Comparison of Micro- and Standard-Size Specimens in Evaluating the Flexural Properties of Scots Pine Wood

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The aim of this study was to investigate the flexural properties (bending strength and modulus of elasticity) of Scots pine wood (*Pinus sylvestris* L.) using micro- and standard-size test specimens. In the standard- and micro-size specimens, the average bending strengths were evaluated as 72.8 and 62.4 MPa, and the bending modulus of elasticity was 9917 and 2884 MPa, respectively. These results showed that the bending strength and modulus of elasticity values of the micro-size specimens were lower than those of the standard-size specimens. The statistically significant effects included the specimen size, individual trees, and the interactions of the specimen size and trees on the bending strength and modulus of elasticity. Furthermore, regression analyses indicated a positive linear regression between the flexural properties of the micro- and standard-size specimens. The results indicated that micro-size specimens can be used to estimate the flexural properties of Scots pine wood when obtaining standard-size specimens is not possible.

Keywords: Micro-size specimens; Standard-size specimens; Bending strength; Modulus of elasticity; Flexural properties

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INTRODUCTION

To determine the mechanical properties of wood, the approach to use both structural-size and small-size clear specimens has grown in popularity. In recent years, micro-size specimens have been used to evaluate the mechanical properties of earlywood and latewood sections, wood strands, and fibers (Plagemann *et al*. 1982; Hunt *et al*. 1989; Deomano and Zink-Sharp 2004; Zink-Sharp and Price 2006; Wu *et al*. 2005; Cai *et al*. 2007; Hindman and Lee 2007; Jeong 2008; Jeong *et al*. 2009; Roszyk *et al*. 2016). In previous studies, researchers used various specimen dimensions and loading rates according to the purpose of the study. Table 1 summarizes the species, specimen size, properties studied, load rates, and the results of previous literature related to micro-size mechanical testing.

Micro-size specimens can be used to determine the mechanical properties of wood when obtaining standard-size test specimens is not possible. To avoid damaging the wood material for use in various applications, the mechanical properties could be determined using micro-size test specimens. Moreover, the test specimens of structural wood material could be taken periodically and their mechanical properties determined. Thus, changes in the mechanical properties of the wood over time could be observed. With the development of micro-size tests, the strength losses from the length of exposure could be determined for the structural applications of the wood. This information would provide a solid base for a true assessment of the necessity of wooden structure renewal.

Table 1. Test Parameters and Results of Previous Studies on Micro-Size Testing

Species	Specimens sizes (mm)	Property studied	Load rate (mm/min)	Results (MPa)	References
Loblolly pine Sweet gum Yellow poplar	5.0 × 0.6 × 25	Bending properties	2.54	MOR and MOE 66.0 and 4086.9 78.6 and 4430.6 89.0 and 5829.4	Deomano and Zink-Sharp (2004)
Loblolly pine	11.0 × 0.68 x 33.0 for bending test 5.07 × 0.66 × 60 for tension test	Bending and tensile properties	0.127	89.2 for MOR 5780 for MOE 43.3 for TS	Hindman and Lee (2007)
White oak Red oak Sweet gum	3.8 × 0.5 × 14.2	Bending properties	0.029	MOR and MOE 91 and 4068 102 and 4799 101 and 5281	Plagemann *et al.* (1982)
Yellow poplar Loblolly pine Willow Red oak	25.4 x 0.508 to 1.27 ×152.4	Tensile strength	0.127	48.5 58.7 22.7 40.7	Cai *et al*. (2007)
Southern pine	25.4 x 3.8 × 152.4	Tensile strength	0.127	50.0	Wu *et al.* (2005)
Yellow poplar	12.7 × 0.79 × 304.8	Tensile strength	1.9	70.3	Hunt *et al*. (1989)
Sweet gum Yellow poplar Red maple	1 × 1 × 4	Compression strength	0.029	39.2 33.5 41.6	Zink-Sharp and Price (2006)

***Note:** MOR: Modulus of rupture (bending strength), MOE: Modulus of elasticity, TS: Tensile strength

There is limited information concerning a comparison of the mechanical properties of micro- and standard-size specimens. In previous studies, researchers compared their findings for micro-size test specimens with the published values in the *Wood* Handbook (Green *et al.* 1999) for standard-size specimens (Deomano 2001; Zink-Sharp and Price 2006; Cai *et al*. 2007). Deomano (2001) reported that the bending strength (MOR) and modulus elasticity (MOE) values of the micro-size specimens were lower than those of standard-size specimens for southern yellow pine, sweet gum, and yellow poplar, except for the MOR of yellow poplar. Cai *et al*. (2007) found that for willow, yellow poplar, red oak, and loblolly pine strands, the tensile strengths were, respectively, 31.1%, 44.2%, 36.2%, and 73.4% lower than that of standard-size specimens. Zink-Sharp and Price (2006) stated that the compression strength of the micro-size specimens was close to, but lower than, the handbook values for the sweet gum, yellow poplar, and maple wood species. This approach of comparing the values obtained from different trees is not valid for obtaining information about the presence of a correlation between the micro-size and standard-size specimens. It is recognized that the tree age and growth conditions, such as the climate, soil characteristics, slope, and altitude, affect the annual ring width and the mechanical properties of wood. Zink-Sharp and Price (2006) also pointed out that a comparison of experimentally determined values with the standard handbook values was often useful, although not all-encompassing. The aim of this paper is therefore to evaluate the flexural properties of micro-size Scots pine

(*Pinus sylvestris* L.) wood and investigate the correlation between micro- and standard-size specimens that are taken from the same tree.

EXPERIMENTAL

Materials

Sample trees were harvested from Bolu Forest Enterprises in the northwestern part of Turkey. Eight trees with straight stems were selected as sample trees. Logs of 3 m in length were cut from each tree at a height of 0.30 m, and then 6-cm-thick planks, including the central pith, were cut from these logs. The planks were dried in an industrial drying kiln until about 18% moisture content. The micro- and standard-size test specimens were prepared from these planks. The cutting plan of the test specimens is shown in Fig. 1. All of the specimens were conditioned in a climate chamber at a temperature of 20 °C and a relative humidity of 65% for three weeks to reach a target moisture content of 12% prior to testing.

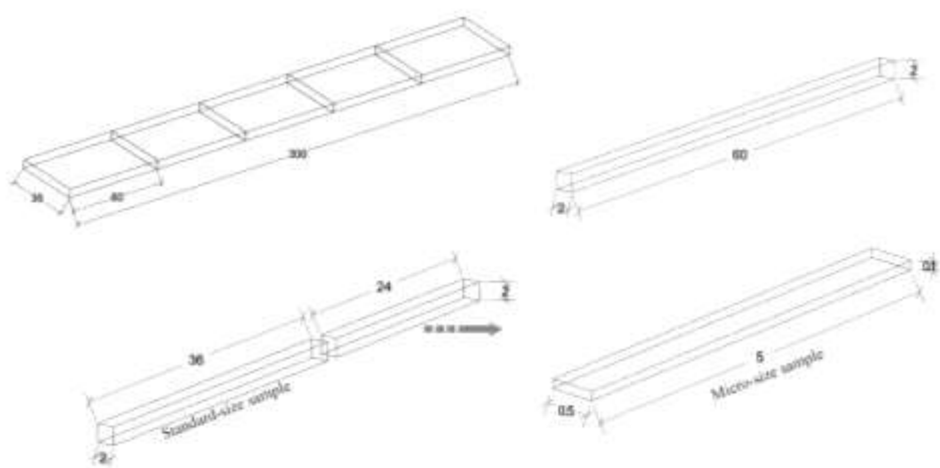


Fig. 1. Cutting plan of standard- and micro-size flexural test specimens

Methods

The specimens were cut according to the International Organization for Standardization (ISO) to determine the bending strength (ISO 13061-3 2014) and modulus of elasticity in bending (ISO 13061-4 2014). The standard-size test specimens were prepared with dimensions of 20 mm × 20 mm × 360 mm for the flexural test. In the three-point bending test, the load was applied tangential to the annual rings, and the span/thickness ratio was 15. A Lloyd (Lloyd Instruments, LS100, FL, USA) universal testing machine with a 10-kN load cell was used for the standard-size tests.

The micro-size tests were performed with a Zwick (Zwick GmbH & Co., ZO50TH, Ulm, Germany) universal testing machine using a 100-N load cell. The same ISO standards were used as a guide for the micro-size specimens. The micro-size flexural test specimens were approximately 0.8 to 1.2 mm x × 5.0 mm × 50.0 mm. The tests were performed with a three-point bending fixture. The same span/thickness ratio, 15, was used for both the micro-size and standard-size bending tests. The micro-size bending test specimen and test setup are shown in Fig. 2.

Data Analyses and Statistical Methods

SPSS Statistics computer software, version 21 was used for the statistical analysis. For the MOR and MOE, all multiple comparisons were first subjected to an analysis of variance (ANOVA) at $p < 0.05$ considering the two factors of specimen size and each individual tree, and their interactions. Post-hoc comparisons were conducted using the Duncan's multiple range test. A regression analysis was used to determine the relationship between the standard- and the micro-size specimens.

(a) (b)

Fig. 2. (a) Standard-size bending test sample and test setup; (b) micro-size bending test sample and test setup

RESULTS AND DISCUSSION

The average MOR and MOE values and Duncan test results of the standard- and micro-size Scots pine wood specimens are shown in Table 2.

Table 2. The Average MOR and MOE Values and Duncan Test Results of Standard- and Micro-Size Scots Pine Wood

Tree No	Bending strength (MPa)						Modulus of elasticity (MPa)					
	Standard-size			Micro-size			Standard-size			Micro-size		
	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
1	77	**66.5**[a]	8.0	80	**60.0**[fgh]	11.9	77	**9590.0**[ab]	1492	80	**2873.1**[f]	695
2	31	**70.9**[bc]	7.4	47	**55.9**[fi]	10.5	31	**7812.3**[c]	1079	46	**2071.3**[g]	577
3	56	**76.5**[d]	8.8	50	**70.8**[k]	12.9	56	**11209.0**[d]	1470	50	**3554.4**[h]	528
4	68	**73.8**[cd]	7.8	70	**64.7**[h]	12.1	68	**9308.9**[a]	1800	70	**2754.1**[f]	712
5	48	**69.1**[ab]	7.9	48	**52.5**[i]	10.5	48	**9278.2**[a]	1578	48	**2348.1**[i]	636
6	41	**87.2**[e]	9.7	43	**73.4**[k]	12.1	41	**12067.5**[e]	1389	44	**3767.5**[h]	860
7	47	**70.8**[bc]	5.9	46	**59.7**[fg]	9.7	47	**10059.5**[b]	1222	46	**2837.0**[f]	560
8	34	**71.7**[bc]	6.0	40	**63.1**[gh]	10.9	34	**9780.0**[ab]	1446	40	**2953.5**[f]	607
Total	402	**72.8**	9.7	424	**62.4**	13.0	402	**9917.3**	1833	424	**2883.9**	846

***Note:** N: Number of specimens, SD: Standard deviation, Groups with same letters in column indicate that there is no statistical difference ($p < 0.05$) between the samples according Duncan's multiply range test.

In the individual trees, the MOR values of the micro-size specimens ranged from 52.5 to 73.4 MPa, and in the standard-size specimens, from 66.5 to 87.2 MPa. Similar trends were observed for the MOR values of micro- and standard-size specimens in individual trees. The standard-size samples had higher MOR values compared to micro-size specimens in all individual trees. The highest MOR values were observed for tree 6, in both the micro- and standard-size specimens. The lowest MOR values were found for tree 5 and tree 1 in the micro- and standard-size specimens, respectively. The MOR values of tree 1 and 5 were very close.

The average MOR value of the micro-size specimens was found to be 62.4 MPa. In previous studies, researchers determined the MOR values of different wood species using micro-size samples. Deomano and Zink-Sharp (2004) reported that the MOR values of micro-size southern pine, sweet gum, and yellow poplar were 66.0 MPa, 78.6 MPa, and 89.0 MPa, respectively. Plagemann *et al.* (1982) determined that the MOR values of micro-size white oak, red oak, and sweetgum were 91 MPa, 102 MPa, and 101 MPa, respectively. Jeong (2008) pointed out that the results of previous studies about the micro-size test are not directly comparable because of different loading conditions and different wood species. In that study, he indicated that the tensile strength of the micro-size loblolly pine wood specimens reported by Hindman and Lee (2007) was 36% higher compared with the work of Cai *et al*. (2007). This variance could be related to some of the differences between the species. Deomano and Zink-Sharp (2004) showed that the MOR and MOE values of wood flakes differed between and within the species.

The average MOR value of the standard-size specimens was found to be 72.8 MPa. Dündar (2005) determined that the MOR in standard-size specimens was 87.3 MPa. The lower MOR values in the current study could be related to tree age and growth conditions. It is well known that tree age and growth conditions such as climate, soil characteristics, slope, and altitude affect annual ring width, density, and the mechanical properties of wood. The results showed that the MOR values of the micro-size specimens were 14.3% lower than those of the standard–size specimens. This could be attributed to the density and ratio of earlywood (EW) and latewood (LW) of the specimens. The density and microfibril angle (MFA) values of EW and LW have an important effect on the mechanical properties of wood. The density of LW was higher compared to EW density. Jeong *et al.* (2009) determined that the LW density from growth ring numbers 1-10 and from growth ring numbers 11-20 had 74% and 26%, respectively, higher than those of EW. The microfibril angles (MFA) in the S2 layer of the EW are generally higher compared to LW MFA. Roszyk (2014) determined the MFA were 16.4° and 9.0° and the average density were 235 kg/m^3 and 665 kg/m^3 in EW and LW of scots pine, respectively. Similar lower values were found by Deomano (2001). He compared his findings for the micro-size specimens with the published values for standard-size specimens in the *Wood Handbook*. He found that the MOR values of the micro-size specimens were lower by 33.3% for southern yellow pine, and by 8.9% for sweet gum, while the values were higher by 21.3% for yellow poplar. He stated that the lower MOR value in the micro-size specimens of yellow poplar wood could be related to differences in the specific gravity between the standard- and micro-size yellow poplar wood specimens.

For the individual trees, the MOE values ranged from 2071.3 to 3767.5 MPa in the micro-size specimens, while the range was from 7812.3 to 12067.5 MPa in the standard-size specimens. The highest and lowest MOE values were observed for trees 6 and 2, respectively, in both the micro- and standard-size specimens. The average MOE value of the micro-size specimens was determined to be 2883.9 MPa. In previous studies, researchers determined the MOE values of different wood species using micro-size samples. Deomano ve Zink-Sharp (2004) found that the MOE values of southern pine, sweet gum, and yellow poplar were 4086.9, 4430.6, and 5829.4 MPa, respectively. Plagemann *et al*. (1982) determined that the MOE values of white oak, red oak, and sweetgum in micro-size samples were 4068, 4799, and 5281 MPa, respectively.

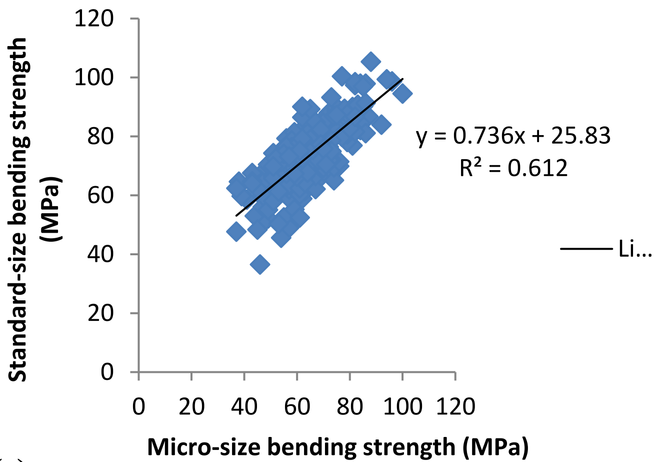
The average MOE value of the standard-size specimens was found to be 9917.3 MPa. Dündar (2005) determined that the MOE in standard-size specimens was 8944.8 MPa. The results indicated that the MOE values of the micro-size specimens were 70.9% lower than those of the standard-size specimens. This could be attributed to the density, ratio of earlywood (EW) and latewood (LW), and thickness of the specimens. Similar lower MOE values were observed by Deomano (2001). He stated that the MOE values of the micro-size specimens were lower by 66.9% for southern yellow pine, 60.8% for sweet gum, and 46.5% for yellow poplar. Zink-Sharp and Price (2006) pointed out that a comparison of experimentally determined values with standard handbook values was often useful, but not all encompassing. In this current study, the micro- and standard-size specimens were taken from the same lumber, and underwent similar test procedures using the same span/thickness ratios and loading rates. To date, there have been no other studies dealing with the relationship between micro- and standard-size specimens that have been taken from the same Scots pine tree, or the same tree of another wood species. This suggests that further studies should be carried out to examine these relationships.

The factors of the specimen size (standard- and micro-size), the individual trees (eight trees), and their interactions on the MOR and MOE are shown in Table 3. For the MOR and MOE, all of the factors were found to be significantly different where $p < 0.0001$.

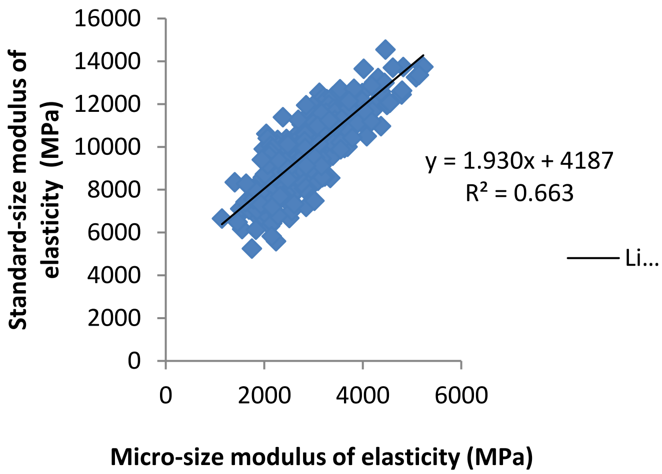
Table 3. The Interactions of Specimen Size and Individual Tree on Bending Strength and Modulus of Elasticity (ANOVA)

Source		Type III sum of squares	Degree of freedo	Mean square	F	P
Bending strength	Specimen size	22422.5	1	22422.47	230.39	0.000
	Individual tree	27030.3	7	3861.47	39.68	0.000
	Specimen size* individual tree	2874.5	7	410.65	4.22	0.000
Modulus of elasticity	Specimen size	9412257575.7	1	9412257575.7	7113.8	0.000
	Individual tree	511322950.4	7	73046135.8	55.2	0.000
	Specimen size* individual tree	88243317.0	7	12606188.1	9.5	0.000

The regression analyses' graphics for the MOR and MOE of the micro- and standard-size wood specimens are shown in Figs. 3a and 3b, respectively. The regression analyses indicated that the flexural properties of the micro-size specimens were significantly correlated with the standard-size specimens ($p < 0.0001$). The MOR and MOE values of the standard- and micro-size specimens showed a positive linear dependency, presenting coefficients of correlation of 78.2% and 81.4% in the linear regression models, respectively.



(a)



(b)

Fig. 3. The regression analyses results for (a) bending strength and (b) modulus of elasticity of the micro- and standard-size wood specimens

CONCLUSIONS

1. The bending strength and modulus of elasticity of the micro-size specimens were 14.3% and 70.9% lower compared to those of the standard-size specimens, respectively.
2. The effects of the specimen size and the individual trees, and the interactions between the size and the trees, on the bending strength and modulus of elasticity were found to be statistically significant.
3. The regression analyses indicated that the flexural properties of the micro-size specimens were significantly correlated with the standard-size specimens. A positive linear regression was observed between the flexural properties of the micro- and standard-size specimens.

4. This study concluded that micro-size test specimens can be used to estimate the standard-size test results for the flexural properties of Scots pine wood.

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