The Effect of Selected Factors on Domino Joint Stiffness

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When designing wooden structures and furniture, it is very important to consider joints that allow the structure to stay together and upright. There are many different types of wood joints. The selection of a joint type and its properties are some of the most important design choices. This article was dedicated to the Domino joint, which allows for strong joints. The Domino joiner is a loose tenon and mortise manufacturing joining tool. This article discusses the effect of selected parameters, such as the type of stress (tensile and compressive), size of the Domino joiner (one-half and one-third thickness), wood species (beech (*Fagus sylvatica* L.) and spruce (*Picea abies* L.)), and adhesive type (polyvinyl acetate and polyurethane), on the joint stiffness. The influence of the annual rings was also monitored.

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

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INTRODUCTION

Furniture design requires structural joints. In terms of the structural rigidity and strength, they are a critical part of the design (Eckelman and Haviarova 2011). Wooden joints are used to connect individual parts in a perfect and functionally satisfying item, such as a furniture component, furniture, or general structure (Halabala 1982). In the joint elements, internal forces are distributed because of external stress, which are transferred from one element to another, usually by compressive contact (Zwerger 2012; Asaff 2014). The wood used in joints should be free of cracks, knots, round surfaces, and other defects that could adversely affect the joint strength (EN 789 2004). The contact surfaces must adhere properly so that the internal forces can be transmitted through the entire surface (Jelínek 2008). The placement of joints is often a limiting factor in the design process (Nutsch *et al.* 2006; Terrie 2009; Horman *et al.* 2010). This fact was confirmed by Tran *et al.* (2015). There is a difference between glued (permanent) and unglued (temporary and demountable) joints. The connecting and mounting means are selected depending on the type of joint. Glued joints dampen vibrations better and increase the overall firmness of the structure (Osten 1996).

In 2006, the company Festool introduced a reliable Domino joiner system that creates strong hidden joints. This is a special type of joint using a loose tenon, or Domino pin, and mortises into which the Domino pin is inserted and glued. This is a joining element with rounded edges, oval cross sections, and grooved surfaces. It is supplied in 14 different sizes. The Domino can be purchased in pieces or in the form of a rod that the customer can shorten as needed. After the adhesive is applied, the Domino adheres to the sides of the hole more tightly because of the swelling properties of wood, which makes the glued joint even stronger. The grooves on the Domino pin support even glue distribution (Nutsch *et al*. 2006; Festool 2016). This system is used for joining parts in the production of furniture and other interior equipment that are used for the manufacture of window structures, joining panels, frames, and exhibition stands. Mortises are easily prepared by a special milling machine or a CNC machine. The appropriate height and depth are also set by the milling machine depending on the dimensions of the selected Domino pin (Festool 2016).

A Domino pin combines the advantages of round and flat pins. It is an improved version that prevents twisting and is firmer. This research tested beech Domino pins.

Aman *et al.* (2008) compared loose mortise and tenon joints with classic mortise and tenon joints using test specimens made of black cherry, oak, and maple wood. The experiments showed that the strength of the joint with a loose mortise and tenon are within the strength range of a pin joint and conventional mortise and tenon joint. The article stated that the loose tenon system may be cheaper and more efficient. The costs of use and primary processing of the material are lower. The fact that two identically machined parts are used for a Domino pin also reduces the production time.

The use of loose tenons in the furniture industry was addressed by Derikvand *et al.* (2015). How the strength is affected by the type of wood used, the dimensions of the loose tenon, its size and shape, glue used, and thickness of the glued joint was examined. A T-type end-to-side joint with a loose tenon was studied by Derikvand *et al.* (2015), and the geometry of the inserted tenon, tightness of the joint, and effect of the type of wood used were observed. Test specimens were subjected to a bending moment, and tenons with a rectangular cross section, rounded cross section, and rounded cross section with longitudinal grooves were compared. The results showed that the rounded tenon formed a joint that was 20% stronger. Derikvand *et al.* (2015) considered the joint tightness to be the most important influence.

Derikvand *et al.* (2015) also dealt with the testing of structural joints using wood-based materials. Under the guidance of a global furniture manufacturer, a suitable method for testing screw joints was studied, as well as a complex method that would evaluate a structure bonded with this type of joint. The results showed that the strength of the screw joints depends on the contact surface and shear forces that form on these surfaces. There were also other important parameters, such as the diameter of the screw thread and its inclination. This method enables an objective assessment of the quality of the structure and the selection of the best joint for the designed furniture (Derikvand *et al.* 2015; Smardzewski *et al.* 2015).

The main objective of this research was to monitor how selected parameters affect the stiffness of the selected structural joint and to compare it with that of other types of joints used in the furniture industry. This information can then be used in practice by furniture manufacturers and designers to simplify the design and production process.

EXPERIMENTAL

Materials

For the experimental testing, two wood species were chosen, Norway spruce (*Picea abies* L.) and beech (*Fagus sylvatica* L.). Logs from the region of Prešov in eastern Slovakia were sawn into beams that were acclimatized in a APT Line II climatic chamber (Binder, Tuttlingen, Germany) to an equilibrium moisture content of 10%. According to ČSN EN 942 (2007), ČSN 91 0001 (2007), and ČSN 91 0000 (2005), this moisture content corresponds to the equilibrium moisture content of furniture components intended for indoor environments. Acclimatization was performed at 20 °C with a relative humidity of

55% for 3 months prior to bonding. The beams were then levelled to an exact thickness with a CNC machine (SCM Record 110 NT, SCM L.T.D, Rimini, Italy).

Beech is a hardwood and is used abundantly in the furniture industry, while spruce is a softwood and is often used in the construction industry.

The logs from the Prešov region in Slovakia were used to create planks, which were shortened to 2 m. The bark and rounded areas were removed. They were then levelled to the required thickness and cut to the final thickness profiles of 25 mm x 45 mm (rails) and 45 mm x 45 mm (stiles). The dimensions of these pieces before they were prepared for bonding are shown in Fig. 1. Each piece was formed by joining a stile with two rails. The red crosses indicate the places that would be milled.

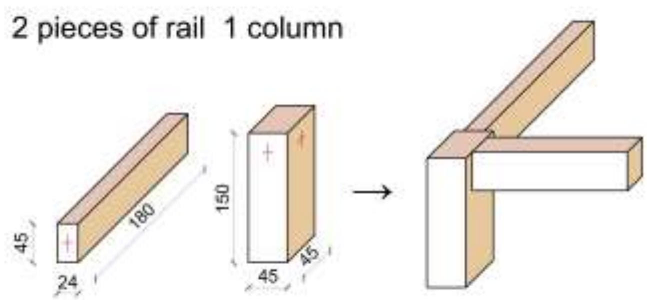


Fig. 1. Test sample preparation scheme in mm; red crosses indicate milling locations

Using CNC milling cutters, mortises in the prepared stiles and rails were created for the subsequent insertion of the Domino pins. There were two versions of the Domino pins, one-third and half-thickness. The pins were shortened to specific lengths. Their placement can be seen in Figs. 2A and 2B. The pin sizes are shown in Fig. 2C, and a detailed view of the joint is shown in Fig. 2D.

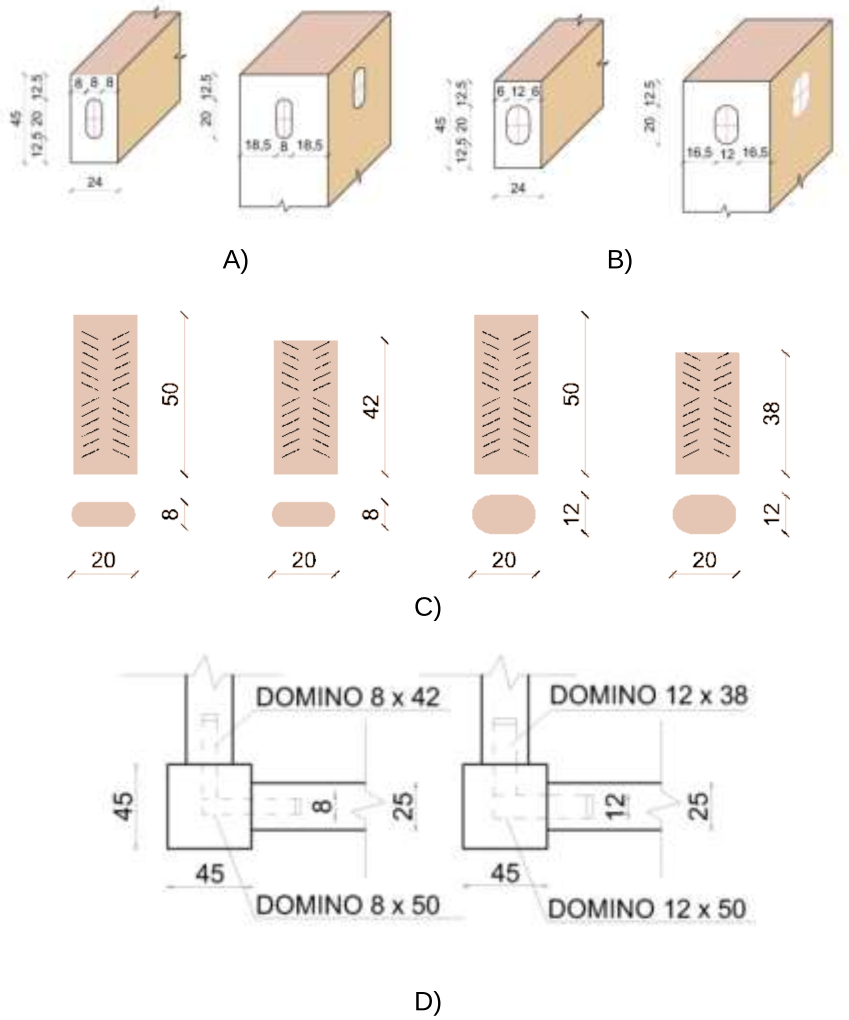


Fig. 2. A) Milling detail for the 8-mm Domino pin, B) milling detail for the 12-mm Domino pin, C) loose tenon Domino pin made by Festool (8-mm and 12-mm thicknesses) and its dimensions used in the experiment, and D) detail of the connection with dimensions; all of the dimensions are in mm

The gluing took place in the workshop of the Czech University of Agriculture in the Pavilion of Wood Sciences. During testing, polyurethane (PUR) and polyvinyl acetate glue (PVAc) were used, specifically AG-COLL 8761/L D3 (EOC, Oudenaarde, Belgium) and NEOPUR 2238R (NEOFLEX, Madrid, Spain), respectively. The technical parameters of both adhesives are shown in Table 1.

In both cases, the adhesive was applied with a brush on both sides of the mortise and Domino pin. To create the necessary cold pressing pressure, a JU 60 industrial press (PAUL OTT, Vienna, Austria) was used with a pressing duration of 60 min.

The PVAc glue coating was 150 g/m^2 to 180 g/m^2, and the PUR glue coating was 180 g/m^2 to 250 g/m^2.

Table 1. Technical Data and Characteristics of the Adhesives

Technical Data	Ag-Coll 8761/L D3	Neopur 2238R
Viscosity (mPas)	5000 - 7000 at 23 °C	2000 - 4500 at 25 °C
Working time (min)	15 – 20	60
Density (g/cm^3)	0.9 - 1.1 at 23 °C	approx. 1.13
NCO content (%)	-	approx. 15.5 - 16.5
Color	white, milk	brown
Open time (min)	15	approx. 20 - 25
Dry matter content (%)	49 – 51	100
pH	3.8 - 4.5	-

The monitored factors are shown in Table 2. A total of 16 different sets of specimens were created. For each set, 10 test specimens were made. In total, 160 test specimens were created.

Table 2. Overview of the Monitored Factors

Wood Type		Glue Type		Depth of Tenon		Type of Loading	
Spruce	Beech	PVAc	PUR	8 mm	12 mm	Compression	Tension

The differences in the fiber deflection in the stile structures are shown in Fig. 3. After testing, each specimen was weighed and the values were recorded. After testing, each sample is weighed for subsequent density determination.

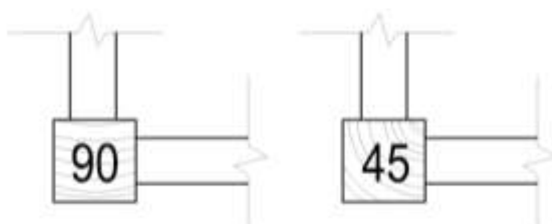


Fig. 3. Diagram of the annual ring deflection

Methods

The moisture content of the samples was determined and verified before and after testing. The moisture content was determined according to ISO 13061-1:2014 (2014). The density was determined according to ISO 3131 (1975).

The experimental testing was performed in the laboratory at the Pavilion of Wood Sciences of CULS on a TIRA 50 universal testing machine (TIRA system GmbH, City, Germany). Figure 4 shows the two types of stresses applied. The testing samples were loaded by the bending moment with the tensile and compressive forces applied in the angular plane.

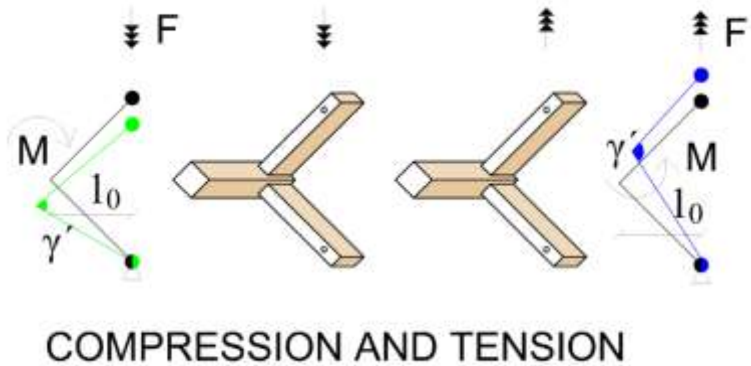


Fig. 4. Diagram of the test samples during loading (compression and tension)

During the test, the change in the distance between the pins in the product was monitored. According to Podlena and Borůvka (2016), the arcsine function was used to calculate the γ angle in radians. Equation 1 was used to calculate the angular displacement, which was initially a right angle:

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

To calculate the change in the torque (ΔM), Eq. 2 was used:

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

where ΔF represents the difference between the two forces that was recorded in the stress-strain diagrams at 10% to 40% of the maximum joint strength and l_0 represents the direction of the force applied to the vertical arm of the tested joint.

The elastic stiffness (c_{elast}; Nm/rad) was calculated according to Eq. 3 as a proportion of the angular displacement in radians.

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

The effects of the individual factors and multi-factor interactions on the elastic stiffness were determined with an analysis of variance (ANOVA) and Fisher's F-test using Statistica 12 software (TIBCO Software Inc., Palo Alto, CA, USA). Based on the *P*-level value, it was determined whether or not the monitored factor affected the stiffness. The achieved results were depicted as diagrams showing 95% and 99% confidence intervals. Correlation analyses were performed with Microsoft Excel software (Redmond, WA, USA).

RESULTS AND DISCUSSION

Table 3 shows the average density and elastic stiffness values of all of the tested sets of specimens. For the spruce specimens, an average density of 0.450 g/m^3 was calculated. The average density of the beech specimens determined at a moisture content of 12% was 0.712 g/m^3. The values obtained corresponded to the densities listed in the scientific literature (Požgaj *et al*. 1993; Wagenführ 2000). For the spruce joints, an average elastic stiffness of 409 Nm/rad was measured. The average elastic stiffness of the beech joints was 778 Nm/rad. A maximum average stiffness of 1397 Nm/rad was found in the set of beech specimens subjected to compressive stress using a one-third length Domino pin.

Table 3. Statistical Analysis of the Density and Elastic Stiffness of the Domino Joint

Type of Wood	Type of Loading	Joint Thickness	Type of Glue	Density (g/cm^3)	Elastic Stiffness (Nm/rad)
Spruce	Compression	Third	PVAc	0.405 (6.9)	361 (34.5)
Spruce	Compression	Half	PVAc	0.403 (4.6)	335 (21.3)
Spruce	Compression	Third	PUR	0.498 (3.6)	607 (53.9)
Spruce	Compression	Half	PUR	0.485 (1.6)	730 (27.8)
Spruce	Tension	Third	PVAc	0.406 (6.7)	322 (35.6)
Spruce	Tension	Half	PVAc	0.413 (4.2)	319 (29.8)
Spruce	Tension	Third	PUR	0.488 (3.4)	352 (40.9)
Spruce	Tension	Half	PUR	0.505 (3.6)	249 (30.5)
Beech	Compression	Third	PVAc	0.698 (6.7)	1397 (50.9)
Beech	Compression	Half	PVAc	0.711 (1.6)	502 (28.4)
Beech	Compression	Third	PUR	0.708 (5.0)	792 (32.5)
Beech	Compression	Half	PUR	0.717 (1.0)	894 (42.9)
Beech	Tension	Third	PVAc	0.721 (1.7)	1301 (53.1)
Beech	Tension	Half	PVAc	0.716 (3.4)	418 (32.0)
Beech	Tension	Third	PUR	0.715 (1.8)	521 (31.9)
Beech	Tension	Half	PUR	0.712 (1.0)	399 (21.4)

Values in parentheses are the coefficients of variation in %

Table 4 presents the results of the 4-factor ANOVA that evaluated the effect of the individual factors and their 2-3-4-factor interaction on the elastic stiffness of the joints. It was clear from the *P*-values that the wood species, type of stress, and thickness of the Domino pin were statistically significant factors for the one-factor analyses. The effect of the adhesive type by itself was not proven to be statistically significant, but in combination with other factors its effect was significant. The interaction of the wood species and Domino pin size was also proven to be significant in a 2-factor analysis. A 3-factor analysis revealed the significant effect of the interaction of the wood species, joint thickness, and type of adhesive. According to the *P*-value of 0.97, the joint effect of all four factors can be considered statistically insignifcant.

Table 5 confirms that the wood species significantly affected the elastic stiffness of the joint ($P < 0.01$). According to the *P*-value of 0.29, it was clear that the effect of the annual ring deflection was an insignificant factor. Even in interaction with the wood species, no significant effect was proven for the annual ring deflection.

Table 4. Multi-factor Statistical ANOVA of Elastic Stiffness of the Domino Joint

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	F	P
Intercept	56369175	1	56369175	546.5438	< 0.01
{1} Type of wood	5439164	1	5439164	52.7370	< 0.01
{2} Type of loading	1885855	1	1885855	18.2849	< 0.01
{3} Thickness of joints	2043851	1	2043851	19.8168	< 0.01
{4} Type of glue	105252	1	105252	1.0205	0.31
1*2	14911	1	14911	0.1446	0.70
1*3	2001238	1	2001238	19.4036	< 0.01
2*3	108103	1	108103	1.0481	0.31
1*4	1622926	1	1622926	15.7355	< 0.01
2*4	1002543	1	1002543	9.7204	< 0.01
3*4	2037999	1	2037999	19.7600	< 0.01
1*2*3	51	1	51	0.0005	0.98
1*2*4	5624	1	5624	0.0545	0.82
1*3*4	1823384	1	1823384	17.6792	< 0.01
2*3*4	146925	1	146925	1.4246	0.23
1*2*3*4	106	1	106	0.0010	0.97
Error	14851804	144	103138		

F = Fisher's F-test; Significance was accepted at P < 0.01

Table 5. Two-factor ANOVA of Elastic Stiffness of the Domino Joint According to the Deflection of the Annual Rings

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	F	P
Intercept	47153746	1	47153746	267.914	< 0.01
1 - Type of wood	4415813	1	4415813	25.089	< 0.01
2 - Deflection of annual rings	441651	2	220825	1.255	0.29
1*2	94480	2	47240	0.268	0.76
Error	27104557	154	176004		

F = Fisher's F-test; Significance was accepted at P < 0.01

Figure 5A shows that wood species had a significant effect on elastic stiffness ($P < 0.01$; Table 4). On average, the beech joints (778 Nm/rad) exhibited a 90% greater elastic stiffness than the spruce joints (409 Nm/rad).

Figure 5B shows how the elastic stiffness was affected by the type of loading ($P < 0.01$). The test specimens subjected to the compressive stress exhibited a 45% greater elastic stiffness on average than the specimens subjected to the tensile stress.

Figure 5C graphically depicts the thickness of the Domino pin, which was a significant characteristic ($P < 0.01$). The one-third thickness pin exhibited a 47% greater elastic stiffness than the half-thickness pin. This was an interesting finding. In previous research that studied a pin joint and mortise and tenon joint, increasing the joint thickness increased its strength (Záborský *et al*. 2017a; Záborský *et al*. 2017b).

In a one-factor analysis, the effect of the adhesive type was not proven to be significant. Figure 5D shows that the elastic stiffness of the joints bonded with the PVAc adhesive was only about 9% higher than that of the joints bonded with the PUR adhesive. In the previous research by the authors (Záborský *et al*. 2017a; Záborský *et al*. 2017b), the bonding factor was proven to be statistically significant.

Figure 5E illustrates how the stiffness was affected by the growth ring direction in the stile of the spruce and beech test specimens. The greatest stiffness was achieved by the specimens with an annual ring deflection of 90° in both wood specimens, but it was not a significant effect, in spite of the fact that the smallest variability was found for the 90° deflection. The same trends were confirmed by the results of the research by Záborský *et al*. (2017a) and Záborský *et al*. (2017b). These are trends of variability, in which the stiffness and shape of a mortise and tenon joint were monitored. The growth ring direction did not significantly affect the results, but the variability trends were identical.

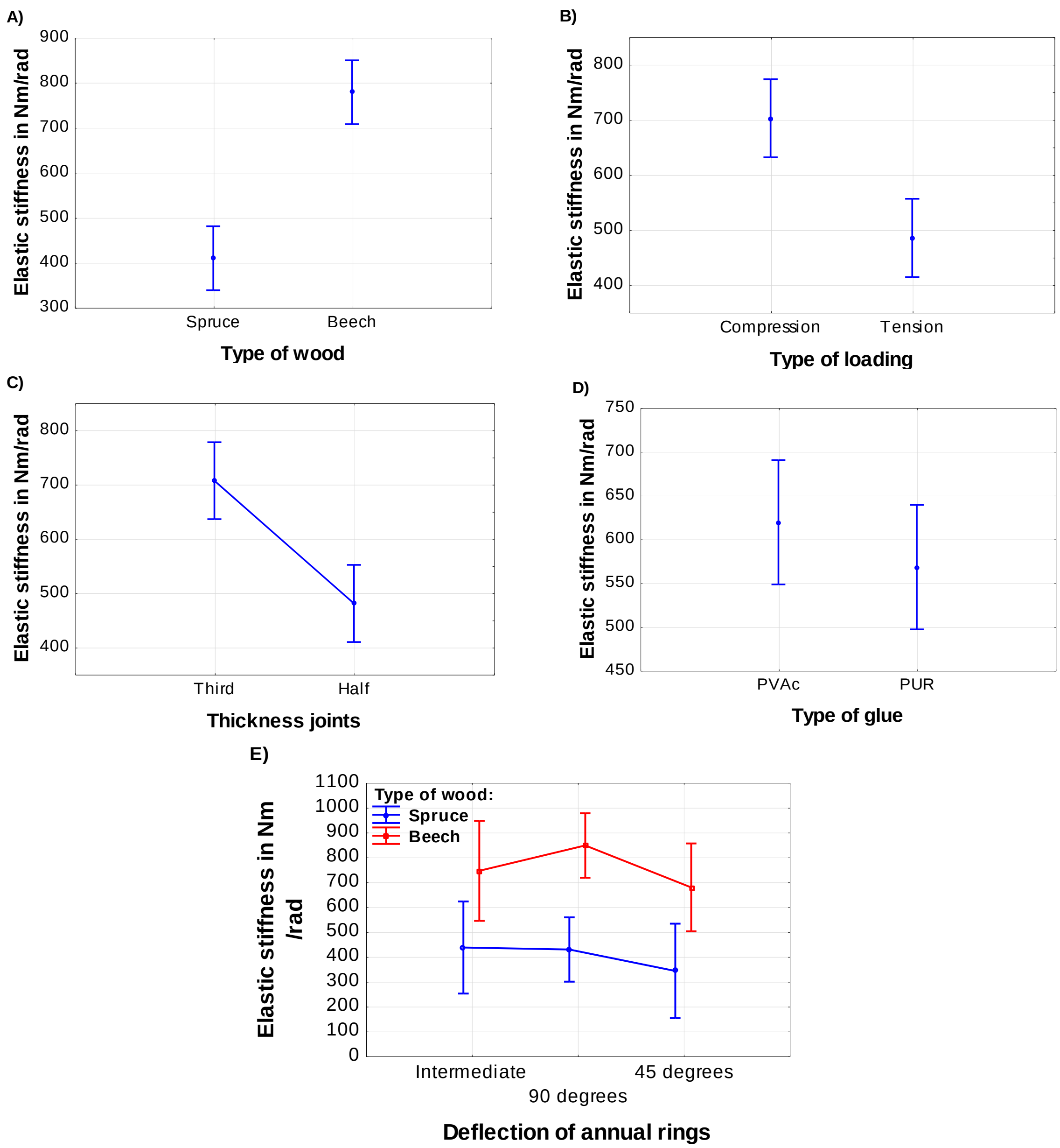


Fig. 5. Graphic visualization of the effect of the wood species (A), type of loading (B), joint thickness (C), type of glue (D), and type of wood and deflection of annual rings (E) on the elastic stiffness

Figure 6 shows the effect of the individual factors on the elastic stiffness, in particular the effect of the wood species and joint thickness. Tendencies toward higher values under compressive stress compared with tensile stress were observed. The effect of the joint thickness with the spruce wood was more or less negligible, but the effect of this factor was very pronounced with beech wood, where there was a 45% decrease in the stiffness with the half-thickness joint compared with the one-third thickness joint.

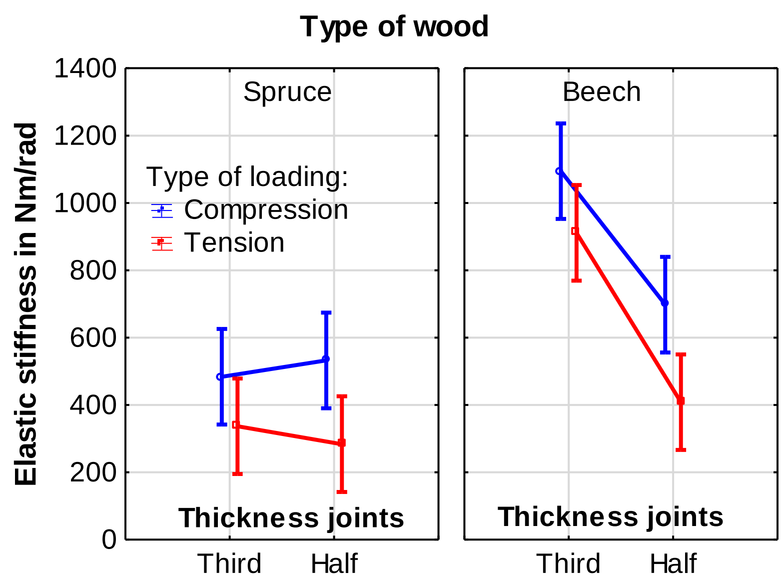


Fig. 6. Graphic visualization of the synergistic effect of the wood species, joint thickness, and type of loading on the elastic stiffness

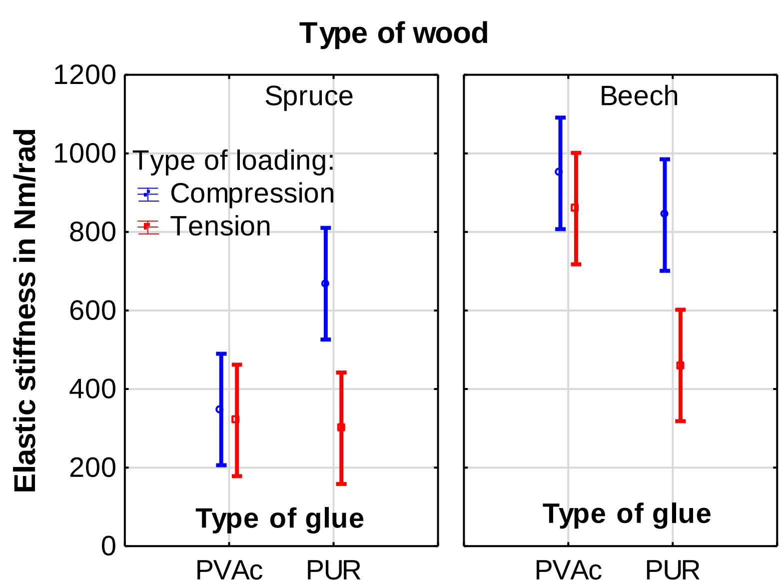


Fig. 7. Graphic visualization of the synergistic effect of the wood species, type of glue, and type of loading on the elastic stiffness

Figure 7 shows the effect of the type of adhesive on the elastic stiffness during compressive and tensile loading of the spruce and beech joints. It was found that the specimens bonded with the PUR adhesive exhibited significantly lower elastic stiffness values under tensile stress compared with the compressive stress. In the beech wood specimens, this decrease was about 45%, and in the spruce wood specimens, the decrease was about 55%. Another interesting finding was that under compressive stress, the stiffness of the spruce joints bonded with the PUR adhesive increased by approximately 92% compared with the joints bonded with the PVAc adhesive. In other cases, the PVAc adhesive generally achieved more consistent results than the PUR adhesive in terms of the effect of the stress type on the stiffness.

Figure 8 shows significant effects of the wood species, joint thickness, and type of adhesive on the elastic stiffness of the joint. The negative effect of the half-thickness beech Domino joint glued with the PVAc adhesive was particularly evident.

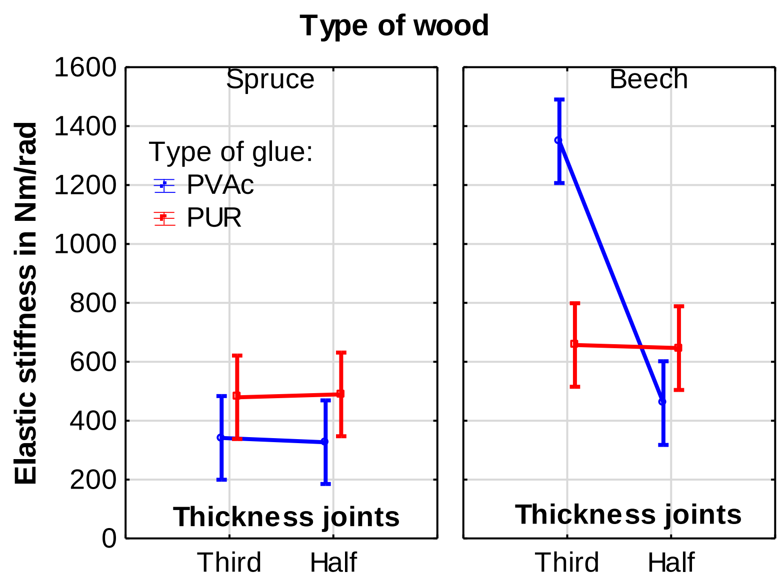


Fig. 8. Graphic visualization of the synergistic effect of the wood species, joint thickness, and type of glue on the elastic stiffness

The dependence of the elastic stiffness on the density and strength of the joint is presented in Fig. 9. A significant effect from the density was only demonstrated when comparing the spruce and beech specimens. When the stiffness of both wood species was monitored, the coefficient of linear dependence (r) was equal to 0.4218, which indicated that there was little correlation between the density and elastic stiffness. Similar results were obtained when researching a dovetail and skewed mortise and tenon joint (Záborský *et al*. 2017b).

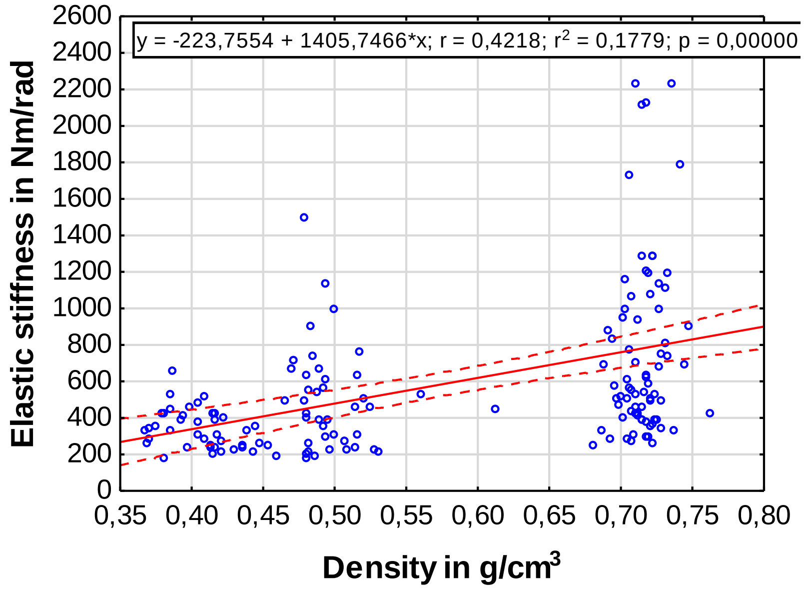


Fig. 9. Dependence of the elastic stiffness on the density of the wood joints

As the elastic stiffness increases, the maximum strength of the joint also increases. However, predicting the stiffness under a maximum load from the elastic stiffness data was not very reliable. Figure 10 shows that the r equaled 0.4869. This was caused by non-linear states that occurred at higher loads and deformations that may no longer be associated with a particular stress. However, it is quite obvious that joints will not actually be subjected to a stress beyond the elastic range. This should not occur in practice with the designed dimensions because of potential subsequent and irreversible deformations.

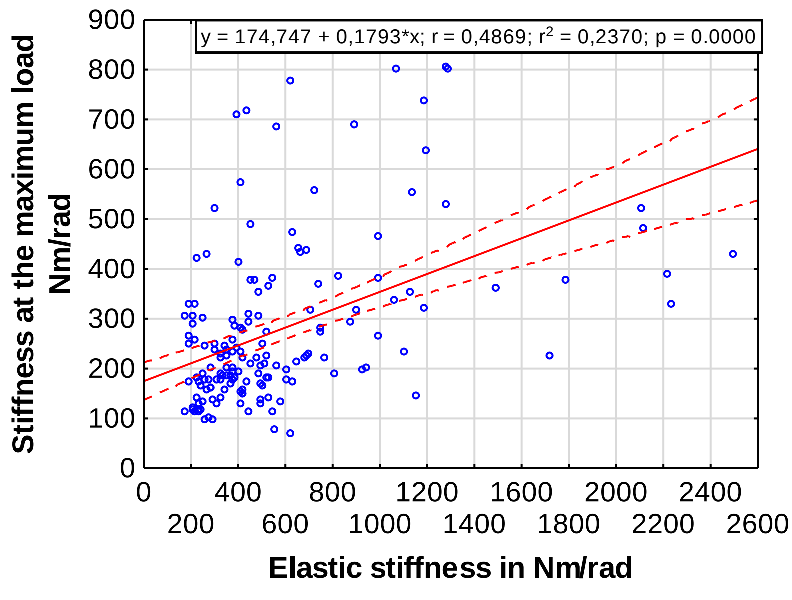
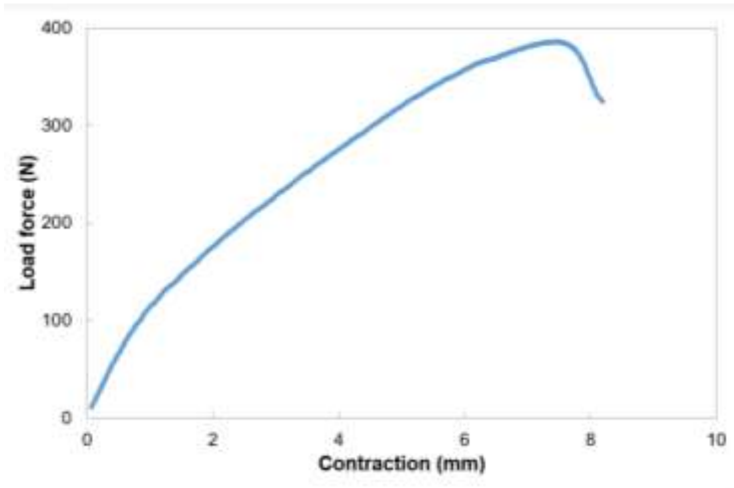


Fig. 10. Dependence of the stiffness at the maximum load on the elastic stiffness of the wood joints

The Tira software generated the real stress-strain diagram of the stress tests during tensile and compressive loading of the Domino joints. The curve shows the changes in the force and path of the loading head during the test before the joint broke. In some cases, the glued joint broke first and then the Domino pin was pushed into the opposite mortise. The testing of the selected specimens is shown in Fig. 11.

A



B

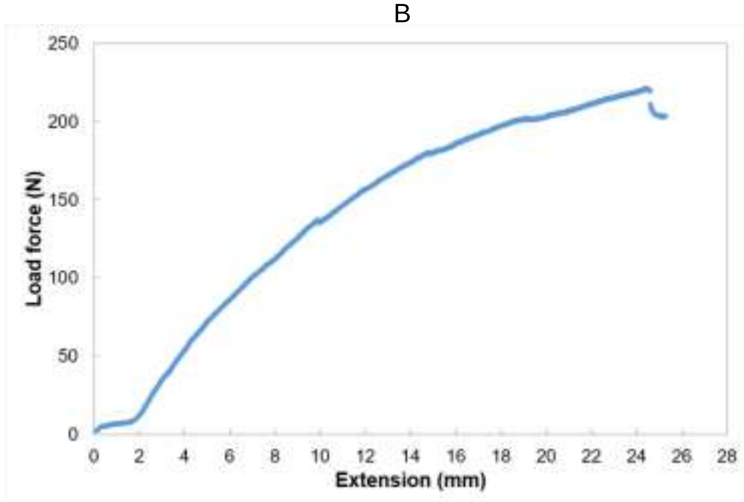


Fig. 11. Actual stress-strain diagram during tensile loading of a half-thickness spruce Domino joint bonded with PVAc glue (A) and during compressive loading of a one-third thickness beech Domino joint bonded with PUR glue (B)

CONCLUSIONS

1. The elastic stiffness of the joint was significantly affected by the wood species, type of stress, and thickness of the Domino pin. As expected, the calculated stiffness of the beech joint was higher than that of the spruce joint by approximately 90%. Under compressive stress, the stiffness of the joint was 45% higher than under tensile stress. With the one-third thickness pin, the stiffness was 47% higher than with the half-thickness pin. After comparing the types of joints, it was found that Domino joints are

the only types of joints in which the half-thickness joint does not increase the stiffness of the joint. For the spruce wood specimens, the stiffness was more or less constant, while for the beech wood specimens, there was quite a significant decrease. This was probably because of the Domino pin geometry and size of the mortises in the rails and stile, where the half-thickness mortises caused the joint to weaken.

2. For the spruce wood specimens, the half-thickness was an unnecessary “luxury”, and for the beech wood specimens, it was absolutely inappropriate. Spruce wood is softer than beech wood, and it apparently better tolerated deformation caused by the Domino joining element, which was made from beech wood.
3. The effect of the adhesive on joint stiffness was not proven to be significant. Joints bonded with the PVAc adhesive only had an approximately 9% higher stiffness. In combination with other individual parameters, the type of glue was significant. The milling quality, thickness of the glued joint, and quality of the work were also important factors.
4. From this comparison, as well as from the results of the experiments in this article, the use of a one-third thickness beech Domino joint bonded with the PVAc adhesive appears to be ideal. The use of a half-thickness beech and spruce Domino joint bonded with the PUR adhesive seems to be the least suitable, especially under tensile stress.
5. Like the density, the effect of the annual ring deflection was only significant between the two wood species. However, predicting the stiffness under a maximum load from the elastic stiffness data was not very reliable. This was because of non-linear states that occurred at higher loads and deformations that may no longer be associated with a particular stress.

ACKNOWLEDGEMENTS

The authors are grateful for the support of "Advanced research supporting the forestry and wood-processing sector´s adaptation to global change and the 4th industrial revolution", No. CZ.02.1.01/0.0/0.0/16_019/0000803 financed by OP RDE and for the support of the University-wide Internal Grant Agency (CIGA) of the Faculty of Forestry and Wood Sciences (Project No. 2016 – 4311).

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Article submitted: December 9, 2017; Peer review completed: January 3, 2018: Revised version accepted: February 9, 2018.
DOI: 10.15376/biores.13.2.2424-2439