STRUCTURAL AND MECHANICAL PROPERTIES
OF YEW WOOD

Daniel Keunecke, Christoph Märki, Peter Niemz
Institute for Building Materials, Wood Physics Group, Zürich, Switzerland

ABSTRACT

Yew wood (*Taxus baccata* L.) is known for its extraordinary mechanical performance compared to other gymnosperms. However, only few mechanical data are available from literature so far. Therefore, the goal of this study was to determine mechanical properties of yew wood such as longitudinal Young’s modulus in bending, fracture toughness $K_{IC}$, shear strength and tensile strength perpendicular to the grain. For comparison only, all tests were applied on spruce wood as well. Furthermore, we measured the microfibril angles of selected yew samples.

Our results confirm the high toughness of yew wood. The Young’s modulus is remarkably low taking the high density of yew into account. A large microfibril angle is discussed as possible explanation for the low Young’s modulus.

KEY WORDS: yew, Young’s modulus, fracture toughness, tensile strength perpendicular to the grain, shear strength, microfibril angle

INTRODUCTION

Yew wood (*Taxus baccata* L.) has an exceptional position within the gymnosperms. Its heartwood is classified as extremely durable, hard, tough and highly elastic (Sell 1997). Therefore, yew wood was used for the manufacturing of arms such as lances or bows in earlier centuries (Bariska 1998). Nowadays, yew is of commercial relevance in the medical sector since its constituents are used to support cancer therapies (Parmar et al. 1999). However, only few reference values are available from literature from the mechanical and technological point of view.

The aim of this study was to give a brief literature review of structural and mechanical characteristics of yew wood and to supplement them with our own findings. While special tissues like branches or compression wood of yew have been investigated in recent years (Burgert et al. 2004, Burgert and Jungnikl 2004), the main focus of this study was on elastic behaviour, strength and toughness of the regularly formed wood of the stem.

We applied non-destructive methods as well as static tests to calculate the Young’s modulus in bending. The fracture toughness $K_{IC}$ was determined by means of CT (compact tension) specimens. In addition, transverse tensile strength and shear strength have been determined.
In order to put the results into perspective, all tests were applied on Norway spruce wood (Picea abies [L.] Karst.) from the same stand as well. We also exemplarily measured the microfibril angles of single yew samples since these are not to be found in literature so far.

**Structural features**

The behaviour under load depends on the structure of a material. In this respect yew wood differs from other gymnosperms. It is characterised by narrow tree rings with wavy tree ring boundaries. A larger quantity of encased dead knots and irregular grain complicates the production of faultless specimens as well as large amounts of compression wood. Only two cell types are formed: Tracheids and homocellular wood rays (Wagenführ 2000). The tracheids are rather short (= 2 mm) with a high cell wall / lumen aspect ratio causing an extremely high density (= 0.67 g cm$^{-3}$) compared to other European gymnosperms. The density gradient between earlywood and latewood tracheids is smaller than in other gymnosperms (Wagenführ 2000). In other words, even in earlywood the cell walls of yew are relatively thick.

Identifying features of the tracheids are the conspicuous spiral thickenings (Fig. 1) (Wergin and Casperson 1961). These are ridges of cell wall material comprising an S-helix about the cell axis over the entire lumen surface (Parham and Kaustinen 1973). The mechanical effects of these spiral thickenings are largely unknown.

![Fig. 1: Spiral thickenings on the surface of yew tracheids (SEM image)](image)

The high percentage of wood rays (Fig. 2) suggests an increased radial reinforcement. A further characteristic feature is the remarkably high extractives content (Uslu 1997, Wagenführ 2000, Mertoglu-Elmas 2003). In Tab. 1 the structural characteristics of yew wood are summarised and compared with spruce wood.
Mechanical properties

The mechanical properties of yew wood are only partly known. Taking its relatively high density into account, the extreme Brinell hardness (Tab. 2) is not surprising. For the longitudinal Young’s modulus in bending, an unusual wide range from 6200 to 15700 MPa is reported (Sekhar and Sharma 1959, Jakubczyk 1966, Sell 1997, Wagenführ 2000). Tensile strength, compression strength and bending strength are slightly higher than the corresponding spruce values; impact bending strength (147 kJ m\(^{-2}\)) is even three times as high (Sell 1997). That is, yew wood is able to resist considerable dynamic loads. Values for transverse stiffness, shear modulus and fracture toughness are still lacking. An overview of the mechanical properties of yew and spruce wood is given in Tab. 2.

MATERIAL AND METHODS

For the specimen production, sample trees from stands close to Zurich (Switzerland) were chosen. The sawn timber was oven-dried to 12% moisture content. Only adult wood from heartwood regions free of compression wood was used for specimen preparation. All specimens were stored in a climate chamber at 20°C and 65% RH until they reached equilibrium moisture content. Furthermore, the density (DIN 52182) was determined.

Determination of Young’s modulus, bending strength and work to ultimate load

Three test procedures were applied; two of them were non-destructive. The latter primarily should verify the validity of the static test. The longitudinal Young’s modulus was calculated on the basis of sound velocity and eigenfrequency for the same set of specimens subsequently used in the static bending test. For this reason, the specimens were cut to dimensions of 400 mm (longitudinal) x 20 mm (radial) x 20 mm (tangential). 60 yew and 60 spruce specimens were tested.
Tab. 1: Structural characteristics of yew and spruce wood

<table>
<thead>
<tr>
<th>Structural characteristics</th>
<th>Yew (Taxus baccata L.)</th>
<th>Spruce (Picea abies [L.] Karst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General characteristics</td>
<td></td>
<td>[1,2,3]</td>
</tr>
<tr>
<td></td>
<td>– clear and wavy tree-ring boundaries</td>
<td>– clear tree-ring boundaries</td>
</tr>
<tr>
<td></td>
<td>– gradual early wood/late wood transition</td>
<td>– gradual early wood/late wood transition</td>
</tr>
<tr>
<td></td>
<td>– no resin canals</td>
<td>– resin canals</td>
</tr>
<tr>
<td></td>
<td>– narrow ringed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– spiral thickenings on the surface of the secondary wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– a large number of knots and grain deviations</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>Raw (MC = 12%) [kg m⁻³]</td>
<td>[1] 640...670...810 630...720</td>
</tr>
<tr>
<td></td>
<td>oven-dry [kg m⁻³]</td>
<td>[1] 610...640...740 590...670 620</td>
</tr>
<tr>
<td>Tracheids</td>
<td>percentage [%]</td>
<td>[1] 86</td>
</tr>
<tr>
<td></td>
<td>length [μm]</td>
<td>[1] 1550...1950...2250</td>
</tr>
<tr>
<td></td>
<td>lumen [μm]</td>
<td>[1] 5...9...14</td>
</tr>
<tr>
<td></td>
<td>wall thickness [μm]</td>
<td>[1] Early wood: 4.2 Late wood: 7.7</td>
</tr>
<tr>
<td>Rays</td>
<td>percentage [%]</td>
<td>[1] 14</td>
</tr>
<tr>
<td></td>
<td>density (rays per mm in tangential direction) [%]</td>
<td>[1] 5...7...10</td>
</tr>
<tr>
<td></td>
<td>width [μm]</td>
<td>[1] 7...10...16</td>
</tr>
<tr>
<td></td>
<td>height [μm]</td>
<td>[1] 80...145...230</td>
</tr>
<tr>
<td></td>
<td>composition</td>
<td>[1] homocellular (radial parenchyma)</td>
</tr>
<tr>
<td>Axial parenchyma</td>
<td>percentage [%]</td>
<td>[1] 0</td>
</tr>
<tr>
<td>Chemical composition</td>
<td>cellulose [%]</td>
<td>[1] 32.6 41.6...48.6</td>
</tr>
<tr>
<td></td>
<td>pentosan [%]</td>
<td>[1] 9.8</td>
</tr>
<tr>
<td></td>
<td>extractives (ethanol benzene) [%]</td>
<td>[1] 7.4...14.3 10.2...20.6 19.2</td>
</tr>
<tr>
<td></td>
<td>ash [%]</td>
<td>[1] 0.3 0.4...0.6 0.2</td>
</tr>
</tbody>
</table>

Tab. 2: Mechanical properties of yew and spruce wood

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Yew (Taxus baccata L.)</th>
<th>Spruce (Picea abies [L.] Karst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength $\sigma_B$</td>
<td>[MPa] 108</td>
<td>[1] 80...90 21...90...245 80</td>
</tr>
<tr>
<td>Tensile strength $\tau_B$</td>
<td>[MPa] 80</td>
<td>[2] 1.5...2.7...4.0 1.7...2.2</td>
</tr>
<tr>
<td>Compression strength $\sigma_C$</td>
<td>[MPa] 57, 58, 48...63</td>
<td>[4] 3.9...4.8</td>
</tr>
<tr>
<td>Bending strength $\sigma_B$</td>
<td>[MPa] 85, 92, 83...100</td>
<td>[1] 30...43...67</td>
</tr>
<tr>
<td>MOE in bending $\sigma_B$</td>
<td>[MPa] 15700</td>
<td>[2] 1.7...2.2</td>
</tr>
<tr>
<td>MOE $\sigma_B$ (rad.)</td>
<td>[MPa] 12000</td>
<td>[4] 40...78...136</td>
</tr>
<tr>
<td>MOE $\sigma_B$ (tang.)</td>
<td>[MPa] 6200...10300</td>
<td>[8] 40...78...136</td>
</tr>
<tr>
<td>Shear strength $\tau_S$</td>
<td>[MPa] 12.8, 14.6</td>
<td>[4] 5.0...7.5 4.0...6.7...12.0</td>
</tr>
<tr>
<td>Shear modulus $G_{L,R}$</td>
<td>[MPa] 629</td>
<td>[9]</td>
</tr>
<tr>
<td>Impact bending strength $a$</td>
<td>[kJ/m²] 147</td>
<td>[1] 40...50 10...46...110 10...45...108</td>
</tr>
<tr>
<td>Fracture toughness $K_{IC}$</td>
<td>[MPa m⁰.⁵] 0.3</td>
<td>[7]</td>
</tr>
<tr>
<td>Brinell hardness $HB$</td>
<td>[MPa] 68, 65...71</td>
<td>[1] 31</td>
</tr>
<tr>
<td>Brinell hardness $HB$</td>
<td>[MPa] 31, 29...59</td>
<td>[2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[9]</td>
</tr>
</tbody>
</table>

Sound velocity

The dynamic Young’s modulus was calculated from the sound propagation time for the longitudinal sound wave passing through the specimen. Equation 1 applies for a rod with a small width and height compared to the wave length of the acoustic signal (Krautkrämer and Krautkrämer 1986):

\[ \text{MOE}_s = \rho_u \cdot c^2 \quad \text{[MPa]} \]  

(1)

where \( \text{MOE}_s \) is the Young’s modulus determined by sound velocity, \( \rho_u \) is the raw density at 20°C and 65% RH and \( c \) is the sound velocity. For these measurements, a STEINKAMP BP5 sound propagation timer (frequency 50 kHz) was used.

Eigenfrequency

The eigenfrequency of bending waves based on impulse excitation technique as described by Görlacher (1984) was measured using a GRINDO-SONIC MK 5 INDUSTRIAL. In both nodal points for first order oscillations, the specimens were supported by foam rubber damped bearings. They were excited by a singular elastic strike with an impulse tool. The vibrations in the tangential direction resulting from the strike correspond to the static bending test. A piezoelectric needle sensed the mechanical vibrations of the specimens and transformed them into electric signals. Young’s modulus calculation was based on equation 2.

\[ \text{MOE}_{b,G} = \frac{4 \pi^2 \cdot f_0^2 \cdot \rho_u \cdot (1 + \frac{i^2}{l^2} \cdot K_1) \cdot 10^{-9}}{m_n^4 \cdot l^2} \quad \text{[MPa]} \]  

(2)

where \( \text{MOE}_{b,G} \) is the Young’s modulus determined by eigenfrequency, \( l \) is the specimen length, \( f_0 \) is the eigenfrequency, \( \rho_u \) is the raw density at 20°C and 65% RH, \( i \) is the radius of inertia \((i^2 = h^2/12, \text{where } h \text{ is the specimen height})\), and \( K_1 \) and \( m_n^4 \) are constants depending on the order of vibration. The following constants are used for first order bending vibrations: \( K_1 = 49.48 \) and \( m_n^4 = 500.6 \) (Görlacher 1984).

Static bending test

A universal testing machine (ZWICK Z100) with 100 kN load capacity was used to perform 3-point bending tests according to DIN 52186. After having passed \( F_{\text{max}} \) load was automatically stopped when the specimen broke or when load decreased to 50% of \( F_{\text{max}} \). The Young’s modulus was calculated on basis of equation 3.

\[ \text{MOE}_B = \frac{l^3}{4 \cdot b \cdot h^3} \cdot \frac{\Delta F}{\Delta f} \quad \text{[MPa]} \]  

(3)

where \( \text{MOE}_B \) is the Young’s modulus determined by 3-point bending, \( l \) is the support span, \( b \) is the specimen width, \( h \) is the specimen height, \( \Delta F \) is any load difference to the proportional limit of the specimen and \( \Delta f \) is the deflection in the centre of the specimen corresponding to \( \Delta F \). Additionally, the bending strength \( \sigma_{bB} \) and work to ultimate load \( w_u \) were determined, the latter as defined by Bodig and Jayne (1982):

\[ w_u = \frac{W_{\text{max}}}{V} \quad \text{[kJ.m}^{-3}] \]  

(4)
where \( w_u \) is the work to ultimate load, \( W_{F_{\text{max}}} \) is the work to \( F_{\text{max}} \), and \( V \) is the sample volume inside the bearings. The peripheral strain (DIN 53452) indicates the maximum strain within the specimen at the time of failure:

\[
\varepsilon = \frac{6 \cdot h \cdot f_{\text{max}}}{l_s^2} \cdot 100 \quad [\%] \tag{5}
\]

where \( \varepsilon \) is the peripheral strain, \( f_{\text{max}} \) is the deflection at maximum load, \( l_s \) is the support span and \( h \) is the specimen height. However, this equation normally applies for homogeneous materials like synthetics. Therefore a systematic error may be expected.

**Fracture toughness test**

CT (compact tension) specimens were used to determine fracture toughness \( K_{IC} \) according to ASTM E 399-90. The specimen geometry can be seen from Fig. 3; circular sawn 37.0 mm notches were extended to 37.5 mm using a knife. Load was recorded by the servo hydraulic SCHENCK testing machine, crack opening displacement was measured by means of a clip on-gage. 40 yew and 40 spruce RL specimens as well as 40 yew and 40 spruce TL specimens were tested (the first letter indicates the load direction; the second indicates the direction of crack propagation). Fracture toughness was determined according to equation 6:

\[
K_{IC} = \frac{F_Q}{B \cdot W}, \quad f(a/W) \quad [\text{MPa m}^{0.5}] \tag{6}
\]

where \( K_{IC} \) is the fracture toughness, \( F_Q \) is the force, \( a \) is the crack length at the beginning of the test, \( B \) is the specimen thickness, \( W \) is the specimen width, and \( f(a/W) \) is a geometry equation (for \( a/W = 0.50 \) applies: \( f(a/W) = 9.66 \)):

\[
f(a/W) = (2 + a/W) \cdot \frac{0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4}{(1 - a/W)^{1.5}} \tag{7}
\]

**Fig. 3: Geometry of CT specimens. All dimensions in mm**
Determination of tensile strength perpendicular to the grain

The transverse tensile strength of yew and spruce specimens was determined by tension tests perpendicular to the grain according to ASTM D 143-94. 10 specimens per species were loaded in the radial direction, another 10 in the tangential direction. Fig. 4 shows the specimen geometry.

![Fig. 4: Geometry of tension specimens. All dimension in mm](image)

Determination of shear strength parallel to the grain

The ultimate shear stress of yew and spruce specimens was determined according to DIN 52187. The shear plane was LR for 7 specimens per species and LT for another 7 specimens.

Measurement of microfibril angles

Exemplary measurements of the microfibril angle (MFA) in the $S_2$ layer were performed on randomly chosen samples of adult yew heartwood. Three 200 $\mu$m thick tangential sections were cut out of four growth rings, respectively. The growth rings were located at a distance of at least 100 rings from the pith. Thus, a total of 12 MFAs was examined by wide angle X-ray diffraction. A position-sensitive detector was used in transmission geometry. The MFA was evaluated on the basis of cellulose (110) reflections (Lichtenegger et al. 1997). The reflections are indexed according to Sugiyama et al. (1990).

RESULTS AND DISCUSSION

Young’s modulus, bending strength and work to ultimate load

The longitudinal Young’s modulus determined in the static bending test was higher for spruce than for yew wood. The mean value for spruce (12100 MPa) is within the range known from literature. Despite the high density, the Young’s modulus for yew (9700 MPa) was relatively low which is in agreement with Jakubczyk (1966) and Sekhar and Sharma (1959). In contrast, none of our values reached a Young's modulus close to 15700 MPa as reported by Sell (1997) although
yew samples free of compression wood, without knots and with as few grain deviations as possible, were tested. The dynamic Young's modulus obtained from eigenfrequency tests was in the same range like the static values. The Young's modulus calculated from sound velocity was proportionally higher for both wood species (~35% for yew and ~29% for spruce) which is due to a methodological problem well described in literature (Bucur 1995). The high correlation between the dynamic and static tests (Figs. 5, 6) confirms the validity of the results. An overview of the results mentioned above is given in Tab. 3.

Fig. 5: Correlation between static and dynamic tests for yew. MOE$_S$ calculated from sound velocity, MOE$_{b,G}$ from eigenfrequency, MOE$_b$ determined with static bending

Fig. 6: Correlation between static and dynamic tests for spruce
Tab. 3: Sound velocity and Young’s modulus determined by dynamic and static tests. MOE$_S$ calculated from sound velocity, MOE$_{b,G}$ from eigenfrequency, MOE$_b$ determined with static bending

Despite the relatively low Young’s Modulus, a mean bending strength of 118 MPa (Tab. 4) was determined for yew wood which is about 40% higher than the corresponding spruce value (86 MPa). The peripheral strain at failure was even 54% higher for yew than for spruce. This high strain and simultaneously high bending strength result in a great work to ultimate load ($w_u$) which is a measure of the combined strength and toughness of a material loaded in bending. It was more than twice as high for yew (173 kJ m$^{-3}$) than for spruce (83 kJ m$^{-3}$). The large elastic portion of $w_u$ compared to spruce wood (Tab. 4) indicates a high extensibility within the elastic range for yew wood, taking the relatively low Young’s modulus into account. The large amount of $w_u$ in the plastic range shows that yew has the ability to absorb a large amount of energy during a plastic deformation. This is characteristic for tough materials and confirms that yew is extremely capable of resisting crack propagation.

Tab. 4: Peripheral fracture strain, bending strength and work to ultimate load

Microfibril angles

Particularly the microfibril angle (MFA) of the helically oriented cellulose fibrils in the S$_2$ cell wall layer influences the mechanical behaviour on cellular level. The larger the MFA, the larger the maximum strain and the lower the Young’s modulus (Reiterer et al. 1999). In order to clarify if the MFA might be responsible for the mechanical behaviour we observed in the bending test for yew wood, we determined the MFA of selected yew samples. A small MFA as explanation for the high extensibility and simultaneously low Young’s modulus of yew would not be feasible.

The MFA we measured for adult yew wood varies from 16° to 31° at a mean value of 23° (Tab. 5). However, these measurements are only exemplary and not statistically firm. Even so, there is
evidence to suggest that the MFA of yew wood is relatively large since much smaller MFA (4-8°) have been reported for the mature wood of northern conifers (Kantola and Seitsonen 1969, Paakkari and Serimaa 1984, Fratzl et al. 1997, Saren et al. 2001).

**Tab. 5: Microfibril angle of yew**

<table>
<thead>
<tr>
<th>Section</th>
<th>Growth Ring A</th>
<th>Growth Ring B</th>
<th>Growth Ring C</th>
<th>Growth Ring D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>18°</td>
<td>27°</td>
<td>19°</td>
<td>26°</td>
</tr>
<tr>
<td>Section 2</td>
<td>16°</td>
<td>24°</td>
<td>23°</td>
<td>26°</td>
</tr>
<tr>
<td>Section 3</td>
<td>17°</td>
<td>31°</td>
<td>22°</td>
<td>26°</td>
</tr>
</tbody>
</table>

**Tensile strength perpendicular to the grain**

In the longitudinal direction, stiffness and strength of wood predominantly depend on the MFA of the S2. The transverse mechanical properties are about one order of magnitude lower than in longitudinal direction. They are primarily influenced by cell geometry (Kahle and Woodhouse 1994), density and ray percentage whereas the role of the MFA is a controversial issue in literature.

The relatively thick cell walls and small lumens of yew tracheids, together with partly extremely narrow tree rings, cause the high density of yew wood. As a consequence, the values we measured for yew (5.9 MPa radial, 4.3 MPa tangential) exceed the values for spruce (3.6 MPa radial, 2.6 MPa tangential) (Tab. 6). In case of both species, the radial tensile strength was nearly 40% higher than the tangential strength due to the stiffening effect of the wood rays which not only influence the radial stiffness but also the radial strength (Burgert 2000).

**Tab. 6: Tensile strength perpendicular to the grain**

<table>
<thead>
<tr>
<th>species</th>
<th>direction</th>
<th>number of specimens</th>
<th>density</th>
<th>tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>ρ [g/cm³]</td>
<td>σmax</td>
</tr>
<tr>
<td>yew</td>
<td>R</td>
<td>10</td>
<td>0.65</td>
<td>5.9</td>
</tr>
<tr>
<td>yew</td>
<td>T</td>
<td>10</td>
<td>0.64</td>
<td>4.3</td>
</tr>
<tr>
<td>spruce</td>
<td>R</td>
<td>10</td>
<td>0.44</td>
<td>3.6</td>
</tr>
<tr>
<td>spruce</td>
<td>T</td>
<td>10</td>
<td>0.44</td>
<td>2.6</td>
</tr>
</tbody>
</table>

**Mode I fracture toughness**

Fracture toughness is defined as the ability of a material to withstand flaws that initiate failure. That is, once a crack is initiated in a material, primary interest focuses on the level of force required for the crack to propagate (Bodig and Jayne 1982). The critical stress intensity factor $K_{IC}$ is a measure of the strength of the critical stress concentration at the tip of a sharp crack. Due to the
strength properties of wood as a function of grain orientation, particularly mode I fracture parallel to the grain has received the attention of wood scientists since wood is weakest when loaded in the radial and tangential direction.

As expected, fracture toughness $K_{IC}$ was significantly higher for yew wood than for spruce wood. As consequence of the correlation with tensile strength perpendicular to the grain, $K_{IC}$ (RL) was about 20% higher than the corresponding TL value in case of yew specimens, for spruce RL specimens even 60% higher. The higher toughness of both wood species in radial direction can be ascribed to the reinforcing effect of wood rays. As well as observed for the peripheral fracture strain in the bending test, $K_{IC}$ was clearly higher for yew in both the radial (+51%) and tangential (+100%) load direction. The results are summarized in Tab. 7.

Tab. 7: Fracture toughness of CT specimens

<table>
<thead>
<tr>
<th>species</th>
<th>direction</th>
<th>number of specimens</th>
<th>density</th>
<th>fracture toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n$</td>
<td>$\rho$ [g cm$^{-3}$]</td>
<td>$K_{IC}$ [MPa m$^{0.5}$]</td>
</tr>
<tr>
<td>yew</td>
<td>RL</td>
<td>40</td>
<td>0.75</td>
<td>0.8</td>
</tr>
<tr>
<td>yew</td>
<td>TL</td>
<td>40</td>
<td>0.70</td>
<td>0.8</td>
</tr>
<tr>
<td>spruce</td>
<td>RL</td>
<td>40</td>
<td>0.42</td>
<td>0.8</td>
</tr>
<tr>
<td>spruce</td>
<td>TL</td>
<td>40</td>
<td>0.42</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Shear strength in the radial and tangential shear planes

Shear strength parallel to the grain is the ability to resist internal slipping of one part upon another along the grain. Compared to values for yew described in literature (Tab. 2), our values for shear strength were slightly higher (LR 18.1 MPa, LT 18.6 MPa); they were about twice as high as the values we measured for spruce (LR 9.6 MPa, LT 8.6 MPa) (Tab. 8). It is conceivable that, besides the high density and the high ray percentage, the way how yew tracheids are meshed due to their irregular grain causes the high shear strength. Since we tested only a small number of specimens, no assessment of differences between the values of the LR and LT planes was possible.

Tab. 8: Shear strength in the LR and LT plane

<table>
<thead>
<tr>
<th>species</th>
<th>direction</th>
<th>number of specimens</th>
<th>density</th>
<th>shear strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n$</td>
<td>$\rho$ [g cm$^{-3}$]</td>
<td>$\tau$ [MPa]</td>
</tr>
<tr>
<td>yew</td>
<td>LR</td>
<td>7</td>
<td>0.71</td>
<td>7.2</td>
</tr>
<tr>
<td>yew</td>
<td>LT</td>
<td>7</td>
<td>0.69</td>
<td>5.4</td>
</tr>
<tr>
<td>spruce</td>
<td>LR</td>
<td>7</td>
<td>0.44</td>
<td>6.5</td>
</tr>
<tr>
<td>spruce</td>
<td>LT</td>
<td>7</td>
<td>0.44</td>
<td>5.1</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Elasticity is defined as ability of a material to return to its original shape when load causing deformation is removed. A highly elastic material is characterized by its extreme extensibility within the elastic range. From this point of view, yew wood proved to be highly elastic. We even observed both a high elastic and fracture strain. Moreover, we showed that a high dense wood species not inevitably has to have a high longitudinal Young’s modulus. In this regard yew wood seems to be an outlier when compared with other gymnosperms. A large MFA is conceivable as explanation for the low stiffness.

Furthermore, a high toughness could be confirmed for yew wood in the longitudinal direction (by means of 3-point-bending tests) as well as in the radial and tangential direction (by means of fracture toughness tests).

The results provide a basis for subsequent studies. Detailed research into micromechanics is essential to understand the mechanical behaviour of yew wood. Correlations between mechanical properties on the one hand and structural properties such as microfibril angle, density, cellular dimensions, ray percentage, grain deviations and extractives content on the other hand should be examined as well.

ACKNOWLEDGEMENTS

We would like to thank Karin Jungnikl (Max Planck Institute of Colloids and Interfaces in Golm, Germany) for the MFA measurements.

This work was supported by the European Cooperation in the field of Scientific and Technical Research (COST, Action E35).
REFERENCES


36
27. Sekhar, A.C., Sharma, R.S., 1959: A note on mechanical properties of taxus baccata. Indian Forester 85: 324-326

STANDARDS

2. ASTM E 399-90: Test method for plain-strain fracture toughness of metallic materials (reapproved 1997)
3. DIN 52182: Testing of wood; determination of density
4. DIN 52186: Testing of wood; bending test
5. DIN 52187: Testing of wood; determination of ultimate shearing stress parallel to grain
6. DIN 52453: Plastics; determination of flexural properties (withdrawn)
Daniel Keunecke  
ETH Zürich  
Institute for Building Materials  
Wood Physics Group  
Schafmattstrasse 6  
CH - 8093 Zürich  
Switzerland  
Tel.: +41 (44) 632 32 32  
Fax: +41 (44) 632 11 74  
E-mail: keunecke@ifb.baug.ethz.ch

Christoph Märki  
ETH Zürich  
Institute for Building Materials  
Wood Physics Group  
Schafmattstrasse 6  
CH - 8093 Zürich  
Switzerland  
Tel.: +41 (44) 632 32 32  
Fax: +41 (44) 632 11 74

Peter Niemz  
ETH Zürich  
Institute for Building Materials  
Wood Physics Group  
Schafmattstrasse 6  
CH - 8093 Zürich  
Switzerland  
Tel.: +41 (44) 632 32 32  
Fax: +41 (44) 632 11 74