Effects of Geometric Parameters of Structural Elements on Joint Stiffness

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Joints are one of the most important issues in the design of furniture structures. Joints in furniture structures made from wood and wood materials represent a critical area because furniture most often breaks at the joints of structural elements. This article discusses the analysis of the effect of selected factors: type of loading (compressive, tensile), wood species (*Fagus sylvatica* L., *Picea abies* L.), thickness of joint (one-third and half the thickness of the tenon), type of glue (polyvinyl acetate and polyurethane), and the annual ring deflection, on the elastic stiffness of joints. These results indicated significant effects for the wood species, thickness of joint, and type of glue used. The annual ring deflection was on the borderline of statistical significance, while its effect was more significant than the effect of the basic material characteristic, *i.e.*, the wood density. The type of loading was not statistically significant.

Keywords: Furniture wood joints; Mortise and tenon; Mechanical loading; Elastic stiffness

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INTRODUCTION

The topic of joints is one of the most important areas in furniture design. Joints in furniture made of wood and wood-based materials are critical points, as furniture is most frequently damaged where structural elements are joined (Terrie 2009; Brett 2014). Joints can be classified as glued, mechanical, melted plastic, welded, and combined joints (Joščák *et al*. 2014).

Joints can be characterized by their effectiveness, expressed as the ratio of the load capacity of the joint to load capacity of the elements. This effective strength ranges between 10% and 30% (Bašista 1972; Joščák 1999). One of the most dangerous cases of joint stress is stress by bending moment in their angle plane (Eckelman *et al.* 2004; Erdil *et al*. 2005; Prekrat and Španic 2009; Uysal *et al.* 2015).

The mortise and tenon joint is one of the most common means of joining structural elements. This joint is usually glued. The mortise and tenon joint must have as little tolerance as possible to ensure joint strength. The greatest joint strength is ensured if adhesive is applied to both the tenon and the inside of the mortise (Forest Products Laboratory 2010). Smardzewski (2002b) examined the distribution of shear stress in joints. Konnerth *et al.* (2006) determined the behavior and durability of beech and spruce wood joints glued with a PVAc adhesive and compared them with other adhesive types. They determined that the glued joint's shear strength was 25% higher for beech than it was for spruce. Adhesive type did not have a significant effect on the glued joint's shear strength. In furniture-making practice, it is common to use thermoplastic PVAc adhesives in gluing products. PVAc adhesives appeared in 1950 and replaced natural adhesives. These adhesives present no risks to human health or the environment (Mitani and Barboutis 2010). Advantages of joining with adhesives include their universal use and lower price compared to other means of joining.

Smardzewski (2002a) examined the dimensions of glued mortises and tenons and proposed a comprehensive static assessment of glued mortise and tenon joints. This research demonstrated that the magnitude of the stress in bending moment depends on tenon length. Prekrat and Španic (2009) used scientific methods to determine the optimal variant of a corner joint using a tenon. They compared three types of corner joints (two round tenons, a tenon combined with pegs, and a round tenon combined with pegs; a steel cylinder; and a screw) stressed by a bending moment. The third joint combination had the highest load capacity while the second combination had the lowest load capacity. Horman *et al.* (2010) examined tenon joints made of spruce using experimental tests and the mathematical finite element method. They used mathematical methods to determine the distribution of normal and shear stress as well as total joint deformation that was comparable to the mechanical test. Tankut *et al.* (2014) presented a mathematical model of a chair and other wooden products using the finite element method. They concluded by noting the advantages to a static solution using the finite element method.

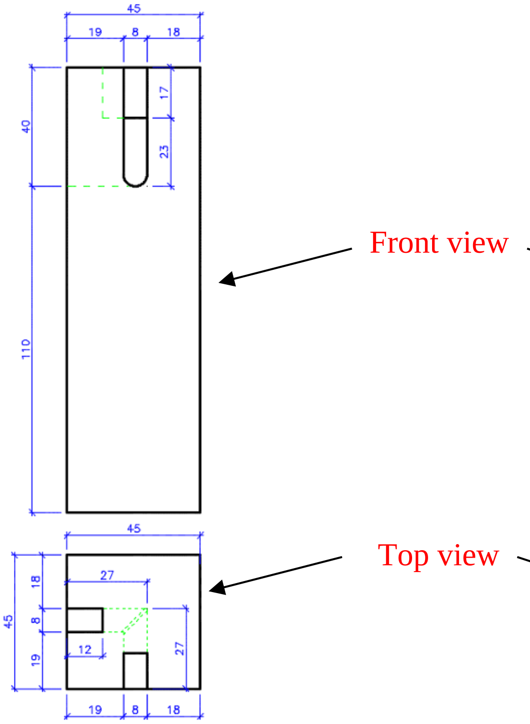
While using a finished product, situations may arise when the wood material is exposed to conditions that under certain circumstances may decrease the glued joint's cohesion. During use, the joint can be exposed to changes in humidity, high temperatures, and cyclic stress. Cyclic stress occurs when an object is repeatedly subjected to stress, which can result in damage caused by material fatigue. Prekrat *et al.* (2012) tested tenon joints of beech chairs cyclically stressed with static and dynamic moments until joint failure. They determined that joint strength decreases with increasing numbers of cycles. Uysal *et al.* (2015) also put footstools under cyclic stress by combining demountable and non-demountable frame joints with footstool legs. All joints were stressed with bending moment. The results indicated that the selected joint type had a statistically significant effect on the resulting strength. Cyclic stress did not have a significant effect on joint strength. This was the reason why we did not make cyclic loading in our research.

The key issue in the present experiments was to determine the stiffness of joints. In general, joints are one of the most critical parts of the entire structure because they weaken the homogeneity of the whole structure in the cross section. In this work the influence of selected factor (type of loading, wood species, thickness of joint - tenon dimensions, type of glue, and the annual ring deflection) was evaluated relative to the stiffness of furniture joints.

EXPERIMENTAL

Materials

For the experiment, Norway spruce (*Picea abies* L.) and beech (*Fagus sylvatica* L.) wood, which was obtained from the Prešov Region in Eastern Slovakia. Planks were cut from these wood species and acclimatized in a climatic chamber (APT Line II; Binder; Germany) at an equilibrium moisture content of 10%, relative humidity of 55%, and temperature of 20 °C. This moisture content corresponds to the equilibrium moisture content of furniture elements according to EN 942 (2007) and ČSN 91 0001 (2007). Parts for mechanical testing were formatted and machined from the dried planks using woodworking machines in the vocational school in Spišská Nová Ves. The sizes of stiles with 8 and 12 mm mortises are shown in Figs. 1 and 2, respectively, while the sizes of rails are shown in Figs. 3 and 4, respectively.



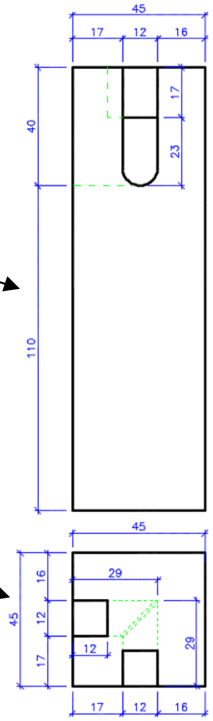


Fig. 1. Stile with 8-mm mortises

Fig. 2. Stile with 12-mm mortises

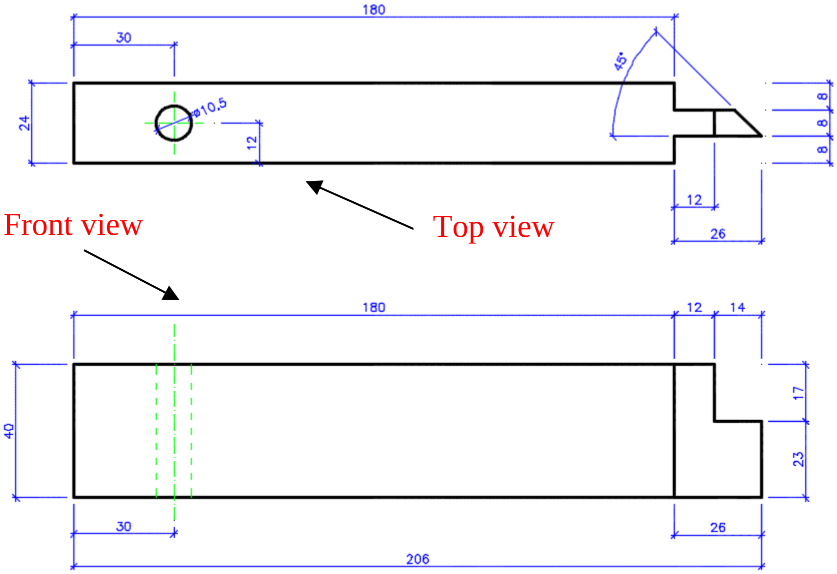


Fig. 3. Rail with 8-mm haunched tenon

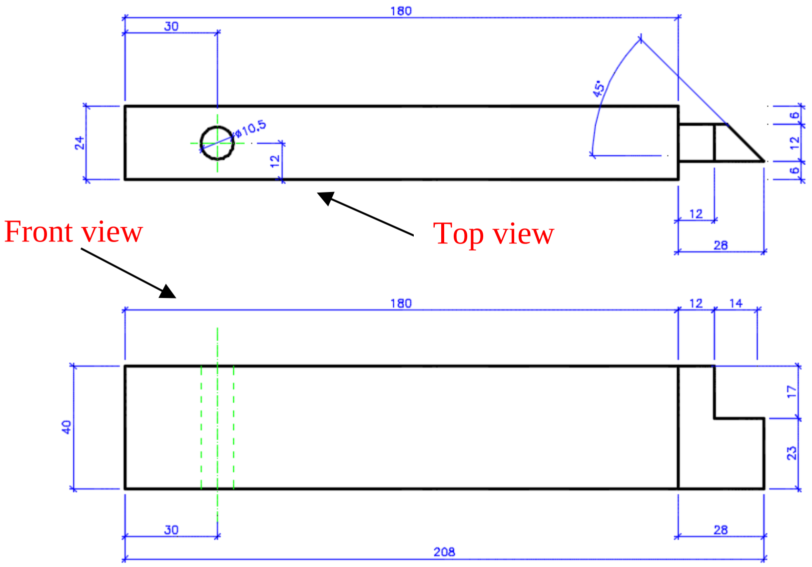


Fig. 4. Rail with 12 mm haunched tenon

Two types of adhesives were used to glue the rails and stiles: single-component waterproof polyvinyl acetate glue (PVAc) type AG-COLL 8761/L D3 (EOC; Belgium) and single-component polyurethane glue (PUR) type NEOPUR 2238R (NEOFLEX; Spain), with parameters listed in Table 1. The adhesive was applied manually using a brush in a recommended one-sided coat 150 to 180 g/m^2 for PVAc, and 180 to 250 g/m^2 for PUR glue, on the tenon and mortise. The specimens were cold-pressed in an industrial press (JU 60; Paul Ott; Austria) for 60 min. After pressing, the test specimens were conditioned in the climatic chamber at an ambient temperature of 20 °C and relative humidity of 55%.

Table 1. Parameters of PVAc and PUR Adhesive

Technical data	AG-COLL 8761/L D3	NEOPUR 2238R
Viscosity (mPa)	5000 to 7000 at 23°C	2000 to 4500 at 25°C
Working time (min)	15 to 20 min	60 min
Density (g/cm^3)	0.9 to 1.1 at 23 °C	*ca.* 1.13
NCO content (%)	-	*ca.* 15.5 to 16.5
Color	white, milk	brown
Open time (min)	15	*ca.* 20 to 25
Dry matter content (%)	49 to 51	100
pH	3.8 to 4.5	-

A total of 160 joints were created. The monitored factors of the joint stiffness were two wood species, two tenon thicknesses, two loading types, and two types of adhesives, creating a total of 16 combinations. For each combination, or set of test samples, were created 10 joints (see diagram in Fig. 5).

Methods

The wood density was determined according to ISO 13061-2 (2014) and Eq. 1,

$$\rho_w = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density of the sample at moisture content w (kg/m^3); m_w is the mass (weight) of the sample at moisture content w (kg); and V_w is the volume of the sample at moisture content w (m^3).

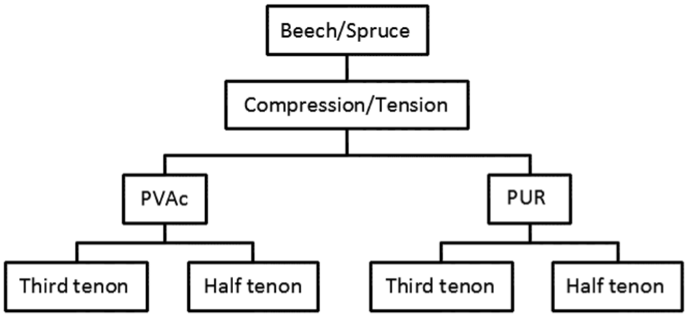


Fig. 5. Categorization of tested joints

The moisture content of samples was determined and verified before and after testing. These calculations were carried out according to ISO 13061-1 (2014).

$$w = \frac{m_w - m_0}{m_0} * 100 \qquad (2)$$

where, w is the moisture content of the samples (%), m_w is the mass (weight) of the sample at moisture content w (kg), and m_0 is the mass (weight) of the oven-dry sample (kg). Drying to oven-dry state was also carried out according to ISO 13061-1 (2014).

Mechanical elastic stiffness test of the corner joint using tensile and compressive stress was evaluated by the universal testing machine TIRA 50 (TIRA system GmbH, Germany). The steel clamp that was used in the work of Podlena and Bořůvka (2016) was also used hereto perform the experiment. Figure 6a shows the experimental testing of the corner joint and its mounting on the device. Figure 6b shows a schematic depiction of the compressive and tensile tests of the corner joint. The perpendicular corner joint is shown in black, whereas the deformed state is shown in purple. The change in distance was recorded between the pins of the device (L → L´), which was used to calculate the angle arcsin function γ'(Podlena and Bořůvka 2016). The change in the angle between the joint rails in degrees was calculated using Eq. 3. From the graph (Fig. 7), the force F (N) was calculated at values ranging from 10% to 40% of the maximum joint strength, which were used to calculate the change in the force ΔF and the difference.The change in moment ΔM (Nm) was calculated according to Eq. 4.

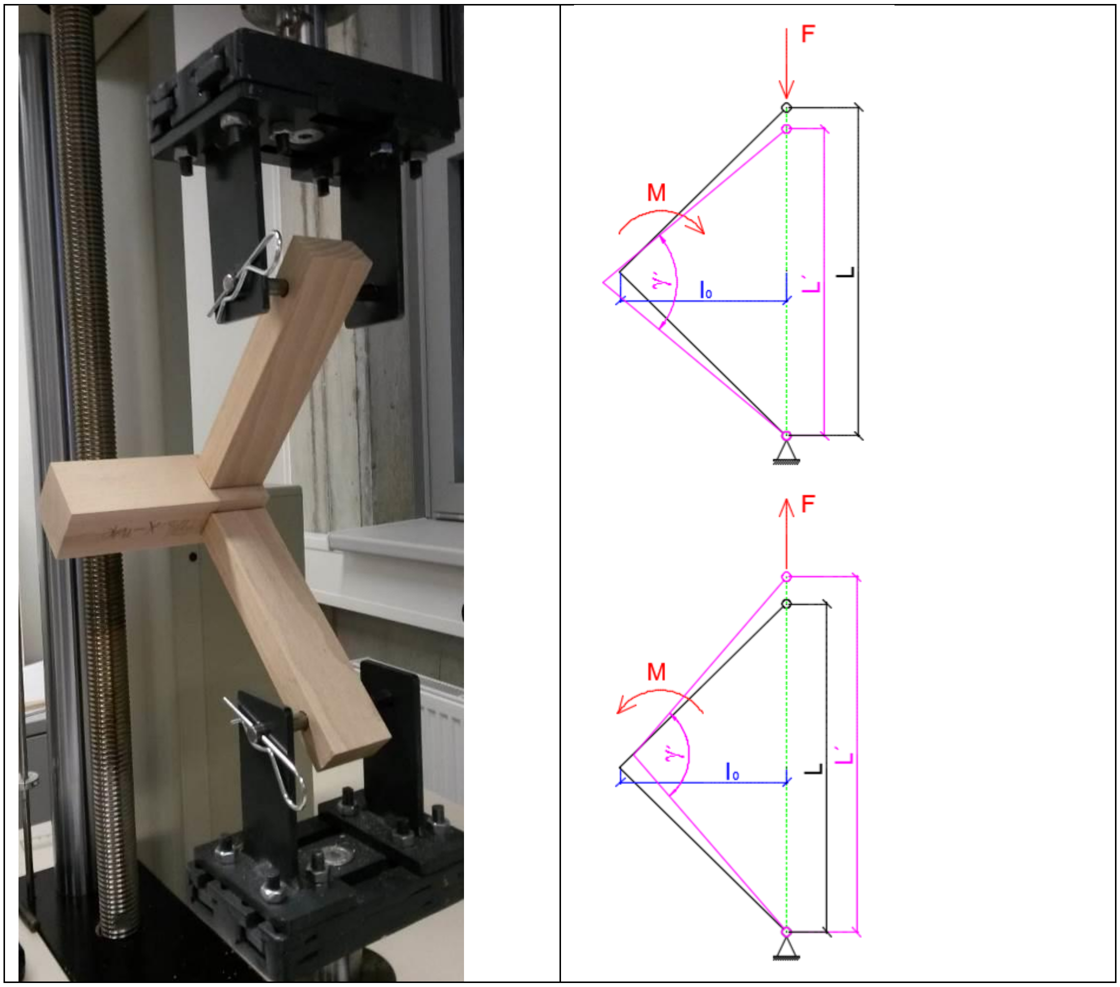
$$\Delta\gamma = 90 \pm \gamma' \qquad (3)$$

$$\Delta M = \Delta F . l_0 \qquad (4)$$

The elastic stiffness c_{elast} (Nm/rad) was calculated as the ratio of the change in moment to the change in angle in radians (Eq. 5).

$$c_{elast} = \frac{\Delta M}{\Delta\gamma} \qquad (5)$$

To determine the influence of the multifactorial analysis and of the individual factors on the elastic stiffness of wood joints, analysis of variance (ANOVA) and mainly the Fischer F-test and correlation analysis were used by employing STATISTICA 12 (Statsoft Inc., USA) software. Based on the P-level value, it was determined whether the monitored factor affected the values on the elastic stiffness of wood joints. The achieved results were processed by the means of diagrams showing a 95 resp. and a 99% confidence interval.



a) b)

Fig. 6. a) Experimental testing; b) schematic depiction of the compressive and tensile stress

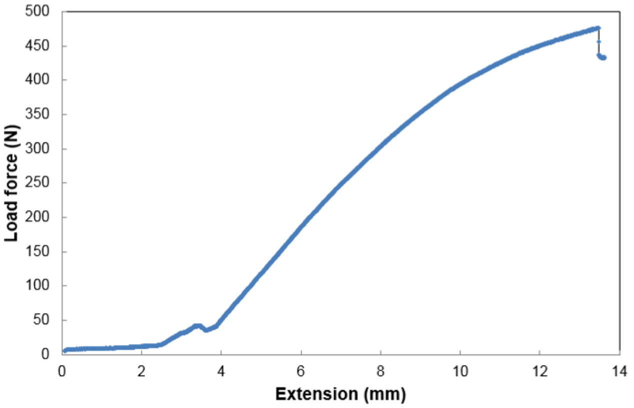


Fig. 7. Work diagram of the spruce joint tensile test

RESULTS AND DISCUSSION

Table 2 shows that the highest average elastic stiffness, 1,627 Nm/rad, was achieved in a beech joint with half-thickness tenons (12 mm) glued with PVAc glue and subjected to tensile stress. The lowest elastic stiffness, 608 Nm/rad,was found in a one-third-thickness tenon (8 mm) made from spruce wood, glued with PUR glue, and subjected to tensile stress. On average, beech joints had a 38% higher value variability than spruce joints.

The average density value of beech wood in the examined joints at 12% moisture content was 0.747 g/cm^3, which is comparable to the results of other authors. Wagenführ (2000) reports a beechwood density at 12% moisture content of 0.720 g/cm^3,whereas Požgaj *et al*. (1993) report 0.712 g/cm^3. The average density of spruce wood examined at 12% moisture content was 0.428 g/cm^3. Požgaj *et al*. (1993) report a spruce wood density at 12% moisture content of 0.421 g/cm^3, and Wagenführ (2000) reported the value of 0.470 g/cm^3. On average, beech joints had 74% higher density values than spruce joints.

Table 2. Basic Statistical Analyses of Density and Elastic Stiffness of Wood Joints (Mortise and Tenon with a Feather)

Type of loading	Wood species	Thickness joint	Type of glue	Density (g/cm^3)			Elastic stiffness (Nm/rad)		
				Mean	Standard deviation	Coefficient of variation (%)	Mean	Standard deviation	Coefficient of variation (%)
Compression	Spruce	Third	PVAc	0.421	0.017	3.9	771	103	13.3
Compression	Spruce	Half	PVAc	0.406	0.025	6.1	763	173	22.6
Compression	Beech	Third	PVAc	0.739	0.014	1.9	952	218	22.9
Compression	Beech	Half	PVAc	0.738	0.010	1.3	1477	158	10.7
Tension	Spruce	Third	PVAc	0.432	0.024	5.7	796	90	11.4
Tension	Spruce	Half	PVAc	0.406	0.021	5.2	714	223	31.3
Tension	Beech	Third	PVAc	0.748	0.010	1.4	1021	268	26.2
Tension	Beech	Half	PVAc	0.735	0.014	1.9	1627	311	19.1
Compression	Spruce	Third	PUR	0.430	0.031	7.1	752	85	11.2
Compression	Spruce	Half	PUR	0.434	0.027	6.1	1052	109	10.4
Compression	Beech	Third	PUR	0.752	0.019	2.5	677	245	36.2
Compression	Beech	Half	PUR	0.739	0.014	1.9	1365	183	13.4
Tension	Spruce	Third	PUR	0.418	0.028	6.7	662	146	22.0
Tension	Spruce	Half	PUR	0.449	0.030	6.7	916	257	28.1
Tension	Beech	Third	PUR	0.740	0.010	1.4	608	195	32.0
Tension	Beech	Half	PUR	0.736	0.008	1.1	998	465	46.6

Table 3 shows the results of the four-factor analysis of variance. The wood species, thickness of joint, and type of glue had a significant effect on the elastic stiffness. The type of loading was not significant. The interaction of all the factors was also insignificant. The significance of the individual combinations of factors is described in detail in Figs. 8, 9, 10 and 11.

Table 3. Multifactor Analysis of Variance for Elastic Stiffness of Wood Joints

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	143456395	1	143456395	2953.590	$P < 0.01$
1 - Type of loading	135726	1	135726	2.794	$P = 0.10$
2 - Wood species	3305097	1	3305097	68.048	$P < 0.01$
3 - Thickness of joint	4465075	1	4465075	91.930	$P < 0.01$
4 - Type of glue	742532	1	742532	15.288	$P < 0.01$
1*2	720	1	720	0.015	$P = 0.90$
1*3	70713	1	70713	1.456	$P = 0.23$
2*3	1906041	1	1906041	39.243	$P < 0.01$
1*4	458867	1	458867	9.448	$P < 0.01$
2*4	1954857	1	1954857	40.248	$P < 0.01$
3*4	216649	1	216649	4.461	$P = 0.04$
1*2*3	5735	1	5735	0.118	$P = 0.73$
1*2*4	127422	1	127422	2.623	$P = 0.11$
1*3*4	76950	1	76950	1.584	$P = 0.21$
2*3*4	302176	1	302176	6.221	$P = 0.01$
1*2*3*4	103108	1	103108	2.123	$P = 0.15$
Error	6994106	144	48570		

Significance was accepted at $P < 0.01$

Table 4 shows the one-factor analysis of variance of the effect of the deflection of annual rings on the elastic stiffness of the joint. According to the level of significance, it can be concluded that the effect of the annual ring deflection on the elastic stiffness of joints was significant.

Figure 8 shows an insignificant effect of the type of loading on the elastic stiffness. Joints subjected to tensile loading had an average of 6% lower values in comparison to joints subjected to compressive loading; however, this difference is insignificant (Table 3).

Figure 9 shows an significant effect of the wood species on the elastic stiffness, which is also confirmed in Table 3. Beech joints had 36% higher elastic stiffness values than spruce joints.

Table 4. One-way Analysis of Variance for Elastic Stiffness of Wood Joints

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	138309425	1	138309425	1081.297	*P*< 0.01
Deflection of annual rings	783805	2	391903	3.064	*P* = 0.05
Error	20081968	157	127911		

Significance was accepted at P < 0.01

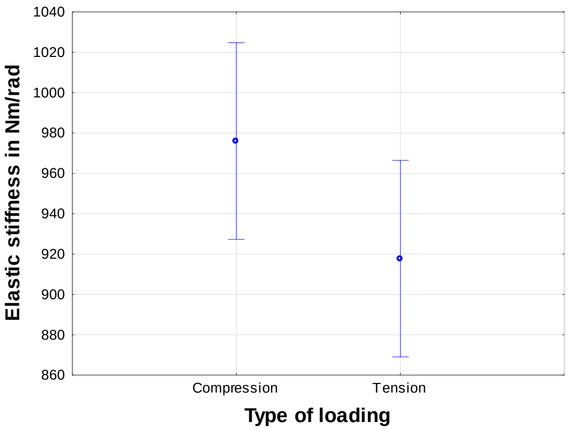


Fig. 8. Influence of loading type on stiffness

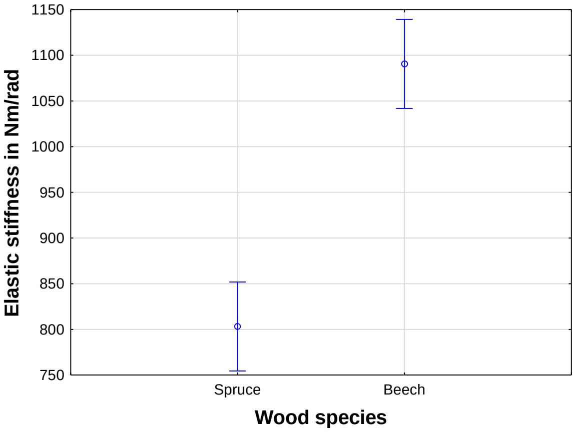


Fig. 9. Influence of wood species on stiffness

The tenon thickness also had a significant effect on the elastic stiffness (Fig. 10, Table 3). Half-thickness tenons (12 mm) had 43% higher stiffness values than one-third-thickness tenons (8 mm). We also recorded a significant effect of the type of adhesive used on the elastic stiffness (Fig. 11, Table 3), where joints glued with PVAc glue had 16% higher values than those glued with PUR glue.

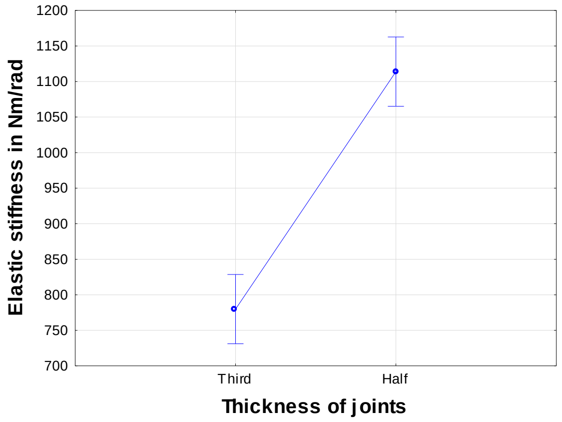


Fig. 10. Influence of thickness joints on stiffness

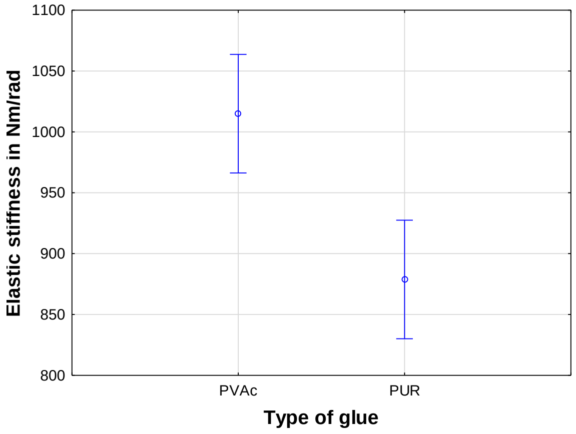


Fig. 11. Influence of type of glue on stiffness

Figure 12 shows a significant effect of the annual ring deflection, at a 0.05 level of significance (Table 4). There was no significant difference between values at about 45° and between 45° and 90°. There was a significant difference between 45° and 90°. The highest stiffness values were recorded at a 90º annual ring deflection. Figure 13 contains a schematic illustration of individual annual ring deflections.

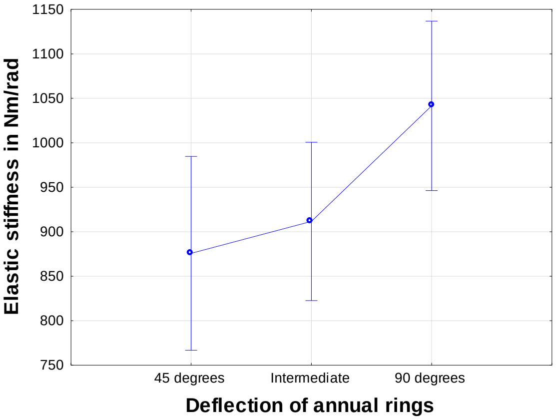


Fig. 12. Influence of deflection of annual rings on stiffness

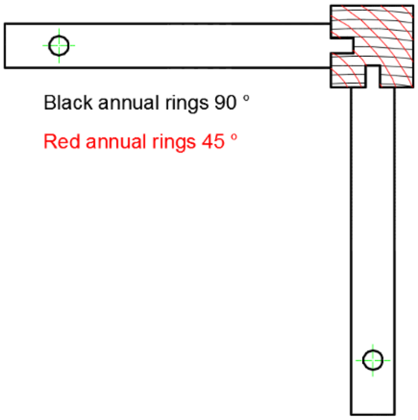


Fig. 13. Schematic illustration of fiber deflection

Figure 14 shows the effect of the interaction of wood species, joint thickness, and type of adhesive on the stiffness. This interaction was on the borderline of statistical significance (Table 3). The graph shows that in a spruce joint glued with PVAc glue there was no significant difference in stiffness between a one-third and half thickness. In all other cases, *i.e.*, in a beech joint glued with PUR and PVAc glue, and a spruce joint glued with PUR glue, the half thickness of the joint results in an increased joint stiffness, and this increase was more pronounced in beechwood (by approx. 68%, compared to 40% in spruce glued with PUR glue). Derikvand and Ebrahimi (2014) experimentally tested mortise and tenon furniture joints from beechwood (*Fagus orientalis* L.) under bending moment. They used two tenon thickness 6 and 8 mm in experiment. They found higher bending moment values for tenon with thickness 8 mm. The trend of higher values of thicker tenons was confirmed also in our research (Fig. 14).

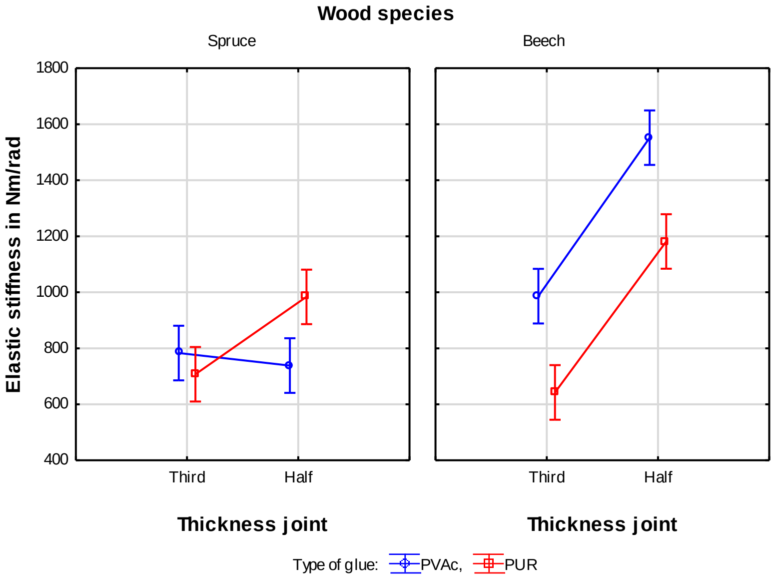


Fig. 14. Influence of interaction of wood species, thickness joint, and type of glue on stiffness

Figure 15 shows that the interaction of the type of loading, wood species, and joint thickness was insignificant (Table 3). The graph shows that in the spruce joint there was not a significant difference in the stiffness between the one-third and half-thickness joint, namely the increase (approx. 14%) is negligible in comparison to the beech joint (approx. 66%). This applies to both types of loading, compressive, and tensile. It was also shown that under tensile stress, there was a greater susceptibility of PUR glue to partially leak (foam) out of the joint, resulting in unfilled spaces in the glued joint.

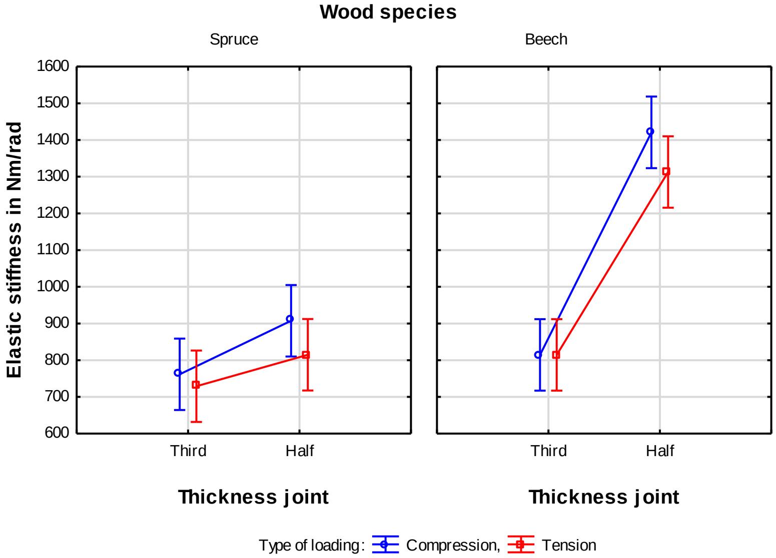


Fig. 15. Influence of interaction of wood species, thickness joint, and type of glue on stiffness

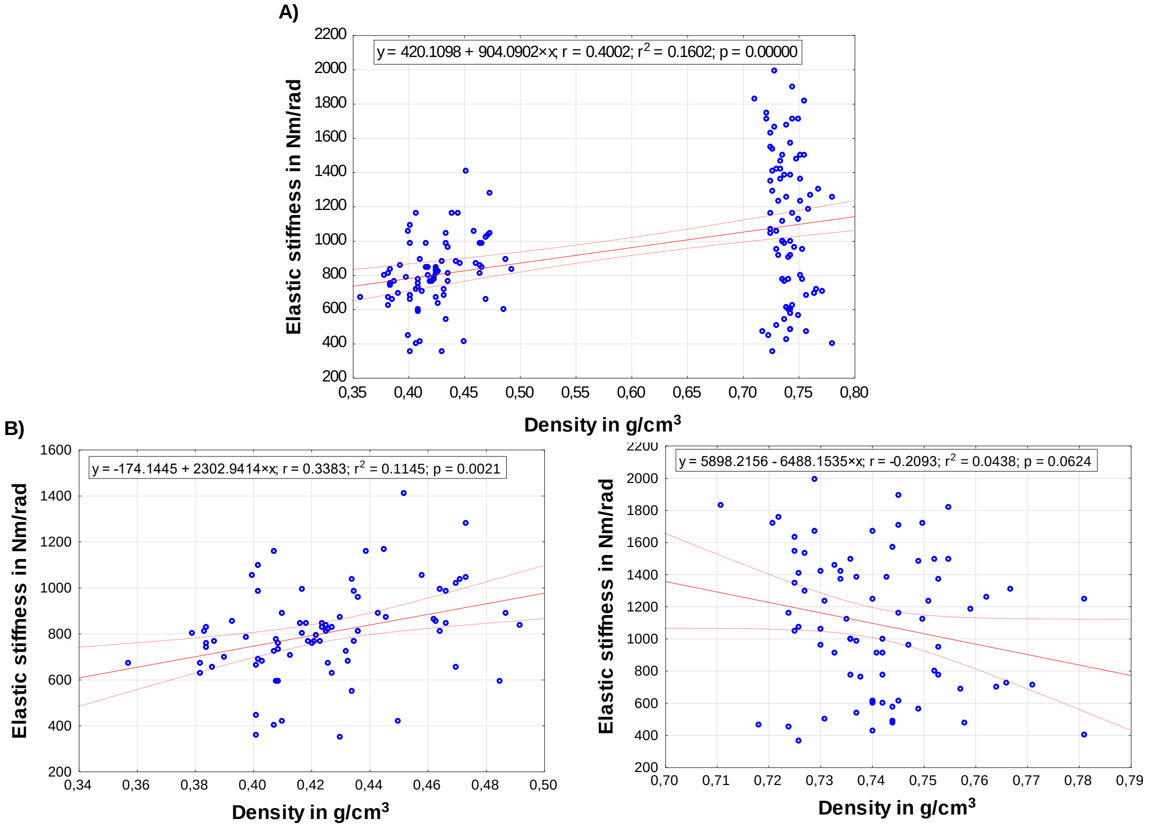


Fig. 16. Dependence of elastic stiffness on density for (A) wood joints, (B) only spruce joints, and (C) only beech joints

The graph of the correlation between density and elastic stiffness clearly points to a higher variability in beechwood, and a positive effect of higher density was only observed in spruce wood; it was not significant in beechwood (Fig. 16). The effect of density is only relevant when different wood species are compared, and not within the same wood species; the annual ring deflection has a more significant effect, which we will examine in more detail in future research.

To confirm the fact that we may only consider the elastic stiffness of joints, Fig. 17 shows the correlation between the elastic stiffness and the stiffness under maximum load. We can see a fairly good dependency from the results of the correlation, *i.e.*, the correlation coefficient of linear dependence is 0.73. This means that the overall strength (stiffness) can be derived only from the elastic stiffness, which is the realistic stress level of structural furniture joints.

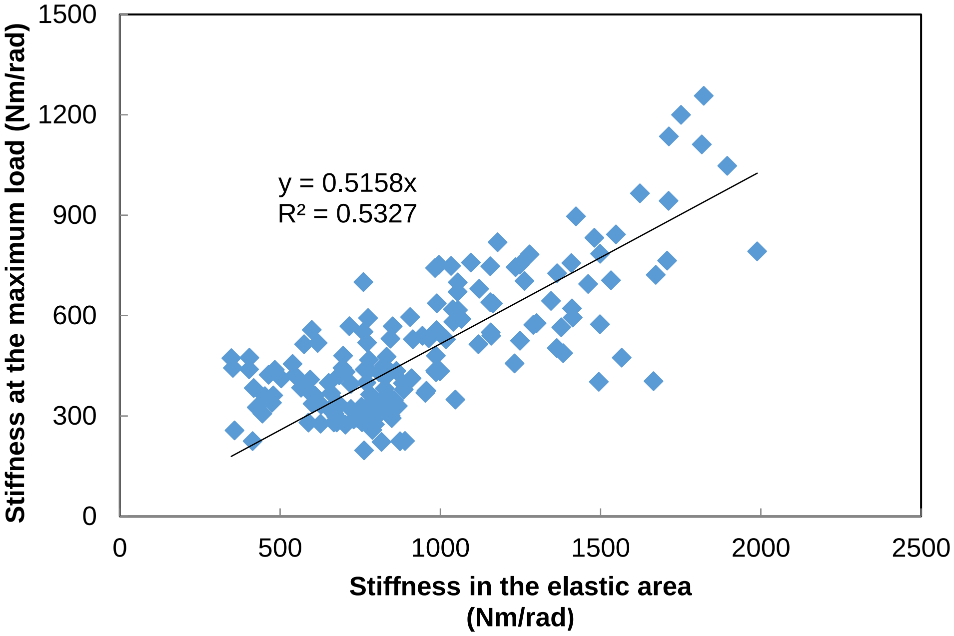


Fig. 17. Dependence of elastic stiffness on stiffness at the maximum load

Comparison with other literature is not easy, because the dimensions, sizes of cross-sections, individual elements, and the proportionality of the joint are not the same. For example, authors Tsioukas *et al.* (2015) experimentally tested a beechwood (*Fagus silvatica* L.) corner joint in their research; the joint consisted of a mortise and tenon, where they combined PVAc and PUR adhesives. Under tensile stress they found 7% higher values with PVAc glue than with PUR glue. The trend of higher levels using PVAc glue was also demonstrated in our research (Fig. 14). Kasal *et al.* (2016) experimentally tested a beechwood (*Fagus orientalis* L.) corner joint from mortise and tenon glued with PVAc adhesive. They mentioned stiffness of L-shaped joints 1,235 Nm/rad for tenon 30 x 30 mm (width x length). This value is similar with our stiffness1,021 Nm/rad of third tenon loaded in tension and glued with PVAc adhesive. In future research, the authors want to focus on a simpler and more precise version of a tenon corner joint, the results of which will be compared with the current results.

CONCLUSIONS

1. The following factors had the most significant effect on the elastic stiffness: wood species, joint thickness, and type of adhesive. The type of loading was an insignificant factor. The annual ring deflection was on the borderline of statistical significance.
2. The joint thickness and type of adhesive were clearly more significant in beech joints than in spruce joints.
3. Focusing on the fiber deflection proved to be a good decision, because the joint stiffness depended on it, and it had a greater effect than the actual density of the material used. In future research it would be appropriate to evaluate this factor in more detail.
4. In wood species with a more homogeneous structure (beech), the benefit of a half-thickness tenon was demonstrated more significantly in comparison to wood species with significant differences between spring and summer wood (spruce).
5. The correlation analysis basically confirmed that it is enough to load the joint in the elastic range during mechanical tests. Not only the stiffness, but the overall strength of the joint can be derived from the elastic stiffness.

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