric (height and size) and material properties to wind load. This phenomena doesn't appear to be accounted for in the SIA reference values and calculation method (nor in the VTA H/D threshold).

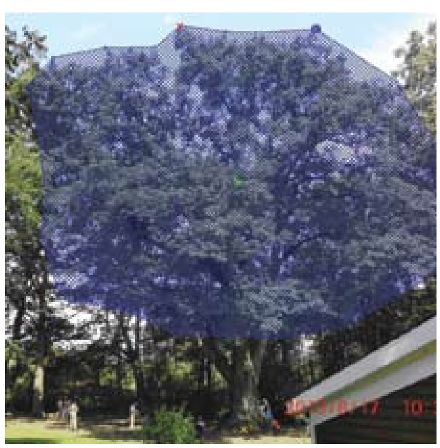
Mature oak

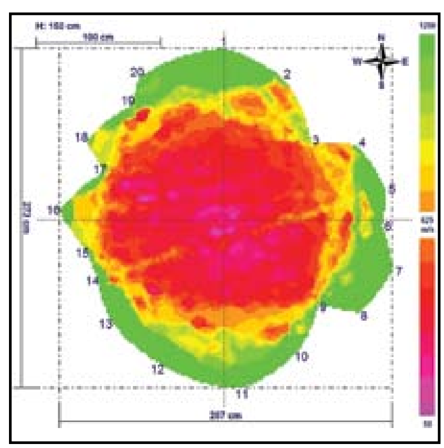
A red oak (*Quercus*) with a large, dense crown near Cleveland (OH, USA) was inspected for safety (**Fig. 4**). Sonic tomography showed that the residual shell wall thickness was significantly thinner than ⅓ of the radius (**Fig. 5**). According to the VTA criterion t/R>⅓, this tree would be considered unsafe. In contrast, the SIA-online application, using conservative assumptions (**Fig. 6**), estimated basic stability at more than 5000% - meaning that, if intact, the tree would be more than 30 times stronger than required (5670/150), based primarily on the ratio of tree-height over breast-height diameter (and the assumed material property reference values). Therefore, according to SIA, this tree should be able to tolerate a lot of decay without being dangerous (**Fig. 7**). The amount of decay this oak tree would be able to tolerate, according to the SIA calculation is represented by the "medium required residual wall thickness" of 1cm (or less than 0.4 inches).

The fact that this tree with extensive decay has stood for many years, indicates that the VTA criterion t/R> ⅓ is not an appropriate threshold for a tree of this size and age, because mature trees tolerate more decay the larger they get (Rinn 2013). Therefore, the VTA threshold should not be used in such cases. However, in the thou-

Figure 4. (Left) Mature oak (*Quercus robur*) near Cleveland (OH) with marked crown.

Figure 5. (Right) The result of the sonic tomography of the oak in Cleaveland reveals significant decay (red) in the trunk. According to the VTA t/R>1/3 rule, this tree is unsafe.





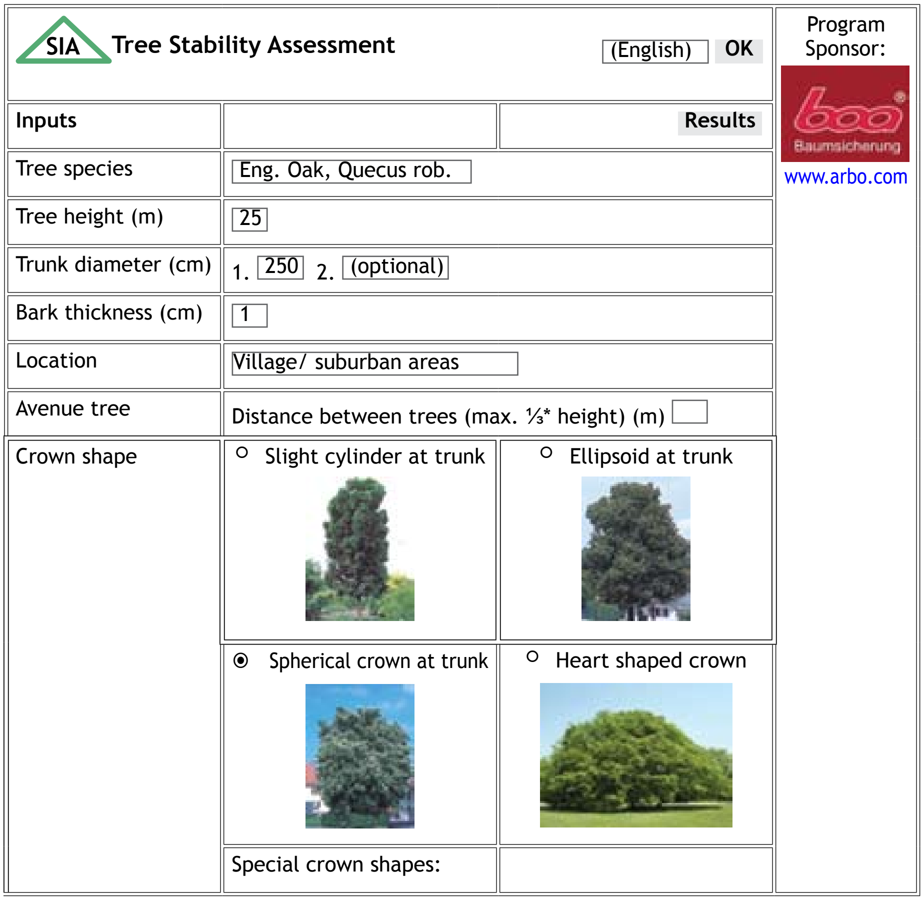


Figure 6. SIA – input form filled out for the Cleveland oak.

sands of tree inspections I've made since 1987, I couldn't find any tree with a residual shell wall thickness of 1cm or similar dimensions as suggested by SIA method, still standing. For that reason, both concepts obviously are not appropriate to assess trees the size and kind of this one.

Checking the corresponding literature of independent and neutral biomechanical scientists clearly demonstrates that the result of the SIA calculation for this mature oak is the consequence of overestimating load-carrying capacity of hollow stems: the SIA form is based on the formulas mentioned above, and these formulas are correct for describing compression failures, only and as long as the shell wall ratio (t/R) is greater than about ¼. Spatz and Niklas (2013) showed that the real load-carrying capacity of hollow wooden cross sections is significantly lower due to other modes of failure rather than just compression and tension. Depending on the length of the defect, as soon as the shell wall thickness is, for example, less than ¼ of the radius, tangential failure is more likely to occur than compression failure (**Fig. 8**). 'Brazier buckling' occurs more often as soon as the shell wall ratio t/R drops below about 1/10. Both failure modes significantly reduce the theoretical load-carrying capacity of stem cross sections with decay or other defects when compared to compression failure.

However, taking into account these two failure modes does not fully explain the huge SIA safety factor for this oak. In addition, the SIA material property and drag co-efficient reference values are most likely inappropriate for this species as well.

Summary

Both the SIA method and the corresponding online application take into account that tree-height and trunk breast-height diameter are important factors when evaluating risk potential for most urban trees to be inspected in terms of safety. However, the two application examples show that the SIA method has some major limitations when applied to actual trees. According to SIA, the poplar trees discussed above should not be standing. The fact that they have remained standing, demonstrates that their safety factor (basic stability) was underestimated by SIA by a factor of at least 5. The safety factor of the mature oak was overestimated by SIA by an even higher factor, for various reasons, and the minimum average shell wall thickness required for sufficient safety (1cm) specified by SIA, is obviously wrong, as well.

The inaccurate results using the SIA method are most likely the result of a combination of incorrect species-specific reference values (confirming the findings of Spatz & Pfisterer 2013), and (according to Spatz & Niklas 2013), incorrect mathematical methods. This should raise the question: when and where does the SIA method deliver correct and reliable results?

So far, I haven't found any publications with data and tangible proof that the SIA method can accurately determine breaking safety of mature urban trees. The lack of supporting data and evidence demonstrating the methods inherent unreliability was presented years ago (see, for example, Rinn 1993). There has been ample time to do the testing, collect the data, analyze the results, and then publish the findings in peer-reviewed journals. I'm at a loss to explain why this hasn't happened. You would expect arborists, unbiased tree risk experts, and academics to be a little skeptical about the current SIA method and online application, and to question why SIA is still being promoted by so many experts in higher education and at conferences worldwide. Interestingly, SIA has even been incorporated into national and international standards, in the absence of adequate supporting data proof, and although examples of where SIA ap-

SIA Tree Stability Assessment	Inputs	Chart: A B C D Bearing strength
Tree species	Eng. Oak, Quercus rob.	
Tree height	25 m	
Trunk diameter	250 cm	
Bark thickness	2 cm	
Location	Village / Suburban area	
Crown shape	Spherical crown at trunk	
Avenue tree	no	
Net trunk diameter	246 cm	
Required diameter acc. to chart A	64 cm	
Basic stability acc. to chart B	5679 %	
Percentage of required residual wall acc. to chart C	0.295	
Medium required residual wall	1 cm	

If withal SIA there are doubts about die tree stability,
we do recommend (in accordance to the directive of the FLL 'Baumkontrolle 2004')
a detailed analyses with the statical integrated method 'elasto/inclino'.

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Figure 7. According to SIA, the Cleveland oak would have a basic safety (when intact) of more than 5000%, meaning the safety factor would be higher than 50. More important in this context is the "Medium required residual wall" specified with 1cm (=0.4"). That means, according to SIA, this tree would need only such a thin shell wall for sufficient breaking safety - quite a contrast to the result of VTA, suggesting the tree is not sufficiently safe. However, the fact that this and many other mature trees are having shell walls much less than 1/3 since decades and survived even strong storm events, proof that both concepts are not correct. The main reason for the surprising stability of hollow mature trees is not the material quality but the fact that annual radial growth continues even when height growth stopped. And this geometric effect leads to an annually increasing safety value so that trees can tolerate more decay the older they get (Rinn 2013). That means, the critical threshold of tolerable loss in load carrying capacity due to defects changes every year as soon as trees do not grow in height any more.

plied to actual trees, like I've shown here, it produced obviously incorrect results.

This situation could be resolved simply and relatively quickly. Validation of the SIA concept could be done by determining the safety of test trees (basic stability) using the SIA online application. Then these trees would have to be loaded to the point of failure, and then the measured result compared with the estimated value. This would produce a correlation (for each species and age class, intact and with defects, between the estimated and real failure values. The coefficient of determination (r) of this correlation will then allow tree risk practitioners to evaluate the precision and reliability of the method (Rinn 2017). In order to achieve reliability, sufficient for tree-risk assessments, the correlation should be significant (for example r^2>0.7). Setting the significance-threshold should be entrusted to neutral and independent scientists and standardization expert panels.

The same testing procedure has to be done with any method that purports to be able to determine tree-safety. Depending on the specified thresholds for precision and reliability, characterized, for example, by r^2, it can then be decided which method might be implemented in, and recommended by national and international standards for tree-risk assessment.

As long as there is no proof regarding which method delivers sufficiently accurate results on breaking or uprooting safety for a particular tree species, age and size class of intact or defective trees, none of the methods should be used on a regular basis for risk assessment. If an unsubstantiated

Figure 8. Typical consequence of torsional failure in a defective tree (*Ulmus* spp.) before compression failure occurs. *Photo: Duncan Slater*

method is used, because there is no better alternative for urban tree-risk assessment, the assessment should be done with extreme care, and only by experts who really know what they are doing. And these experts need to openly and honestly acknowledge the limitations of the method(s) used.

Frank Rinn
Heidelberg, Germany

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