# Trees and Statics: Non-Destructive Failure Analysis

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Traditional tree risk assessment is focussed on determining the extent of cavities or hollowness in tree trunks by boring holes. Using these invasive tree assessment methods can not only damage living cells but may also encourage fungal growth (LIESE, DUJESIEFKEN, 1996) and the spread of decay.
New engineering based statics integrating methods (SIM) developed by WESSOLLY and SINN at the University of Stuttgart allow for non-invasive and precise assessments of a tree´s breaking and uprooting safety. Statics integrating inspections are carried out with pulling tests (elasto-inclino method) that exert a wind substituting load on the tree using a winch and a steel cable. The reaction of the stressed trees under a defined load is measured with high resolution devices (elastometer and inclinometer) and the data obtained are compared with those of sound trees. In all safety calculations using the SIM, three major components are considered: wind-load, material properties of green wood and the surface of the load bearing structure (trunk diameter, extent of hollowness). Tree inspectors and practitioners may use a more simplified variation, the SIA method (**s**tatics **i**ntegrating **a**ssessment) which also follows international engineering conventions and allows for quick on-site-assessment at little cost.

Urban trees are exposed to a variety of different stress factors such as: road salt in winter, vibrations caused by traffic, soil compaction and dust and heat emissions from asphalt and buildings. The root system is often affected by limited space, shallow soils, and soil excavations for utility installations.

Lopping of roots not only leads to decay in the root system but may also cause damage to the trunk wood by reducing the breaking and tipping (uprooting) safety. Several methods have been developed for tree inspection to calculate and predict the danger of failure. Most of these methods focus on the residual walls of the trunk, often neglecting the material properties of the tree species and wind loads that occur during storms.

This paper presents an engineering-based approach to the problem of tree safety assessment, rather than an approach based on traditional boring methods. The term *tree statics* was created in the early 1980s when Lothar Wessolly, the leading engineer of a project on lightweight constructions in nature at the University of Stuttgart, and Günter Sinn, a landscape architect, were working on a tree-friendly, noninvasive method to help determine the safety of trees without causing severe destruction. Now, 15 years later, a group of 25 specially trained, court-certified tree consultants in different European countries are using the tree-friendly elasto-inclino method (pulling test) that was derived from the results of Wessolly's and Sinn's research (WESSOLLY 1998, SINN 1983).

Data from more than 3,000 static inspections on trees throughout Europe were collected and statistically evaluated. As a result of this work, practitioners, supplied only with an altimeter and a measuring tape, are able to obtain a quick overview of the breaking safety of a tree at a reasonable cost, using the statics integrated assessment (SIA) method.

## WHAT IS STATICS?

The following definition is from the *Columbia Encyclopedia* (6th edition, 2001) on the Internet (www.bartleby.com/65/st/statics.html). Statics is defined as "a branch of mechanics concerned with the maintenance of equilibrium in bodies by the interaction of forces upon them. It incorporates the study of the center of gravity and the moment of inertia. In a state of equilibrium, all the forces acting on a body are exactly counterbalanced by equal and opposite forces, thus keeping the body at rest. The principles of statics are widely applied in the design and construction of buildings and machinery." Tree statics deals with the breaking safety of tree trunks and the tipping (uprooting) safety that describes the anchoring potential of the root system.

Trees are loaded primarily by wind gusts but also by snow, ice, and their own weight (dead weight). As tree height and wind sail increase, greater loads are exerted on the crown during storms and transferred into the trunk. As the trunk moves in a storm, its marginal fibers extend on the tensile side and shorten on the compressive side. These alterations in length can be measured with a sensitive instrument called an elastometer (extensometer).

In tree statics, the ability of a tree to withstand wind loads of gale force is calculated by including the shape of the load-bearing structure (trunk and crown), the properties of green wood, and the forces that occur in a gale-force wind gust (Figure 1).

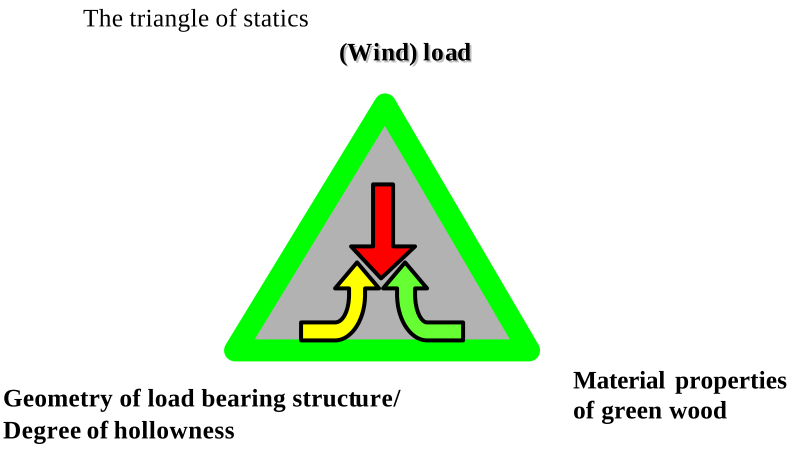


**Figure 1. The triangle of statics.** According to international engineering conventions three major components and the interactions amongst them must be incorporated in any safety calculation: load, load bearing surface (= resistive bending moment) and the individual material properties. If the load impact on a structure is high, strong materials are required in order to avoid massive material waste. The shape or the form of the load-bearing material must be optimized to increase the load bearing capacity. A good example is the Eiffel tower in Paris, France. This is a hollow structure constructed with steel struts. Near the ground, its diameter increases significantly, raising the resistive bending moment and increasing the breaking safety by optimizing the load bearing geometry. If the load is low, the material does not need to be as strong, and the load-bearing structure, which is the tree trunk in this case, can be hollow. The interaction of the three components: load or effective wind force, material properties, and shape of the load-bearing structure, must be part of a correct stability or safety calculation.

When boring into a trunk to detect the residual wall thickness or the load bearing geometry, it should not be forgotten that only an infinitesimally small part (hole diameter 2-10 mm) of the load-bearing geometry can be inspected with one single hole and that many holes may severely damage the tree through potential fungal infection and decay. It becomes obvious that boring only provides partial information and may lead to the destruction of the tree. Therefore it is imperative that serious engineering based safety assessments (e.g. SIM) also incorporate the predicted loads affecting the tree. These loads can be determined based on data available from local weather stations and the individual characteristics of the tree inspected (crown surface area, tree height, and aerodynamic drag factor of the tree crown).

Calculations based solely on a constant ratio between residual wall thickness and trunk diameter may significantly err if they do not take into account the geographical and environmental conditions that the tree is subjected to. A smaller and more protected tree in a suburban area will tolerate more hollowness inside the trunk before it fails in a storm than a larger, taller tree of the same residual wall thickness in an exposed area on a coastline. The determination of the extent of decay (residual wall detection) makes sense only when the load impact has been previously determined.

## LOADS OCCURRING ON TREES

The dead weight of a tree is negligible because on average wood can resist a compressive load of 20 N/mm2 (2,901 psi). The weight of a 10-tonne (11-ton) tree can be borne on a surface of only 50 $cm^2$ (7.75 $in^2$). However, snow loads often affect the breaking safety of branches more severely than short gusts because green wood tends to creep and form cracks when constantly stressed.

The strongest influences on a tree’s stability are wind and storm gusts. Slight winds cause swaying that stimulate the creation of self-supporting reaction wood. However, wind does not generally blow steadily and continuously. The air stream pulsates and rotates and is capable of stimulating a tree at its natural frequency and feeding energy into the tree’s swaying system up to the point where it ruptures. Such dynamic effects occur primarily on isolated forest trees or on trees that have been pruned incorrectly (e.g., by crown raising- pruning off too many of the lower branches). Solitary trees, with branches almost touching the ground, are not as affected by dynamic loading in their trunks because the flexible leaves, twigs, and branches help to dampen oscillations.

Tall trees with large crowns have a greater crown surface area exposed to higher wind forces. The wind forces increase as the distance from the ground increases. In a storm tall, large trees are exposed to exponentially higher wind loads than smaller trees.

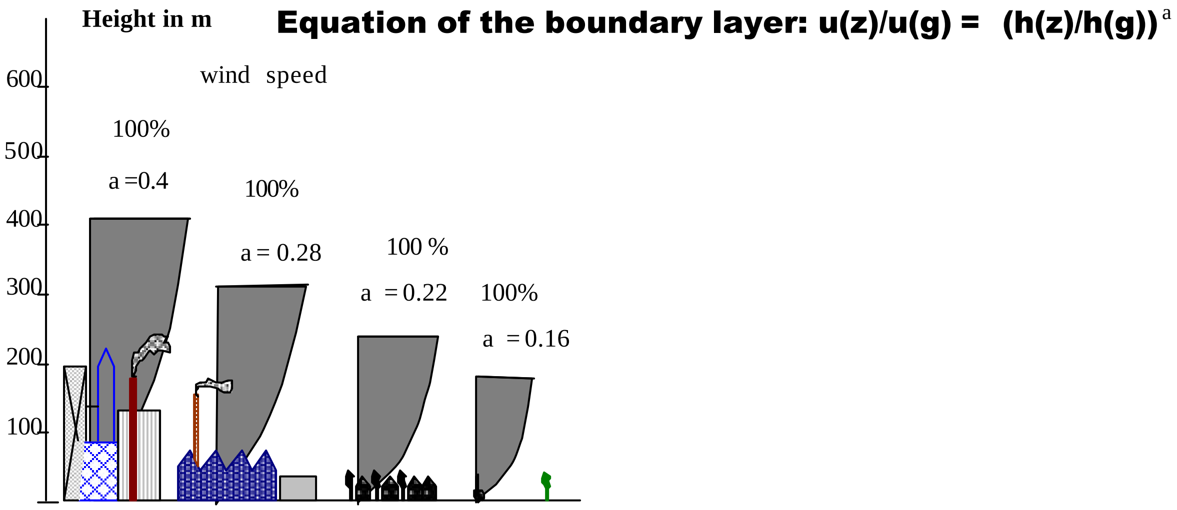
## WIND SPEED AND WIND PRESSURE

Wind speed and wind pressure depend on several factors:

1. Geographical situation: Wind loads are different everywhere. Wind charts are available for estimating the expected maximum wind force for a given period of time. Weather stations have comprehensive documents on prevailing wind directions.
2. Topographical situation: The second factor influencing wind speed is the location of a tree. Wind loads are significantly different between trees located on flat lowland or close to the ocean where they are subjected to heavy gusts and trees located on a site that is protected by the brow of a hill or on the leeward side of a mountain chain.
3. Seasonal and meteorological influences: In cold weather, the air density increases and causes higher wind pressure. Some trees may be in full leaf when fall or spring storms occur. A combination of cold weather and storms may lead to a high wind pressure on a tree’s crown. Proper safety statements have to include this information (WESSOLLY, SINN, 1989).

Wind profiles over different topographies show that storm gusts in exposed areas without any protection reach their full speed at a height of about 250 m (820 ft) (Figure 2). Terrains with a rougher surface, such as suburban areas with flat, one to two-storey buildings, cause turbulence in the boundary layer that leads to a slowdown of the wind speed (KAMEI, MARUTA, 1979, STATHOPOULOS, 1985) and a decrease of the resulting wind pressure on tree crowns. With higher buildings, more disturbance occurs in the boundary layer, which reduces the velocity of the air stream. Over an extremely rough surface area with tall buildings (e.g., downtown areas of cities), the wind reaches its full undisturbed force at heights of about 600 m (1,969 ft). Therefore, trees in exposed, open countryside sites or near the ocean need to have thicker stems than those in more sheltered areas.

Although rough surfaces slow down the wind speed in the boundary layer, tall buildings (with their even surfaces) and mountain chains can cause blast pipe (wind tunnel) effects that stress a tree as much or even more than if it were positioned in an exposed, unprotected site on a field (ECCS, 1978; HIRTZ, 1981, STATHOPOULOS, STORMS, 1986, WESSOLLY, 1998). A serious load analysis must take these facts into consideration.



**The surface roughness of different terrains influences the wind speed at greater heights**

**Figure 2.** Increased wind speed with height above ground level (Davenport, 1965). The surface roughness of different terrains influences the wind speed to greater heights.

A doubling of the wind speed increases the pressure on tree crowns by a factor of 4, according to:

$$q = r/2 * u^2$$

where $q$ = wind pressure, $r$ = air density, and $u$ = wind speed (Figure 3)

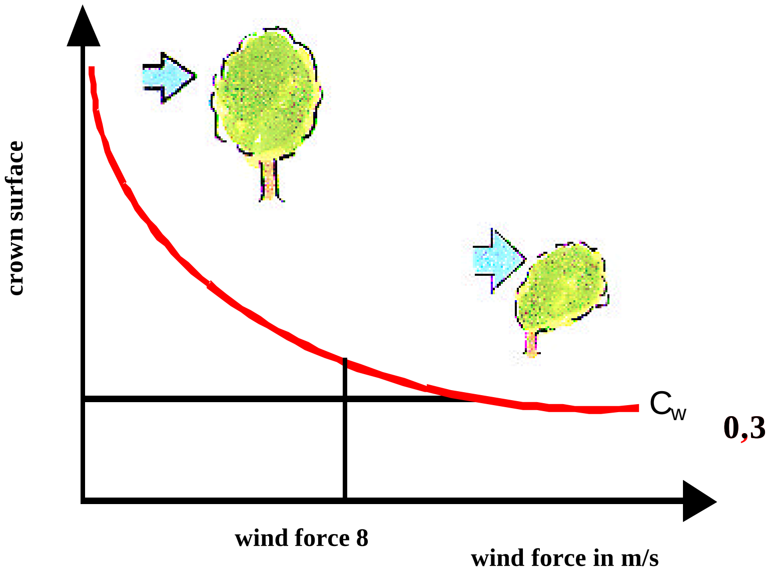


**Figure 3.** **Wind resistance of tree crowns and the aerodynamic drag factor ($c_w$) (Davenport, 1965).** During a storm, leaves, twigs, and branches are bent by the strong air stream. This reduces the amount of wind-exposed surface (MAYHEAD, 1973) and in turn reduces energy inputs into the trunk and root system. This situation is comparable to a heavy storm on a sailing boat when the skipper strikes the sails. In a permanent research project on the stormy northern edge of the island of Corsica in the Mediterranean, it could be found that the aerodynamic drag factor ($c_w$ value), even of the stiffest oaks, decreases to as low as 0.3—a value that is striven for in the car industry. The latest high mileage car developed by Volkswagen using only 1 litre of fuel for a distance of 100 km (237 mi/ gallon) has an aerodynamic drag factor of 0.14, which comes close to a birch (*Betula pendula* ) or a weeping willow (*Salix alba “Tristis”*) with their flexible twigs.

It was also found that trees exposed to a wind speed of more than 40 mph (equaling wind force 8 on the Beaufort scale) have reached their maximum elasticity and cannot further reduce their exposed surfaces. Higher wind velocities will only cause negligible reductions of crown surfaces. It is important to include the wind resistance of tree crowns into tree safety calculations. (Table 1 provides proposed aerodynamic drag factors.)

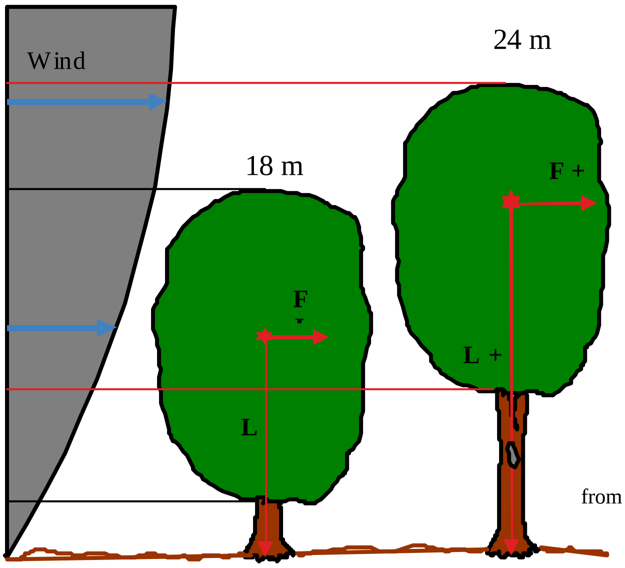
## GROWTH FORM AND LEVER EFFECT

Wind speed increases rapidly with increasing height above the ground. This fact leads to the conclusion that tall trees receive higher loads in a gale than smaller ones. In taller trees, more surface area in the upper crown is exposed to higher wind speeds. Therefore, the wind pressure is notably higher. Tall trees need larger trunk diameters than smaller ones or, in other words, taller trees need thicker residual walls.

Improper pruning in which the lower branches are cut off may lead to compensatory growth and taller trees. Taller trees with a load center high above the ground effectively become long levers and are exposed to higher wind pressure ($M_b$) according to:

$$M_b = F * l,$$

where F= force and h= height of load center.



from Wessolly 1998

Bending moment: $M_b = F \times L$

320 kNm 640 kNm

**Figure 4.** Statical influence of crown raising on trees. In this example the taller tree (right) has the same crown surface as the smaller one. Due to the difference of height the taller tree is exposed to twice as high bending moments than the smaller. Experienced arborists should consider these facts before pruning.

**Table 1. Stuttgart table of wood strength (Wessolly and Erb 1998).**

| Species | Modulus of elasticity ($N/mm^2$) | Comparable strength in longitude ($N/mm^2$) | Elastic limit (%) | Proposed Aerodynamic drag factor ($c_w$) |
|---|---|---|---|---|
| *Abies alba* | 9500 | 15 | 0.16 | 0.20 |
| *Acer pseudoplatanus* | 8500 | 25 | 0.29 | 0.25 |
| *Acer negundo* | 5600 | 20 | 0.36 | 0.25 |
| *Acer campestre* | 6000 | 25.5 | 0.43 | 0.25 |
| *Acer saccharinum* | 6000 | 20 | 0.33 | 0.25 |
| *Acer saccharum* | 5450 | 20 | 0.37 | 0.25 |
| *Aesculus hippocastanum* | 5250 | 14 | 0.26 | 0.35 |
| *Ailanthus altissima* | 6400 | 16 | 0.25 | 0.15 |
| *Betula pendula* | 7050 | 22 | 0.31 | 0.12 |
| *Chamaecyparis lawsonia* | 7350 | 20 | 0.27 | 0.20 |
| *Cedrus deodora* | 7650 | 15 | 0.20 | 0.20 |
| *Fagus sylvatica* | 8500 | 22.5 | 0.26 | 0.25–0.30 |
| *Alnus glutinosa* | 8000 | 20 | 0.25 | 0.25 |
| *Fraxinus excelsior* | 6250 | 26 | 0.42 | 0.20 |
| *Picea abies* | 9000 | 21 | 0.23 | 0.20 |
| *Picea omorika* | 9000 | 16 | 0.18 | 0.20 |
| *Carpinus betulus* | 8800 | 16 | 0.18 | 0.25 |
| *Castanea sativa* | 6000 | 25 | 0.42 | 0.25 |
| *Cercis siliquastrum* | 0 | 15 | — | 0.20 |

| | | | | |
|---|---|---|---|---|
| *Larix decidua* | 5035 | 17 | 0.32 | 0.15 |
| *Liriodendron tulipifera* | 5000 | 17 | 0.34 | 0.25 |
| *Pinus pinaster* | 8500 | 18 | 0.21 | 0.20 |
| *Pinus sylvestris* | 5800 | 17 | 0.29 | 0.15 |
| *Platanus* × hybrid | 6250 | 27 | 0.43 | 0.25 |
| *Populus* × *canescens* | 6050 | 20 | 0.33 | 0.2–0.25 |
| *Populus nigra* 'Italica' | 6800 | 16 | 0.24 | 0.30 |
| *Populus nigra* | 6520 | 20 | 0.31 | 0.2 |
| *Populus alba* | 6400 | 20 | 0.31 | 0.2 |
| *Pseudotsuga menziesii* | 1000 | 20 | 0.20 | 0.20 |
| *Pyrus communis* | 5800 | 17 | 0.29 | 0.30 |
| *Quercus robur* | 6900 | 28 | 0.41 | 0.25 |
| *Quercus rubra* | 7200 | 20 | 0.28 | 0.25 |
| *Robinia pseudoacacia* | 7050 | 20 | 0.28 | 0.15 |
| *Robinia monophyla* | 5200 | 20 | 0.38 | 0.15–0.20 |
| *Salix alba* | 7750 | 16 | 0.21 | 0.20 |
| *Salix alba* 'Tristis' | 7000 | 16 | 0.23 | 0.20 |
| *Sequoiadendron gigantum* | 4550 | 18 | 0.40 | 0.20 |
| *Sophora japonica* | 6450 | 20 | 0.31 | 0.15 |
| *Sorbus aria* | 6000 | 16 | 0.27 | 0.25 |
| *Tilia* x *hollandica* | 4500 | 17 | 0.38 | 0.25 |
| *Tilia euchlora* | 7000 | 17.5 | 0.25 | 0.25 |
| *Tilia tomentosa* | 8350 | 20 | 0.24 | 0.25–0.30 |
| *Tilia platyphyllos* | 8000 | 20 | 0.25 | 0.25 |
| *Tilia cordata* | 8300 | 20 | 0.24 | 0.25 |
| *Ulmus glabra* | 5700 | 20 | 0.35 | 0.25 |

## MATERIAL PROPERTIES

### Wood Strength

It is obvious that the material properties of green, moist wood are not relevant to the forestry industry. Therefore only a few reports regarding the material properties of green wood can be found in the literature. To determine and study the material properties of green wood, WESSOLLY and his team modified testing methods and collected data on all tree species available from the Stuttgart City Council's tree unit (WESSOLLY, ERB 1998). The result was the Stuttgart Strength Catalog in which compressive and shearing strengths in all anatomical directions were reported. It was found that the compressive properties of green wood of Central European tree species vary between 14 N/mm$^2$ (2,031 psi) for Horsechestnut (*Aesculus hippocastanum*) and 28 N/mm2 (4,068 psi) for English oak (*Quercus robur*). The mean value for compressive strength of Central European tree species is 20 N/mm$^2$ (2,900 psi). Since the variation of material properties of Central European tree species is rather small they enter safety calculations as an almost constant factor. Therefore, the differences in material properties between the tree species of Central Europe can almost be neglected.

Tree safety calculations (SIM) in other climatic zones need to be based on the material properties of the local vegetation. Green wood material testing carried out by LAVERS (LAVERS, 1983) showed that trees of the tropical regions can reach compressive strength values of up to 120 N/mm$^2$. The variation of material properties in those regions may differ quite significantly from those of Central Europe. This emphasizes the need to increase material property research in different climatic zones.

## Elastic Limit and Elasticity

According to Hooke's law, the stress ($\sigma$) created in an elastic material is proportional to strain ($\varepsilon$), within the elastic limit.

Every material, including wood, has an individual elastic limit, which is defined as the compressive strength divided by the modulus of elasticity or $\varepsilon = \sigma_{max.}/E$. If the elastic limit is exceeded permanent deformation occurs.

In classical material testing, specimens of wood are cut to defined sizes (2 x 2 x 6 cm) and stressed until rupturing of the fibers occurs. A measured force is exerted via a load cell connected to a cross-beam (INSTRON INC.) and the shortening of the fibers is recorded at a rate of 10-50 values per second, thus providing dense reliable data. In the first stage of such compressive testing the fibers remain elastic and will return to their original position when the introduced force is reduced (Figure 5; also Table 1, elastic limit column). This situation is comparable to trees swaying in moderate storm gusts where the fibers will be loaded and stressed only within their elastic limits. If the force on a wood specimen is continuously increased, the fibers begin to creep (= primary failure, the stress - strain curve flattens) and finally collapse (=secondary failure). The same situation can occur with healthy trees of sound wood during gusts of gale force or even in tornados. In such extreme weather conditions the fibers of a tree are overstressed and over bent for a short period of time followed by fiber buckling on the compressive side of the trunk and finally the rupture of the whole trunk.

Consequently, tree safety engineers measure the alterations in fiber length during a pulling test. These alterations are directly related to the elastic limit and knowledge of these values allows for the assessment of the breaking safety. The alterations in the marginal fibers are measured with an elastometer (extensometer) at a resolution of 1/1000mm.

Sound, healthy trunks can be quickly distinguished from those with thin residual walls by obtaining relatively higher strains in the marginal fibers. Damage during the pulling tests is avoidable if the elastic limits given in the Stuttgart Strength Catalog are observed.

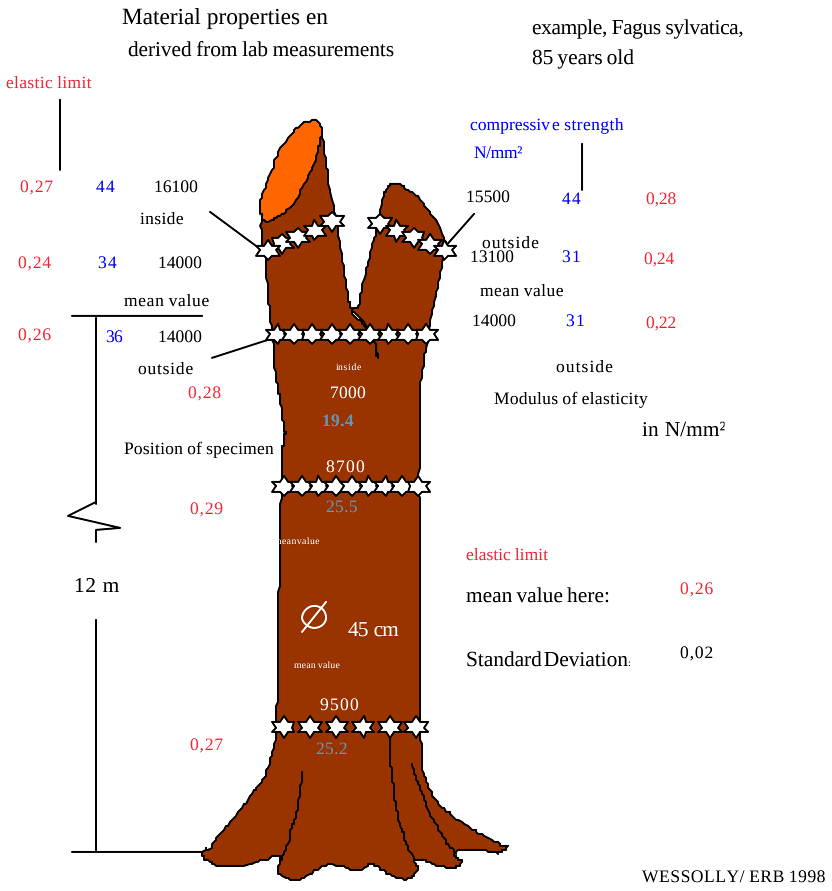


**Figure 5.**
Despite the fact that material properties (compressive strength and E-modulus) can differ quite significantly within the same trunk, the elastic limit is fairly constant with only a small deviation of 0.2% around the mean (WESSOLLY, 1988a, 1988b) .

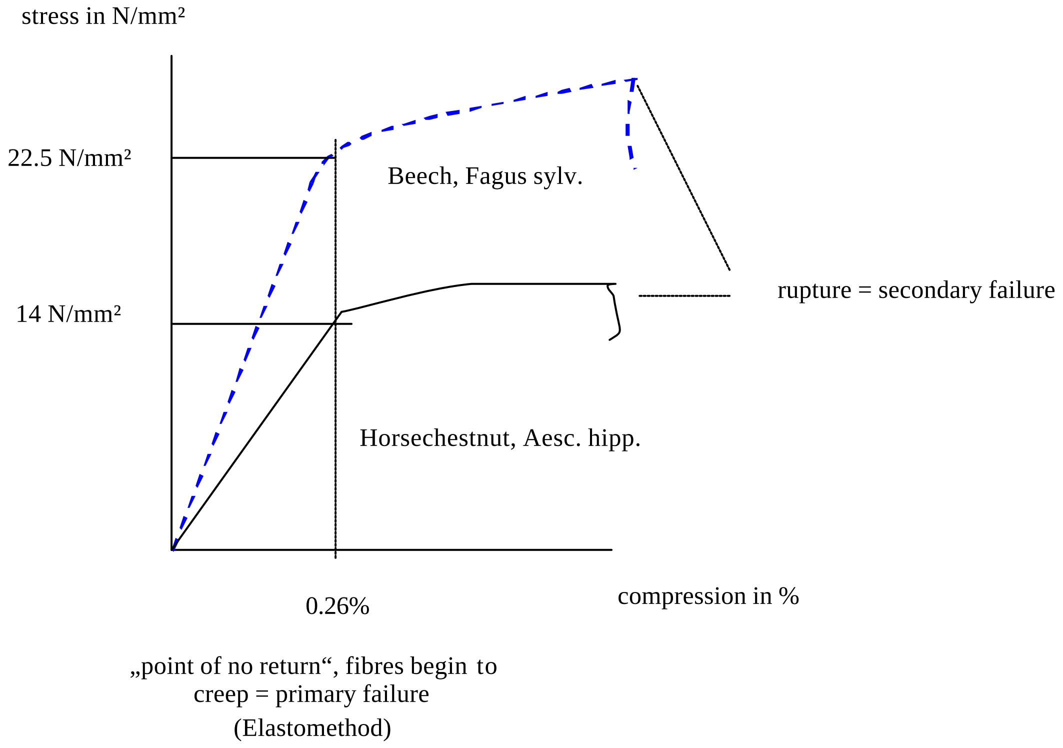


**Figure 6.** The green wood of European Beech (*Fagus sylvatica*) is significantly stiffer ($E_{mod}$ = 8000 N/mm$^2$) and stronger (22 N/mm$^2$) than that of Horsechestnut (*Aesculus hippocastanum*) ($E_{mod}$ = 5250 N/mm$^2$; 14 N/mm$^2$). Obviously *Aesculus hipp*. compensates its low compressive strength with high elasticity. Nevertheless, the value for the elastic limit for both species is the same (0.26%). The variation of material properties between tree species of Central Europe is rather small.

## GEOMETRY OF THE LOAD-BEARING TRUNK

Hollow constructions are not necessarily unsafe. Sail boat masts and telescopic car antennae are both hollow structures designed to withstand certain wind pressures. To obtain a stable and lightweight construction, an optimal relationship between the load-bearing capacity and the thickness of the residual wall has to be determined. The resistive force that withstands bending forces is called the resistive bending moment. It is defined as:

$$M_{\text{crsec}} = d^3 \times \pi/32 \text{ or } M_{\text{crsec}} \sim d^3 \times 0.1$$

A short example demonstrates the influence of the trunk diameter on load-bearing capacity. An oak tree with a 100 cm diameter ($100^3 \times 3.1415/32 = 98{,}174.8$ cm$^3$) has a resistive bending moment of 98,175 cm$^3$. A more protected oak tree nearby with a smaller diameter of 75cm will only have a resistive bending moment of 41,416 cm$^3$. The difference of just 25 cm in diameter causes a 58 % decrease in bending resistance of the thinner tree. It can therefore be concluded that the thicker the trunk, the higher the safety reserves.

When calculating strength losses due to cavity size on a purely geometrical level (CLARK & MATHENY, 1994), it is important to know the basic strength of an individual trunk with its wind resisting crown as a reference, otherwise the question will be “strength loss of what?”. Geometrical analysis alone cannot provide sufficient results, if the load situation is unclear.

## DIAMETER GROWTH AND FUNGUS DECAY

Healthy trees increase in diameter every year (annual ring growth). The annual growth of the trunk leads to a continuous increase in the resistive bending moment of the tree. Provided an old tree is healthy and vigorous, the annual growth can compensate for the strength loss caused by large cavities. An increase of 5 mm (0.2 in.) radial growth can compensate for a 30cm (12in.) diameter central hollow spot in the trunk. Especially when dealing with old trees, it is important not to disturb the fragile fluxing balance between decay, rot, and wood destruction inside the trunk, and wood growth around the circumference.

## TIPPING SAFETY

The assessment of the tipping safety of trees is impossible using only visual assessment methods. Root excavations also provide insufficient information and cause significant disturbance to the rhizosphere.
A reliable determination of the tipping safety of trees can only be achieved by stressing a tree under similar conditions created by wind gusts (Inclino Method, SINN, 1983). Scientific research (BADER 2000, WESSOLLY 1998, SINN, 1985b, SINN 1985c) has shown that only roots near the trunk were stressed when the tree was subjected to pulling forces. A severe uprooting danger occurred when the roots were severed within approximately 1 to 1.3 m of the trunk of the tree.

The generalized tipping curve was derived from scientifically based destructive pulling tests of more than 400 trees of different species under different soil conditions. It shows that the primary failure of the uprooting process already occurs at 2.5 to 4 degrees of lean. From 4 degrees of lean onwards no further increase in pulling force is necessary until a lean of 45 to 60 degrees’ inclination is reached (WESSOLLY, 1998). From 45 to 60 degrees onwards, the dead weight of the tree supports the falling process (secondary failure).The influence of root rot or lopping on the tree’s stability can be determined using the mathematical function of this curve (Figure 8) in mathematical calculations.

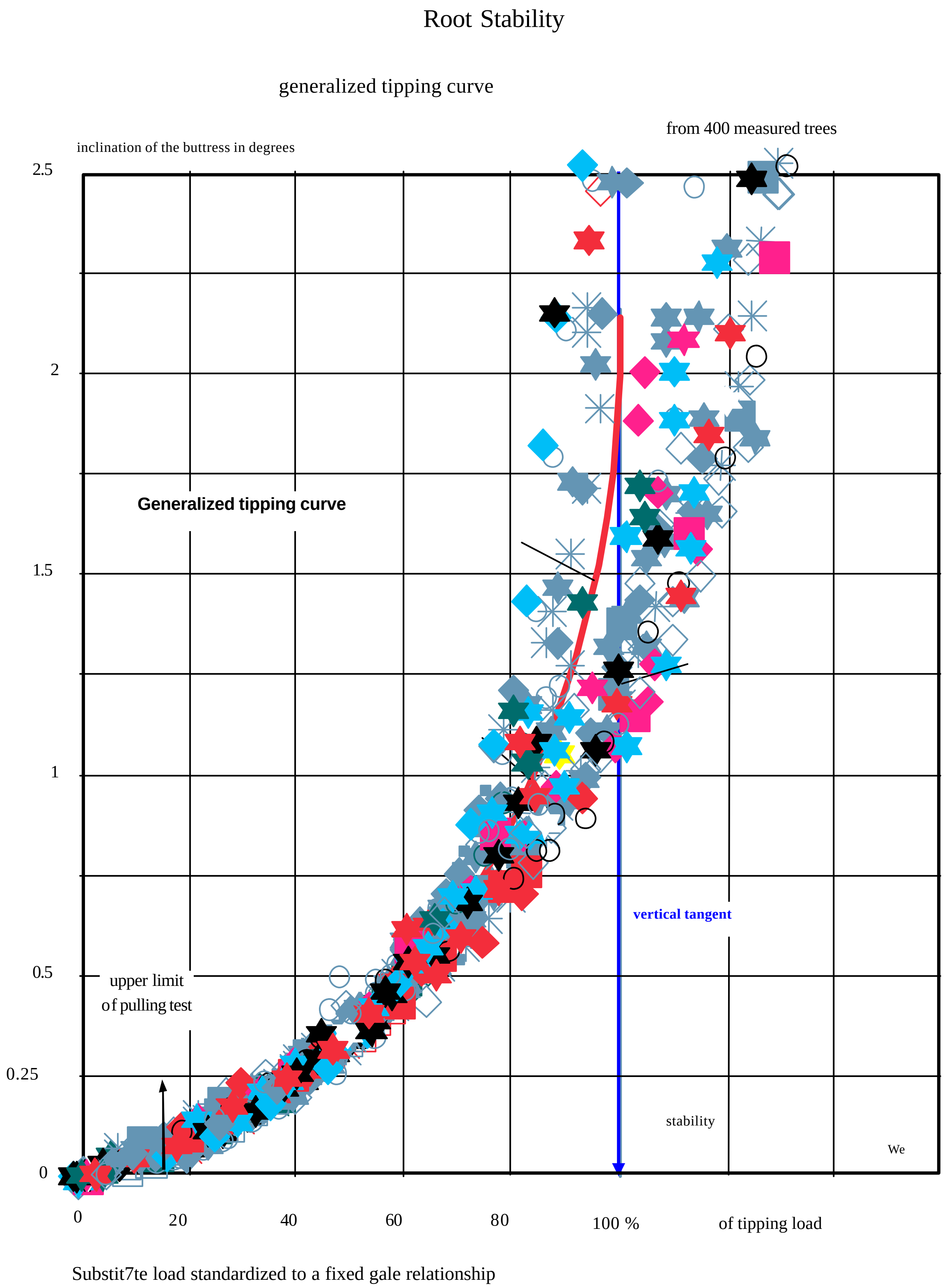


**Figure 7: Root stability as generalized from a tipping curve of over 400 trees (Wessolly and Erb 1998).**

## LOAD ANALYSIS

Load analysis begins with a photograph of the tree. The image of the crown is digitized and the exposed surface of the crown is calculated. Other influencing factors such as wind velocity, air density at a certain temperature, the roughness of the topography, the aerodynamic drag factor, and the tree height have to be incorporated in an engineering based load analysis (SINN, 1985a, WESSOLLY, 1998).

Wind force on the tree:

$$F = f \times c_w \times \rho/2 \times \Sigma(u\ (z)^2 \times A\ (h\ (z)))$$

Bending/tipping moment:

$$M_t = M_{b\ max} = f \times c_w \times \rho/2 \times \Sigma(u(z)^2 \times h(z) \times A(h(z)))$$

where:

$M_t$ = tipping/uprooting moment (Inclino method)
$M_{b\ max}$ = bending moment (Elasto method)
$F$ = force
$f$ = natural frequency factor
$\rho$ = air density
$u_z$ = wind velocity
$h_z$ = height of specific area unit in crown surface
$A$ = crown surface in m² at respective height
$c_w$ = aerodynamic drag factor

## ELASTO-INCLINO METHOD (PULLING TEST METHOD)

The elasto-inclino method helps to determine the breaking and tipping safety of a tree by pulling it with a steel cable attached to a winch and simultaneously recording its reaction under a measured load (using a dynamometer) (Figure 9). The method follows strict principles used in engineering by integrating load input, material properties, and the load-bearing geometry in all calculations (c.f. Fig.1, triangle of statics).

### Breaking Safety (Elasto Method)

The elastometer measures alterations in length of the marginal fibers at a resolution of 0.001 mm. The elastometer pins are positioned in the marginal fibers of a trunk on either the tension or compression side. Pulling the tree with a certain force causes an extension (tensile side) or a compression (compressive side) in the marginal fibers. Hidden hollow spots in a trunk can be detected by high alteration recordings of the elastometer. To avoid damage to the fibers, the pulling test can be stopped shortly before reaching the specific elastic limit of the particular species. In the daily practice of pulling tests, tensile forces of 1-2 metric tons (10-20 kN) are necessary to deliver sufficient results. To avoid damage during testing, the first measurements are always taken at or near the obvious weakest point identified through visual assessments.

### Tipping Safety (Inclino Method)

The inclinometer pins are positioned in the bark at the base of the trunk to avoid bending influences. Due to the inclinometer's resolution of 0.01 degrees, the reaction of the statically effective trunk near root system can be recorded. Decay in the root system, cut roots, and poor root development can be detected clearly when high inclination readings are recorded. To avoid damage in the root system, the pulling procedure is always stopped at a maximum value of 0.25 degrees (regardless of the tensile stress) because at this trunk lean, 40% of a gale load (40% = wind force 8) is already reached.

Before the measurements a photograph of the entire tree is taken and digitized to determine the exposed surface area and the symmetry of the crown. After the measurements, a load analysis is performed to provide data regarding the wind pressure and bending moments occurring at the bottom of a trunk in a gale. The inclinometer values and the pulling force values together with the results of the load analysis are compared with the values of the generalized tipping curve. So far, the inclino method is the only method that provides reliable information about the anchoring potential of a tree.

## Elasto-Inclino Method and Load Analysis

The SIM methods can only be used on solitary trees (e.g., road trees, trees in parks). A load analysis for forest trees has not yet been developed and load analysis for single branches does not work. Wind speed and site conditions, as well as the flexibility of the branches (aerodynamic behavior) and the exposed surface area, are important factors for tree safety calculations using the elasto-inclino method.

Data on impacting forces and effective moments are generated by a computer model that simulates the wind forces occurring during a gust of 33 m/s (76. mph, 118km/h, gale force 12). Simultaneously, data from pulling tests and of sound trunk wood are adjusted and compared with the loads, thus leading to a safety value given in per cent (%). Trees should have a safety factor of at least 100 % under these conditions. Engineers always tend to calculate on the “safe side,” using a safety factor of at least 1.5 (=150 %). A tree with safety values > 150 % has significant reserve strength and is regarded as safe.

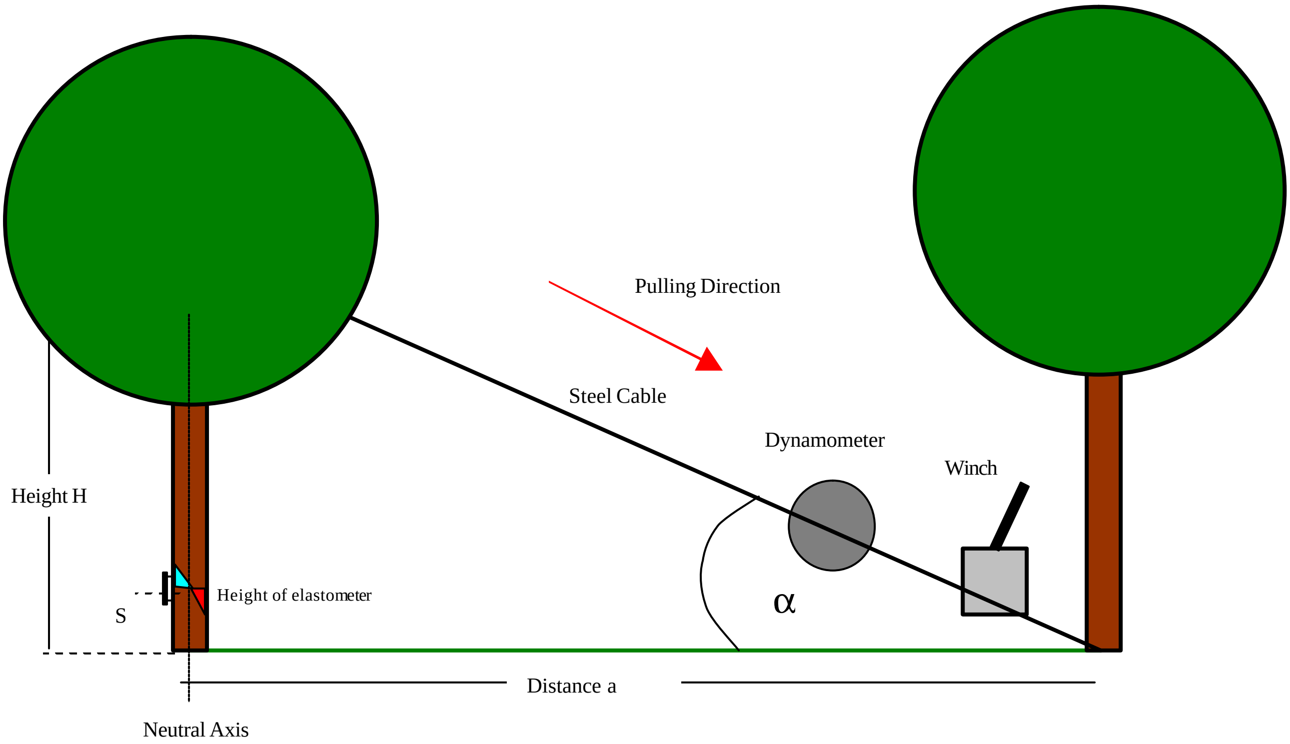


**Fig 8.** Arrangement of pulling test procedure. The dynamometer serves to determine the tensile force F, which is raised constantly during the test to a maximum value of 20-30 kN. In a bending process the outermost marginal fibers are stressed highest and have to withstand strains, whereas the center of a trunk (neutral axis) remains stress free. These alterations in length (Δl) in the marginal fibers are proportional to stresses (Hooke´s law) and can be measured during the pulling test using the elastometer. Because stress (σ) can be understood as an effective force exerted on an area, it can be said that a certain moment of force is exerted on the resistive cross-section of the tree. High alterations in length can be obtained from hollow trees with a smaller resistive bending moment due to material loss in the center caused by decay.

$$S = \mathbf{M_{b\ (bendingmoment)} / W_{(cross\ section\ modulus)}}$$

where: $M_b = F^* (H - S)^* \cos \alpha$ and $W = d_1^{\,2} * d_2 \text{ x } \pi/32$

with:

| | |
|---|---|
| σ | stress in $N/mm^2$ |
| F | force in N (dynamometer) |
| H | height of cable attachment |
| S | height of elastometer, measuring plane |
| α | angle of steel cable |
| $d_1$ | trunk diameter, 1 m above ground |
| $d_2$ | trunk diameter perpendicular to $d_1$, 1 m above ground |

The distance between winch attachment point and tree is a; H is the distance between anchor point and ground level. Consequently, the load angle α can be calculated according to:

$$\mathbf{\cos a = a^2 / \text{Ö}\overline{a^2 + H^2}}$$

According to Hooke´s law, stress is proportional to strain. From this fact it can be concluded that the E-modulus (Young´s Modulus) stays constant within the range of elastic deformation. Consequently, the E-modulus can be determined by

$$\mathbf{E} = s \;/ e\,, \qquad \text{where} \quad e = \Delta l / l$$

with:
$\sigma$ = stress; E= modulus of elasticity; e= strain, $\Delta l$ from measured value (elastometer),
l for reference length of elastometer. L = 200 mm

## SUMMARY

Following international engineering standards, serious tree safety analysis has to incorporate the interrelation of occurring loads, material properties of green wood and the load bearing geometry. Boring into a tree’s trunk to determine the thickness of the residual wall (= load bearing geometry), while neglecting wind load and material properties, could lead to wrong results and may be harmful to the health of a tree.

Tree inspectors should consider that smaller trees with thick trunks have higher safety reserves than taller and larger ones and therefore may tolerate larger cavities without being unsafe. The local topography and exposure also have a significant influence on tree safety assessment. Despite the fact that trees in cities seem to be more sheltered than those on a coast line, both locations can expose a tree to the same wind loads. This is due to the fact that the even surfaces of long and tall buildings or mountain chains may create wind tunnel effects that often lead to increased gust speeds.

Compressive tests on green wood have shown that the differences between Central European tree species show only little variation with a mean value of 20 N/mm². In subtropical and tropical regions the strength properties differ significantly from those of Central European trees (Lavers, 1983). Therefore further research in this field is required if the SIM are to be used outside Central Europe.

Using the pulling test method, which integrates load, material and load bearing geometry and simulates wind loads, the uprooting and breaking safety of trees can be determined without severe damage of the wood tissues.

The new statics integrating methods (SIM) provide a significant move forward because they minimize the boring/drilling into trees and provide a scientific approach to tree failure analysis based on sound engineering principles.

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