Effect of Selected Factors on Stiffness of Dowel Joints

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Furniture must be designed to suit the intended use. Producers need to guarantee its quality and stiffness. During external loading, there are internal forces that can be transmitted and may result in a failure. This article examines the dowel joint, which is one of the most popular furniture joints. It discusses the effects of selected parameters, such as type of loading (tension and pressure), the size of the dowel (one-half or one-third of the joined parts), wood species [beech (*Fagus sylvatica* L.) and spruce (*Picea abies* L.)], and the adhesives type (polyvinyl acetate and polyurethane), on the joint stiffness. The effect of the annual rings was also monitored; however it was not determined as significant. Based on the results, the dowel joint is recommended with greater diameters and while using PVAc gluing. Article also deals with test simulation in virtual environment using the programme Solidworks.

Keywords: Furniture wood joints; Dowel; Loose tenon; Elastic stiffness

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INTRODUCTION

Joints are one of the most important components in furniture production. These elements significantly affect the overall behavior of the structure of the joined components (Hajdarevic and Martinovic 2014). Joints as such can be classified as critical elements of furniture structures due to the relatively low effectiveness of the joint (Joščák 1999). One of the most important aspects in considering and designing wooden structures and furniture is selecting a joint type that will guarantee the required structural properties (Záborský *et al.* 2017a,b). With a suitable type of joint, it is possible to achieve considerable simplification of the structure itself and improve its integrity (Sabareth 2014; Svoboda *et al.* 2015).

Dowel joints are currently one of the most commonly used types of structural joints (Segovia and Pizzi 2012; Tas *et al.* 2014). These joints have a great advantage in terms of the economy and the ratio of production difficulty to the resulting joint properties. Today, there is a wide range of the dowels themselves, varying in diameter, length, and surface treatment (Nutsch *et al.* 2006). Dowel joints can be defined by several different characteristics (Eckelman 2003), of which the elastic stiffness of the joint is very important. Furniture joints generally exhibit nonlinear behavior, unlike separate joining elements, which classifies this type of joint as a semi-rigid joint (Eckelman and Havierova 2011). The semi-rigidness of the joint essentially expresses the possibility of the formation of an angle of rotation under the influence of a load force. Once the load force is removed, the angle of rotation also disappears, returning the joint to its original state (Nicholls and Crisan 2002).

The elastic stiffness of a joint can be influenced by several factors (Masui *et al.* 2013). In this article, the authors focused on several important factors that affect the elastic stiffness of dowel joints, such as the type of load, joint thickness, type of adhesive used, annual ring deflection, and finally the type of bonded wood or composite material. The significance of the type of load and total load force is quite a topical issue, and it was also addressed by Uibel and Blaß (2007). In terms of geometric parameters, the thickness of the joint itself is a very important factor (O'Loinsigh *et al.* 2012). It is generally known that better joint stiffness is generally achieved with a thicker joint, but this fact is also influenced by other factors, particularly the type of adhesive used. The importance of choosing the right type of adhesive was pointed out by Tankut (2007). The research of Tas (2010) concerned corner and L-shaper corner joints while using dowels with three types of glue. His research showed that in order to increase the quality and life span of the furniture, he suggested the use of L shaped corner joints while using the silicon based glue. Duncan test comparisons of load types in this research indicated that tension loading values were two times greater than compression loading values. The same author (Tas 2010) investigated, both theoretically and empirically, the behavior of a bookcase loaded under moment forces. He loaded the test samples with tension and compression. As a conclusion, in order to use YL-Lam bookshelf and similar wooden pieces after a low-magnitude earthquake, he advised to use polyurethane as binder if treenail and composite are used as the joint during the production stage. In case of the use of screw type joints, he advised the use of polyurethane and silicone binders.

The aim of this article is to determine the elastic stiffness of beech rail to leg joints under the influence of the above-mentioned factors. The testing samples were loaded by bending moment (Fig. 5) with tensile and compressive forces in the angular plane. Beech wood dowels with a diameter of 8 mm and 12 mm were used as the joining element. Regarding the use of the joints, they were compared with traditional constructional joints.

EXPERIMENTAL

Wooden Materials used in Experiment

Beech wood (*Fagus sylvatica* L.) was used to make the experimental specimens of a rail to leg dowel joint (Polana, Zvolen, Slovakia). Table 1 shows average mechanical properties of the used wood given from the literature (Požgaj 1997; Wagenführ 1985; Dinwoodie 2010).

Table 1. Mechanical Properties of *Fagus sylvatica* L.

Mechanical Property	Units	Beech Wood
Average Dried Weight	g/cm^3	710
Janka Hardness	N	6460
Modulus of Rupture	MPa	103-110
Elastic Modulus	MPa	10 000-18 000
Crushing Strength	MPa	57

Preparation of Samples

A schematic depiction of the tested joints is shown in Fig. 1. The cutting was performed at a moisture content of 10%, relative humidity of 55%, and at a temperature of 20 °C. The moisture content of the test specimens corresponded with the moisture content of furniture elements according to EN 942 (2007) and ČSN 91 0001 (2007). The specimens for mechanical testing were made from dried lumber using woodworking machines at a vocational school in Spišská Nová Ves (Slovakia).

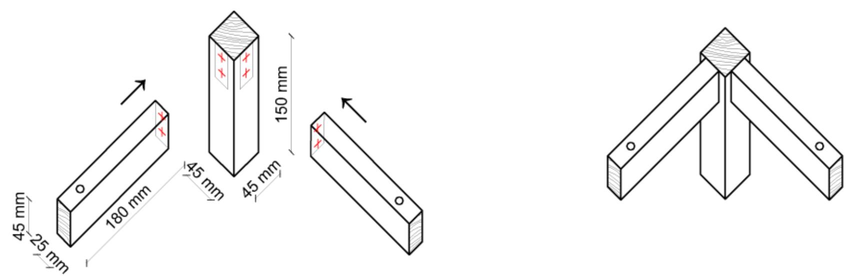

Fig. 1. Schematic depiction of the sample preparation

Beech wood dowels with a diameter of 8 mm and 12 mm were used as the joining elements. Holes for the dowels were drilled into the prepared rails and legs using 8-mm and 12-mm drill bits. Joints with 8-mm dowels corresponded with a joint thickness that was 1/3 the thickness of the rail, and 12-mm dowels corresponded with a joint thickness that was 1/2 the thickness of the rail. The location of the dowels and their dimensions can be seen in Figs. 2A, 2B, and 2C.

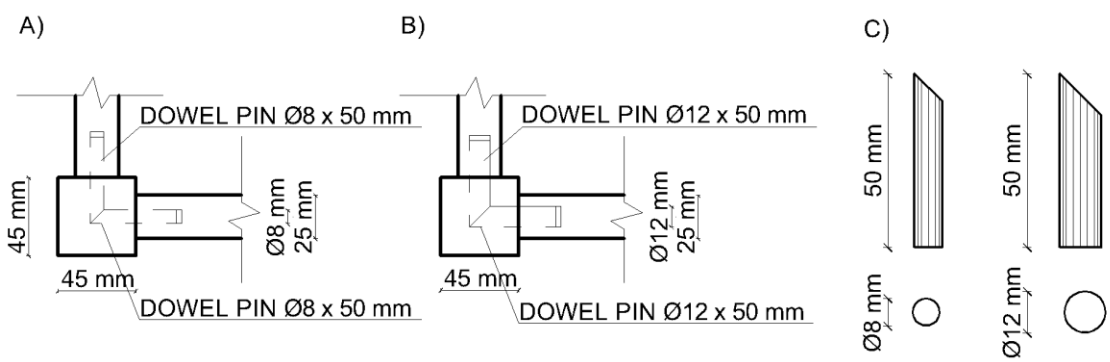

Fig. 2. A) Schematic depiction of the location of the dowels (C) 8 mm and 12 mm), and B) detailed view of the dowels used and their dimensions

Gluing

The joining elements were glued with two types of adhesives: single-component, waterproof polyvinyl acetate adhesive (PVAc) AG-COLL (EOC, Oudenaarde, Belgium) 8761/L D3 (EOC, Oudenaarde, Belgium), and single-component polyurethane adhesive (PUR) NEOPUR 2238R (NEOFLEX, Madrid, Spain). Detailed parameters of these adhesives are given in Table 2. The adhesives were applied manually to the holes in a single-sided coating of 150 g/m^2 to 180 g/m^2 for PVAc, and 180 g/m^2 to 250 g/m^2 for the PUR adhesive. The test specimens were cold pressed in manual clamps. After the pressing, the samples were conditioned in a climatic chamber at 20 °C and at a relative humidity of 55% one month.

Table 2. Parameters of the PVAc and PUR Adhesives

Technical Data/ Adhesive	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	60
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, milky	Brown
Open time (min)	15	*ca.* 20 to 25
Dry matter content	49 to 51	100
pH	3.8 to 4.5	-

Figure 3 shows a schematic depiction of the annual ring deflection. In this study, the authors investigated the effect of three types of annual ring deflection, namely 45°, 45° to 90°, and 90°.

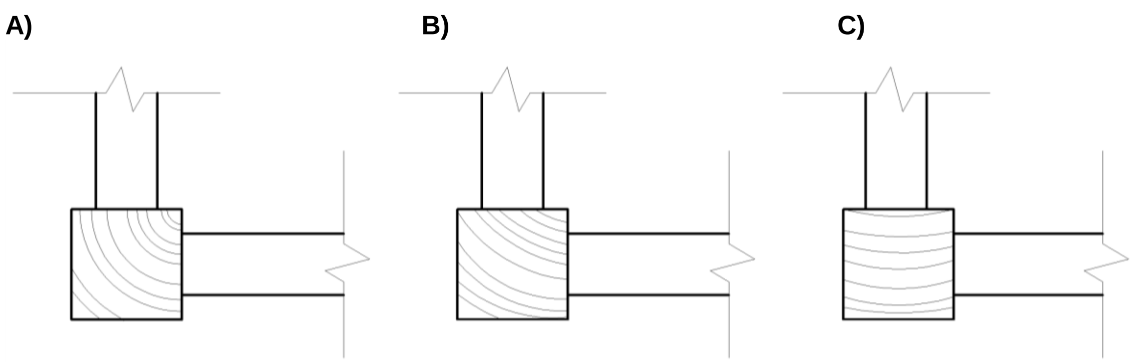

Fig. 3. Schematic depiction of annual ring deflection: A) 45°, B) 45° to 90°, and C) 90°

Table 3 shows a categorization of all tested joint types. A total of 80 joints were created, and the monitored factors affecting the elastic stiffness were two joint thicknesses (1/2 and 1/3), two types of loading (compressive/tensile), two types of adhesives used (PVAc and PUR). For each monitored factor, 10 joints were created. The study also tracked three basic annual ring deflection angles (45°, 45° to 90°, and 90°), but this information was classified separately.

Table 3. Categorization of Monitored Factors of Tested Samples

Type of Loading	Glue Type	Size of Dowel	Annual Ring Deflection
- Compression - Tension	- PVAc - PUR	- Ø12 mm (1/2 joint thickness) - Ø8 mm (1/3 joint thickness)	- 45 - (45-90) - 90

Methods

The moisture content of the samples was determined and verified before and after testing. These calculations were done according to the ISO 13061-1 (2014) standard. The wood density was determined according to the ISO 13061-2 (2014) standard.

Drying to oven-dry state was also conducted according to ISO 13061-1 (2014). The mechanical elastic stiffness of the rail to leg joints were evaluated under diagonal tension and compression loadings using a universal testing machine TIRA 50 (TIRA System GmbH, Schalkau, Germany). The steel clamp that was used in the work of Podlena and Borůvka (2016) was also used in this study to perform the experiment.

Figure 4A documents the mounting on the test sample device in the machine. Figure 4B and 4C show a schematic depictions of the compression (A) and tension (B) loadings of the rail to leg dowel joints. The joint before loading is shown in black, whereas the deformed state after loading is shown in blue and green. The change in distance was recorded between the dowels of the device ($L \rightarrow L'$), which was used to calculate the angle arc-sin function γ' (Podlena and Borůvka 2016). The change in the angle between the joint rails in degrees was calculated using Eq. 1,

$$\Delta\gamma = 90 \pm \gamma' \tag{1}$$

$$\Delta M = \Delta F . l_0 \tag{2}$$

where ΔF represents the difference between the two forces (N) that was recorded in the stress-strain diagrams (Fig. 4) at 10% to 40% of the maximum joint strength, and l_0 represents the vertical arm (mm) of the tested joint in the direction of the loading force.

The elastic stiffness, c_{elast} (Nm/rad), was calculated according to Eq. 3 as the ratio of the change in torque to the angular displacement in radians:

$$c_{elast} = \frac{\Delta M}{\Delta \gamma} \tag{3}$$

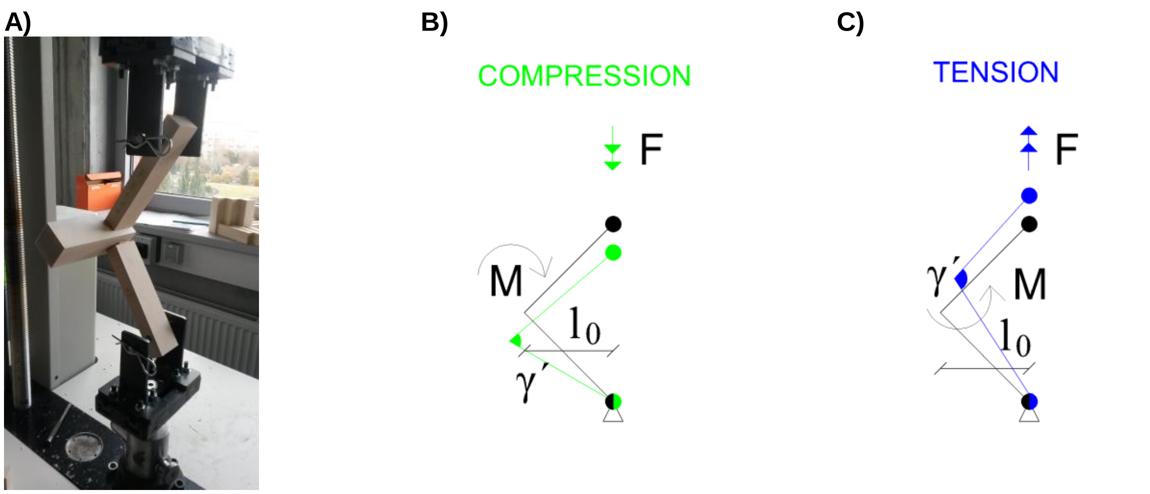

Fig. 4. A) Picture of the experimental while testing; B) schematic depiction of the compression loading; C) schematic depiction of the tension loading (where the original shape is depicted in black and the deformed shape is depicted in blue and green)

Figures 5A and 5C show the real stress-strain curve during the tensile loading of joints with a 1/2 and 1/3 joint thickness. Figures 5B and 5D show the real stress-strain curve during the compression loading of joints with a 1/2 and 1/3 joint thickness.

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

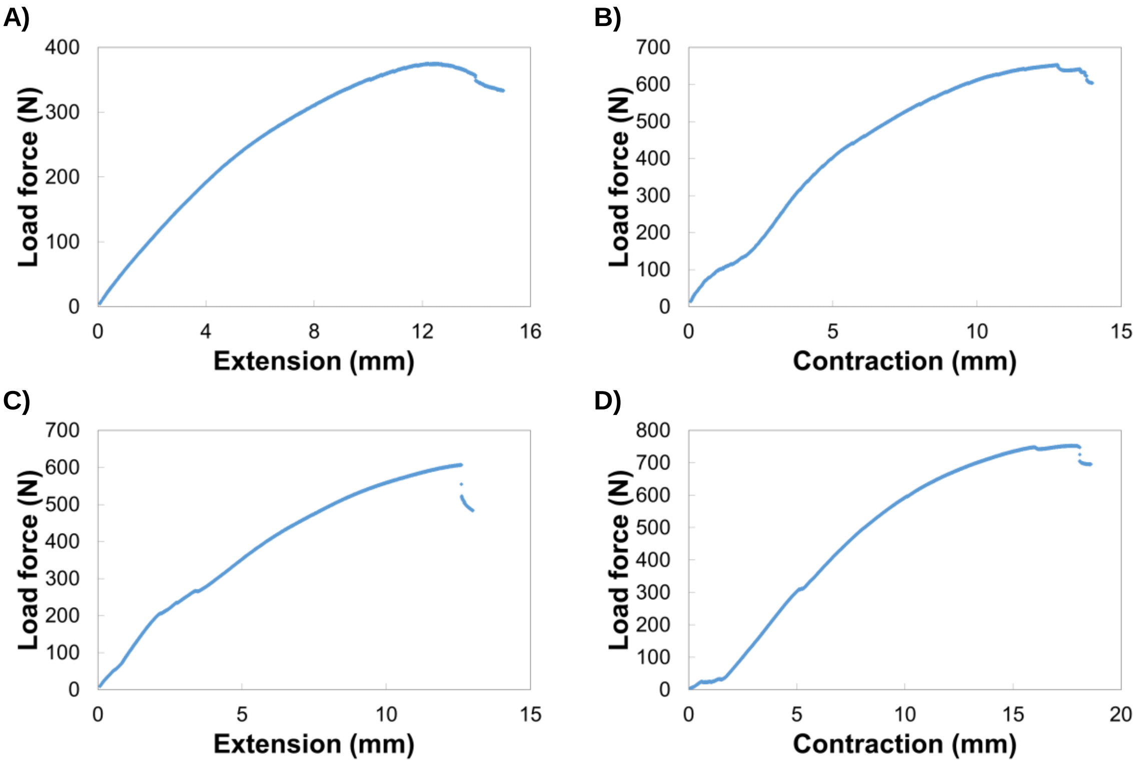

Fig. 5. Course of the stress-strain diagram: A) during tension loading of a joint with 8-mm dowels; B) during compression loading of a joint with 8-mm dowels; C) during tension loading of a joint with 12-mm dowels, and D) during compression loading of a joint with 12-mm dowels

SIMULATIONS

Simulations were performed using SolidWorks (SolidWorks 11, Waltham, MA, USA) to compare the authors' findings. A computer-generated model in the simulated SolidWorks environment can be seen in Fig. 6A.

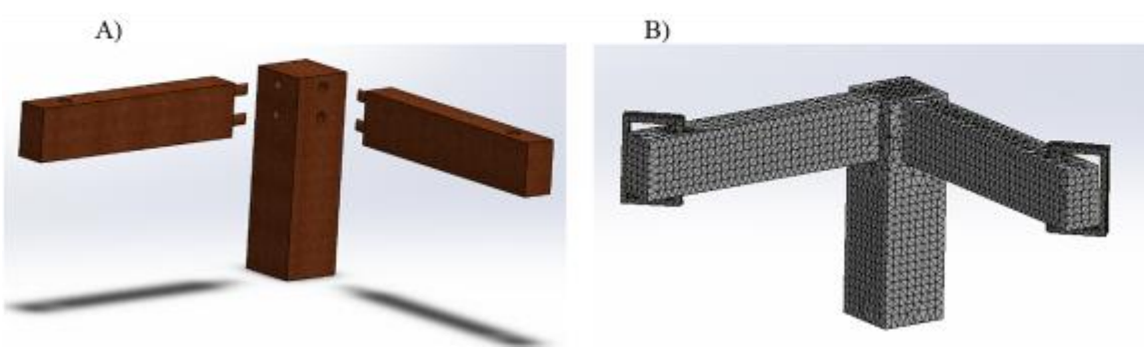

Fig. 6. A) Dowel joint model and B) finite element network on the model

This rail to leg dowel joint was defined as a general joint in the simulation, unlike the model in a previous article (Kasal *et al.* 2016), in which a shaped separate adhesive film was used to simulate the corner joint. In the version selected in the current study, the program assumes that the bodies are glued without having to shape and define the adhesive film.

After the model was created, it was necessary to create a finite element network, which is an essential part of the simulation of the deformation and strain (Tran *et al.* 2015). However, this shaping method is not perfect because its interface focuses on high gradients in a weak extent due to the layers (Duong *et al.* 2011). SolidWorks can design a finite element network to suit the subsequent simulation. To perform the load simulation, it was necessary to select the applied force. In the case of tested rail to leg dowel joints, a load force of 225 N was chosen. The created finite element network is shown in Fig. 6B.

For the simulation to work properly, the values of the selected properties of the material used must be entered into the program. Because the simulation did not take into account the adhesive film, only the beech wood values were entered into the program, which were taken from previous literature (Požgaj *et al.* 1997; Dinwoodie 2010). These values are listed in Table 4. Due to the absence of previous literature, the yield limit of the beech wood was estimated.

Table 4. Selected Material Properties Used to Simulate the Joint Loading

Selected Material Properties		
Density (12% moisture)	ρ12 (kg/m^3)	750
Compressive strength	σtl‖ (MPa)	56.7
Compressive strength	σtl⊥R (MPa)	12.9
Compressive strength	σtl⊥T (MPa)	8.5
Tensile strength	σt‖ (MPa)	133.5
Tensile strength	σt⊥R (MPa)	3.4
Tensile strength	σt⊥T (MPa)	4.4
Shear strength	τLR‖ (MPa)	12.6
Shear strength	τLT‖ (MPa)	15.1
Shear strength	τLR⊥ (MPa)	14.2
Modulus of elasticity	EtlL (MPa)	13,700
Modulus of elasticity	EtlR (MPa)	2,240
Modulus of elasticity	EtlT (MPa)	1,140
Shear modulus of elasticity	GLR (MPa)	1,610
Shear modulus of elasticity	GLT (MPa)	1,060
Shear modulus of elasticity	GRT (MPa)	460
Yield strength	σk (MPa)	90
Poisson number	μRL (-)	0.45
Poisson number	μTL (-)	0.51
Poisson number	μTR (-)	0.75
Poisson number	μLR (-)	0.073
Poisson number	μRT (-)	0.36
Poisson number	μLT (-)	0.044

RESULTS AND DISCUSSION

Table 5 shows the values of a basic statistical analysis of the density and elastic stiffness of beech joints. The elastic stiffness was measured while monitoring factors such as the type of stress, joint thickness, type of adhesive used, and annual ring deflection. The elastic stiffness values are listed as averages, as well as the standard deviation and the coefficient of variation. When comparing beech dowel joints with haunched mortise-tenon beech joints (Záborský *et al.* 2017a), the elastic stiffness values were approximately 16% lower. The same tendency of the effect of the joint thickness was confirmed, *i.e.*, in comparison with the one-third thickness, the half-thickness had a significantly positive effect in both types of joints. The effect of the type of stress in both types of joints was not confirmed. Unlike a mortise and tenon joint, the type of adhesive had no significant effect on the dowel joint, *i.e.*, there was only a statistically significant decline when the PUR adhesive was used during tension loading, while a significant effect was demonstrated in a mortise and tenon joint even under compression loading. It can be concluded that there was not much difference between these types of joints.

Table 5. Basic Statistical Analyses of Density and Elastic Stiffness of Wood Joints

Type of Loading	Joint Thickness	Glue Type	Density (g/cm^3)	Elastic Stiffness (Nm/rad)
Compression	Third	PVAc	0.699 (2.9)	546 (44.0)
Compression	Half	PVAc	0.699 (1.5)	1148 (13.9)
Compression	Third	PUR	0.708 (1.6)	724 (29.9)
Compression	Half	PUR	0.697 (2.5)	1174 (19.5)
Tension	Third	PVAc	0.692 (2.3)	867 (49.0)
Tension	Half	PVAc	0.696 (2.2)	1287 (34.5)
Tension	Third	PUR	0.687 (1.8)	685 (19.7)
Tension	Half	PUR	0.689 (2.5)	1093 (20.7)

Note: Values in parentheses are coefficients of variation (CV; %)

After comparing the significance level of individual factors "P," it can be said that a statistically significant effect was only found for the joint thickness. This finding is documented in Table 6 (Fig. 7).

Table 6. Multi-factor ANOVA for the Elastic Stiffness of Wood Joints

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher´s F-test	Significance Level
Intercept	70783375	1	70783375	845.941	P < 0.01
1 - Type of loading	144924	1	144924	1.732	P = 0.19
2 - Joint thickness	4411343	1	4411343	52.721	P < 0.01
3 – Glue type	37317	1	37317	0.446	P = 0.51
1*2	63174	1	63174	0.755	P = 0.39
1*3	418984	1	418984	5.007	P = 0.03
2*3	33888	1	33888	0.405	P = 0.53
1*2*3	24764	1	24764	0.296	P = 0.59
Error	6024535	72	83674		

Note: Significance was accepted at $P < 0.01$

Table 7 shows the level of significance "P" for the effect of the annual ring deflection. The effect of the annual ring deflection was found to be statistically insignificant, but the lowest stiffness variability was clearly confirmed at a deflection of approximately 90°.

Table 7. One-way ANOVA for Elastic Stiffness of Wood Joints

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	22705066	1	22705066	157.763	P < 0.01
Deflection of annual rings	77177	2	38589	0.2681	P = 0.77
Error	11081752	77	143919		

Significance was accepted at P < 0.01

As shown in Fig. 7, where the effect of all the monitored factors on the elastic stiffness of the wood joint is shown, it was clear that the joint thickness was the most important factor (Fig. 7B). The half-thickness joint exhibited approximately 66.6% higher stiffness values compared to the one-third thickness (this increase was most notably demonstrated in joints subjected to compressive stress and bonded with PVAc adhesive). In the case of the type of loading and type of adhesive (Figs. 7A and 7C), the differences were not as great, as the statistical evaluation demonstrated.

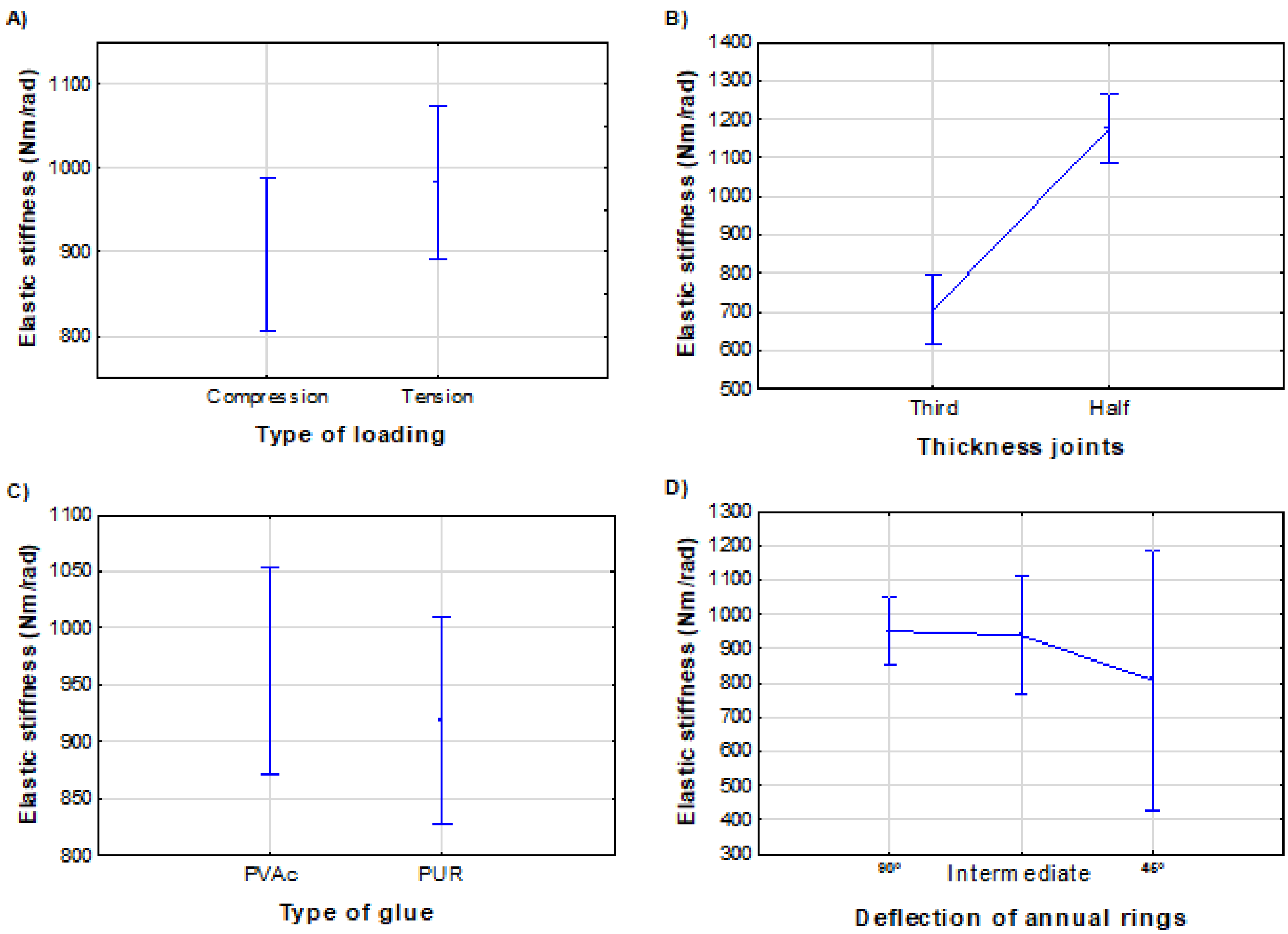

Fig. 7. Graphic visualization of the effect of the A) type of loading, B) joint thickness, C) type of glue, and D) deflection of annual rings on the elastic stiffness

On average, the elastic stiffness values were only approximately 9.3% higher under tensile stress than under compressive stress. There were also very small differences between the PVAc and PUR adhesives. The PVAc adhesives only achieved values that were approximately 4.7% higher.

Figure 8 shows a graphical representation of the effects of the selected monitored factors on the elastic stiffness of the joint. In the first case (Fig. 8A), the combined effect of the joint thickness and the selected type of stress is shown. It was demonstrated that half-thickness joints exhibited significantly higher elastic stiffness values under compressive stress as well as tensile stress. In the case of compressive stress, half-thickness joints achieved an average of 82.8% higher values in comparison with one-third thickness joints, and in the case of tensile stress, the half-thickness joints achieved an average of 53.3% higher values in comparison with values obtained in the samples with a one-third joint thickness.

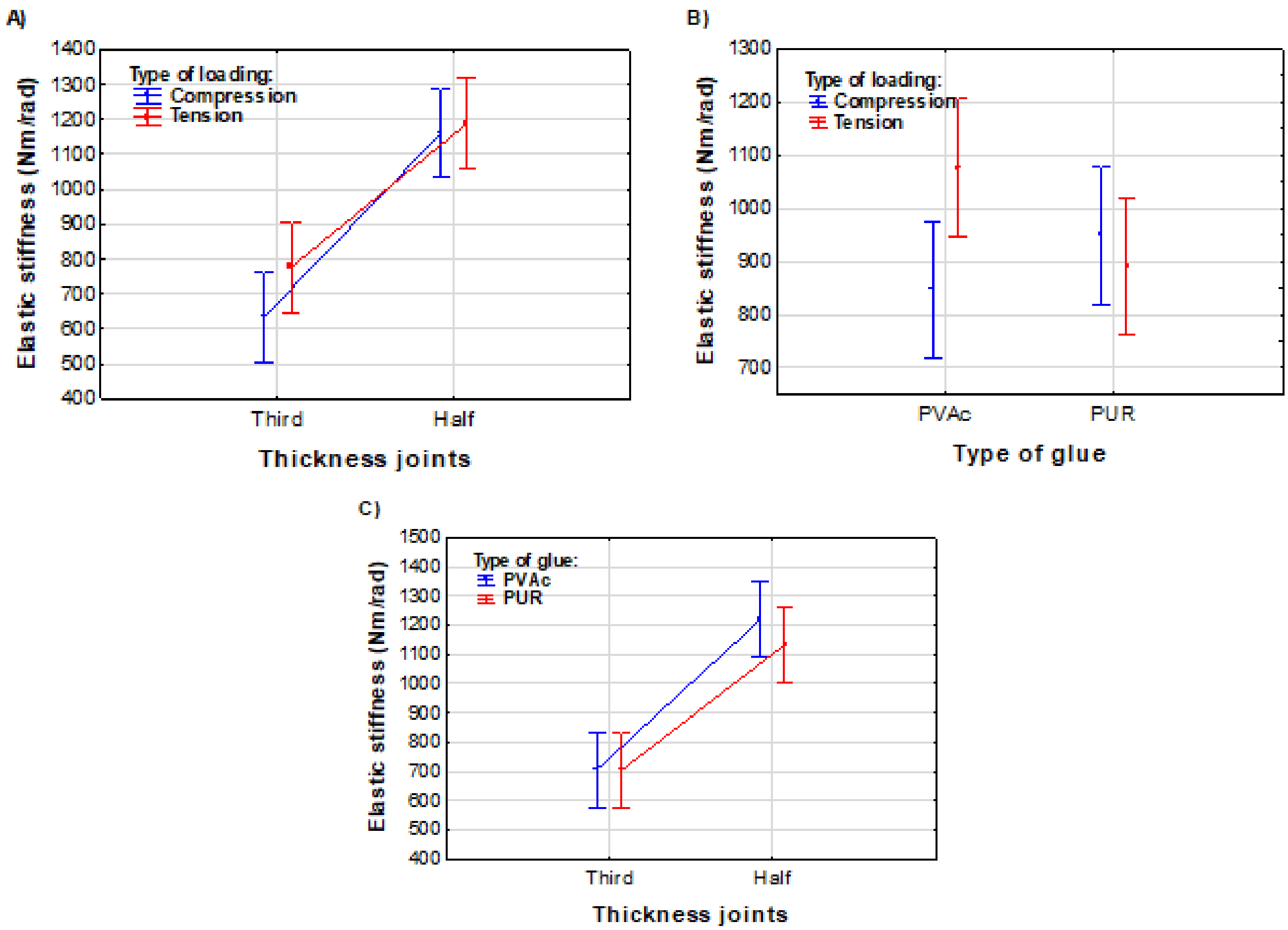

Fig. 8. Graphical visualization of the effect of the joint thickness and type of loading (A), type of glue and type of loading (B), and joint thickness and type of glue (C), on the elastic stiffness

The statistically significant difference between elastic stiffness values when PVAc adhesive was used, with respect to the type of stress, is noteworthy (Fig. 8B). In this case, the elastic stiffness of the joint subjected to tensile stress was approximately 27.1% higher than when subjected to compressive stress. Conversely, when the joints were bonded with PUR adhesive, the change in the elastic stiffness was the opposite. In this case, joints subjected to compressive stress achieved an average of 8.5% higher elastic stiffness values than those obtained when they were subjected to tensile stress. The difference in elastic stiffness between joints bonded with PVAc and PUR adhesive with a one-third thickness joint was practically negligible, close to 0.3% (Fig. 8C). However, in the case of a half-thickness joint, the difference was more significant; in this case the joints glued with PVAc glue achieved approximately 7.4% higher elastic stiffness values than joints glued with PUR glue.

Figure 9 illustrates the synergistic effect of all three main monitored factors that affect the elastic stiffness of the joint. As shown, with the use of PVAc glue and tensile stress, the average elastic stiffness of the joint was higher than in the case of the average values obtained with compressive stress. In contrast, this trend was the opposite when PUR glue was used. When comparing the average elastic stiffness values obtained from the one-third thickness joints under compressive stress, the authors found that when PUR adhesive was used, they achieved average elastic stiffness values that were 32.6% higher than in the same type of joint glued with PVAc adhesive. In contrast, when subjected to tensile stress, this type of joint exhibited higher values when PVAc adhesive was used; the average values were approximately 21% lower than in the same type of joint glued with PUR adhesive. In the case of half-thickness joints, the differences in average elastic stiffness values were not as significant as in the previous case. The smallest difference was found under compressive stress, and with the use of PUR adhesive, 2.6% higher average values were obtained in comparison with the average values obtained with PVAc adhesive, which is a very negligible difference. A greater difference was found in the case of joints subjected to tensile stress. In this case, the joints bonded with PUR adhesive exhibited approximately 15.1% lower average elastic stiffness values in comparison with joints bonded with PVAc adhesive.

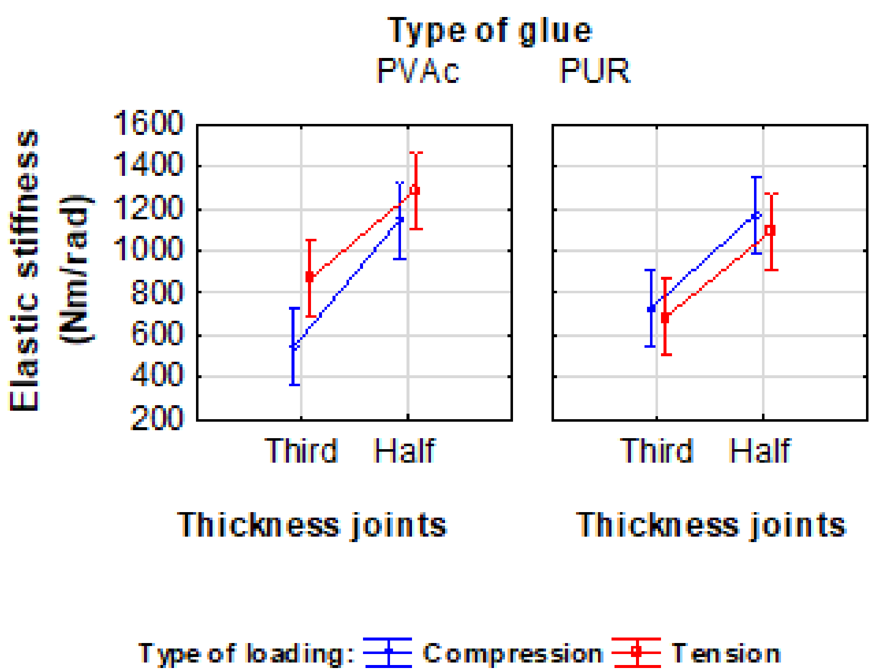

Fig. 9. Graphic visualization of the synergistic effect of the type of glue, thickness joints, and type of loading on elastic stiffness

Figure 10 shows a graph of correlation between the elastic stiffness of the joint and the density, which indicated that this dependence was relatively low. This dependence was expressed by correlation coefficient *r*, which reached a value of 0.02.

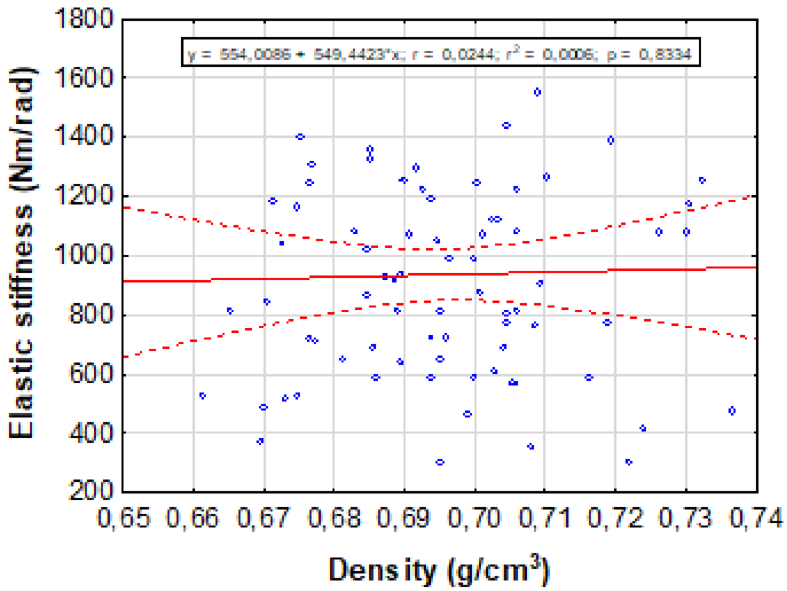

Fig. 10. Dependence of the stiffness at maximum load on the elastic stiffness of beech wood joints

Figure 11 shows that there was a linear dependence between the elastic stiffness and stiffness at maximum load (r = 0.26), which means that the maximum joint stiffness can also be poorly predicted based on the elastic stiffness. There was also a relatively large variance of values and occurrence of extremes.

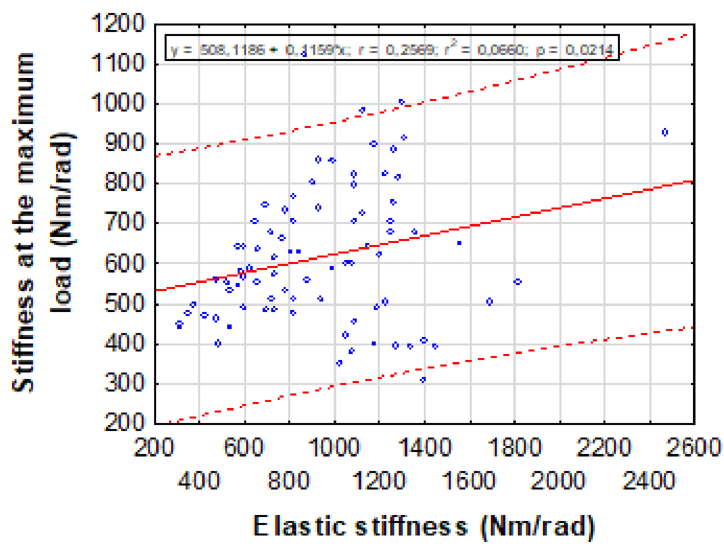

Fig. 11. Dependence of the stiffness at maximum load on the elastic stiffness of beech wood joints

Figure 12 shows a linear dependence between the density and annual ring width (r = 0.54). Diaconu *et al.* (2016) reported a significant but very slight effect of the annual ring width on the density of beech wood. This effect can also be seen in the results of this article in Fig. 11, showing the dependence of the density on the annual ring width. There was a slight increase in density as the annual ring width increased. The correlation coefficient of the linear dependence was 0.5432, which indicated a slight dependence.

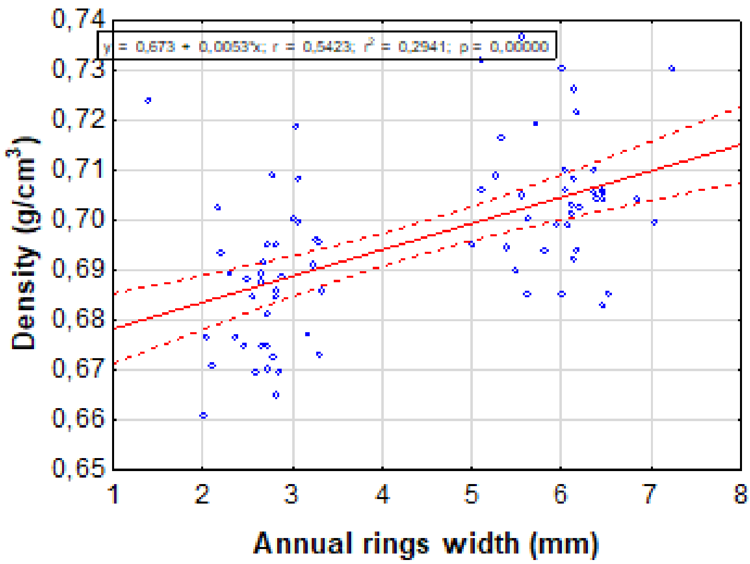

Fig. 12. Dependence of the density on the annual ring width in wood joints

SIMULATION RESULTS

In a simulation of tension loading, a deformation slightly above 4 mm was achieved between the steel clamps. In a simulation of compression loading the deformation reached very similar values, which differed in the order of tenths of a millimeter. The values obtained from the simulation can be compared with the graphs of the tests performed on samples with 8-mm dowels.

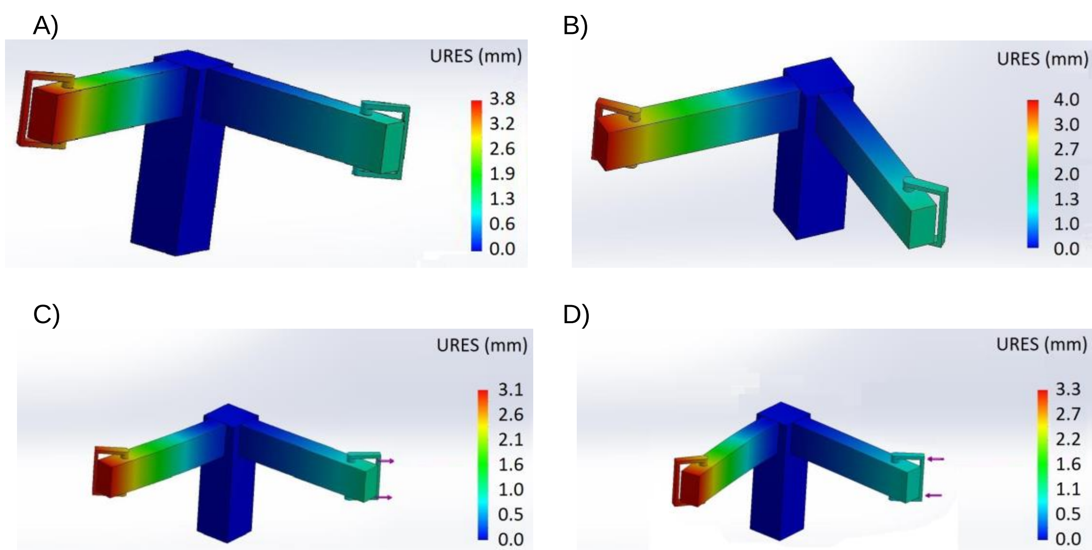

Fig. 13. A) Deformation simulation using tension loading on a joint with 8-mm dowels, B) during compression loading of a joint with 8-mm dowels, C) during tension loading of a joint with 12-mm dowels, and D) during compression loading of a joint with 12-mm dowels

As with the joints with 8-mm dowels, the deformation achieved in the compressive and tension loading simulation only differed in the order of tenths of a millimeter. The total deformation was slightly above 3 mm, which was roughly one millimeter less than in the simulation of joints with 8-mm dowels. The deformation values from the simulation can be compared with graphs showing the course of the tests below in Figs. 13A and 13B, where the deformation at a load force of 225 N reached similar values.

CONCLUSIONS

1. In beech dowel joints, an interesting trend was observed with respect to the selected type of loading using single-component, waterproof polyvinyl acetate adhesive (PVAc) and single-component polyurethane adhesive (PUR) adhesives. With PVAc adhesives, the joints achieved higher elastic stiffness values under tension loading in both joints with a 1/3 joint thickness and joints with a 1/2 joint thickness. For PUR adhesives there was an opposite trend, which means that higher average elastic stiffness values were achieved by joints subjected to compressive stress. In spite of this trend, there were no significant differences between the average elastic stiffness values of joints glued with PVAc and PUR adhesives.
2. The best average elastic stiffness value of beech dowel joints, 1287 Nm/rad, was achieved for joints with a 1/2 joint thickness glued with PVAc adhesives and subjected to tension loading, while joints with a 1/3 joint thickness glued with PVAc adhesives subjected to compression loading achieved the lowest elastic stiffness values, namely 546 Nm/rad. The authors' simulation of tested dowel joints always overestimated the deformation with respect to reality by approximately 30%.
3. The elastic stiffness of the joint tested was compared with a haunched mortise and tenon joint that was influenced by the same factors, and it was demonstrated that a dowel joint exhibited approximately 16% lower elastic stiffness values in comparison with a haunched mortise and tenon joint. The monitored factors in both types of joints manifested themselves with a different intensity and to a different extent.
4. The findings of the results of this work can be transferred to practical use. It should be noted that good preparation of the material itself, which plays a big role in the result, is a very important prerequisite for the creation of a sufficiently stiff joint. A definite recommendation for the production of solid wood furniture dowel joints is the use of dowels with greater diameters, as confirmed by the research of other authors as well.

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