# USE OF THE FRACTOMETER TO DETERMINE THE STRENGTH OF WOOD WITH INCIPIENT DECAY

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**Abstract.** A fairly new method (Visual Tree Assessment on a biomechanical basis, VTA) and a handy tool for measuring wood quality in terms of strength and stiffness (the Fractometer) are presented together with a new mechanically equivalent model for wood. The paper gives help in interpreting the results gained by Fractometer measurements.

At the Forschungszentrum Karlsruhe GmbH the VTA method was developed in cooperation with the tree consulting office Helge Breloer. The method is based on the assumption that trees strive for an external shape with even distribution of mechanical stresses. This means that there exists neither weak spots of predetermined failure nor places where material is wasted. When this optimum state of even-stress distribution is disturbed by the presence of internal defects (decay, cracks, etc.), the tree will form locally thicker annual growth rings at the height of the defect in order to re-establish the even-stress distribution. This repair growth is a defect symptom. The symptoms are warning signals in the body language of trees. According to German jurisdiction, trees have to be inspected more thoroughly when these warning signals (each time there is additional material that seems to be out of place) are found in the tree, and when there is increasing concern, additional interventions in the tree are allowed. Typical symptoms and related defects have previously been described (Fig. 1) [8].

Another defect, which is not related to decay and hollowness, is the decreasing tensile effect of tension wood in deciduous trees. This can lead to a progressive lean of branches or to additional leaning of trees. The best indicator for this purpose is the bark. On the lower side one can often find compressed bark, on the upper side thin and loose bark, which easily snaps off (Fig. 2).

As a result of the decreasing amount of tension wood, thicker annual growth rings are found on the lower side of a leaning branch or tree, since the tree there undergoes increasing compressive stresses. In contrast, vital branches form a high amount of tension wood on their upper sides, which is revealed by the bark pattern as well. More light and broad axial stripes are found between the bark plates in places of higher radial growth.

Decay and cracks (Fig. 1) should be confirmed and surveyed by modern measuring technigues. Decisions for corrective treatment should then be based on tree assessment and failure criteria. The Metriguard Stress Wave Timer is an excellent tool

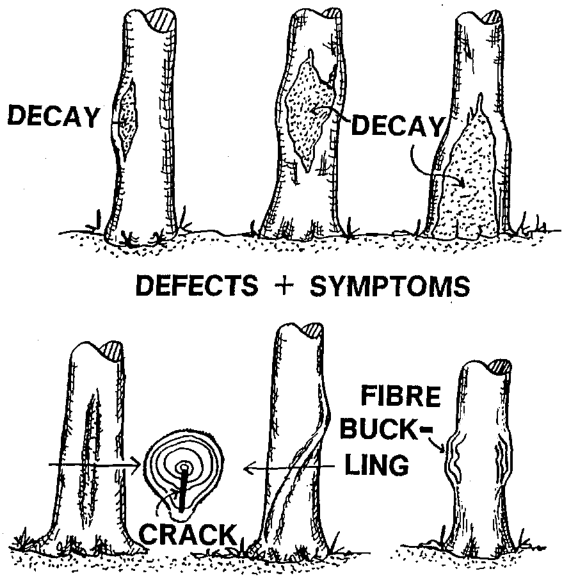


**Fig. 1. Defects and related symptoms.**

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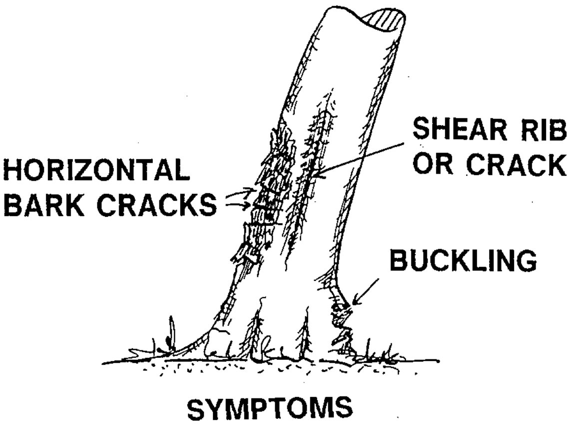


**Fig. 2. Progressive lean indicated by bark symptoms.**

for defect confirmation especially for large diameter trees. It is less effective for defect survey [4] as it cannot determine the geometry of the defect precisely. Hence, this work focuses on the possibilities for diagnosis by use of the Fractometer.

## Assessing failure potential with the Fractometer

It was shown in field studies that a tree may fail when more than approximately 70% of the radius is decayed or hollow [5,14,15]. Trees that have been heavily pruned or have lost branches may still stand even when 80% of the radius is hollow. Simply measuring the remaining wall thickness is not sufficient. It also has to be proved that the strength of the remaining wood is sufficiently high.

In order to classify the decay action from a biomechanical point of view, a simple wood model was proposed [3] (Fig. 3a). This complex system is now converted into a simpler mechanically equivalent model (Fig. 3b) which suffices to understand the decay action, the effect on the mechanical properties (stiffness and strength), and the related failure potential of the tree. The primary cell wall and the middle lamella are replaced by lignin chimneys, which are glued together. The smaller percentage of lignin being in the secondary wall can also be imagined to be shifted into the lignin chimneys. Each individual chimney is filled with a hollow cellulose rope, which represents the secondary cell wall. These cellulose ropes give

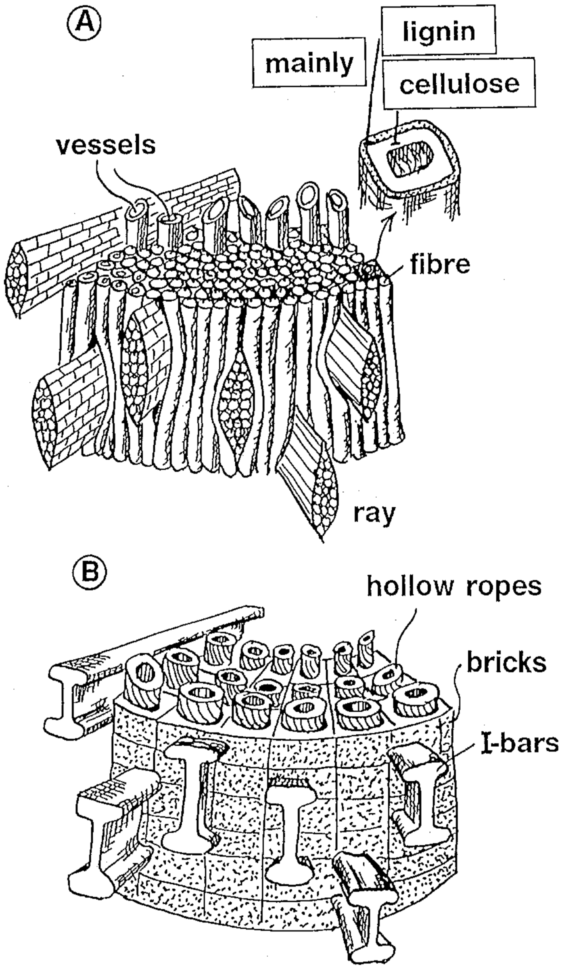


**Fig.3. Ring- porous tree ring. A: Sketch of natural structure. B: Mechanically equivalent model.**

tensile strength and the lignin chimneys provide compressive strength. One would expect thinner lignin walls and more cellulose ropes in tension wood and thicker lignin walls with less cellulose ropes in compression wood (reaction wood) or also in other wood, loaded by compression.

The cross-section of a wood ray has a smooth spindle shape in order to smoothly divert the fibres around the ray (Fig. 3a). The rays interlock the tree rings especially in ring- porous wood in order to prevent them from yielding under shear loading (each bending load due to wind is accompanied by shear stresses, which are highest at the neutral axis of bending). This interlocking action of the

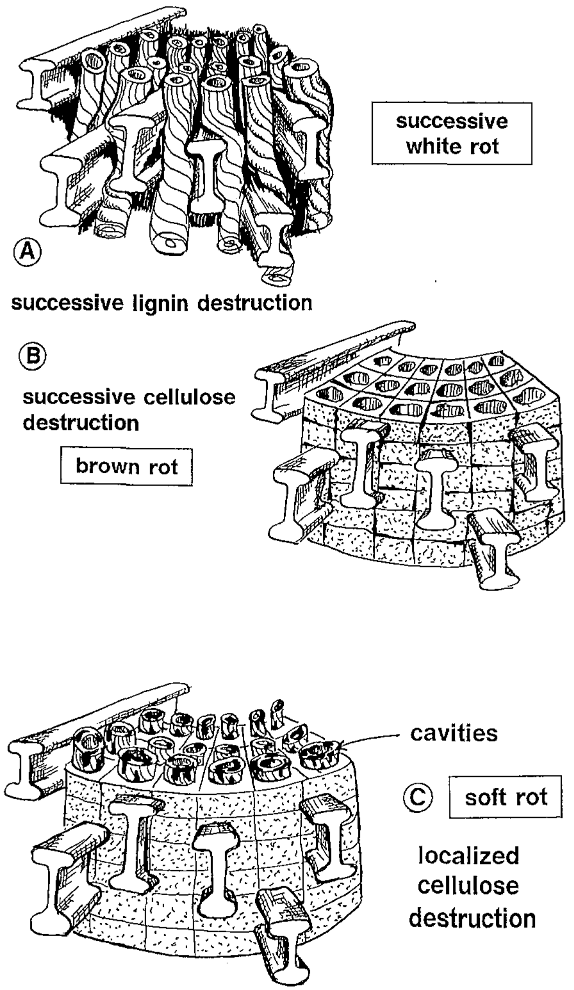


**Fig.4. Decay actions. A: Successive white rot with ductile failure potential. B: Brown rot with brittle failure potential. C: Soft rot with delayed brittle failure potential**

rays leads to bending stresses within the rays. Therefore, they are represented as I-bars (Fig. 3b). Mattheck and Schwarze [10] have shown for common ash trees that the upper and lower tips of the wood ray's cross-section are more lignified than the remaining part of the ray. In this case the ray is really equivalent to an I-bar made of homogeneous material.

If decay attacks the wood structure, there are two extreme possibilities. Successive white rot (Fig. 4a) first attacks preferably the lignin chimneys and leaves the cellulose ropes in the longitudinal fibres as well as in the radial rays for a period of time. The wood is now a network of cellulose ropes which may be compared with a wicker chair. In this case the wood is very soft, but is still tough and strong under tensile loads. The other extreme possibility is brown rot (Fig. 4b), which attacks the hollow cellulose ropes and leaves the lignin chimneys. The damaged structure is still very stiff, but extremely brittle [16]. Soft rot can be imagined as a slowly working brown rot producing small cavities in the cellulose ropes (Fig. 4c).

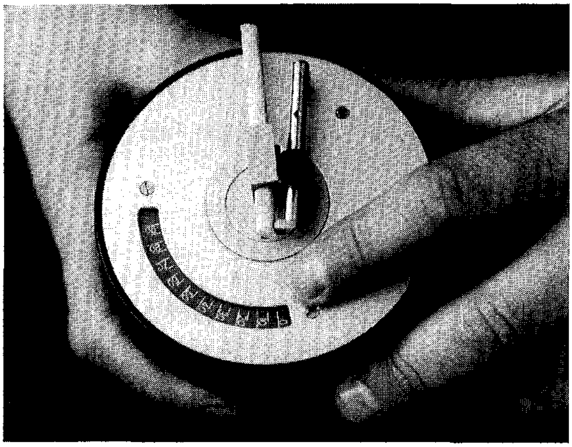

**Fig.5. Fractometer I determines radial bending stiffness and strength using an increment core.**

Even without much mycological knowledge, one can classify the decay action by use of the Fractometer I (Fig. 5). This device breaks a radial increment core, 5 mm in diameter, under bending loads. The bending angle and bending load at fracture are determined. Table 1 gives a list of reference values for fracture loads of the most relevant European trees.

What happens now in the two extreme decay situations?

**Brown rot**

- small fracture angle (10 to 15 degrees, depending on the species)
- small fracture load
- potential of sudden brittle failure, like a cracker or an old dry biscuit

**Successive white rot**

- large bending angle (25 to 35 degrees, depending on the species)
- large fracture load

**Table 1. Classification of trees into Fractometer categories (100 Fractometer units = 26 MPa max. bending stress in the core)**

| Species | Fracture moment in Fractometer units | | |
|---|---|---|---|
| | Green | Yellow | Red |
| **Hardwoods** | | | |
| ash | 80-59 | 58-38 | 37-18 |
| birch | 40-30 | 29-20 | 19-10 |
| black alder, sweet chestnut | 50-38 | 37-25 | 24-12 |
| black locust, beech, hornbeam, maple, oak, plane | 120-89 | 88-58 | 57-27 |
| poplar, willow | 20-15 | 14-10 | 9-5 |
| elm | 110-82 | 81-54 | 53-26 |
| horsechestnut | 70-52 | 51-34 | 33-16 |
| lime | 60-46 | 45-30 | 29-14 |
| **Softwoods** | | | |
| Douglas fir | 7-6 | 5-4 | 3-2 |
| fir, larch, pine | 15-12 | 11-8 | 7-4 |
| spruce | 20-15 | 14-10 | 9-5 |
| yew | 90-67 | 66-44 | 43-21 |

If any decay is present, the values for the surrounding healthy wood need to be within the green range.

The same applies to wood in leaning trees.

In heavily pruned trees, values in the yellow range may be acceptable. Wood with values in the red range is weak and should be regarded as unable to support the tree safely , so that severe crown reduction or felling may be needed. However, a fixed use of the table is dangerous. It is important to look at the tree as a system and not at the increment borer core only (e.g. a black poplar with 80 Fractometer units was felled because the tree had clear signs of local failure (fibre buckling) and was slanting heavily). For the fracture angles see ref. [9].

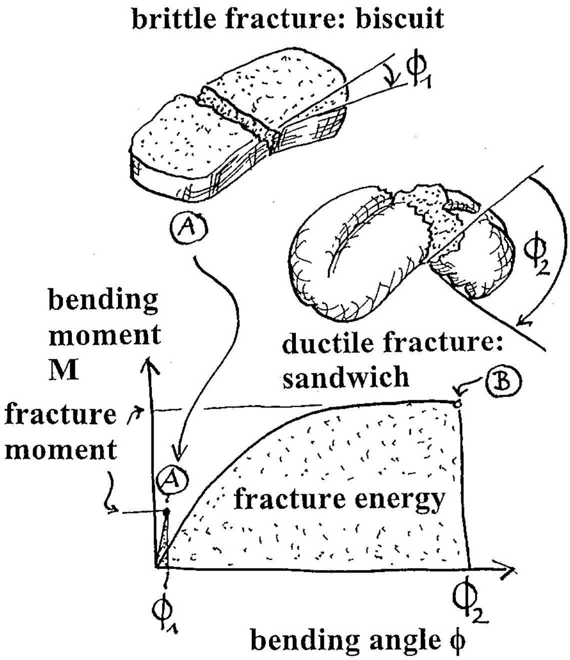


**Fig.6. Quantitative illustration of brown rot- biscuit trees and successive white rot- sandwich trees. The work to fracture is the area below the bending moment- angle curve**

- potential of ductile failure, like a tough sandwich or bred roll, indicated by bulges, loose bark or progressive lean (Fig. 6)

Table 2, taken from [9] gives a diagnosis help for all possible combinations of bending angle and fracture load. The Fractometer may also give information on how well the barrier zones [12, 13] are able to stop further decay propagation:

When the Fractometer readings suddenly change at one point along the core, indicating an abrupt transition between healthy and decayed wood, the barrier zone is very efficient. But when

**Table 2. Decay classification on the basis of Fractometer readings [9].**

| Fractometer | | decay effect | wood property |
|---|---|---|---|
| fracture moment | fracture angle | | |
| large | small | low | high stiffness and high strength |
| large | large | lignin destruction | low stiffness but high strength |
| small | small | cellulose destruction | high stiffness but low strength |
| small | large | lignin and cellulose destruction | low stiffness and low strength |

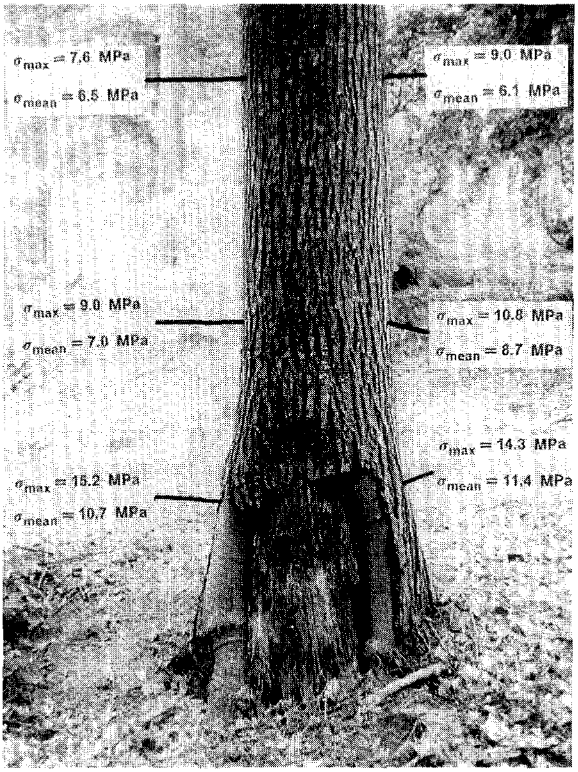


**Fig. 7. Locally increased Fractometer values in the remaining wall thickness of a hollow sweet chestnut prove a strong will to survive for that individual tree (100 Fractometer units = 26 MPa max. bending stress in the core).**

the wood quality continuously decreases from the bark along the core, the barrier zones are weak and there is no good future for the tree.

The Fractometer is also a tool that can assess the "fighting spirit" of the tree, ie., it's will to survive. Albrecht [1] has shown in field studies that the wood quality (i.e., Fractometer values) is higher at places where the tree has formed additional material by repair growth. As an example, Fig. 7 gives the increasing radial bending strength of an increment core taken from the remaining wall thickness at the level of a hollow within a tree. This higher wood quality is only found in the repair growth of trees with a high amount of vigour. Trees low in vigour have a low wood quality in the symptom area because they use poor material in the repair growth. In this sense the Fractometer can assess the "psychology" of a tree, which is an important help in determining the prognosis. At

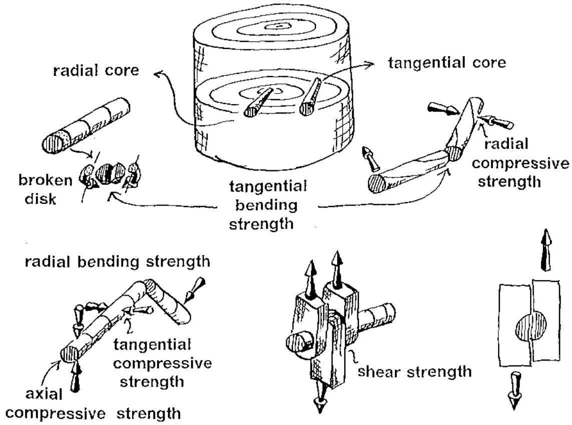


**Fig. 8. Wood properties which can be measured from an increment core.**

the Forschungszentrum Karlsruhe GmbH, we currently consider how precisely other strength properties of wood can be determined using increment cores. Fig. 8 gives an overview of these possibilities. First results are very encouraging and we hope to replace the awkward specimen preparations for expensive testing machines by simply taking increment cores and breaking them in several different failure modes.

A first step was done by developing Fractometer II, shown in Fig. 9. This device measures the radial bending strength and longitudinal compressive strength. It was used to investigate the strength drop at the transition zone between healthy and decayed wood for different types of fungal attack on several wood species. Fig. 10 shows the distribution of longitudinal compressive strength and radial bending strength along increment cores taken from the butt of a beech tree (*Fagus silvatica*) infected by *Meripulus giganteus*. In all cases considered, the longitudinal and the radial strength drastically decreased at the same annual growth ring. Since this result was confirmed for white rot, brown rot and soft rot, one may conclude that the previous Fractometer I (Fig. 5) is sufficient for tree diagnosis.

Strength assessment is not only restricted to decayed or hollow stems. If buttress roots are decayed, one may also classify the failure potential by ductile (white rot) or brittle failure modes (brown rot) according to Fig. 4 and related Fractometer

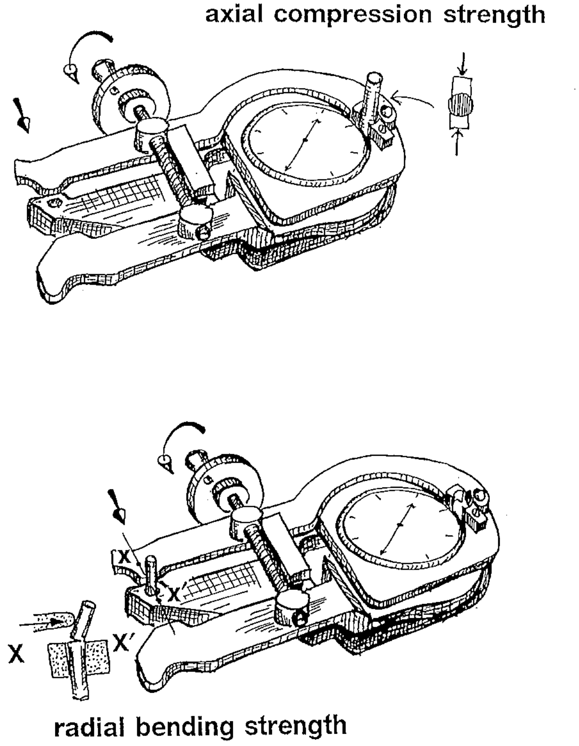


Fig. 9. The design and functional options of Fractometer II.

measurements. Smiley and Fraedrich [14] as well as Matheny and Clark [2] claim that trees are considered to be hazardous if 1/3 or more of the root system is decayed or missing. They state that an individual assessment is important for root defects. The size of the root cross-section also has to be regarded. After one has made sure that the decayed butt is not more than 70% hollow, thereby excluding stem failure, all the buttresses have to be checked, for example, by use of a Resistograph [11] or by use of a simple battery-operated drill looking at the colour and structure of the wood shavings.

In the case of discoloured or smelling wood shavings, or even when a low Resistograph drilling resistance was measured, the authors prefer to remove an increment core from this root in order to get information on the potential of brittle or ductile failure behaviour, which is very important in case that a tree damaged by decay should remain standing at its position.

An assessment of the importance of the individual root can be done with the help of Mohr-Coulomb's Law [7]. It states, that the shear strength of soil increases with the contact pressure of the shear faces against each other (Fig. 11). This law is well- known and accepted in soil mechanics. An immediate conclusion can be drawn with regard to the root morphology. When there is a prevailing wind direction, the soil on the windward side of the

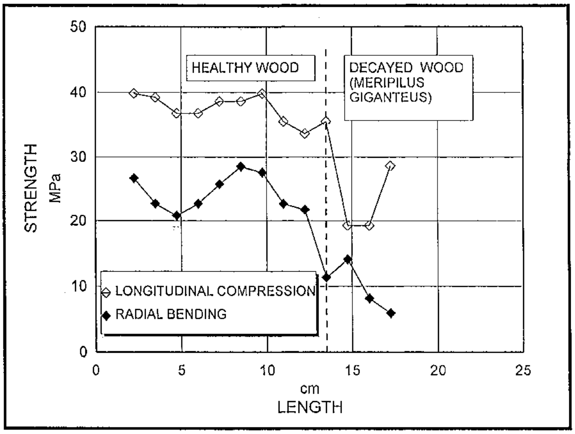


**Fig. 10. Similar drop of longitudinal compressive strength and radial bending strength at the border line between healthy and decayed wood.**

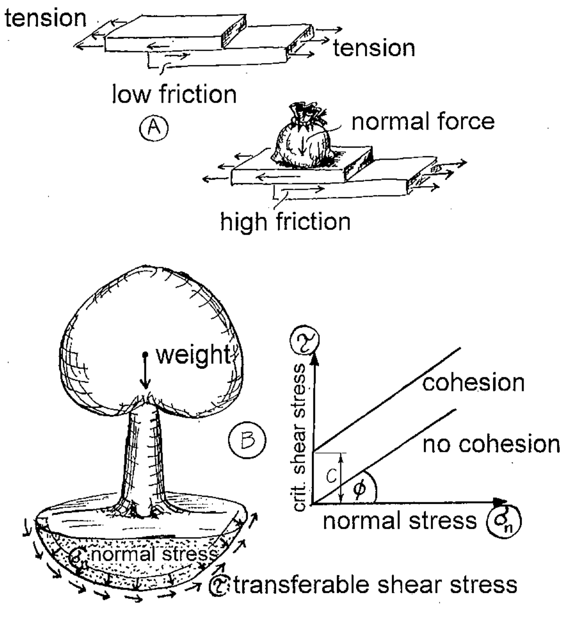


**Fig. 11. Illustration of Mohr- Coulomb's Law. The shear strength of the soil increases with increasing pressure on the shear faces.**

tree is lifted and the soil on the lee side of the tree is compressed by the root system. According to Mohr- Coulomb's Law, the soil on the windward side is therefore weaker. Hence, there are more, longer and stronger roots necessary at this side of the tree to reinforce the weak soil. At a certain distance from the stem, where no roots further reinforce the soil, all the wind load must be carried by the soil alone. This distance must be larger at the windward side (Fig. 12).

Also the upslope roots of trees growing on slopes and leaning downward are stronger and longer. In case these roots are decayed or missing, one should not rely on the failure criterion mentioned before. Even 30% decay can already be dangerous under these circumstances. First warning signals are soil cracks at a certain distance from the tree or progressive lean of the tree due to soil movements.

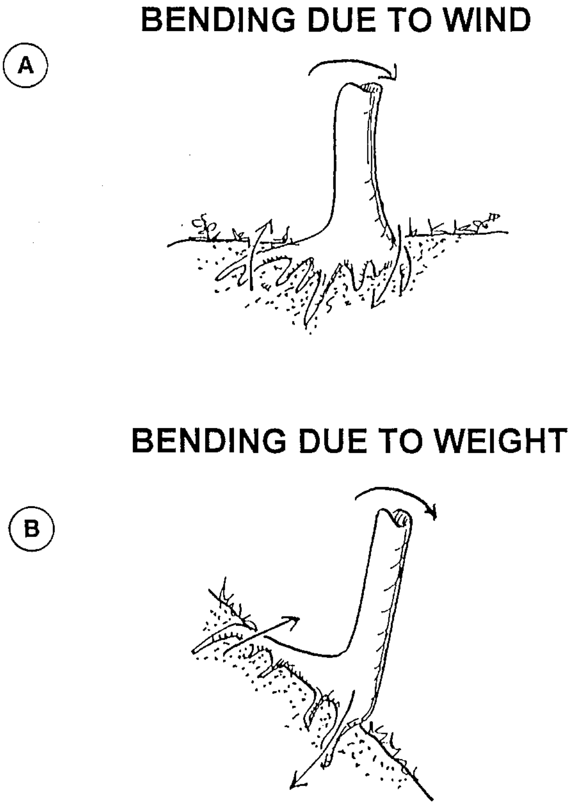


**Fig. 12. More, stronger and longer roots are necessary on that side of a tree, where the soil is lifted. A: One- sided wind loading. B: Slope trees.**

On the other hand, the authors have seen many trees still standing when 50% of the roots were missing on the lee side or on the downslope side of leaning trees. However, the safety factor, which is usually S = 4.5 in trees [6], is expected to be drastically reduced in these cases. The safety factor S = fracture load / normal service load.

## Conclusion

The aim of this paper is to show the importance of the Fractometer as a tool for assessment of the effect of decay in a simplified mechanical wood model. Since the strength of wood controls the safety of a tree, a device is recommended that measures strength properties directly, as for example, the Fractometer.

Field studies have shown that radial strength drops in the same way as longitudinal strength due to decay action. Highly vigorous trees have a stronger repair wood, which is a measure of the tree's will to survive.

The complete VTA procedure is published [8] and a detailed description of many defect symptoms, including all relevant failure modes as far as is known to the authors. In addition, legal aspects are given [7].

In the past, a large variety of different equipment for tree safety assessment has been brought on the market. It is important to note that all the equipment, including the Fractometer, is only able to measure and quantify what one has already seen before. Most important of all is the experience of the arborist, and this will never change in the future since it cannot be substituted by any kind of measuring device.

Mechanical terms such as stiffness, strength, Mohr- Coulomb's Law, ductile and brittle fracture are a "must" for people, who assess the safety of a tree. The VTA method tries to bridge the gap between tree biology and biomechanics. It tries to give the arborist's experience a scientific basis founded on field studies, computer simulations and materials science.

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## Literature Cited


1. Albrecht W. 1994. Unpublished results of the Karlsruhe Nuclear Research Center.
2. Matheny, N., and J. Clark. 1994. A Photographic Guide to the Evaluation of Hazard Trees in Urban Areas. 2 nd edition, International Society of Arboriculture, Savoy, Illinois, USA.
3. Mattheck C. 1994. *Wie das Bauminnere zusammenhält.* Deutscher Gartenbau 19: 1142- 1145.
4. Mattheck C., and K. Bethge. 1993. *Decay detection with the Metriguard Stress Wave Timer.* J. Arboric. 19 (6): 374-378.
5. Mattheck C., K. Bethge, and D. Erb. 1993. *Failure criteria for trees.* Arboric. J. 17: 201-209.
6. Mattheck C., K. Bethge, and J. Schäfer. 1993. *Safety factors in trees.* J. Theoretical Biology 165: 185-189
7. Mattheck C., and H. Breloer. 1994. Handbuch der Schadenskunde von Bäumen- der Baumbruch in Mechanik und Rechtsprechung. Rombach Verlag Freiburg, 2 nd edition (English translation: Handbook of failure analysis of trees- Understanding the body language of trees) to appear in 1995 by Her Majesty's Stationary Office, London
8. Mattheck, C. and H. Breloer. 1994. *Field guide to VTA (Visual Tree Assessment).* Arboric. J. 18: 1-23.
9. Mattheck, C., H. Breloer, and K. Bethge. 1994. *A guide to Fractometer tree assessment.* Arborist News 3(2) 9-12.
10. Mattheck, C., and F. Schwarze. 1994. *Die Holzstrahlen als getarnte I- Balken in einem mechanischen Ersatzmodell.* Allgemeine Forst- und Jagdzeitung 165: 197-201.
11. Rinn, F., B. Becker, and B. Kromer. 1992. Penetration-resistance measurements: density profiles of conifers and deciduous trees, Lundqua Report, Lund University, Proceedings of the International Dendrochronological Symposium, Ystad, Sweden 1990, pp 274- 276
12. Shigo, A. 1989. A New Tree Biology, Shigo and Trees, Associates, Durham, New Hamshire, USA
13. Shigo, A. 1991. Modern Arboriculture. Shigo and Trees, Associates, Durham, New Hamshire, USA.
14. Smiley, T., and B. Fraedrich. 1993. Hazardous tree evaluation and management. Bartlett Tree Research Laboratory, Charlotte NC, 37 pp.
15. Wagner, W. 1963. Judging hazard from native trees in California recreational areas - a guide for professional foresters. U.S. Forest Service Research Paper PSW-P1, Berkeley, California Forest Service, U.S. Department of Agriculture.
16. Wilcox, W.W.1987. *Review of the literature on the effects of early stages of decay on wood strength.* Wood and Fibre 9: 252-257



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**Résumé.** Une nouvelle méthode impartiale pour l'évaluation visuelle d'un arbre sur une base biomécanique, avec l'apport d'un outil manuel qu'est le fractomètre, est décrite. Cette méthode permet de mesurer la qualité du bois en regard de sa force et de sa dureté à l'aide d'un nouveau modèle d'équivalence mécanique du bois qui est décrit. L'article donne des informations pour aider à l'interprétation des résultats récoltés à partir des mesures du fractomètre

**Zusammenfassung.** Es werden eine relativ neue Methode, VTA, zur qualifizierten Sichtkontrolle von Bäumen auf biomechanischer Basis, ein neues und handliches Werkzeug (Fractometer) zur Bestimmung der Holzqualität in Form von Festigkeit und Steifigkeit sowie ein neues mechanisches Ersatzmodell für Holz vorgestellt. Der Artikel ist eine Hilfe zur Interpretation von Fractometer Meßergebnissen und soll dem Fractometeranwender die Baumdiagnose erleichtern.