Mature urban trees are important habitats but often hollow or decayed.

How hollow are these trees “allowed” to be?

=>

From wood anatomy to biomechanics, tree statics and urban/traffic safety

Frank Rinn, Heidelberg/Germany

1. I am not an Arborist and still do not know all tree and fungi species!
2. After working on our family carpentry, I studied physics and then invented/developed methods for inspecting trees, timber/structures, tree-rings in arboriculture, forestry, engineering, dendro-chronology, such as:

1986> resistance drilling (patented 1990). . . DENSITOMAT™/RESISTOGRAPH®

1990> tree-ring measurements. . . . . LINTAB™/TSAP™/LIGNOVISION™

1995> sonic tomography (patented 1999, EU, USA). . . . . ARBOTOM®

1999> dynamic load-tests. . . . . DYNATIM™

2000> tree appraisal software. . . . . ARBOTAX™

2004> root (plate) diagnostics. . . . . ARBORADIX™

2010> tree inspection software for mobile devices. . . . . ArboMech/-WiLo/-StApp

...

> research & innovation awards in 1989, 1992, 1997, 1998, 2004, 2012.

Why talking about (urban) tree safety and tree inspection?

Trees live on earth since millions of years.

Trees survived many natural catastrophic events.

Trees survive storms, snow loads, and other treads.

> **Trees are natural structures with sufficient inherent safety!**

But, sometimes trees break or uproot, so accidents happen.

> Are natural structures safe enough for our (urban) requirements?

> Can we assess and evaluate breaking/uprooting safety of trees in order to foresee potential hazards and accidents early enough?

> We have to understand tree bio-mechanics and thus wood anatomy and the methods of assessment and evaluation!

Albert Einstein said, only when you are able to explain physics to the farmers on the market, you really understand it!

(He was not only correct in his theory of relativity)

> We need to understand tree-safety/risk, assessment methods & results

>> in order to be able to determine tree-safety as accurately as possible

>> for explaining our findings and evaluations to clients, administrations, insurance companies, lawyers, and judges

>> for our own (physical & legal) safety as tree-experts

> When you struggle with something presented here, please ask immediately!

Recently in Tucson, Arizona:

Not too many trees but...

Are trees safer?


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Are trees safe (enough) by nature?

> Yes, but only in a statistical average because nature accepts a certain failure rate and (partially deadly) consequences.

Are modern urban trees different?

> Yes, genetically impoverished and under non-natural site conditions!

Do we need to inspect and monitor tree health and stability?

> **Yes, as long as we expect a 'safe' urban environment and habitat at minimum costs, fulfilling human and natural needs.**

Are trees a mechanical structure with equally strong parts?

> Generally 'nearly' yes but not completely!

Orgin of 12'000 registered acidents by trees (in Singapore):

~70%	broken branches crowns
~20%	tipping trees
~10%	broken stems

> urban tree stem breakage is quite rare although street / park trees are often quite decayed / hollow!

> Hypothesis of "constant stress" has to be adapted/changed.

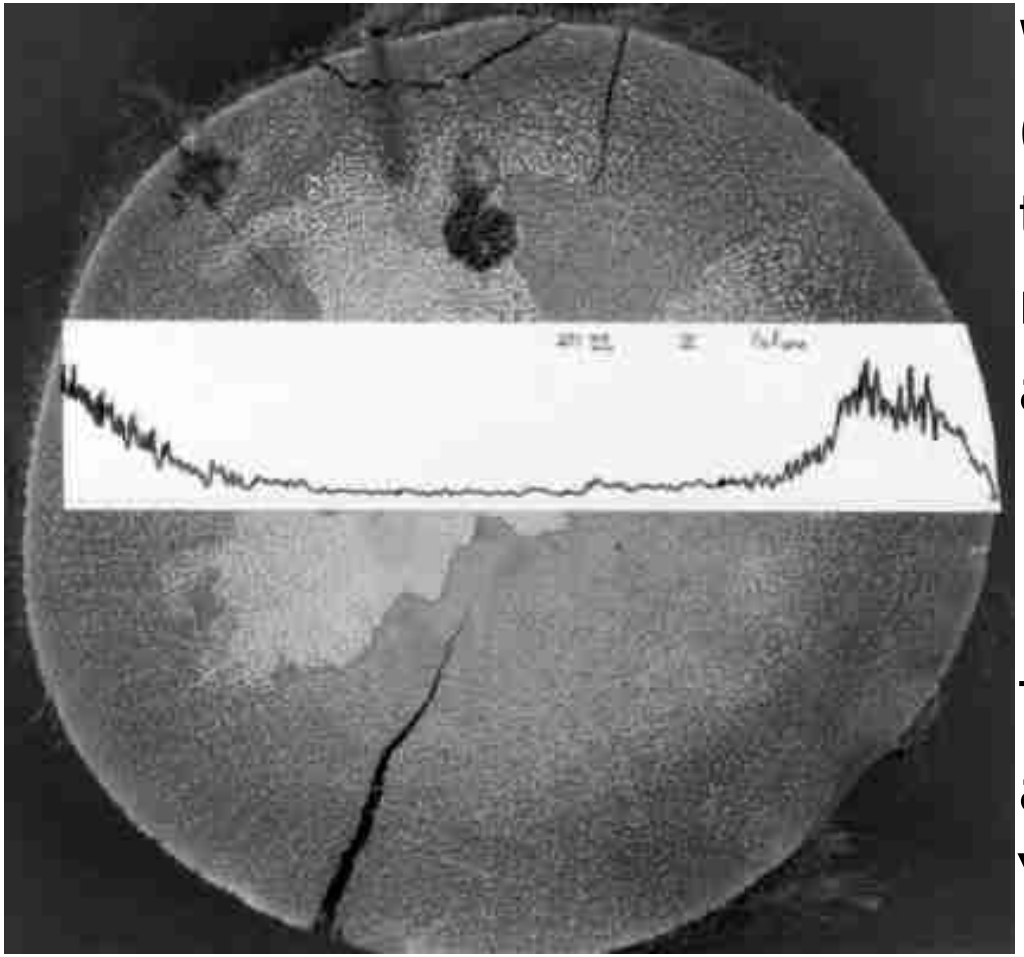
What is tree (traffic) safety?

(... extremely simplified basics ! ...)

$$\text{“safety”} = \text{“safety factor”} = \text{“stability”} = \frac{\text{load carrying capacity}}{\text{load}}$$

1. Trunk bending safety	2. Uprooting safety

1. Trunk bending safety



When resistance drilling was developed (1986-88), profiles from coconut palm trunks showed that about 1/3 of the radius has a significantly higher density and strength compared to the center.

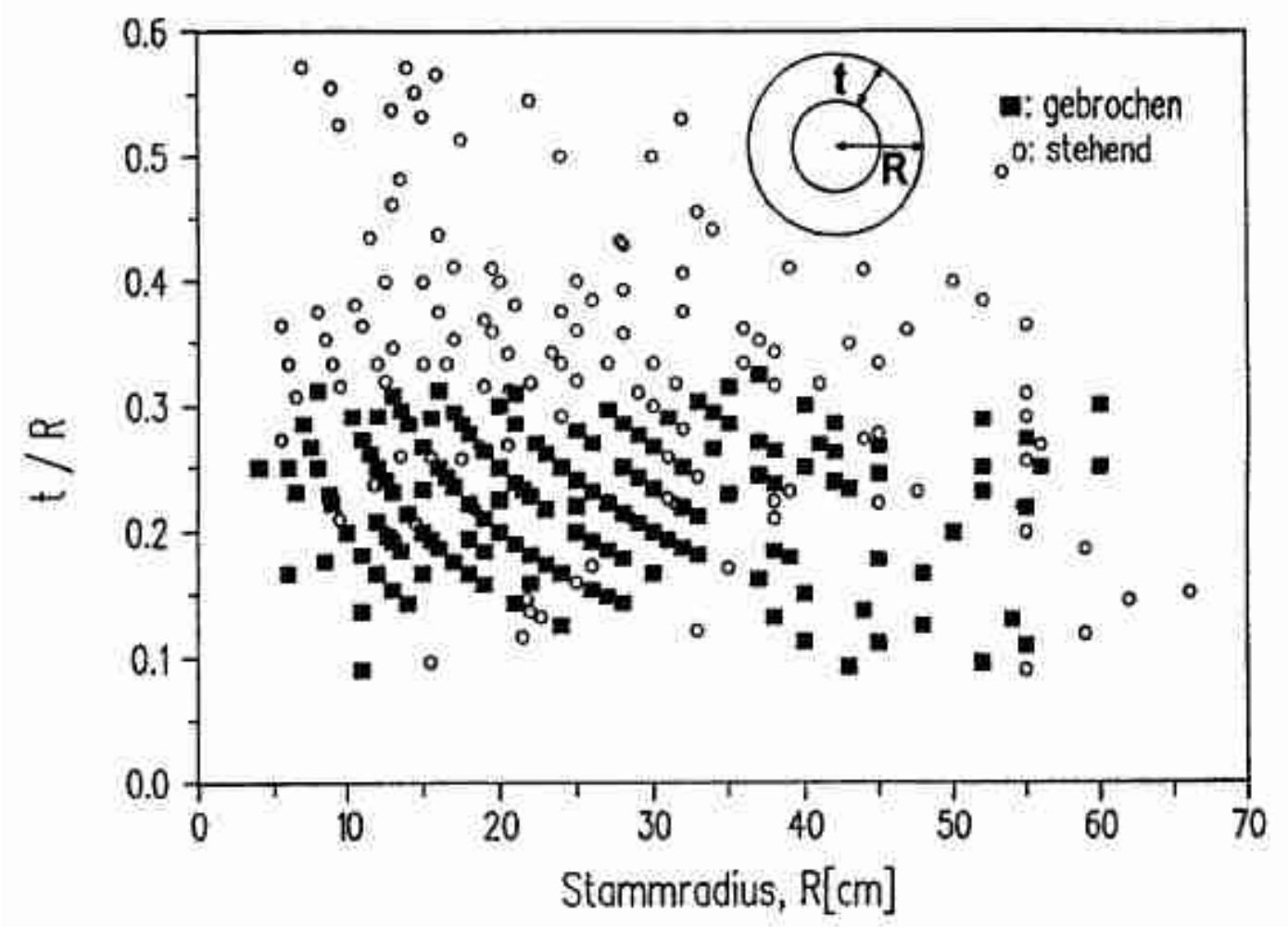
>

This was interpreted as a sign for natural 'mechanical design' or 'architecture' for slender structures with small crowns loaded by wind.

=> Mattheck & Breloer 1994: . . . . . t/R>1/3 for enough safety!

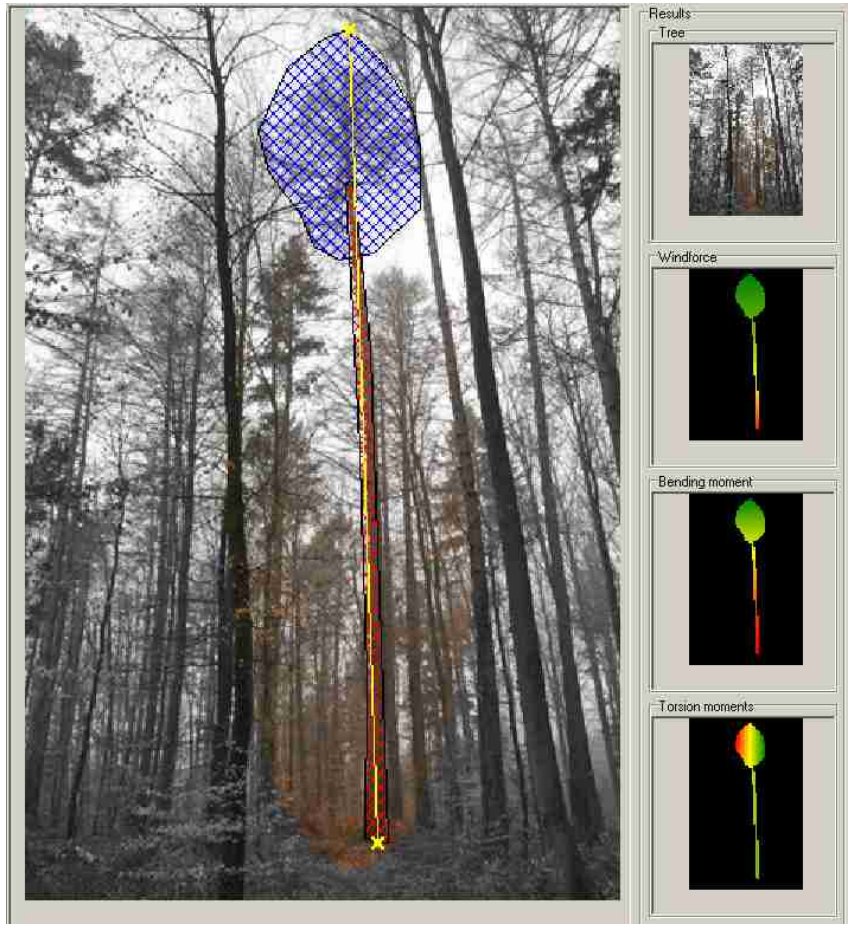
Circles: standing trees

Black squares: broken trees with circular stems and central voids/decay



Mechanically, many palms and slender forest stand conifers look quite similar in terms of wind loading, thus the so-called '1/3-rule" seemed to be confirmed by natural observations:

=> worldwide, the '1/3-rule' quickly developed to the most accepted threshold for judging tree safety because it seemed CORRECT, SCIENTIFIC, AND SIMPLE.



BUT

Would you have cut this tree down because of this extent of decay?

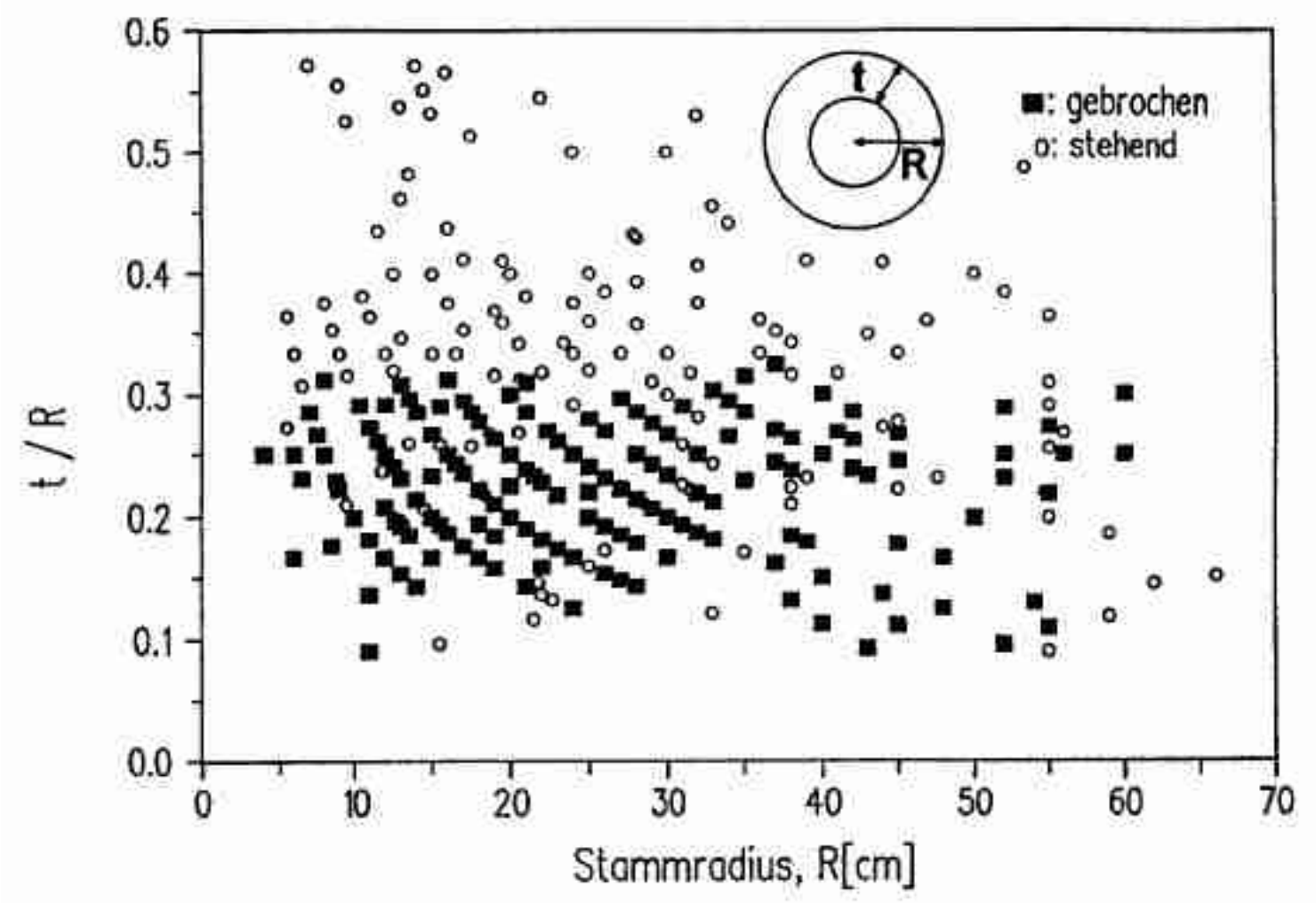
...

too bad

...

This tree cracked and failed while I was (resistance) drilling at stem base in order to look for decay - but it was completely intact!

=> The graph is not wrong but not complete: black squares are missing above t/R~1/3 representing broken trees with less decayed or even intact stems:



=> slightly decayed and even intact trees may break under certain conditions..
. . . . . (to be identified by scientists and arborists)!

=> thin shell-walls (t/R<1/3) seem to increase breakage probability - but when and how?. . . . . (to be identified by scientists and arborists)!

=> the '1/3-rule' is not a natural law but just a hint on a specific natural property or behaviour of structures like slender conifer trees with centrally rotten circular cross sections under wind load

And, ...

Why do such kind of trees still stand (some since decades)?

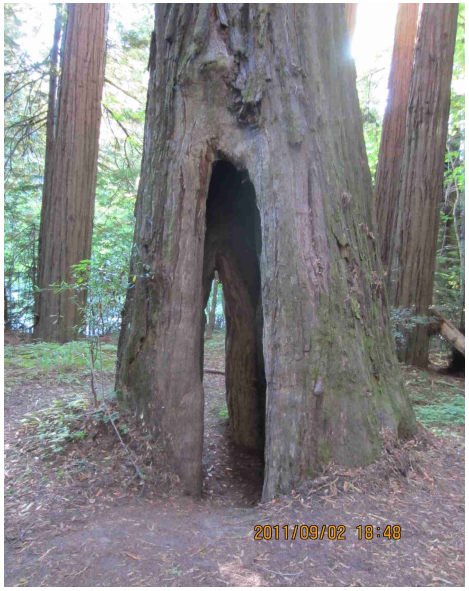
Obviously, these rotten trees do not read books on bio-mechanics ...

These trees continuously ignore rules of stability/safety!


2011/09/02 18:39


2011/09/03 18:46


2011/09/03 14:42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CHANDELIER
TREE
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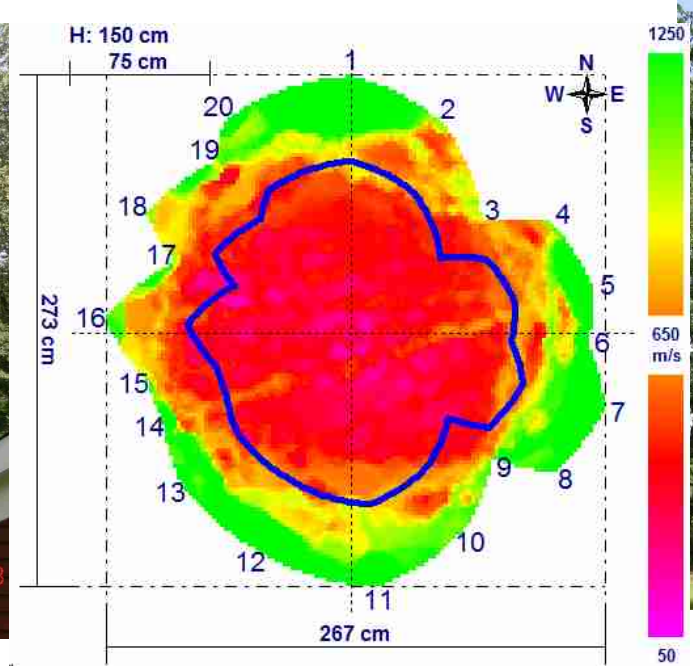
2013/8/17 10:38


H: 150 cm
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2013/8/17 10:38


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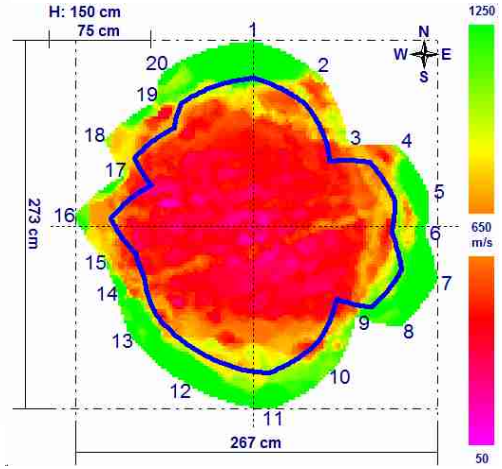
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There are many old and even very high trees that are standing up since decades, although heavily decayed and much more hollow than the 1/3-rule 'allows'!

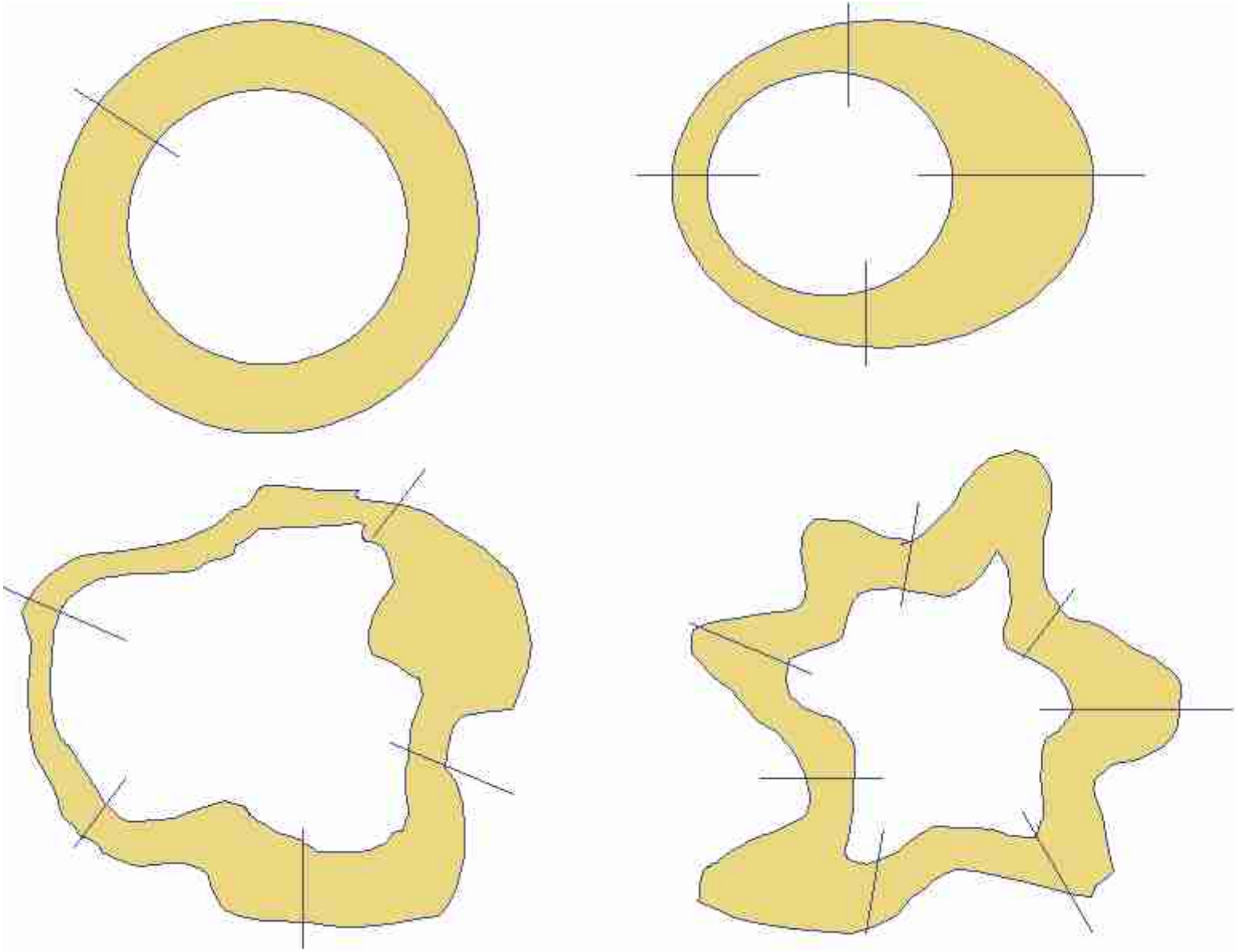
=> Who is wrong?

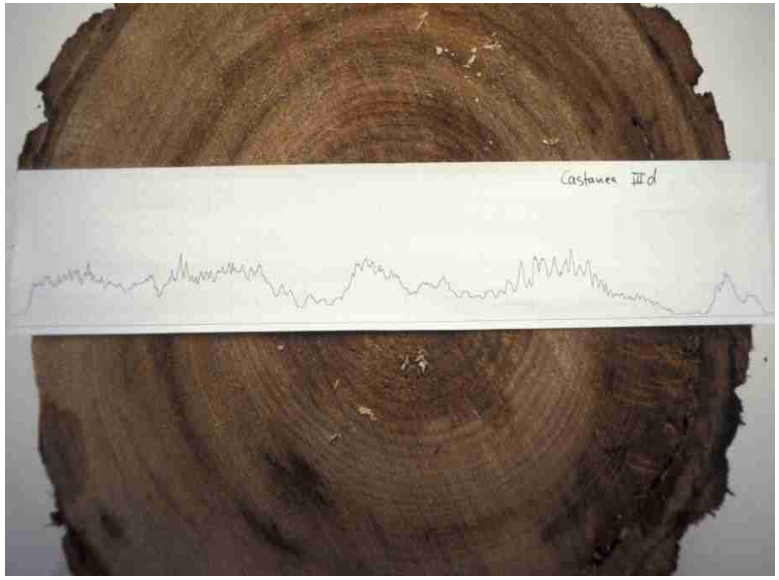
> The old rotten/hollow trees?

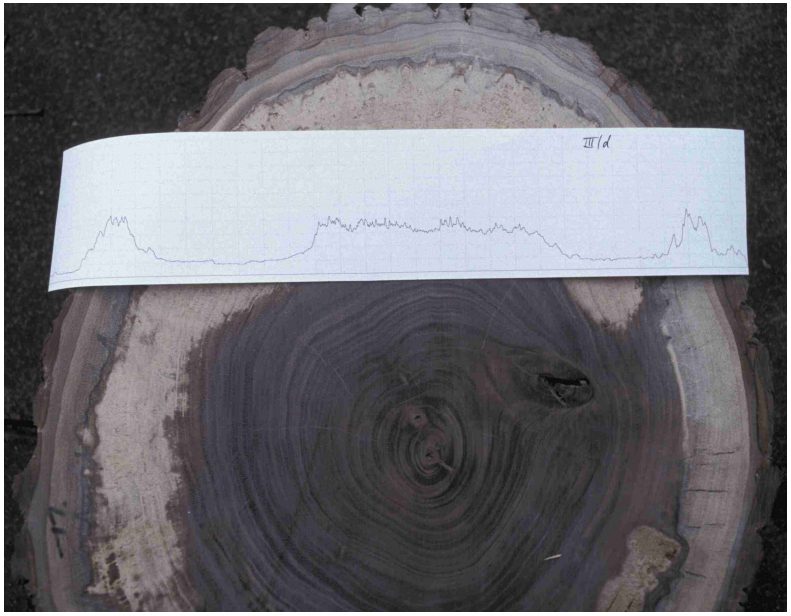
> The 1/3-rule? or Science?

> Or we? Arborists? Experts?

Can the '1/3-rule' be valid for the kind and age class of trees in the urban environment we have to inspect in terms of safety?




Castanea IIId


IIIId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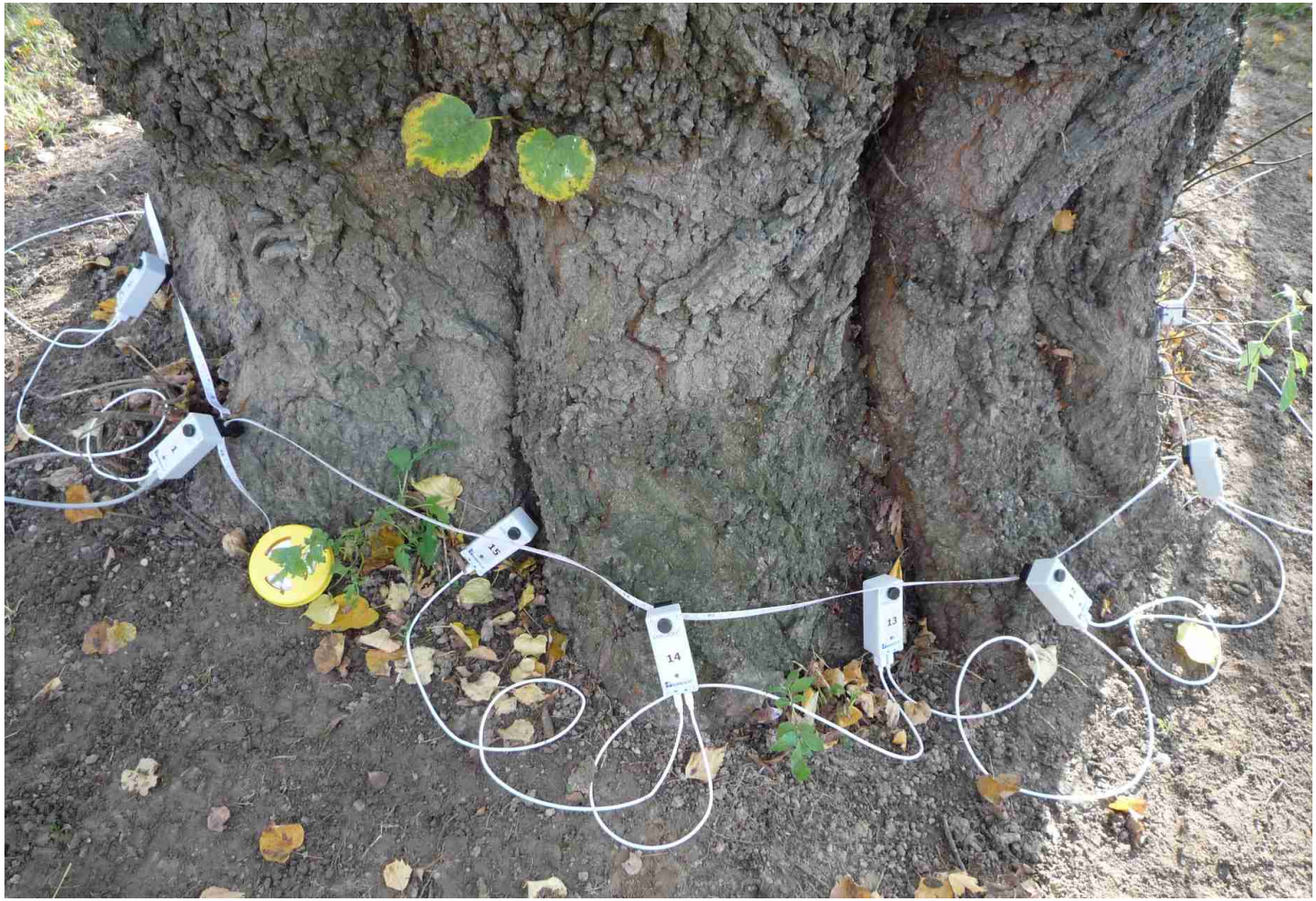
=> stem/trunk shape and size are different from slender forest trees!



Mature (urban) trees that have to be inspected in terms of safety

1. are mostly old and do not grow in height any more since many years
2. have non-circular stem cross sections
3. mostly have non-concentric decay
4. may even have included bark

=> the simple '1/3 rule' may be appropriate for a certain kind and age class of trees (young, centrally rotten circular stem) but most likely not valid for the typical mature urban tree to be inspected!

B U T W H Y ?

Load carrying capacity of stem cross section =

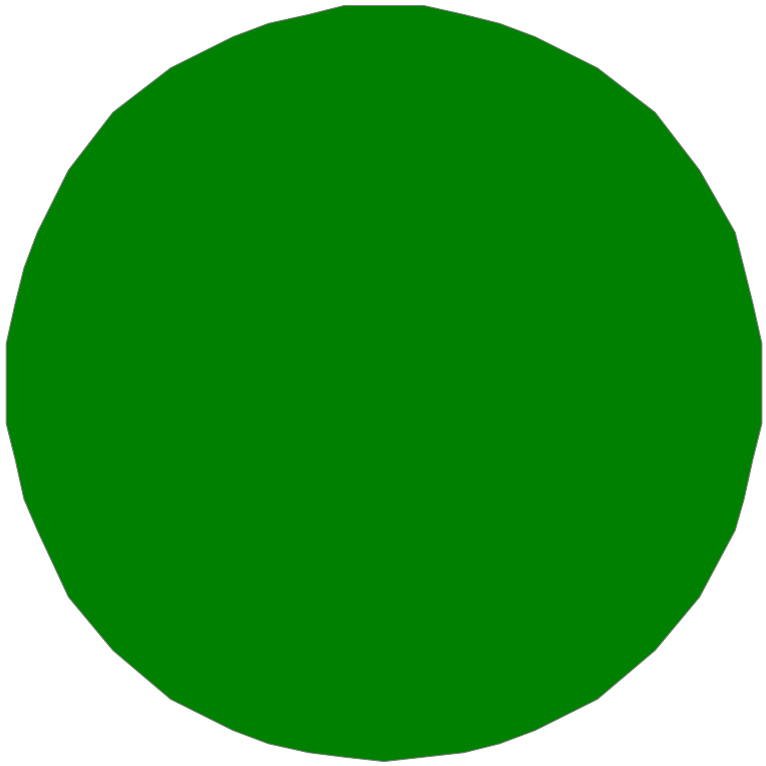
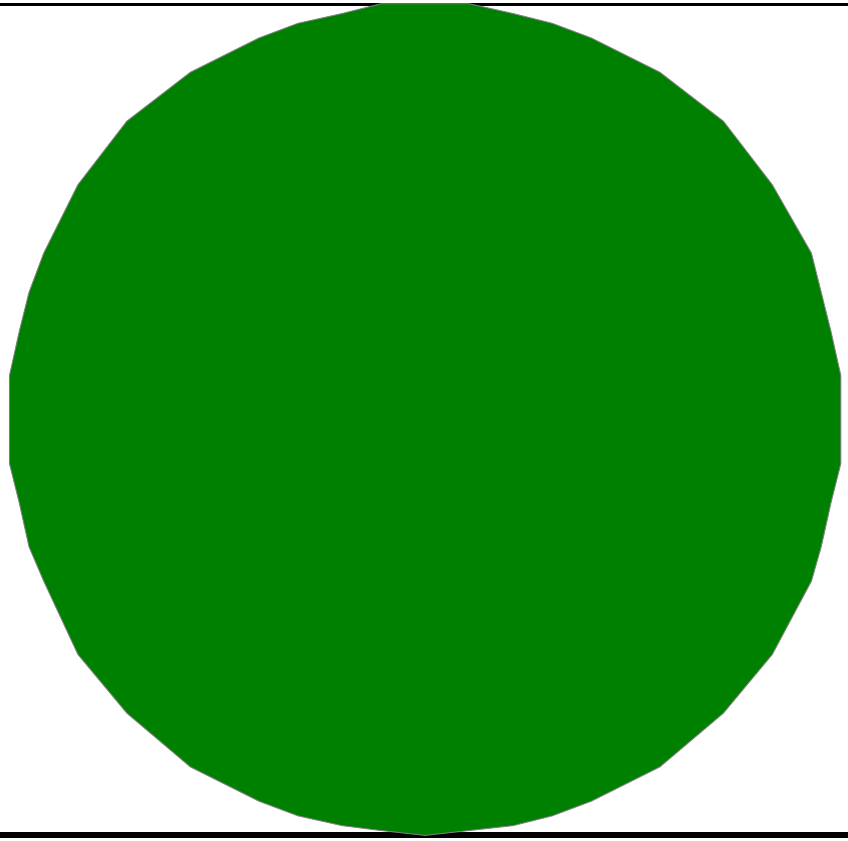
Function of strength, shape, and size ...

=> stability ~ strength * $(\text{diameter})^3$

=> Δ stability ~ $(2*D)^3 = 8*D^3$

radial increment 1% => stability increment 3%!

radial increment 10% => stability increment 33%!

	
100cm	100+10cm = 110cm => LCC + 33%

THE MOST IMPORTANT POINT:

- urban trees commonly reach their maximum total height at a certain age
- load mainly depends on wind
- wind load mainly depends on tree height
- when height does not increase any more, load does not increase
- radial increment goes on and stability increases with it (>>>proportional)
- the older the trees
  - the higher their basic safety (by design)
  - the more hollow they can be providing similar / more safety!
- can we determine how much safer? YES!

Numerical estimations

Mechanical stress (σ) in a cross section is usually defined as the acting force (F) divided by the area (A):

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

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

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

W characterizes the section modulus what 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:

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

Strain (ε = ?L / L) as a consequence of external loading and modulus of elasticity (E) help understanding the influence of material strength (σ_{max}) on maximum load that can be applied without damaging:

$$\varepsilon = \frac{\sigma}{E} = \frac{M}{(E * W)}$$

As soon as the stress is higher than the material strength (σ_{max}), failure occurs:

$$\sigma = \frac{M}{W} ! < \sigma_{max} = E * \varepsilon_{max}$$

Therefore, maximum applicable bending moment M_{max} is determined:

$$M_{max} = W * \sigma_{max}$$

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

$$M_{max} \quad D^3 * \sigma_{max}$$

Therefore, a doubled strength value (σ_{max}) leads to a double maximum applicable bending load (M_{max}). A doubled diameter leads to an eightfold bending load:

$$(2*D)^3 = 8*D^3$$

In addition, if a newly built tree-ring has a higher material strength property, this does not change the material strength values of the given internal wood. Thus the corresponding increase of the total load carrying capacity is quite marginal as compared to the impact of the enlarged diameter. As a consequence, the influence of geometrical growth of a cross section is more important than changes in material properties by about approximately one order of magnitude. Thus, in first order, we can characterize the load carrying capacity of a cylindrical cross section by its diameter.

Age trend => continuous girth increase even after maximum crown sized reached

As already shown by Bräker (1981), ring width of mature trees often stabilizes on a nearly constant value. If we assume ring width after having reached maximum tree height (time point y=0) is a percentage (p) of the diameter at this time (D_1), we can estimate later diameters (D_2), y years 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: how hollow is an old tree allowed to be? For easier evaluation we transform diameter values into shell wall thickness (t) and radius (R):

$$t/R = 1 - d/D$$

Now we set W_2 != W_1 and calculate the required t/R-ratio:

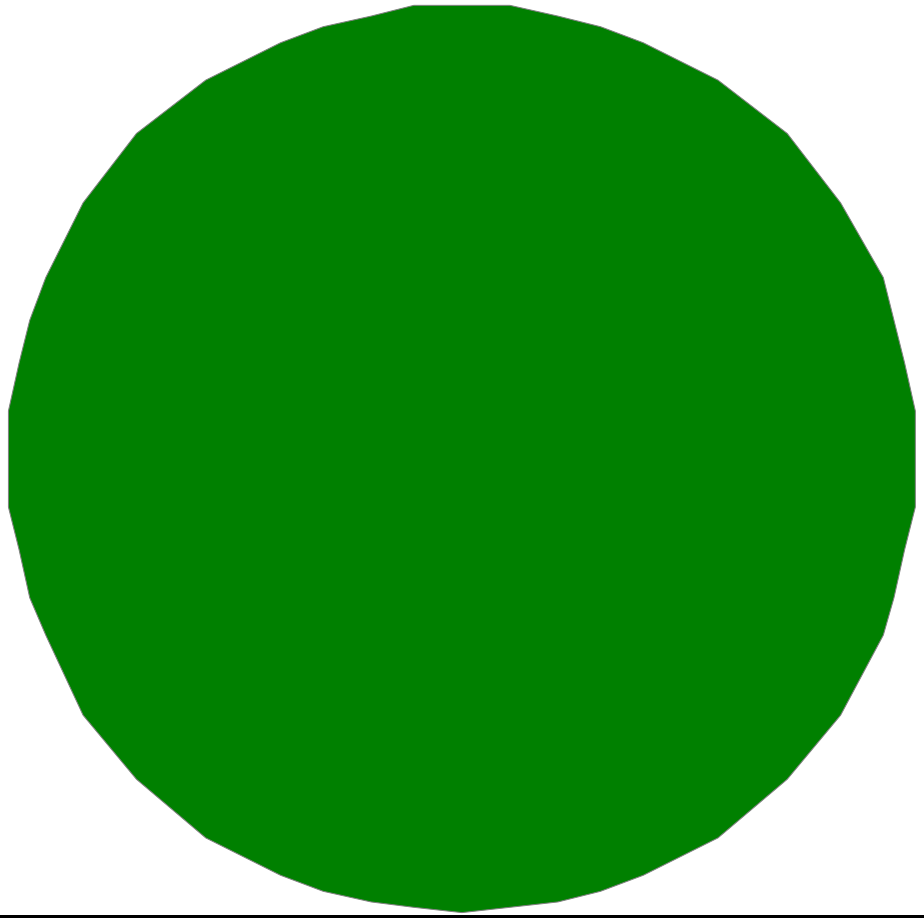
$$\frac{t_2}{R_2} = 1 - \sqrt[4]{1 - \frac{\left(1 - \left(1 - \frac{t_1}{R_1}\right)^4\right)}{(1 + y * p)^3}}$$

Any practical meaning?

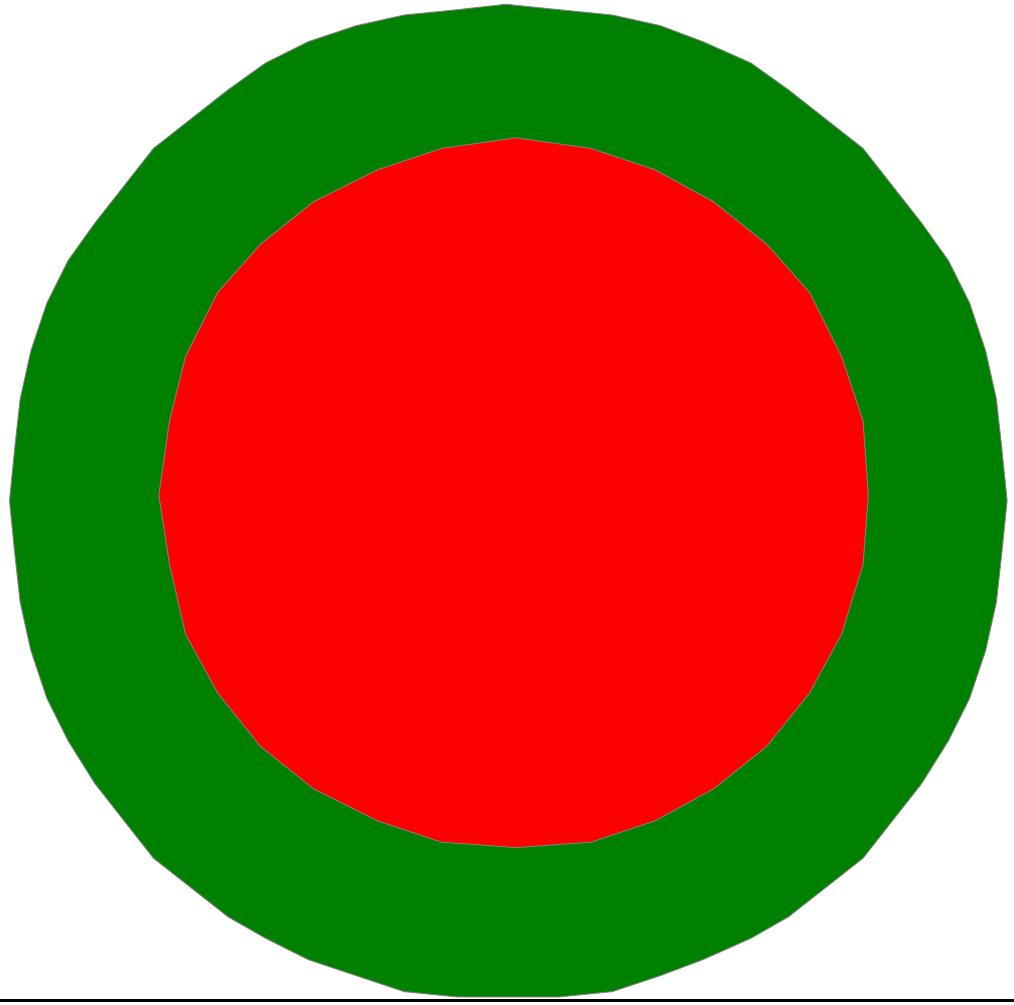
Yes!

Original trunk cross section and 20 years later with the same load carrying capacity:

60cm



66cm/47cm => t≈ 10cm => t/R≈0.28



Original trunk cross section and 20 years later with the same load carrying capacity:

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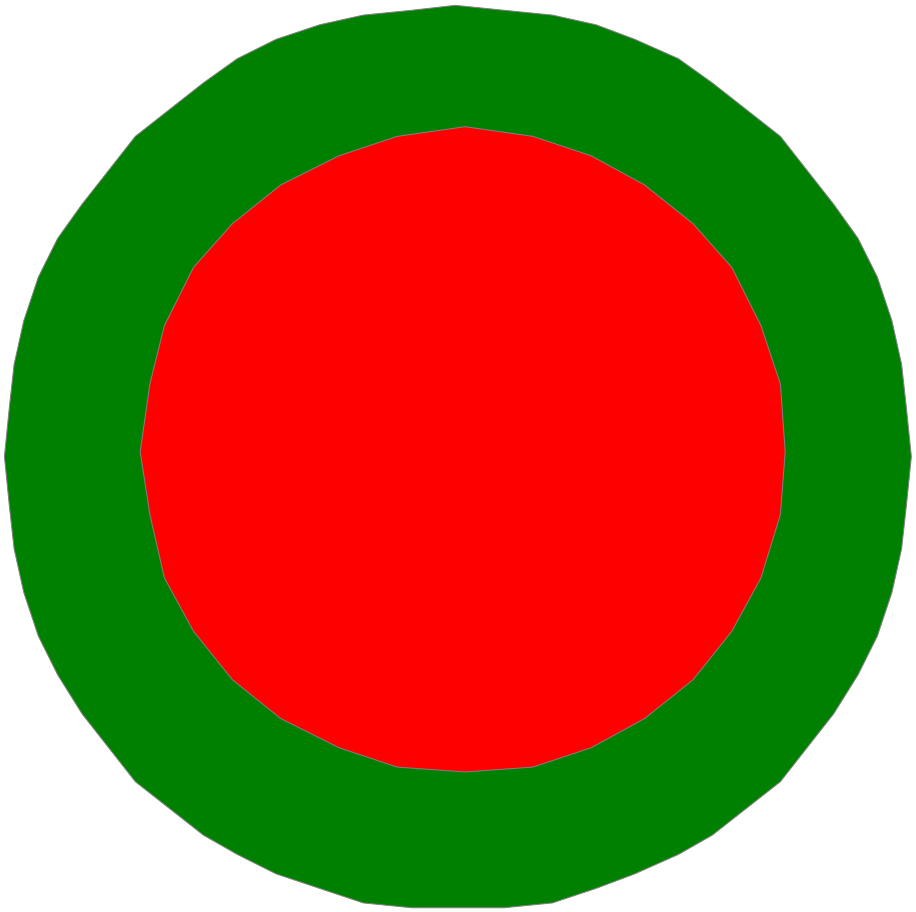
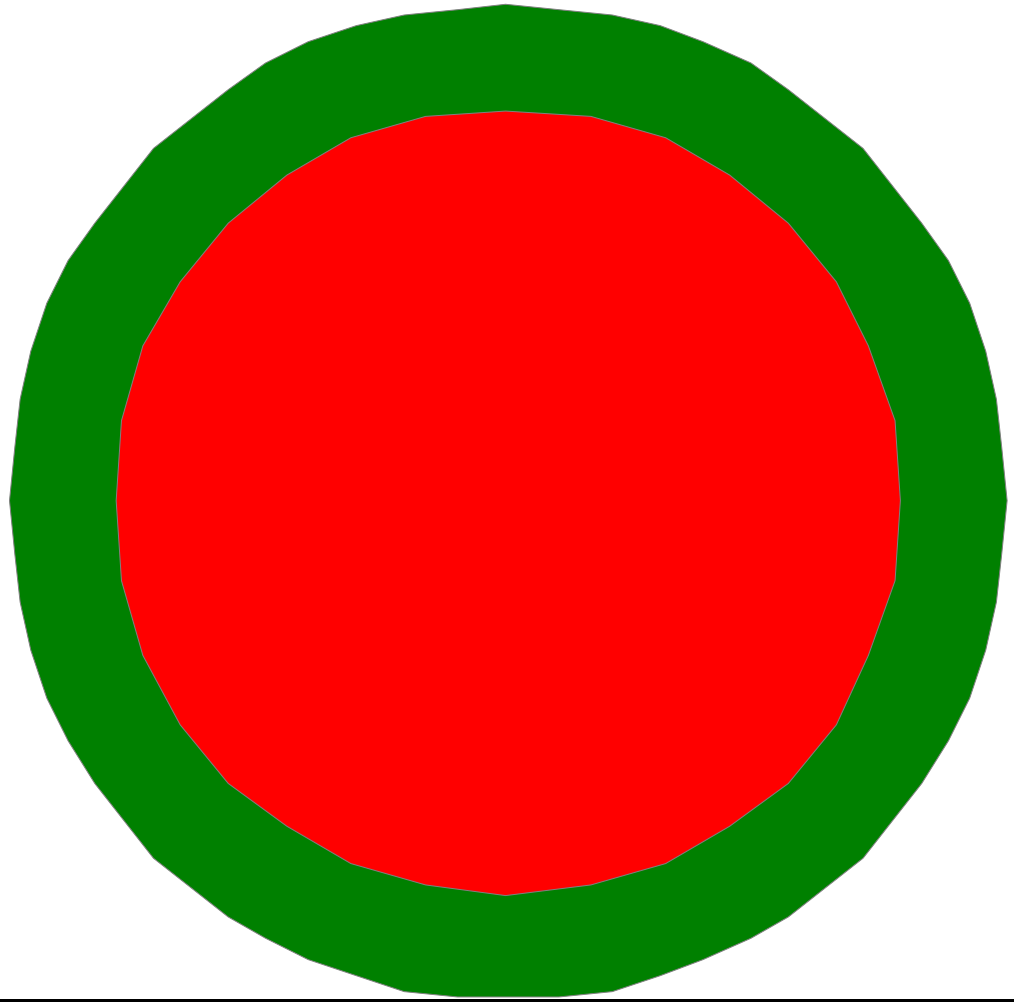


66cm/52cm => t≈ 10cm => t/R≈0.21 ≈ 1/5



- Even small radial increments lead to strong growth of load carrying capacity!
- On the other hand: even big internal decay/voids lower LCC only slightly!

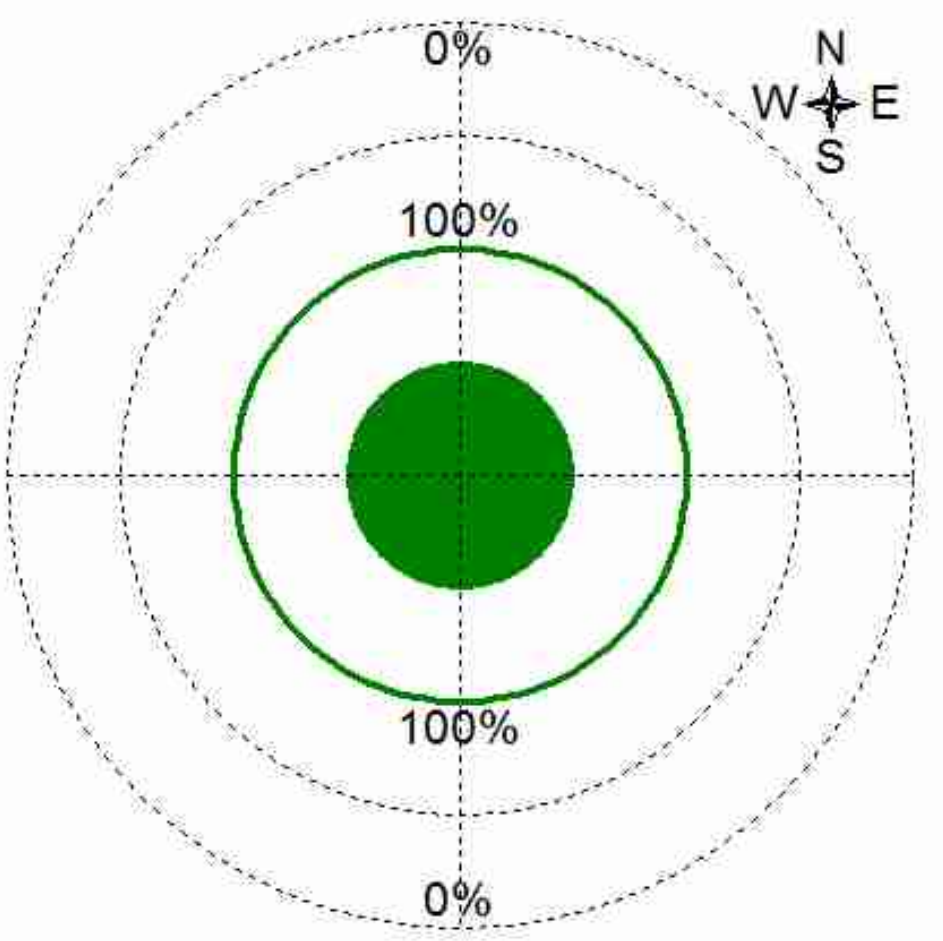
=> **Although mature trees often grow slow radially (in girth), this still leads to a continuous and significant increase of natural ('basic') stability. Thus, even strongly decayed mature trees may be safer than young/juvenile trees (intact or slightly damaged)!**

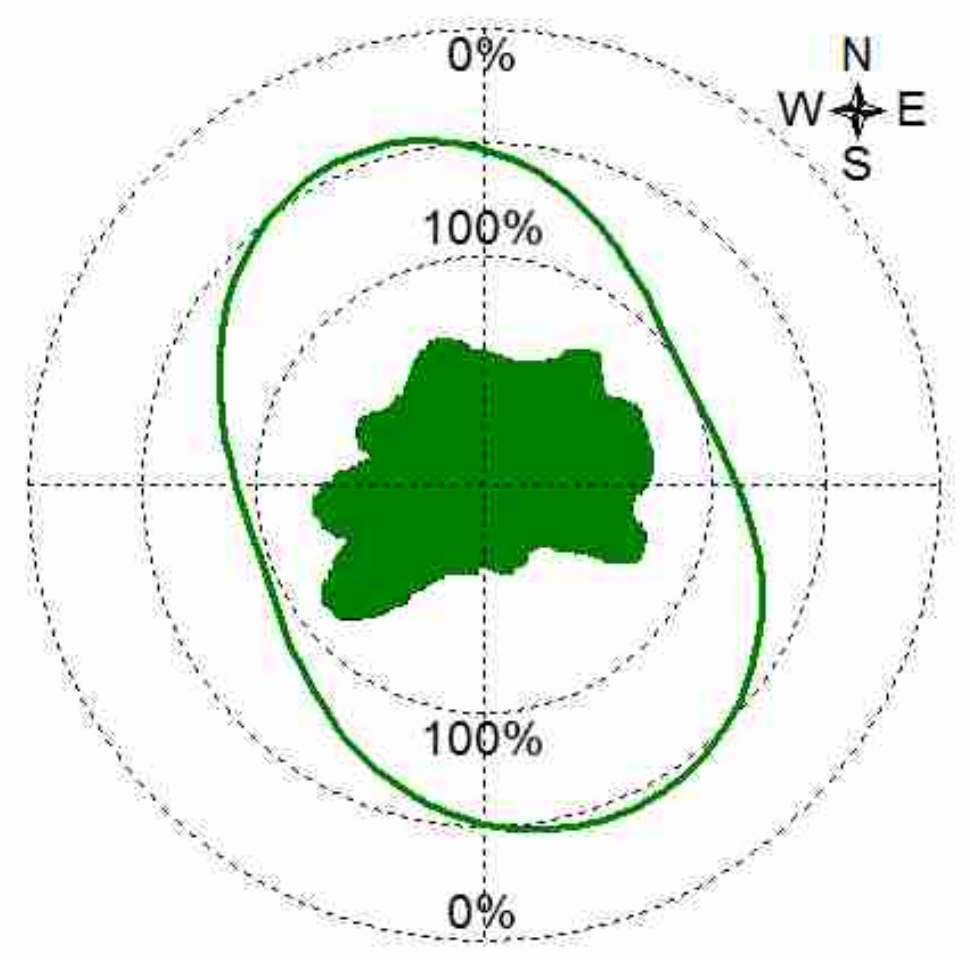
=> Because size matters much³ more than material quality, assessment of size and shape of cross sections (by tomography) is more important than measurement of material properties of shell walls / remaining wood!

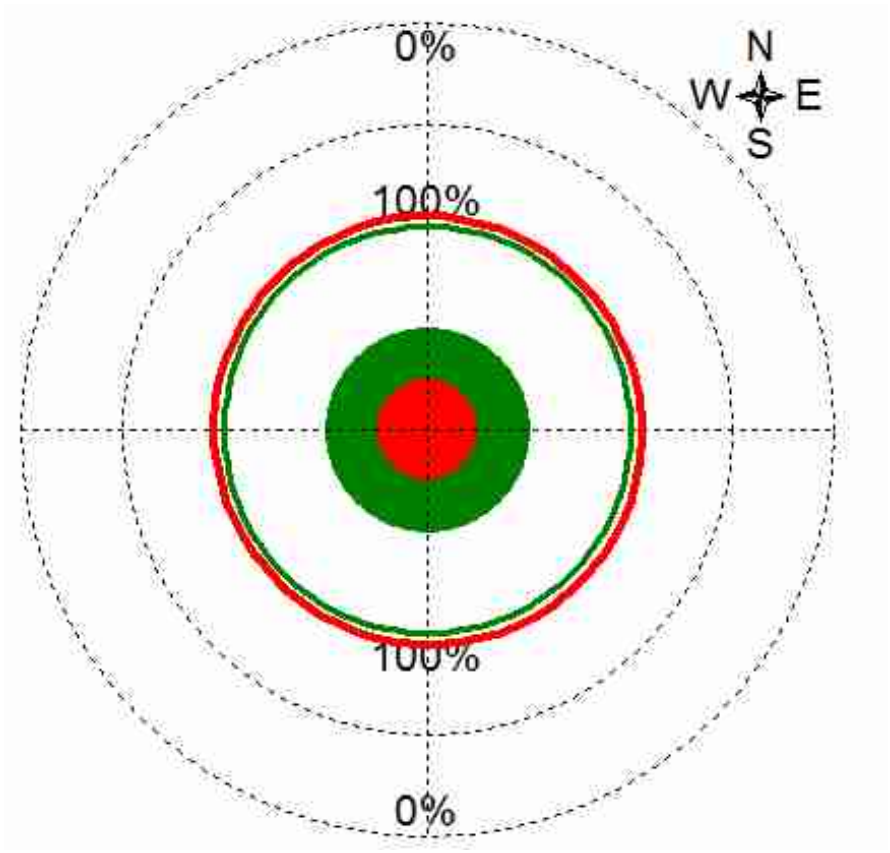
=> Estimation of future development of stability (safety) requires assessment of decay extension rate and radial increment growth trends!

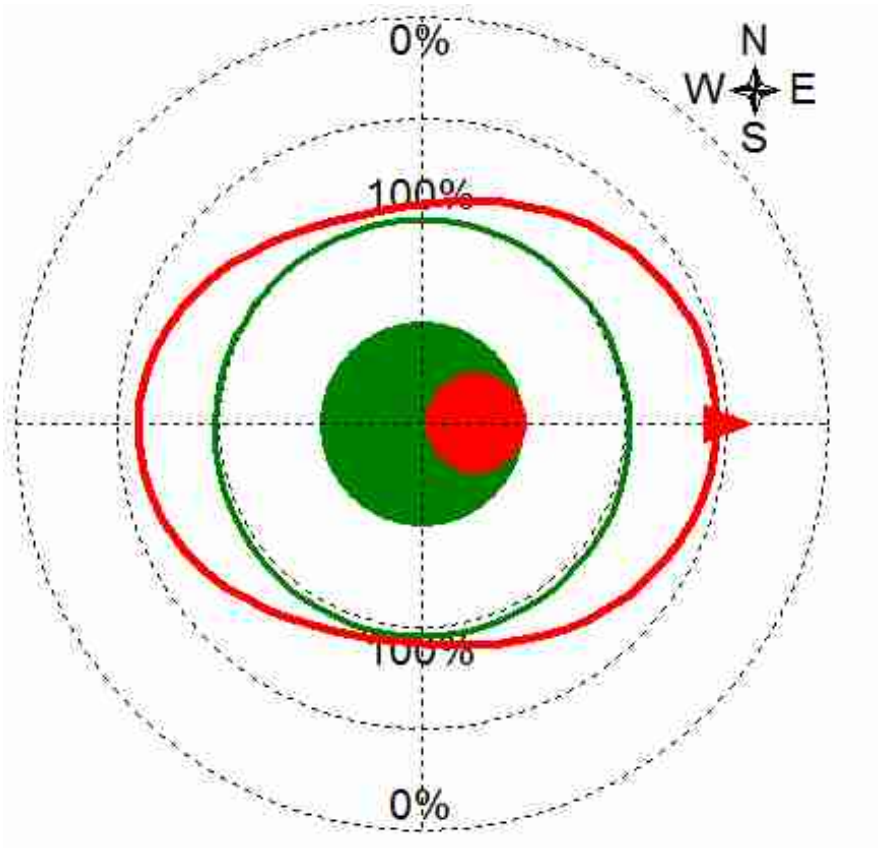
For understanding this and application of practical consequences, some biomechanical back-ground is required:

Cross-sectional shape determines directional load carrying capacity:





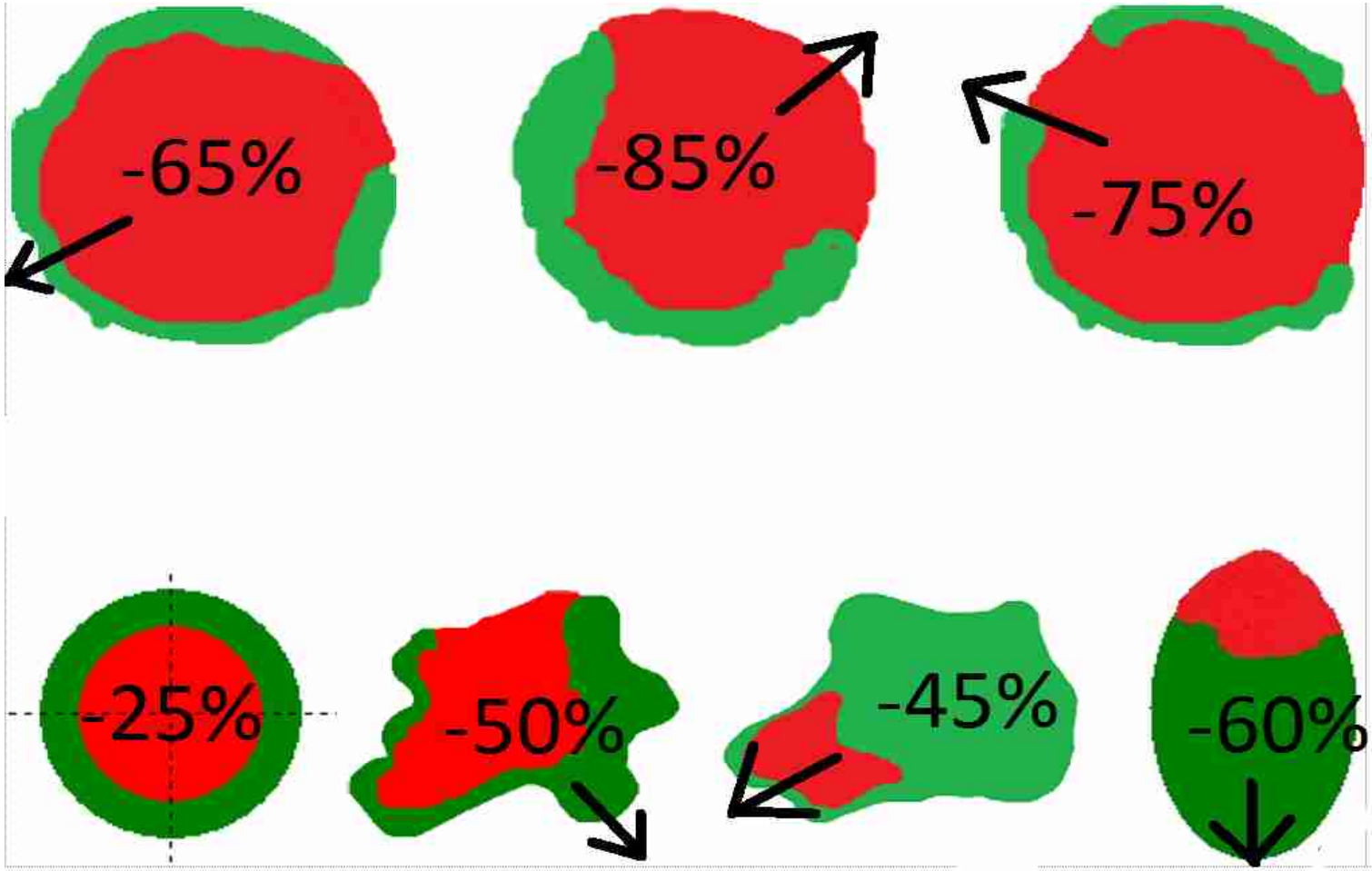




> central decay has only small impact on load carrying capacity
> location of decay is more important than size in terms of LCC
=> many drillings or (better!) sonic tomography helps locating the internal decay!

But, relative strength loss of a cross section can be calculated:
based on the geometrical distribution of intact and decayed parts.

And the weakest bending direction can be determined.



- Structural strength loss (loss in load carrying capacity)
  - is not equivalent to cross sectional defect area size!
  - may be both much lower or much higher!

But, this approach only takes into account bending loads and leads to crazy results if it comes to real thin shell walls below t/R=1/10!

What does this mean for the typical mature urban tree?

What is the tree safety factor of mature urban trees?

And how does it develop (with age)?

=> we have to understand the internal structure of wood and trees!

=> we have to learn

> wood anatomy (on a cellular level)

> bio-mechanics of the tree as a structure

=> Conclusions: the '1/3-rule' (t/R>1/3) ...

... explains a typical natural mechanical design: breakage failures becomes more likely for trees still growing in height with centrally rotten circular stem cross sections (such as often found in slender forest conifers or coconut palms)

... is not valid for the typical mature urban tree arborists have to assess and evaluate:

> Mature urban trees require less shell wall for sufficient safety: as soon as height growth stagnates, the continuing girth growth increases basic stability steadily.

> Safety-wise acceptable hollowness depends on tree, age, size, shape, site, and has to be determined and evaluated individually!

> This needs education, understanding, and training (i.e. ISA-TRAQ + ...)!

=> Study vegetables and fruit before eating (at home, not in the shop! ☺)!

=> Do not just believe 'scientists' exclusively working, teaching, and recommending one kind of machine or one manufacturer's products (this is not science but marketing)!

=> Read books/papers, goto lectures/seminars/conferences/workshops, and build your own competence by questioning everything and everyone (even me) ... ☺ ...

. . . . . THANK YOU!. . . . . .