SELECTED MECHANICAL PROPERTIES AND FRACTURE CHARACTERISTICS OF YEW WOOD

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ABSTRACT

Yew wood (*Taxus baccata* L.) is known for its extraordinary mechanical performance compared to other gymnosperms. The goal of this study was to examine selected mechanical properties of yew wood since only few mechanical data are available. Therefore, the longitudinal Young's modulus in bending was determined by means of static and dynamic test procedures. In addition, fracture toughness K_{IC} was determined for the RL and TL crack propagation direction. For comparison only, all tests were applied on spruce wood as well. Our investigations confirm the high toughness of yew wood whereas the Young's modulus is clearly lower than reference values given in literature. Compared to spruce wood, a relatively high peripheral strain and work to ultimate load was found. The evaluation of fracture patterns on the macro scale reveals conspicuous shear surfaces for bending specimens. Our results lead to the conclusion that detailed research into the micromechanics of yew wood will be essential to understand structure-function relationships.

Introduction

The exceptional position of yew wood (*Taxus baccata* L.) within the gymnosperms is well known. It is classified as extremely hard, tough and highly elastic [1]. Due to these remarkable properties, it was common practice to make arms such as bows, lances and crossbows from yew wood in earlier centuries. Nowadays, yew wood is not of commercial relevance any longer. Since yew is legally protected in many countries, its mechanical properties are only partly known. Taking its relatively high density (≈ 0.67 g/cm^3) into account, the extreme Brinell hardness ($HB_{\parallel} \approx$ 60-70 MPa [1 - 4], $HB_{\perp} \approx$ 30 MPa [1,4]) is not surprising. The longitudinal Young's modulus is reported to be 12000 [2] respectively 15700 MPa [1]. 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 [1]. That is, yew wood is able to resist considerable dynamic loads. Values for shear modulus and fracture toughness are still lacking.

The main focus of this study was on elastic behaviour and toughness of the regularly formed wood of the stem. Non-destructive methods as well as static bending tests were applied to calculate the Young's modulus. Macroscopic fracture patterns of the bending specimens were subsequently examined. In addition, fracture toughness K_{IC} was determined by means of CT specimens. In order to put the results into perspective, the tests were applied on Norway spruce wood (*picea abies* [L.] Karst.) from the same stands as well.

Materials and Methods

All sample trees were chosen from two yew respectively two spruce stands in and close to Zurich, Switzerland (therefore mentioned as yew No. 1, 2 and spruce No. 1, 2 in the following). The sawn timber was oven-dried to 12% moisture content. Only adult wood from heartwood regions free of compression wood were used for specimen preparation. The specimens were stored in a climate chamber at 20°C and 65% RH until they reached equilibrium moisture content. Furthermore, density (DIN 52182) and moisture content (DIN 52183) were determined.

1. Determination of Young's modulus, bending strength and work to ultimate load

Three test procedures were applied, two of them nondestructive. 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). 34 yew specimens and 36 spruce specimens from stand No. 1 were tested as well as 30 yew specimens and 30 spruce specimens from stand No. 2.

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 member with a small width and height compared to the wave length of the acoustic signal [5]:

$$MOE_s = \rho_u \cdot c^2 \tag{1}$$

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. A STEINKAMP BP5 sound propagation timer was used (frequency 50 kHz).

Eigenfrequency
A GRINDO-SONIC MK 5 INDUSTRIAL was used to measure the eigenfrequency as described by Görlacher [6]. 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 tangential direction resulting from the strike correspond to the static bending test. A piezoelectric needle senses the mechanical vibrations of the specimens and transforms them into electric signals. Young's modulus calculation was based on equation 2.

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

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 intertia ($i^2 = h^2/12$, where h is the specimen height), and K_1 and m_n^4 are constants depending on the order of vibration. For first order bending vibrations the following constants are used [6]: K_1 = 49.48 and m_n^4 = 500.6.

Static bending test
A universal testing machine (ZWICK Z100) with 100 kN load capacity was used to apply 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.

$$MOE_B = \frac{l^3}{4 \cdot b \cdot h^3} \cdot \frac{\Delta F}{\Delta f} \tag{3}$$

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 within the elastic deformation range of the specimen and Δf is the deflection in the centre of the specimen corresponding to ΔF. In addition to the Young's modulus, also bending strength σ_{bB} and work to ultimate load w_u were determined, the latter as defined by Bodig and Jayne [7]:

$$w_u = \frac{W_{F_{max}}}{V} \tag{4}$$

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:

$$\varepsilon = \frac{6 \cdot h \cdot f_{max}}{l_s^2} \cdot 100\% \tag{5}$$

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. This equation normally applies for homogeneous materials like synthetics.

2. 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 figure 1; 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. 39 yew and 40 spruce RL specimens as well as 43 yew and 49 spruce TL specimens, all coming from stand No. 1, 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:

$$K_{IC} = \frac{F_Q}{B \cdot \sqrt{W}} \cdot f(a/W) \tag{6}$$

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):

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

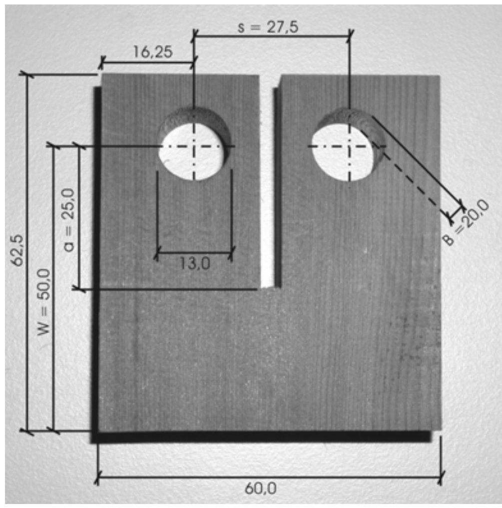

Figure 1. CT specimen. All dimensions in [mm].

Results and Discussion

1. 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 spruce mean values (11600 and 12500 MPa) are within the known range. In spite of the high density, the Young's modulus for yew (9100 and 10200 MPa) was clearly lower than the reference values given in literature for *Taxus baccata* L. [1,2]. None of our values reached the Young’s modulus reported by Sell [1] although yew samples from two stands, without knots and with as few grain deviations as possible, were tested. In contrast, the values agree with the Young’s modulus of Pacific Yew (*Taxus brevifolia*) [8]. It has to be considered, however, that the latter have been published in 1935. The dynamic Young's modulus obtained from eigenfrequency tests was in the range of the static values. As expected, the Young's modulus calculated from sound velocity was proportionally higher, which is a long established fact [9] and applies for both wood species. Since the dynamic tests highly correlate with static bending (fig. 2) and the values determined for spruce seem feasible, mistakes of the test procedure can be excluded. An overview of the results mentioned above is given in table 1.

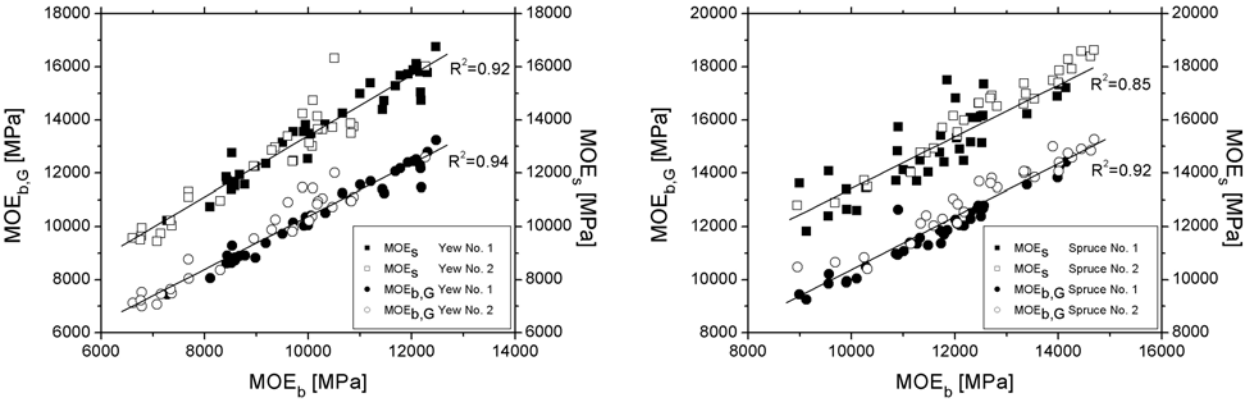

Figure 2. Correlation between static and dynamic tests for yew (left hand side) and spruce specimens (right hand side).

Table 1**.** Sound velocity and Young's modulus determined by dynamic and static tests.

	stand	number of specimens		equilibrium moisture content	density	sound velocity	Young's modulus (MOE)		
		n		emc [%]	ρ [g/cm^3]	c [m/s]	MOE_s [MPa]	$MOE_{b,G}$ [MPa]	MOE_b [MPa]
Yew	1	34	$\bar{x}$	12.8	0.71	4380	13600	10500	10200
			v		7.0%	8.3%	13.1%	15.2%	15.1%
Yew	2	30	$\bar{x}$	12.5	0.64	4420	12400	9600	9100
			v		10.8%	9.8%	15.7 %	17.4%	17.4%
Spruce	1	36	$\bar{x}$	12.8	0.42	5930	15000	11700	11600
			v		4.8%	3.1%	10.2%	11.1%	11.4%
Spruce	2	30	$\bar{x}$	12.5	0.44	6060	16100	13100	12500
			v		6.4%	3.3%	10.5%	11.0%	12.1%

Despite the relatively low Young's Modulus, a mean bending strength of 112 and 124 MPa (table 2) was determined for yew wood which is about 25 to 50% higher than the corresponding spruce values (83 and 88 MPa). Also the peripheral strain at failure was significantly higher for yew (2.2% and 1.9%) compared to spruce (1.2% and 1.3%) (*it should be considered that the used equation usually applies for homogeneous materials such as synthetics*). 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 about twice as high for yew (202 and 152 kJ/m^3) as for spruce (75 and 89 kJ/m^3). Compared to spruce wood, the large elastic portion of w_u 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 is able to absorb a large quantity of energy during a plastic deformation. This is characteristic for tough materials and confirms that yew is extremely capable of resisting crack propagation.

Table 2. Peripheral strain, bending strength and work to ultimate load.

	stand	number of specimens		equilibrium moisture content	density	peripheral strain	bending strength	work to ultimate load		
		n		emc [%]	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	1	34	$\bar{x}$	12.8	0.71	2.2	124	202	41	161
			v		7.0%	34.2%	12.0%	48.7%	16.2%	54.8%
Yew	2	30	$\bar{x}$	12.5	0.64	1.9	112	152	42	110
			v		10.8%	25.9%	15.4%	37.6%	17.7%	46.8%
Spruce	1	36	$\bar{x}$	12.8	0.42	1.2	83	75	13	62
			v		4.8%	13.2%	10.1%	25.2%	15.8%	28.7%
Spruce	2	30	$\bar{x}$	12.5	0.44	1.3	88	89	16	73
			v		6.4%	12.7%	10.7%	22.9%	16.7%	26.4%

2. Fracture paths of bending specimens on the macroscopic level

The yew bending samples showed a variety of crack patterns. In the tension zone, brittle fracture surfaces were formed in the RT plane. Multiple parallel shear surfaces in the LR plane frequently reached a length of 20 cm or even more in longitudinal direction (fig. 3.1). Half the specimens abruptly broke into at least two pieces (fig. 3.2). In individual cases shear areas ran diagonally from the lower to the upper specimen surface (fig. 3.3). Several specimens showed a zigzag crack pattern (fig 3.4). Compression failure was rarely visible to the naked eye. In contrast, the spruce specimens showed a predominantly uniform fracture behavior. Both, brittle and fibrous fracture surfaces were found in the tension zone. A single shear area being rather short (about 3 to 5 cm in longitudinal direction) compared to yew wood was formed; compression failure was visible without exception (fig. 4.1). None of the spruce specimens was broken into two or even more pieces. The following details were observed for both wood species and confirm well-known crack patterns of gymnosperms: In the radial direction of the tension zone, the crack often momentary propagates along the tree ring boundary before it jumps across the next growth ring (fig. 4.2). Whereas in tangential direction, the crack stepwise jumps from one wood ray to the next (fig. 4.3). Wood rays are also visible on the shear surfaces (fig. 4.4). In other words, tree ring boundaries turned out to be weak points as well as the contact area between wood rays and longitudinally oriented tracheids.

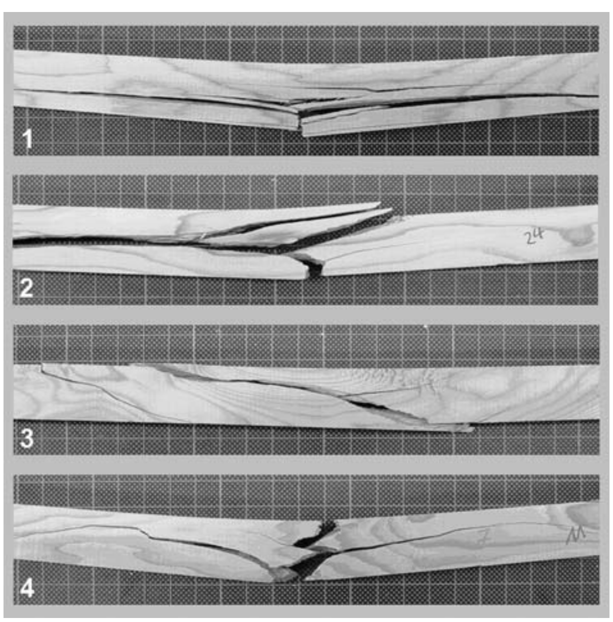

Figure 3. Variable fracture patterns for yew bending specimens.

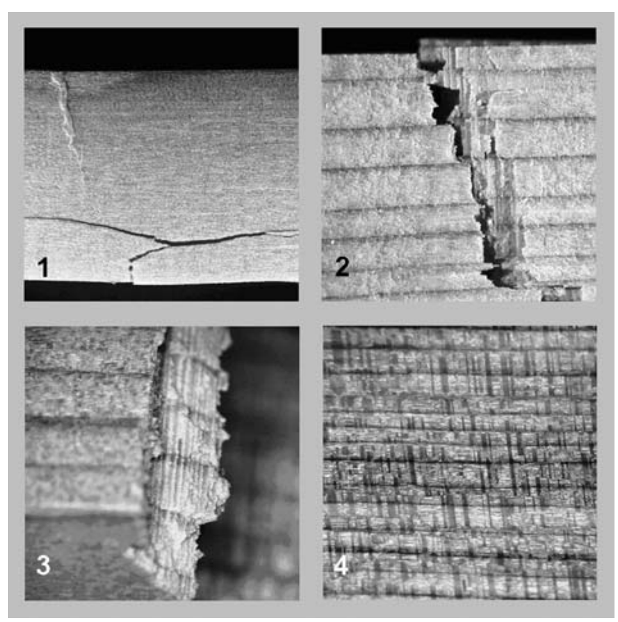

Figure 4. Details of fracture patterns on the macro scale. Image 1: Spruce. Images 2 to 4: Yew.

3. Fracture toughness

Fracture toughness is defined as the ability of a material to resist crack propagation. 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. In case of yew wood, K_{IC} (RL) was about 20% higher than the corresponding TL value, for spruce RL specimens even 60% higher. The higher toughness of both wood species in radial direction is caused by the reinforcing effect of wood rays, which is reported by Reiterer et al. [10]. Table 3 gives an overview of the results.

Table 3. Results of the fracture toughness test.

	number of specimens		equilibrium moisture content	density	fracture toughness
	n		emc [%]	ρ [g/cm^3]	K_{IC} [kJ/m^2]
Yew RL	39	$\bar{x}$	13.2	0.75	0.56
		v	0.5%	6.7%	25.0%
Yew TL	43	$\bar{x}$	12.9	0.71	0.46
		v	0.3%	9.9%	26.1%
Spruce RL	40	$\bar{x}$	12.1	0.42	0.37
		v	0.3%	4.8%	13.5%
Spruce TL	49	$\bar{x}$	12.2	0.42	0.23
		v	0.3%	7.1%	8.4%

Conclusions

Elasticity is defined as ability of a material to return to its original shape when load causing deformation is removed. The crucial factor for a highly elastic material is its extreme extensibility within the elastic range. Therefore, yew wood proved to be highly elastic in our study. None of the gymnosperms reaches a comparably high elastic strain. Furthermore, a high toughness could be confirmed for yew wood loaded in longitudinal direction as well as in radial and tangential direction, the latter by means of CT specimens.

The results provide a basis for subsequent studies. Detailed research into micromechanics is essential to understand the failure characteristics of yew wood, e.g. the conspicuous shear surfaces. Particularly the microfibril angle of the helically oriented cellulose fibrils in the thickest tracheid cell wall layer S_2 influences the mechanical behaviour on cellular level. Various other properties such as density, cell dimensions, wood ray percentage, grain deviations and extractives have to be considered as well. Within this study, however, it was not possible to quantify their influence.

Acknowledgments

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