Fracture Diagnosis of Trees

Part 1:
Statics-Integrated Methods - Measurement with Tension Test

The Expert's Method

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Introduction

The establishment of a generalized tilt curve valid for all trees shows that stability can be determined without injury by a tension test (Inclinometer method). As yet, no other reliable method is known for monitoring stability.
This paper will deal with safety against fracture, and will deal with some still unanswered questions from the FLL Discussion on tree statics. It will show how the **Statically Integrated Methods of Diagnosis** (SIM) correspond to the current state of knowledge and research, and to the procedure according to German Standard DIN 1055 and the 1992 ZTV.

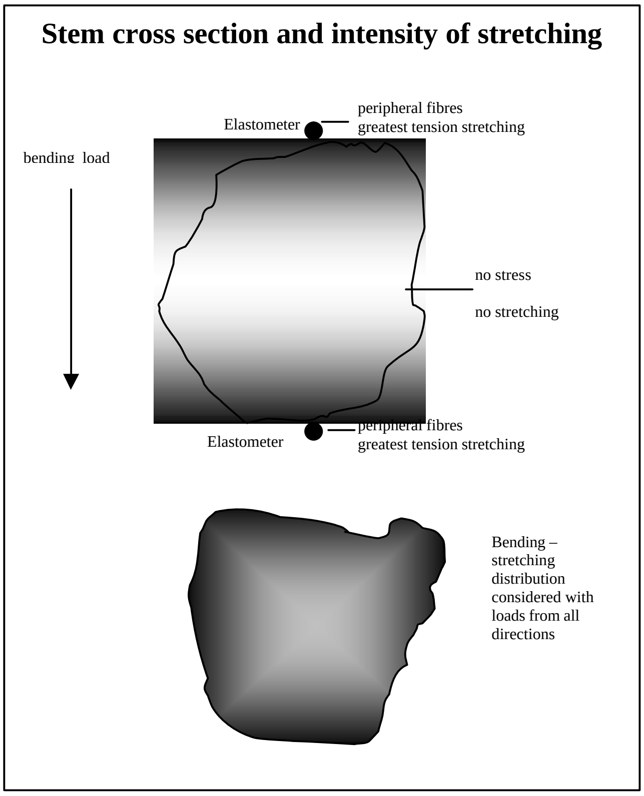
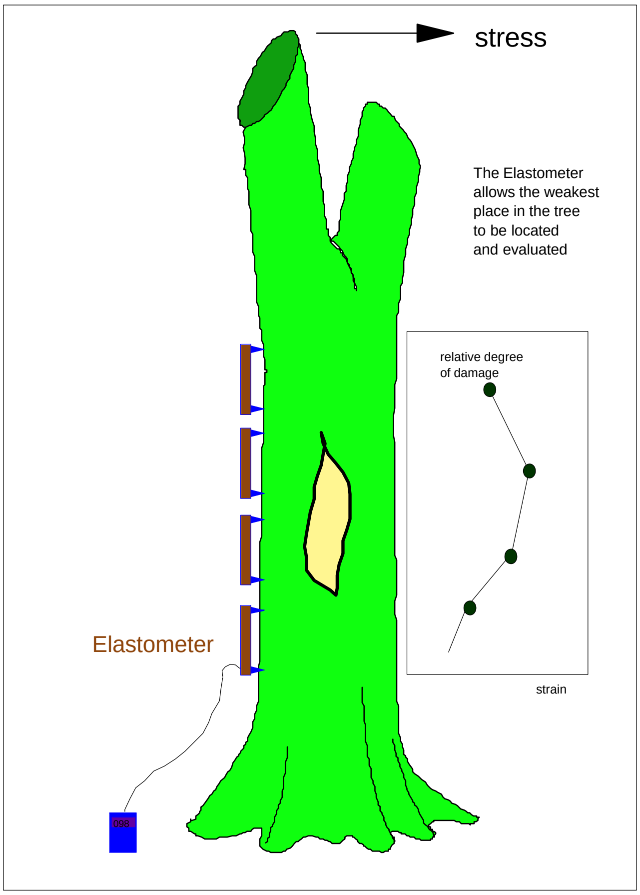


fig. 1

The blackest areas have the greatest load and thus the greatest stretchuing of the wood fibres. The picture shows clearly that as regards statics the tree interior is largely unimportant. The degree of stretch of the peripherical fibres depends on the load and on all other fibres. Therefore the peripheral fibre stretching is representative. The Elastometer is located here.

The wood fibres stretch under load

Under wind loading, the individual wood fibres in the tree must in their totality conduct the force from the crown into the ground. The more wood fibres that are involved in this, the less each one has to withstand. Fungi destroy fibres and the lignin supporting the fibres. The carrying capacity is broken down in these regions. The rest of the fibres must take on greater forces. In erect trees, under their own weight each fibre is stressed with the same force in the longitudinal direction. However, under bending some fibres do not have to withstand anything, i.e. the fibres in the stem centre. In contrast, the stress increases with increasing distance from the stem centre, and reaches its maximum directly beneath the bark (Fig. 1). However, the internal stress decreases with increasing tree diameter. The fibres are relieved by the more favourable lever effect, i.e. the distance to the centre: with a stem of twice the diameter, under the same load the stretching of the fibres falls to an eighth. This means it depends on the lever. This can be clearly pictured on a balance: the further the small counterweight is pushed outwards, the greater the weights which are balanced. In contrast, the importance of the fibres for tree statics decreases with increasing proximity to the pith. The same also applies for defects in the interior of the tree. The tree simply no longer notices them. Accordingly, searching for defects in the tree interior for the acute statics is quite unnecessary in straight stems.



The Elastometer
allows the weakest
place in the tree
to be located
and evaluated

fig. 2

The Elastometer can be moved as often as required. In this way a spatial picture of the statics situation can be produced. The weakest cross-section is found and determined quantitatively in relation to the sound zone as the relative degree of damage in percent.

The failure process in wood

“With wind loading the stem bends, the elastic limit is exceeded, and creep processes occur in the compression zone. In the first stage fibre compressions occur from the periphery, without the longitudinal delaminations described by Mattheck and Bethge being observed. At first these fibre compressions can only be (observed microscopically [Author's note: or with the Elastometer], and only with persistent or increasing load do macroscopic compression lines develop, which spread out increasingly in the direction of the tension side. These compressions 'absorb' the compressive stresses until the fracture load is reached on the tension side and the stem breaks, without 'delamination' necessarily occurring" (Lesnino & Glos, 1994). Example: standing spruce trees extremely bent under wind load exhibit these compression zones.

The fibres on the windward side are pulled, and those on the lee side compressed. They are deformed in the longitudinal direction. The stiffer they are, i.e. the higher the E- modulus, the less they give. Up to a certain stretch limit they do this without sustaining lasting damage. As the fibres withstand compression less well than tension (1:2), the compression load capacity is the valid measurement limit. The start of the plastic deformation is called the elasticity limit (Fig. 3). This means: **the maximum compression of the fibres lying immediately below the bark is the decisive criterion for assessing fracture resistance. This applies** for any cross-sectional shape. If many fibres are involved in reducing the bending load, they are deformed less: the marginal (i.e. peripheral) fibres are thus some way from elastic limit (Fig. 3).

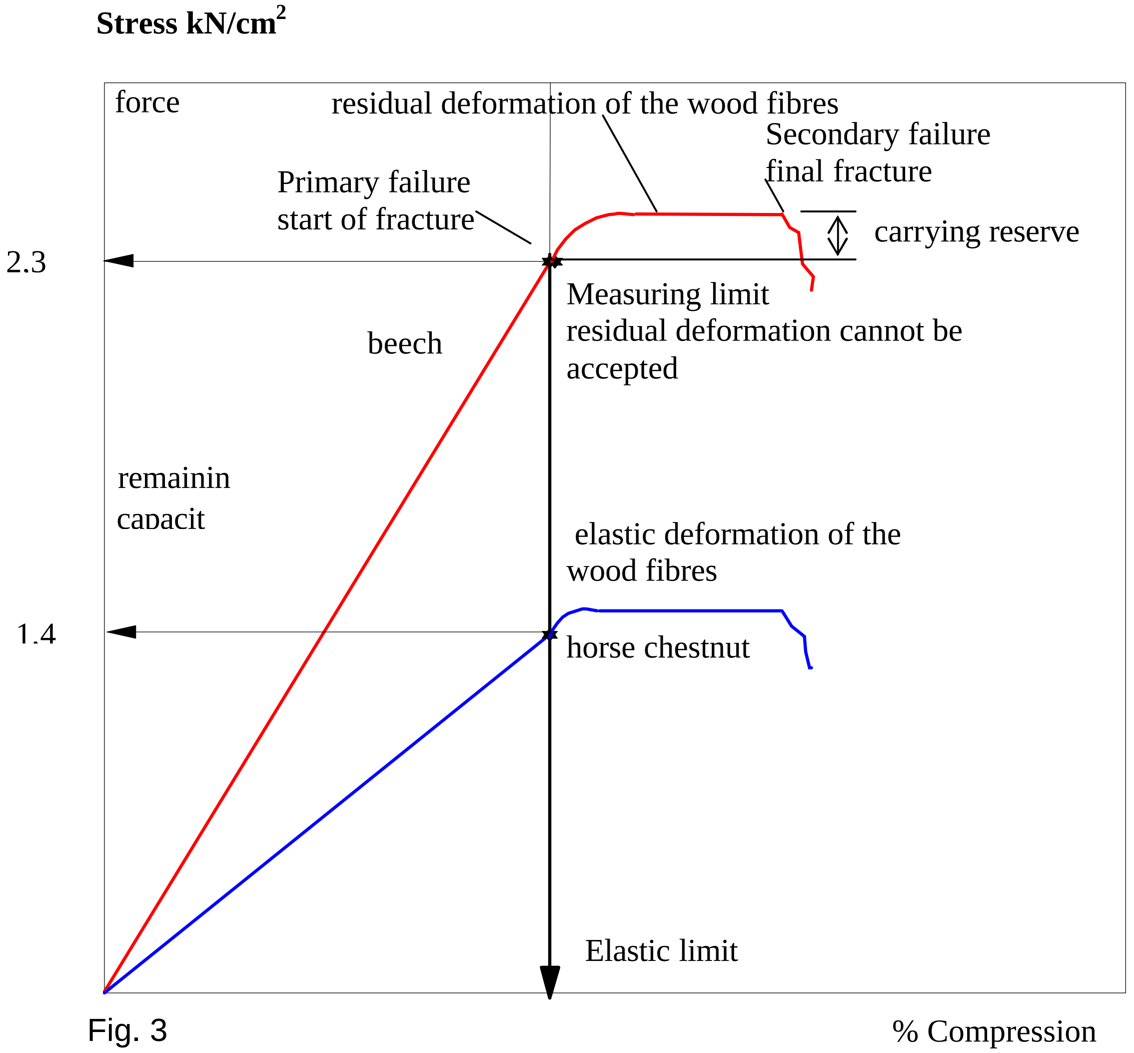


Fig. 3

The deformation behaviour of the wood under compression is divided into two zones: elastic and plastic. The transitional point is the elastic limit, the most important measure of whether the tree is still fracture safe. It si the measurement threshold for tree safety. Despite different material data, beech and horse chestnut, for example, have the same elastic limit.

Possibility of measuring peripheral fibre stretching

The bark lies like a scaly armour over the peripheral fibres and, when healthy, makes every movement with them. If the bark has loosened, this is quickly noticed as no stretching occurs when the tree is bent.
If the bark moves with the peripheral fibres, their stretching under bending load can be recorded with two points in the bark. As bark is fungus-resistant, it is absolutely free of injury. The essential and comprehensive information for tree statics is now available (Spatz, 1993). The tree crown is pulled, like the wind but somewhat less violently; the tree loads its fibres, and that is recorded where the most strongly stretched fibres are located. To work like the wind is reproducible. It is logical to cause the tree to react in its totality, and to record this reaction with the finest instruments; this gives the most accurate insight into the tree's carrying capacity.

The development of the Elastometer, which non-destructively measures the stretching of the representative peripheral fibres, and the tension test were the cogent consequence of the failure process of trees under bending load!

Without causing injury the Elastometer method can:

1. find the weakest place in the tree.
2. determine the size of the weakest place relative to the adjacent cross-sections.
3. determine the residual carrying capacity of a hollow as opposed to a solid part of the tree.
4. determine the wind load at which the tree will break.
5. quantitatively use tree statics to predict fracture safety.
6. non-destructively monitor exactly the same place some years later.
7. assess subsequently released or pruned trees with the same validity as free-grown solitary trees.

Location and measurement of the weakest place

The Elastometer measures the stretching of the peripheral fibres, and can non-destructively analyze the tree from the outside and also locate the place which gives way most, even with hidden cavities. If an overload should occur in a storm, this most probably is the fracture position. The relative weakness is determined in comparison to the positions above and below it. In comparison with the mean E modulus of all the measured trees of the same species (Table 1), we obtain the residual carrying capacity of the hollow tree as against a solid cross-section. The residual carrying capacity or residual wall thickness is important for completing the overall picture of the tree's statics, and for making a prediction. It is not decisive for assessing the acute safety.

Determination of the residual wall thickness is more dependent on stiffness scatter than the determination of the fracture force. This means that the prediction of the tree's fracture load is more accurate. Why this is so is explained below.
In principle: scatters in the material data in the green wood involve imprecision for

predicting tree safety. However, this is not a fundamental problem which could ruin the diagnostic approach. The stress analyst always calculates so that the structure lies on the safe side. The less scatter he needs to incorporate in his calculations, the better the tree's chances. Kollmann et al. (1951) found considerable scatter in the material values (stiffness or strength) considered in isolation in the tree. But their results extend over the whole tree from the base to the top. Our own measurements have confirmed that the stiffness of the wood in the tree increases from base to top, but the strength and the carrying capacity also increase.

Accuracy

Knowledge of biological and mycological processes limits the scatter to be considered. Accordingly there is a clear improvement in the accuracy of the residual carrying capacity determined for a hollow cross-section. The overwhelming part of the statics problems is caused by root rots. After root trimming, the fungus penetrates into the stem base, spreads upwards in a dome-shape and causes a butt rot. For this reason the vast majority of investigations target the lower 2 m of the stem. This considerably reduces the scatter of the E modulus and strength (Table 1, Fig. 4). The mean compression strength of all the trees is 2 kN/cm^2 , the mean E modulus of the broadleaved trees occurring in urban situations is 677, standard deviation 102 (see Table 1).

This means that concentrating on particular parts of trees improves the accuracy in predicting residual carrying capacity. Because the compression strength values of all green woods in the lower stem are similar, the geometry of the cross-section is much more important than the tree species.

Quote: **“It is the wall-thickness/radius ratio which determines the tree fracture, and not the tree species“** (Author's note: or different strengths) (Mattheck, Bethge, Breloer, 1994). However, that is only part of the true situation, and if load analysis is neglected, errors will be made (see below).

It must be remembered: the material scatter of the healthy stem wood under pure bending stress is not the governing factor in tree failure.

Determination of the failure load

The accuracy of determining the fracture load with the Elastometer is much greater than the residual carrying capacity, and applies over the whole tree. This is because determining the fracture load by means of the Elastometer is based not on stiffness or compression strength but on the elastic limit (Fig. 3 and Table 1).

The Elastometer precisely targets the failure process in wood described above by Glos & Lesnino (1994). According to Spatz (1994) it is also valid for hollow bodies up to the primary failure.

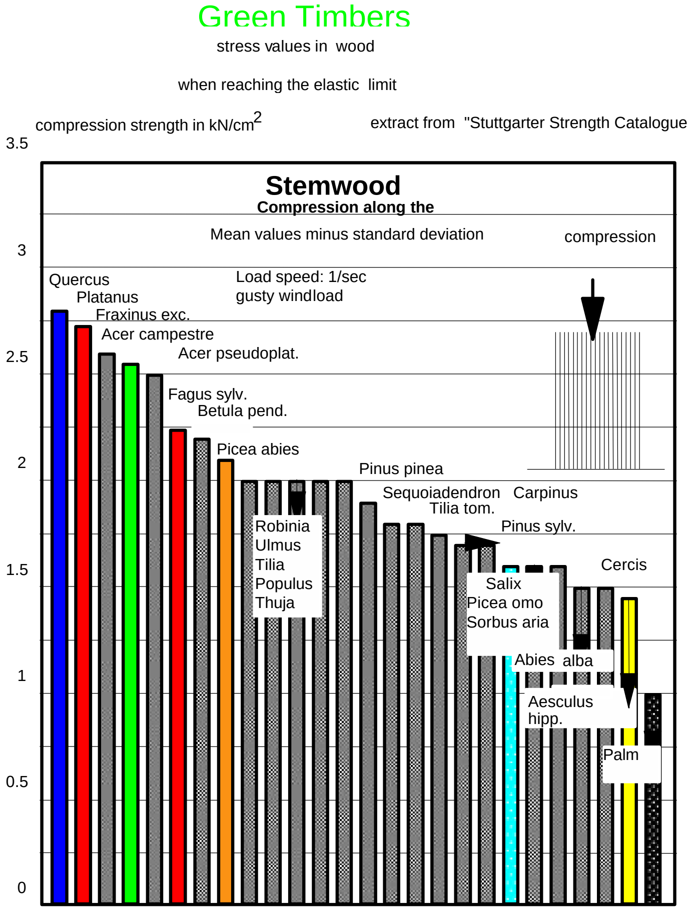


fig.4
The stress value on reaching the elastic limit averages 2kN/cm^2 for the stemwood of all the trees. Oak is 2,8, horse chestnut 1,4.

What is the elastic limit?

The elastic limit is the ratio of compression strength (primary failure = reaching the elastic limit) to stiffness at the point at which the wood starts to incur lasting damage with further load increase (Fig. 3).
Spatz (1994) called reaching the elastic limit primary failure. The fracture of trees occurring later is the result of secondary failure. It has nothing to do with the primary failure which is reliably analyzed by the Elastometer method. The fracture pattern gives no indication as to the start of failure, but the start of failure is decisive for assessing safety. Large-scale trials on standing trees have shown that even with large cavities the elastic limit is reached before the secondary failure, and thus the Elastometer

method gives relevant results regarding the start of failure (Wessolly, 1993). The engineer responsible for the stress analysis never considers the secondary failure, only the primary failure. Therefore the elastic limit is the only sensible measurement in assessing the traffic safety of trees as regards fracture.

The elastic limit exhibits much less scatter in the tree than the stiffness or compression strength values considered in isolation. This is clearly shown in Fig. 5

on the 200 compression samples of a beech fork: the E moduli lie between 700 and 1610 and the compression strengths between 1.94 and 4.4 kN/cm^2. Despite the very high differences between the individual positions and material values, the elastic limit of 0.26% determined from all the beech trees is valid for the whole tree!

This means that measurements can be made with the same elastic limit as a basis over large parts of the tree without great inaccuracies. The Elastometer value is compared with the elastic limit in the tension test. As stretching and force up to the elastic limit are in a fixed linear relationship (Fig. 3), it is easy to see whether the elastic limit in the organ is exceeded or not. How does it behave in fungus-infected trees?

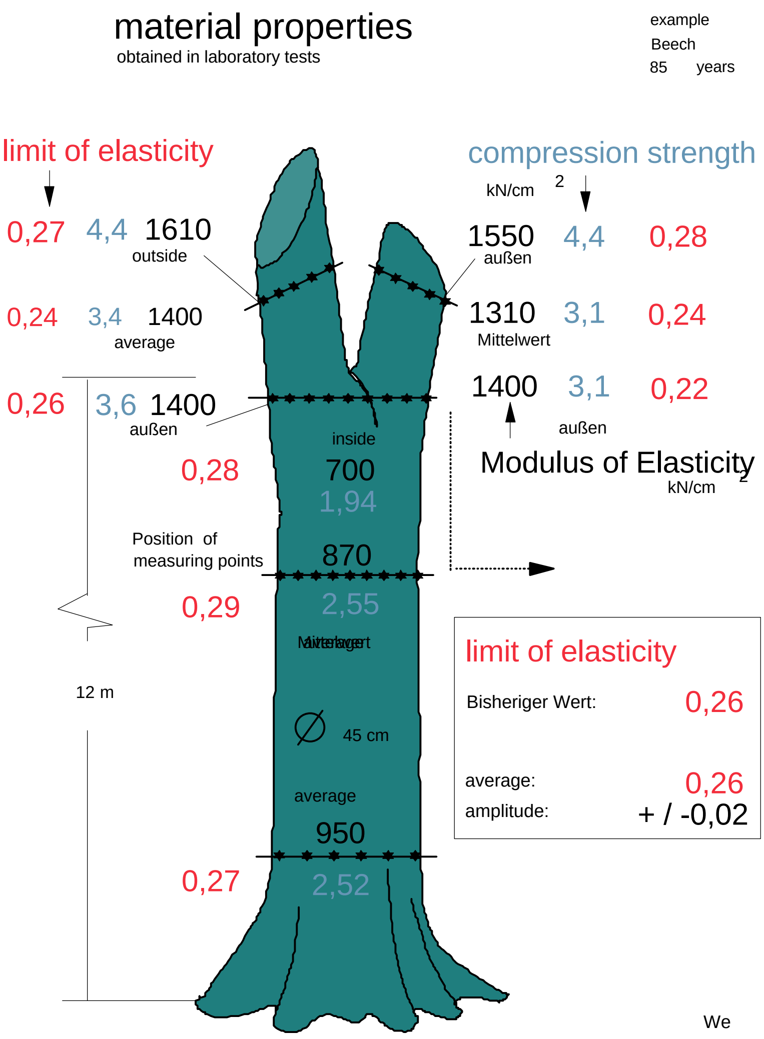


fig 5.
Despite great differences in the individual values of stiffness and strength, the elastic limit stretching is amazingly constant. Accordingly the Elastometer measurement is very reliable. The limiting stretch valuefor beech is 0,26. This should not exceed in a storm. Therefore the statics status of the tree can be assessed very well with one imiting stretch value.

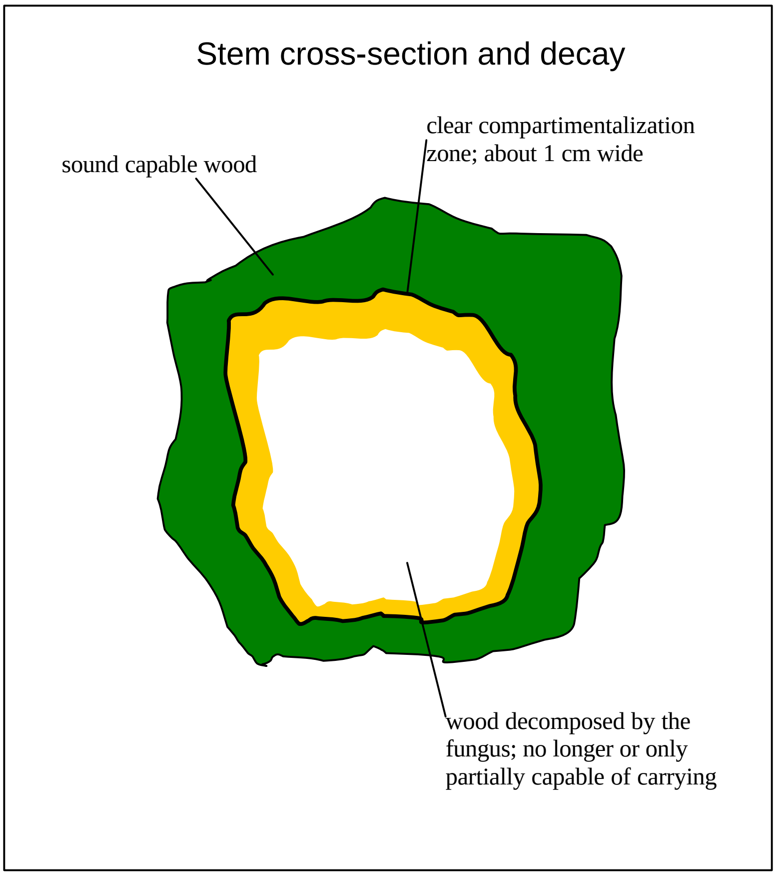


fig.6
The compartimentalization clearly seperates the healthy outer wood from the fungus-infected and decaying wood. In the lower stem zone which is most endangered, no knot disturbs the healthy zone. The lower stem is knot-free. Therefore it is correct to work with strength values of defect-free samples. in fracture the tree
starts to fail from the the outside
inwards.

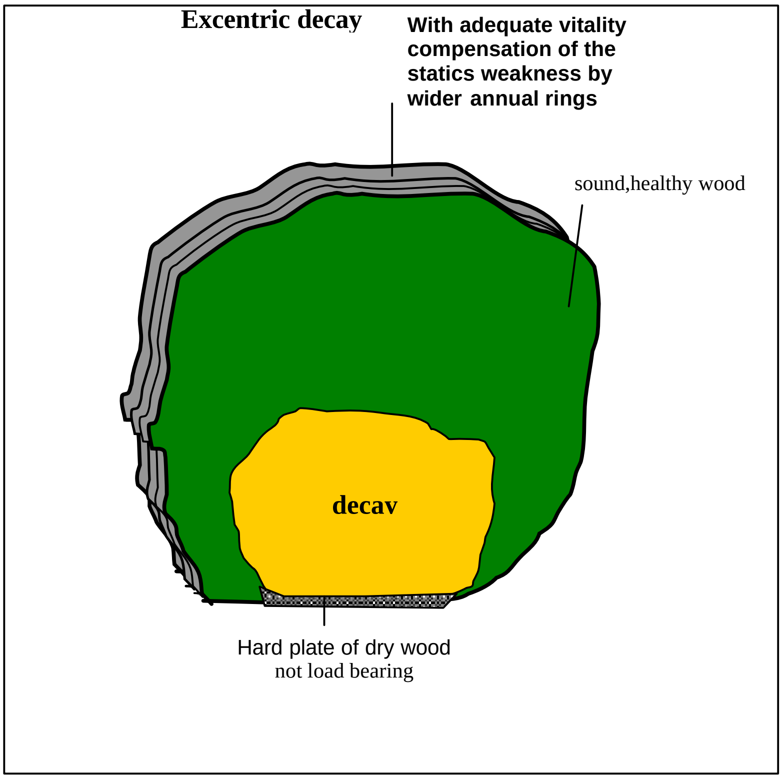


Fig. 7

With adequate vitality the tree compensates for its statics weakness by thicker annual rings in the direction of the weakness. The front plate
of dry wood is usually decayed at the transition to the moist soil and can bear no load. With severe bending it can no longer move with the elastic tree. It breaks without having any significance as regards statics.

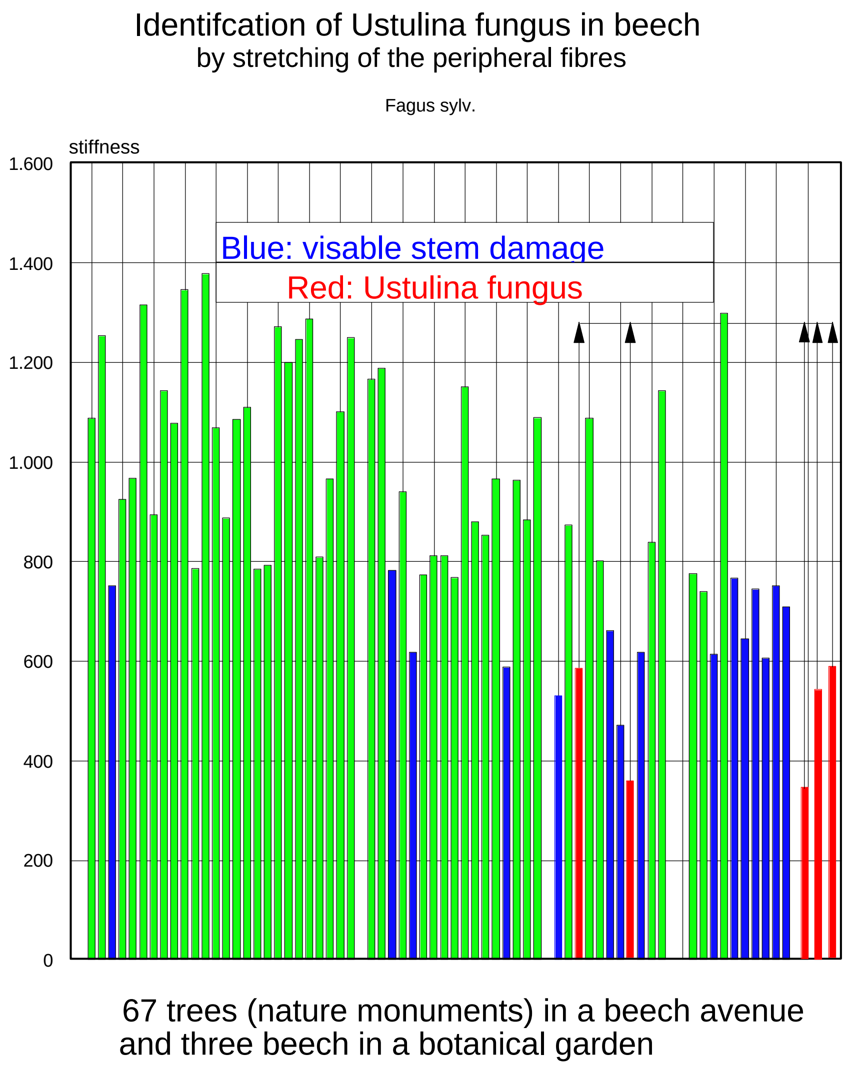


fig. 8
Identification of Ustulina fungus in beech by measuring the stretching of the peripheral fibres; 67 old trees in a beech avenue and 3 beech trees in a botanical garden. Here it is clear that trees attacked by Ustulina fungus can be clearly identified with the Elastometer and tension test. On the tree with the smaller red column the fruit bodies between the root spurs had appeared only months later. (The large values and high fluctuation range of the Elastometer readings are explained by the immense competion growth of the trees 30 to 40 m high). Despite identical age, stem diameters ranged from 44 cm to 120 cm
(the thinner the stiffer).

Digression on fungi

Fungi break down the wood inwards from lopping wounds, causing white or brown rot. It occurs faster in old wood and wood no longer needed by the tree (depending on species and whether heartwood or falseheart is present). The rate of breakdown decreases, the further the fungus advances towards the cambium where the most vigorous cells are found. The compartmentalization boundary formed by toxic substances sharply separates healthy defect-free wood (Fig. 6) from the fungus-infected and decayed wood. The defect-free sound wood carries the load. Because of its shrinkage checks and knots, structural timber behaves quite differently: it is not permissible to apply values from small samples. Accordingly, in testing structural timber reliable values are obtained only via large samples. However, an old hollow tree differs fundamentally from sawn dry girder beams having shrinkage checks. The lower stem cylinder of the tree is 'knot-free' and has no stress-relevant wood defects (see also the illustrations in Shigo, Vollbrecht, Hvass, 1985): therefore comparison with material data from small defect-free samples of green wood is valid. Because of its higher carrying capacity, reaction wood provides an extra gain in safety.
One point: rotten wood behaves differently from sound wood. Moreover, the tree is

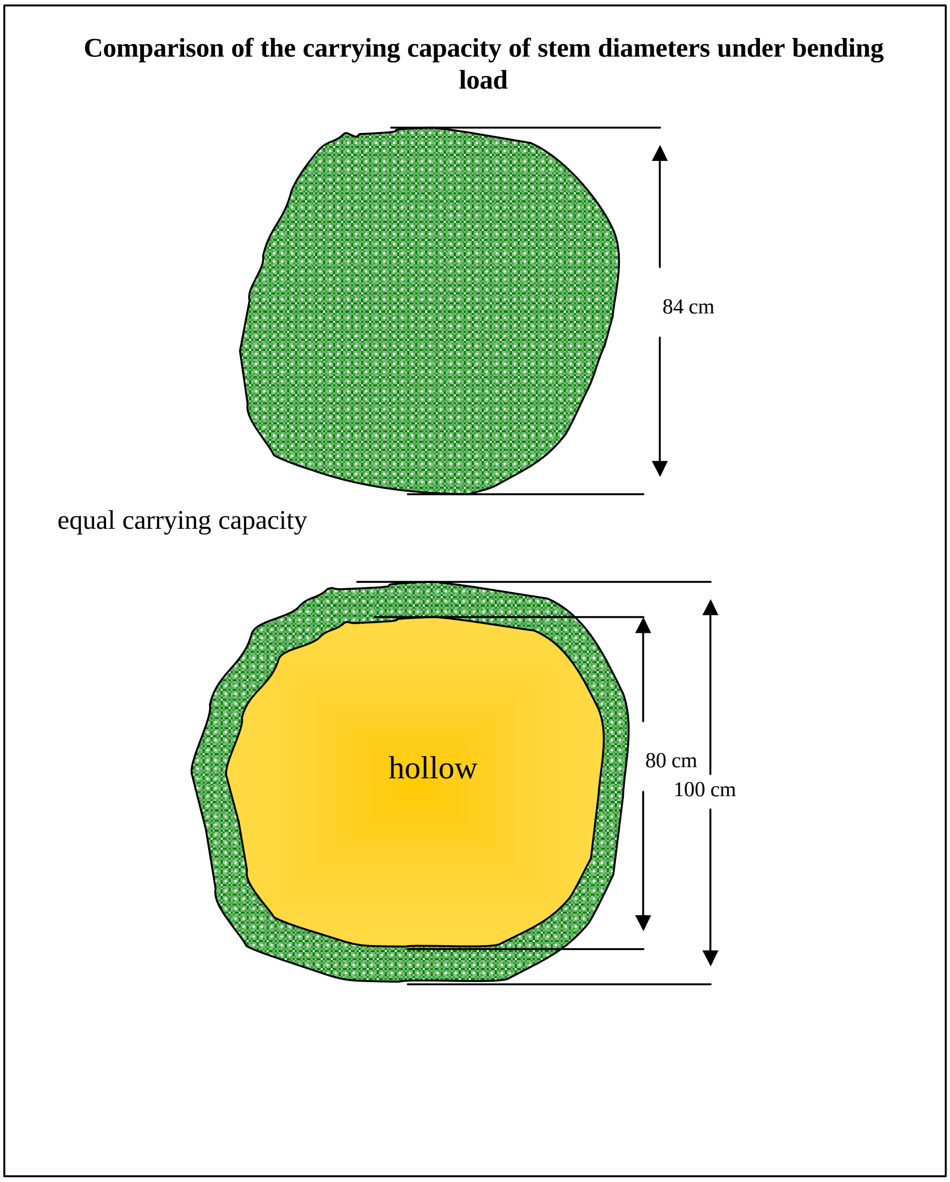
not comparable to a thoroughly rotten apple. The position of the load-bearing wood fibres is important. With the lopping off of large roots or large branches, the tree becomes rotten from the inside. But the load is borne outside, in the healthy zone (Fig. 1, 6, 7). If the tree were to decay from the outside after collision damage or bark loosening, it would never involve the whole diameter. Even then, it is only the healthy elastic wood which bears the load - a brittle-fracturing tree is unknown. Brittle, dried-out sheets of wood in the tree, for example after collision damage, are not involved in the load bearing. They are usually decayed in the transitional zone between the above-ground stem and the soil (Fig. 7).

Possible limits of a measurement

There is one fungus which advances rapidly, encircles zones, compartmentalizes itself in its territory, and then decays this region so much that the affected wood loses its strength more quickly than its stiffness. In this individual case problems could arise in interpreting the Elastometer measurement. However, all trees attacked by the Ustulina fungus were identified with the Elastometer.

The explanation is that the Ustulina fungus encircles the large area of falseheart of a beech tree, for example, and then decays it to white rot. Further out, towards the cambium, when it becomes interesting as regards statics, the encircled zones are smaller. The younger the wood cells, the more fungus-resistant they are. A small area of brittleness then has no effect on the total carrying situation. The residual stem thickening in beech trees attacked by Ustulina
indicates that the permanently operative weight of the tree contributes more to the basal thickening than short-term wind action.
The effect of the Ustulina fungus extends finally to that of the other fungi. Therefore the statics deficit is measurable by the Elastometer (Fig. 8). Laboratory tests derived from statics have led to erroneous conclusions. Here again the position of the fungus decay in the structure is important! On the other hand, it is correctly observed that: **"To the best of our knowledge, all the other measuring techniques fail, at least in the 'early stage' of decay" (Schwarze,** Mattheck, Breloer, 1993).

The early stage of fungus attack is however unimportant for safety. The breakdown processes go on for decades. And how can the problem tree be found if it develops no symptoms? (Wiebe, 1994).



Comparison of the carrying capacity of stem diameters under bending load

fig. 9

The two cross-sections are carrying the same amount and could easily be from the same tree. The cavity is not important. The important thing is the load in the crown, and and this can differ very considerably with identical tree diameter. This is shown elastic limit (primary failure) is equally valid for the cross-sections and thus the Elastometer method does work. The only difference is the fracture pattern (secondary failure) which is unimportant for safety prediction.

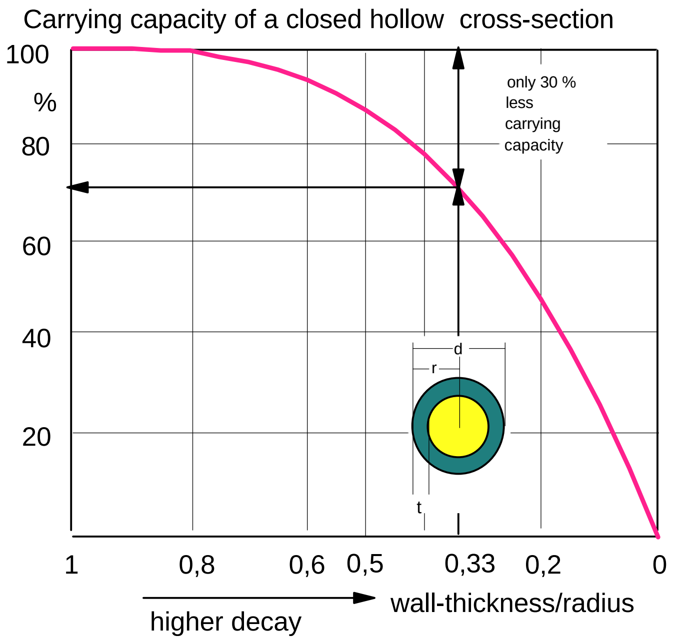


Fig.10
The course of the resistance moment shows a progressively decreasing carrying capacity from a wall-thickness/radius ratio of 0,35. from this point on an expert would conclude that the tree´s statics is affected. Why is clearly shown in Fig. 13: it is a matter of crown evaluation. 0,3 This limit can never be a carte blanche for felling, for the tree has only lost 15% of its carrying capacity (see Part 2, Table 2)

Development of symptoms

Reaction-wood formation depends on the tree species (Hoester, 1994). Accordingly, the capability of compensating stretch-differences under permanent load will develop differently. Not every tree can exhibit its problem. Moreover, the tree which does exhibit it has already reacted to it and has possibly completely compensated. This then is the classical task of the Elastometer method. Formation of symptoms does not necessarily mean that treatment is needed - indeed, often the contrary.

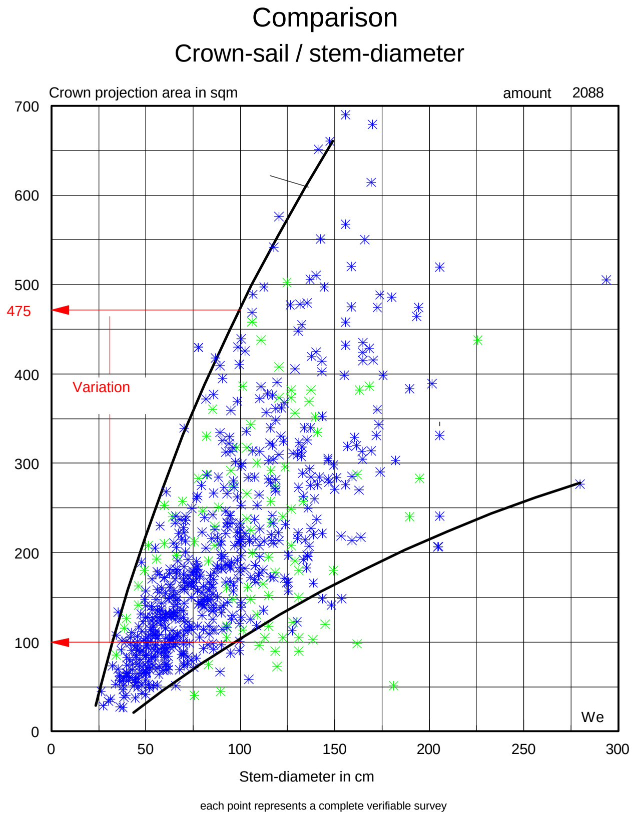


Fig.11

The crown sail areas of the trees may differ greatly with identical stem diameter. The unpruned crown of the one tree may be 5 times greater than of another with the same stem-diameter.
This rejects the 0,3 theory as aguiding reference value for expert tree diagnosis. This becomes particularly clear from Fig. 10 with 25% carrying loss allowed for the tree. Accordingly, tree diagnosis of tree statics strives to evaluate the crown sail as accurately as possible. Each of the 2088 points in the two Figures represents a verifiable survey.

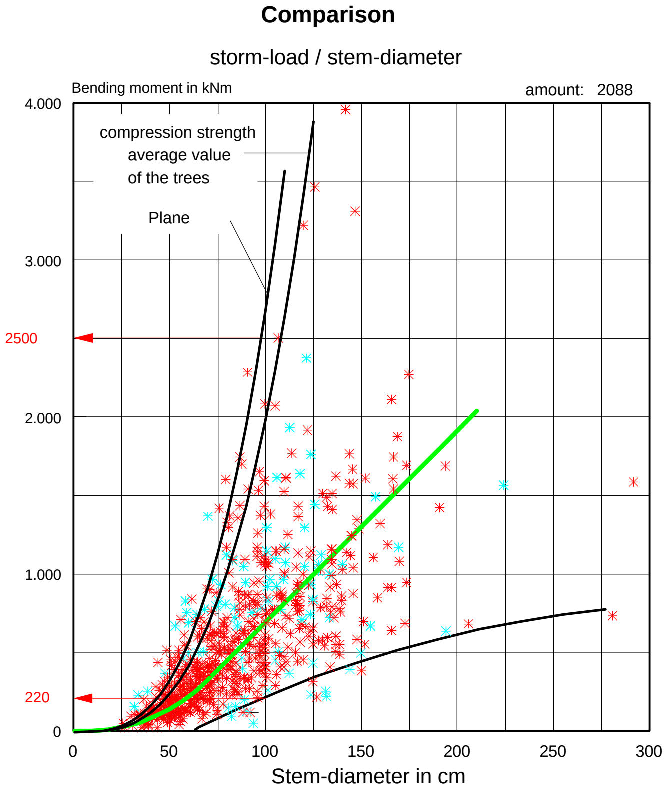


Fig. 12

At the same stem diameter the tree crowns possess different areas.
In addition, they also differ in height. The loading of the stem in a storm may range by up to 800% in free-standing unpruned trees having the same stem-diameter.
This strengthens the result of Fig.11. Reference to the damaged stem cross-section is therefore revealed as a false approach, leading to faulty results which tend to go in favour of the tree. Here it is clearly shown that a general safety value of 4, 5 does not exist. The self-measurement theory is not tenable. The statics of each tree must be determined individually.

Weighting in the statics triangle

Now for incorporation into the safety prediction.
So far the same attention has been paid to the three influential factors in the statics triangle (material, geometry, load) in the Elastometer method. Other methods are based only on the material or on stem geometry. Evaluation of over 1000 verifiable safety reports by Sinn and Wessolly has for the first time revealed the weighting:
According to this the sail area of one tree may be five times greater than that of another having the same stem diameter (Fig. 11). The sail area itself is only a rough measure of a storm load, as tree crowns may be spherical, cylindrical or pear-shaped. Then there is the different wind permeability. Taking these influences into account, when determining wind load by German Standard DIN 1055 refined by Davenport & Zuranski (1972), the range of the storm-moment: stem-diameter ratio is increased by a factor of 8 (Fig. 12). This means that, depending on the tree, one stem may be eight times more stressed than another one. Accordingly, the residual wall thickness is definitely of subordinate importance. Fig. 8 makes this clear. Both cross-sections are carrying the same and could easily come from the same tree. The diagrams in Figs. 11 and 12 show clearly that a firm safety factor of 4.5 does not exist in trees. These results imply: **Every tree loading must be individually determined.**

Influence on the statics

evaluation of 460 trees

Range of variation of the three elements of the statics triangle

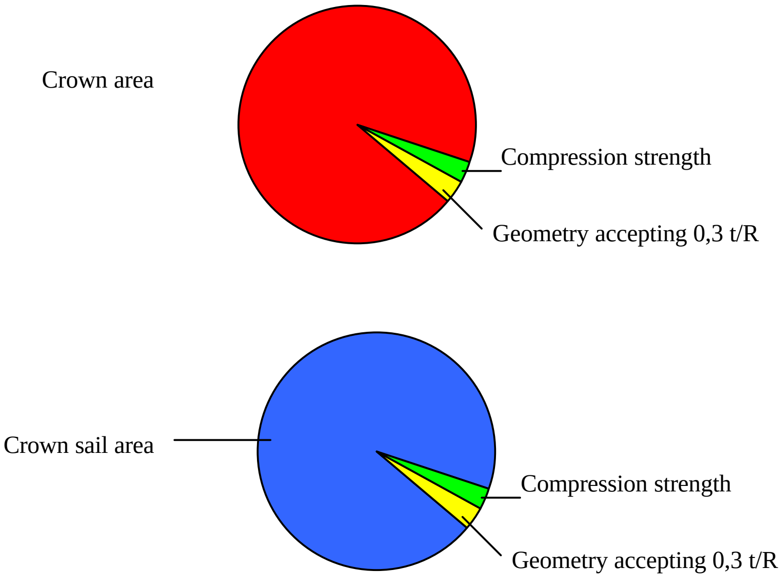


Fig. 13
This summarizes the influence of the three elements of the static triangle. It is clear that the crown sail of the tree must be individually evaluated, for ist influence is over-proportional to the range of varaiation of strength and geometry(here accepting 0,3 t/R limit) In evaluating trees it is quite impossible to work with general safety values (e.g. 4.5) or to refer merely to the stem cross-section. All the methods not based on statics do not go deeply enough into this point, and therefore lead to false results.

Even more interesting is the fact that when the other two influential factors of the statics triangle are compared, the scatter of the material is 25% at most (elastic limit). With a residual wall thickness: radius ratio of 0.3, the tree has only forfeited 25% of its carrying capacity (Fig. 10). Comparing the possible scatters, we obtain a storm-stressl material-scatter/decay-degree ratio for load: material geometry as 800:25:25. However, all the previous evaluations allow more than the 0.3 t/R limit (Table 2 in Part 3, see below). If we go to 0.1 t/R, however, the primacy of the load analysis does not alter, viz. load : material : geometry as 800:25:75. In Fig. 13 the overwhelming importance of the wind load becomes clear. Any omission of the most accurate crown evaluation possible will give a false safety diagnosis.
Only than is the **statics triangle** complete. Expert statics-integrated tree monitoring is based on individual-tree analysis of **1. load, 2. geometry and 3. material (Wessolly 1993). Result: it depends on the wind load!**

To provide precise load analysis, the Institute for Tree Diagnosis, in conjunction with Special Research Area 230 of Stuttgart University, is running a research project in Corsica to determine the cw value of trees. Here the tree reaction in a storm is measured with an Elastometer. The stretching values are reproducible by a tension test in calm weather. This gives us the storm load (Wessolly, 1993). It is more difficult to assess the safety values of trees in a closed stand. Here we may notionally release the tree, or we may restrict ourselves to relative measurements on the tree's surface. The same also applies to branches which are integrated into the crown. The Elastometer method is strictly directed to the behaviour of the tree under wind load. (See here the description by Dr Lesino and Prof. Dr. Glos from the Wood Research Institute of Munich university). It is also valid for hollow stems (Prof. Dr. Spatz). **The Elastometer method is integral and clearly comprehensible** (Prof. Dr. Spatz, Freiburg university, in the 2nd and 3rd FLL discussion on tree statics).

Summary

The failure behaviour of trees in a storm allows only one computational possibility of fracture safety analysis: simulation of wind load and Elastometer measurement of the compression of the heaviest-loaded peripheral fibres located directly beneath the bark. Their behaviour is representative for the carrying capacity of the cross-section. How much these fibres can be compressed before they are irreversibly damaged is described by the elastic limit. This species-specific limit is constant over extensive tree zones. Moreover, evaluation of 975 assessments revealed that the load analysis is by far the most decisive criterion in assessing fracture safety. A blanket assesssment such as: the tree itself can best measure its own loading and put on the thickness growth needed, is contradicted by the result presented in this paper. Admittedly, every tree possesses the tendency to form reaction wood, but whether it actually does depends on tree species, vitality and site. The development of symptoms also shows straightaway that the tree can counter its problem.

Responsibility for traffic safety cannot be handed back to the tree itself by pointing out the self-measurement theory or a non-existent general safety value of 4.5 for example. Expert tree diagnosis cannot be satisfied with that.
Quantitatively verifiable monitoring of fracture safety is only possible with a tension test with the Elastometer: this provides non-destructive spatial determination of the carrying capacity of a part of a tree and prediction of the fracture load, via the elastic limit of the green wood.
In association with the wind load we will obtain the greatest possible information on the safety status against tree fracture. The SIA method was developed for the practitioner. It is discussed in the next part, and derives from the results presented here.

The **Statics Integrated Methods** (SIM) are the only currently available methods which can provide non-destructive verifiable values both for fracture safety and for tree stability. They are based on DIN 1055 and fulfil the requirement for gentle methods of tree care.

(The literature references are given in Part 3 of this series).