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STRUCTURAL AND MECHANICAL PROPERTIES OF YEW WOOD

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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.

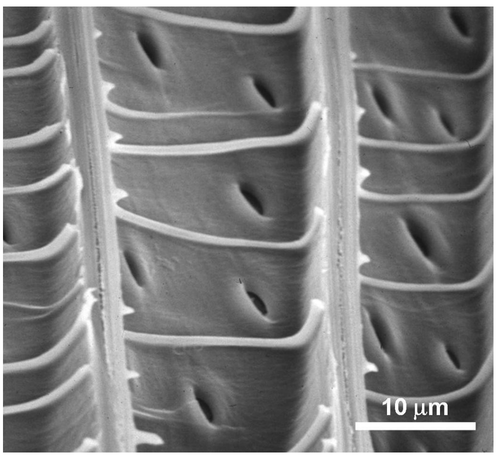

Fig. 1: Spiral thickenings on the surface of yew tracheids (SEM image)

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.

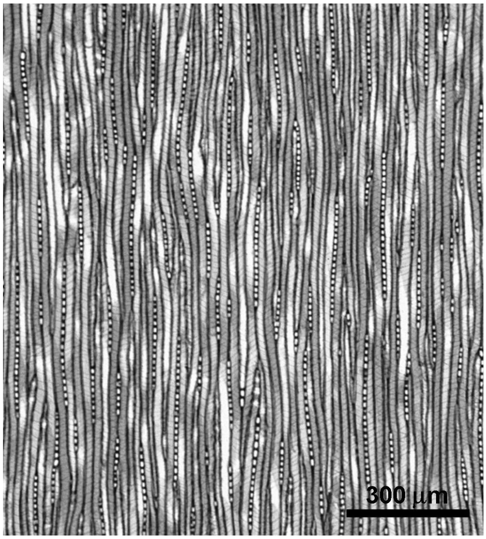

Fig. 2: High ray percentage (tangential microtome section)

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

Structural characteristics			**Yew (*Taxus baccata* L.)**		**Spruce (*Picea abies* [L.] Karst.)**	
General characteristics			– clear and wavy tree-ring boundaries – gradual early wood/late wood transition – no resin canals – narrow ringed – spiral thickenings on the surface of the secondary wall – a large number of knots and grain deviations	[1,2,3]	– clear tree-ring boundaries – gradual early wood/late wood transition – resin canals	[1,3]
Density	Raw (MC = 12%)	[kg m^{-3}]	640…670…810 630…720	[1] [4]	330…470…680 430…470	[1] [1]
	oven-dry	[kg m^{-3}]	610…640…740 590…670 620	[1] [4] [5]	300…430…640 400…430	[1] [4]
Tracheids	percentage	[%]	≈ 86	[1]	94…95…96	[1]
	length	[µm]	1550…1950…2250	[1]	1300…2800…4300	[1]
	lumen	[µm]	5…9…14	[1]	3…17…22	[1]
	wall thickness	[µm]	Early wood: 4.2 Late wood: 7.7	[1]	Early wood: 3.5 Late wood: 10.7	[1]
Rays	percentage	[%]	≈ 14	[1]	4…5…6	[1]
	density (rays per mm in tangential direction)		5…7…10	[1]	4…5…7	[1]
	width	[µm]	7…10…16	[1]	8…14	[1]
	height	[µm]	80…145…230	[1]	100…150…190	[1]
	composition		– homocellular (radial parenchyma)	[1]	– heterocellular (radial parenchyma and radial tracheids)	[1]
Axial parenchyma	percentage	[%]	0	[1]	0…1…6	[1]
Chemical composition	cellulose	[%]	32.6 41.6…48.6	[1] [6]	42.0	[1]
	pentosan	[%]	9.8	[7]	6.8…12.0	[1]
	lignin	[%]	28.8 26.1…28.8	[1] [6]	24.0	[1]
	extractives (ethanol benzene)	[%]	7.4…14.3 10.2…20.6 19.2	[1] [6] [7]	1.5	[1]
	ash	[%]	0.3 0.4…0.6 0.2	[1] [6] [7]	0.6	[1]

[1] Wagenführ (2000) [2] Kucera (1998) [3] Grosser (1977) [4] Sell (1997)
[5] Jakubczyk (1966) [6] Uslu (1997) [7] Mertoglu-Elmas (2003)

Tab. 2: Mechanical properties of yew and spruce wood

Mechanical properties			**Yew (*Taxus baccata* L.)**		**Spruce (*Picea abies* [L.] Karst.)**	
Tensile strength	σ_{tB} ∥	[MPa]	108	[1]	80…90 21…90…245 80	[1] [2] [3]
Tensile strength	σ_{tB} ⊥	[MPa]	3.3…4.5	[4]	1.5…2.7…4.0 1.7…2.2 3.9…4.8	[2] [5] [6]
Compression strength	σ_{cB} ∥	[MPa]	57 58 48…63	[1] [2] [4]	40…50 33…50…79 40 30…43…67	[1] [2] [3] [7]
Bending strength	σ_{bB} ∥	[MPa]	85 92 83…100	[1] [2] [4]	65…77 49…78…136 68 42…66…116	[1] [2] [3] [7]
MOE in bending	MOE_b ∥	[MPa]	15700 12000 6200…10300 7000	[1] [2] [4] [8]	10000…12000 7300…11000…21400 10000	[1] [2] [3]
	MOE_b ⊥ (rad.)	[MPa]			800 170…540…690 700	[3] [9] [10]
	MOE_b ⊥ (tang.)	[MPa]			450 170…540…690 400	[3] [9] [10]
Shear strength	τ_B	[MPa]	12.8 14.6	[4] [8]	5.0…7.5 4.0…6.7…12.0	[1] [2]
Shear modulus	G_{LR}	[MPa]			629	[9]
	G_{LT}	[MPa]			781	[9]
	G_{RT}	[MPa]			37	[9]
Impact bending strength	a	[kJ/m^{-2}]	147	[1]	40…50 10…46…110 10…45…108	[1] [2] [9]
Fracture toughness	K_{IC} RL	[MPa m^{0,5}]			0.3 0.27…0.47	[7] [11]
	K_{IC} TL	[MPa m^{0,5}]			0.3 0.25…0.42	[7] [11]
Brinell hardness	HB ∥	[MPa]	68 65…71 59…(98)	[1] [2] [9]	31 32	[1] [2]
	HB ⊥	[MPa]	31 29…(59)	[1] [9]	12…16 12	[1] [2]

[1] Sell (1997) [2] Wagenführ (2000) [3] DIN 68364 (2003) [4] Sekhar and Sharma (1959)
[5] Pozgaj et al. (1997) [6] Welling (1987) [7] Niemz (1993) [8] Jakubczyk (1966)
[9] Kollmann (1951) [10] Keylwerth (1951) [11] Logemann and Schelling (1992)

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):

$$MOE_s = \rho_u \cdot c^2 \qquad [MPa] \qquad (1)$$

where MOE_s is the Young's modulus determined by sound velocity, ρ_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.

$$MOE_{b,G} = \frac{4\pi^2 \cdot l^4 \cdot f_0^2 \cdot \rho_u}{m_n^4 \cdot i^2} \cdot \left(1 + \frac{i^2}{l^2} \cdot K_1\right) \cdot 10^{-9} \qquad [MPa] \qquad (2)$$

where $MOE_{b,G}$ is the Young's modulus determined by eigenfrequency, l is the specimen length, f_0 is the eigenfrequency, ρ_u is the raw density at 20°C and 65% RH, i is the radius of inertia ($i^2 = h^2/12$, where h 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_{max}, load was automatically stopped when the specimen broke or when load decreased to 50% of F_{max}. The Young's modulus was calculated on basis of equation 3.

$$MOE_B = \frac{l^3}{4 \cdot b \cdot h^3} \cdot \frac{\Delta F}{\Delta f} \qquad [MPa] \qquad (3)$$

where 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, ΔF is any load difference to the proportional limit of the specimen and Δf is the deflection in the centre of the specimen corresponding to ΔF. Additionally, the bending strength σ_{bB} and work to ultimate load w_u were determined, the latter as defined by Bodig and Jayne (1982):

$$w_u = \frac{W_{F_{max}}}{V} \qquad [kJ.m^{-3}] \qquad (4)$$

where w_u is the work to ultimate load, W_{Fmax} is the work to F_{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:

$$\varepsilon = \frac{6 \cdot h \cdot f_{max}}{l_s^2} \cdot 100 \qquad [\%] \qquad (5)$$

where ε is the peripheral strain, f_{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:

$$K_{IC} = \frac{F_Q}{B \cdot \sqrt{W}} \cdot f(a/W) \qquad [\mathrm{MPa\ m}^{0,5}] \qquad (6)$$

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):

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

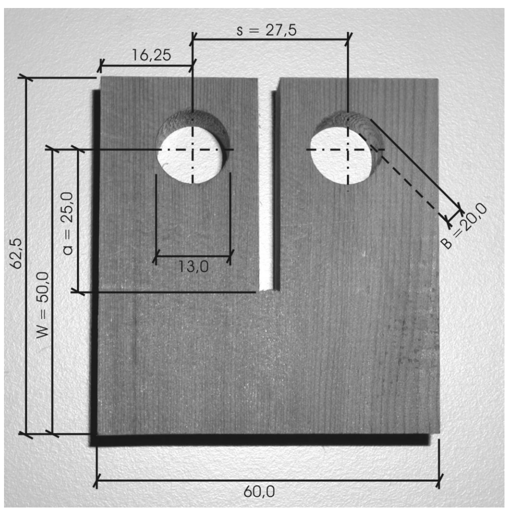

Fig. 3: Geometry of CT specimens. All dimensions in mm

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.

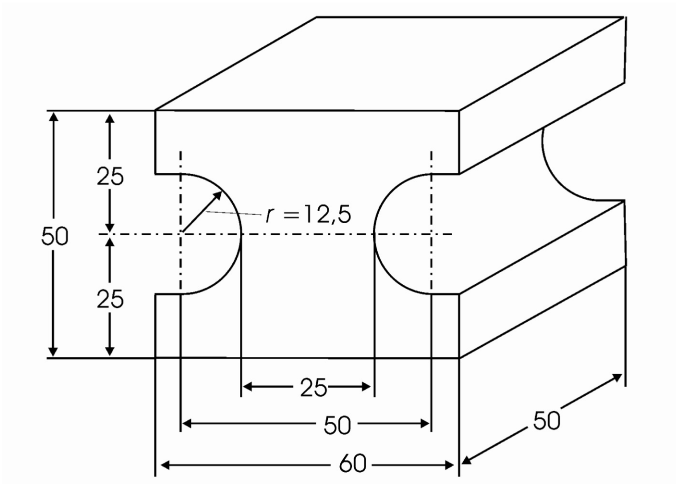

Fig. 4: Geometry of tension specimens. All dimension in mm

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 µm 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.

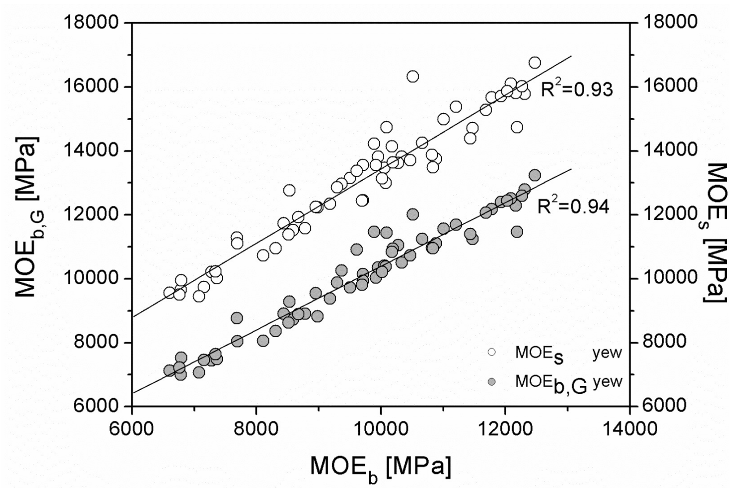

Fig. 5: Correlation between static and dynamic tests for yew. MOE_S calculated from sound velocity, $MOE_{b,G}$ from eigenfrequency, MOE_b determined with static bending

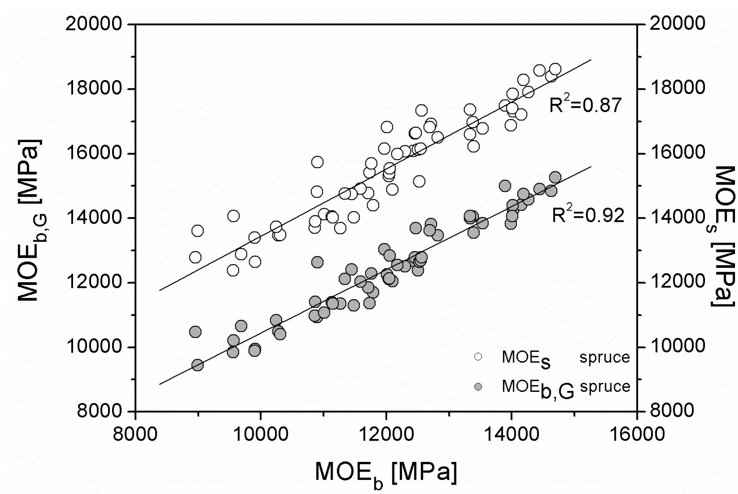

Fig. 6: Correlation between static and dynamic tests for spruce

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

	number of specimens	density		sound velocity	Young's modulus (MOE)		
	n		ρ [g cm^{-3}]	c [m s^{-1}]	MOE_s [MPa]	$MOE_{b,G}$ [MPa]	MOE_b [MPa]
yew	60	$\bar{x}$	0.68	4410	13100	10100	9700
		v%	10.6	9.0	15.2	16.8	17.0
spruce	60	$\bar{x}$	0.43	6010	15600	12500	12100
		v%	6.1	3.2	10.5	12.0	12.2

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

	number of specimens	density		peripheral strain	bending strength	work to ultimate load		
	n		ρ [g cm^{-3}]	ε [%]	σ_{bB} [MPa]	w_u [kJ m^{-3}]	$w_{u\,el.}$ [kJ m^{-3}]	$w_{u\,plast.}$ [kJ m^{-3}]
yew	60	$\bar{x}$	0.68	2.0	118	173	41	132
		v%	10.6	30.8	14.5	47.8	17.8	55.4
spruce	60	$\bar{x}$	0.43	1.3	86	83	15	68
		v%	6.1	13.2	10.3	24.8	18.2	27.8

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

	Growth Ring A	Growth Ring B	Growth Ring C	Growth Ring D
Section 1	18°	27°	19°	26°
Section 2	16°	24°	23°	26°
Section 3	17°	31°	22°	26°

Tensile strength perpendicular to the grain

In the longitudinal direction, stiffness and strength of wood predominantly depend on the MFA of the S_2. 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

species	direction	number of specimens	density		tensile strength
		n		ρ [g cm^{-3}]	$\sigma_{tB} \perp$ [MPa]
yew	R	10	$\bar{x}$	0.65	5.9
			v%	5.3	19.9
yew	T	10	$\bar{x}$	0.64	4.3
			v%	2.2	14.2
spruce	R	10	$\bar{x}$	0.44	3.6
			v%	6.8	24.6
spruce	T	10	$\bar{x}$	0.44	2.6
			v%	6.8	14.7

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

species	direction	number of specimens	density		fracture toughness
		n		ρ [g cm^{-3}]	K_{IC} [MPa m$^{0.5}$]
yew	RL	40	$\bar{x}$	0.75	0.56
			v%	6.7	25.0
yew	TL	40	$\bar{x}$	0.70	0.46
			v%	6.7	24.6
spruce	RL	40	$\bar{x}$	0.42	0.37
			v%	4.8	13.5
spruce	TL	40	$\bar{x}$	0.42	0.23
			v%	6.4	9.3

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

species	direction	number of specimens	density		shear strength
		n		ρ [g cm^{-3}]	τ_B [MPa]
yew	LR	7	$\bar{x}$	0.71	18.1
			v%	7.2	17.2
yew	LT	7	$\bar{x}$	0.69	18.6
			v%	5.4	15.3
spruce	LR	7	$\bar{x}$	0.44	9.6
			v%	6.5	10.6
spruce	LT	7	$\bar{x}$	0.44	8.6
			v%	5.1	4.0

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.

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REFERENCES

1. Bariska, M., 1998: Verwendung des Eibenholzes gestern und heute. Schweizerische Zeitschrift für Forstwesen 149(5): 340-348
2. Bodig, J., Jayne, B.A., 1982: Mechanics of wood and wood composites. Van Nostrand Reinhold. New York, 712 pp.
3. Bucur, V., 1995: Acoustics of wood. CRC Press. Boca Raton, 284 pp.
4. Burgert, I., 2000: Die mechanische Bedeutung der Holzstrahlen im lebenden Baum. Dissertation, Hamburg, 173 pp.
5. Burgert, I., Fruhmann, K., Keckes, J., Fratzl, P., Stanzl-Tschegg, S., 2004: Structure-function relationships of four compression wood types: micromechanical properties at the tissue and fibre level. Trees - Structure and Function 18(4): 480-485
6. Burgert, I., Jungnikl, K., 2004: Adaptive growth of gymnosperm branches - ultrastructural and micromechanical examinations. Journal of Plant Growth Regulation 23(2): 76-82
7. Fratzl, P., Jakob, H.F., Rinnerthaler, S., Roschger, P., Klaushofer, K., 1997: Position-resolved small-angle X-ray scattering of complex biological materials. Journal of Applied Crystallography 30(2): 765-769
8. Görlacher, R., 1984: A new method for determining the modulus of elasticity of timber. Holz als Roh- und Werkstoff 42(6): 219-222
9. Grosser, D., 1977: Die Hölzer Mitteleuropas. Springer. Berlin, 208 pp.
10. Jakubczyk, B., 1966: Technical properties of the yew wood from the preserve Wierzchlas. Sylwan 10: 79-86
11. Kahle, E., Woodhouse, J., 1994: The influence of cell geometry on the elasticity of softwood. Journal of Materials Science 29(5): 1250-1259
12. Kantola, M., Seitsonen, S., 1969: On the relation between tracheid length and microfibril orientation measured by X-ray diffraction in conifer wood. Annales Academiae Scientiarum Fennicae A VI Pysica 300, 10 pp.
13. Keylwerth, R., 1951: Die anisotrope Elastizität des Holzes und der Lagenhölzer. Deutscher Ingenieur-Verlag. Düsseldorf, 40 pp.
14. Kollmann, F., 1951: Technologie des Holzes und der Holzwerkstoffe. Springer. Berlin, 1050 pp.
15. Krautkrämer, J., Krautkrämer, H., 1986: Werkstoffprüfung mit Ultraschall. Springer. Berlin, 708 pp.
16. Kucera, L.J., 1998: Das Holz der Eibe. Schweizerische Zeitschrift für Forstwesen 149(5): 328-339
17. Lichtenegger, H., Reiterer, A., Tschegg, S., Fratzl, P., 1997: Determination of spiral angles of elementary fibrils in the wood cell wall: Comparison of small angle X-ray scattering and wide angle X-ray diffraction. In: Butterfield BG editors. IAWA-press pp 140-156
18. Logemann, M., Schelling, W., 1992: The fracture toughness of spruce and the essential influences - investigations for mode-1. Holz als Roh- und Werkstoff 50(2): 47-52
19. Mertoglu-Elmas, G., 2003: Chemical components of heartwood and sapwood of common yew (Taxus baccata L.). Journal of Environmental Biology 24(4): 489-492
20. Niemz, P., 1993: Physik des Holzes und der Holzwerkstoffe. DRW. Leinfelden-Echterdingen, 243 pp.
21. Paakkari, T., Serimaa, R., 1984: A Study of the Structure of Wood Cells by X-Ray-Diffraction. Wood Science and Technology 18(2): 79-85

22. Parham, R.A., Kaustinen, H., 1973: On the morphology of spiral thickenings. IAWA Bulletin 2: 8-17
23. Parmar, V.S., Jha, A., Bisht, K.S., Tanega, P., Singh, S.K., Kumar, A., Poonam, Jain, R., Olsen, C.E., 1999: Constituents of the yew trees. Phytochemistry 50(8): 1267-1304
24. Pozgaj, A., Kurjatko, G., Chovanec, D., Babiak, M., 1997: Štruktúra a vlastnosti dreva. Príroda. Bratislava, 483 pp.
25. Reiterer, A., Lichtenegger, H., Tschegg, S., Fratzl, P., 1999: Experimental evidence for a mechanical function of the cellulose microfibril angle in wood cell walls. Philosophical Magazine a - Physics of Condensed Matter Structure Defects and Mechanical Properties 79(9): 2173-2184
26. Saren, M.P., Serimaa, R., Andersson, S., Paakkari, T., Saranpaa, P., Pesonen, E., 2001: Structural variation of tracheids in Norway spruce (*Picea abies* [L.] Karst.). Journal of Structural Biology 136(2): 101-109
27. Sekhar, A.C., Sharma, R.S., 1959: A note on mechanical properties of *taxus baccata*. Indian Forester 85: 324-326
28. Sell, J., 1997: Eigenschaften und Kenngrössen von Holzarten. Baufachverlag. Dietikon, 87 pp.
29. Sugiyama, J., Okano, T., Yamamoto, H., Horii, F., 1990: Transformation of Valonia cellulose crystals by an alkaline hydrothermal treatment. Macromolecules 23: 3196-3198
30. Uslu, Y., 1997: Adi Porsuk (*Taxus baccata* L.) Odun ve Kabugunun Kimyasal Bilesimi. Master thesis, Karadeniz Technical University, Trabzon
31. Wagenführ, R., 2000: Holzatlas. Fachbuchverlag Leipzig. München, 707 pp.
32. Welling, J., 1987: Die Erfassung von Trocknungsspannungen während der Kammertrocknung von Schnittholz. Dissertation. Hamburg, 222 pp.
33. Wergin, W., Casperson, G., 1961: Über Entstehung und Aufbau von Reaktionsholzzellen. 2. Mitteilung: Morphologie der Druckholzzellen von *Taxus baccata* L. Holzforschung 15: 44-49

STANDARDS

1. ASTM D 143-94 (2000): Standard Test Methods for Small, Clear Specimens of Timber
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)

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