IS LATERAL STRENGTH IN TREES CONTROLLED BY LATERAL MECHANICAL STRESS?

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Abstract. It is shown experimentally that lateral tensile stresses perpendicular to the fiber orientation computed for three ash trees under wind loading are well correlated to lateral strength perpendicular to the grain. These measurements were done with cores taken from trees with an increment borer and broken with a fractometer. Lateral stresses can lead to delamination of wood. This danger is minimized by local distribution of strength according to lateral stresses.

Metzger (1) was the first who found a relation between tree design and mechanical loading. He showed that the stems of spruce trees taper in a manner which leads to a constant mechanical stress along the stem. This principle of even load distribution was generalized to biological load carriers and was called the "Constant Stress Axiom" by Mattheck and co-workers (2,3,4). The obvious advantage of an even load distribution on a time average of all wind directions, etc., is that neither overloaded points (weak spots!) exist on a tree's surface nor underloaded points where the material would be wasted. If a trees is wounded this even load distribution is disturbed by locally higher mechanical stress (notch stresses!) and the tree tries to restore the constant stress state by wound healing (2,3). However, the constant stress axiom is limited to stresses in the direction of the grain and is not valid for lateral stresses.

The failure mode illustrated in Fig. 1 (5) is caused by internal lateral stresses. Especially spruce trees, but also poplar trees, occasionally fail by root-stem joint delamination which leads to an axial crack running up the stem. If this loose delaminated fiber bundle is suddently stretched due to further wind movements, the stem usually breaks at shoulder level of an adult man. This failure is caused by lateral stresses which are also illustrated in Fig. 1. It is easy to imagine that these lateral stresses are zero on the surface and have a maximum inside the stem.

The questions to be considered here are: 1) Does the tree "know" this internal danger due to lateral stresses acting perpendicular to the fiber orientation? 2) Is there some reaction in the tree to avoid this failure type? In other words: Is there a distribution of lateral strength (wood quality) according to the distribution of lateral stress?

Stress Analysis

Three common ash trees (*Fraxinus excelsior*) were studied. The trees were growing along a former riverside and were approximately 22 to 25 meters high and 60 to 90 years old. A side-view photograph was taken from each of them and a finite-element calculation has been performed under bending load, to get an idea of the stress distribution inside the tree. In all three cases the lateral stresses show a local maximum just at that point where root delamination usually starts (Figs. 2-4). This failure mechanism has been described before (3).

The Finite-Element Method (FEM) is an engineering standard method which can be applied with any commercial FEM code on the market. The FEM subdivides the mechanical structure into a mesh of finite elements. Starting from approximate displacement gradients from nodal point to nodal point within the mesh, the mechanical equilibrium state is found by minimum energy principles. The method is so widely used in all parts of mechanical engineering (3) that a detailed description will not be given here.

Strength Measurements

At the Karlsruhe Forschungzentrum Karlsruhe GmbH, a small wood testing device (6) was developed to measure the bending strength of a 5 mm diameter drilling core taken out of the tree with an

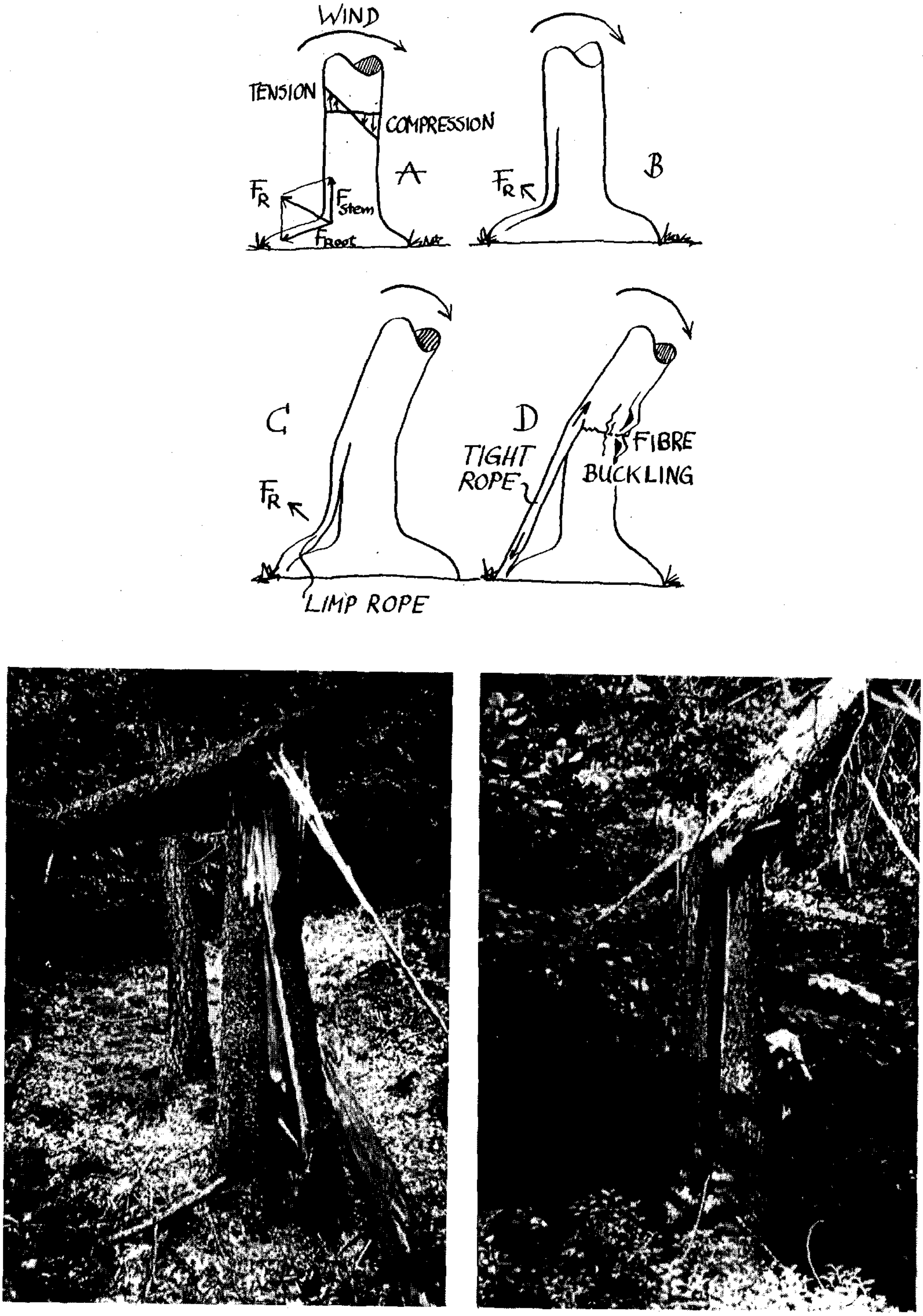

Figure 1. Failure of root-stem joint by delaminating wood fibers.

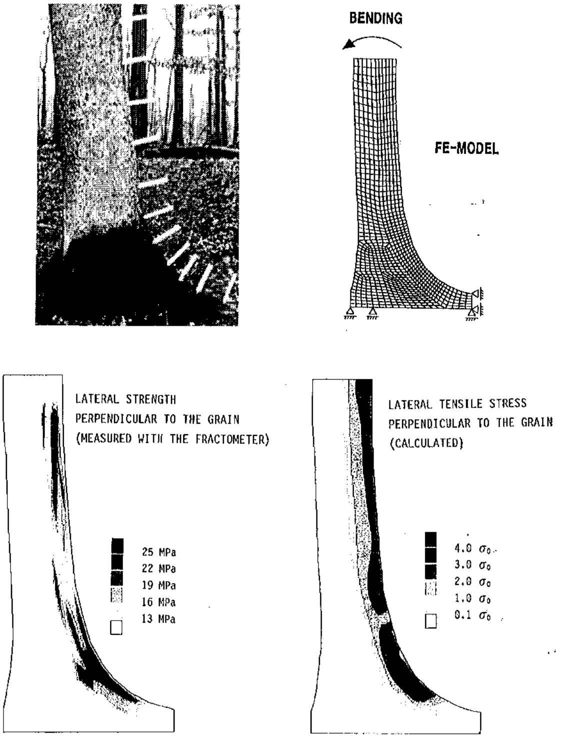

Figure 2. Distribution of lateral strength according to distribution of lateral stress.

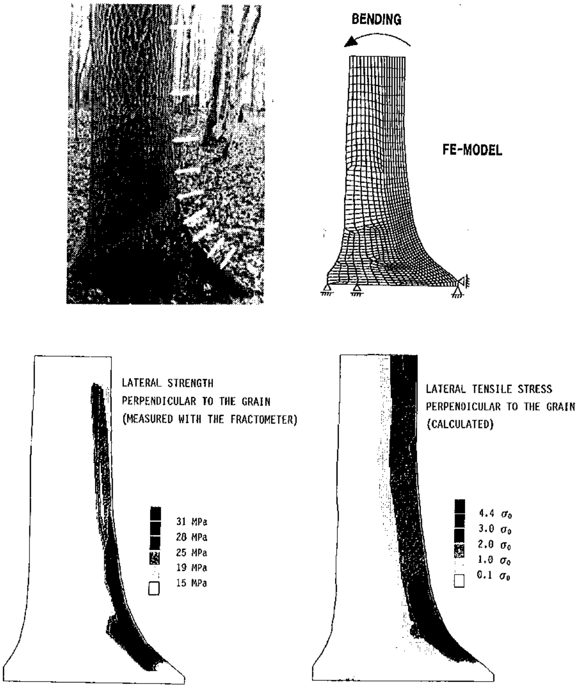

Figure 3. Distribution of lateral strength according to distribution of lateral stress.

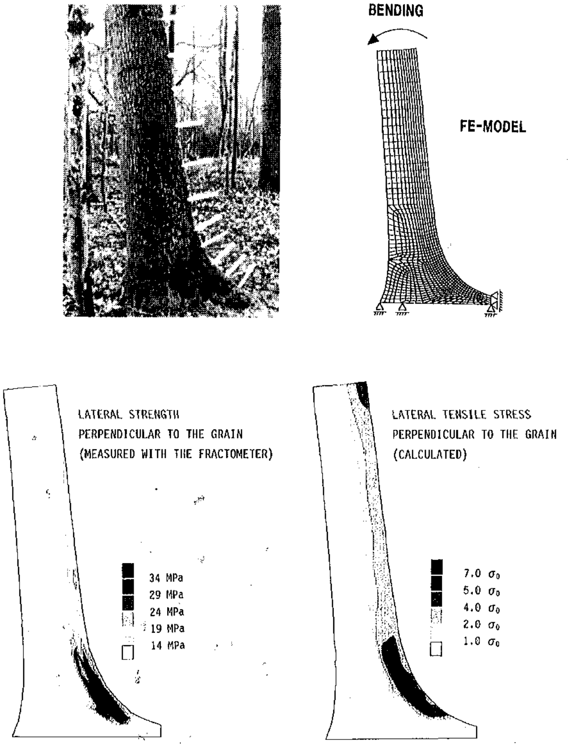

Figure 4. Distribution of lateral strength according to distribution of lateral stress.

increment borer. The device is called a fractometer (Fig. 5).

Field studies with different tree species (6,7,8) have shown that there is a correlation between the size and density of the wood rays and the lateral strength of wood measured with the fractometer. However, the measurements published by Mattheck and others (6,7) were done at similar points on each stem and no local distribution of strength within the individual stems was considered. The white arrows in Figs. 2-4 indicate where a drilling core was taken out of the ash trees. These cylindrical samples were broken with the fractometer incrementally and the strength distribution within the core and from core to core within the stem was recorded. The result is shown in Figs. 2-4. In any case there is an evident increase in lateral strength (perpendicular to the grain) in the same zone where highest lateral stresses were computed Since the FEM model of the tree is limited here to two dimensions and the exact value of the bending load caused by wind could

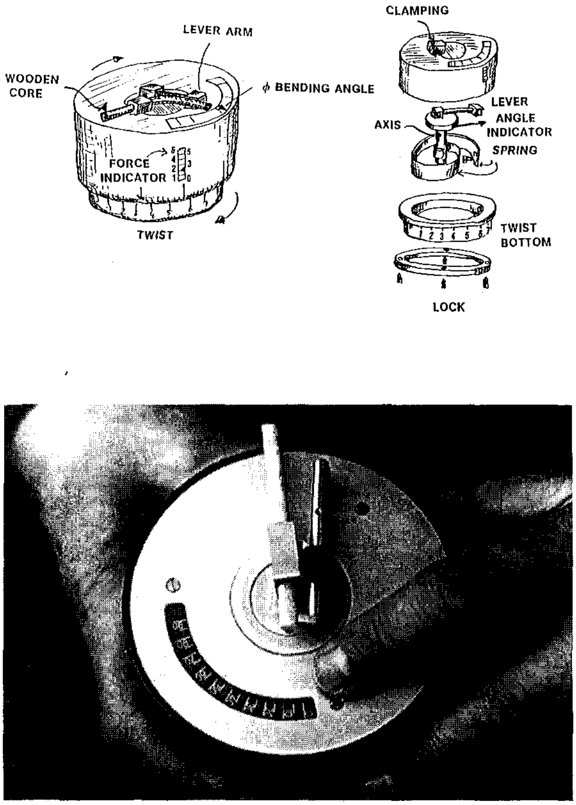

Figure 5. Fractometer.

not be given as well, a more quantitative comparison between stresses calculated and strength measured would be speculative. In this preliminary stage of investigation only the location of maximum stress and strength is compared.

Because the location of maximum lateral strength moves during the lateral thickening of the tree stem, there must be a mechanism which first increase, and than decrease, the lateral strength of the wood. Because the cambium is distant from that spot, an unknown mechanism seems to exist inside the stem. In simple words, the splitting resistance of wood in the tree trunk is greatest where the highest splitting stresses are computed.

Previous field studies (6) have shown that trees with good strength, such as oak, beech, plane, maple, etc., have larger wood rays or a higher density. On the other hand, trees with small or uniseriate ray cross-sections, such as popular, willows and conifers, have poor strength and low fractometer values. It seems that the fractometer value increases with ray size and number. One should expect that this stress-correlated optimum lateral strength distribution is done by adaptation of the density, size and structure of wood rays (8). Also the degree of lignification or the quantity of cellulose in the wood ray cells can be imagined as a regulator of lateral strength. It is too early to state generally that the strength of biomaterials is controlled by local mechanical stress, but there indicators of where to look for further confirmation.

Conclusions

The major results of the study are:

• High lateral tensile stress (perpendicular to the grain) acts locally close to the root-stem junction inside the stem, at some distance from the cambium.

• At laterally loaded zones tree splitting is prevented by increases in the lateral strength of the wood.

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Literature Cited

1. Metzger, H. 1893. *Der Wind als maßgebender Faktor für das Wachstum der Bäume.* Mündener Forstliche Hefte 3.
2. Mattheck, C. 1991. Trees - The Mechanical Design. Springer-Verlag, Berlin
3. Mattheck, C. 1992. Design in der Natur. Rombach Verlag, Freiburg
4. Mattheck, C. and H. Breloer. 1993. Handbuch der Schadenskunde von Bäumen - der Baumbruch in Mechanik und Rechtsprechung. Romback Verlag, Freiburg.
5. Mattheck, C. and K. Bethge. 1990. *Wind breakage of trees initiated by root delamination.* Trees - Structure and Function 4: 225-227.
6. Mattheck, C. and K. Bethge. 1993. *Das Fractometer: Eine Faschenprüfmachine für Holz.* Allgemeine Forstzeitschrift 3: 114-115.
7. Mattheck, C. and H. Breloer. 1992. *Feldanleitung für Baumkontrollen mit VTA (Visual Tree Assessment).* Landschaftsarchitektur 6: 25-32.
8. Schweingruber, F. H. 1990. Anatomie Europäischer Hölzer. Paul Haupt Verlag, Stuttgart.

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Zusammenfassung. Die Untersuchung dreier Eschenwurzelanläufe hat gezeigt, daß die gemessene Holzfestigkeitsverteilung senkrecht zum Faserverlauf mit der berechneten Zugspannungsverteilung senkrecht zum Faserverlauf in Korrelation steht. Im Bereich hoher Zugspannungen senkrecht zum Faserverlauf wurden auch hohe Holzfestigkeitswerte bestimmt. Zugspannungen senkrecht zum Holzfaserverlauf können zu Delamination des Holzfaserverbundes führen. Der Baum schützt sich gegen diesen Schadensfall durch eine spannungsgesteuerte Holzfestigkeitsverteilung. Die Querfestigkeit im Baum ist dort am größten wo auch die höchsten Querzugspannungen wirken.