Mechanical Properties of Grand Fir Wood Grown in the Czech Republic in Vertical and Horizontal Positions

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Strength properties were evaluated for Grand fir wood (*Abies grandis* /Douglas/ Lindl.), a North American species that is considered to be a promising species for the Central European forestry industry. The bending, compression, and impact strengths of wood from Grand fir trees grown in the Czech Republic area were tested, including their variability within a stem and correlation to wood density. The average values of the compression strength reached 39.577 MPa; the bending strength was 78.119 MPa, the impact strength was 4.186 J/cm^2, and the density was 410.267 kg/m^3. The greatest dependence of the strength characteristics on the evaluated density was shown in the case of bending at the vertical bottom position (r = 0.95). Compression strength values were observed to highly correlate with the density at vertical positions (bottom and middle) in the first site (r = 0.98). The values of the correlations between density and impact strength were observed to be moderate or poor in the vertical position, where a good value was shown in the middle position (r = 0.87). The results of the study suggest that Grand fir is a satisfactory substitute for indigenous species of fir in the Czech Republic; with respect to bending strength and toughness, it can replace the most important commercial conifer, spruce.

Keywords: Grand fir; Introduced species; Wood properties; Strength; Density; Variability

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INTRODUCTION

At the end of the 20th century, the Czech forestry faced a radical change in species composition, *i.e.*, substitution of the silver fir (*Abies alba* Mill.), a significant original domestic softwood, that decreased from an original representation of 19.8% to just 1.0% in 2012 (Ministry of Agriculture 2012). Historically, silver fir was an important original and abundant coniferous tree species whose wood was used for a wide range of purposes in the Czech Republic and throughout the Central region of Europe. This species lives for 500 to 800 years, growing to a height of 50 m and a diameter of 100 cm.

Several potential substitute species from other geographic areas have been identified to replace the silver fir (Podrázský *et al.* 2013). The final selection was a North American species, Grand fir (*Abies grandis* /Douglas/ Lindl.). The original habitat of *A. grandis* is the Northwest coast of North America. It reaches a height of 76 m and a diameter of 152 cm, and lives for approximately 250 years. It was introduced to the region of Central Europe as a prospective tree species to be planted for production of lumber, and has also been introduced as an ornamental tree in Hawaii and in Europe (St.

John 1973; Otto 1982; Foiles *et al.* 1991; Alden 1997; Klinka 2007). In Germany, Grand firs have been introduced from North America and have a lot of economic value with their potential to raise the production of wood in domestic forests due to drought tolerance and ecological compatibility (Friedrich 1981; Nörr 2004).

Several experiments conducted at forestry sites in the Czech Republic have focused on the evaluation of growth, production of wood, and impact on the surrounding environment; results showed that Grand firs have the potential to replace domestic wood species and to contribute to forestry in the region (Podrázský and Remeš 2009; Fulín *et al.* 2013; Salem *et al.* 2013). There were pilot studies in neighboring countries to evaluate the characteristics of *A. grandis* wood (Hapla *et al.* 2013), but no such studies are currently taking place in the Czech Republic where the species composition of coniferous trees in the region is very poor.

Many studies have reported that *A. grandis* has a quick growing mass yield, but with low density values, and can be effective in industrial applications (Hapla 2006; Hof *et al.* 2008; Mitze 2010; Vos and Kharazipour 2010; Lukašek *et al.* 2012). The timber, regarded as weaker and less resistant to decay than many other species and susceptible to bacterial infections in wet-wood, is used primarily as a source of pulpwood (Burns and Honkala 1990; Alden 1997). Wagenführ (2007) reported that the wood density is 450 kg/m^3 and the compression strength value is 47 MPa; the wood is described as moderate to moderately low in strength, stiffness, shock resistance, and nail withdrawal.

Mechanical properties of wood are significant indicators of wood quality from the viewpoint of its use for construction purposes. Strength properties are closely related to the density of the wood, and several studies reported the correlation between the density and strength properties (Barnett and Jeronimidis 2003; Sonderegger *et al.* 2008). Also, density is one of the basic indicators of wood quality and used as a criterion of strength grading, depending on the vertical and horizontal position in the stems (Panshin and De Zeeuw 1980; Salem *et al.* 2013).

This study is the first report on the strength properties as well as the density of *A. grandis* wood from two locations in the Czech Republic. The evaluation was performed with consideration of the vertical and horizontal positions and growing site.

EXPERIMENTAL

Materials

Site descriptions and sample preparation

The sampling began in 2013, and all the measurements were completed by the end of August 2014. At the first location (Site 1), *A. grandis* trees are located close to the village of Kostelec nad Černými lesy (49° 59′ 39″ N, 14° 51′ 20″ E, latitude 49.994167, longitude 14.855556) situated 25 to 50 km south-east of Prague; the area is an intermediate warm and intermediate wet region. The location is characterised by an average annual temperature of 8.14 °C, average total annual precipitation of 662.6 mm, an average growing season of 150 to 160 days, and pseudogley soils. Individual sites were distributed between elevations of 325 and 430 metres a.s.l. Tree species composition at the site was as follows: Norway spruce 40%, European beech 20%, Grand fir 20%, and European larch 20%. The descriptions of the localities have been previously reported by Podrázský and Remeš (2009) and Tauchman *et al*. (2010). The forest stands in this region are the property of the Czech University of Life Sciences and represent a considerable extent of the plot used for the research activities of the Faculty of Forestry and Wood Sciences.

The second location (Site 2) is located at Kynšperk nad Ohří (50° 7′ 8″ N, 12° 31′ 59″ E, latitude 50.118889, longitude 12.533056). Age-felled sample trees ranged from 35 to 45 years. Tree diameters ranged from 27 to 37 cm, with heights in the range of 24 to 30 m. This area is an intermediate warm and intermediate wet region characterised by an average annual temperature of 7 to 8°C, an average total annual precipitation of 550 to 700 mm, and an average growing season of 140 to 160 days. The site is situated at the elevation of 470 metres a.s.l. Tree species composition at the site was as follows: spruce 60% and Grand fire 40%. The all stands were regularly managed (*e.g*. thinning) in accordance with the forest management plan (10-years period).

From each tree stem, three sections 150 cm long ((bottom (1), middle (2), and top (3) sections)) were taken from each tree, as described previously (Langum *et al.* 2009; Lukašek *et al.* 2012), to evaluate the impact of vertical and horizontal positions in the stem. The sections represent different vertical positions in the trunk. When acquiring the specimens, the initial orientation in the plants was considered in terms of horizontal position (Sonderegger *et al.* 2008).

The sections were numbered (1, 2, 3, 4, and 5) from pith to bark for recognition of the horizontal position. The preparation of test samples and subsequent wood testing were done in accordance with the standard method ČSN 49 0101 (1980) in the laboratory with controlled temperature and relative humidity. The mechanical and wood density tests were conducted at a moisture content (MC) of 12% according to ČSN 49 0103 (1979) and ISO 3131 (1975).

Methods

Mechanical properties

Bending strength for 486 clear samples with dimensions of 20 mm × 20 mm × 300 mm was determined in accordance with ČSN 49 0101 (1980). The samples were conditioned in a controlled room (20 °C and 65% relative humidity) according to ČSN 49 0103 (1979) until the MC reached equilibrium. At 12% MC, the wood density (2485 samples) was measured according to ČSN 49 0108 (1993). The density was determined using the following formula,

$$\rho = \frac{m}{a \cdot b \cdot l} \cdot 10^{6} \quad \left[kg \cdot m^{-3} \right] \tag{1}$$

where ρ is the density of the wood, m is the mass of a test piece (g), and a, b, and l are the dimensions of the test piece (mm).

The bending strength was measured according to the following formula (ČSN 49 0115),

$$\sigma = \frac{3 \cdot F_{\max} \cdot l}{2 \cdot b \cdot h^{2}} \quad \left[MPa \right] \tag{2}$$

where F_{max} is the maximum load (N), l is the distance between the two supports (mm), h is the height of the test piece (mm), and b is the width of the test piece (mm).

Compression strength (924 samples) was evaluated on test specimens with dimensions of 20 mm × 20 mm × 30 mm according to the following formula (ČSN 49 0110),

$$\sigma = \frac{F_{\max}}{a \cdot b} \quad [MPa] \tag{3}$$

where F_{max} is the maximum load (N) and a and b are the transverse dimensions of the sample (mm).

Impact strength (386 samples) was assessed with respect to vertical position only on samples with dimensions of 20 mm × 20 mm × 300 mm using the following formula (ČSN 49 0117),

$$A = \frac{Q}{b \cdot h} \quad [J \cdot cm^{-2}] \tag{4}$$

where Q is the energy expended to break the sample (J) and b and h are the sample dimensions in the radial and tangential directions (cm), respectively.

Statistical analysis

The mechanical properties and density values of *A. grandis* wood, with respect to the vertical and horizontal positions and the growing sites, were statistically analyzed using the general linear model (GLM) procedure in SAS version 8.2 (2001). A comparison among the least square (LS) means of factors and levels with 95% confidence intervals (CI) was performed using Duncan's multiple-range test to identify significant differences and to compare the means between the obtained values. Linear correlations were used to evaluate the dependence of the mechanical properties on the density of wood from both sites.

RESULTS AND DISCUSSION

Data presented in Tables 1 and 2 shows that the average density of the Grand fir wood was 410.267 kg/m^3; this value is close to the value from the trees growing in their original geographic area (449 kg/m^3) (Alden 1997). The compression and bending strength values (39.577 and 78.119 MPa, respectively) were higher than the values reported from the original area (36.5 and 68 MPa, respectively) (Alden 1997), and the impact strength value was 4.186 J/cm^2, which is similar to values reported for other softwood species. Lukašek *et al.* (2012) reported that the density at 12% MC of *A. grandis* growing in the Czech Republic was 405 kg/m^3, and Hapla *et al.* (2014) reported that the oven dry density varied with different height in compression wood, sapwood, and heartwood, *i.e.*, at the height of 1.5 m the values were 0.449 g/cm^3 (compression wood), 0.354 g/cm^3 (heartwood), and 0.457 g/cm^3 (sapwood).

The data calculated from the two sites (Table 1) indicated that there were variations in the values in the studied variables for both sites, and the variation were with respect to tree age, wood anatomy, environmental and soil conditions, silvicultural practice (Bektas *et al.* 2003; Miranda *et al.* 2007), and the position of the test piece within the tree (de Palacios *et al*. 2008).

Table 1. Descriptive Statistics for Density and Selected Mechanical Properties of *A. grandis* Wood

Value	Density (kg/cm^3)	Bending strength (MPa)	Impact strength (J/cm^2)	Compression strength (MPa)
Mean	410.267	78.119	4.186	39.577
Confidence -95%	408.237	76.329	4.042	39.126
Confidence +95%	412.297	79.910	4.329	40.029
Median	403.935	77.158	4.066	39.071
Minimum	313.675	40.990	1.678	24.546
Maximum	608.857	137.410	9.369	59.673
Lower Quartile	370.554	64.070	3.118	34.239
Upper Quartile	440.581	89.160	4.856	44.319
Variance	2662.413	403.398	2.058	48.314
Std.Dev.	51.599	20.085	1.435	6.951
Confidence SD -95%	50.203	18.897	1.340	6.646
Confidence SD +95%	53.075	21.434	1.544	7.285
Coef. Var.	12.577	25.710	34.275	17.563
Standard error	1.035	0.911	0.073	0.230

Table 2. Comparison among the Values of Selective Properties from Commercial Softwoods and Values from Grand Fir in the Present Study

Factor	Giant fir[a]	Grand fir (original area)[b]	Silver fir (*Abies alba*)[b]	Spruce (*Picea abies*)[b]	Pine (*Pinus sylvestris*)[b]	Grand fir (present study)
Density (kg/cm^3)	430	449	350 - 410 to 750	470 to 680	330 - 510 to 980	410.267
Compression strength (MPa)	36	36.5	31 - 47 to 59	33 - 50 to 79	35 - 55 to 94	39.577
Bending (MPa)	68	61.4	47 - 73 to 118	49 - 78 to 136	80-205	78.119
Impact strength (J/cm^2)	3.7	not compatible	3.0 - 4.2 to 12.0	1.0 - 4.6 to 11.0	1.5 - 4.0 to 13.0	4.186

[a]Data from Wagenführ (2007); [b]data from Alden (1997)

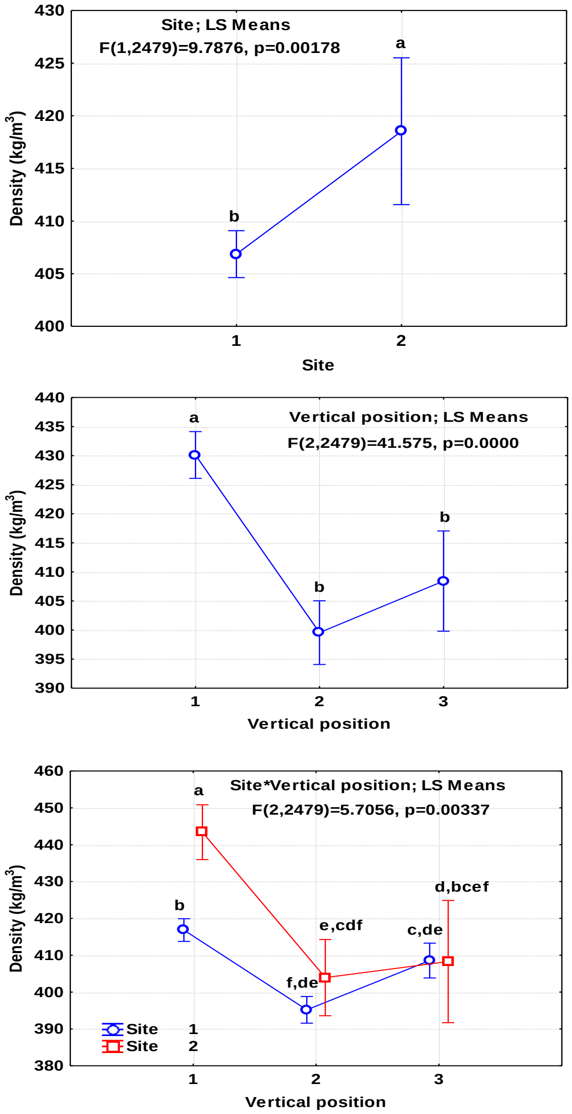
Effect of Growing Site and Position of Wood Samples on Wood Density of *A. grandis*

The variations in density in wood as affected by vertical position (bottom, middle, and top sections) and growing site are shown in Fig. 1 and Table 3. The site, vertical position, and interaction between them significantly ($P < 0.001$) affected the density values. Additionally, the density values at site 2 were higher than those from site 1, and the value from the bottom vertical position in the two sites was higher than the values from the middle and top positions. The density was highest at the bottom (Hapla *et al.* 2013). Furthermore, the values from the middle position at the two sites were lower than those from the top position, but the difference was not significant.

With respect to the horizontal positions (Table 3 and Fig. 2), there was a clear trend of increasing density values from pith to bark, with a highly significant ($P < 0.001$) effect of horizontal position as well as the interaction between the site and horizontal position. On the other hand, the differences in wood density values between the two sites were not significant ($P = 0.59$).

Table 3. *A. grandis* Density (kg/m^3) with Respect to Site and Vertical and Horizontal Positions

Site	Density (kg/cm^3)							
	Vertical position			Horizontal position				
	Bottom	Middle	Top	1	2	3	4	5
1	416.829	395.183	408.560	377.5144	386.0486	411.3676	458.1581	496.1373
2	443.393	403.928	408.283	386.6842	397.5248	408.5339	437.2294	492.9532



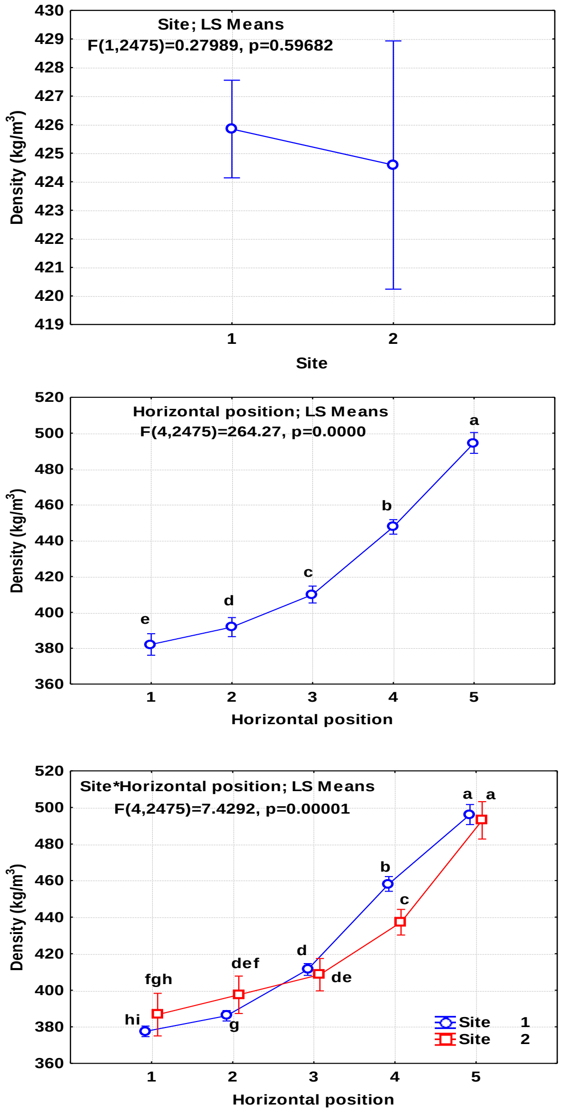


Fig. 1. Effect on wood density of vertical position of *A. grandis* wood with growing site

Fig. 2. Effect on wood density of horizontal position of *A. grandis* wood with growing site

Vertical bars denote confidence intervals of 0.95. Means with the same letters are not significantly different at P < 0.05 according to Duncan's multiple-range test. Mean values of Bottom section (1), middle section (2), and top section (3) from the studied trees for each site

Table 4. Bending Strength (MPa) of *A. grandis* Wood with Respect to Site and Vertical and Horizontal Positions

Site	Bending strength (MPa)							
	Vertical position			Horizontal position				
	Bottom	Middle	Top	1	2	3	4	5
1	83.233	67.231	64.158	58.496	66.496	73.608	88.785	101.919
2	86.292	77.591	73.802	67.196	74.746	81.313	93.217	105.583

Effect of Growing Site and Position of Wood Samples on Mechanical Properties of *A. grandis*

Figure 3 (vertical position) and Fig. 4 (horizontal position) show the bending strength values of *A. grandis* wood as affected by the two sites. Both the site and position of wood had a highly significant ($P < 0.001$) effect on bending strength. On the other hand, the interaction between the site and vertical or horizontal position was not significant. Furthermore, the highest values of bending strength (vertical position) were observed in the bottom positions from sites 2 and 1, with values of 86.292 and 83.233 MPa, respectively (Table 4).

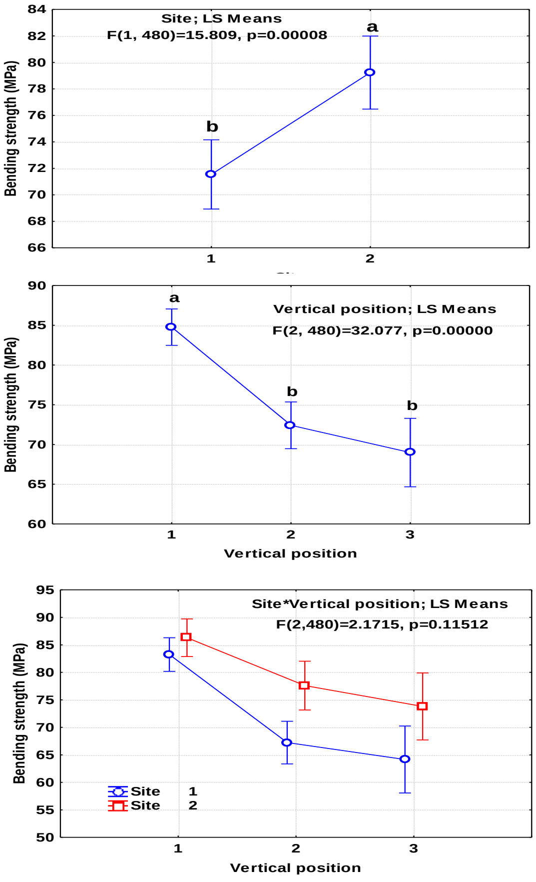


Fig. 3. Effect on bending strength of vertical position of *A. grandis* wood with growing site

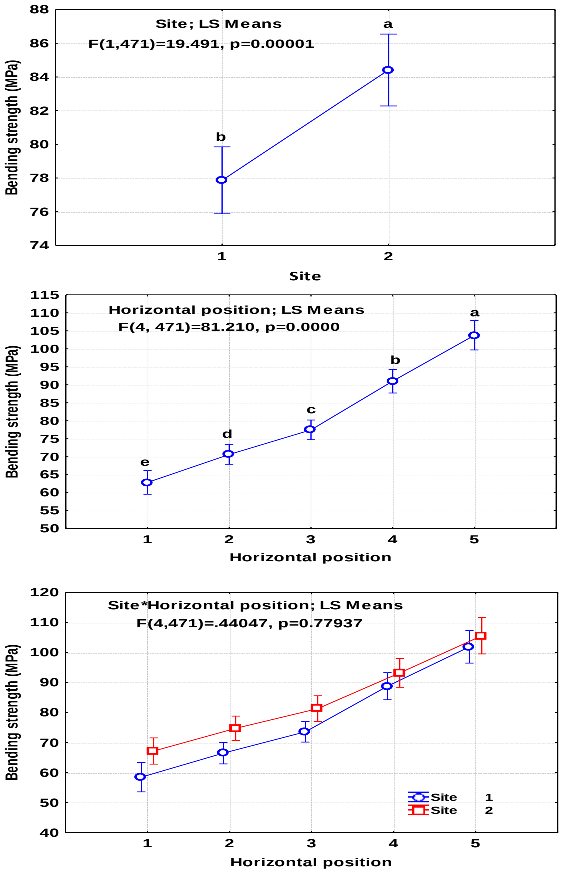
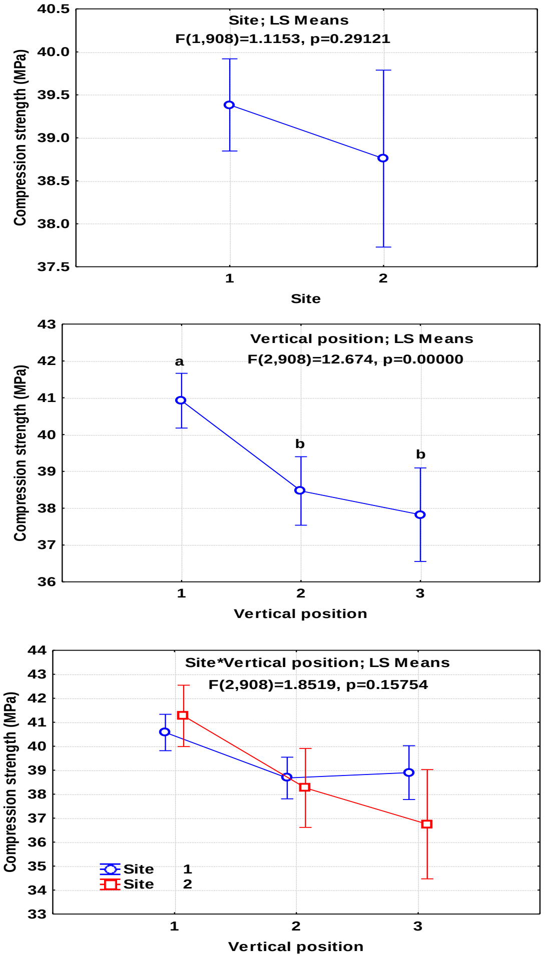


Fig. 4. Effect on bending strength of horizontal position of *A. grandis* wood with growing site

Vertical bars denote confidence intervals of 0.95. Means with the same letters are not significantly different at $P < 0.05$ according to Duncan's multiple-range test. Number 1 defines the closest position to the center (pith) of a stem

With respect to horizontal position, the height values of bending strength were shown in section number 5, in sites 2 and 1 with values of 105.583 and 101.919 MPa, respectively. The bending strength increased from pith to bark and from top to bottom of the tree stem (Table 4).

Compression strength, as shown in Fig. 5, was significantly affected by vertical position (P<0.001), but not by site (P = 0.29) or the interaction between vertical position and growing site (P = 0.15). The bottom sections from the two sites were observed to have the highest compression strength, with values of 40.573 MPa and 41.265 MPa, respectively (Table 5). The compression strength was significantly (P < 0.001) affected by horizontal position, growing site, and the interaction between them (Fig. 6). The values uniformly increased from pith to bark (Table 5).



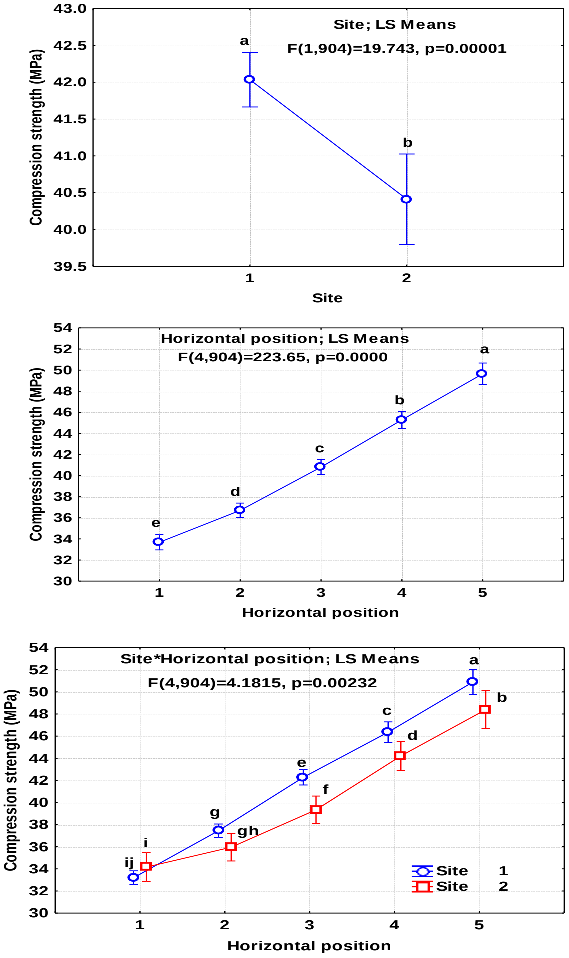


Fig. 5. Effect on compression strength of vertical position of *A. grandis* wood with growing site

Fig. 6. Effect on compression strength of horizontal position of *A. grandis* wood with growing site

Vertical bars denote confidence intervals of 0.95. Means with the same letters are not significantly different at P < 0.05 according to Duncan's multiple-range test

Table 5. Compression Strength (MPa) of *A. grandis* Wood with Respect to Site and Vertical and Horizontal Positions

Site	Compression strength (MPa)							
	Vertical position			Horizontal position				
	Bottom	Middle	Top	1	2	3	4	5
1	40.573	38.676	38.900	33.198	37.446	42.273	46.357	50.895
2	41.265	38.261	36.748	34.161	35.956	39.336	44.211	48.396

For the impact strength, we measured only the effect of vertical position, which showed that the bottom position of wood had a significant effect ($P < 0.001$) on the measured values, whereas neither the growing site ($P = 0.85$) nor the interaction between vertical position and growing site ($P = 0.35$) had a significant effect (Fig. 7). The highest values were observed in the bottom section at both sites (4.384 and 4.571 J/cm^2, respectively), but these values were not significantly different (Table 6). Some of the above results are similar to those found in the study of González-Rodrigo *et al.* (2013) with respect to the variation throughout the tree stem of the wood of *A. alba*, the study of Machado and Cruz (2005) on Maritime pine, and the study of Antony *et al.* (2011) on planted loblolly pine in the United States.

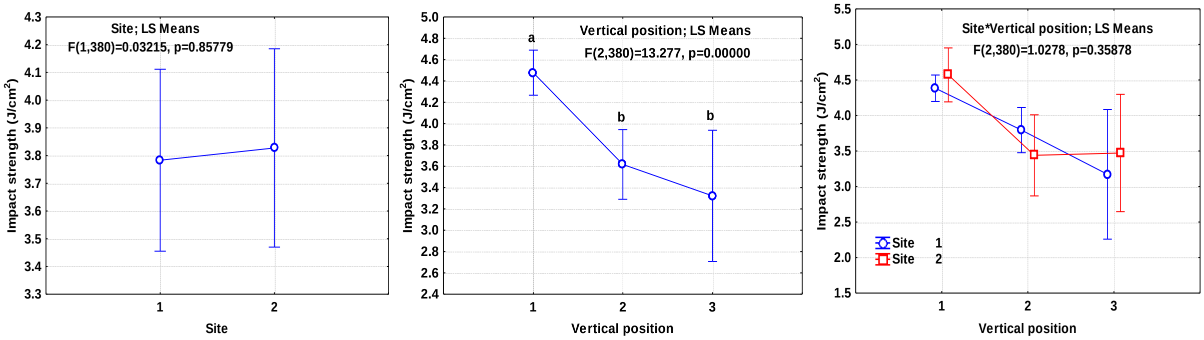


Fig. 7. Effect on the impact strength of vertical position of *A. grandis* wood with growing site. Vertical bars denote confidence intervals of 0.95. Means with the same letters are not significantly different at $P < 0.05$ according to Duncan's multiple-range test

Table 6. Effect of Interaction between Site and Vertical Position on the Values of Impact Strength (J/cm^2)

Site	Impact strength (J/cm^2)		
	Bottom	Middle	Top
1	40.573	38.676	38.900
2	41.265	38.261	36.748

Correlation between Density and Selected Mechanical Properties *of A. grandis* Wood

To determine the value and benefits of wood as a bioresource for the production of wood-based material, the relationships among the density and various mechanical properties of *A. grandis* wood was found by determining the regression equations and correlation coefficients (r). Several studies have reported that wood quality and mechanical and physical properties of wood can be indicated by wood density (Niemz 1993; Niemz and Sonderegger 2003; Esteban *et al.* 2009; Lukášek *et al.* 2012).

Additionally, density can influence harvesting and transport costs, strength properties, and the yield in the paper and fiber industry (Hapla *et al.* 2014).

In the present study, 38 correlations among the density and the bending and compression strength values (from the two sites and all vertical and horizontal wood sampling positions), as well as impact strength (two sites and vertical position), were measured.

At the first site, the correlation coefficients for density and bending strength (Table 7) ranged from r = 0.35 (horizontal position 1) to r = 0.93 (vertical bottom position). The samples from the middle position showed a very good correlation with the density (r = 0.89). Additionally, the samples from horizontal position 3 had a good relationship with density (r = 0.74). At site 2, high correlation coefficient values (r = 0.91, 0.89, and 0.85) were observed between density and samples from horizontal position 3, the bottom vertical position, and horizontal position 4, respectively.

Table 7. Correlation between Bending (MPa) and Density (kg/m^3) at Different Vertical and Horizontal Positions for Two Sites

Position	Sample	Site 1	Site 2
Vertical	Bottom	Y=-86.07+0.42X; r=0.93; r^2=0.87	Y=-72.18+0.35X; r=0.89; r^2=0.80
	Middle	Y=-127.59+0.49X; r=0.89; r^2=0.80	Y=-27.51+0.35X; r=0.77; r^2=0.60
	Top	Y=-95.92+0.41X; r=0.82; r^2=0.68	Y=17.45+0.13X; r=0.33; r^2=0.11
Horizontal	1	Y=-12.7+0.19X; r=0.35; r^2=0.12	Y=-41.45+0.26X; r=0.72; r^2=0.52
	2	Y=-38.02+0.29X; r=0.70; r^2=0.50	Y=-20.70+0.23X; r=0.68; r^2=0.47
	3	Y=-173.75+0.62X; r=0.74; r^2=0.55	Y=-46.72+0.31X; r=0.91; r^2=0.83
	4	Y=-249.26+0.75X; r=0.71; r^2=0.50	Y=-82.30+0.39X; r=0.85; r^2=0.72
	5	Y=-294.67+0.81X; r=0.70; r^2=0.49	Y=-155.43+0.51X; r=0.79; r^2=0.63

Y, Bending strength (MPa); X, Density (kg/m^3).

Compression strength values were highly correlated (Table 8) with density at vertical positions (bottom and middle) at the first site (r = 0.98), followed by horizontal positions 3 (r = 0.89) and 4 (r = 0.86). At the second site, a good correlation was observed between values from the bottom vertical position (r = 0.90) and horizontal position 4 (r = 0.90).

Table 8. Correlation between Compression Strength (MPa) and Density (kg/m^3) at Different Vertical and Horizontal Positions for Two Sites

Position	Sample	Site 1	Site 2
Vertical	Bottom	Y=-20.25+0.15X; r=0.98; r^2=0.96	Y=-15.9+0.11X; r=0.90; r^2=0.81
	Middle	Y=-20.92+0.15X; r=0.98; r^2=0.96	Y=1.79+0.0.08X; r=0.71; r^2=0.50
	Top	Y=18.95+0.05X; r=0.29; r^2=0.08	Y=10.39+0.06X; r=0.61; r^2=0.37
Horizontal	1	Y=18.69+0.036X; r=029; r^2=0.08	Y=28.09+0.017X; r=0.17; r^2=0.03
	2	Y=-20.25+0.15X; r=0.66; r^2=0.43	Y=15.89+0.0.049X; r=0.37; r^2=0.13
	3	Y=-44.88+0.21X; r=0.89; r^2=0.79	Y=8.80+0.075X; r=0.69; r^2=0.48
	4	Y=-23.46+0.15X; r=0.86; r^2=0.74	Y=-10.32+0.12X; r=0.90; r^2=0.81
	5	Y=-19.87+0.15X; r=0.82; r^2=0.68	Y=-4.03+0.10X; r=0.79; r^2=0.63

Y, Compression strength (MPa); X, Density (kg/m^3).

Density and impact strength had moderate or poor correlations (Table 9) in the vertical position, although a good value was shown for the middle position (r = 0.87) from site 2. The low correlations could be explained by the differences between the density of sapwood and heartwood like reported in the study of Hapla *et al.* (2013), who demonstrated that juvenile wood was the reason for the significant difference between sapwood and heartwood, which has lower cell wall / lumen ratio (Zobel and van Buijtenen 1989). Also, in vertical position the correlation was highly significant, and this result is in agreement with Risi and Zeller (1960), Stern (1963), and Olesen (1973), where the density is normally decreasing with height in the case of softwoods.

Table 9. Correlation between Density (kg/m^3) and Impact Strength (J/cm^2) at Different Vertical Positions for Two Sites

Position	Sample	Site 1	Site 2
Vertical	Bottom	$Y=-1.59+0.013X$; $r=0.50$; $r^2=0.25$	$Y=-5.71+0.002X$; $r=0.57$; $r^2=0.32$
	Middle	$Y=-1.06+0.01X$; $r=0.52$; $r^2=0.27$	$Y=-9.86+0.03X$; $r=0.87$; $r^2=0.76$
	Top	$Y=-.58+0.009X$; $r=0.26$; $r^2=0.069$	$Y=1.47+0.007X$; $r=0.54$; $r^2=0.29$

Y, Impact strength (MPa); X, Density (kg/m^3).

Generally, the vertical bottom position and horizontal positions 3 and 4 in the tree stem had good correlations with density and bending and compression strength. On the other hand, the correlation between density and impact strength was unconvincing. Additionally, the variations could be related to the compression wood, which was previously reported that the density was higher in case of sapwood (Esteban *et al.* 2009; Lukášek *et al.* 2012; Hapla *et al.* 2013). Furthermore, Giant fir has enormous growth dynamic, which procures an eccentric secondary thickness and leads to the formation of compression wood (Riebel 1994).

Previously, Cown (1992), Houllier (1993), Houllier *et al.* (1995), and Zhou *et al.* (2008) found that there has been an urgent need for management tools to integrate both growth and wood quality information, leading to a new generation of more detailed models; these models have been developed for fast-growing species of coniferous plantations in different regions around the world (*e.g.*, *Pseudotsuga menziesii*, western-hemlock, *Tsuga heterophylla*, Radiata pine, and Scots pine), as well as for Norway spruce (Behrendt *et al.* 2007; Dohrenbusch and Bolte 2008; Spellmann and Kehr 2008; Müller *et al.* 2009).

In the present study, we attempted to determine details concerning the relationship between the density and selected mechanical properties for an introduced coniferous species in the Czech Republic to ensure a long-term supply for wood processing industries. The results provide practical data for the timber-oriented sorting of Grand fir logs. The vertical bottom sections of the stems could be suitable for lumber and other wood products (particleboard, paper, fiberboard, *etc.*) because of the significant correlations among the density and mechanical strengths.

The differences obtained in the mechanical properties of *A. grandis* may be due to the limited number of tested wood specimens with considering the local variability of the species, where some variations were found to have resulted from specific conditions of the two studied sites (Brown *et al.* 1952; Blanco *et al.* 1997). Further studies on mechanical properties from other stands of *A. grandis* from the Czech Republic will be useful for the generality of the obtained results form *A. grandis*.

CONCLUSIONS

1. The differences in the mechanical properties of *A. grandis* may be due to the limited number of tested wood specimens when considering the local variability of the species.
2. The average values of mechanical properties were compression strength (39.577 MPa), bending strength (78.119 MPa), and impact strength (4.186 J/cm^2) with a density of 410.267 kg/m^3.
3. The highest correlations of the strength characteristics with density were shown in the case of bending at the vertical bottom position (r = 0.95) and for compression strength at vertical positions (bottom and middle) at the first site (r = 0.98). The impact strength showed moderate or poor correlations with the vertical position, although a good value was shown for the middle position (r = 0.87).
4. The site, vertical position, and interaction between them all significantly (P < 0.001) affected the density. The site and position of wood had a highly significant (P < 0.001) effect on bending strength. Compression strength was significantly affected by vertical position, but not by site (P = 0.29).
5. As general results, the vertical bottom position and horizontal positions 3 and 4 in the tree stem had good correlations among the density and bending and compression strengths. On the other hand, the correlation between the density and impact strength was unconvincing.

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