

Micro-Tensile and Compression Strength of Scots Pine Wood and Comparison with Standard-Size Test Results

Mikrovlačna i mikrotlačna čvrstoća škotske borovine i usporedba s rezultatima ispitivanja čvrstoće na uzorcima standardne veličine

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ABSTRACT • The goal of this study was to investigate the tensile and compression strength of Scots pine wood (*Pinus sylvestris* L.) using micro- and standard-sized test specimens. In the standard- and micro-sized specimens, tensile strength was evaluated as 76.9 MPa and 91.5 MPa and compression strength as 43.8 MPa and 36.3 MPa, respectively. The results showed that the compression strength of the micro-sized specimens was lower compared to the standard-sized specimens, while the tensile strength was higher in the micro-sized specimens. With the exception of the effect of specimen size and individual tree interaction on tensile strength, statistically significant effects were found for specimen size, individual trees and the interactions of the size and trees on the tensile and compression strength. Moreover, regression analyses indicated a positive linear regression between the strength of micro- and standard-sized specimens. Micro-sized specimens can be used to estimate the tensile and compression strength of Scots pine wood, when it is not possible to obtain standard-size specimens.

Key words: micro-sized specimens, standard-sized specimens, tensile strength, compression strength

SAŽETAK • Cilj istraživanja bio je usporediti vlačnu i tlačnu čvrstoću borovine (*Pinus sylvestris* L.) određenu na mikrouzorcima i na ispitnim uzorcima standardne veličine. Vlačna čvrstoća borovine određena na ispitnim uzorcima standardne veličine iznosila je 76,9 MPa, a na mikrouzorcima 91,5 MPa, dok je tlačna čvrstoća borovine izmjerena na standardnim ispitnim uzorcima bila 43,8 MPa, a na mikrouzorcima 36,3 MPa. Rezultati su pokazali da je tlačna čvrstoća borovine određena na mikrouzorcima manja od tlačne čvrstoće izmjerene na ispitnim uzorcima standardne veličine, dok je vlačna čvrstoća borovine izmjerena na mikrouzorcima veća od vlačne čvrstoće standardnih uzoraka. Uz izuzetak interakcijskog utjecaja veličine ispitnog uzorka i pojedinačnog stabla od kojega su uzorci izrađeni na vlačnu čvrstoću, statistička analiza dobivenih podataka pokazala je signifikantan utjecaj veličine ispitnog uzorka, pojedinačnog stabla od kojega je izrađen ispitni uzorak i interakcije veličine uzorka i

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stabilna od kojega je uzorak izrađen na vlačnu i tlačnu čvrstoću borovine. Usto, regresijska je analiza podataka pokazala pozitivnu linearnu regresiju između čvrstoće mikrouzoraka i čvrstoće ispitnih uzoraka standardne veličine. Iz toga se može zaključiti da se za procjenu vlačne i tlačne čvrstoće škotske borovine mogu upotrijebiti mikrouzorci kad god izrada ispitnih uzoraka standardne veličine nije moguća.

Ključne riječi: mikrouzorci, ispitni uzorci standardne veličine, vlačna čvrstoća, tlačna čvrstoća

1 INTRODUCTION

1. UVOD

Scots pine is an important tree species native to Eurasia. In Turkey, it covers about 5 % (738 000 ha) of the total Turkish forestland. Moreover, it exhibits superior technological properties and a high potential for utilization. In order to determine the mechanical properties of wood, the approach has been to use structural-size and small-size clear specimens. In recent years, micro-size specimens have been used to evaluate the mechanical properties of earlywood and latewood sections, wood strands, and fibers (Plagemann, 1982; Hunt *et al.*, 1989; Groom *et al.*, 2002; Mott *et al.*, 2002; Deomano and Zink-Sharp 2004; Cai *et al.*, 2007; Hindman and Lee 2007; Jeong 2008; Jeong *et al.*, 2009).

In previous studies on micro-sized testing, researchers used various specimen dimensions and loading rates according to the purpose of the study. Deomano and Zink-Sharp (2004) investigated the bending properties of southern yellow pine (*Pinus* spp.), sweet gum (*Liquidambar styraciflua* L.), and yellow poplar (*Liriodendron tulipifera* L.) wood. Samples of 25 × 5.0 × 0.6 mm flakes were used to calculate the modulus of rupture (MOR) and modulus of elasticity (MOE) of these wood species, with the loading rate of 2.54 mm/min. Hindman and Lee (2007) measured the bending and tensile properties of both earlywood and latewood sections of loblolly pine (*Pinus taeda*) strands. The dimensions of the bending test samples were 33.0 × 11.0 × 0.68 mm and of the tensile test samples 60 × 0.66 × 4.58 mm for earlywood, and 60 × 0.66 × 3.3 mm for latewood. The loading rate was 0.127 mm/min.

The tensile properties of willow (*Salix* spp.), yellow poplar (*Liriodendron tulipifera* L.), red oak (*Quercus* spp.) and loblolly pine (*Pinus taeda*) wood strands were investigated by Cai *et al.*, (2007). Hunt *et al.*, (1989) conducted tensile testing to determine the tensile strength and tensile modulus of yellow poplar strands (*Liriodendron tulipifera* L.) with a 2224 N load cell at a test speed of 1.9 mm/min. Their study revealed that the average tensile strength and tensile modulus was 70.3 MPa and 11.8 GPa, respectively.

Zink-Sharp and Price (2006) determined the compression strength of sweetgum (*Liquidambar styraciflua* L.), yellow poplar (*Liriodendron tulipifera* L.), and red maple (*Acer rubrum*) wood species using 1 × 1 × 4 mm specimens. The test was conducted at 12 % moisture content (MC) with a loading speed of 0.029 mm/min. They found that the compression strength of sweetgum, yellow poplar and red maple wood were 39.2, 33.5 and 41.6 MPa, respectively.

Micro-size specimens can be used to determine the mechanical properties of wood, when it is not pos-

sible to obtain standard-size test specimens. In order to avoid damaging the wood in various applications, the mechanical properties can be determined by using micro-size test specimens. Furthermore, the test specimens of structural wood material can be taken periodically and their mechanical properties can be determined. In this way changes in the mechanical properties of wood can be observed over time. With the development of micro-size tests, the strength losses due to exposure time can be determined for structural wood applications. This information can provide a solid base for a true assessment of the necessity of wooden structure renewal.

The mechanical properties of specimens are dependent on the specimen dimensions. This phenomenon is called size effect (Weibull, 1939). According to the theory of size effect (weakest link theory), the strength is dependent on the size of highly stressed volume. The basis for this theory is that there is a greater probability that a region of low strength will occur in a member of large volume than in a member of small volume. This region of low strength is assumed to cause complete failure of the member (Weibull, 1939).

The analysis of the factors influencing the size effect of strength and elastic properties is very complex and a number of hypotheses have been developed in the last 100 years. To simplify the matter, it is helpful to consider different species and different mechanical tests separately (Schotzhauer *et al.*, 2015). Madsen and Buchanan (1986) also stated that the size effect is dependent on wood species.

There is limited information concerning the comparison of tensile and compression strength of micro- and standard-size specimens. In previous studies, researchers compared their findings of micro-size test with values published in Wood Handbook for standard-size specimens (Zink-Sharp and Price, 2006; Cai *et al.*, 2007). Cai *et al.*, (2007) found that the tensile strength of willow, yellow poplar, red oak and loblolly pine strands, was, 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 handbook values for 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 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. The goal of this paper is, therefore, to evaluate the tensile and compression strength of micro-size Scots pine (*Pinus sylvestris* L.) wood and investigate the

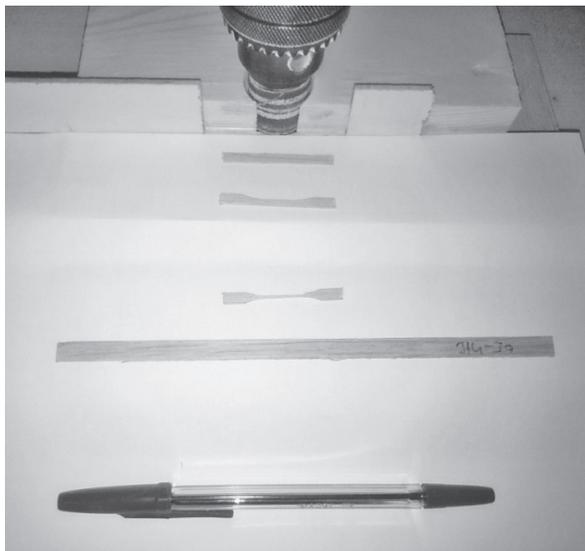


Figure 2 Micro-size tensile test specimens and preparation process

Slika 2. Mikrouzorci za ispitivanje vlačne čvrstoće i proces njihove pripreme

variance (ANOVA) at $p < 0.05$ considering two factors (specimen size and individual tree) and interactions. Post-hoc comparisons were conducted using Duncan's multiple range tests. Regression analysis was used to determine the relationship between standard- and micro-size specimens.

3 RESULTS 3. REZULTATI

The average tensile strength values and Duncan test results of the standard- and micro-size Scots pine wood specimens are shown in Table 2. The tensile strength values of the standard- and micro-size specimens were determined as 76.9 MPa and 91.5 MPa, respectively. The results showed that the tensile strength values of the micro-size specimens were 19.0 % higher compared to the standard-size specimens. For individual trees, the tensile strength values ranged from 75.7

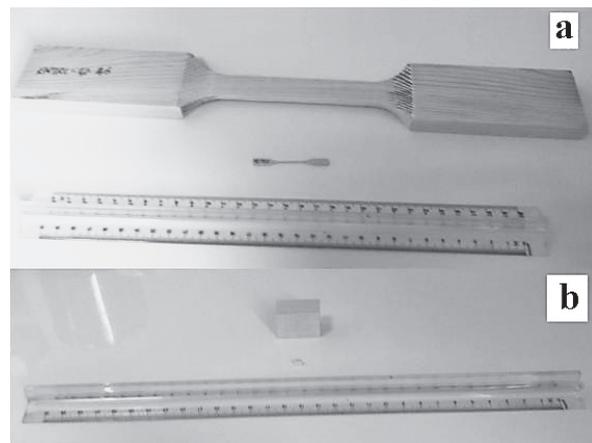


Figure 3 Micro- and standard-size test specimens for (a) tensile and (b) compression

Slika 3. Mikrouzorci i ispitni uzorci standardne veličine za ispitivanje: a) vlačne čvrstoće, b) tlačne čvrstoće

MPa (tree 2) to 111.8 MPa (tree 6) in the micro-size specimens and from 66.6 MPa (tree 5) to 89.9 MPa (tree 6) in the standard-size specimens. The highest tensile strength values were observed for tree 6 in both the micro- and standard-size specimens.

The average compression strength values and Duncan test results of the standard- and micro-size Scots pine wood specimens are shown in Table 3.

The compression strength values of standard- and micro-size specimens were found to be 43.8 MPa and 36.3 MPa, respectively. The results showed that the compression strength of the micro-size specimens were 17.1 % lower compared to the standard-size specimens. For individual trees, the compression strength values ranged from 31.9 MPa (tree 2) to 40.9 MPa (tree 6) in the micro-size specimens and from 36.3 MPa (tree 2) to 51.9 MPa (tree 6) in the standard-size specimens. The highest compression strength values were observed for tree 6 in both the micro- and standard-size specimens.

Table 2 The average tensile strength values and Duncan test results of standard- and micro-size Scots pine wood

Tablica 2. Prosječne vrijednosti vlačne čvrstoće i rezultati Duncanova testa za podatke dobivene na mikrouzorcima i ispitnim uzorcima standardne veličine

Tree No. Broj stabla	Tensile strength, MPa / Vlačna čvrstoća, MPa					
	Standard-size / Uzorci standardne veličine			Micro-size / Mikrouzorci		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
1	32	66.9 ^a	22.4	31	83.1 ^{de}	31.2
2	15	74.0 ^{ab}	22.6	15	75.7 ^d	25.1
3	23	85.1 ^{bc}	26.9	23	94.7 ^{def}	33.2
4	35	83.1 ^{bc}	17.5	35	98.2 ^{ef}	36.2
5	25	66.6 ^a	14.7	23	80.4 ^{de}	21.5
6	28	89.9 ^c	24.7	27	111.8 ^f	35.0
7	30	77.8 ^{ab}	19.3	28	89.9 ^{de}	31.8
8	31	70.9 ^a	12.4	29	89.4 ^{de}	33.9
Total	219	76.9	21.5	211	91.5	33.1

N – Number of specimens; Groups with same letters in column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiply range test.

N – broj uzoraka; među prosječnim vrijednostima označenim istim slovom u stupcu nije utvrđena statistički signifikantna razlika ($p < 0,05$) prema Duncanovu višestrukom usporednom testu

Table 3 The average compression strength values and Duncan test results of standard- and micro-size Scots pine wood
Tablica 3. Prosječne vrijednosti tlačne čvrstoće i rezultati Duncanova testa za podatke dobivene na mikrouzorcima i ispitnim uzorcima standardne veličine

Tree No. Broj stabla	Compression strength, MPa / Tlačna čvrstoća, MPa					
	Standard-size / Uzorci standardne veličine			Micro-size / Mikrouzorci		
	N	Mean	Std. Deviation	N	Mean	Std. Deviation
1	51	40.3 ^e	6.1	47	32.5 ⁿ	5.8
2	43	36.3 ^h	5.4	42	31.9 ⁿ	5.7
3	47	48.6 ^k	5.9	44	39.6 ^r	6.3
4	61	44.9 ⁱ	7.0	59	35.8 ^{pr}	6.6
5	46	40.6 ^g	6.1	45	35.2 ^o	6.4
6	57	51.9 ^m	7.2	55	40.4 ^r	7.0
7	41	41.3 ^g	5.1	40	34.1 ^{no}	5.0
8	58	43.7 ⁱ	4.2	53	36.3 ^{op}	6.1
Total	404	43.8	7.5	385	36.3	6.8

N – Number of specimens; Groups with same letters in column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiply range test.

N – broj uzoraka; među prosječnim vrijednostima označenim istim slovom u stupcu nije utvrđena statistički signifikantna razlika ($p < 0,05$) prema Duncanovu višestrukom usporednom testu

The factors of the specimen size (standard- and micro-size), individual trees (eight trees) and their interactions on the tensile and compression strength are shown in Table 4. For the tensile strength, specimen

size and individual tree were significantly different ($p < 0.000$), while the interaction of specimen size and individual tree was not ($p = 0.811$). For the compression strength, all factors were significantly different.

Table 4 The interactions of specimen size and individual tree on tensile strength and compression strength (ANOVA)

Tablica 4. Interakcije veličine uzorka i pojedinačnog stabla na vlačnu i tlačnu čvrstoću (ANOVA)

Source Izvor		Type III sum of squares Zbroj kvadrata – tip III.	df	Mean square Kvadrat srednje vrijednosti	F	P
Tensile Strength vlačna čvrstoća	Specimen size / veličina ispitnog uzorka	18692.1	1	18692.1	26.28	0.000
	Individual tree / pojedinačno stablo	34072.4	7	4867.5	6.84	0.000
	Specimen size * individual tree veličina ispitnog uzorka * pojedinačno stablo	2644.8	7	377.8	0.53	0.811
Compression strength tlačna čvrstoća	Specimen size / veličina ispitnog uzorka	10571.7	1	10571.7	284.1	0.000
	Individual tree / pojedinačno stablo	11217.9	7	1602.6	43.1	0.000
	Specimen size * individual tree veličina ispitnog uzorka * pojedinačno stablo	829.1	7	118.4	3.2	0.003

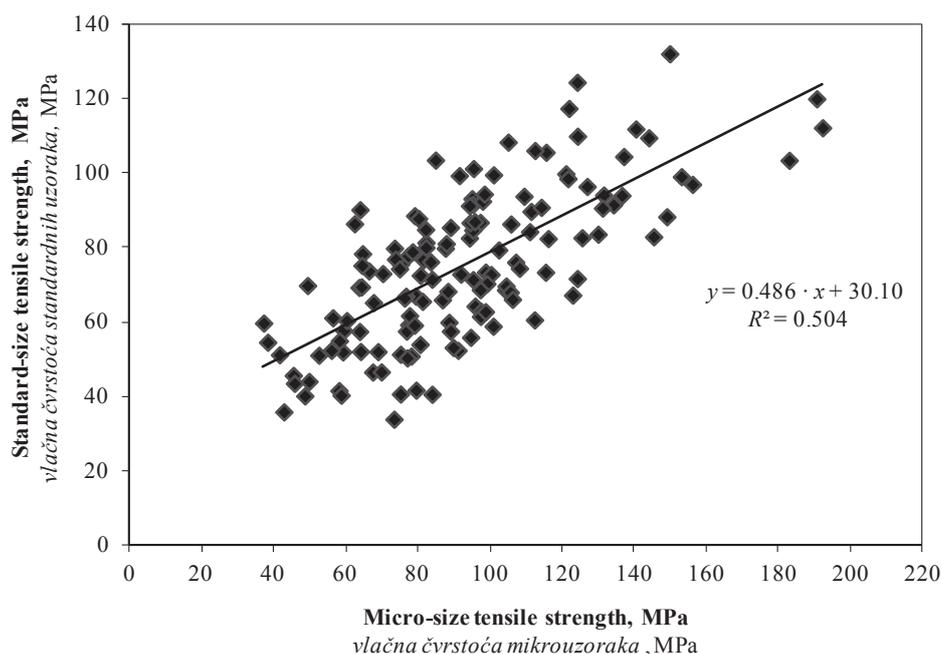


Figure 4 Regression analysis results for tensile strength of micro- and standard-size wood specimens

Slika 4. Regresijska analiza rezultata vlačne čvrstoće mikrouzoraka drva i ispitnih uzoraka standardne veličine

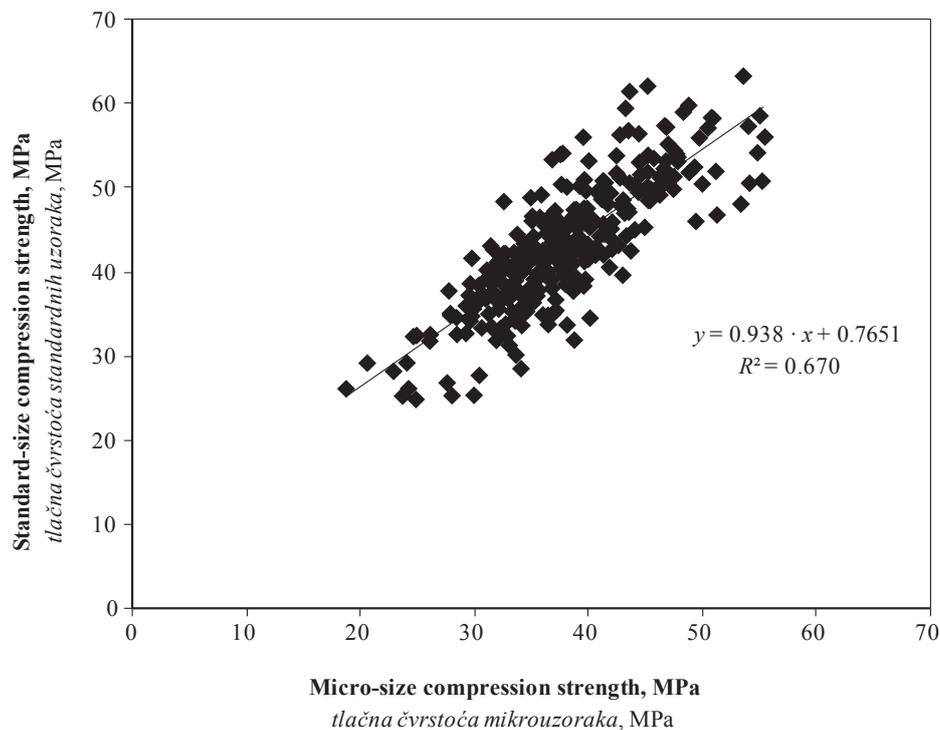


Figure 5 Regression analysis results for compression strength of micro- and standard-size wood specimens
Slika 5. Regresijska analiza rezultata tlačne čvrstoće mikrouzoraka drva i ispitnih uzoraka standardne veličine

Regression analysis graphics for the tensile and compression strength of the micro- and standard-size wood specimens are shown in Figures 4 and 5, respectively. The regression analysis indicated that all measured properties of the micro-size specimens were significantly correlated with the standard-size specimens ($p < 0.000$). The tensile and compression strength values of the standard- and micro-size specimens showed a positive linear dependency, presenting coefficients of correlation of 71.0 and 81.9 percent, respectively, in linear regression models.

4 DISCUSSION

4. RASPRAVA

In previous studies about the tensile strength of micro-size test specimens, researchers determined the tensile strength value of some wood species. Cai *et al.*, (2007) determined that the tensile strength values of yellow poplar, loblolly pine, willow and red oak wood strands were 48.5 MPa, 58.7 MPa, 22.7 MPa and 40.7 MPa, respectively. Additionally, the tensile strength of southern pine strands was determined as 50.0 MPa (Wu *et al.*, 2005), of loblolly pine strands as 43.3 MPa (Hindman and Lee 2007) and of yellow poplar strands as 70.3 MPa (Hunt *et al.*, 1989). The gage length, sample thickness, loading rate and sample shape (dog-bone or rectangle shape) affect tensile strength of micro-size samples. Unlike previous studies, in the current study, micro-size tensile strength specimens were prepared in the dog-bone shape. Kohan *et al.*, (2012) compared the tensile strength and modulus of elasticity of rectangular and tapered (dog-bone) wood strands. They concluded that the dog-bone shaped

specimens had 16 % and 27 % higher tensile strength and modulus of elasticity, respectively, than the rectangular specimens, and that the variation in mechanical properties was not statistically different for the two shapes. The higher tensile strength value in the micro-size specimens could be attributed to the dimensions of the specimens, loading rate, ratio of earlywood and latewood or gauge length. Jeong (2008) pointed out that the results of previous studies are not directly comparable because of different loading conditions and different wood species. In his study, he indicated that the tensile strength of micro-size loblolly pine wood specimens reported by Hindman and Lee (2007) was 36 % higher compared to the work of Cai *et al.*, (2007). This comparison clearly shows the effect of specimen dimensions and loading rate on the strength properties of micro-size specimens. Price (1976) concluded that tensile strength increased as gauge length increased. Jeong *et al.*, (2008) concluded that tensile strength and MOE generally increased as the thickness increased, and the thickness of the specimen wood strands significantly affected the tensile strength and MOE of southern pine wood. In order to decrease the variability of test results, they recommended a 0.254 mm/min loading rate and a strand thickness of between 0.794 and 1.91 mm.

The results showed that the tensile strength value of the micro-size specimens was higher than that of the standard-size specimens. This is compatible to Weibull's theory, which states that with increasing volume, the strength decreases. Schneeweiß and Felber (2013) mentioned a strong decrease in tensile strength when increasing the length of the specimens. Conversely, previous studies have stated that the tensile strength of micro-size specimens was lower than that of standard-

size specimens (Price 1976; Cai *et al.*, 2007). Cai *et al.*, (2007) reported that the tensile properties of willow, yellow poplar, red oak, and loblolly pine wood strands were significantly lower than those of standard-size. When compared to the tensile strength of standard-size specimens in Wood Handbook, those of wood strands from willow, yellow poplar, red oak, and loblolly pine were lower by 31.1 %, 44.2 %, 36.2 % and 73.4 %, respectively. Price (1976) observed similar results for micro-size sweet gum specimens. In previous studies researchers compared their findings with published values in Wood Handbook (Green *et al.*, 1999) for the same 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 micro-size and standard-size samples. It is recognized that tree age and growth conditions such as climate, soil characteristics, slope and altitude affect the annual ring width and the mechanical properties of wood.

The results of the present study showed that the compression strength value of the micro-size specimens was lower compared to the standard-size specimens. Similar results were seen by Zink-Sharp and Price (2006) in sweet gum (*Liquidambar styraciflua* L.), yellow poplar (*Liriodendron tulipifera*) and maple (*Acer rubrum*) wood. They found that the compression strength of the micro-size specimens was close to but lower than handbook values for all studied species. They explained that the exact cause of this difference was unknown, but that there were at least two probable explanations. The size effect was one possibility and the second was that damage created by specimen preparation had a more significant impact on the intra-ring specimens than on the standard-size specimens. Another reason of the differences between the compression strength of micro- and standard size samples can be the failure mode. Schlotzhauer *et al.*, (2015) concluded that the mode of failure is also affected by the specimen dimensions.

The compression strength results of the present study are contradictory to Weibull theory. Schneeweiß (1964) concluded that the volume strength dependence is a function of absolute specimen volume. He established three different categories. At volumes below 10 cm³ (Category 1) and above 1000 cm³ (Category 3), Weibull's theory applies. In between (Category 2), the volume is considered an influencing factor of low importance. Schneeweiß (1964) stated that the compression strength of Spruce wood first decreased with increasing specimen volume then increased slightly to maximum and finally decreased again. Madsen and Buchanan (1986) stated that the size effect is dependent on wood species. Schlotzhauer *et al.*, (2015) observed that the compression strength increased as specimen volume increased in beech, oak and lime wood, while the specimen dimensions did not influence the compression strength of maple, birch and ash wood.

5 CONCLUSIONS

5. ZAKLJUČAK

Based on this study, the following conclusions can be drawn:

1. The compression strength of the micro-size specimens were 17.1 % lower compared to the standard-size specimens, while tensile strength was 19.0 % higher in micro-size specimens.
2. The effects of specimen size, individual trees and the interactions between size and trees on tensile and compression strength were statistically significant, except for the effect of the interaction of specimen size and individual trees on tensile strength.
3. The regression analysis indicated that tensile and compression strength of the micro-size specimens was significantly correlated with the standard-size specimens. A positive linear regression between the micro- and standard-size specimens was found for tensile and compression strength.
4. Micro-size test specimens can be used to estimate the standard-size test results for the tensile and compression strength of Scots pine wood.
5. Dog-bone shape micro-size tensile strength samples at given dimensions can be used to determine tensile strength of wood. For the loading rate, ISO standards can be used as a guide for the micro-size specimens.

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