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Research paper

Fracture tolerance of reaction wood (yew and spruce wood in the TR crack propagation system)

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ABSTRACT

The fracture properties of spruce and yew were studied by in-situ loading in an environmental scanning microscope (ESEM). Loading was performed with a micro-wedge splitting device in the TR-crack propagation direction. The emphasis was laid on investigating the main mechanisms responsible for a fracture tolerant behavior with a focus on the reaction wood. The fracture mechanical results were correlated with the features of the surface structure observed by the ESEM technique, which allows loading and observation in a humid environment. Some important differences between the reaction wood and normal wood were found for both investigated wood species (spruce and yew), including the formation of cracks before loading (ascribed to residual stresses) and the change of fracture mode during crack propagation in the reaction wood. The higher crack propagation resistance was attributed mainly to the different cell (i.e. fiber) geometries (shape, cell wall thickness) and fiber angle to the load axis of the reaction wood, as basic structural features are responsible for more pronounced crack deflection and branching, thus leading to crack growth retardation. Fiber bridging was recognized as another crack growth retarding mechanism, which is effective in both wood species and especially pronounced in yew wood.

1. Introduction

The softwood species Common yew (*Taxus baccata* L.) and Norway spruce (*Picea abies* [L.] Karst.) strongly differ from each other regarding their anatomical structure. The growth rings of yew are narrower, and the growth ring boundaries are often wavy. A large amount of encased knots degrades the value of yew wood, while the high extractives content increases its durability (Wagenführ, 2000). The crucial difference between both species, however, is their raw density: yew has a high raw density with a relatively small gradient from earlywood to latewood, while the spruce density is about

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30% lower, and the gradient from earlywood to latewood is high (Keunecke et al., 2009). Especially due to these last-mentioned differences, both species are very well-suited for deriving fundamental structure-property relationships which establish correlations between the mechanical behavior of a material and its structural composition.

A comparison of both species' structure-property relationships regarding the longitudinal load direction has been addressed in diverse studies in the past (Keunecke et al., 2008a,b; Keunecke and Niemz, 2008), mainly with a focus on the linear elastic mechanical behavior. The mechanical response of wood loaded perpendicularly to the grain, however, is governed by different mechanisms. The role of the microfibril angle (MFA) is not too pronounced in this direction, whereas density plays a crucial role. In a previous study (Keunecke et al., 2007), a micro-wedge splitting test and microscopic methods were applied to characterize the elastic and fracture mechanical behavior of yew specimens (and of spruce as a reference species) in the transverse plane; the wedge splitting method used in this study was developed by Tschegg (1986) and modified by Frühmann et al. (2003) to test comparatively small specimens. Differences between both species regarding fracture mechanical properties and fracture behavior were ascribed to microstructural features (cell wall/lumen ratio; density gradient in the radial direction). The yew specimens were stiffer and stronger than spruce and showed mainly intercellular fracture, whereas cell-wall fracture and intercellular fracture occurred in spruce earlywood.

This current study is a continuation of the previous one (Keunecke et al., 2007) and, again, a purely basic research study without any practical (e.g. engineering-related) application interest regarding the tested species. However, exploring the functional principles of complex wooden materials that hold a special position regarding their structure-property relationships can contribute to a better understanding of wood mechanics. This may be important for researchers in biomechanics or even biomimetics, where artificial high-performance materials are developed by mimicry of biological structures.

In this paper, the focus is placed on the compression wood of spruce and yew. The starting point was our interest in the further structure-property relationships of the species yew which, among gymnosperms, hold an outstanding position in this regard. To complete our previous studies, which were mainly focused on the longitudinal load directions and the "normal" wood tissue, the transverse properties of the special tissue "compression" wood were analyzed in this study.

Compression wood is the reaction wood formed by conifers when they are subjected to mechanical stress (e.g. as a result of wind exposure or excess of snow). It is rich in lignin, and the tracheids are characterized by a round cross-sectional shape and intercellular spaces. The MFA of compression wood is clearly higher than that of normal wood, even though the differences are smaller for yew than for spruce wood. Once again, the micro wedge splitting test was used to ascertain how these structural differences to normal wood are reflected in the mechanical properties and fracture characteristics. Data evaluation was based on the principles of non-linear elastic fracture mechanics and of the fracture energy concept. Fracture phenomena such as crack paths and fracture surfaces were recorded simultaneously with the loading test in an environmental scanning microscope (*in-situ* ESEM) so that a correlation of mechanical data and crack features at the specimen surfaces was possible.

As mentioned above, it was not intended to present engineering applications of the tested material, since compression wood is avoided for engineering structures: this is particularly due to its dimensional stability, which – as a consequence of changes in ambient humidity (and therefore the wood moisture content) – is poor. A high microfibril angle in the secondary cell wall layer could be the reason for this, which, in combination with the high raw density of compression wood, results in extreme warping of boards and beams which goes along with shrinkage-induced cracks.

2. Material and testing procedure

Micro-wedge splitting tests were performed on yew (Taxus baccata L.) and spruce reaction wood (P. abies [L.] Karst.) in the chamber of an ESEM. For the sake of comparison, former results of experiments on normal wood are included, which were performed outside the ESEM (Keunecke et al., 2007). In order to assure that this is a true comparison, some experiments with the same material were performed ex-situ. The moisture content was kept approximately constant during the in-situ as well as ex-situ experiments, and the specimen shapes were identical in both experiments. Since the results were similar, it is assumed that it is justified to compare the in-situ and ex-situ results. The same was found in an earlier study (Frühmann et al., 2003).

For specimen production for this and the former study by Keunecke et al. (2007), green heartwood boards of five yew and five spruce stems from the area around Zurich in Switzerland were cut with a circular saw from breast height to 26 mm × 30 mm thick pieces. They were air-seasoned for several months until they reached a moisture content (MC) of approximately 15%–17%. Then, they were further stored in a conditioned room at 20 °C and 65% RH until equilibrium MC was reached. A series of forty specimens was machined to shapes and dimensions as shown in Fig. 1(a) and stored again at 20 °C and 65% RH.

A starter notch with a width of 1 mm was introduced with a band saw and sharpened with a razor blade. It was oriented in the TR crack propagation direction (*T*: load direction tangential, *R*: direction of crack growth radial) in all specimens (Fig. 1(a)). The loading device, which is a further development of the wedge splitting device of Tschegg (1986), is shown in Fig. 1(b): a loading head with two rolls moves against the slanted specimen surfaces and thus generates a mode *I* load, which causes crack propagation from the starter notch. The loading piece is attached to a load cell to determine the acting force (*F*). The specimen is placed vertically on a horizontal plate and supported by a bearing pin at the bottom, allowing the broken parts of the specimen to move apart. Friction between the rolls and the wood specimens is negligible, as could be shown in pre-tests (Frühmann et al., 2003). The load cell and the horizontal plate are attached to a micro-tension-compression machine constructed to fit into the chamber of an ESEM. The machine