

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

Ersan Güray,<sup>a</sup> Ali Kasal,<sup>b,\*</sup> Selçuk Demirci,<sup>c</sup> Erkan Ceylan,<sup>d</sup> and Tolga Kuşkun<sup>b</sup>

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

*Contact information:* a: Department of Civil Engineering, Faculty of Engineering, Muğla Sıtkı Koçman University, 48000 Kötekli, Muğla, Turkey; b: Department of Woodworking Industrial Engineering, Faculty of Technology, Muğla Sıtkı Koçman University, 48000, Kötekli, Muğla, Turkey; c: Department of Wood Science and Furniture Design, Ege University, 35000, Izmir, Turkey; d: Department of Materials and Materials Processing Technologies, Bingöl University, 12000, Bingöl, Turkey;

\* Corresponding author: alikasal@mu.edu.tr

## 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 ( $\sigma$ ) is determined by Eq. 1,

$$\sigma = \frac{M}{Z} \quad (1)$$

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):

$$MOR = \frac{M_{ultimate}}{Z} = \frac{F_{ultimate}L}{4Z} \quad (2)$$

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  $\sigma$  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 ( $\Delta$ ):

$$\Delta = \frac{FL^3}{48E_L I} \quad (3)$$

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

$$MOE = \frac{FL^3}{48\Delta I} \quad (4)$$

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. Pěňčík (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:

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

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

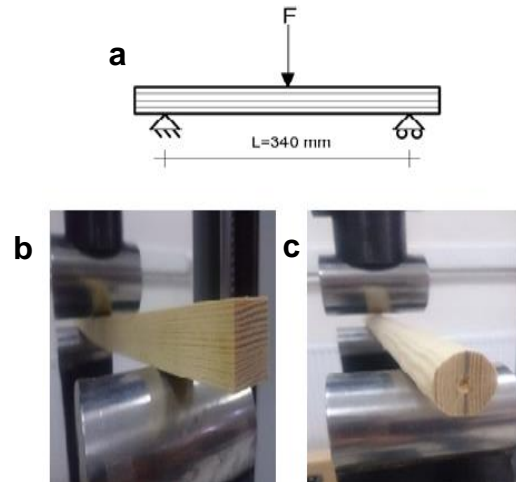
where  $MOR_{ijkl}$  is the bending strength (N/mm<sup>2</sup>);  $MOE_{ijkl}$  is the modulus of elasticity (N/mm<sup>2</sup>);  $\mu_1$  is the population mean bending strength for all combinations of wood species, cross-sectional geometry, and force direction (N/mm<sup>2</sup>);  $\mu_2$  is the population mean *MOE* for all combinations of wood species, cross-sectional geometry, and force direction (N/mm<sup>2</sup>);  $A$  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;  $\rho$  is the replication parameter;  $\varepsilon$  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<sup>3</sup>, 0.56 g/cm<sup>3</sup>, 0.40 g/cm<sup>3</sup>, 0.49 g/cm<sup>3</sup>, 0.44 g/cm<sup>3</sup>, 0.44 g/cm<sup>3</sup>, and 0.52 g/cm<sup>3</sup> 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).

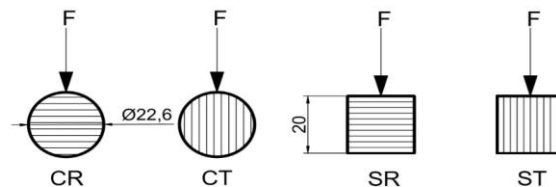
The square-sectioned specimens were sized at 20 mm by 20 mm, while the circular-sectioned specimens were 22.6 mm in diameter, to obtain equal cross-sectional areas for both cross-sectional geometries. The span was 340 mm for all specimens. The specimens were loaded at the center point by a standard bearing 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  $65\% \pm 3\%$  and a temperature of  $20\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$  for at least a month prior to testing to reach an equilibrium MC of  $12\% \pm 0.2\%$ , 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 <sup>2</sup> ) |         |      | MOE (N/mm <sup>2</sup> ) |         |      |
|-----------------|--------------------------|-----------------|--------------------------|---------|------|--------------------------|---------|------|
|                 |                          |                 | 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 <i>MOR</i>    |                    |                |             |         |           |
|--------------------------|--------------------|----------------|-------------|---------|-----------|
| 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 <i>MOE</i>    |                    |                |             |         |           |
| 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    | <i>MOR</i> (N/mm <sup>2</sup> ) |    | <i>MOE</i> (N/mm <sup>2</sup> ) |    |
|-----------------|---------------------------------|----|---------------------------------|----|
|                 | 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. As 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 | <i>MOR</i> (N/mm <sup>2</sup> ) |    | <i>MOE</i> (N/mm <sup>2</sup> ) |    |
|--------------------------|---------------------------------|----|---------------------------------|----|
|                          | 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 | <i>MOR</i> (N/mm <sup>2</sup> ) |                 | <i>MOE</i> (N/mm <sup>2</sup> ) |                 |
|-----------------|--------------------------|---------------------------------|-----------------|---------------------------------|-----------------|
|                 |                          | Mean                            | Circular/Square | Mean                            | 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<sup>2</sup>, 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 ( $\sigma$ ) 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  $(1/12)bh^3 = 13333.33 \text{ mm}^4$  and  $(1/4)\pi r^4 = 12805.71 \text{ mm}^4$ . Inserting them into the bending stress formulas (Eqs. 7 and 8) resulted in the following, for square sections and circular sections, respectively,

$$\sigma_1 = \frac{Mc}{I} = 7.50 \cdot 10^{-4} \text{ MN/mm}^2 \quad (7)$$

$$\sigma_2 = \frac{Mc}{I} = 8.82 \cdot 10^{-4} \text{ MN/mm}^2 \quad (8)$$

where  $\sigma_1$  is the maximum bending stress in the square section, and  $\sigma_2$  is the maximum bending stress in the circular section. Their ratio ( $\sigma_2/\sigma_1$ ) 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 <sup>2</sup> ) |    | MOE (N/mm <sup>2</sup> ) |    |
|-----------------|--------------------------|----|--------------------------|----|
|                 | 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 | <i>MOR</i> (N/mm <sup>2</sup> ) |                   | <i>MOE</i> (N/mm <sup>2</sup> ) |                   |
|-----------------|-----------------|---------------------------------|-------------------|---------------------------------|-------------------|
|                 |                 | 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).

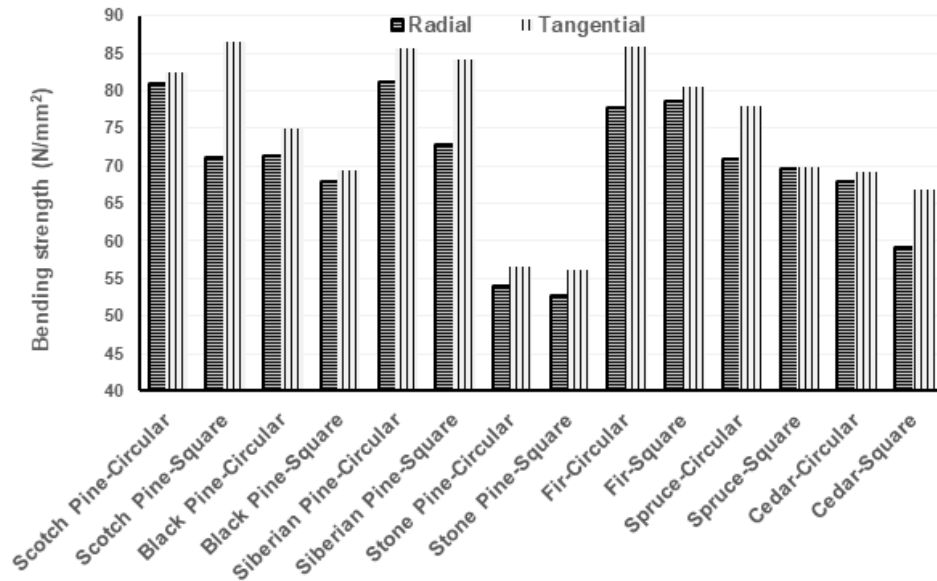


Fig. 3. Comparisons of the *MOR* of the specimens for each of the evaluated factors

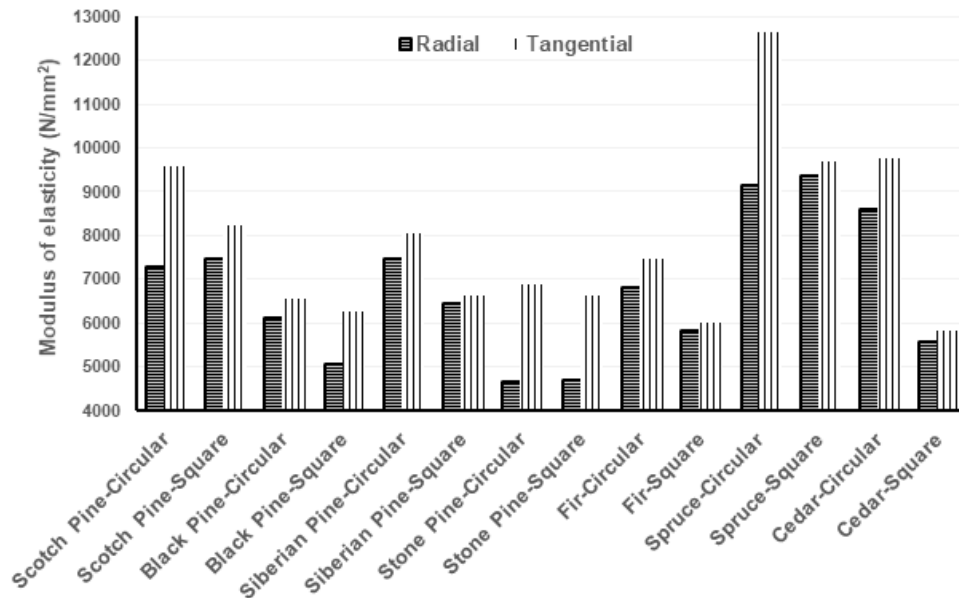


Fig. 4. Comparisons of the *MOE* of the specimens for each of the evaluated factors

## 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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