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Journal Article

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Publication date:
2013-10

Permanent link:
https://doi.org/10.3929/ethz-b-000080314

Originally published in:
Holzforschung 67(7), https://doi.org/10.1515/hf-2012-0151

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Mechanical performance of yew (*Taxus baccata* L.) from a longbow perspective

Abstract: Yew (*Taxus baccata* L.) longbow was the preferred weapon in the Middle Ages until the emergence of guns. In this study, the tensile, compression, and bending properties of yew were investigated. The advantage of yew over the other species in the study was also confirmed by a simple beam model. The superior toughness of yew has the effect that a yew longbow has a higher range compared with bows made from other species. Unexpectedly, the mechanical performance of a bow made from yew is influenced by the juvenile-to-mature wood ratio rather than by the heartwood-to-sapwood ratio. A yew bow is predicted to have maximized performance at a juvenile wood content of 30–50%, and located at the concave side (the compressive side facing the bowyer). Here, the stiffness and yield stress in compression should be as high as possible.

Keywords: archery, axial strength, bending tests, longbow, yew (*Taxus baccata* L.)

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Introduction

The longbow probably earned most of its reputation during the Hundred Years' War (1337–1453) fought between the English and the French. The important victories of the English were attributed to the efficiency of the English archers and their weapons. The strategy was to organize a large number of archers to fire simultaneously to a limited area, striking the enemy with the devastating power of thousands of arrows. Here, the strength of the longbow lied in its range rather than in its accuracy; the maximum distances of medieval bows are largely unknown, but a Mary Rose longbow replica was found to shoot an impressive 328 m (Strickland and Hardy 2005). Technically speaking, a longbow is a bow not significantly recurved with slender limbs. It has a circular or D-shaped cross-section, and its height is roughly equal to that of the archers. The shape allows for a fairly long draw, but the demands on the material in the bow are high. In ancient and modern times, longbows are usually made from one single piece of wood, preferably straight grown and with a minimum of knots and defects, which weakens the material (Figure 1a).

As a rule of thumb, the best bow materials are those that combine a high specific bending strength with a relatively low specific modulus (Hickman et al. 1947). In general, a good bow is one to which a high force can be applied under a large elastic deformation, which guarantees that a large amount of elastic energy stored during the draw is transferred effectively into kinetic energy of the arrow when the bowstring is released. Yew (*Taxus baccata* L.) has been preferred by man for bow-making for thousands of years. See, for instance, the official Web site of the glacier mummy Ötzi (http://www.iceman.it/). Yew has also been preferred for other tough wooden utensils to such an extent that the species is now protected in many European countries. Despite its popularity, the number of studies on yew is still small. Yew wood is unusually homogenous and fine-grained, with a high strain to failure (Keunecke 2008). Moreover, yew has a high specific bending strength as well as a low specific elastic modulus (Hardy 2006). Bows made from yew possess qualitative properties, such as a smooth draw and an easy spring-back (Allely et al. 2000).

In the present article, the mechanical properties of yew are compared with those of other wood species from a longbow perspective. The question to answer was what makes yew such an outstanding material for longbows. Yew bows are rare, so mechanical data from tests on small clear wood samples were used in a simple beam model to predict the maximum elastic energy per area (EEA; here called toughness). (For calculation of EEA please see the Mechanical testing section.) Moreover, the ideal heartwood-to-sapwood (hw/sw) ratio in the cross-section of the

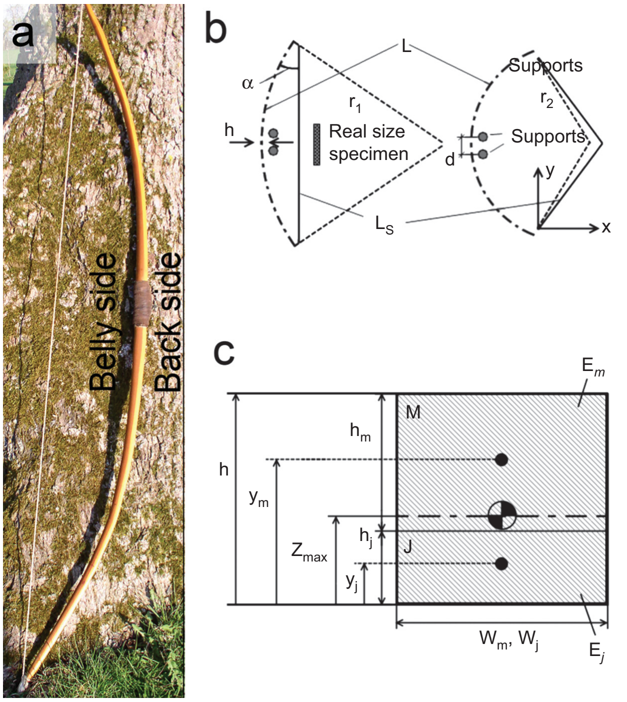

Figure 1 Basic data of a yew longbow.
(a) A typical longbow; the dark heartwood (hw) is on the concave (belly) and the lighter sapwood (sw) is on the convex (back) side (Photo: Alexander Ravenna). (b) Schematic drawing of the bow model including length L 1800 mm and height h 30 mm, length of the string L_s 1740 mm, and distance between the supports d 90 mm (representing the bowyer's hand). Undrawn position (left) and drawn position (right). (c) Cross-section of the bow model consisting of a juvenile (j) wood and mature (m) wood section with stiffness E_j and E_m, respectively. The image displays the distance to the centroid of each subsection (y_j and y_m) and the distance to the centroid and thereby the neutral axis of the whole cross-section z_{max}. The width and height of each subsection (w_j, w_m, h_j, and h_m) were used as input data for calculation of the mechanical performance of the model bow. (The total height h of the cross-section is also displayed in (b).)

bow was investigated, with the heartwood on the concave side (i.e., the compressive side facing the bowyer). There are some publications to the topic, but no general conclusion can be drawn (Stemmler 1942; Allely et al. 2000; Hardy 2006; Bertalan 2007). Therefore, the mechanical performance of yew heartwood and sapwood was investigated. The hypothesis to verify or reject was that the hw/sw ratio is of importance for the bow performance.

Materials and methods

Materials and manufacturing of samples

In the focus of the study was yew (*Taxus baccata* L.), the data of which were compared with those of juniper (*Juniperus communis* L.) and pine (*Pinus silvestris* L.). The yew and the juniper (originating from four and three separate stems, respectively) had been air-dried after cutting. The pine (two stems) was received from a commercial retailer (industrial drying procedure unknown).

The samples for mechanical testing (free of cracks, knots, and other defects) were manufactured by cutting and milling. The groups of sapwood samples YEW2(sw)$_t$ and YEW2(sw)$_c$ had been positioned adjacent to their respective counterpart in the heartwood groups YEW2(hw)$_t$ and YEW2(hw)$_c$ and at a distance of 40–60 mm from the bark in the original yew stems (diameter ~150 mm) to minimize the impact from morphologic differences. The access to yew wood was limited; thus, samples of a smaller size than standard recommendations were machined. For the tensile tests (t-test), dog-bone-shaped samples with dimensions of 4×2×180 mm^3 (R×T×L) were prepared (length of the waist was 90 mm). The dimensions of the compression test (c-test) samples were 10×10×40 mm^3 (R×T×L). The four-point bending test (4PB-test) specimens had a size of 15×15×300 mm^3 (R×T×L). For a list of samples, see Table 1.

Extraction

The main difference between heartwood and sapwood is the presence of extractives in the former (Tsoumis 1991). Because access to yew sapwood was extremely limited, sapwood was mimicked by extraction of heartwood material. Also, a limited number of true sapwood and heartwood samples were compared. A total number of 26 heartwood samples were chosen (16 from the t-test group and 10 from the c-test group). To minimize the morphologic differences between the extracted groups YEW1(hwextr)$_t$ and YEW1(hwextr)$_c$ and the reference groups YEW1(hwref)$_t$ and YEW1(hwref)$_c$, each extracted sample was positioned adjacent to its reference in the original stem.

Soxhlet extraction with acetone was carried out separately on the tension and compression samples. Acetone is less hazardous than dichloromethane (Sjöström and Alén 1999), and its low boiling

Table 1 Groups of samples for mechanical tests.

Type of test, species	Name of group	*n* of samples	Type	Treatment
t-test				
Yew	YEW1(hwextr)$_t$	16	hw	Extraction
Yew	YEW1(hwref)$_t$	17	hw	–
Yew	YEW2(hw)$_t$	30	hw	–
Yew	YEW2(sw)$_t$	24	sw	–
Juniper	JUN$_t$	17	(hw/sw)	–
Pine	PINE$_t$	16	(hw/sw)	–
c-test				
Yew	YEW1(hwextr)$_c$	10	hw	Extraction
Yew	YEW1(hwref)$_c$	10	hw	–
Yew	YEW2(hw)$_c$	74	hw	–
Yew	YEW2(sw)$_c$	31	sw	–
Juniper	JUN$_c$	10	hw	–
Pine	PINE$_c$	10	sw	–
4PB-test				
Yew	YEW$_b$	9	(hw/sw)	–
Juniper	JUN$_b$	6	(hw/sw)	–
Pine	PINE$_b$	2	(hw/sw)	–

hw, heartwood; sw, sapwood.

temperature (57°C) prevents thermal degradation of the wood constituents. Yew is rich in extractives compared with other softwood species (Mertoglu-Elmas 2003). Therefore, it was decided from separate experiments that the total extraction time for each sample should be ~36 h (~140 cycles).

Density, moisture content, and extractives content

For determination of density, moisture content (MC), and extractives content (EC), the samples previously tested in tension were used because these were the least likely to have undergone irreversible deformation and thereby volumetric change. The density measurements included samples from the nonextracted group of yew YEW1(hwref)$_t$ and all the juniper and pine samples tested in tension. The weight of the conditioned [23°C, 53% relative humidity (RH)] samples was registered. Density in the conditioned state $\rho_{\mathrm{RH53\%}}$ was estimated by immersion of each sample in limonene (Sigma-Aldrich, Stockholm, Sweden) and measuring the liquid volume displaced. In contrast to mercury, limonene allows further usage of samples. The samples were thereafter oven-dried (103°C) until an equilibrium (defined as change in weight <0.1% per 24 h) was reached. The dry weight was registered, and MC was calculated based on weight differences. The same procedure was done after extraction to determine the EC (Table 2).

Mechanical testing

All samples were conditioned (23°C, 53% RH) until an equilibrium was reached. The t-test and c-test experiments were performed in a controlled environment (23°C, 53% RH). The four-point bending tests (FPBT) were performed in an uncontrolled environment, but the conditioned samples were kept in plastic bags until right before the test, which took ~5 min. For the axial t-test and c-test, an Instron model 5566 (Instron, Stockholm, Sweden) with a 10 kN load cell was used. The strain was measured by means of a video extensometer. The crosshead speed in the t-test was set to 15 mm min^{-1}, whereas the corresponding number in the c-test was 7 mm min^{-1} (corresponding to a strain rate of ~17% min^{-1}). The choice of strain rate was based on a longbow model combined with empirical data on longbow shooting. The bow was modeled as an initially straight beam with a quadratic cross-sectional shape (height h, width w 30 mm, length L 1800 mm) and strung with a string of length L_s 1740 mm or ~60 mm shorter than the bow (Walk et al. 2009) (Figure 1b). During bracing, the bow is subjected to four-point bending (distance between the inner supports representing the bowyer's hand is d 90 mm). The length of the bow along its symmetry axis is constant, whereas the convex and concave side (the back and the belly) of the bow are stretched and contracted, respectively. In both the strung but undrawn position and the fully drawn (draw length 1050 mm) position, the bow is assumed to bend around an arc with known radius (from Figure 1b: r_1=2000 mm and r_2=705 mm), forming a circular sector (Hickman et al. 1947). From the geometrical data, the tensile/compression strain in the fully drawn position is estimated to 1.4%. Moreover, the draw time from undrawn to fully drawn position is estimated to 5 s, which gives the strain rate applied in the experiments (17% min^{-1}).

For the 4PB-tests, an Instron model 5567 (Instron, Stockholm, Sweden) with a 30 kN load cell was available. Four point bending was preferred to a three-point bending, because the former is more realistic in imitating the distributed load from the bowyer's hand during the draw. The distance between the outer and inner supports in the rig was 270 and 90 mm, respectively. Crosshead speed was 2.7 mm min^{-1} (Standard EN 408: 2003), and the sample was oriented so that the force was directed in the R direction. The deflection of the beam was measured by digital speckle photography (DSP). A series of images of the sample surface were digitally recorded before and during the loading of the sample. The images were then processed in the DSP software ARAMIS (GOM, Braunschweig, Germany) for calculation of deflection. For surface recognition, a spray-paint speckle pattern had been applied to the samples before testing. (For recent advances of DSB and digital image correlation, see Taguchi et al. 2011; Davis et al. 2012; Peng et al. 2012.)

Table 2 Density, MC, and EC in samples.

Species	Density[a] $\rho_{\mathrm{RH53\%}}$, kg/m^3	MC[a], %	EC[a], %
Yew	667 (38)	8.9 (0.1)	5.9 (1.0)
Juniper	767 (29)	11.9 (0.6)	4.3 (0.5)
Pine	596 (31)	10.4 (0.2)	2.3 (0.2)

[a]Data based on the heartwood yew group YEW1(hwref)$_t$ and both groups of juniper and pine previously tested in tension (JUN$_t$, JUN$_c$, PINE$_t$, and PINE$_c$). Numbers in parentheses are standard deviations.

Table 3 Mechanical properties of samples tested in tension, compression, and four-point bending.

Type of test, name of group			EEA, kJ/m^2
t-test	**Tensile strength σ_t, MPa**	**Tensile stiffness E_t, GPa**	
YEW1(hwextr)$_t$	119 (20)	11.3 (1.4)	51.7 (18.1)
YEW1(hwref)$_t$	112 (18)	11.6 (1.6)	47.2 (17.1)
YEW2(hw)$_t$	95 (20)[a]	9.4 (1.2)[a]	30.4 (17.9)
YEW2(sw)$_t$	111 (28)	10.9 (2.9)	35.2 (23.6)
JUN$_t$	115 (23)	9.6 (0.6)	46.7 (15.2)
PINE$_t$	119 (15)	11.7 (1.0)	49.6 (8.7)
c-test	**Yield stress in compression σ_c, MPa**	**Compression stiffness E_c, GPa**	
YEW1(hwextr)$_c$	61 (10)	13.1 (1.9)	8.9 (1.7)[a]
YEW1(hwref)$_c$	68 (10)	12.7 (1.5)	11.6 (1.7)
YEW2(hw)$_c$	62 (6)[a]	9.3 (0.8)	9.6 (2.1)[a]
YEW2(sw)$_c$	54 (6)[b]	9.2 (1.0)[b]	7.8 (1.6)
JUN$_c$	50 (3)[b]	10.4 (1.5)[b]	8.3 (1.3)
PINE$_c$	51 (4)[b]	12.5 (0.8)[b]	6.0 (0.8)
4PB-test	**MOR (MPa)**	**MOE (GPa)**	
YEW$_b$	105 (25)	11.5 (2.7)	14.3 (3.3)
JUN$_b$	84 (17)	7.4 (1.0)	10.2 (3.3)
PINE$_b$	86 (5)	8.0 (0.7)	12.0 (0.7)

[a]Significant at the 5% level (two-sided Student's t-test) in comparison with the corresponding yew reference. [b]Numbers used for calculation of elastic energy in the bow model. Numbers in parentheses are standard deviations.

The following data were calculated: (t-tests) stiffness and strength, (c-tests) stiffness and yield stress, (4PB-tests) and modulus of elasticity (MOE) and modulus of rupture (MOR) (Table 3). For calculation of tensile and compression stiffness, a straight line was fitted to the initial linear (0–0.5% strain) part of the curve. In the 4PB-tests, the linear part of the curve was used together with information on the experimental setup and sample dimensions for calculation of MOE and MOR (Standard EN 408:2003). EEA (toughness) was also determined for each type of test by calculating the area under the initial linear part of the force deflection curve and dividing the result by the specimen cross-sectional area. A discrepancy of 5% between the curve and a fitted straight line marked the upper boundary.

Bow model

To estimate the elastic performance (within the elastic region) of a full-size yew longbow, a beam model (Figure 1b and c) subjected to 4PB-test. Classical beam-theory (Sundström 2010) was applied for calculations. The preceding mechanical tests revealed that the performance of heartwood is not related to the extractives *per se* but are more likely a result of heartwood being composed of juvenile wood with high density. Therefore, the performance of a bow composed of juvenile and mature wood was investigated. In yew, density and stiffness increase from bark to pith (Keunecke 2008). Therefore, stiffness of the mature wood (E_m) was set to the lowest experimental value measured (9.2 GPa; Table 3), and the relation between E_m and the stiffness of the juvenile wood (E_j) was described as

$$E_j = nE_m, \tag{1}$$

where n varies from 1.0 to 2.0. Moreover, juvenile-to-mature wood (j/m) ratio in the cross-section was varied from 1:0 to 0:1. A beam composed of two subsections with different moduli can be replaced by an equivalent beam in which the width of the stiffer (here, juvenile) subsection is expanded by a factor n [from Eq. (1)]. This results in a shift of the centroid of the cross-section through which the neutral axis goes, and position of the axis was calculated from

$$z_{max} = \frac{y_m w_m h_m + y_j n w_j h_j}{w_m h_m + n w_j h_j}, \tag{2}$$

where y_j, w_j, h_j, y_m, w_m, and h_m are the distances to the centroid, width, and height of each subsection (Figure 1c). For juniper and pine with constant stiffness, $z_{\max}$ was simply set to $h/2$ (or 15 mm). The theoretical maximum force P, with which the bow model could be loaded elastically, was evaluated by

$$P = \frac{4\sigma I}{(L-d)z_{\max}}, \tag{3}$$

where σ is stress (the yield stress in compression was used as input; Table 3), I is the second moment of area (calculated as $wh^3/12$ for all species), d is the distance between the inner supports, and L is the length of the bow. Next, the values on P were used for calculation of theoretical maximum elastic deflection δ according to

$$\delta = 0.020756\frac{PL^2}{EI}. \tag{4}$$

Eq. (4) is dependent on the stiffness E. For the yew bow composed of two subsections with different stiffness, I in Eq. (4) was therefore calculated by applying the parallel axis theorem to an equivalent beam with the width of the juvenile subsection expanded by factor n.

EEA was calculated for the theoretical full-size bow according to EEA=$P\delta/2$ from Eqs. (3) and (4) in combination with experimental results of the species (Table 3).

Results and discussion

First, density, EC, and MC in the samples were determined (Table 2). Regarding the density, the values for all three species were in accordance with data from literature (for comparison, see Keunecke 2008). Similar to juniper, yew is a slow-growing species with a high density compared with many other softwood species. The MC of yew was lower compared with both juniper and pine. MC is related to the EC, because extractives fill the nanopores, micropores, and macropores and thereby reduce the moisture uptake (Hillis 1971). Thus, the extractives provide protection by their toxicity against bacteria and fungi and by lowering the MC to levels less favorable for microorganisms. Here, the EC was higher for yew (5.9±1.0 wt.%) than for the other two species (Table 2). However, in this regard, the data are closer to that reported for yew sapwood than for heartwood (Mertoglu-Elmas 2003), although the yew samples had the characteristic brown color of heartwood. From this, it is obvious that EC cannot be judged based on the optical appearance of the wood alone.

Concerning the mechanical tests, the tensile strength did not differ significantly between the three species, whereas the yield stress in compression was higher for yew compared with both juniper and pine. Moreover, yew displayed a large variety in tensile/compression stiffness, and the values were both higher and lower compared with values for the other species (Table 3). In relation to its high density, the axial stiffness of yew is surprisingly low. The relative density (i.e., wood density ρ_{wood} divided by cell wall density ρ_{cw}) can be considered to scale linearly to the relative axial stiffness (i.e., wood stiffness E_{wood} divided by cell wall stiffness E_{cw}) according to

$$\frac{\rho_{\text{wood}}}{\rho_{\text{cw}}} = C\frac{E_{\text{wood}}}{E_{\text{cw}}}, \tag{5}$$

where C is a constant commonly set to 1 (Gibson and Ashby 1997). E_{cw} and ρ_{cw} in wood have previously been nominally determined to 35 GPa and 1500 kg m^{-3}, respectively (Gibson and Ashby 1997). Combined with the data on density (670 kg m^{-3}) in this study, yew should theoretically have an axial stiffness of approximately 15–16 GPa, which is higher than the registered stiffness (9.2–13.1 GPa). However, axial wood stiffness does not rely on density only but also on the microfibril angle (MFA), which has turned out to be significantly higher in yew compared with other softwood species (Keunecke et al. 2009). A higher MFA results in lower stiffness and allows for a higher elastic stretching of the material. This is favorable in a longbow because more elastic energy can be stored in the material.

In this study, the juniper specimens had an even higher density compared with yew. Juniper should consequently have an even higher stiffness, but this was not the case. One explanation could be that the juniper had an even higher MFA. However, this was not investigated further.

From a bowyer's perspective, the EEA is one of the most informative parameters, because it indicates how much elastic energy is stored in the bow during a draw and could be theoretically transferred to the arrow when the string is released. From the t-test, c-test, and 4PB-test curves (Figures 2a,2b and 3), the EEA for each species was calculated. EEA in tension and compression could not explain why yew is preferred as a bow material, and yew displayed a wide range of values, both higher and lower, compared with juniper and pine. From the 4PB-tests, however, EEA for yew was significantly higher compared with the other two species (Table 3). The difference is displayed in Figure 3, where it is obvious that EEA in bending is at least as large for yew as for pine and juniper, or larger. The practical interpretation is that a bow made from yew has a larger range.

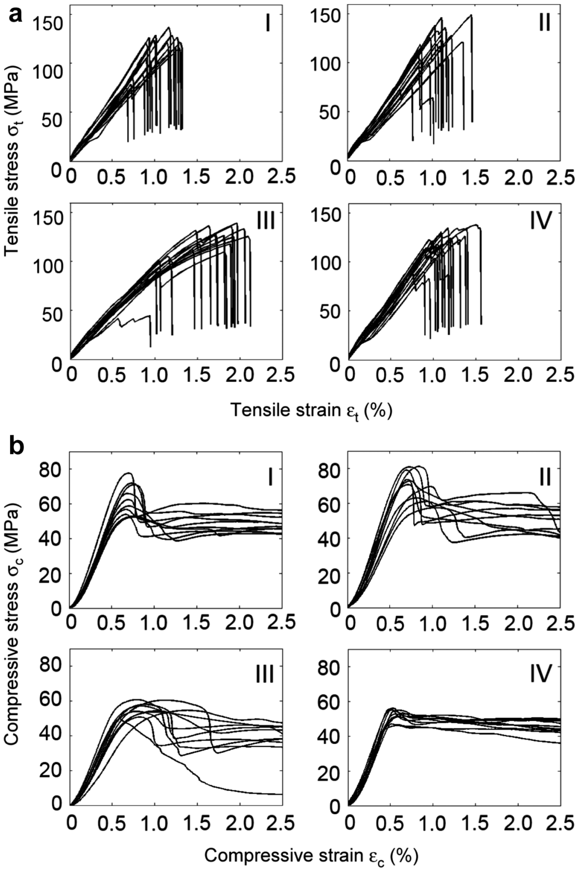

Figure 2 Stress-strain curves for samples loaded in (a) tension and (b) compression: (I) extracted yew heartwood, (II) nonextracted yew heartwood, (III) juniper, and (IV) pine.

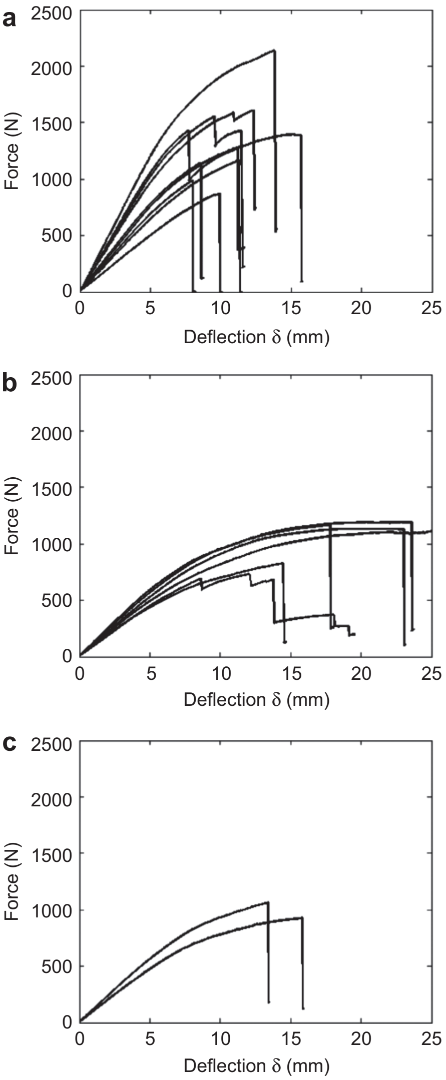

Figure 3 Force-deflection curves from small samples loaded in FPBT: (a) yew YEW$_b$, (b) juniper JUN$_b$, and (c) pine PINE$_b$.

The experimental results from the 4PB-tests (Table 3) were compared with the theoretical values on maximum force and EEA stored in the model for a full-size longbow (Figure 4). The model results were, to large extent, in agreement with the 4PB-test results. Only for a high juvenile wood stiffness E_j in combination with a high j/m ratio in the yew bow model did the EEA for the juniper and pine bows exceed that of the yew bow (Figure 4c).

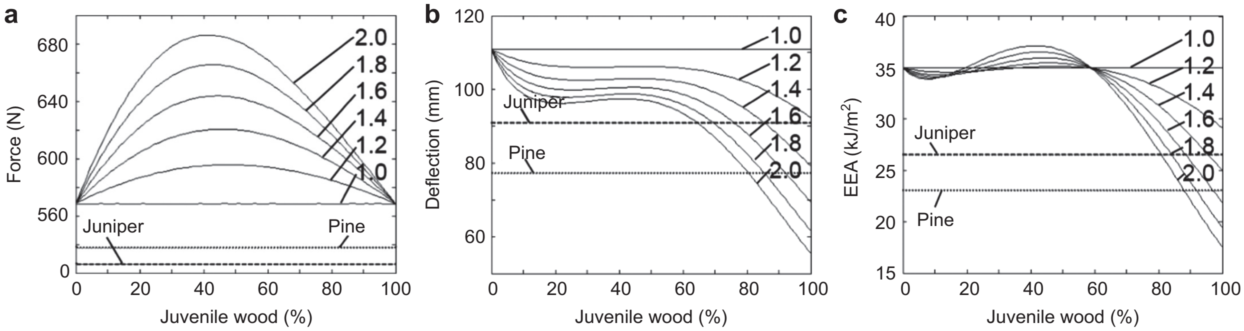

Figure 4 Theoretical values as a function of juvenile wood moiety in a longbow model: (a) force, (b) deflection, and (c) EEA. The cross-section is set to consist of juvenile wood on the compression side ("belly") and mature wood on the tension side ("back"). See Figure 1a–c. The stiffness of the juvenile wood is a factor *n* stiffer compared with the mature wood, where *n* is varied from 1.0 to 2.0.

In practice, bows are regularly subjected to bending beyond the elastic limit (Allely et al. 2000; Hardy 2006). Such a bow is still able to spring back and be fully elastic at higher strains, but with a small permanent bending deformation, "set". From this perspective, yew is a good bow material because it can withstand high strains to failure (Figure 3). This is also true for juniper. However, as seen from the b-test experiments, juniper starts to deform inelastically at lower load. A juniper bow is therefore likely to take a permanent set at a small draw and not spring back properly when released.

From the DSP images, it was found that failure in the 4PB-test specimens mostly occurred due to shear failure in the LT plane and that failure was initiated in and characterized by the delamination of the earlywood-to-latewood (EW-LW) transition. High shear strength and fracture toughness should therefore also be desirable traits when choosing the optimal material for a longbow. Yew has been shown to possess both high shear strength (Keunecke 2008) and high fracture toughness. Keunecke et al. (2007) found that the critical load at which crack propagation was initiated was almost twice as high for yew compared with spruce, and that the yew specimens featured crossover fiber bridging a characteristic almost absent in the spruce samples. Fibers or fiber bundles bridging the crack is known to contribute significantly to the fracture toughness (Sorensen and Jacobsen 1998), and the ability of withstanding high deformation without developing macroscopic cracks is highly desirable for longbows. The behavior is explained by the morphology and microstructure of yew, which has a high content of rays contributing to the R reinforcement (Keunecke et al. 2007). Also, the difference in cell-wall thickness between earlywood and latewood in yew is small, which suppresses cracking at the earlywood-latewood interface (Evans et al. 1990).

The impact of sw/hw ratio on the mechanical performance of a yew bow was also in focus. According to Stemmler (1942), the sapwood moiety should not be higher than $^1/_3$ or less. Allely et al. (2000) stated that sapwood merely plays a "cosmetic" role in yew longbow production. Bertalan (2007) suggested that the sw/hw ratio could be within an interval of $^1/_8$–$^1/_2$. A problem is that the suggestions are based mainly on traditional handicraft experience rather than on a solid mechanics approach. The recommendations from the practical point of view have also to do with the optimized utilization of the material. The juvenile wood of yew contains many dead knots from atrophied branches, which are highly undesirable. In mature trees with larger diameters, the number of knots in the outer wood decreases because older trees have fewer branches. The outer part of the stem is more utile also because the pith is avoided. Choosing a D-shaped bow cross-section with the belly facing towards the center of the stem maximizes the number of bows one can make from a single stem but also automatically results in a certain hw/sw ratio (Figure 5). This is probably the background of the proposed hw/sw ratios.

For the true heartwood and sapwood samples tested in this study, a significant difference in tensile stiffness,

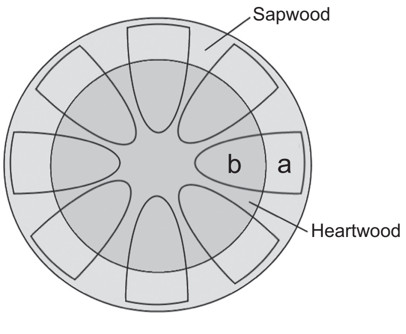

Figure 5 Optimized utilization of the material, which not necessarily results in optimized performance of the bow: positioning of the D-shaped bow cross-sections in the yew stem: (a) back side (tension) and (b) belly side (compression).

tensile strength, and yield stress in compression was established, with a higher yield stress of true heartwood (Table 3). However, as no significant difference in tensile strength, tensile stiffness, yield stress in compression, or compressive stiffness could be established between the groups of extracted and nonextracted heartwood samples, the mechanical performance is probably not related to the extractives *per se*. Instead, it is more likely that heartwood is mainly composed of juvenile wood and the sapwood of mature wood. The difference in MFA and density between juvenile and mature wood is well known, and the influence of these parameters on the mechanical performance is large (Bader et al. 2012). Thus, the hw/sw ratio can be ignored when choosing the material for your yew longbow. One should instead focus on the choice of the j/m ratio, but the juvenile wood should still be located to the belly (compression side) of the bow. More information about the optimal j/m composition was found from our longbow model, where the content of juvenile wood was varied from 0% to 100%, and the stiffness of the juvenile wood was set to be by a factor 1.0–2.0 higher compared with the stiffness of the mature wood. The results are displayed in Figure 4. Accordingly, the highest applicable force is achieved for a juvenile wood content of 30–50% (Figure 4a), whereas the largest deflection is naturally achieved when the stiffness is minimized (Figure 4b). Most interestingly, the EEA is maximized for a juvenile wood content of 30–50% (Figure 4c).

Conclusions

Tensile, compression, and 4PB-tests tests were performed on yew, pine, and juniper, and the stiffness and strength were determined. Whereas tensile strength did not differ between the three species, yield stress in compression was higher for yew. Moreover, yew displayed a surprisingly low stiffness, considering its high density. This can probably be ascribed to its unusually high MFA. The experimental data in combination with a simple bow model showed that yew has a high toughness, which means that a large amount of elastic energy can be stored in a yew bow and transferred to the arrow. Consequently, a bow made from yew is likely to have a larger range, compared with bows from other wood species. The 4PB-tests in this study also showed that yew could withstand high strains in the plastic region before failure. Bows are often subjected to bending beyond the elastic limit, and therefore this is another desirable trait. The remarkable ability of yew to withstand large deformations and resist crack formation has been ascribed to the high MFA and a high amount of rays in the radial direction, where the later results in a fiber bridging behavior.

It was found that heartwood performed better in terms of yield stress in compression than sapwood. However, the difference was not related to the extractives. Instead, the difference is probably related to morphologic traits because yew heartwood is likely to be composed mainly of juvenile wood, which differs from mature wood in terms of MFA and density. Based on our experimental and model results, the guideline for making a bow with maximum performance is to include approximately 30–50% juvenile wood on the belly side. Moreover, the stiffness and yield stress in compression for the juvenile wood should be as high as possible compared with the mature wood on the backside of the bow.

Acknowledgements: The authors wish to thank Elli Ovegård, Sara Jansson, and Robert Sandell for able help in mechanical testing. The bow building expert and Swedish longbow champion Roland Bexander is also gratefully acknowledged for fruitful discussions and contributing with valuable information on the subject. Gabriella Josefsson is acknowledged for valuable comments on the article.

Received September 19, 2012; accepted January 18, 2013; previously published online March 13, 2013

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