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Tensile Performance of Traditional and Modern Corner Joints in Wooden Structures

Vlačna svojstva tradicionalnih i modernih kutnih spojeva u drvnim konstrukcijama

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ABSTRACT • *Corner joints are critical points of wooden structures not only in furniture construction but also in traditional wooden architecture, especially in constructions without nails. This study was performed to determine the effects of particular factors such as the axis of assembly, types of material, and adhesive on the tensile performance of various modern and traditional types of wooden corner joints. For this purpose, various corner joint specimens were prepared with three different wooden materials: Scots pine (Pinus sylvestris Lipsky) wood, Lombardy poplar (Populus nigra Lipsky) wood, and Medium Density Fibreboard (MDF) using two different adhesives: polyvinyl acetate (PVAc) and polyurethane (Desmodur-VTKA) glues; and five different wooden joint types: dowel, tongue-and-groove, half-blind dovetail, screw, and eccentric screw joints. Tensile performance tests, vertical and parallel to the axis of assembly, were carried out according to ASTM D 1037 guidelines. Experiments indicated that, while the tensile performance of MDF specimen connected with a screw and PVAc adhesive was the highest under loading parallel to the axis of assembly (4592 N); it was the lowest under loading parallel to the axis of assembly in MDF specimen connected with tongue-and-groove joint and PVAc adhesive (260 N), respectively. As a result, it may be advantageous to apply screwed joints in corners for high tensile strength in parallel to the axis of the assembly.*

KEYWORDS: *tensile performance; construction materials; corner joints; wooden joints*

SAŽETAK • *Kutni su spojevi kritične točke drvnih konstrukcija ne samo u proizvodnji namještaja nego i u tradicionalnoj drvnoj arhitekturi, posebice u konstrukcijama bez čavala. Ovo je istraživanje provedeno kako bi se utvrdili učinci specifičnih čimbenika kao što su os montaže, vrsta materijala i vrsta ljepila na vlačna svojstva različitih modernih i tradicionalnih vrsta drvnih kutnih spojeva. Za tu su svrhu pripremljeni različiti uzorci kutnih spojeva od tri vrste drvnog materijala: od drva bijelog bora (Pinus sylvestris Lipsky), drva lombardijske topole (Populus nigra Lipsky) i od srednje guste ploče vlaknatice (MDF), uz uporabu dvaju različitih ljepila: polivinilacetatnoga*

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(PVAc) i poliuretanskoga (Desmodur-VTKA) te uz pet različitih vrsta drvnih spojeva: moždanika, pera i utora, poluzatvorenog lastina repa, vijka i ekscentra. Ispitivanja vlačnih svojstava okomito i paralelno s osi montaže provedena su u skladu s normom ASTM D 1037. Rezultati su pokazali da su najbolja vlačna svojstva MDF uzorka spojenoga vijkom i PVAc ljepilom pod opterećenjem paralelno s osi montaže (4592 N), a najlošijima su se pokazala vlačna svojstva MDF uzorka spojenoga perom i utorom te PVAc ljepilom pod opterećenjem paralelno s osi montaže (260 N). Prema tome, primjena vijaka u kutnim spojevima može biti dobar izbor za postizanje visoke vlačne čvrstoće paralelno s osi montaže.

KLJUČNE RIJEČI: *vlačna svojstva; konstrukcijski materijali; kutni spojevi; drvni spojevi*

1 INTRODUCTION
1. UVOD

Wood is a sustainable, environmentally friendly and renewable material that has good strength compared to its density. Moreover, it is compatible with other building materials and can be very long-lasting when used properly (Bozkurt, 2011). With these features, it was used as a basic building material in traditional Turkish architecture from furniture to building elements such as: lateral and vertical bracing elements, roof trusses, door-window frames, etc. The widespread use of wood in Anatolia has led to the development of various jointing techniques, generally called "Çantı" (Figure 1).

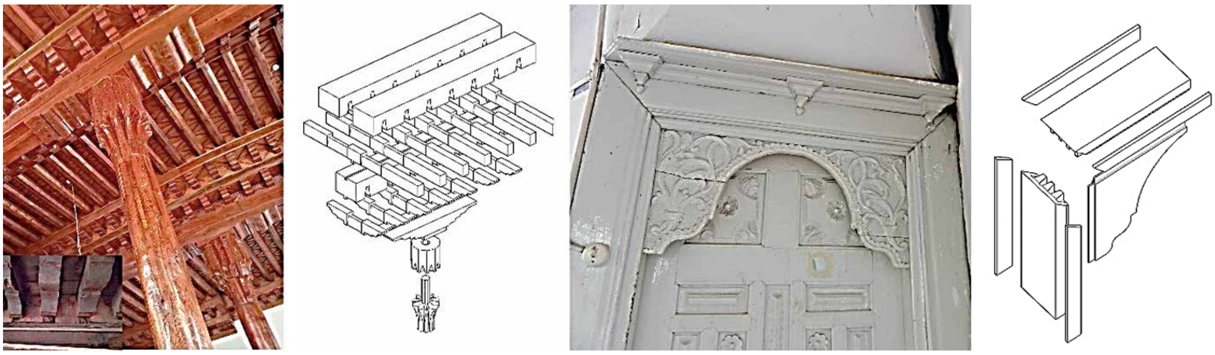
Finger jointing (Kurtboğaz Geçme) is one of the popular techniques of the "Çantı" in the Eastern Black Sea region and is implemented by interdigitating pieces together with dowels instead of nails. These elements are used to carry the load of the building, to create windows and door frames and they provide room corners (Akbaş and Özcan, 2018). The dovetail technique (Kırlangıç Kuyruğu) is another common type of interdigitating, frequently used in floor and corner jointing. In the dovetail, the male tongue does not come out of the female groove as a result of its special "V-shaped" tapering structure.

The dovetail joint is an ancient technique, the first examples of which were found in Ancient Egypt used in sleds carrying heavy stones in the pyramid construction (Arnold, 1991; Edwards, 2010). It has been widely used in simple carpentry, sophisticated decorative joints, basic building techniques, and the highest standards of cabinet making. Hence, as Edwards (2010) conveyed, dovetail jointing can represent the history of furniture and timber building construction and production. Another example where wood is interdigitated without using nails is found in the structure of the historical hypostyle wooden mosques of Anatolia (Figure 1a). In these mosques, wooden beams are connected by tapered grooves tightly together like a single dovetail. These kinds of joints provide flexible jointing that increased the strength of the structures against lateral and vertical loads. Thanks to this strength, these structures survived today as an important work of traditional building art (Develi, 2019). However, as steel and concrete replaced the wood material in contemporary Turkish architecture, currently, these traditional wooden details are not used by modern construction. Nevertheless, the experiences gained from these structures in terms of construction techniques are still used in the construction of wooden doors, windows, and furniture.

Since ancient times, narrow pieces have been widely used with tongue-and-groove, and dowel joints in wooden interdigitating furniture constructions (Küreli, 1988). Nevertheless, the invention of finger jointing had strengthened the joints in wooden corners – such as window and door frames, furniture, and various wooden structural bearing elements (columns, beams)- 60-80 % more than the use of dovetail and tongue-and-groove jointing (Örs,1987; Altınok, *et al.*, 2010). Today, many connections and bonding techniques have been developed with increasing wooden sectors especially furniture production. It is important for carpenters to know which type and size of loads will be applied during the use of the wooden element. To ensure efficient use conditions, the elements and joints of furniture must be designed to meet these expected loads. Moreover, new materials and techniques may advance the details and may help carpenters to strengthen the wooden corners.

In addition to traditional techniques, there are also detachable connecting fittings (threaded bolt with a pivot pin (so-called Minifix), Lamello Clamex P 15, Lamello Invis Mx, Clamex P14, Tenso P14), which have been spreading rapidly in recent years (Kasal, 2004). Although there are many separate or comparative studies on the structural capacity of wooden corners of these joints in the literature (Gou *et al.*, 2019; Atar *et al.*, 2017; Simeonova, 2016; Jivkov and Marinova, 2016; Smardzewski *et al.*, 2014), those related to the relatively new Clamex P14 and Tenso P14 fasteners are few in number (Saar *et al.*, 2015; Karaman, 2019; Prekrat *et al.*, 2019; Karaman, 2020, Karaman, 2021).

The strength of a wooden corner depends not only on the materials but also on the joint types. This study surveyed the rigidity of edge-to-edge joints in wooden corners. Edge-to-edge joints are statically critical points of box-type wooden elements such as door and window frames (Figure 1b), cabinets, chests, etc.



a) b)

Figure 1 a) Photo and detail of "Çantı" technique in a traditional Turkish wooden hypostyle mosque; Ulucami in Ayaş-Ankara b) Photo and detail of a wooden corner of a door frame in a traditional Turkish house; Kızılcabölük – Denizli
Slika 1. a) Fotografija i detalj tehnike *çantı* u tradicionalnoj turskoj drvnoj hipostilnoj džamiji Ulucami u Ayaş-Ankari, b) fotografija i detalj drvnog kuta dovratnika u tradicionalnoj turskoj kući (Kızılcabölük – Denizli)

Moreover, additional mechanical forces may occur in kinetic box-type wooden elements such as drawers. Whether it is static or kinetic, compelling forces in the corners may cause deformation over time in box-type wooden elements. To determine these deformations, various researches have been carried out on the effects that a corner can be exposed to.

In box-type construction, the strength and durability of the structure depend on the torsional stiffness and rigidity of the plates. Box-type constructions are mostly four-sided, forming a frame with a backplate. If the main box carries other frames, such as drawers and cabinet doors, then the structure is generally defined as frame-type wooden construction. A bookshelf is an example of a box-type and a laundry cabinet with drawers can be given as an example of the frame-type (Eckelman, 1978).

As a critical point of carpentry both for furniture and building construction, the performance of wooden joints had been a subject of interest for many years. Some of these studies focused on the bending behavior of jointing details (Chen *et al.*, 2016; Kamperidou and Vasileiou, 2012) while others such as Rad *et al.* (2019) focused on tension. Within many studies on tension and compression resistance of wooden corners, most of them were about the resistance of furniture corners. As regards these studies, glued (fixed) and non-glued (disassembled) joints for corners used in the production of box-type furniture, fiberboards have better results than particleboards, and also, non-glued (disassembled) joints have better performance than glued (fixed) joints (Atar, 2006; İmirzi, 2000; Efe, *et al.*, 2003; Hrovatin and Zupančič, 2013; Kasal, *et al.*, 2006; Şakacı, 2010; Efe, *et al.*, 2012). Efe and Kasal stated that multifix fasteners are more successful than minifix fasteners (Efe, *et al.*, 2000). Şafak (2000) indicated that corner joints with non-glued multifix have the best performance. As a result of the literature review, it is seen that studies mostly focused on the comparison of two-factor affecting the tensile strength of wooden corners. Nevertheless, this study aims to analyze the tensile performance of wooden corner joints under 4-factor interaction: the jointing technique, the type of material, the axis of assembly, and the type of adhesive.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The test specimens for analysis of wooden corner joints were prepared by using Scots pine (*Pinus sylvestris* Lipsky), Lombardy poplar (*Populus nigra* Lipsky), and medium density fiberboard (MDF), which were preferred due to their wide use in furniture and construction industry. Two kinds of adhesives - polyvinyl acetate (PVAc) and polyurethane (Desmedur-VTKA), and 5 kinds of joinery techniques - 8x35 mm dowel joint, tongue-and-groove joint, half-hidden dovetail joint, 4 mm × 60 mm philips-headed flat screw joint, and eccentric joints, were selected. Additionally, the assembly of the plates was done in two different axes, parallel and perpendicular to the axis of the assembly. Hence; 300 (2 × 5 × 3 × 2 × 5) different tests were executed with 2 adhesives, 5 joinery techniques, 3 materials, 2 axes of assembly with 5 specimens each.

Each test specimen consisted of two plates, A and B, and the thickness of all the specimens was chosen as 16 mm. A is in 100 mm × 109 mm dimensions while B is 100 mm × 125 mm, and their placement is shown in Figure 2. In the test specimen with dowel joint, wedge dowels of 8 mm in diameter and 35 mm in length were used. Dowel holes were drilled in the beveled combination with two centers 8 mm in diameter and 23 mm in depth and 8 mm in diameter and 12 mm in depth on the face of the plate B, so that the center of the dowel on plate A would be symmetrical to the center of the

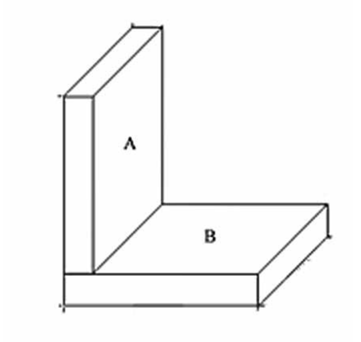


Figure 2 Dimensions of test specimen (dimensions in mm)
Slika 2. Izgled ispitnog uzorka (dimenzije u mm)

hole and directly fit in. The dimensions of the wooden dowel joint specimen are shown in Figure 3a. Approximately 150 g of adhesive was applied with a brush on the overlapping surfaces of plates A and B and the dowel holes; afterward, a torsion force at a pressure of 0.2-3 N/mm^2 was applied to assemble the test specimens. Assembly of test specimens was carried out under (20±2) °C temperature and (65±3) % relative humidity in the conditioning chamber and they were heated until they reached the counterweight.

The dimensions of the test specimen, which was produced by circular saw cutting on the principles of the tongue-and-groove joint, are shown in Figure 3b. The test specimen was assembled by applying a pressure of 0.2-3 N/mm^2 with clamp after applying with a brush approximately 150 g of adhesive to the overlapping surfaces of plates A and B. The assembled samples were allowed to reach constant weight in the conditioning chamber under the temperature of (20±2) °C and relative humidity of (65±3) %.

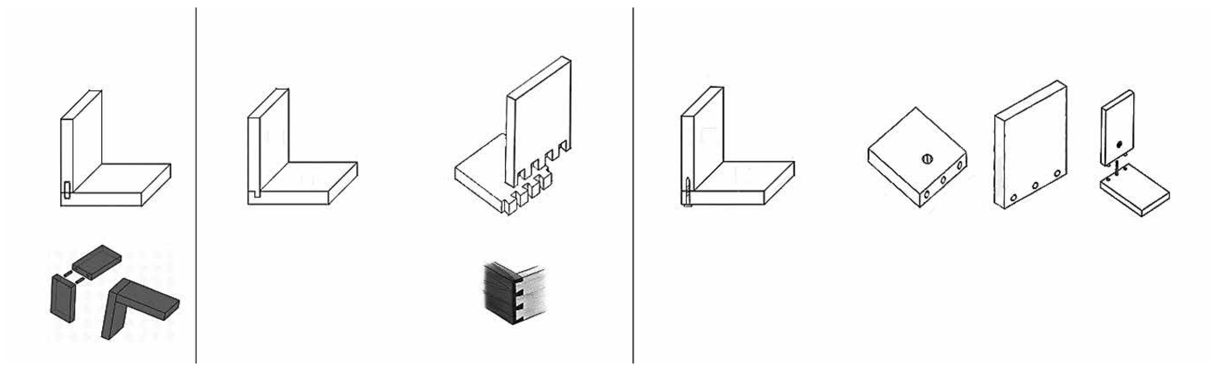
The pins and tails of the test specimen with a half-blind dovetail joint were cut in a threading machine. The dimensions of the specimen are shown in Figure 3c. Test specimens were assembled by applying a pressure of 0.2-3 N/mm^2 on the tacked planes after applying approximately 150 g of adhesive with a brush to the overlapping surfaces of plates A and B. The assembled samples were stored until reaching a constant weight in the conditioning chamber under the temperature of (20±2) °C and relative humidity of (20±2) %.

In the test specimen with the screw joint, the screw pilot holes were drilled by using the horizontal and vertical drilling machines. In the preparation of the specimen, the principles stated in TS EN 326-1 were respected (TS EN 326-1, 1999). Accordingly, a pilot hole, with a diameter of about 60 % of the thread diameter of the connecting screw, was drilled in the edges of panels. The depth of the pilot hole was 5 times its diameter. The connections of the screws complied with the recommendations of ASTM 1037 and the manufacturers (ASTM D 1037, 2006). Accordingly, the screws were connected to the pilot slots and the screw axis, so that they were perpendicular to the edges of the plates (TS EN 13446, 2005). The screws used in the experiments (4 mm × 60 mm) had a diameter of 4mm, while the hole diameter was (2.5±0.5), the pilot hole diameter was (12.5±0.5), and the screwing depth was (20.5±0.5) mm (Figure 3d).

For the test specimen with eccentric joint, the operations on the plate were carried out with the hole drilling machine. The dimensions of the test specimen are shown in Figure 3e. After drilling the holes, the parts of the eccentric connecting joint were assembled so that the plates A and B were mounted following the specified principles for the non-adhesive eccentric connecting. The assembled test specimens were stored until reaching a constant weight in the conditioning chamber with a temperature of (20±2) °C and relative humidity of (65±3) %.

2.2 Testing and data analyzing procedure
2.2. Ispitivanje i analiza podataka

After the selection of the wood material as defined in TS 2470, TS 64-3, and EN 622-3, the prepared



a) b) c) d) e)

Figure 3 Test specimens: a) Wooden dowel jointed test specimen - DJ, b) Test specimen with tongue-and-groove joint - TGJ, c) Test specimen with half-blind dovetail joint – DTJ, d) Test specimen with screw joint – SJ, and e) Test specimen with eccentric (Minifix) joint – MJ
Slika 3. Ispitni uzorci: a) drvni ispitni uzorak spojen moždanikom – DJ, b) ispitni uzorak spojen perom i utorom – TGJ, c) ispitni uzorak spojem poluzatvorenim lastinim repom – DTJ, d) ispitni uzorak spojen vijkom – SJ, e) ispitni uzorak spojen ekscentrom (Minifixom) – MJ

Table 1 Measured tensile stress values as Kgf
Tablica 1. Izmjerene vrijednosti vlačnog naprezanja kao Kgf

Joinery tech. *Tehnika spajanja*	**Test**	**Parallel to the axis of assembly (I)** *Paralelno s osi montaže (I)*						**Vertical to the axis of assembly (II)** *Okomito na os montaže (II)*					
	Wood *Drvo*	**Scots Pine (Sp)** *Borovina (Sp)*		**Poplar (Po)** *Topolovina (Po)*		**MDF**		**Scots Pine (Sp)** *Borovina (Sp)*		**Poplar (Po)** *Topolovina (Po)*		**MDF**	
	Adh.	PVAc	PU	PVAc	PU	PVAc	PU	PVAc	PU	PVAc	PU	PVAc	PU
DJ	max.	162	140	152	130	192	202	260	302	246	265	300	302
	min.	150	120	130	106	164	157	219	256	205	190	252	276
	s	5.02	7.12	7.98	8.87	11.43	18.9	16.54	17.72	17.64	31.4	19.51	10.6
	v	25.2	50.8	63.8	78.8	130.8	358	273.8	314	311.5	986	380.8	113
	x	155.8	129.4	140.6	119.6	178.4	176	241.4	277	224	234	274.6	289
TGJ TGJTG	max.	95	195	60	150	31	73	126	182	116	142	102	126
	min.	58	158	30	100	22	58	89	103	72	110	68	98
	s	15.36	14.97	11.45	19.38	3.67	5.97	14.72	32.91	17.72	11.9	14.2	11.4
	v	236.2	224.2	131.2	375.8	13.5	35.7	216.7	1083	314	143	201.8	130
	x	74.2	175.8	45.8	130.6	26	63.8	105.2	141.4	95	126	85.4	113
DTJ	max.	243	273	243	263	330	355	234	283	233	263	212	217
	min.	218	235	190	223	276	320	208	230	196	220	187	192
	s	10.08	14.84	21.01	15.17	22.71	13.1	9.98	29.03	14.69	16.9	11.56	9.39
	v	101.7	220.3	441.7	230.3	516	171	99.7	401.5	216	288	134.5	88.3
	x	232.8	253.4	211.8	242.6	301	336	221.2	255	215	242	198	202
SJ	max.	380	350	374	334	471	460	350	338	332	321	460	395
	min.	345	309	300	296	450	436	316	296	297	285	514	349
	s	14.81	15.82	28.6	15.17	8.22	9.94	13.01	16.51	14.42	13.9	17.12	20.2
	v	219.5	250.3	818.3	230.2	67.7	98.8	169.3	272.8	208.2	195	293.3	410
	x	362	331.4	338.4	313.8	459.2	446	333.6	315.4	312.2	304	435.6	371
MJ	max.	205		182		155		223		184		340	
	min.	148		136		122		200		159		300	
	s	22.34		18.29		14.01		8.98		10.84		15.3	
	v	499.3		334.8		196.3		80.7		117.7		234.2	
	x	177.6		157.6		134.4		212.8		173.2		322.2	

s – Standard deviation / *standardna devijacija*, *v* – Variance / *varijanca*, *x* – Average / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo* specimens were tested with 3000 kp capacity SEIDNER test device in the laboratory of Gazi University, Faculty of Technology, Department of Wood Products Industrial Engineering. By using the standard procedure of ASTM D 1037, an axial tension test was conducted under 2 mm/min in the pressure arm. The forces on the test specimens were recorded as Newton. In this research, the effects of various factors - such as types of material, adhesive, and load cases - on the tensile performance of defined corner joints in box-type wooden structures were studied. Multiple variance analysis (MANOVA) was conducted to determine the effects of these factors on tensile performance, and the DUNCAN test was used to indicate the level of significance with a 5 % margin of error.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Measured tensile stress values of different joinery techniques according to the types of material and adhesive under two different load cases are given in Table 1, and the results of the multivariate analysis of the tensile performance of the different joinery techniques according to the types of material, and adhesive, and under two different load cases are given in Table 2. The analysis indicated that the difference between the factors – joinery techniques, types of material, axis of assembly, and types of adhesive – are statistically significant (α = 0.05). The Duncan test results are used to determine which groups of differences are significant and they are given in the comparison of interactions.

The average values of tensile performance in terms of joinery techniques are given in Table 3. The tensile strength of the screwed joint (SJ) (3603 N) is maximum for all test specimens, while the tongue-and-groove joint (TGJ) (986 N) is minimum. Regarding the joinery technique, the tensile strength performance of the screw joint is followed by the half-blind dovetail joint (DTJ), dowel joint (DJ), and the minifix joint (MJ), respectively. In terms of material, the tensile strength results from the highest to the lowest value are in order of Medium-Density Fiberboard (MDF) (2436 N), Scots pine wood (Sp), and Poplar wood (Po) (1979 N). This higher strength can be explained by the high density and homogeneous structure of MDF material, and test results draw a parallel between the obtained results and the material densities.

The tensile performance of the vertical load case (2343 N) gives better performance than the parallel one (2061 N). This higher tensile strength of vertical loading can be explained by the shear force resistance of all joints. These higher results of non-axial performance in tensile strength than axial can be explained by the shear force resistance of types of jointing. And finally, the tensile strength performance of polyurethane-based adhesive (Pu) (Desmodur-VTKA) is higher (2257 N) than that of polyvinyl acetate (PVAc) adhesive (2148 N). This result can be explained by the higher mechanical adhesion of polyurethane.

The mean values of the tensile performance of the binary interactions are given in Table 4. The highest tensile performance in terms of the binary interaction is found to be in the interaction of joinery technique and type of material pairing. Maximum tensile strength is observed in the MDF + screw joint (SJ) (4282 N) pair, while the minimum in the MDF + tongue-and-groove joint (TGJ) (722 N). As seen in Table 4, the tensile per-

Table 2 Multivariate analysis of tensile performance
Tablica 2. Multivarijatna analiza vlačnih svojstava

Source *Izvor*	**Degrees of freedom** *Stupnjevi slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednja vrijednost kvadrata*	***F* value** *F-vrijednost*	***P*<5 % (Sig)**
Joinery techniques (A) / *tehnika spajanja (A)*	4	2146354.447	536588.612	2109.121	0.0000
Types of material (B) / *vrsta materijala (B)*	2	104485.127	52242.563	205,3452	0.0000
AxB	8	139201.273	17400.159	68.3933	0.0000
Axis of assembly (C) / *os montaže (C)*	1	59643.000	59643.708	234.4335	0.0000
AxC	4	253630.833	1079.13	249.2311	0.0000
BxC	2	2158.260	18020.951	4.2416	0.0155
AxBxC	8	144167.607	8899.853	70.8334	0.0000
Types of adhesive (D) / *vrsta ljepila (D)*	1	8899.853	13513.928	34.9819	0.0000
AxD	4	54055.713	866.923	53.118	0.0000
AxBxD	8	3546.687	337.08	1.7426	0.0494
AxCxD	4	11999.620	615.97	11.7915	0.0000
BxCxD	2	1231.940	89.408	2.4211	0.0210
AxBxCxD	8	7123.260	254.413	3.4998	0.0008
Error / *pogreška*	240	61059.200			
Total / *ukupno*	299	2999627.747	-	-	

Table 3 Average tensile performances in terms of joinery techniques (N)
Tablica 3. Srednja vlačna svojstva s obzirom na tehnike spajanja (N)

Joinery techniques* / *Tehnike spajanja**	*X*	HG
Screw joints (SJ) / *spoj vijcima (SJ)*	3603	A
Half-blind dovetail joints (DTJ) / *spoj poluzatvorenim lastinim repom (DTJ)*	2426	B
Dowel joints (DJ) / *spoj moždanikom (DJ)*	2034	C
Eccentric (Minifix) joints (MJ) / *spoj ekscentrom (Minifixom) (MJ)*	1963	D
Tongue-and-groove joints (TGJ) / *spoj perom i utorom (TGJ)*	986	E
Type of material** / *vrsta materijala***		
MDF (MDF)	2436	A
Scots pine (Sp) / *borovina (Sp)*	2192	B
Poplar (Po) / *topolovina (Po)*	1979	C
Axis of assembly***/ *os montaže****		
Tensile strength vertical to the axis of assembly (non-axial) (IIV) *vlačna čvrstoća okomito na os montaže (neaksijalno) (IIV)*	2343	A
Tensile strength parallel to the axis of assembly direction (axial) (IP) *vlačna čvrstoća paralelno s osi montaže (aksijalno) (IP)*	2061	B
Type of adhesive**** / *vrsta ljepila*****		
Polyurethane (Pu) / *poliuretan (Pu)*	2257	A
Polyvinyl acetate (PVAc) / *polivinilacetat*	2148	B

**LSD*=5.731, ***LSD*=4.432, ****LSD*=3.625, *****LSD*=3.625, HG – Homogeneity groups / *homogenost grupa*, *X* – Mean / *srednja vrijednost*

formance in terms of jointing technique and the axis of assembly interaction is the highest in the screw joint (SJ) (3752 N), and the lowest in the tongue-and-groove joint (TGJ) (863 N) both in axial tensile loading. In screw joint (SJ) under the tensile loading in the axial direction, no deformation was caused in plate A and B. The only deformation occurred in the form of burying the head of the screw into the plate. In some of the test specimens, it is observed that the screw broke under tension. During the non-axial (vertical) tensile loading, fiber-debonding in plate A and deformation of the fibers in plate B are observed.

When the tensile performance of the jointing technique and types of adhesive interaction is considered, screw joint (SJ) + PVAc adhesive (3735 N) pair has the maximum strength, while tongue-and-groove joint (TGJ) + PVAc adhesive (719 N) has the minimum. The observations during the performed tests demonstrated that in SJ+ PVAc joint the adhesive lost its performance at 200-250 kgf/m loading, whilst the performance of the screw was maintained up to 450-500 kgf/m loading. Hence, it can be concluded that this type of jointing can be applied without glue, which does not have a function.

Tensile performance in terms of material type and the axis of assembly interaction is found to be the highest in MDF + non-axial loading (2615 N) and the lowest in poplar (Po) + axial loading (1858 N). During the tests, no deformation was observed in the plates in tensile loading parallel to the axis of the assembly. In the direction vertical to the axis of assembly, it was observed that the MDF, which is a composite material, was deformed in the form of breakage, while the pine and poplar were deformed in the form of peeling. When tensile performance in terms of the type of material and type of adhesive interaction is considered, the polyurethane adhesive (Pu) adhesive + MDF (2457 N) pair has the highest performance and the PVAc adhesive + poplar (Po) wood (1914 N) pair has the lowest. As shown in the last part of Table 4, the tensile performance in terms of load cases and type of adhesive interaction is found to be the highest in the polyurethane adhesive (Pu) (2387 N) + vertical to the axis of the assembly pair and the lowest in the polyvinyl acetate adhesive (PVAc) (1996 N) + parallel to the axis of assembly pair.

The average values of the tensile performance of triple interactions are given in Table 5. As MDF + axial tensile loading pair is similar in both the highest and the lowest tensile performance rates of the triple interaction between joinery technique, type of material, and axis of assembly, the joinery technique is found as a critical variable; hence, the tensile strength of screw joint technique (SJ) is the highest (4529 N), while tongue-and-groove joint technique (TGJ) is the lowest (449 N). In traditional half-blind dovetail jointing, which took the second place in the ranking of test specimens, the joint was peeled off. It is thought that this may be related to the form and dimensions of the teeth of the dovetail joint. However, to obtain more detailed information on this issue, it would be beneficial to carry out further studies in this direction. The dowel jointing took third place in the tensile performance rankings. During the tests, it was observed that no deformation occurred in the plates under the axial (parallel) tensile loading, and the dowels remained on the plate A side. Under non-axial (vertical) tensile loading, plate B (female) appeared to be deformed by the failure of the fibers. In some of the test specimens, the deformation was observed as the breakage of the dowel.

Table 4 The average value of tensile performance of binary interactions (N)
Tablica 4. Srednja vrijednost vlačnih svojstava u binarnoj interakciji (N)

Jointing technique + Type of material* *Tehnika spajanja +vrsta materi-jala**	*X*	HG	**Jointing technique + Axis of assembly**** *Tehnika spajanja + os montaže***	*X*	HG	**Type of material + Axis of assembly***** *Vrsta materi-jala + os montaže****	*X*	HG	**Joinery technique + Type of adhesive****** *Tehnika spajanja + vrsta ljepila*****	*X*	HG	**Type of material + Type of adhesive******* *Vrsta materi-jala + vrsta ljepila******	*X*	HG	**Axis of assembly + Type of adhesive******** *Os montaže + vrsta ljepi-la*******	*X*	HG
SJ+MDF	4282	A	SJ+IP	3752	A	MDF+IIV	2615	A	SJ+ PVAc	3735	A	MDF+PVAc	2415	A	IIV+PVAc	2300	B
SJ+ Sp	3356	B	SJ+IIV	3454	B	MDF+IP	2257	B	SJ+ Pu	3471	B	MDF+Pu	2457	A	IP+ Pu	2127	C
SJ+Po	3171	C	DTJ+IP	2629	C	Sp+IIV	2316	B	DTJ+ Pu	2554	C	Sp+ Pu	2269	B	IP+PVAc	1996	D
DTJ+MDF	2595	D	DJ+IIV	2568	C	Po+IIV	2100	C	DTJ+PVAc	2298	D	Sp+PVAc	2116	C			
DTJ+ Sp	2404	E	MJ+IIV	2361	D	Sp+IP	2069	C	DJ+PVAc	2025	E	Po+Pu	2045	D			
MJ+MDF	2283	F	DTJ+IIV	2223	E	Po+IP	1858	D	DJ+Pu	2044	E	Po+ PVAc	1914	E			
DJ+MDF	2298	F	DJ+IP	1501	F				MJ+ PVAc	1963	E						
DTJ+Po	2279	F	MJ+IP	1565	F				MJ+ Pu	1963	E						
MJ+ Sp	1952	G	TGJ+IIV	1112	G				TGJ+Pu	1253	F						
DJ+Sp	2009	G	TGJ+ IP	863	H				TGJ+PVAc	719	G						
DJ+Po	1796	H															
TGJ+Po	995	K															
TGJ+MDF	722	L															
MJ+Po	1654	I															
TGJ+ Sp	1242	J															

**LSD*=9.926, ***LSD*=8.105, ****LSD*=6.278, *****LSD*=8.098, ******LSD*=6.273, *******LSD*=5.122, HG – Homogeneity groups / *homogenost grupa*, *X* – Mean / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, IP – Axis I-parallel to the axis of assembly / *os I – paralelno s osi montaže*, IIV – Axis II-vertical to the axis of assembly / *os II – okomito na os montaže*, Sp – Scots pine / *borovina*, Po – Poplar / *topolovina*, MDF – Medium density fiberboard / *srednje gusta ploča vlaknatica*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo*

Table 5 Mean values of tensile performance of triple interactions (N)
Tablica 5. Srednja vrijednost vlačnih svojstava u trostrukoj interakciji (N)

***Jointing technique + Type of material + Axis of assembly** / **Tehnika spajanja + vrsta materijala + os montaže*					
Factors	*X*	HG		*X*	HG
DJ+MDF+IIV	2820	F	SJ+MDF+IP	4529	A
DJ+Sp+IIV	2592	G	SJ+MDF+IIV	4035	B
DTJ+Po+IP	2272	H	SJ+Sp+IP	3467	C
DJ+Po+IIV	2292	H	SJ+Sp+IIV	3245	D
DTJ+Sp+IIV	2381	H	SJ+Po+IP	3261	D
DTJ+Sp+IP	2426	H	DTJ+MDF+IP	3188	DE
DJ+MDF+IP	1775	J	MJ+MDF+IIV	3222	DE
DJ+Sp+IP	1426	L	SJ+Po+IIV	3082	E
DJ+Po+IP	1301	LM	DTJ+Po+IIV	2286	H
TGJ+Sp+IP	1250	MN	DTJ+MDF+IIV	2002	I
TGJ+Sp+IIV	1233	MN	MJ+Sp+IIV	2128	I
TGJ+Po+IIV	110	NO	MJ+Po+IIV	1732	J
TGJ+MDF+IIV	995	OP	MJ+Sp+IP	1776	J
TGJ+Po+IP	882	P	MJ+Po+IP	1576	K
TGJ+MDF+IP	449	Q	MJ+MDF+IP	1344	LM
****Jointing technique + Type of material + Type of adhesive** / ***Tehnika spajanja + vrsta materijala + vrsta ljepila*					
DTJ+Sp+Pu	2542	G	SJ+MDF+PVAc	4474	A
DJ+MDF+Pu	2330	HI	SJ+MDF+Pu	4090	B
DJ+MDF+PVAc	2265	IJ	V+Sp+PVAc	3478	C
DTJ+Sp+PVAc	2265	IJ	SJ+Sp+Pu	3234	D
DJ+Sp+Pu	2032	KL	SJ+Po+PVAc	3253	D
DJ+Sp+PVAc	1986	L	SJ+Po+Pu	3090	E
DTJ+Po+PVAc	2134	L	DTJ+MDF+Pu	2695	F
DJ+Po+ PVAc	1823	MN	DTJ+MDF+Pu	2495	G
DJ+Po+Pu	1770	NO	DTJ+Po+Pu	2424	GH
TGJ+Sp+Pu	1586	P	MJ+MDF+PVAc	2283	HIJ
TGJ+Po+Pu	1285	Q	MJ+MDF+Pu	2283	HIJ
TGJ+Sp+PVAc	897	R	MJ+Sp+PVAc	1952	LM
TGJ+MDF+Pu	887	R	MJ+Sp+Pu	1952	LM
TGJ+Po+PVAc	704	S	MJ+Po+PVAc	1654	OP
TGJ+MDF+PVAc	557	T	MJ+Po+Pu	1654	OP
*****Joinery technique + Axis of assembly + Type of adhesive** / ****Tehnika spajanja + os montaže + vrsta ljepila*					
DJ+IIV+Pu	2669	D	SJ+IP+PVAc	3865	A
DTJ+IP+Pu	2775	D	SJ+IIV+PVAc	3605	B
DTJ+IP+PVAc	2482	E	SJ+IP+Pu	3639	B
DJ+IIV+PVAc	2467	EF	SJ+IIV+Pu	3303	C
DJ+IP+PVAc	1583	I	MJ+IIV+PVAc	2361	FG
DJ+IP+Pu	1419	J	MJ+IIV+Pu	2361	FG
TGJ+IP+Pu	1234	K	DTJ+IIV+Pu	2332	G
TGJ+IIV+Pu	1271	K	DTJ+IIV+PVAc	2114	H
TGJ+IIV+PVAc	952	L	MJ+IP+PVAc+	1565	I
TGJ+IP+PVAc	486	M	MJ+IP+Pu	1565	I
******Type of material + Axis of assembly + Type of adhesive** / *****Vrsta materijala + os montaže + vrsta ljepila*					
Sp+IIV+Pu	2403	B	MDF+IIV+Pu	2598	A
Sp+IIV+PVAc	2228	CD	MDF+IIV+PVAc	2632	A
Sp+IP+Pu	2135	D	MDF+IP+Pu	2316	BC
Sp+IP+PVAc	2003	EF	Po+IP+Pu	2161	D
Po+IP+Pu	1928	F	MDF+IP+PVAc	2198	D
Po+IP+PVAc	1788	G	Po+IIV+PVAc	2039	E

**LSD*=14.04, ***LSD*=14.03, ****LSD*=11.45, *****LSD*= 8.871 HG – Homogeneity groups / *homogenost grupa*, *X* – Mean / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, IP – Axis I-parallel to the axis of assembly / *os I – paralelno s osi montaže*, IIV – Axis II-vertical to the axis of assembly / *os II – okomito na os montaže*, Sp – Scots pine / *borovina*, Po – Poplar / *topolovina*, MDF – Medium density fiberboard / *srednje gusta ploča vlaknatica*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo*

Likewise, in the triple interaction between joinery technique, type of material, and type of adhesive, the joinery technique appeared as a critical factor since MDF + PVAc pair is similar in both the highest and lowest combinations. Hence, the tensile strength of the screw joint (SJ) is found to be the highest (4474 N), while the tongue-and-groove joint (TGJ) is the lowest (557 N). Although the tongue-and-groove joint had the worst performance due to the tensile performance rankings, no deformation was observed on the glued surfaces of tongue or groove. In the tensile loading both parallel and vertical to the axis of assembly, it is seen that the deformation does not occur in the plate A which is broken by 8 mm; and the broken part is left on the plate B. The reason for the low values may be due to the rupture of the fibers during the preparation of the tongue and groove. It is not recommended to use this joinery technique at the wooden corners as its strength is very low and it is easy to deform.

In triple interaction of joinery technique, the axis of assembly, and type of adhesive in terms of tensile performance, the axis of tensile force applied parallel to the axis of assembly appeared similar in both the highest and the lowest tensile performance rates. As the axis of assembly is the same in both cases, the highest combination is found to be in screw joint (SJ) + PVAc pair (3865 N), while tongue-and-groove joint (TGJ) + PVA is the lowest (486 N). In terms of the type of material, axis of assembly, and type of adhesive interaction, the highest tensile performance was found to be in MDF + IIV + PVAc trio (2632 N), while the lowest in Po+IP+PVAc (1788 N).

When the 4-factor (type of material, joinery technique, type of adhesive, and axis of assembly) effects on the tensile performance are considered, SJ + MDF + PVAc + IP is the highest (4592 N), while TGJ + MDF + PVAc + IP is the lowest (260 N).

The Duncan test results for 4-factor interaction of the jointing technique, the type of material, the axis of assembly, and the type of adhesive, affecting the tensile performance of wooden corner joints are given in Table 6.

According to the test results, the screw joint has increased the tensile performance by 49 % of half-blind dovetail jointing (DTJ), 77 % of dowel joint (DJ), 84 % of the eccentric joint (MJ) with minifix apparatus, and 265 % of tongue-and-groove joint (TGJ). In terms of types of material, the MDF has increased the tensile performance by 11 % of Scots pine wood (Sc) and 23 % of Poplar wood (Po). According to the tests on the effect of the types of adhesive on the tensile performance, the polyurethane glue is 5 % higher than the polyvinyl acetate glue. The tensile performance in terms of the axis of assembly shows that the non-axial (vertical) tensile performance value is 14 % higher than the axial (parallel) tensile performance in the assembly direction. The results on PVA adhesives are compatible with the study of Taghiyari *et al*. (2017) and the results on the effects of types of materials on the tensile performance of corner joints are in accordance with the study of Yıldız and Çavuş (2008).

4 CONCLUSIONS
4. ZAKLJUČAK

Thanks to the developments in building materials and chemicals, many new details regarding wooden corner joints have been produced in the last century. Parallel to these developments, traditional wooden construction details tend to be abandoned. Nevertheless, the wisdom of traditional know-how may still be valid. The results of testing traditional and modern jointing details, with natural and artificial materials, revealed interesting information that can guide us to better design wooden corners.

The existing literature is mostly focused on the comparison of two-factor affecting the tensile strength of wooden corners; hence, they do not draw a holistic frame for the evaluation of corner joints. In this respect, this study is original as it analyzes the tensile performance of wooden corner joints under multiple factor interactions. This study contributes to the current literature by examining the interaction of four different factors: the jointing technique, the type of material, the axis of assembly, and the type of adhesive.

Upon considering the tensile performance results, the screwed joint, which is thought to be low-cost and easy to work with, can be recommended for wooden corner joints. The traditional half-blind dovetail jointing technique took the second place in the performance rankings, followed by the dowel joint and then the contemporary eccentric joint. Due to the tensile performance rankings, the worst performance is observed in the tongue-and-groove joint. Therefore, it is not recommended to use this joinery technique for the wooden corners as its strength is very low and it is easy to deform. Consequently, it can be stated that for wooden corner joints, it may be advantageous to apply screw joint, MDF, and PVAc glue under tension parallel to the assembly axis.

As seen from the results, the contemporary materials and techniques are not always better than the traditional ones, as the traditional half-blind dovetail jointing technique took the second place in the performance rankings among all joints. Although it is the most historic technique, its performance is still compatible with the modern ones and applicable in carpentry. Nevertheless, the advantage of modern techniques and materials, such as screw joint and MDF is undeniable, so that the wisdom gained by experience in tradi-

Table 6 Duncan test results on 4-factor interaction (joinery technique, type of material, axis of assembly, and type of adhesive) affecting tensile performance
Tablica 6. Rezultati Duncanova testa za četverostruku interakciju (tehniku spajanja, vrstu materijala, os montaže i vrstu ljepila) koji utječu na vlačna svojstva

Joinery technique + Type of material + Axis of assembly + Type of adhesive *Tehnika spajanja + vrsta materijala + os montaže + vrsta ljepila*	*X*	**HG**	**Joinery technique + Type of material + Axis of assembly + Type of adhesive** *Tehnika spajanja + vrsta materijala + os montaže + vrsta ljepila*	*X*	**HG**
SJ + MDF + IP+ PVAc	4592	A	DTJ + Sp + IIV + Pu	2128	NOP
SJ + MDF + IP+ Pu	4466	AB	DTJ + Po + IP + PVAc	2118	NOP
SJ + MDF + IIV + PVAc	4356	B	YK + MDF + IIV + Pu	2024	OP
SJ + MDF + II V+ Pu	3714	C	DTJ + MDF + IIV + PVAc	1980	PQ
SJ + Sp + IP + PVAc	3620	C	DJ + MDF + IP + PVAc	1784	QR
SJ+ Po + IP + PVAc	3384	D	MJ + Sp + IP + PVAc	1776	QR
DTJ + MDF + IP + Pu	3366	D	MJ + Sp + IP + Pu	1776	QR
SJ + Sp + IIV + PVAc	3336	DE	DJ + MDF + IP + Pu	1766	QR
SJ + Sp + IP+ Pu	3314	DEF	TGJ + Sp + IV + Pu	1758	QR
MJ+ MDF + IIV + PVAc	3222	DEFG	MJ + Po + IIV + PVAc	1732	R
MJ + MDF + IIV + Pu	3222	DEFG	MJ + Po + IIV + Pu	1732	R
SJ + Sp + IIV + Pu	3154	EFG	MJ + Po+ IP + PVAc	1576	RS
SJ + Po + IP + Pu	3138	EFG	MJ + Po + IP + Pu	1576	RS
SJ + Po + IIV + PVAc	3122	FG	DJ + Sç + IP+ PVAc	1550	RS
SJ + Po + II + Pu	3042	GH	TGJ + Sp + IIV + Pu	1414	ST
DTJ + MDF + IP + PVAc	3010	GH	DJ + Po + IP + PVAc	1406	ST
DJ + MDF + IIV + Pu	2894	HI	MJ + MDF + IP + PVAc	1344	TU
DJ + Sp + IIV + Pu	2770	I	MJ + MDF+ IP+ Pu	1344	TU
DJ + MDF + IIV + PVAc	2746	IJ	TGJ + Po + IP + Pu	1306	TU
DTJ + Sp + IIV + Pu	2550	JK	DJ + Sp + IP + Pu	1294	TU
DTJ+ Sp + IP + Pu	2534	KL	TGJ + Po + IIV + Pu	1264	TUV
DTJ + Po + IIV+ Pu	2426	KLM	DJ + Po + IP + Pu	1196	TUV
DTJ + Po + IP + Pu	2422	KLM	TGJ + MDF + IIV + Pu	1136	UVW
DJ + Sp + IIV + PVAc	2414	KLM	TGJ + Sp + IIV + PVAc	1052	VWX
DJ + Po + IIV + Pu	2344	KLMN	TGJ + Po + IIV + PVAc	950	WXY
DTJ+Sp + IP + PVAc	2318	LMN	TGJ + MDF + IIV + PVAc	854	XY
DJ + Po + IIV + PVAc	2240	MNO	TGJ + Sp + IP + PVAc	742	YZ
DTJ + Sp + IIP + PVAc	2212	MNO	TGJ + MDF + IP + Pu	638	Za
DTJ + Po+ IIV + PVAc	2150	NOP	TGJ + Po + IP + PVAc	458	ab
MJ +Sp + IIV + PVAc	2128	NOP	TGJ + MDF + IP + PVAc	260	bc

**LSD*=14.04, ***LSD*=14.03, ****LSD*=11.45, *****LSD*=8.871, HG – Homogeneity groups / *homogenost grupa*,*X* – Mean / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, IP – Axis I-parallel to the axis of assembly / *os I – paralelno s osi montaže*, IIV – Axis II-vertical to the axis of assembly / *os II – okomito na os montaže*, Sp – Scots pine / *borovina*, Po – Poplar / *topolovina*, MDF – Medium density fiberboard / *srednje gusta ploča vlaknatica*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo*

tional carpentry can be evolved by contemporary technological advances to get higher performance in wooden details.

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