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THE BENDING MODULUS OF ELASTICITY OF SUBFOSSIL ELM WOOD

Sara Essert
University of Zagreb, Faculty of Science, Division of Botany Department of Biology
Zagreb, Croatia

Vera Rede, Zrinka Švagelj
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Department of Materials
Zagreb, Croatia

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ABSTRACT

The paper presents the results of the research of the bending modulus of elasticity of some 700 year old subfossil elm wood (*Ulmus minor*) retrieved from the Sava riverbed (Bosnia and Herzegovina). The subfossil elm wood is very rare to find and is highly appreciated in this form for its beautiful appearance and specific mechanical properties. Adult elm trees are nowadays also very scarce in natural forest stands of SE Europe, due to the invasion of the Dutch elm disease (*Ophiostoma novo-ulmi* Brasier) some fifty years ago.

The bending MOE was determined in the longitudinal direction and the angles between the direction of load and the annual growth ring orientation were 0°, 45°, and 90°. The obtained values of the bending modulus of elasticity are within the range of those obtained for a recent elm, which shows that numerous centuries spent in anoxic aquatic conditions have not affected the investigated property of subfossil elm. The study showed that the annual growth ring orientation significantly affects the MOE of subfossil elm wood in the longitudinal direction. The highest values were obtained at the angle of 45° (L45°), and the values for L0° and L90° are very similar.

The variability and heterogeneity of the MOE was described with the two-parameter Weibull distribution and the results follow the Weibull distribution.

KEYWORDS: Subfossil elm wood, bending modulus of elasticity, annual growth ring orientation, Weibull distribution.

INTRODUCTION

Modulus of elasticity defines an important mechanical properties which expresses the resistance of a material to elastic deformation. MOE depends on the strength of atomic bonding, i.e. it depends on the atomic structure of the material (Ashby and Jones 2012). MOE values are significantly different for each wood species. Moreover, they vary within the same wood species. Furthermore, MOE values also depend on the orientation of wood microstructure, i.e. on the position of the tested sample in regard to three principal axes: longitudinal (L), radial (R) and tangential (T). The MOE values in the longitudinal direction are 42 to 122 times greater than those in the radial and tangential directions for softwoods and 12 to 62 times greater for hardwoods. Also, the radial MOE is 1.5-6 times greater than the tangential MOE (McBurney and Drow 1962, Nairn 2007, Green et al. 1999).

The bending MOE in the longitudinal direction depends on the angle between the direction of loading and annual growth rings. In the longitudinal direction, the load acts perpendicular to the grain and the angles between the direction of loading and the annual growth rings can be from 0 to 90 degrees. For some wood species, a change in the angle between the direction of loading and annual growth rings does not affect the MOE; however, some other species have a maximum MOE at a particular angle (e.g. 0°, 45°, 90°, or others) (Green et al. 1999).

Material thickness, degree of densification, and previously cyclic loading also has effect on the modulus of elasticity and others bending characteristics (Gaff et al 2017 a, b, Gaff et al 2016, Gaf and Babiak 2017).

This study was carried out on a sample of almost 700 year old subfossil elm wood retrieved from the bed of the river Sava in the area between the villages Grebnice and Domaljevac (north Bosnia) in 2014. In this area, during exploitation of gravel, subfossil trunks are often found. That are mostly penduculate oak trunks (*Quercus robur*), and rarely some other species like elm (*Ulmus*) and ash (*Fraxinus*) (Pearson et al. 2014, Sinković et al. 2009). We chose to investigate exactly elm subfossil wood because before our extensive study (Rede et al. a, b) there were no literature data on mechanical or abrasive properties of that rare subfossil wood species.

Due to its great importance for conservators, engineers and wood technologists, the effect of time on the mechanical and chemical properties of wood has received much attention over the last few decades (Tinter et al. 2016, Kolar et al. 2014, Krutul et al. 2010, Kohara 1953, Piao et al. 2010, Hirashima et al. 2005). A large number of researchers have reported that the MOE remains unchanged over time or that it is not significantly affected by the passing of time. However, there are data which show that the MOE of some samples of aged wood and salvaged timber either increased (by up to 27 %), or decreased (by up to 42 %) (Cavalli et al. 2016).

When determining the effect of the passing of time, it is desirable to know the initial properties of the tested materials, so that aged and recent wood samples can be compared. In this research, literature data (Horvat and Krpan 1967) on recent elm were used in order to compare them with the results obtained for the aged wood. Namely, the Dutch elm disease, which culminated in the period 50-60 years ago, left the natural forests of SE Europe without adult healthy elm trees (Špiranec 1971, Wilkinson 1973); therefore it was impossible for us to get samples of recent elm for comparison.

MATERIALS AND METHODS

Samples studied in our research originate from a subfossil elm trunk excavated from the Sava riverbed, on the border between Croatia and Bosnia. The samples were taken from the exterior part of the heartwood. Radiocarbon analysis (conducted at the Ruđer Bošković Institute, Zagreb, Croatia), estimated, with a 95 % probability, that the elm trunk originates from the period between 1263 and 1400 cal AD.

By inspecting the three characteristic sections under an OLYMPUS BX 51-P light microscope and by studying reference literature on wood anatomy (Schweingruber 2015, Wheeler and Manchester 2007); and elm ecology (Nikolić 2017, Šilić 2005, Trinajstić 2001), the samples are determined as *Ulmus minor* species (Fig. 1a).

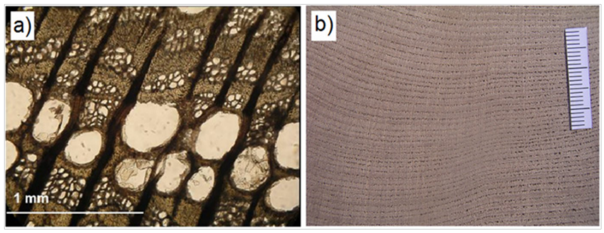


Fig. 1: Micro (a) and macro (b) cross section of the sample (Ulmus minor).

The examination of the sample microstructure showed that the share of vessels amounts to approximately 29 %, of fibers and parenchyma 52 %, and of ray 19 %.

The share of cellulose in the investigated elm was 45.3% according to MEBAK (1997), that of lignin 34.3% according to Sluiter et al. (2008), and the rest included hemicellulose, extractives, and ash. These values are in the range found in literature data for recent elm.

The longitudinal modulus of elasticity E (GPa) was determined by the tree-point bending test. The test was carried out using a Messphysik BETA 50-5 screw drive testing machine.

The load applied to the tested sample, measured with a GTM load cell, was 6.3 kN; the deflection was measured with a video extensometer (ME 46, Messphysik). The diameter of both loading and support rollers was 10 mm and the distance between centers of the support rollers was 74 mm. All the samples were tested at the same cross-head speed (2.8 mm·min^{-1}). During the entire test, the temperature in the laboratory was 22°C and the relative moisture content was 48%.

For this test, 96 samples in the form of a prism, with the same dimensions of approximately 6 x 6 x 82 mm, were used. The average annual growth ring width at sampling sites was 1.05 mm and the annual growth rings were almost parallel to each other (Fig. 1b). The length of all samples coincided with the natural axes of fiber orientation in the wood, and the load was applied perpendicular to the fiber. The direction of the load in relation to the orientation of annual growth rings was 0°(L0°), 45°(L45°), and 90°(L90°) (Fig. 2). Thirty two samples were tested for each annual growth ring orientation.

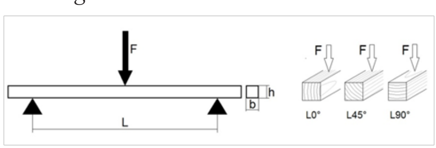


Fig. 2: Tree-point bending test arrangement and direction of load in relation to annual growth ring orientation.

The content of moisture (7.5 %) and the density of wood (0.532 g·cm^{-3}) were determined after the bending test according to ISO 13061 (2014). The width and thickness of the samples to be tested were measured before testing. During each test, the load-deflection relations were registered.

The bending modulus of elasticity for each sample was calculated from the following formula:

$$E = \frac{L^3(F_2 - F_1)}{4bt^3(a_2 - a_1)}$$

where: L - the distance between the centers of supports (mm),
b - the width of the tested sample (mm),
h - the thickness of the tested sample (mm),
$(a_2 - a_1)$ - the increment in deflection (corresponding to $F_2 - F_1$),
$(F_2 - F_1)$ - the increment in load on the linear region of the load-deflection curve (N),
$F_1 \approx 0.1F_{max}$ and $F_2 \approx 0.4F_{max}$.

The variability and heterogeneity of the MOE was described with the two-parameter Weibull distribution. This well-established statistical method is widely used for assessing the reliability of measuring mechanical properties of wood and other heterogeneous materials (Shih-Hao 2014, Chen et al. 2007).

RESULTS AND DISCUSSION

The results of our research are presented in Tab. 1. The table contains sample sizes, values of MOE (minimum, maximum and mean), standard deviation, coefficient of variation, Weibull parameters, and coefficient of determination for each annual growth ring orientation.

The results show that there were significant differences between the longitudinal MOE at various ring orientation. The highest values were measured at L45°. The mean value at L45° is higher by 29.8 % than the one at L90° and by 25 % higher than the mean value at L0°. The MOE values at L0° and L90° are very similar and they differ from each other only by 3.9 %. The highest standard deviation is observed at L45°, and the lowest at L90°.Coefficients of variation are almost the same for all the annual growth ring orientations and lower than the allowed one (0.22) for MOE (Green et al. 1999).

Tab. 1: Statistical analysis results for the measured longitudinal modulus of elasticity at three annual growth ring orientations, L0°, L45°, and L90°.

		L0°	L45°	L90°
Sample size		32	32	32
Minimum MOE values (GPa)		5.252	7.560	5.361
Maximum MOE values (GPa)		9.632	12.310	9.761
Mean MOE values (GPa)		7.600	9.501	7.317
Standard deviation		1.140	1.315	1.133
Coefficient of variation		0.150	0.138	0.155
Weibull parameters	shape	8.17	8.70	7.79
	scale	8.13	9.95	7.69
Coefficient of determination		0.96	0.92	0.95

The anisotropic highly porous structure, layering of the wood and most of all the orientation of the ray cells in relation to the annual rings, causes the variation in MOE values of investigated samples. Rays of elm wood are most usually 4-5 seriate and from 30-50 cells high. They flare slightly along growth ring boundaries. Fig. 3 shows the microstructure of longitudinal section at three annual ring orientations.

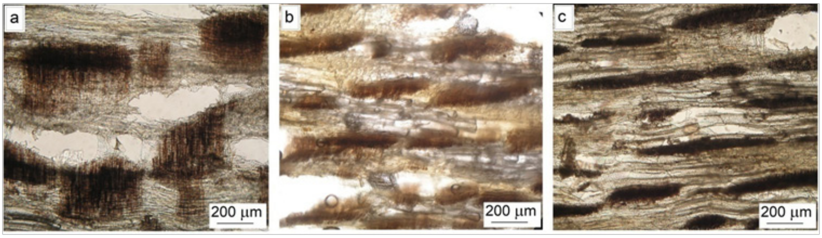


Fig. 3: Microstructure of longitudinal section at three annual growth ring orientations: L0° (a), L45° (b) and L90° (c).

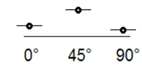
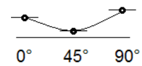
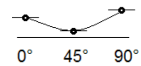
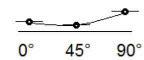
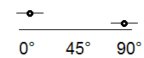
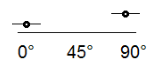
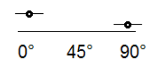
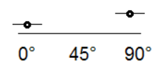
The effect of time passing on the values of bending modulus of elasticity

Original mechanical properties of our subfossil elm are unknown and it is very difficult to determine the exact influence of the passing of time on the MOE. We also could not compare our results with those obtained for recent elm from the same location because elm trees in natural forest stands were destroyed by the epidemic Dutch elm disease. We compared our results with the MOE values from the available literature (Horvat and Krpan 1967); this comparison showed that the MOE values for subfossil elm are in the range found in literature data for recent elm (5.9-16 GPa). This indicates that very specific environmental conditions in the period of 700 years have not significantly affected the MOE of elm wood. Cavalli et al. (2016) presented results of several studies with very non-concordant conclusions about the effect of time on MOE. Most studies reported that MOE increased or remained unchanged over time, while some reported that MOE decreased. Research into subfossil wood from the same geographic locations ours was done on oak (Sinković et al. 2009) and elm (Rede et al. 2017a, b). The comparison between the recent and about 5900 year old subfossil oak (abonos) showed that the static bending strength increased and compressive strength decreased over time (Sinković et al. 2009). Results of the study into the effect of annual growth ring orientation on the bending strength of subfossil elm are in agreement with our results for MOE (Rede et al. 2017a).

The effect of annual growth ring orientation on the values of bending modulus of elasticity

The influence of annual growth ring orientation on the MOE is not the same for all wood species. The obtained results were compared with the results from available literature (Tab. 2).

Tab. 2: Summary of the literature investigating the annual grow ring orientation effect on the MOE.

Wood taxa	Literature	Type of stress	Scheme
Ulmus minor (subfossil)	our research	bending	
Picea abies	Miksic et al. 2013	compression	
Picea abies	Garab et al. 2010	compression	
Taxus baccata	Garab et al. 2010	compression	
Eucalyptus tereticornis and *Cassia ferruginea*	Lahr et al. 2014	bending	
Erisma uncinatum, Aspisdosperma polyneuro and *Hymenaea stilbocarpa*	Lahr et al. 2014	bending	
Pseudotsuga menziesii	Grotta et al. 2005	bending	
Robinia pseudoacacia	Adamopoulos 2002	bending	

The relationship between the bending MOE and the ring orientation at L0° and L90° for the investigated subfossil elm coincides with the results for the species *Eucalyptus tereticorni*, *Cassia ferruginea* (Lahr et al. 2014) and *Pseudotsuga menziesii* (Grotta et al. 2005). The results for *Robinia pseudoacacia* (Adamopoulos 2002), *Erisma uncinatum, Aspisdosperma polyneuro* and *Hymenaea stilbocarpa* (Grotta etal. 2005) are opposite than the ones from our study. Studies dealing with the L45° ring orientation were done only for the species *Picea abies* and *Taxus baccata* (Miksic et al. 2013, Garab et al. 2010) and their results for the MOE are opposite from ours. A possible cause of that could be found in the fact that in those investigations the compression was used instead of bending.

Statistical analysis

Fig.4 shows the variations in MOE with the probability density function, the cumulative distribution function, and the Weibull plot. The coefficients of determination for all directions are very similar and close to one, which shows great goodness of fit. The Weibull shape parameter was the highest at L 45°, which indicates the lowest degree of variability in MOE for this annual growth ring angle. The Weibull shape parameters at L0° and L90° were very similar.

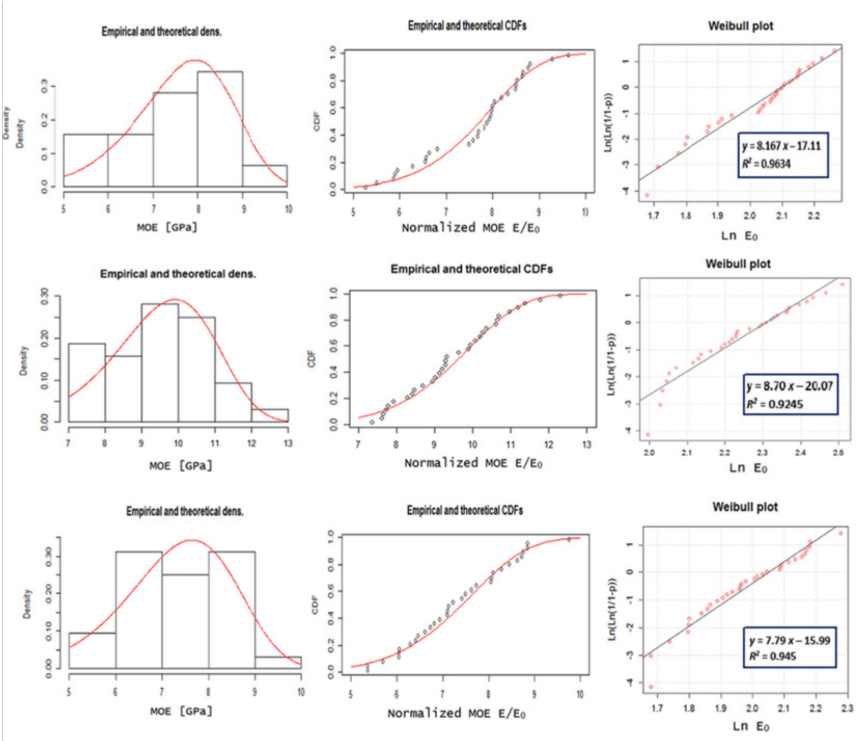


Fig. 4: The probability density function, the cumulative distribution function and the Weibull plot for the L0° (top), the L45° (middle), and the L90° orientation (down).

CONCLUSIONS

The purpose of this study was to investigate the longitudinal MOE of 700 year old subfossil elm and the effects of both the passing of time and the annual growth ring orientation (L0°, L45° and L90°) on the MOE values. Using the three-point bending test on elm wood samples the following major conclusions were obtained:

1. The MOE values for all directions are within the range of values for recent elm, which shows that several centuries of trunk ageing in specific anoxic conditions on the river bed have not significantly affected the MOE.
2. The orientation of annual growth rings under bending has very big influence on the longitudinal MOE. The highest value was obtained for L45° (9.5 GPa), and the values for L0° (7.6 GPa) and L90° (7.3 GPa) are very similar.
3. The obtained MOE values for all directions follow the Weibull distribution. The highest Weibull shape parameter was at L45°. The coefficients of determination for all directions were close to one.

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Sara Essert*
University of Zagreb
Faculty of Science
Division of Botany
Department of Biology
Marulićevtrg 20/Ii
10000 Zagreb
Croatia
Corresponding author: sara.essert@biol.pmf.hr
Phone: +385/91/581-36-34

Vera Rede, Zrinka Švagelj
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
Department of Materials
Ivana Lučića 5
10000 Zagreb
Croatia