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Method for substitute modulus determination of furniture frame construction joints

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Abstract: The goal of the performed experiments was to determine the strength, stiffness, and modulus of the elasticity of dowel, mortise and loose-tenon, and mortise and tenon L-type furniture joints under diagonal tension and compression loads. The specimens were constructed from Turkish beech (*Fagus orientalis* L.), white oak (*Quercus alba*), and white walnut (*Juglans cinerea* L.) and were assembled with a water-resistant PVA_C adhesive. According to the obtained results, the highest stiffness/strength values were estimated in mortise and tenon joints constructed of white oak, whereas dowel joints constructed from Turkish beech showed the lowest stiffness/strength and deformability. The elasticity modulus of the experimental joints expressed their stiffness better than the stiffness coefficient. The accuracy of the developed elasticity modulus model of the examined joints was verified positively both by experimental studies and numerical calculations.

Key words: Elasticity modulus, furniture joints, numerical analysis, stiffness, substitute modulus, wood species

1. Introduction

Furniture design and construction is an applied art. As such, it must take into consideration not only aesthetic and functional preferences and fashions but also rigidity and strength requirements (Smardzewski and Gawronski, 1998). Mortise and tenon joints are still widely used in wooden constructions. Despite the increasing use of dowel joints, mortise and tenon joints are irreplaceable for some types of furniture construction. Wilczyński and Warmbier (2003) analyzed the influence of joint dimensions on the bending strength and stiffness of mortise and tenon joints. This study showed that tenon length has the greatest effect on joint strength. The influence of tenon width is less significant, and the effect of tenon thickness is slight. In addition, joint stiffness depends first of all on tenon width, whereas the effects of tenon length and thickness are less significant. Efe et al. (2005) investigated the bending moment capacity of traditional and alternative T-type end-to-side-grain joints constructed of Turkish beech (*Fagus orientalis* L.), European oak (*Quercus borealis* L.), and Scotch pine (*Pinus sylvestris* L.). Experimental results indicated that traditional adhesive-based mortise-and-tenon joints yielded the highest bending moment capacity among the 4 types of tested joints, and that minifix plus dowel joints had the lowest bending moment capacity. Oktaee et al. (2014) determined the effects of tenon geometry on the bending moment capacity of simple and haunched mortise and tenon joints under the action of both compressive and tensile loads. Optimum results were obtained with joints constructed with 10-mm-thick tenons that were 37.5 mm wide and 30 mm long. Tenon length was found to have the greatest effect on joint capacity, whereas tenon width was found to have a much smaller effect. Erdil et al. (2005) determined the effects of wood species, adhesive type, rail width, tenon depth, and tenon length on bending strength and flexibility of mortise and tenon T-type joints. The results also indicated that tenon depth had a more significant effect on joint flexibility than tenon length. Furthermore, the presence of a shoulder on the rail member of a mortise and tenon joint substantially contributes to the stiffness of the joint. Prekrat and Smardzewski (2010) examined the strength of mortise and tenon joint in the construction of a chair with a connecting piece in order to determine the distribution of shear and normal stresses in the glue bond and to ascertain the influence of the glue line on this strength. The performed investigations revealed that the shape of the glue line exerted a definite influence on the strength of the examined tenon joint. Moreover, the pressure of the tenon on the mortise via a layer of glue bond changed the form and size of its stresses. Tankut and Tankut (2005) determined the strength of round tenon/round mortise,

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rectangular tenon/rectangular mortise, and rectangular tenon/round mortise joints assembled under nominally identical conditions with different end configurations.

The results showed that rectangular end mortise and tenon are about 15% stronger than both round end mortise and tenon and rectangular end tenon fitting into round end mortise joints. Meanwhile, joint geometry has a significant effect on the strength of these particular joints. Ratnasingam and Ioras (2013, 2011) compared the fatigue strength of rectangular mortise and tenon furniture joints constructed with polyvinyl acetate (PVA_C) and urea-formaldehyde adhesives. The results showed that for both materials the allowable design stresses for rectangular mortise and tenon joints could be set at 20% of their bending strength. Hrovatin et al. (2013) studied the strength of joints with a wooden ring. These results were compared to the strength of mortise and tenon and dowel joints. It was established that the average ultimate strength of joints with a wooden ring was higher than the ultimate strength of the tenon joints, which was chosen as an upper reference limit. Kamperidou et al. (2011) tested the stiffness and strength of the 3 most frequently used joints in upholstered furniture frames, constructed of beech and poplar. The research included the following joints: mortise and tenon, double dowel, and double gusset plates, which were constructed and tested both in corner (L-type) and in middle (T-type) joints. Based on these results, it was concluded that the tension strength value of these joints could be sufficiently estimated by the measured bending strength value of the corresponding joints. Eckelman (1979) investigated the strength and stiffness of dowel joints in flatwise bending. The results indicated that close-fitting dowel joints have substantial strength in flatwise bending. A high proportion of strength is lost, however, if the members are not closely fitted together. In addition, the flexibility of the joints in flatwise bending was much greater than for in-plane bending. Several studies have examined the effect of joint dimensions on the strength and stiffness of dowel L-type joints. Warmbier and Wilczyński (2000) studied the relationships between dimensions and bending strength and stiffness of dowel corner joints. As a result, the greatest increase in the strength of the joint is achieved by increasing the dowel diameter. An intermediate increase is achieved by increasing the depth of dowel embedment and a slight increase by increasing dowel spacing. Najafi (2013) investigated the withdrawal and shear strengths of dowel joints.

Results indicated that withdrawal strength was reduced insensibly in 15% conditioned moisture content. Furthermore, embedment diameter strongly affected withdrawal strength, as strength increased by 0.5 mm less than dowel diameter. Eckelman (1971) analyzed the bending strength and moment rotation characteristics of T-type end-to-side-grain two-pin moment-resisting dowel joints. The results showed that the bending strengths of the joints were found to regularly increase as rail width and/or dowel spacing were increased. Aman et al. (2008) indicated that loose tenon joint strength falls somewhere between that of the dowel joint and the conventional mortise and tenon joint. Derikvand et al. (2014, 2013) analyzed the effects of bottom shoulder width tenon depth of embedment tenon width and tenon wood species on the bending moment capacities of T-type mortise and loose-tenon furniture joints constructed with PVA_C adhesive. Regarding the framed structure of furniture, there are several types of corner joints, such as mitered joints, that are commonly used in the construction of furniture structures. Maleki et al. (2012) determined stress analysis as an efficient procedure for evaluating the strength of mitered corner joints in furniture structures. The effects of adhesives on bending resistance of mitered corner joints containing dovetails under diagonal tensile and compressive loads were determined by Altun et al. (2010). Results indicated that the highest bending moment capacity under diagonal tensile loading was obtained in the specimens bonded with CA adhesive, and the highest bending moment capacity under diagonal compression loading was obtained in the specimens glued with PVA_C adhesive. Dalvand et al. (2013) confirmed the effect of joint type and numbers and types of dovetail keys on diagonal tension and compression performance of corner joints in a furniture frame. Smardzewski and Kłos (2011) developed an alternative method of numerical modeling of dowel joint rigidity of board elements, using nodes of substitute linear elasticity modulus for this purpose. A different method of joint rigidity was analyzed by Tankut and Tankut (2011). Since joints are often the weakest points in furniture construction, a detailed analysis of the factors influencing their load-bearing capacity and its effectiveness in utilizing the full strength of the wood is reported here. As a result of this analysis, the value of the ratio of the section modulus of the joint W_p to the section modulus of the element W_e has been established as the criterion for determining the correctness of construction based on material strength and production technology. The main shortcoming of traditional methods of stiffness evaluation of frame construction furniture joints is the lack of possibility of application of the obtained results to numerical calculations. A new criterion for joint stiffness assessment can be their elasticity modulus. Smardzewski et al. (2013) determined the effect of creeping on changes in the rigidity of selected joints used in constructions of upholstered furniture, expressed as the substitute modulus of elasticity. For this reason, an attempt was made to elaborate a method of simplified modeling of furniture joint stiffness for the needs of numerical calculations

(Smardzewski and Kłos, 2011; Smardzewski et al., 2013). In the proposed method, joint stiffness was expressed by means of a modulus of elasticity in the form of a load and deflection function.

The aims of this study were as follows: 1) assessment of the impact of certain wood species on the bending strength of dowel and loose-tenon joints, as well as mortise and tenon joints; 2) determination of the stiffness coefficient of the above-mentioned joints; 3) determination of the elastic modulus for the joints; 4) numerical calculations of joint stiffness, which were assigned elastic modulus; and 5) verification of the calculation results on the basis of experimental investigations.

2. Materials and methods

2.1. Assessment of joint strength and stiffness

Dowel, loose tenon, and mortise and tenon joints were used in the present study as 3 types of commonly employed practice joints in the construction of furniture frames. The dimensions of the L-type joints used and the mutual positions of individual furniture elements are shown in Figure 1. Horizontal and vertical frames were manufactured from Turkish beech (*Fagus orientalis* L.), white oak (*Quercus alba*), and white walnut (*Juglans cinerea* L.). Experimental samples were cut from timber seasoned in a laboratory facility, where relative air humidity was maintained at 65 ± 5% and temperature at 21 ± 1 °C until wood reached a constant mass of about 8%. Tenons and mortises in frames were made with standard machines ensuring an accuracy of 0.05 mm of clearance between the dowel (tenon) and the socket (mortise). The maximum distance between the hole (mortise) bottom and the front of the dowel (tenon) amounted to 2 ± 0.1 mm. Dowels measuring 8 × 35 mm and loose-tenons with dimensions of 8 × 40 × 40 mm were constructed of beech wood. PVA_C adhesive (Kleiberit 303 Colle D3 glue) intended for water-resistant joints was used to glue the joint specimens. After the gluing process, the specimens were seasoned for 1 week in the same laboratory facility in which the timber was seasoned, securing identical humidity and temperature conditions. During tests, samples were subjected to static diagonal compression (closing) and tension (opening) loads (Figure 2). Each treatment comprised 10 replications, and the total number of samples was 180 [3 (type of joints) × 3 (wood species) × 2 (loading type) × 10 (replicates)]. Table 1 shows the designations and descriptions of the individual joints.

Experiments were performed on an Instron testing machine (Norwood, MA, USA) in accordance with the diagram shown in Figure 2. During the test, measurements were taken of P_i, Q_i forces with 0.01 N of accuracy as well as of DP_i, DQ_i deflections in the direction of action of these forces with 0.01 mm of accuracy. The loading velocity amounted to 10 mm/min. The loading was terminated when the sample was broken for P_{max}, Q_{max} or when the load decreased. On the basis of the recorded values, joint stiffness characteristics were determined in the form of $P = f(DP)$, $Q = f(DQ)$ dependences. The stiffness coefficient was determined as the quotient of loading and deflection:

$$K_{el}^{c} = \frac{P_{el}}{DP_{el}} \quad [\mathrm{N/mm}], \text{ where}$$

$$\begin{cases} P_{el} = \frac{\sum_{i=1}^{n} P_i}{n}, \\ DP_{el} = \frac{\sum_{i=1}^{n} DP_i}{n}, \; DP_i \in \leq 0.5, 1 \geq \end{cases} \tag{1}$$

$$K_{el}^{o} = \frac{Q_{el}}{DQ_{el}} \quad [\mathrm{N/mm}], \text{ where}$$

$$\begin{cases} Q_{el} = \frac{\sum_{i=1}^{n} Q_i}{n}, \\ DQ_{el} = \frac{\sum_{i=1}^{n} DQ_i}{n}, \; DQ_i \in \leq 0.5, 1 \geq \end{cases} \tag{2}$$

where K_{el}^{c}, K_{el}^{o} are stiffness coefficients of joints subjected to compression and tension; and P_{el}, Q_{el} are loads corresponding to deflections from the range of linear elasticity DP_{el}, DQ_{el}, which were calculated as means from DP_i, DQ_i measurements ranging from 0.5 mm to 1.0 mm. This range corresponded to 0.05–0.5 (P_{max}, Q_{max}).

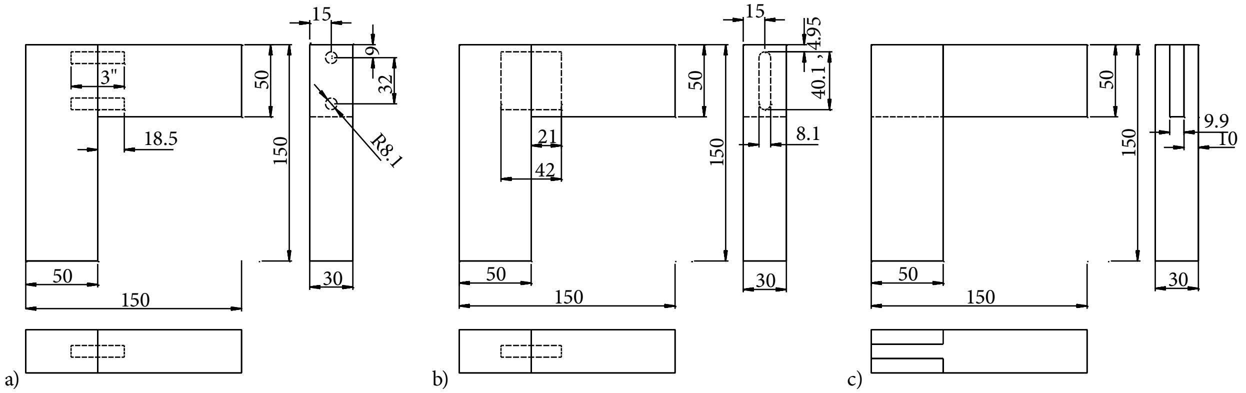

Figure 1. Dimensions (mm) of test joints: **a)** dowel joint; **b)** mortise and loose-tenon joint; **c)** mortise and tenon joint.

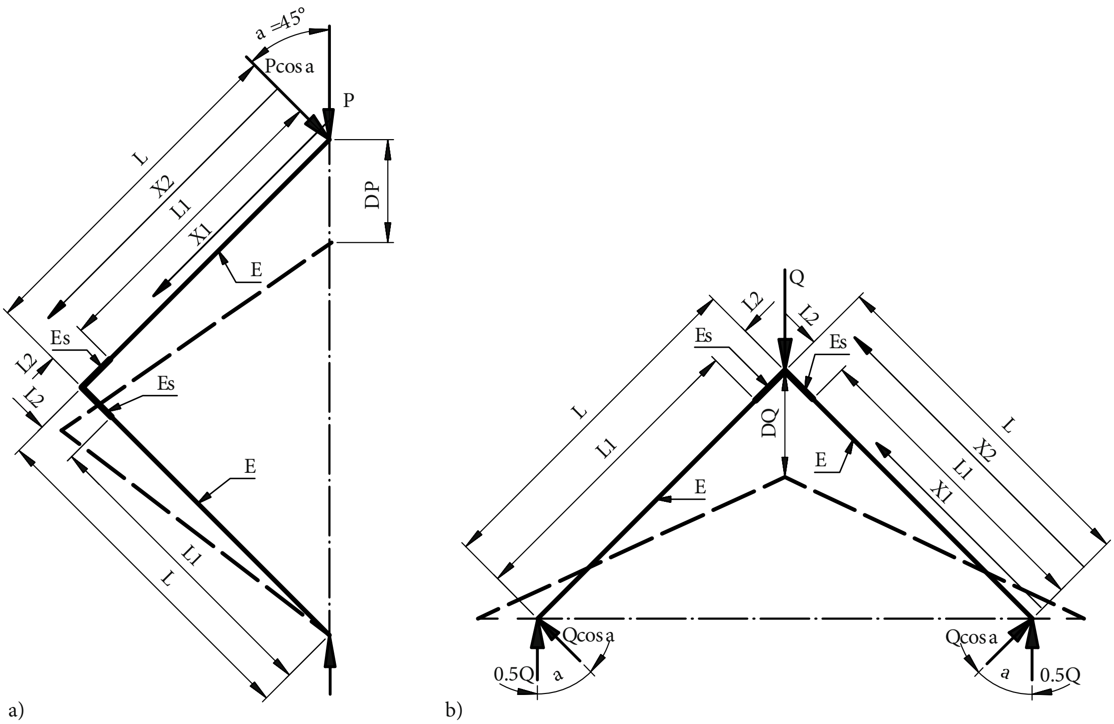

Figure 2. Method of joint loading. Calculation diagram: **a)** compression; **b)** tension.

Table 1. Description of joint specimens.

Symbol	Description of joints	
	Wood species	Type of joints
BD	Beech	Dowel
BLT		Loose-tenon
BMT		Mortise and tenon
OD	Oak	Dowel
OLT		Loose-tenon
OMT		Mortise and tenon
WD	Walnut	Dowel
WLT		Loose-tenon
WMT		Mortise and tenon

2.2. Determination of the elastic modulus of joints

The calculation model presented in Figure 2 was employed to estimate joint elasticity modulus. In this model, $L = 150$ mm designates the length of the joint arms; $L_2 = 50$ mm is the height of the frame cross-section; $L = L_1 + L_2$; x_1, x_2 are ranges of integration; E is the wood linear elasticity modulus; and E_s is the joint modulus of elasticity.

In the case of the joint subjected to compression, the constitutive equation describing the DP deflection in the direction of force P assumes the following form (Figure 2a):

$$DP = 2\left(\int_0^{L_1} \frac{P\cos^2\alpha}{EJ} x_1^2 dx_1 + \int_{L_1}^{L=L_1+L_2} \frac{P\cos^2\alpha}{E_s J} x_2^2 dx_2\right), \qquad (3)$$

$$J = bL_2^3/12, \qquad (4)$$

where J is the moment of inertia and b denotes the width of the frame cross-section at 30 mm. The solution of this equation yielded the following:

$$DP = \frac{2P\cos^2\alpha}{3J}\left(\frac{L_1^3}{E} + \frac{L^3 - L_1^3}{E_S}\right) \quad [\text{mm}]. \tag{5}$$

Therefore, the elasticity modulus of the joint assumed the following form:

$$E_S = \frac{2PE\cos^2\alpha(L^3 - L_1^3)}{3EJ\,DP - 2P\cos^2\alpha L_1^3} \quad [\text{MPa}]. \tag{6}$$

For the joint subjected to tension, the constitutive equation describing the *DQ* deflection in the direction of action of force *Q* assumes the following form (Figure 2b):

$$DQ = 2\left(\int_0^{L_1}\frac{Q\cos^2\alpha}{2EJ}x_1^2dx_1 + \int_{L_1}^{L=L_1+L_2}\frac{Q\cos^2\alpha}{2E_SJ}x_2^2dx_2\right). \tag{7}$$

$$DQ = \frac{Q\cos^2\alpha}{6J}\left(\frac{L_1^3}{E} + \frac{L^3 - L_1^3)}{E_S}\right) \quad [\text{mm}] \tag{8}$$

and

$$E_S = \frac{QE\cos^2\alpha\left(L^3 - L_1^3\right)}{6EJDQ - Q\cos^2\alpha\, L_1^3} \quad [\text{MPa}]. \tag{9}$$

It was further decided to ascertain the physicomechanical properties of the applied wood species. The linear modulus of elasticity *E*, static bending strength, or modulus of rupture (*MOR*), as well as wood density, were determined in accordance with appropriated standards (Polish Committee for Standardization, 1963, 1977a, 1977b) (Table 2). In all, 90 samples were employed, i.e. 10 replications for each treatment.

Using Eqs. (6) and (9), E_s was calculated for each joint specimen and the obtained results were then used for numerical calculations.

2.3. Numerical modeling of joint stiffness

Practical elasticity modulus usefulness of L-type joints was verified on the basis of numerical calculations. Figure 3 presents a model for an L-type joint consisting of 8 elements and 9 nodes. In this model, elements between nodes 1 and 4 and 6 and 9 were beams with the elastic modulus *E* and Poisson coefficient of n = 0.3. Beams between nodes 4 and 6 were characterized by a modulus of elasticity of E_s (n = 0.3). The length of the beams as well as their cross-sectional dimensions corresponded to the joint dimensions depicted in Figure 1. The model was loaded with a concentrated force P_{el}, Q_{el}, i.e. in the same way as in the performed laboratory tests (Figures 2a and 2b). Joint stiffness was determined with the assistance of Eqs. (1) and (2) in accordance with the loading diagrams. Calculations were conducted with 2013 Autodesk Simulation Multiphysics software.

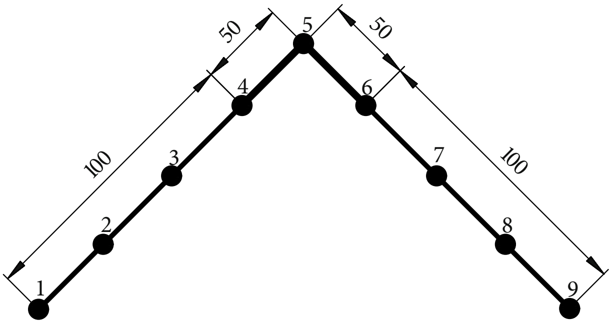

Figure 3. Model of numerical calculations (mm).

3. Results and discussion

3.1. Strength and stiffness of joints

Characteristic failure images of individual types of joints are presented in Figure 4. In all cases, it was the adhesive bond that underwent shearing. In addition, in the case of dowel joints, depending on the loading type, either the top (closed joints) or the bottom (opened joints) dowel pin was pulled out. In the case of loose-tenon joints, either the top or bottom edge was pulled out. On the other hand, in mortise and tenon joints, they underwent damage as a result of the rotation of the tenon and mortise.

Figures 5a–5d illustrate the stiffness of the examined joints in the form of dependences between the load and the deflection. These dependences are of nonlinear nature and hence their failures occurred outside the range of linear elasticity. It is evident from Figure 5 that the strength of the joints under tension was greater than the strength of the joints under compression. This obvious difference is the

Table 2. Physicomechanical properties of wood species.

Wood species	Density [kg/m^3]		*MOR* [MPa]		*E* [MPa]	
	$\overline{X}$	COV (%)	$\overline{X}$	COV (%)	$\overline{X}$	COV (%)
Oak	740	1.8	111.4	6.8	12,917	13.50
Beech	530	1.4	108.3	5.0	14,250	4.50
Walnut	610	6.1	59.8	12.0	7269	19.60

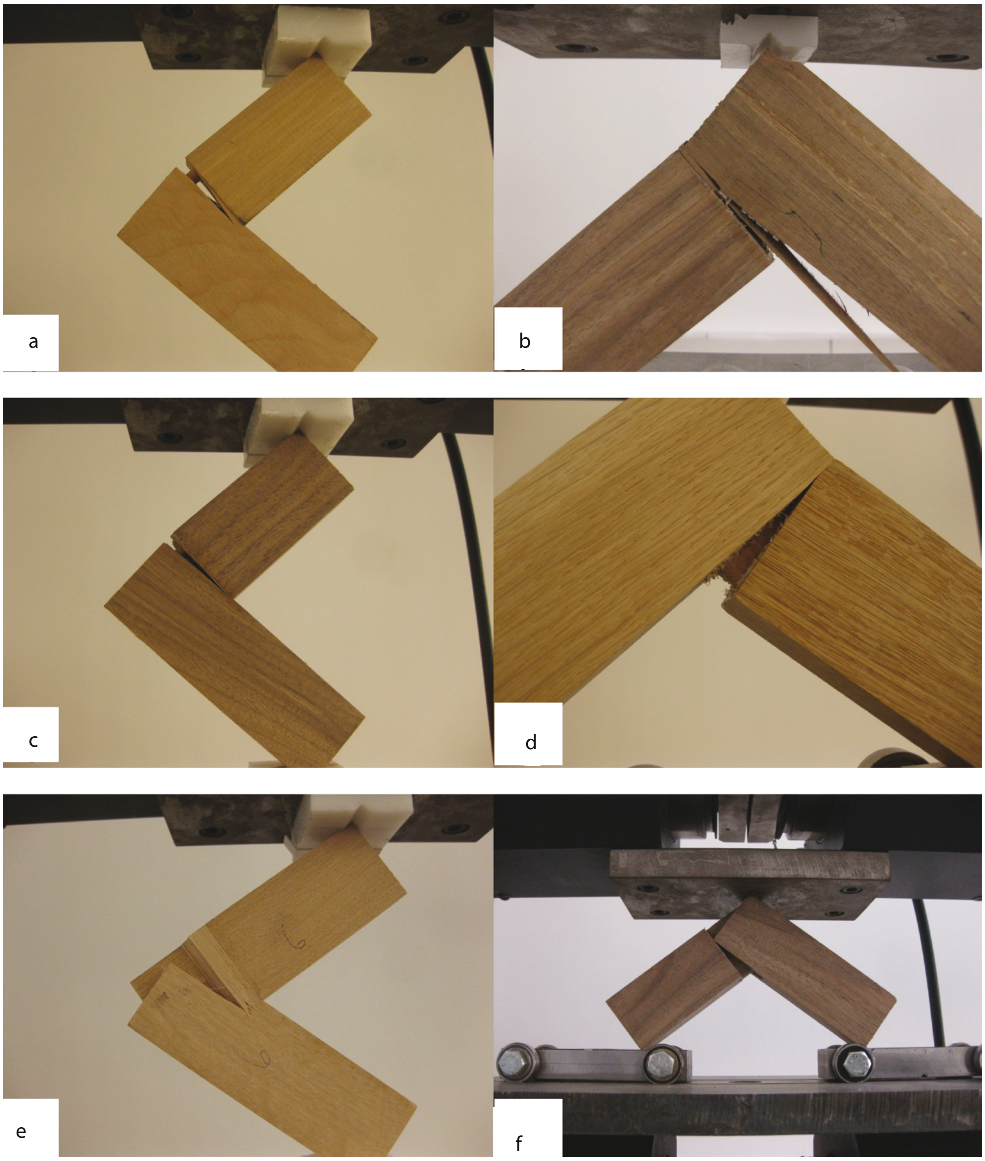

Figure 4. Examples of failure modes: **a, b)** dowel joints; **c, d)** mortise and loose-tenon joints; **e, f)** tenon and mortise joints

result of different patterns of support and loading as well as of value differences among the support forces. It is also evident that mortise and tenon joints exhibited the highest strength and deformability, whereas those with mortise and loose-tenon showed slightly lower values, and dowel joints demonstrated the lowest strength and deformability (Figures 5b and 5d). The same tendencies are expressed by the figures in Table 3, in which maximum breaking forces P_{max}, Q_{max} and their corresponding deflections DP_{max}, DQ_{max} are collated. It is clear from the analysis of the data that in the group of joints under tension, the mean strength of the tenon and mortise joints was 97.7% higher in comparison with the mean strength of the loose-tenon joints and 216.7% higher than the mean strength of the dowel joints. In the group of joints under compression, these differences were 133.2% and 261.5%, respectively. The above-mentioned differences can be primarily attributed to the shape of the connectors and dimensions of glue bonds (Warmbier and Wilczyński, 2000; Wilczyński and Warmbier 2003; Derikvand et al., 2013). The strength of the dowel joint is determined by the bending and shear strength of wooden dowel pins (Smardzewski, 2008). On the other hand, the strength of mortise and tenon joints depends on the torsion area of the glue bond. In the case of the mortise and tenon joint this area amounts to 2 × 50 × 50 mm, whereas in the case of the loose-tenon joint it amounts to 2 × 40 ×

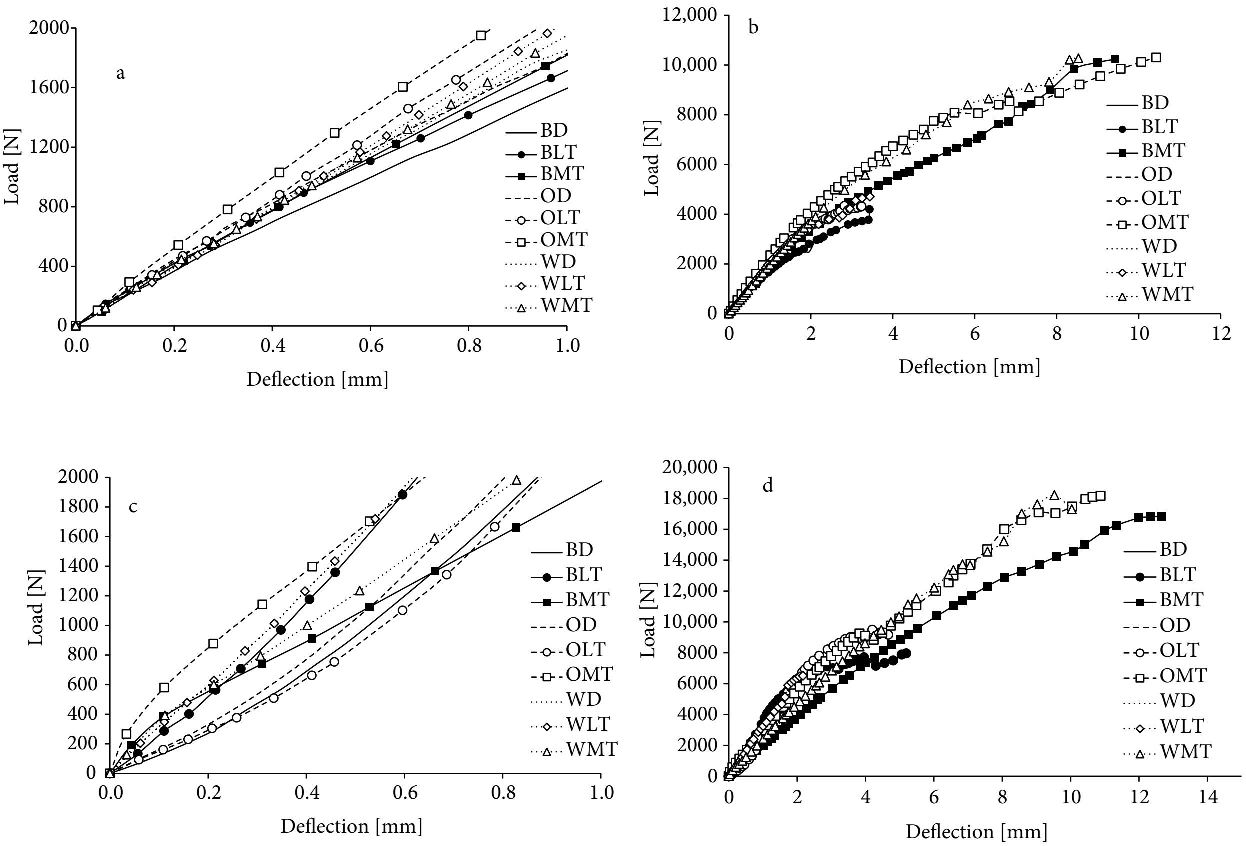

Figure 5. Stiffness of joints: **a)** compression: linear-elastic range; **b)** compression: entire range; **c)** tension: linear-elastic range; **d)** tension: entire range.

Table 3. Load capacities of joints.

Type of joint	Type of test	P_{max}, Q_{max}		DP_{max}, DQ_{max}	
		[N]	COV (%)	[mm]	COV (%)
BD	Compression	3003	16	2.12	13
OD		2420	14	1.51	9
WD		3102	15	1.72	15
BLT		4194	20	3.43	28
OLT		4312	11	3.24	15
WLT		4703	13	3.44	22
BMT		10,236	21	9.42	25
OMT		10,302	25	10.43	40
WMT		10,271	27	8.53	36
BD	Tension	5102	23	2.16	16
OD		4903	16	1.94	19
WD		6510	23	2.17	26
BLT		7958	11	5.19	22
OLT		9168	12	4.66	12
WLT		9331	9	6.07	31
BMT		16,842	7	12.65	10
OMT		18,168	20	10.88	33
WMT		17,293	24	10.04	20

40 mm. Therefore, the difference is 56%. That is why the mortise and tenon joints exhibited greater strength than loose-tenon joints. It should also be emphasized that the highest strength in the group of mortise and tenon joints was observed in joints constructed of oak, whereas in the group of dowel and loose-tenon joints it was observed in joints constructed of walnut. Considering the low bending strength of walnut, as well as its lower linear elasticity modulus in comparison to beech and oak (Table 2), the described regularities required additional analyses of the stiffness of the examined joints.

Figures 5a and 5c present a section of the curves from Figures 5b and 5d comprising segments of linear elasticity for deflections not exceeding 1 mm. It is evident in these figures that the stiffness of all joints under compression was contained between the stiffness of OMT and BD joints. On the other hand, the stiffness of the joints under tension was contained between the stiffness of OMT and OLT joints. Mean P_{el}, Q_{el}, DP_{el}, and DQ_{el} values for the range of deflections from 0.5 mm to 1 mm are presented in Table 4. On the basis of these values, stiffness coefficients , were calculated. It is evident from this collation that the WLT joints exhibited the highest (3841 N/mm) stiffness during the tension test. The stiffness of the remaining joints ranged from 51% (OLT) to 85% (OMT) of the stiffness of the reference solution. In the compression test, the highest stiffness was obtained in the OMT joints (2416 N/mm). The stiffness of the remaining joints in the same group ranged from 65% (BD) to 88% (OLT) of the OMT joint stiffness. Moreover, the calculated stiffness coefficients exhibited a tendency whereby the loose-tenon joints as well as the mortise and tenon joints were characterized by highest stiffness in tension and compression tests within the elastic range, respectively. The reason for which the stiffness of loose-tenon joints exceeds the stiffness of mortise and tenon joints is the nature of the glue bond (Smardzewski, 1998; Prekrat and Smardzewski, 2010). Figure 6 illustrates the distribution of tangential stresses in the glue bond of the loose-tenon and mortise and tenon joints. It is evident in this figure that in the case of the loose-tenon glue bond, two opposite distributions of resultant tangential stresses τ and τ_{Max} are generated, which constitute a response to external bending moments and transverse forces (Figure 6a). This division results from

Table 4. Stiffness values of joints.

Type of joint	Type of test	E_s [MPa]	P_{el}, Q_{el} [N]	DP_{el}, DQ_{el} [mm]		a/b d/c	[N/mm]		
				Experiment	FEM		Experiment	FEM	Differences
				(a)	(b)		(c)	(d)	by %
BD	Compression	4579	1496	0.94	1.01	0.93	1592	1481	6.97
OD		5612	1535	0.82	0.89	0.92	1873	1725	7.90
WD		6578	1485	0.79	0.87	0.91	1880	1707	9.20
BLT		5001	1582	0.92	0.99	0.93	1720	1598	7.09
OLT		6555	1471	0.69	0.74	0.93	2132	1988	6.75
WLT		7310	1459	0.72	0.80	0.90	2027	1824	10.01
BMT		5411	1474	0.80	0.87	0.92	1842	1694	8.03
OMT		7644	1474	0.61	0.66	0.92	2416	2233	7.57
WMT		6933	1562	0.80	0.88	0.91	1953	1775	9.11
BD	Tension	1361	1364	0.66	0.69	0.96	2066	1977	4.31
OD		1494	1351	0.60	0.63	0.95	2251	2144	4.75
WD		2227	1340	0.43	0.46	0.93	3116	2913	6.51
BLT		1994	1339	0.45	0.48	0.94	2975	2790	6.22
OLT		1313	1372	0.69	0.73	0.95	1989	1879	5.53
WLT		2830	1383	0.36	0.38	0.95	3841	3639	5.26
BMT		1334	1541	0.76	0.80	0.95	2027	1926	4.98
OMT		2233	1578	0.48	0.51	0.94	3288	3094	5.90
WMT		1679	1450	0.60	0.64	0.94	2417	2266	6.25

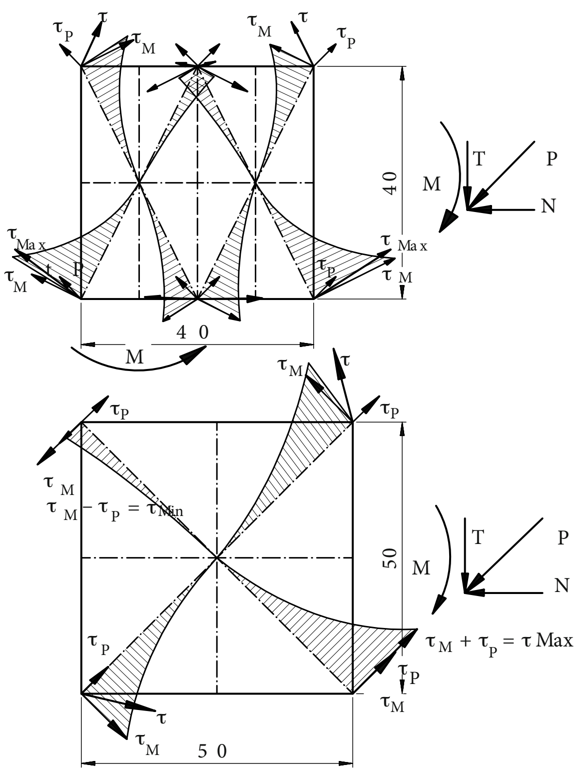

Figure 6. Distribution of tangential stresses in joint glue bond: **a)** loose-tenon; **b)** tenon and mortise. M: Bending moment; P: resultant force equals external load; T: vertical constituent of P force (shear force); N: horizontal constituent of P force (normal force); τ_P: tangential stress caused by load *P*; τ_M: tangential stress caused by moment *M*; τ: resultant tangential stress from τ_P, τ_M; τ_{Max}: maximal resultant tangential stress.

the fact that the loose-tenon undergoes bending separately in the vertical and horizontal frame. This causes the stresses that constitute a response to a bending moment and transverse forces in the vertical frame to appear in the left part of the glue bond, whereas the stresses that are a response to forces in the horizontal frame appear in the right part of the bond. In the case of the mortise and tenon joint, only one distribution of stresses occurs, constituting a response to external loads (Figure 6b). Hence, for the constant value of external loads, the tangential stresses of Figure 6a cause smaller nondilatational strains of the glue bond than the stresses illustrated in Figure 6b. Therefore, smaller nondilatational strains of the glue bond result in smaller deflections of bonds.

Another noticeable tendency was that the stiffness of the examined bonds depended on the applied wood species. For the joints under tension, walnut turned out to have the dominant role, whereas in the case of the joints under compression, oak played the most important role. This was the result of the character of loads and elastic properties of wood and glue bond (Maleki et al., 2012; Dalvand et al., 2013; Derikvand et al., 2014). The scope of deformations of the torsional bond and the adhesive wood layers depends on their shape elasticity modulus (Kirchhoff's modulus) (Smardzewski, 1998; Wilczyński and Warmbier, 2003; Prekrat and Smardzewski, 2010). Higher Kirchhoff's modulus of adherents and glue favors small joint deformations and deflections.

3.2. Joint elastic modulus

Table 4 and Figure 7 show the elasticity modulus of the examined joints. It is evident that joints subjected to compression were characterized by 2–3 times higher values of this modulus in comparison to joints that were subjected to tension. In the group of joints under compression, the highest elasticity modulus was found in the OMT joints. Moreover, mortise and tenon joints, with the exception of WMT, exhibited higher elasticity than loose-tenon joints and dowel joints. It is also interesting to note that joints constructed of walnut, with the exception of WMT, were characterized by the highest elasticity modulus. Walnut, in comparison to beech and oak, exhibited the lowest elasticity modulus *E*, low *MOR* strength, and moderate density. Therefore, it is possible to put forward a hypothesis that the high elasticity of these joints depends on glue adhesion forces to wood. Dependences between types of joints and wood species for the joints under tension were similar.

It is evident from the above discussion that the elastic modulus of joints E_s expresses joint stiffness more effectively than the coefficient (Smardzewski and Kłos, 2011; Smardzewski et al., 2013). The coefficient depends solely on the load and its corresponding deflection. The elasticity modulus, on the other hand, is a complex function of many variables. Apart from the load and its corresponding deflection, it also depends on the material elasticity of the arms of a given joint as well as on the length and cross-section dimensions of frames. It is also more convenient to apply this solution to virtual prototyping methods that utilize finite elements methods (Wilczyński and Warmbier, 2003; Gawronski, 2005; Tankut and Tankut, 2011).

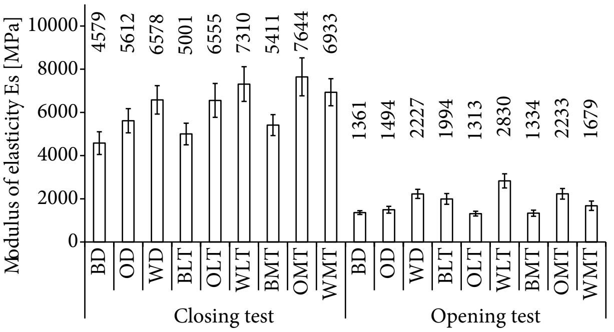

Figure 7. Mean modulus of joint elasticity and standard error.

3.3. Results of numerical calculations

The results of numerical calculations of DP_{el}, DQ_{el} deflections as well as , elasticity coefficients together with their reference to the results of empirical tests are collated in Table 4. It is clear in this table that the experimental results differ only slightly from the results of the numerical calculations. The values determined numerically differ from the laboratory results by 4%–10%. Taking into account the scale of error and comparing it with the results of similar experimental coefficients (Smardzewski and Kłos, 2011; Smardzewski et al., 2013), the model could be considered successful. A number of conclusions and general remarks can be put forward on the basis of the obtained results and their analysis. Joints manufactured from walnut and oak were characterized by the highest strength. Mortise and tenon as well as mortise and loose-tenon joints distinguished themselves by high strength and stiffness. Elasticity modulus of joints expressed their stiffness better than the stiffness coefficient. The accuracy of the elaborated model of joint elasticity modulus was verified positively by experimental investigations as well as by numerical calculations. The application of joint elasticity modulus simplifies the numerical analysis of frame furniture construction.

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