On the composite design of wood branches leading to improved bending strength

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Abstract. Wooden branches are designed to carry large bending moments, and so are longer composite structures, e.g. rotor blades for wind turbines. Being a natural fibrous composite material, wood is made from relatively simple biopolymer building blocks. In this preliminary work, we describe the composition and structure of softwood branches, including 3D images from X-ray computed tomography. The main difference in branch structure compared with other wood tissues is the reaction wood formed on the compressive side in e.g. spruce and pine. A simple beam is used to show that maximum bending moment is multiplied several times solely from the reaction wood. This is noteworthy, since chemical composition of the reaction wood does not differ significantly from the rest of the wood. The tissue gradients in the branch resulting from variation in density, microfibrillar angle and cell geometry contribute to the strength improvements. In composite structures, sandwich design is used to improve the load carrying capacity. From a general perspective, also local features as found in wood, such as smooth gradients and controlled cellular structure, could be further explored to improve bending strength in engineered composite materials.

1. Introduction

Structures in trees have developed by evolution to carry load efficiently. In particular, branches show a structure designed to support bending moments. Like manufactured composite components, trees are made of an anisotropic material, that can be optimized for its loading conditions. In this work, we will address a feature in softwood branches which may be of relevance also for composite components carrying significant moment forces, e.g. rotor blades in wind turbines. This feature concerns the formation of reaction wood close to the intersection of the branch to the stem. First, we review some of relevant material features of wooden branches.

Wood itself is composed of a few key components, mainly cellulose, hemicellulose and lignin. However, wooden material is still able to adapt to different environmental conditions and forces acting upon the tree during growth and leading to wide variation in properties, e.g. mechanical properties [1].

One such adaptation is reaction wood. This type of wood is formed to counteract gravity’s impact in leaning stems or branches. In broad-leaved trees (angiosperms) the reaction wood is called tension wood, while in conifers (gymnosperms) it is called compression wood. Tension wood is formed on the upper side of the branch or stem, i.e. the tensile side. Compression wood is formed on the lower side of the branch or stem, i.e. the compressive side [2,3]. In figure 1 the formation of compression wood due to growth stresses on the compressive side is shown.
When looking closer at compression wood in branches of gymnosperms, it can be observed on the lower side of the branch that compression wood is formed, while on the upper side opposite wood is formed. Opposite wood is very similar in morphology and properties to normal wood. Compression wood, however, differs substantially from normal wood in its chemical composition and morphology. It contains more lignin and less cellulose, as well as a less hemicellulose (mannan and xylan), but more of the hemicellulose galactan. In figure 2 the hierarchical structure and the angle of the cellulose microfibrils is shown for normal wood and compression wood. The angle of the cellulose microfibrils in the cellular wall is higher in compression wood, especially in the middle layer of the secondary cell wall (S2-layer). The outer layer of the secondary cell wall (S1-layer) is thicker. There is no inner layer of the secondary cell wall in compression wood. The tracheids (wood fibers) have overall a thicker cell wall and are more round in cross sectional shape. The annual rings are wider in compression wood, giving the branch an elliptical rather than circular shape (eccentric growth), as can be seen in figure 1 [2,4–6].

All these factors lead to a change in mechanical properties and better adaption to sustain the load. Hence it is mechanically different to normal wood due to its higher density, increased longitudinal shrinkage, reduced stiffness and reduced tensile strength, but increased compressive strength [3].

This study aims to understand the mechanisms that leads to improved mechanical properties in compression wood of branches, even though it consists of the same building stones as regular wood. This understanding can be used as an inspiration in the future for improving engineered composite materials.

![Figure 1](image1.png)
**Figure 1.** Macroscopic changes of the tree trunk due to stem leaning inducing compressive growth stress and hence formation of compression wood (CW). The figure is taken from [7].

![Figure 2](image2.png)
**Figure 2.** Comparison of tracheid of normal wood (A) and compression wood (B). Differences in shape of the tracheids and the angle of cellulose microfibril in the different layers of the cell wall are shown. M is the middle lamella. P is the primary cell wall. S1 is the outer layer, S2 is the middle layer, and S3 is the inner layer of the secondary cell wall. The figure is taken from [8].

2. Methods

2.1. Computer tomography

Samples for morphological studies were taken from a young Norway Spruce (Picea abies) tree, approximately 10 years old. After conditioning the samples at an ambient environment (21°C and 65%
relative humidity) for at least 2 months, the sample was scanned in a computer tomograph (Bruker Skyscan 112). X-ray computed tomography allows to investigate the anatomy of wood and analyzing wooden structures in three dimensions without needing to dissect the sample [9]. The scan was carried out with a resolution of 6.5 µm. This allows identifying annual year rings and larger structures, but not cellular structures in the scanned wooden sample. Resolution was limited due to size of the sample and the design of the CT-scanner. Computer tomography is based on imaging sample with the help of X-ray showing density differences. After reconstruction of the images from different angles, the sample was three-dimensionally visualized in the software Avizo (ThermoFisher Scientific).

2.2. Beam model

Figure 3. Pure bending of composite beam of two materials with different Young’s moduli and strength. $E_o$ is the Young’s modulus in opposite wood, while $E_c$ is the Young’s modulus in compression wood.

To capture the main deformation mechanism, it is sufficient to consider basic beam theory. Looking at a bending moment in the branch, the branch can be simplified to a composite beam of two materials with different Young’s moduli and strength, as shown in figure 3. The height and width of one layer is equal, so as total height of the beam 0.2 m and 0.1 m were chosen. The Young’s modulus and strength of tensile loading were taken from [10]. Micro-tensile testing was performed on thin sheets of wood from the compressive side and tensile side of branches of Norway spruce to obtain these properties. However, no ultimate strength was found, so the yield strength at a strain of 1.5 % was used instead as a limit value. The compressive strength of opposite wood is estimated based on results from [11]. It was shown that the compressive strength in is approximately 50 % of the tensile strength in normal wood and clear samples. The compressive strength of compression wood is based on findings since 1904, where several studies showed that the compressive strength in compression wood is 50 % higher than the compressive strength in normal wood [3]. All values used in this model are listed in table 1.

This model is an example of the potential of using materials of different Young’s modulus and strength. However, the mechanical performance of tree branches is also depending volume ratio of opposite wood and compression wood, shape of the cross section and further factors.

Table 1. Young’s modulus and strength used for calculation of one model of branch with only normal wood and a second model with compression wood.

|                      | normal wood | compression wood |
|----------------------|-------------|------------------|
| Young’s modulus opposite wood in MPa | $E_o$ 3250 | 3250             |
| Young’s modulus compression wood in MPa | $E_c$ 3250 | 1000             |
| Tensile yield strength in MPa | $\sigma_o$ 40 | 40                |
| Compressive strength in MPa | $\sigma_c$ 20 | 30                |

3. Results

3.1. Computer tomography

Computer tomographic images of the branch of a young spruce tree, as e.g. in figure 4, show that the annular rings on compression side of the branch are thicker, leading to an eccentric cross section of the branch. However, no difference in density could be measured between opposite wood and compression wood for this particular sample. This might be due to the juvenile state of the tree. Juvenile wood usually
has a low specific gravity. Former studies have shown that the mechanical properties are closely related to density of the wood [3].

Figure 4. Image of a sample of a stem-branch joint of a young spruce tree (A). Computer tomographic scan of a part of same sample with a resolution of 6.5 μm (B). For the CT-image, black means low density of the material and white means high density.

3.2. Beam model
The ratio $n$ of the Young’s modulus in opposite wood $E_o$ and compression wood $E_c$ is

$$n = \frac{E_o}{E_c}$$

(1)

The neutral axis $Y$ can be determined to be

$$Y = \left(\frac{h^4}{4} + nA \frac{3h^4}{4}\right) \left(A + nA\right)^{-1}$$

(2)

The second moment of area $I$ is

$$I = \frac{b}{12} \left(\frac{h}{2}\right)^3 + A \left(\frac{h}{2} - Y\right) + n \frac{b}{12} \left(\frac{h}{2}\right)^3 + nA \left(\frac{3h}{4} - Y\right)$$

(3)

The maximal bending moment $M_{max}$ before breaking of opposite side $M_{max,o}$ and compressive side $M_{max,c}$, based on the strength in compression wood $\sigma_c$ and opposite wood $\sigma_o$, is

$$|M_{max,o}| = \frac{\sigma_o I}{|0 - Y|}$$

(4)

$$|M_{max,c}| = \frac{\sigma_c I}{|h - Y|}$$

(5)
The two models showed, that the compressive side of the branch will fail first. However, in compressive wood the moment which can be applied before failure is approximately 1.8 times higher than for a branch only consisting of normal wood. The results are shown in table 2. In this model the non-rectangular shape and eccentric growth of the branch was not considered, which could lead to further increase of the maximum moment the branch with compression wood in this model would be able to sustain. Former studies showed that in other tree species, the work needed to the reach the maximum load for static bending is around 2 higher for compression wood than normal wood [3].

Table 2. Maximal bending moment of normal wood and compression wood for compressive side and opposite side.

|                       | normal wood | compression wood |
|-----------------------|-------------|------------------|
| Maximal bending moment of compressive side in Nm | $M_{\text{max,c}}$ | 0.4             | 0.7             |
| Maximal bending moment of opposite side in Nm    | $M_{\text{max,o}}$ | 0.8             | 1.7             |

4. Concluding remarks
In slender composite components, a sandwich structure is usually adopted, with composite sheaths and a lightweight foam core. In wooden branches subjected to bending moments, the upper and lower sides are composed of different types of material, where the former is strong in tension and the latter strong in compression. This is not unlike the situation for reinforced concrete beams, which different designs are used for the compressive and tensile sides. In this case, the tensile side is reinforced by steel bars to compensate for the low tensile strength of unreinforced concrete. In softwood branches, a reaction wood is formed on the lower side to accommodate the compressive loads more efficiently.

Despite very similar molecular composition as the normal wood, the compression wood contributes to an astonishing increase in bending strength, estimated to several times the value for a beam that does not contain any compression wood. The main differing features of the compression wood are the more cylindrical shape of the cells and the higher microfibrillar angle, which contributes to its significant compressive properties. The wood material can be regarded as a fibre composite material. In engineered composite structures, a sandwich design is used to carry large moments, typically as two composite faces separated by a foam core. Features found in wood branches, including smoother material gradients, with varying fibre orientation and density, could be explored further for engineered composite structures. Manufacturing costs are of course a limiting factor, but evolving processing techniques could be developed to make composite structure with improved bending properties in a cost efficient way.

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