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A deterministic model combining NDT to estimate permissible bending loads on trees

Ingo Muench[1] | Simon Loske[1]

Correspondence

Prof. Dr. Ingo Muench
TU Dortmund University
Institute of Structural Mechanics
and Dynamics
August-Schmidt-Str. 8
44227 Dortmund
Email: ingo.muench@tu-dortmund.de

[1] TU Dortmund University,
Dortmund, Germany

Abstract

The stability of trees is the subject of numerous studies, as their loss poses a threat to life and limb. Bending loads are responsible for the two most common failure modes: uprooting and stem break. Uprooting is strongly related to soil conditions, water saturation and the root system itself. These parameters are difficult to measure in situ. Since both failure modes result in loss of vitality, arguments from evolutionary theory suggest that roots and stems should have similar load limits under normal conditions. Therefore, we propose a deterministic model to estimate the allowable bending load in the stem of European beech (Fagus sylvatica). The model assumes a non-linear stress distribution in the cross section. Destructive bending tests show that damage progresses in three stages. Furthermore, the local compressive and tensile strength in fibre direction are crucial parameters to determine the ultimate load. Since the tensile strength cannot be measured by NDT, the experimental data from the large-scale tests are used to relate this parameter to the compressive strength from the NDT data. This provides a method for determining the risk of a tree, for example in urban areas. It is also useful for estimating the allowable limit of engineering loads on trees.

Keywords

Stability of trees, green wood, bending test, ultimate load, tree houses, compression strength

1 Introduction

From our point of view, trees represent natural load-bearing structures whose material variability can be captured by NDT and mapped into a deterministic mechanical model based on laboratory test data. The essential parameters for this can be deduced from basic considerations of tree biology and natural loading effects. Trees have three main organs: crown, stem and root. For structural analysis, the tree is a cantilever and therefore a statically determined system. This means that the internal forces in the stem can be easily determined if the acting loads are known.

In addition to weight loads (e.g. self-weight, snow, etc.), this system of a tree has to balance horizontal loads from wind via bending and shear forces. The resulting bending stresses can be described as dominant, as a short opening example will show. The following assumptions are made:

- 1/3 of the above-ground mass is gathered in the crown
- The crown begins with a strong branch at the height of 18 m
- The stem can be idealized as a truncated cone up to the first strong branch
- The truncated cone tapers from 70 cm to 40 cm in diameter
- The wood has a density of 1000 kg/m3 (water weight included) in its vital state

Under these conditions, the crown and stem have a weight of 1.2 and 2.4 tons respectively. In both the lower and upper sections of the truncated cone, the corresponding normal compressive force in the longitudinal direction of the trunk results in a compressive stress of 0.09 N/mm^2.

Niklas & Spatz [1] list the tensile and compressive strength of "green wood" for 161 tree species. The compressive strength ranges from 5.9 to 79.9 N/mm^2, the tensile strength even from 14 to 148 N/mm^2. So, the result of the above calculation is well below the compressive strength of 161 species of wood, so weight can hardly be considered as the main cause of damage in the stem. However, this is only true if the center of gravity of the weight has little or no eccentricity to the trunk axis. Any deviation from this constraint implies bending effects which, among other things, require equilibrium of the deformed system.

As is the practice in [1], the wood of a living tree will also be referred to as green wood to distinguish it from dried

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wood. For European beech (Fagus sylvatica), [1] gives a tensile strength of 65 N/mm^2 and a compressive strength of 27.6 N/mm^2, so that the compressive stress in the opening example represents only 3 ‰ of the material's strength capacity. The compressive strength considered in [1] is even lower than the values given in other publications, e.g. [2,3], which quantify the compressive strength of European beech up to 36 N/mm^2, i.e. 30% higher.

If snow loads are assumed to be in the range of the tree's own weight or at most 100% above this, the normal force load would still be only about 2% of the material's strength capacity. However, since fallen trees can be observed, this can be attributed to two main causes:

1. damage to the stem or root system due to environmental influences (drought, fungal attack, etc.)
2. bending stress, usually due to wind action

In certain cases, crown asymmetry also leads to a combination of bending and torsional stresses, which can result in extensive fiber delamination along the stem axis. However, such damage to the wood matrix does not always induce the ultimate load limit. Especially if the resulting compliance (rotation around the vertical axis) causes a reduction in load. Trees damaged in this way develop a slightly twisted reinforcing rib along the trunk in the area of delamination, see Figure 1.

Figure 1 Slightly twisted reinforcing ribs along the trunk axis. Source: Ingo Muench/TU-Dortmund

Furthermore, the position of the reinforcement rib indicates the direction of the wind during the damage event, as otherwise, in combination with the bending load, there would have been a large reduction in the required bending resistance and thus total failure. This aspect will not be discussed further, but it should be noted that flexibility in the crown and shaft can certainly lead to a reduction in the wind load on the system. This aspect implies that not only the strength values of the wood matrix but also its elasticity can play a role in risk management. Very flexible tree species such as the Sand Birch (Betula pendula) can significantly reduce the wind load within the branch structure, but also by deformation of the trunk.

The detection of damage in the stem or root system is the subject of tree inspection guidelines, e.g. [4,5,6], which are not discussed here. This article assumes vital trees with an intact wood matrix, whose roots have no weak points. A list of factors that negatively affect the stability of trees can be found in [7].

If the bending load exceeds the strength of the wood in the trunk, a chain of failure mechanisms occurs, which are described in Chapter 2 on the basis of experimental observations. A deterministic model for predicting the flexural strength is also presented. Chapter 3 explains the procedure of the proposed NDT method and its validity on the basis of a study. The paper concludes with a summary and outlook in Chapter 4.

2 Bending load capacity of trees

2.1 Aspects of the bending load capacity

Several aspects of the bending capacity of green wood can be derived from our own ultimate load tests on whole stems of European beech. Since the natural clamping by the roots cannot be reproduced in the laboratory, three-point bending tests are carried out with a span of 6 m, see Fig. 2. This means that the specimen is also subjected to shear forces in the area of the maximum bending moment, which is more similar to the natural loading scenario than, for example, a four-point bending test, which is free of shear forces over a longer distance.

Nevertheless, we place two slings at a short distance (about 0.4 m) in the center of the field to reduce the compression between the slings and the outer fibers. In addition, a bending compression zone with a free surface is obtained in the area of the maximum bending moment. Therefore, the test arrangement could also be described as a four-point bending test. However, due to the small distance between the slings in relation to the shaft diameter, we will refrain from doing so.

Figure 2 Ultimate load test on a whole stem under bending. Source: Ingo Muench/TU-Dortmund

Compared to dried and technically processed wood, we observe that green wood is more deformable before the first, thin fiber bundle on the tensile side suddenly breaks. The influence of natural imperfections such as knots is less important than, for example, acute fiber bundle damage close to the surface.

The morphology of a tree and the formation of its stem are the result of its genetics, its location and a variety of individual environmental influences. Each tree is therefore unique and an imperfect specimen. The intensity of these imperfections does not necessarily increase with the age of the tree, although the likelihood of exceptional environmental influences causing local damage (see Figure 1) does cumulate over time. This includes natural processes such as the death of lower branches as trees grow taller. The following comparison illustrates this.

Test specimen A contains a knot cavity with incipient callus formation between the two central webs, see Fig. 3, left. The wood matrix of specimen B, on the other hand, is much more homogeneous in this area, but shows signs of acute, orange-colored fiber crushing caused by a gripping arm, see Fig. 3 right. In the bending test, these crushes in specimen B lead to initial breakage of the outer fiber bundles and initiate further abrupt damage throughout the cross section. In specimen A, the failure also starts at the imperfection, but is less abrupt.

Figure 3 Damage patterns in the bending test on imperfect test specimens with branch hole and incipient callus formation (left) and fiber crushing (right). Source: Ingo Muench/TU-Dortmund

This observation suggests that natural imperfections in the wood matrix, e.g. by knots, are less disadvantageous to the ultimate bending strength of the whole trunk than acute fiber damage close to the surface, as in specimen B. This is consistent with the argument that a tree is a living organism whose resistance and growth mechanisms to critical environmental influences are important for its fitness in terms of evolutionary optimization. Callus formation on a branch cavity is such a genetically anchored growth mechanism. It is also evident that extreme wind load is a critical environmental impact.

Tree collapse can take the form of crown or stem breakage or uprooting. The latter is highly dependent on the properties of the soil as well as temporary conditions such as the water content of the soil. Such parameters are difficult to verify using NDT methods, therefore we focus on the bending strength of the stem.

Assuming an evolutionary optimization of the whole organism, the stem and root system should have similar resistance to wind load in order to have high fitness within a population. For European beech, foundation failure and stem breakage above the root extension can be observed in situ, see Figure 4. The damage pattern shows several features that we also observe in the bending test, see Fig. 3. These include the fracture of fiber bundles in V-shaped cracks up to 100 cm long. There is also delamination of the entire cross section with extensive shear gaps along the length of the stem. In addition, Figure 4 shows the delamination of the flexural compression zone on the left side of the stem.

In our ultimate load tests, damage in the bending compression zone marks the limit of elastic resistance to bending. In the pure compression test as well as in the compression zone of the bending test, local buckling of fibers occurs, see Fig. 5. In the bending test, however, a smaller buckling length (approx. 5 mm) and a different buckling shape perpendicular to the surface can be observed.

Figure 4 Damage pattern of a broken European beech that was subjected to a wind load from the right and then fell to the left, as shown in the picture. Source: Ingo Muench/TU-Dortmund

For NDT purposes it is therefore preferable to determine the compressive strength in the fiber direction of the wood matrix. Furthermore, testing the outermost layers of the wood is sufficient to determine the bending load-bearing capacity.

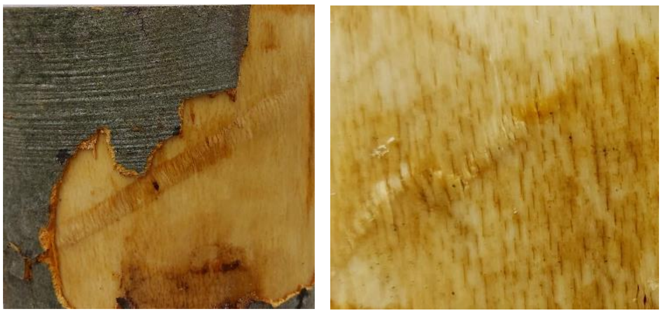

Figure 5 Damage pattern in the pure compression test (left) and in the compression zone of the bending test (right). Source: Ingo Muench/TU-Dortmund

2.2 Test results and modelling of the ultimate bending resistance

Our deterministic model for the ultimate bending resistance is based on a non-linear stress distribution, which is limited to the compressive strength in the longitudinal direction of the fiber in the bending compression zone. To describe the stress function, a linear function is chosen on the tension side and a 3rd order polynomial on the compression side with the following constraints:

1. C^1-continuity to the linear stress curve
2. Limitation to the compressive strength
3. Fading stress gradient at the edge of the compression zone
4. Parity of the stress blocks

Note that the C1 continuity implies two conditions. Furthermore, the position of the stress zero line is required to maximize the area of both stress blocks. All conditions are shown in Figure 6.

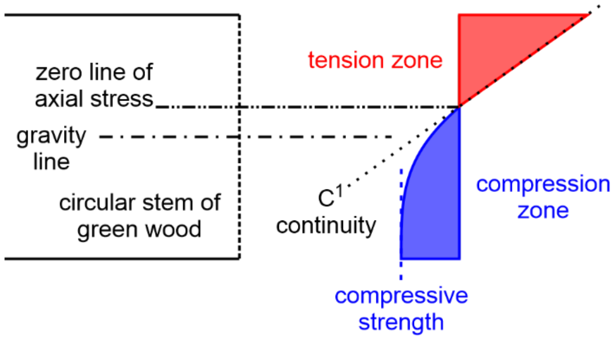

Figure 6 Nonlinear stress model for green wood in the ultimate load state of bending. Source: Ingo Muench/TU-Dortmund

The non-linear stress model replaces the linear model when the elastic capacity is reached, see also [8]. This approximates a typical load-deflection curve, as shown in Figure 7, until the ultimate load is reached.

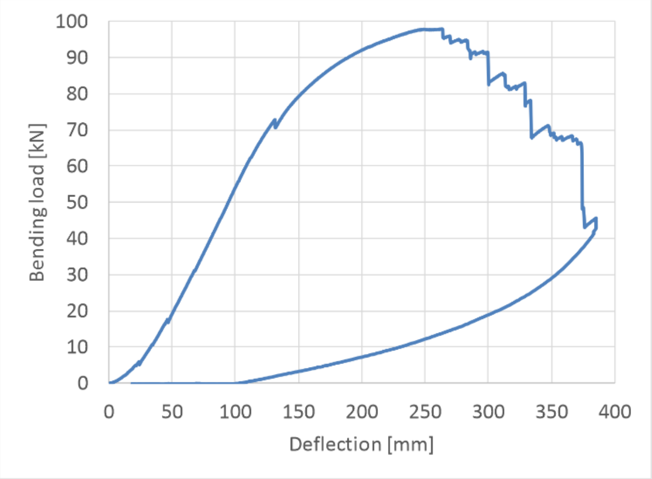

Figure 7 Typical load-displacement curve of a bending test. Source: Ingo Muench/TU-Dortmund

Except for initial flexibility in the test setup up to about 18 kN, the load-displacement curve in Figure 7 is almost linear up to about 62 kN. The flattening of the curve is due to the buckling of the fibers in the bending compression zone, which shifts the position of the zero-stress line towards the tensile zone, cf. Fig. 6. The associated increase in tensile stress is followed by the fracture of thin fibre bundles near the surface. This marks the upper load drop in the present test in Figure 7.

As the load is applied under displacement control, the supercritical behavior after reaching the ultimate load can also be measured. After a number of fiber bundles at the surface have ruptured (quivering in the diagram), the first delamination of a partial cross section occurs, resulting in a jump in the bending resistance. This process is repeated about seven times in the load-displacement diagram shown in Figure 7 and tends to become stronger and stronger. At a deflection of 38 cm, the maximum stroke of the test machine is reached and unloading follows.

3 Implementation of the NDT method

3.1 Determining the compressive strength using thin cores

As explained in Chapter 2, the compressive strength of the outer wood layers is the central parameter in the non-linear stress model for determining the load-bearing capacity. This parameter can be obtained using thin cores, which are usually closed by the tree's own repair mechanisms within a growth period. We therefore consider this method to be non-destructive. Other material tests, such as tensile strength, would require the removal of larger fiber bundles. The following section also explains why only a few cores are needed to obtain meaningful results.

Cores as small as 5 mm in diameter can be tested for compressive strength in the fiber direction using a device such as the Fractometer II [3]. It should be noted that the moisture content of such thin cores can quickly decrease after removal and affect the measurement result. Comparative compression tests with larger samples up to whole stem cross sections, see Fig. 5. left, have shown good agreement with the following results using thin cores in our studies with European beech.

3.2 Studies on the significance of thin cores

Four test specimens of the ultimate load experiments described in chapter 2 were tested on compressive strength with the Fractometer II within the undamaged area by means of a high number of drill core removals. The trees were taken simultaneously from the same site and tested under laboratory conditions.

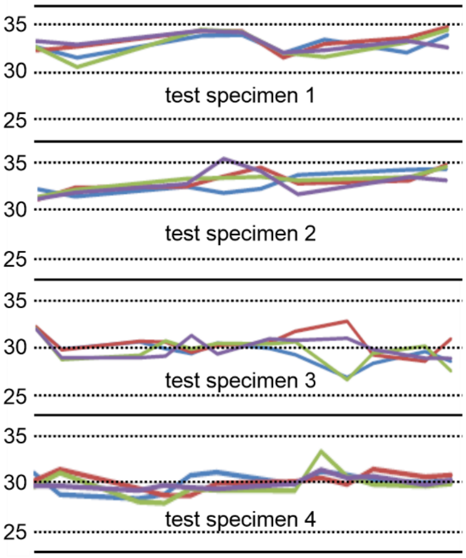

Figure 8 Average compressive strength over the height of the specimens for four radial cores per cross-section (shown in different colors). Source: Ingo Muench/TU-Dortmund

Four cores were taken from each of 8 to 12 cross-sections per stem at 0/90/180/270 degrees. Approximately 25 measurements were carried out on each core with the Fractometer II. This means that approx. 4000 observation units from four trees are available for this measurement campaign. The average compressive strength for each of the four cores is shown in Fig. 8 over the height of the test specimen. Only for specimens 1 and 2 does Figure 8 show a weak trend towards higher strength in the direction of the crown. However, this trend is smaller than the variation between the four cores per section. Thus, the exact height of the sampling does not play a decisive role.

However, care must be taken [8] to ensure that the core is free of any imperfections caused by branches. This tends to become more difficult with decreasing distance from the crown, as can be seen from the variance of the 4 curves in Figure 8. Taking a sample at a height of approximately 2 to 6 m above the root extension seems to be representative for the specimens tested here, which is also reflected in the histograms, see Fig. 9 for specimen 1.

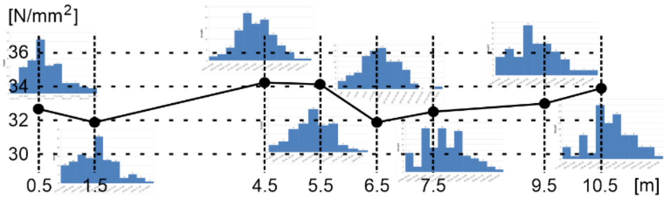

Figure 9 Mean compressive strength of the four cores over the height of specimen 1 with representation of the histograms for 100 to 120 measurements per cross-section in each case. Source: Ingo Muench/TU-Dortmund

As can be seen from Fig. 8 for test specimens 3 and 4, the individual compressive strength of approx. 29 N/mm^2 can be below the data of 36 N/mm^2 for green wood of European beech [2,3]. This is important, for example, when predicting the load-bearing capacity of trees for technical installations.

4 Summary and Outlook

This article places the importance of the ultimate bending resistance of trees in the context of general stability. Experiments on whole stems have provided information on the failure mechanism due to bending loads. These are translated into a deterministic model for the ultimate bending resistance of trees. The compressive strength of the wood matrix plays a special role and is particularly important. A study of the compressive strength of green wood in Section 3.2 shows that even trees from the same location, tested under identical conditions, develop different strength values. Similar differences are also reported in the relevant literature [1,2,3], so that it seems sensible to check individual compression strength, depending on genetics, location and environmental influences [7].

Even with small cores, which usually close after one growth period, the individual compressive strength and therefore the expected ultimate bending resistance can be determined. The side from which the sample is taken is of secondary importance. However, if the bending load is known, the side of the compression zone should be chosen.

One such application is shown in Figure 10. Trees (European beech) are used for the entire foundation of a permanent building. This is connected to the trees by inclined cables, so that the resulting horizontal forces result in an additional bending load on the trees. This bending load needs to be kept below a risk analysis threshold, which is determined by the investigation presented here.

Figure 10 Foundation of a permanent building using inclined cables fixed on trees. Source: Ingo Muench/TU-Dortmund

Future plans are to extend the studies to other tree species. Furthermore, the integration of residual stresses due to growth processes is in our focus [9]. Residual stress contributes to the reduction of the compressive stress in the bending compression zone. The present deterministic model does not include this effect and should therefore be considered as conservative.

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