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EFFECT OF MATERIAL, ADHESIVE AND LOADING ON THE STIFFNESS OF WOODEN DOWEL JOINTS

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ABSTRACT

The objective of this study was to evaluate the effects of selected parameters, such as type of loading (compression and tension), the wooden dowel species, and the adhesives type on the joint stiffness. Beech, oak, and Scots pine woods were used as wooden dowel material, and polyvinylacetate (PVAc) and polyurethane (PUR) adhesives were used as adhesive agents. Elastic stiffness on diagonal tension and compression tests were applied on 120 pieces of test samples prepared. The results showed that there was found out that the highest average elastic stiffness value of 656 Nm/rad was achieved in the oak dowel joints bonded with PVAc adhesive under compression loading. The lowest average value of 293 Nm/rad was found in the Scots pine dowel joints subjected to compression stress using PUR adhesive. On average, the elastic stiffness of the oak dowel joints bonded with PVAc adhesive was 17% higher than the elastic stiffness of the Scots pine dowel joints bonded with PUR adhesive. The influence of the wooden dowel species and the adhesive type were found statistically significant.

KEYWORDS: Elastic stiffness, dowel joints, adhesive, compression, tension.

INTRODUCTION

One of the main advantages of using wood as a structural material is that each structural element can easily be connected with a wide range of fasteners, and the joints may entirely consist of wooden members (Gaff and Babiak 2017). Connections play a significant role on structural stiffness, and the lack of information about their in-service designers.

The connections in timber structures are often designed by using dowel-type connections and they make a significant contribution to the overall structural stiffness.

Dowel-type connections are the main fastening technique used worldwide in timber structures. The singular approach to wood connections can be attributed not only to the effectiveness of combining different materials, such as wood and steel, but also to the highly anisotropic behavior of wood. Fundamental to an efficient utilization of dowel-type connections is the understanding of their mechanical behavior under loading (load-slip behavior, stress distributions, ultimate strength, and failure modes). The mechanical behavior of wood connections is a complex problem governed by a number of geometric, material, and loading parameters (wood density, fastener slenderness, end distances, edge distances, spacing and number of fasteners, fastener/hole clearances, friction, and loading configuration) (Santos et al. 2013). Dietsch and Brandner (2015) have studied dowel-type timber joints and the typical failures that can be encountered in such connections, and reported that dowel-type joints can also be subjected to brittle failures that result from a concentration of high tensile forces perpendicular to the grain, as well as shear stresses. These stresses are due to many reasons, such as the wedge effect of mechanical fasteners or amplification of restrained shrinkage due to moisture fluctuations. Lathuillière et al. (2015) studied the effect of reinforcement on dowel-type joints and found that reinforcement helped to overcome the low resistance of timber by increasing the tensile strength perpendicular to the grain and the shear strength. Preventing such stresses to be taken entirely by timber elements will result in increasing the overall loadcarrying capacity and prevent brittle failures.

Dowels are commonly used in the field of woodworking applications and construction (toys, furniture, timber roof trusses, etc.) as construction joints (Segovia and Pizzi 2012). Dowels have also been used to increase the connection stiffness. The resin fills the clearance between the dowel and the holes, allowing a better stress distribution around the holes, increasing the ultimate strength of the connection, and improving the immediate load take up of the connection (Davis and Claisse 2001). Larsen and Jensen (2000) proposed the use of semi-rigid connections made of expanded tube fasteners replacing the solid dowels to increase the ductility of the connection and, consequently, the energy dissipation capacity. Moreover, the semi-rigid connection stiffness required for modelling and predicting the in-service dynamic behaviour of dowel-type connections is different from the stiffness required for static loading.

The 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 (Záborský et al. 2018b).

Various factors can affect the strength of dowel joints, including wood species, dowel length, depth of dowel embedment, dowel type, hole diameter, distance between holes, number of dowels, adhesive type and consumption, tightness of fit, boring speed, and feed rate (Eckelman 2003, Kuzman et al. 2015, Georgescu et. al. 2019). Dowel joint sizing (e.g., dowel length, dowel diameter, and adhesive consumption) is based on the studies that have been developed for untreated wood (Eckelman 2003, Smardzewski 2015).

Generally, the size of the bending moment and the stiffness of the dowel joints is affected by the dowel spacing, diameter, and the depth of the dowel (Warmbier and Wilczynski 2000).

Zhang (1991) stated that the optimal diameter was 8 mm, the optimal depth of dowel embedment in a face member was 16 mm, and the optimal depth of dowel embedment in the edge member of the corner joints was 25.4 mm. Joint stiffness increases when a greater number of dowels is used. Adhesive bonding technology has played an essential role in the development and growth of conservation and the repair of timber structures (Gaff et al. 2016). Better joint stiffness is achieved with a thicker joint, but this property is influenced by other factors, particularly the type of adhesive used. Tankut (2007) emphasized the importance of the choosing the right type of adhesive.

Joints made with dowels of beech had higher resistance than dowels of hornbeam, which showed that dowel made of different wood species could also influence the joint properties, too (Dalvand et al. 2014).

Georgescu and Bedelean (2017) analyzed the effect of dowel length, dowel spacing, and depth of dowel embedment on the mechanical strength of dowel joints made of ash (*Fraxinus excelsior).* They reported that the compression and tensile strengths of dowel joints increases when the dowel length increases, the distance between holes increases, and the ratio of dowel embedment in the rail of the int decreases. Záborský et al. (2019) investigated the elastic stiffness of spruce (*Picea abies* L.) The effects of selected factors such as the type of loading (compression *versus* tensile), the size of the dowels (one-half *versus* one-third of the thickness of the joined elements), the type of adhesive used (polyvinyl acetate *versus* polyurethane), and annual ring deflection were examined. Spruce dowel joints exhibited the highest elastic stiffness values with a higher-diameter dowel glued with PUR adhesives and subjected to compression loading. Zaborsky et al. (2019) reported that a dowel joint exhibited approximately 16% lower elastic stiffness values in comparison with a haunched mortise and tenon joint. Podlena et al. (2020) explained that it is a mechanical property related to the strength of the adhesive, the strength of the wood and the wood/glue intermediate section.

The aim of this study was to determine the elastic stiffness of Black pine rail to leg joints under the influence of the selected factors wooden dowel used (beech, oak, and Scots pine), adhesive used (PVAc and PUR), and type of loading (tension and compression force in angular plane). The use of the joints was compared with that of the traditional constructional joint.

MATERIAL AND METHODS

Material

Black pine wood (*Pinus nigra* Arnold) was used to make the experimental specimens of a rail to leg dowel joint. Wood species used in the production of dowels are beech (*Fagus orientalis* L.), oak (*Quercus petraea* L.), and Scots pine (*Pinus sylvestris* L.). The wood dowels had prepared with a cylindrical shape in nominal dimensions of 8 mm × 50 mm. Wood materials were randomly selected from the commercial suppliers in Karabük, Turkey. Care has been taken to ensure that the timbers are straight, fibrous, knot-free, and sapwood.

Adhesives

Polyvinyl acetate (PVAc), and polyurethane adhesives which are commonly used in the wood industry and box- type furniture manufacture, were used in this study. The single-component polyvinyl acetate (PVAc) adhesive Kronen Holzleim D4 manufactured by the German Kronen Company (Fenstertechnik Institut Rosenheim, Germany) was used in this study. Polyvinylacetate (PVAc) adhesive which falls into durability class D4 according to DIN EN 204 (2016), was used as an adhesive, odorless and fireproof, easy to apply, quick setting, cold applied. The properties of this glue used were determined as press compression 0.1-0.8 N/mm^2, pH 3.5, viscosity (20°C) 16000-15000 mPas, density 1.08 g/cm^3 and wood bonding time at 20°C for 35-40 min determined by the company (Kronen 2019). Polyurethane (PUR; Egger Decor, Gebze, Kocaeli, Turkey) is a single component polyurethane-based adhesive. Easy to apply, low viscosity and high bonding strength, water resistant, 15-20 min press time and 5-10 min. The surface has a drying time and is a transparent adhesive (Romabant 2019).

Preparation of experimental samples

Wood materials were kept in the conditioning room at 20 ± 2°C and 65 ± 3% relative humidity until their weight became stable. Then, 1000×11×11 mm pieces were cut from sapwood and dowels with 8 mm diameter were produced from these pieces using a dowel machine. Joint specimens were constructed of the black pine wood. Each specimen consisted of three wooden elements (Fig. 1). The rail members of each joint were measured 180 mm length by 45 mm width by 25 mm thickness. The leg members of each joint were measured 150 × 45 × 45 mm (length × width × thickness). The dowels with a diameter of 8 mm and a length of 50 mm were used as the joining elements. Using 8 mm drill bits, holes were drilled according to the dowel sizes and rails. Joints with 8 mm dowels corresponded to a joint thickness that was 1/3 the thickness of the rail. The distance between the centerlines of the two dowels was 15 mm. The specimens for mechanical testing were made from dried lumber using woodworking machines at a Vocational and Technical Anatolian High-School in Banaz-Uşak (Turkey).

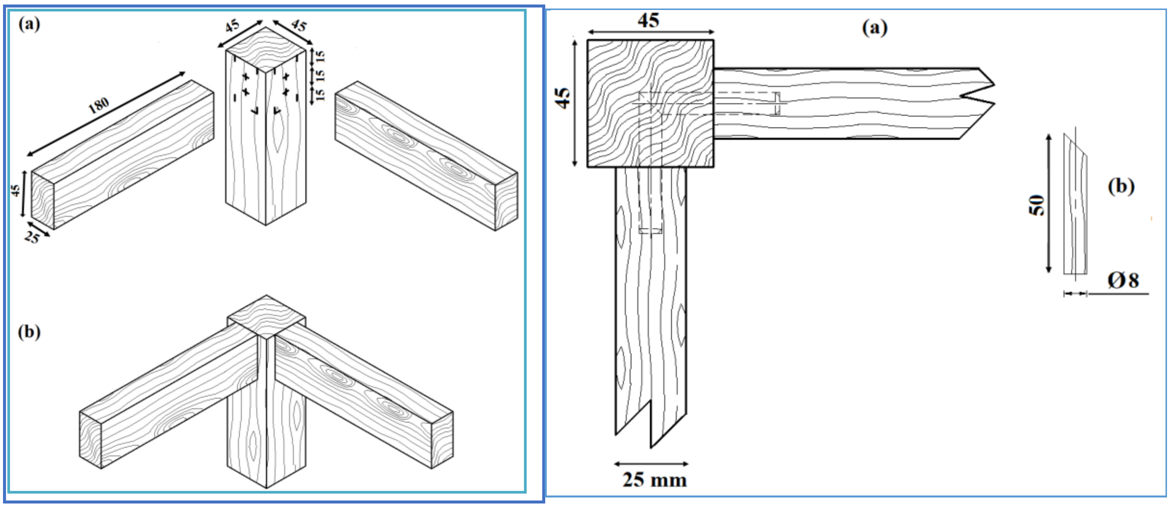

Fig. 1: Rail and leg members and configuration of the dowels' location (dimensions in mm).

The evaluated factors of the joint stiffness were three types of wooden dowel (beech, oak and Scots pine), two types of adhesives (PVAc and PUR), and two types of stress (compression and tension). The number of examined factors resulted in 12 combinations, where 10 pieces of test joints were examined for each combination. A total of 120 joint pieces were produced for this study. Before the compression and tension tests, the samples were stabilized at 20±2°C and at 65±3% relative humidity until the samples had 12% moisture content.

Methods

The mechanical elastic stiffness of the rail to leg joints were evaluated under diagonal tension and compression loadings using an AG-IS universal testing machine placed in the laboratory of Karabük University Safranbolu Vocational High-School having a capacity of 50 kN (Fig. 2a).

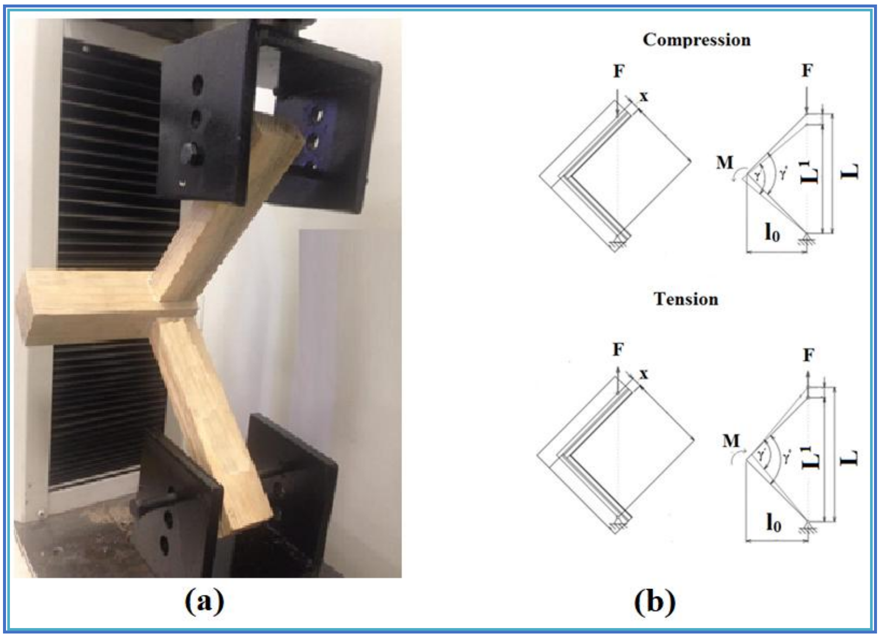

Fig. 2: a) Experimental setup, b) the compression and the tension loading.

Schematic depictions of the compression and tension loadings of the rail to leg dowel joints (Fig. 2b). The rails were connected using steel fixtures with rotating steel tenons with a diameter of 10 mm, which were inserted into the holes in the joint rail. This study used the same type of steel clamp that was used in the work of Podlena and Borůvka (2016), Záborský et al. (2017b, 2018b).

During the experimental test, the size of the arm force was a constant value (l_0 = 127 mm) for all of the samples. This size was derived from the product of the distance (a + x) and cosine of half of the original angle (γ_0 = 90°). The result of the acting force (F) changed the original distance between the pins of the fixture (L´), which resulted in a deviation in the internal angle of the joints (γ´). This was calculated using the following Eq. 1 (Podlena et al. 2015):

$$\gamma^1 = 2\,arcsin\frac{L^1\,(mm)}{2(a+x)\,(mm)} \qquad \text{(rad)} \qquad (1)$$

The change in the angle between the joint rails in degrees was calculated using Eq. 2:

$$\Delta\gamma = 90 \pm \gamma^{1} \qquad (2)$$

To calculate the change in the torque (ΔM), Eq. 3 was used:

$$\Delta M = \Delta F \times l_0 \qquad (3)$$

where: ΔF- represents the difference between the two forces (N) that was recorded in the stress-strain diagrams 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 loading force.

The elastic stiffness (celast; Nm/rad) was calculated according to Eq. 4 as proportion of the angular displacement in radians.

$$c_{elast} = \frac{\Delta M}{\Delta\gamma} \qquad (4)$$

Data analyses

The adhesives, wooden dowel species, loadings methods their interaction on mean the elastic stiffness of wood joints were analyzed using the analysis of variance (ANOVA). The analysis of variance (ANOVA) of the elastic stiffness at a 95% significance level ($\alpha = 0.05$), and multiple comparison test (Tukey HSD) were used to determine the statistical significance of the difference in variants using SPSS program (Statistical Software, a computer-based statistical package) program, version 22.

RESULTS AND DISCUSSION

Averages of density and elastic stiffness of wooden dowel joints are given Tab. 1. The elastic stiffness was measured while monitoring factors such as type of wooden dowel, the type of stress, 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.

The highest average elastic stiffness value of 656 Nm/rad was achieved in the oak dowel joints bonded with PVAc adhesive under compression loading. The lowest average value of 293 Nm/rad was found in the Scots pine dowel joints subjected to compression stress using PUR adhesive. On average, the elastic stiffness of the oak dowel joints bonded with PVAc adhesive was 124% higher than the elastic stiffness of the Scots pine dowel joints bonded with PUR adhesive. Záborský et al. (2017b) examined the effect of wood species, adhesive type, and annual ring directions on the stiffness of rail to leg mortise and tenon furniture joints. As results, the elastic stiffness of the beech joints was reported 30% higher than the elastic stiffness of the spruce joints.

Tab. 1: Averages of density and elastic stiffness of wooden dowel joints.

Loading	**Material of wooden dowel**	**Adhesive**	**Density (g/cm^3)**	**Elastic stiffness (Nm/rad)**
Compression	Beech	PUR	0.675	530 (5.84)
Compression	Beech	PVAc	0.687	567 (3.35)

Compression	Oak	PUR	0.696	561 (4.81)
Compression	Oak	PVAc	0.705	656 (3.51)
Compression	Scots pine	PUR	0.523	376 (5.85)
Compression	Scots pine	PVAc	0.531	455 (4.39)
Tension	Beech	PUR	0.667	467 (8.41)
Tension	Beech	PVAc	0.678	551 (5.08)
Tension	Oak	PUR	0.694	524 (5.78)
Tension	Oak	PVAc	0.701	613 (4.24)
Tension	Scots pine	PUR	0.538	293 (5.80)
Tension	Scots pine	PVAc	0.548	371 (11.05)

Values in parentheses are coefficients of variation (%).

Tab. 2 presents the results of the three-factor ANOVA test that evaluated the effect of individual factors and their interaction on the elastic stiffness of the joints.

Tab. 2: Multifactor analysis of variance for elastic stiffness of wooden dowel joints.

Source of variance	df.	Sum of square	Mean square	F value	P value
Intercept	1	29633754.673	29633754.673	37602.133	0.000
1-loading	1	89343.641	89343.641	113.368	0.000
2-wooden dowel	2	979304.865	489652.433	621.318	0.000
3-adhesive	1	176889.605	176889.605	224.454	0.000
1*2	2	12821.726	6410.863	8.135	0.001
1*3	1	1323.817	1323.817	1.680	0.198
2*3	2	4973.325	2486.663	3.155	0.047
1*2*3	2	4410.904	2205.452	2.798	0.065
Error	108	85113.402	788.087		
Total	120	30987935.958			

adjusted R squared = 0.937 (adjusted R squared = 0.931)

Note: Significance was accepted at $P < 0.05$.

It was clear from the significance level p-value that the type of loading, type of wooden dowel species, type of adhesive and two-way interactions of the type of loading×type of wooden dowel species (1×2), type of wooden dowel species×type of adhesive (2×3) were statistically significant factors for the one-factor analysis ($p \leq 0.05$). Two factor interactions of the type of loading×type of adhesive (1×3) and three factor interactions of the type of loading×type of wooden dowel species×type of adhesive (1×2×3) were statistically insignificant ($p \leq 0.05$). Tukey test was carried out in order to determine these differences. The elastic stiffness of the joints mean according to independent effects of test variables were given in Tab. 3.

Tab. 3: Independent effects of test variables on mean values of the elastic stiffness of wooden dowel joints.

Source		Elastic stiffness (Nm/rad)	SD	HG
Loading	Compression	524	3.62	A
	Tension	470	3.58	B
Wooden dowel	Oak	588	4.42	A
	Beech	529	4.40	B
	Scots pine	374	4.24	C

Adhesive	PVAc	535	3.86	A
	PUR	459	3.61	B

SD- standart devision, HG- homogeneity groups.

The elastic stiffness was affected by the type of loading, type of wooden dowel (beech, oak and Scots pine, and type of adhesive (PVAc or PUR). The samples were tested under a compression test, which showed 11% greater elastic stiffness (Tab. 3) than the tension test.

Záborský et al. (2018a) explained that elastic stiffness of domino joints was under compression stress, the stiffness of the joint was 45% higher than under tensile stress. As a result, the samples were tested under a compression test, which showed 23% greater elastic stiffness. Záborský et al. (2019) investigated the elastic stiffness of spruce (*Picea abies* L.) dowel joints. As a result, compression stress of the samples was exhibited approximately 32% higher elastic stiffness than the under tensile stress. Similar results were obtained when researching a mortise and tenon joints used on wooden window profiles (Podlena and Borůvka, 2016), geometric parameters of structural elements (Záborský et al. 2017a), effect of wood species, adhesive type, and annual ring directions on the stiffness of rail to leg mortise and tenon furniture joints (Záborský et al. 2017b), domino joints (Záborský et al. 2018a), spruce dowel joints (Záborský et al. 2019).

For wooden dowel species, the oak dowel with joints showed significantly higher the elastic stiffness value than other dowels (Tab. 3). The mean elastic stiffness of oak dowel joints was approximately 11% and 57% higher than beech dowel joints, and Scots pine dowel joints, respectively. The situation with the species of lumber used for dowels can explain with the structural properties of the materials. Záborský et al. (2019) investigated the elastic stiffness of spruce (*Picea abies* L.) dowel joints. As a result, the average elastic stiffness of the beech joints was exhibited approximately 141% higher than the stiffness found in the spruce joints.

The highest elastic stiffness value according to type of adhesive were obtained in PVAc adhesive (535 Nm/rad), and the lowest was in PUR (459 Nm/rad). The mean elastic stiffness of the joints bonded with PVAc adhesive was approximately 17% higher than joints bonded with PUR adhesive. These results correspond with the results obtained in the research conducted in recent years research by the some authors (Záborský et al. 2017a,b, 2018a,b).

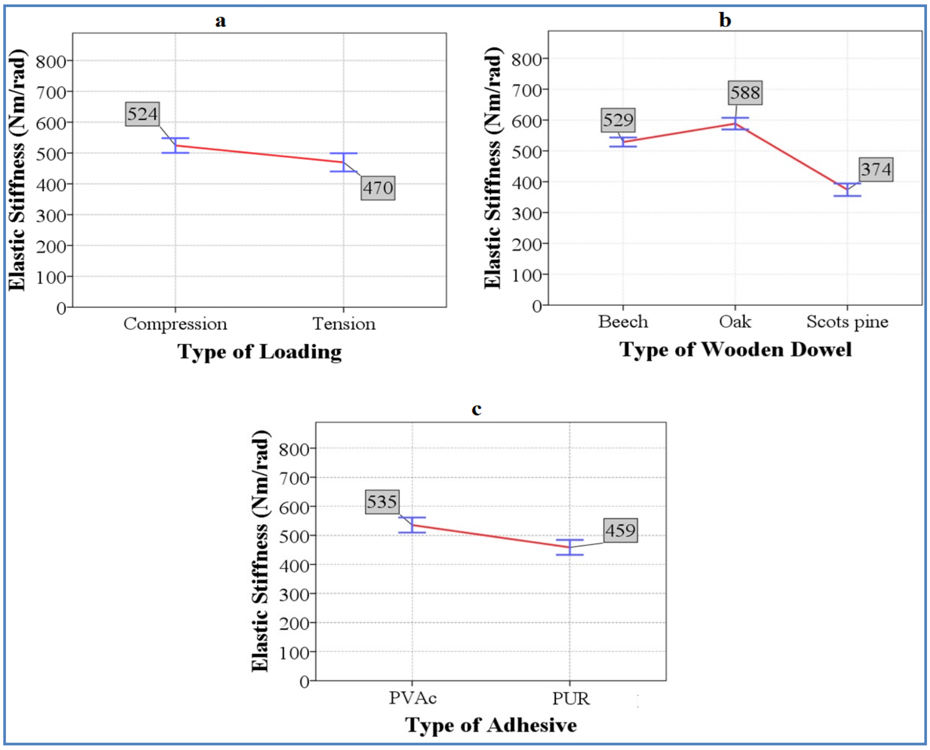

Fig. 3: a) Graphic visualization of the type of loading, (b) type of wooden dowel; and (c) type of adhesive.

As shown in Fig. 3, where the effect of all the monitored factors on the elastic stiffness of the wooden dowel joints are shown, it was clear that the wooden dowel species was the most important factor (Fig. 3b). The oak dowel joint exhibited approximately 57% higher stiffness values compared to the Scots pine dowel. In the case of the type of loading and type of adhesive (Figs. 3a,c), the differences were not as great, as the statistical evaluation demonstrated. The samples were tested under a compression test, which showed 11% greater elastic stiffness (Fig. 3a) than the tension test. For adhesive type (Fig. 3c), the elastic stiffness of joints bonded with PVAc adhesive was 17% higher than that of joints bonded with PUR adhesive.

Fig. 4 shows a graphical representation of the effects of the selected monitored factors on the elastic stiffness of the joint. In the first case (Fig. 4a), the combined effect of the type of wooden dowel and the selected type of stress is shown. In the case of compression stress, oak dowel joints were achieved an average of 11% and 46% higher values than in comparison with beech dowel joints, and Scots pine dowel joints, respectively. In the case of tension stress, oak dowel joints were achieved an average of 12% and 71% higher values than in comparison with beech dowel joints, and Scots pine dowel joints, respectively.

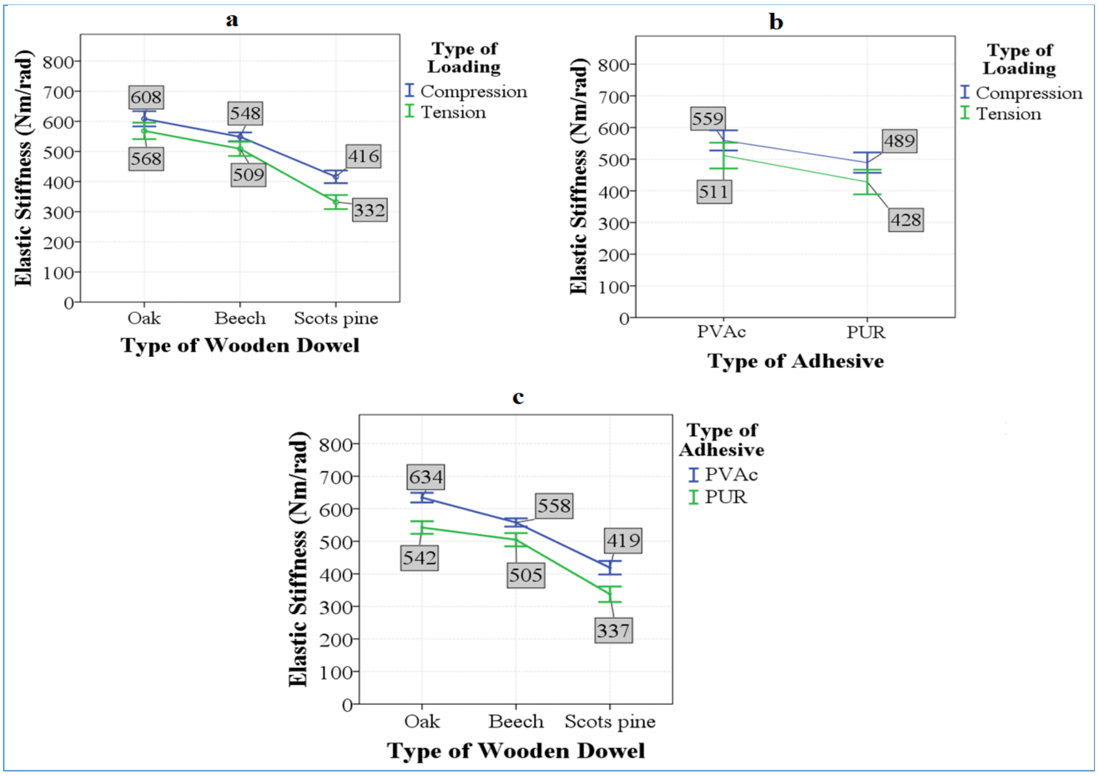

Fig. 4: The effect of (a) type of wooden dowel and type of loading; (b) type of adhesive and type of loading; (c) type of wooden dowel and type of adhesive on mean values of elastic stiffness

In the first case (Fig. 4b), the combined effect of the type of type of adhesive and the selected type of stress is shown. It was demonstrated that the sample joints bonded with PVAc were exhibited significantly higher elastic stiffness values under compression stress as well as tension stress. In the case of compression stress, the PVAc joints achieved an average of 14% higher values in comparison with PUR joints. In the case of tension stress, the PVAc joints achieved an average of 19% higher values in comparison with values obtained in the samples with PUR joints.

Fig. 4c shows the interaction of the elastic stiffness of joints bonded with PVAc and PUR adhesives with oak, beech and Scots pine dowels. The elastic stiffness of the oak dowel joints bonded with PVAc was 17% lower than the PUR adhesive with the oak dowel joint. The elastic stiffness of the beech dowel joints with PVAc adhesive was 10% higher compared to the joint bonded with PUR. The elastic stiffness of the Scots pine dowel joints bonded with PVAc was 24% higher than the PUR adhesive with the Scots pine dowel joints. Thus, in all of the cases (beech, oak and scots pine dowel), the PVAc adhesive showed higher values of elastic stiffness compared with the PUR adhesive.

CONCLUSIONS

The aim of this study was to determine the elastic stiffness of Black pine rail to leg joints under the influence of the selected factors wooden dowel used (beech, oak, and Scots pine), adhesive used (PVAc and PUR), and type of loading (tension and compression force in angular plane). Finally, the characteristic and accuracy of the dowel joints were compared and the final conclusions were as follows: *(1)* The elastic stiffness of the joint was significantly affected by the type of wooden dowel, type of loading, and type of adhesive of the dowel joints. As expected, the calculated stiffness of the oak dowel joint was higher than that of the Scots pine dowel joint by approximately 57%. *(2)* Under compression stress, the stiffness of the joint was 11% higher than under tension stress. *(3)* The effect of the adhesive on joint stiffness was proven to be significant. The average elastic stiffness of the joints bonded with PVAc adhesive was approximately 17% higher than joints bonded with PUR adhesive. *(4)* The best average elastic stiffness value of dowel joints, 656 Nm/rad, was achieved for joints with oak dowel glued with PVAc adhesives and subjected to compression loading, while joints with a Scots pine dowel glued with PUR adhesives subjected to tension loading achieved the lowest elastic stiffness values, namely 293 Nm/rad.

From this comparison, as well as from the results of the experiment, the use of an oak dowel joint bonded with the PVAc adhesive appears to be ideal. The use of Scots pine dowel joint bonded with the PUR adhesive seems to be the least suitable, especially under tensile stress. Planning product design and production with an engineering design approach in the furniture industry, and evaluating the data obtained during this planning to obtain sufficient durability as well as aesthetic appearance will make positive contributions. Considering the functions of the furniture and the loads it will carry, knowing the characteristics of the joining methods to be used will positively affect the value and economic life of the furniture.

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