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SOME ORTHOTROPIC ELASTIC PROPERTIES OF *FAGUS ORIENTALIS* AS INFLUENCED BY MOISTURE CONTENT

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ABSTRACT

The aim of this study was to investigate the influence of moisture content on some orthotropic elastic properties of Oriental beech (*Fagus orientalis)*. The elastic properties investigated include E_L, E_R, E_T, ν_{LR}, ν_{LT}, ν_{RL}, ν_{RT}, ν_{TL} and ν_{TR} under compression. Compression strength in all orthotropic directions was also studied. Specimens were cut from sapwood of beech logs and sorted into four matched MC groups. Clear wood samples were conditioned at 20°C and 50, 65, 85, 95 % RH and subjected to compression tests. A digital image correlation technique was used to capture the strains during testing. Young modulus, Poisson ratios, and compression strength were calculated and compared for all orthotropic directions. Results indicated that Young modulus and compression strength of the samples tested were strongly affected by moisture content. Poisson rations seem to less sensitive to the MC changes.

KEYWORDS: Moisture, Young's modulus, Poisson's ratio, Oriental beech.

INTRODUCTION

Wood always equilibrates to a wide range of moisture content (MC) levels in use, and most of its properties are considerably influenced by the MC. Particularly regarding the properties and the use of wood in structural applications, MC is known to be one of the major influencing factors (Ross 2010). Most of the strength properties and elastic properties of wood vary inversely with the MC of the wood below fiber saturation point (FSP) (Panshin and de Zeeuw 1980). Above fiber saturation point the mechanical properties are constant with changes in moisture content. At very low MC (0-10 %), some strength properties may decrease again after reaching a maximum value (Ross 2010). The various mechanical properties have a different sensitivity to changes in MC, with strength properties more sensitive than stiffness properties and static properties more sensitive than dynamic properties (Dinwoodie 2000).

The effect of MC on the mechanical properties of wood is extensively studied over the last decades. A detailed discussion can be found in Gerhards (1982), Green and Kretschmann (1994) and Kretschmann and Green (1996). In general, most mechanical properties were found to increase as MC decreased FSP to 6 %, and they reach a maximum about 6 % MC. This reduction in mechanical properties is presumably a result of drying degrade that occurs at low MC levels.

While the influence of MC on the mechanical behavior of wood in the *L* direction is relatively well known (Gerhards 1982), investigations on the behavior in the perpendicular directions (*R* and *T*) are limited. The interest on the moisture dependent orthotropic behavior is not new. So far, only few studies studied moisture dependent elastic properties of wood in the *R* and *T* directions (McBurney and Drow 1962; Hering et al. 2012a; Hering et al. 2012b; Ozyhar et al. 2013a; Ozyhar et al. 2013b). Furthermore, moisture-dependent wood strength in the *R* and *T* directions, remain widely unrevealed for most wood species. The usable data are limited to a few references (Kretshmann and Green, 1996; Ozyhar et al. 2013a; Ozyhar et al. 2013b). While selected moisture dependent elastic properties for some wood species can be found in (Kretshmann and Green, 1996; Ross 2010), in general, only few properties were tested for a given property–MC combination in most investigations. As a consequence, comprehensive datasets including the moisture-dependent orthotropic elastic and strength values are missing for most wood species. Elastic and strength properties based on the three dimensional approach are essential input parameters required for advanced computational models such as finite elements used in engineering analysis.

The mechanical investigation regarding Turkish wood species generally concerned with behavior at constant MC of 12 %. Although data needed for three dimensional modeling of mechanical behavior depending on the MC change, no information is available for this purpose. In this study, a set of elastic and strength parameters is determined in uniaxial compression tests at different moisture conditions. The parameters evaluated and reported here comprise the Young's moduli, Poisson‘s ratios, and compression strengths in all orthotropic directions.

MATERIAL AND METHODS

Small clear wood samples were prepared from beech (*Fagus orientalis*) logs harvested from Devrek Forest District in Turkey. They were approximately 50 cm in diameter. The logs were transferred and sawn to lumber. Only sapwood lumbers were used in order to prepare small clear specimens. 60 samples with nominal dimensions of 20 x 20 x 60 mm for each direction (*L, R, T*) from radial or tangential planks were prepared. Before testing, compression specimens were randomly divided into four groups and conditioned in climatic chambers at 50, 65, 85 and 95 % relative humidity (RH) at a temperature of 20°C. After the specimen had reached equilibrium MC, uniaxial compression tests were carried out using a Zwick 100 universal testing machine. All tests were performed at standard climatic conditions (65 % RH and 20°C). To minimize the influence of the MC change, specimens were tested immediately after removal from the climatic chamber. Wood MC was determined by the oven-drying method. The feed rate was defined in such a way that the failure of the specimen should be reached in 90 (±30) s. The strains were evaluated using the digital image correlation (DIC) technique. A high contrast random dot texture was sprayed on the surface of the specimen with air-brush to ensure the contrast needed for the evaluation of the displacements. Pictures were taken with a frequency of 4 Hz of the cross-sectional surface area of the specimen during testing (Fig. 1).

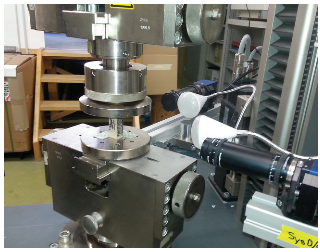

Fig. 1: Compression test set up.

By means of the mapping software (VIC 2D, Correlated Solution), the surface strains were calculated from the displacements that occurred during deformation. A more detailed description of the strain computation by the DIC technique is given in Keunecke et al. (2008). Apparent densities of the samples were calculated according to TS2472 (2005) using the stereometric method. The stress-strain curves obtained were used in order to evaluate Young's moduli and strength properties of the specimens. The Young's modulus was calculated from the ratio of the stress σ to the strain ε measured in the linear elastic range:

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i} = \frac{\sigma_{i,2} - \sigma_{i,1}}{\varepsilon_{i,2} - \varepsilon_{i,1}} \quad i \in R, L, T \tag{1}$$

The Poisson's ratio ν, defined as

$$\nu_{ij} = -\frac{\varepsilon_i}{\varepsilon_j}, \quad i, j \in R, L, T \quad \text{and} \quad i \neq j, \tag{2}$$

where: ε_i - represents the active strain component in the load direction
ε_j - the passive (lateral) strain component, which was determined in the linear elastic range from the linear regression of the passive–active strain diagram.

Since the strength behavior of wood in R and T directions is obscure, maximum compression strength was calculated using 0.2 % yield values using following formula.

$$\sigma_{UCS} = P_{max}/A \tag{3}$$

where: σ_{UCS} - represents yield strength,
P_{max} - the yield load and
A - the cross-sectional area of the specimen.

A one-way layout ANOVA analysis was performed on each direction tested using SAS statistical analysis software to interpret effects of MC on the properties measured of the clear wood samples.

RESULTS AND DISCUSSION

Average stress-strain curves of the specimens tested are presented in Fig. 2. Average values for Young's modulus of the specimens tested are presented in Tab. 1.

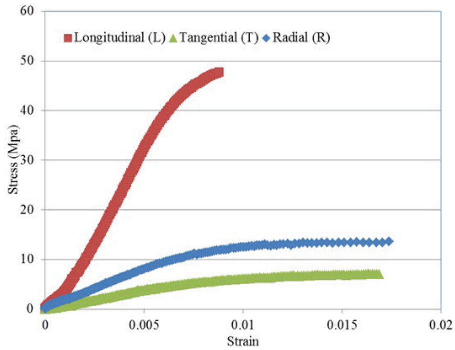

Fig. 2: Average stress-strain curves obtained from testing.

Tab. 1: Young's moduli (N.mm^{-2}) values for Oriental beech (Fagus orientalis).

@ 20°C R.H. (%)		E_L	E_R	E_T
50	Mean	14092	2137	902
	Cov (%)	24	26	14
	n	15	15	15
	Density (g.cm^{-3})	0.68	0.66	0.64
	M.C. (%)	10.65	10.23	10.97
65	Mean	13360	1684	824
	Cov (%)	10	21	8
	n	14	15	15
	Density (g.cm^{-3})	0.69	0.67	0.64
	M.C. (%)	13.40	11.82	13.64
85	Mean	11586	1481	706
	Cov (%)	18	8	11
	n	14	11	14
	Density (g.cm^{-3})	0.68	0.68	0.64
	M.C. (%)	16.53	16.53	16.62
95	Mean	10135	1214	616
	Cov (%)	12	10	17
	n	15	15	15
	Density (g.cm^{-3})	0.67	0.68	0.65
	M.C. (%)	20.36	20.40	20.95

*Values sharing the same capital letter within a column are not statistically different at the 0.05 level of confidence.

There was a good match among the density values in the different MC groups. In comparison to available literature references at similar MC, the measured density values were comparable. Density of beech wood grown in Turkey is ranged from 0.589 to 0.669 g.cm^{-3}

(Bektas et al. 2002). Coefficient of variation in Young's modulus values ranged from 8 to 26 % which is acceptable for mechanical properties of wood. The ratio of Young's modulus in *L, R* and *T* directions was approximately 16:2:1 which is somewhat different from reported in Hering et al. (2012a) for European beech (*Fagus sylvatica*). The Young's modulus in *T* direction for Oriental beech (*Fagus orientalis)* is higher than *Fagus sylvatica*. In general, Young's modulus in all anatomical directions tended to increase at lower MC as expected. ANOVA results indicated that the three Young's modulus values are affected by moisture content significantly.(Pr<F = 0.001; R^2 = 0.93;Coefficient of variation = 29). Duncan test was used to make comparison among MC groups (Tab. 1). Young's modulus in the direction perpendicular to the grain (*R, T*) changes with MC at higher rates. The changing rates of Young's modulus due to 1 % MC in *L, R* and *T* directions were nearly 2.8, 4.3 and 3.2 %, respectively. Similar trend in mechanical properties due to the MC changes was reported by Gerhards (1982), Ross (2010), Hering et al. (2012a) and Ozyhar et al. (2013a). The modulus of elasticity for *Fagus orientalis* grown in Turkey in bending reported in the literature varies from 11621 to 16000 $N.mm^{-2}$ (Bektas et al. 2002). Fig. 3 shows that Young's modulus conforms closely to straight-line relationships with moisture content.

The Poisson's ratios calculated from the compression tests are presented in Tab. 2. Poisson ratio was assumed to be 0.3 for most application in structural analysis of wood and wood framed structures such as furniture frames wood because there was no data available for Oriental beech *Fagus orientalis*. It was found that Poisson ratio varies from 0.046 in *LT* plane to 0.726 in TR plane. Coefficient of variation in Poisson's ratios ranged from 13 to 60 %. In general, all calculated Poisson' ratios are identical to those of reported for European beech and some hardwood species with the exception of the high Poisson's ratio in the *LR* plane. Poisson's ratios in the *LT* and *LR* plane showed the highest coefficient of variation. Wide variation in the Poisson's ratios of wood due to a high coefficient of variation was also implied by Hering et al. (2012a); Ozyhar et al. (2013a); Jeong et al. (2010); Mizutani and Ando (2015). Fig. 4 illustrates relationships between Poisson's ratios and moisture content for beech wood.

Tab. 2: Poisson ratios for Oriental beech (Fagus orientalis).

20°C R.H. (%)		ν_{LT}	ν_{RT}	ν_{LR}	ν_{TR}	ν_{RL}	ν_{TL}
50	Mean	0.046	0.652	0.095	0.726	0.572	0.533
	Cov (%)	29	29	60	15	25	19
	n	15	15	14	14	15	15
	Density ($g.cm^{-3}$)	0.64	0.64	0.66	0.66	0.68	0.68
	M.C. (%)	10.97	10.97	10.23	10.23	10.65	10.65
65	Mean	0.056	0.633	0.107	0.704	0.608	0.573
	Cov (%)	57	30	44	24	22	35
	n	15	15	13	13	14	14
	Density ($g.cm^{-3}$)	0.64	0.64	0.67	0.67	0.69	0.69
	M.C. (%)	13.64	13.64	12.82	12.82	13.40	13.40
85	Mean	0.054	0.685	0.104	0.728	0.659	0.572
	Cov (%)	55	30	41	13	17	24
	n	13	14	15	15	14	14
	Density ($g.cm^{-3}$)	0.64	0.64	0.68	0.68	0.68	0.68
	M.C. (%)	16.62	16.62	16.53	16.53	16.53	16.53
95	Mean	0.054	0.636	0.083	0.716	0.685	0.628
	Cov (%)	52	28	29	21	20	39
	n	15	15	15	15	15	15
	Density ($g.cm^{-3}$)	0.65	0.65	0.68	0.68	0.67	0.67
	M.C. (%)	20.95	20.95	20.40	20.40	20.36	20.36

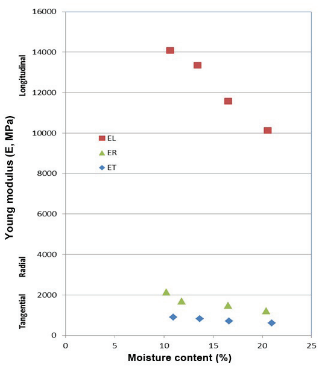

Fig. 3: Comparison of the moisture-dependent Young's moduli for Oriental beech (Fagus orientalis).

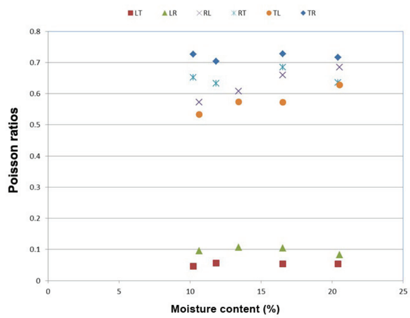

Fig. 4: Comparison of the Poisson ratios for beech wood.

ANOVA results indicated that the effect of MC on Poisson's ratios is not significant for the MC levels tested. Thus, Duncan test was not performed. Only the Poisson's ratio in *RL* plane seemed to be highly correlated with MC showing an increase with increasing MC. The other Poisson ratios are not well correlated with MC showing some fluctuations with MC. Although no profound effects of MC on Poisson's ratios LR, TR, and RT were found in the studies of Drow and McBurney (1954); a slight decrease in Poisson's ratios with increasing MC was reported by Hering et al. (2012a), and a significant effect of MC on Poisson's ratios was implied by Mizutani and Ando (2015) for wider range of MC (0-177 %).

Average values for CSin L, R, T directions calculated in this study are presented in Tab. 3.

Tab. 3: Strength values for Oriental beech (Fagus orientalis) (N.mm^{-2}).

20°C R.H. (%)		E_L	E_R	E_T
	Mean	54.13	14.04	8.40
	Cov (%)	23.67	7.86	24.17
50	n	15	15	15
	Density (g.cm^{-3})	0.68	0.66	0.64
	M.C. (%)	10.65	10.23	10.97
	Mean	49.07	12.60	7.65
	Cov (%)	19.12	5.99	21.65
65	n	15	15	15
	Density (g.cm^{-3})	0.69	0.67	0.64
	M.C. (%)	13.40	12.82	13.64
	Mean	38.88	10.81	6.8
	Cov (%)	15.73	10.61	38.51
85	n	15	15	15
	Density (g.cm^{-3})	0.68	0.68	0.64
	M.C. (%)	16.53	16.53	16.62
	Mean	33.91	9.29	5.96
	Cov (%)	14.60	15.00	36.65
95	n	15	15	15
	Density (g.cm^{-3})	0.67	0.8	0.65
	M.C. (%)	20.36	20.40	20.95

*Values sharing the same capital letter within a column are not statistically different at the 0.05 level of confidence.

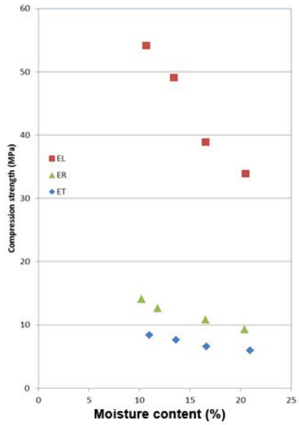

Fig. 5: Comparison of strength values for Oriental beech (Fagus orientalis).

ANOVA results indicated that the three CS values are significantly affected by MC. (Pr<F = 0.001; R^2= 0.88; Coefficient of variation = 6.85). Duncan test was used to make comparison among MC groups. CS of Oriental beech used in this study appears to be somewhat lower in *L* direction than average reported by Bektas et al. (2002) and identical to those reported by Skarvelis and Mantanis (2013). The ratio of CS in L, R and T directions was approximately 6.4:1.64:1.CS in *L, R, T* directions of Oriental beech tested in this study is somewhat higher than those reported for European beech by Ozyhar et al. (2013a). The changing rates of CS due to 1 % MC in *L, R* and *T* directions were nearly 2, 0.5 and 0.25 %, respectively. Fig. 5 illustrates that the relationship between compression strengthand MC is nearly a straight-line.

CONCLUSIONS

The results of this study reveal that elastic properties and compression strength in three anatomic directions of Oriental beech (*Fagus orientalis)* are significantly different. The results also indicate that significant influence of MC on both the Young's modulus and CS is clearly visible. Results of the study also show that most of the Poisson's ratios of Oriental beech are insensitive to the MC levels measured. The results found in the study affirm the importance of knowing the MC dependency of the mechanical behavior of wood and provide data for numerical simulations taking into account the hygroscopic nature of wood. Results of the study can be utilized in advanced modeling behavior of beech wood where exposed to structural loads and MC.

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