Effects of Cross-sectional Geometry and Force Direction on Bending Strength and Modulus of Elasticity of Some Softwood Beams

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The effects of cross-sectional geometry and force direction on bending strength (*MOR*) and modulus of elasticity (*MOE*) were investigated in selected softwoods. The specimens were constructed of Scots pine (*Pinus sylvestris*), Black pine (*Pinus nigra*), Siberian pine (*Pinus sibirica*), Stone pine (*Pinus pinea*), Nordmann fir (*Abies nordmanniana*), Oriental spruce (*Picea orientalis*), and Lebanon cedar (*Cedrus libani*). A total of 280 specimens were prepared from these seven species in two different cross-sectional geometries (circular and square, equal in area) and tested in two characteristic force directions (tangential and radial) by 10 replications. They were subjected to three-point bending tests according to TS 2474 (2005) and TS 2478 (2005) to obtain the *MOR* and *MOE*. The results showed that the type of cross-sectional area and direction of applied force, individually or together, had considerable effects on the *MOR* and *MOE*. The *MOR* values of the circular-sectioned specimens were 5% greater than those of the square-sectioned specimens. The *MOE* values of the circular-sectioned specimens were on average 19% greater than those of the square-sectioned specimens. The *MOR* and *MOE* values were on average 7% and 17% greater, respectively, for the force applied in the tangential direction.

Keywords: Softwood; Beams; Bending strength; Modulus of elasticity; Circular cross section; Square cross section; Radial; Tangential

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INTRODUCTION

Wood, like stone, has been used as a construction material throughout history. Although it has complex mechanical characteristics, such as anisotropy or heterogeneity, humans have utilized the unique characteristics of wood in a wide variety of applications, such as cottages, shelters, ships, furniture, and home decoration.

Wood has several advantages as a natural resource and structural material. It is easily obtained from forests and is economically practical as a ready to use raw material. It is highly strong, considering its density, and provides good heat insulation in structures. It is a very workable material; nearly any kind of shape or type of cross-sectional geometry can be manufactured.

Wood is also environmentally friendly, as it fully decomposes in nature and is easily recycled. In addition to being renewable, wood does not require fossil fuels in its production, reducing carbon monoxide and carbon dioxide emissions. This distinguishes it from other common construction materials including brick and steel.

Wood is diverse in its material properties such as density and cell length and can be heterogeneous. Consequently, variations can occur in the development of the wooden body that could eventually affect its mechanical properties (Dinwoodie 2000). Furthermore, wood is orthotropic, having different and independent mechanical properties along three mutually perpendicular axes: longitudinal, radial, and tangential. The longitudinal axis is parallel to the fiber (grain), the radial axis is normal to the growth rings (perpendicular to the grain in the radial direction), and the tangential axis is perpendicular to the grain but tangent to the growth rings (Forest Products Laboratory 2010). Therefore, mechanical properties of a wood material should be determined and explained according to the grain directions.

Softwood trees are much more common (at approximately 80%) in nature. The wood is supplied as planks and beams. Softwood is especially applied in construction, in roofs, inner parts, and other building components (*e.g*., fixtures) because of its practical malleability and light weight. A considerable amount of wooden structures is created by the Turkish woodworking industry, and softwood is particularly preferred.

The fibers are elongated longitudinally in the wooden beams, which provides for maximum strength in bending. In applications, wooden beams are subjected to other loadings in addition to bending, such as tension, compression, and shear. Still, most structural failures occur due to bending (Frese and Blaß 2011). In bending failure, cracks occur in the tangential direction at the compression zone, called kink bands, and in the longitudinal direction at the tension region. The longitudinal cracks are caused by the rupture of the fibers, such that a sudden collapse, which will eventually occur due to these failures at the tension region. Therefore, the cross-sectional properties and grain direction of wooden beams are important to the resistance to bending forces. Thus, it is important to evaluate and compare the bending strengths and moduli of elasticity of the softwoods that are utilized in wooden structures.

In this study, the maximum stress in the beam (σ) is determined by Eq. 1,

$$\sigma = \frac{M}{Z} \tag{1}$$

where M is the maximum bending moment and Z is the section modulus of the cross-section. The modulus of rupture (MOR) reflects the ultimate load carrying capacity of a specimen in bending and is proportional to the ultimate moment in the specimen. In the case of the three-point testing as performed in this work, (Fig. 1):

$$MOR = \frac{M_{ultimate}}{Z} = \frac{F_{ultimate}L}{4Z} \tag{2}$$

In Eq. 2, $M_{ultimate}$ is the ultimate moment, $F_{ultimate}$ is the ultimate load, and L is the length of the beam. It is slightly greater than the tensile strength. Modulus of rupture is an accepted criterion of strength, although it is not a true stress because the formula (Eqs. 1) by which it is computed is valid only up to the elastic limit, beyond which σ exceeds the yield stress (Forest Products Laboratory 2010). The inelastic behavior of the wood can be viewed as changing the section of modulus. It is called plastic section of modulus and is defined for isotropic materials. However, in the case of wood, for which there are more variable properties, it is better and desirable to define an experimentally determined equation for the MOR.

The modulus of elasticity (MOE) depends on direction in the wood because wood is anisotropic. The primary directions in wood are longitudinal, radial, and tangential, and the elastic moduli are denoted by E_L, E_R, and E_T, respectively. The MOE is determined from three-point or four-point bending tests, rather than from an axial test. A specimen has its maximum strength when the fibers are oriented longitudinally; the MOE measured in bending tests is generally that in the longitudinal direction, E_L. The upper limit of the elastic region of the stress-strain curve is assumed to be in an interval of 10% and the 40% of the rupture stress (TS EN 310 1999; Smardzewski 2015), and MOE is calculated by taking the average of results in this interval. In the elastic region, the center point deflection of the beam (Δ):

$$\Delta = \frac{FL^3}{48E_L I} \tag{3}$$

In Eq. 2, I is the second moment of inertia of the section. In this study, MOE was determined by:

$$MOE = \frac{FL^3}{48\Delta I} \tag{4}$$

Some studies have been performed on the effects of cross-sectional geometries on the mechanical properties of wooden furniture joints. Likos *et al*. (2012) examined the bending moment capacities and moment rotation characteristics of mortise and tenon joints as a function of tenon cross-sectional geometry, grain direction, length, and shoulder fit. According to the results, joints with 25.4-mm-long diamond-shaped tenons had greater moment capacity than either rectangular or circular tenon joints, while joints with 38-mm-long or 51-mm-long rectangular tenons had greater capacities than joints with diamond or circular tenons. In a similar study, Likos *et al*. (2013) investigated the effect of cross-sectional tenon geometry on the static and cyclic load capacities of side chairs constructed with circular, square, and diamond-shaped mortise and tenon joints. The results showed that the chairs with mortise and tenon joints had cyclic strength to static strength ratios of 56.5%, 66.8%, and 69.2% for rectangular, circular, and diamond-shaped tenons, respectively. Kasal *et al*. (2010) determined the bending strengths and elastic moduli of laminated veneer lumber (LVL) and solid wood materials constructed of beech (*Fagus orientalis*), Scots pine (*Pinus sylvestris* L.), and poplar (*Populus nigra*). The results showed that the laminated materials, which had several technical and economic advantages, could be used instead of solid wood materials in structures and in production of furniture frames. Pěnčík (2015) used a general material model in combination with an idealization of annual rings with cylindrical surfaces for the modeling of wood specimen tests of Scots pine. The results showed good agreement between the numerical analysis and experimental testing.

There has been little information available in the literature concerning both the bending strength of wooden beams sectioned with different geometries and interaction of grain direction with applied force. This study was performed, accordingly, to compare the maximum bending strength and MOE values of selected softwood species and to investigate the effects of cross-sectional geometry and force direction on bending strength and MOE in softwoods that are commonly utilized in wooden structures. In summary, the objectives were tested as follows: to determine how bending strength and MOE in selected softwoods are affected by the cross-sectional geometry and how bending strength and MOE in selected softwoods are affected by the grain direction of the applied force.

EXPERIMENTAL

Experimental Design

Altogether, 28 sets of specimens consisting of 10 replicates each, for a total of 280 specimens, were prepared to obtain both MOR and MOE data from the bending strength tests. Full linear models (Eqs. 5 and 6) for three-point experiments were considered to evaluate the influences of wood species (Scots pine, black pine, Siberian pine, stone pine, Nordmann fir, Oriental spruce, and Lebanon cedar), cross-sectional geometry (circular, square), and force direction (radial, tangential) on the MOR and MOE of the specimens. The model equations were formed as follows:

$$MOR_{ijkl} = \mu_1 + A_i + B_j + C_k + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (ABC)_{ijk} + \rho_l + \varepsilon_{ijkl} \quad (5)$$

$$MOE_{ijkl} = \mu_2 + A_i + B_j + C_k + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (ABC)_{ijk} + \rho_l + \varepsilon_{ijkl} \quad (6)$$

where MOR_{ijkl} is the bending strength (N/mm^2); MOE_{ijkl} is the modulus of elasticity (N/mm^2); μ_1 is the population mean bending strength for all combinations of wood species, cross-sectional geometry, and force direction (N/mm^2); μ_2 is the population mean MOE for all combinations of wood species, cross-sectional geometry, and force direction (N/mm^2); A is the discrete variable representing the effect of wood species; B is the discrete variable representing the effect of cross-sectional geometry; C is the discrete variable representing the effect of force direction; (AB), (AC), and (BC) are discrete variables designating the two-way interactions among the three variables; (ABC) is the discrete variable designating the three-way interactions among the three variables; ρ is the replication parameter; ε is the random error term; i is the index for the wood species (1 to 7); j is the index for the cross-sectional geometry (1 or 2); k is the index for the force direction (1 or 2); and l is the index for the replicate (1 to 10).

Preparation and Testing of the Specimens

Seven different softwood species were examined in the study: Scots pine (*Pinus sylvestris*), Black pine (*Pinus nigra*), Siberian pine (*Pinus sibirica*), Stone pine (*Pinus pinea*), Nordmann fir (*Abies nordmanniana*), Oriental spruce (*Picea orientalis*), and Lebanon cedar (*Cedrus libani*). The woods were obtained from commercial suppliers in İzmir, Turkey. These species are commonly utilized in the woodworking industry as a structural material. The average densities were 0.52 g/cm^3, 0.56 g/cm^3, 0.40 g/cm^3, 0.49 g/cm^3, 0.44 g/cm^3, 0.44 g/cm^3, and 0.52 g/cm^3 for Scots pine, Black pine, Siberian pine, Stone pine, Nordmann fir, Oriental spruce, and Lebanon cedar, respectively. The specimens were conditioned to and tested at 12% ± 0.2% moisture content (MC). Moisture contents and densities of the woods were determined in accordance with TS 2471 (2005) and TS 2472 (2005), respectively.

All of the specimens were tested under static bending loads. Tests were performed on a 50-kN-capacity universal testing machine (Mares, Istanbul, Turkey) in the mechanical test laboratory of the Wood Science and Industrial Engineering Department of Muğla Sıtkı Koçman University (Muğla, Turkey) in accordance with TS 2474 (2005). Modulus of elasticity values were calculated according to TS 2478 (2005).

The square-sectioned specimens were sized at 20 mm by 20 mm, while the circular-sectioned specimens were 22.6 mm in diameter, to obtain equal cross-sectional areas for both cross-sectional geometries. The span was 340 mm for all specimens. The specimens were loaded at the center point by a standard bearing block (Fig. 1).

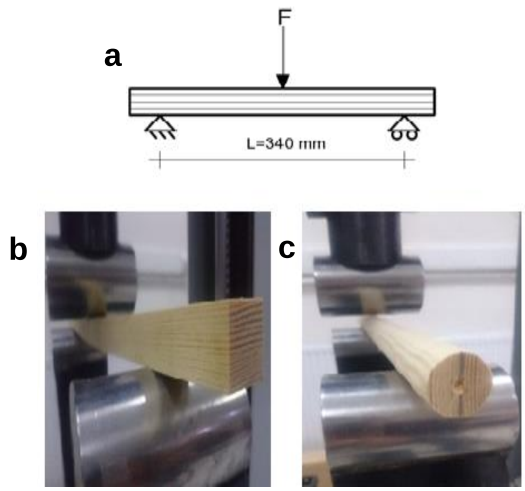

Fig. 1. Static bending test setup: three-point experiment illustration (a) and sample images from laboratory (b and c)

Deflections were measured using a dial gage clamped to measure exactly from the bottom face at the midpoint of the specimens. Dial gage readings were taken at regular intervals as the specimens were loaded.

Half of the specimens were tested with the force parallel to the radial direction, while the other half were tested with the force parallel to the tangential direction. The cross-sectional geometries of the specimens according to force and grain direction are shown in Fig. 2.

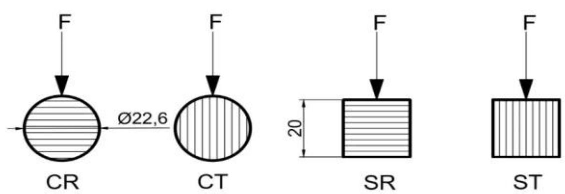

Fig. 2. Cross-sections (in mm) of the specimens; CR: circular-radial, CT: circular-tangential, SR: square-radial, ST: square-tangential

All of the test specimens were held in a controlled environment with a relative humidity of 65% ± 3% and a temperature of 20 °C ± 2 °C for at least a month prior to testing to reach an equilibrium MC of 12% ± 0.2%, ideally. Representative samples were taken from each specimen to determine the MC and specific gravity. Although the specimens were held in a controlled environment set to yield 12% MC, the MC values varied within and among the wood species. The sample specimens had not reached the ideal equilibrium MC of 12%. Their MC had reached a value less than 12% even after conditioning, and their actual MC was approximately 7%.

The MOR and MOE data were adjusted to the air dry (MC = 12%) strength values based on the *Wood Handbook* (Forest Products Laboratory 2010) and Berkel (1970), having different MC values from the air-dry condition. The *Wood Handbook* suggests adjusting the MOR values with a 4% increase in strength per 1% decrease in MC, while adjusting the MOE values with a 2% increase in stiffness per 1% decrease in MC (Forest Products Laboratory 2010). These conventions were applied in this study; both square and circular cross-sectional specimens' test results were adjusted to 12% MC for consistency with the literature.

RESULTS AND DISCUSSION

All failures occurred between 60 s and 90 s. In general, the test specimens failed in an ordinary manner; in other words, no unexpected failures occurred in the tests. Specimens failed with fracture near the midpoint of the spans. Mean MOR and MOE values with their coefficients of variation, along with least significant difference (LSD) comparison test results for three-way interactions of specimens, are given in Table 1. The letter "A" corresponds to the greatest value, and the remaining letters extend to "M" with respect to the magnitude of the homogeneity group (HG). Scots and Siberian pines seemed the strongest, and stone pine was the weakest, when the homogeneous groups of MOR were checked. According to the MOE results, Oriental spruce was the stiffest species, and stone pine was the most flexible. Standard deviations were at most 37% and 44% for MOR and MOE, respectively, because the wood had highly un-deterministic behaviors in practice.

Table 1. Mean *MOR* and *MOE* Values with Their Coefficients of Variation

Wood Species	Cross-sectional Geometry	Force Direction	MOR (N/mm^2)			MOE (N/mm^2)		
			Mean	COV (%)	HG	Mean	COV (%)	HG
Scotch pine	Circular	Radial	80.99	6.85	CDE	7287	8.75	FG
		Tangential	82.44	6.88	ABCD	9580	15.09	B
	Square	Radial	71.02	3.19	GHIJ	7483	16.35	EF
		Tangential	86.59	13.39	A	8234	19.21	D
Black pine	Circular	Radial	71.41	2.84	GHI	6135	8.23	IJK
		Tangential	74.99	9.56	FG	6545	12.85	HI
	Square	Radial	67.93	4.48	IJ	5078	5.43	LM
		Tangential	69.45	5.78	HIJ	6256	7.96	HIJK
Siberian pine	Circular	Radial	81.16	10.89	BCDE	7480	11.93	EF
		Tangential	85.60	4.03	AB	8065	12.50	DE
	Square	Radial	72.75	11.09	GH	6454	4.12	HIJ
		Tangential	84.19	5.53	ABC	6621	8.10	GHI
Stone pine	Circular	Radial	54.04	4.17	L	4668	5.82	M
		Tangential	56.66	4.45	KL	6876	12.37	FGH
	Square	Radial	52.68	8.77	L	4715	5.23	M
		Tangential	56.19	4.78	KL	6632	11.26	GHI
Nordmann Fir	Circular	Radial	77.77	6.79	EF	6821	5.71	FGH
		Tangential	85.76	5.29	A	7476	6.39	EF
	Square	Radial	78.67	7.01	DEF	5824	7.38	JK
		Tangential	80.44	3.76	CDE	5993	15.55	IJK
Oriental Spruce	Circular	Radial	70.88	3.99	GHIJ	9156	8.98	BC
		Tangential	77.92	7.55	DEF	12560	6.64	A
	Square	Radial	69.55	5.86	HIJ	9350	11.23	B
		Tangential	69.85	9.09	HIJ	9673	4.71	B
Lebanon Cedar	Circular	Radial	67.82	7.91	IJ	8603	6.79	CD
		Tangential	69.12	6.53	HIJ	9752	7.99	B
	Square	Radial	59.08	1.66	K	5586	8.1	KL
		Tangential	66.82	5.54	J	5819	8.16	JK

COV: Coefficient of variation; HG: Homogeneity group

A three-factor analysis of variance (MANOVA) general linear model procedure was performed for individual data to analyze the main effects and interaction factors on the means of MOR and MOE, respectively. Minitab (Version 17) statistical software was utilized for the statistical analyses (Minitab, LLC, State College, PA, USA). The MANOVA results (Table 2) indicated that the main effects and three-factor interactions of wood species, cross-sectional geometry, and force direction were significant at the 5% confidence level for both MOR and MOE. However, as shown in Table 2, the analysis of variance for the MOR values showed that the two-way interactions were not significant at the 5% level. Comparing F-values to one another, it can be concluded that MOR was mainly affected by wood species. For MOE, the stiffness of the specimen depended mainly on cross-sectional geometry and wood species.

Table 2. Summary of the MANOVA Results for MOR and MOE Values

MANOVA for MOR					
Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	p - value
Wood species	6	22238.8	3706.46	138.03	0.000*
Cross-sectional geometry	1	940.9	940.87	35.04	0.000*
Force direction	1	1763.4	1763.40	65.67	0.000*
WS × CSG	6	170.4	28.40	1.06	0.389
WS × FD	6	327.4	54.57	2.03	0.062
CSG × FD	1	64.5	64.51	2.40	0.122
WS × CSG × FD	6	883.2	147.19	5.48	0.000*
Error	252	6766.8	26.85		
Total	279	33155.3			
MANOVA for MOE					
Wood species	6	558674399	93112400	154.51	0.000*
Cross-sectional geometry	1	108070424	108070424	179.33	0.000*
Force direction	1	85961530	85961530	142.64	0.000*
WS × CSG	6	70853426	11808904	19.60	0.000*
WS × FD	6	30318575	5053096	8.39	0.000*
CSG × FD	1	13000862	13000862	21.57	0.000*
WS × CSG × FD	6	22848237	3808039	6.32	0.000*
Error	252	151861805	602626		
Total	279	1041589258			

* Statistically significant; WS: Wood species; CSG: Cross sectional geometry; FD: Force direction

Table 3. Mean Comparisons for Wood Species for MOR and MOE

Wood Species	*MOR* (N/mm^2)		*MOE* (N/mm^2)	
	Mean	HG	Mean	HG
Scotch pine	80.26	A	8146	B
Black pine	70.94	B	6004	E
Siberian pine	80.93	A	7160	C
Stone pine	54.89	D	5723	E
Nordmann Fir	80.66	A	6529	D
Oriental Spruce	72.05	B	10207	A
Lebanon Cedar	65.71	C	7440	C

Values followed by the same capital letter are not significantly different. HG: Homogeneous group

LSD multiple comparison at 5% significance level was performed to determine the mean differences of treatment combinations. Mean comparisons for main effects and three-way interaction effects were examined for *MOR* and *MOE*, respectively. Table 3 gives mean comparisons of *MOR* and *MOE* of specimens. Aa a result, *MOR* and *MOE* values of specimens were significantly affected by the wood species. The specimens constructed of Siberian pine, Nordmann fir, and Scots pine showed the greatest *MOR* values, while the specimens constructed of stone pine showed the lowest *MOR* values. The differences between *MOR* values of Siberian pine, Nordmann fir and, Scots pine were not significant. Similarly, *MOR* values were not significantly different between black pine and Oriental spruce. Oriental spruce had the greatest *MOE* values, while black pine and stone pine had the lowest values. *MOE* values of specimens constructed of Siberian pine and Lebanon cedar were not statistically different. Table 4 gives mean comparisons of *MOR* and *MOE* of the specimens for cross-sectional geometry.

Table 4. Mean Comparisons for Cross Section for *MOR* and *MOE*

Cross-sectional Geometry	*MOR* (N/mm^2)		*MOE* (N/mm^2)	
	Mean	HG	Mean	HG
Circular	74.04	A	7937	A
Square	70.37	B	6694	B

Values followed by the same capital letter are not significantly different. HG: Homogeneous group

Results indicated that the cross-section had a significant effect on the *MOR* and *MOE* values of the specimens at the 5% significance level. The circular cross-sectioned specimens had a greater *MOR* than the square cross-sectioned specimens. Similarly, the circular cross-sectioned specimens had greater *MOE* values than the square cross-sectioned specimens. The mean values and the ratios of *MOR* and *MOE* values of the specimens according to the cross-sectional geometry for each wood species are given in Table 5.

Table 5. Ratios of *MOR* and *MOE* Values according to Cross-Sectional Geometry for Each Wood Species

Wood Species	Cross-sectional Geometry	*MOR* (N/mm^2) Mean	*MOR* Circular/Square	*MOE* (N/mm^2) Mean	*MOE* Circular/Square
Scotch pine	Circular	81.71	1.04	8433	1.07
	Square	78.80		7858	
Black pine	Circular	73.20	1.07	6340	1.12
	Square	68.69		5667	
Siberian pine	Circular	83.38	1.06	7783	1.19
	Square	78.47		6538	
Stone pine	Circular	55.35	1.02	5772	1.02
	Square	54.43		5674	
Nordmann Fir	Circular	81.76	1.03	7148	1.21
	Square	79.56		5909	
Oriental Spruce	Circular	74.40	1.07	10903	1.15
	Square	69.70		9511	
Lebanon Cedar	Circular	68.47	1.09	9177	1.61
	Square	62.95		5702	
		Mean	1.05	Mean	1.19

The Siberian pine, Nordmann fir, and Scots pine specimens had the greatest *MOR* in both circular and square cross-sections, while stone pine had the lowest *MOR*. For each wood species, the *MOR* values of the circular-sectioned specimens were on average 5% greater than in the square-sectioned specimens. The *MOE* values of the circular-sectioned specimens were on average 19% greater than in the square-sectioned specimens. Erdil

(2002), Acar *et al*. (2018), and basic engineering formulas indicate that circular cross-sections have 18% greater stress than predicted by conventional bending stress expressions for square cross-sections.

Markwardt and Wilson (1935) suggested that a beam of given cross-sectional area carries the same amount of load regardless of whether the cross section is circular, square, or diamond shaped. Contrarily, the bending stress of square cross-section was found to be 18% and 41% greater than those in the circular and diamond cross-sections, respectively. Therefore, a 1.18 form factor may be applied to circular cross-sections, and 1.41 to diamond cross-sections (Erdil 2002; Acar *et al*. 2018).

In this study, both the square and circular cross-sections had an area of 400 mm^2, resulting in the width (b) and the depth (d) of the square section as $b = h = 20$ mm and a circular section with a radius (r) of 11.3 mm. The maximum bending stress (σ) caused by a bending moment (M) at a section will occur at the top or the bottom line of the section, such that the distances from the neutral axis (c) of each section are 10 mm and 11.3 mm, respectively. Moments of inertia (I) of cross sectional areas were calculated with respect to their neutral axes as (1/12) $bh^3 = 13333.33$ mm^4 and (1/4) $\pi r^4 = 12805.71$ mm^4. Inserting them into the bending stress formulas (Eqs. 7 and 8) resulted in the following, for square sections and circular sections, respectively,

$$\sigma_1 = \frac{Mc}{I} = 7.50 \cdot 10^{-4}\ M\ \mathrm{N/mm^2} \tag{7}$$

$$\sigma_2 = \frac{Mc}{I} = 8.82 \cdot 10^{-4}\ M\ \mathrm{N/mm^2} \tag{8}$$

where σ_1 is the maximum bending stress in the square section, and σ_2 is the maximum bending stress in the circular section. Their ratio (σ_2/σ_1) is 1.18, approximately, which is agreeable with the given value in Erdil (2002) and Acar *et al*. (2018). The given theoretical calculated form factor for bending strength was not verified by results of the tests performed in this study.

Wolfe *et al*. (2001) mentioned a form factor for the correction of bending strength of square cross-sectional specimens to circular cross-sectional specimens. It is also stated in the study of Newlin and Trayer (1941), which found that, even though circular cross-sectional specimens have an 18% smaller section modulus (I/c), their bending strength is equal to that of square cross-sectional specimens. These results agree with this study.

Table 6 shows the ranked mean comparisons for *MOR* and *MOE* of specimens with respect to force directions.

Table 6. Mean Comparisons for Force Direction for *MOR* and *MOE*

Force Direction	MOR (N/mm^2)		MOE (N/mm^2)	
	Mean	HG	Mean	HG
Radial	69.70	B	6761	B
Tangential	74.72	A	7869	A

Values followed by the same capital letter are not significantly different. HG: Homogeneous group

The force direction had a significant effect on the *MOR* and *MOE* values of the specimens at the 5% significance level. According to the mean comparison results, the specimens tested with the force parallel to the tangential direction showed greater *MOR* and *MOE* values than the specimens tested with the force parallel to the radial direction. The mean values and the ratios of the *MOR* and *MOE* values of the specimens according to the force direction for each wood species are given in Table 7.

Table 7. Ratios of *MOR* and *MOE* Values according to Force Direction for Each Wood Species

Wood Species	Force Direction	*MOR* (N/mm^2)		*MOE* (N/mm^2)	
		Mean	Tangential/Radial	Mean	Tangential/Radial
Scotch pine	Radial	76.00	1.11	7385	1.21
	Tangential	84.51		8907	
Black pine	Radial	69.67	1.04	5607	1.14
	Tangential	72.22		6401	
Siberian pine	Radial	76.96	1.10	6977	1.05
	Tangential	84.90		7343	
Stone pine	Radial	53.36	1.06	4691	1.44
	Tangential	56.42		6754	
Nordmann Fir	Radial	78.22	1.06	6323	1.07
	Tangential	83.1		6735	
Oriental Spruce	Radial	70.21	1.05	9253	1.21
	Tangential	73.88		11162	
Lebanon Cedar	Radial	63.45	1.07	7095	1.10
	Tangential	67.97		7785	
		Mean	1.07	Mean	1.17

The results consistently indicated that the *MOR* and *MOE* values of the specimens were affected by the force direction. For each tested softwood species, the specimens tested with the force parallel to the tangential direction showed greater *MOR* and *MOE* values than those of the specimens tested with the force parallel to the radial direction. The *MOR* values increased by an average of 7% when the specimens were tested with the force parallel to tangential direction; similarly, the *MOE* values increased by an average of 17% when the specimens were tested with the force parallel to tangential direction.

Ranked mean comparisons of the *MOR* values of specimens, tested with respect to three-way interactions of wood species, cross-sectional geometry, and force direction, are shown in Fig. 3. The three-way interactions showed that the *MOR* of the specimens was affected by the wood species, cross-sectional geometry, and force direction according to the grain direction. In general, *MOR* of the specimens increased when they were loaded in the tangential direction, and circular-sectioned specimens had greater *MOR* values than those of square-sectioned specimens. The greatest *MOR* values were obtained with the circular-sectioned Scots pine specimens in the tangential direction and square-sectioned Nordmann fir specimens in the tangential direction. The lowest *MOR* values were obtained with the circular or square-sectioned stone pine specimens in the radial direction (Table 1).

Figure 4 shows ranked mean comparisons of the *MOE* values of the specimens, tested with respect to three-way interactions of wood species, cross-sectional geometry, and force direction. The results of the three-way interactions showed that the *MOE* values of the specimens were affected by the wood species, cross-sectional geometry, and force direction according to the grain direction. As with the *MOR* values, the *MOE* values of the specimens increased when they were loaded in the tangential direction, and circular-sectioned specimens had greater *MOE* values than those of square-sectioned specimens. The greatest *MOE* values were obtained with the circular-sectioned Oriental spruce specimens in the tangential direction, while the lowest *MOE* values were obtained with the circular- or square-sectioned stone pine specimens in the radial direction (Table 1).

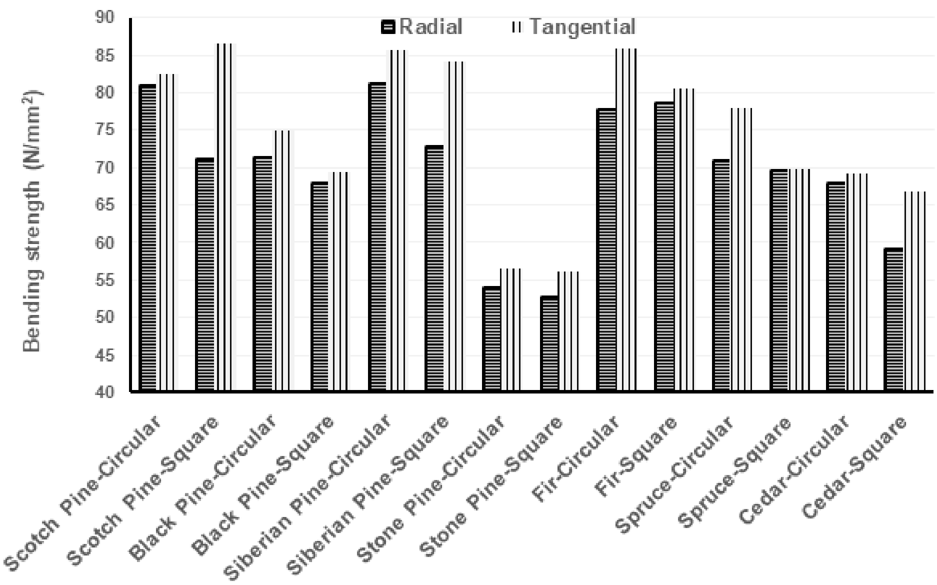

Fig. 3. Comparisons of the *MOR* of the specimens for each of the evaluated factors

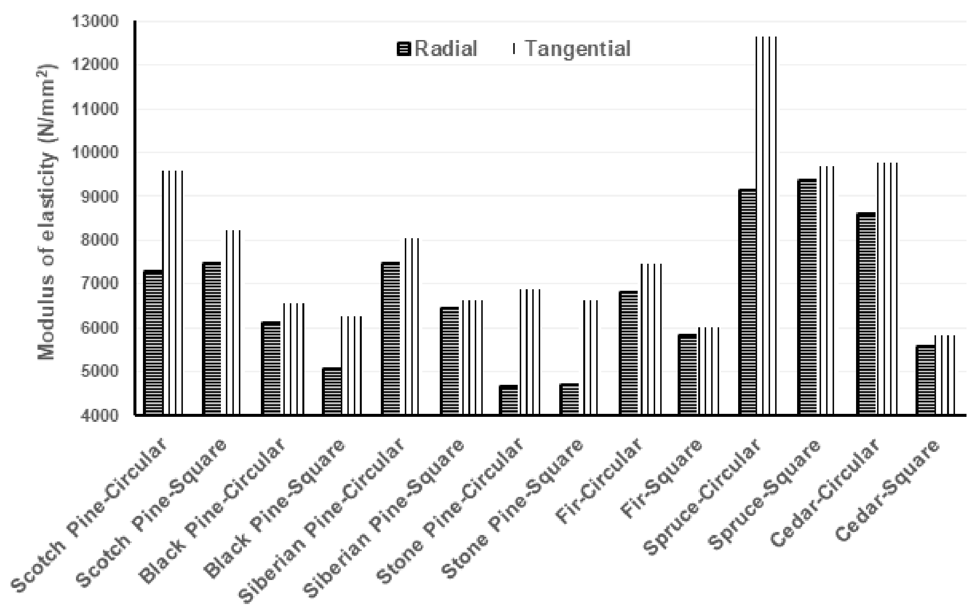

Fig. 4. Comparisons of the *MOE* of the specimens for each of the evaluated factors

CONCLUSIONS

1. The wood species, cross-sectional geometry, and force direction significantly affected the modulus of rupture (*MOR*) and modulus of elasticity (*MOE*) values of the softwood specimens at the 5% significance level.
2. The *MOR* and *MOE* values of the specimens increased when they were loaded in the tangential direction, and circular-sectioned specimens had greater *MOR* and *MOE* values than those of square-sectioned specimens.

3. The *MOR* values of the circular-sectioned specimens were on average 5% greater than those of the square-sectioned specimens. The *MOE* values of the circular-sectioned specimens were on average 19% greater than those of the square-sectioned specimens.
4. The *MOR* values increased by an average of 7% when the specimens were tested with the force parallel to the tangential direction. The *MOE* values increased by an average of 17% when the specimens were tested with the force parallel to the tangential direction.

The results of this study provided fundamental information on the strength properties of the selected softwood species, which will help optimize products of the woodworking industry and the engineering design of wooden constructions.

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