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Bending Moment of Mortise-and-Tenon Joints in a Crossed Chair Base

Moment savijanja spojeva s čepom i rupom na križnoj potkonstrukciji sjedala stolice

ABSTRACT • *This paper investigated the bending moment of chair base joints. The ultimate bending moments (maximum moment), calculated on the base of the measured maximum applied loads (maximum force), were compared for the front leg and rear leg joints of a chair base. The joints had different angles between the stretcher and the leg (joint angle) as well different tenon lengths (30 mm and 32 mm). The results of the tests indicated that for different test specimen configurations but the same tenon-and-mortise geometry, the maximum force of joints with a smaller value of joint angle (front leg joints) was higher than the force values of joints with a larger angle (rear leg joints) for all tenon lengths. However, the results showed less difference among the calculated bending moments of the analysed sets of joints. A significant difference was not revealed between the bending moments of joints with a smaller value of joint angle and the bending moments of joints with a larger angle for all tenon lengths. A significant difference between the bending moments for the tenon length of 30 mm and tenon length of 32 mm was determined for rear leg joints but not for front leg joints. The presented approach of joint strength analysis through the testing of specimens with different shapes and dimensions are applicable to research and practice.*

KEYWORDS: *chair; mortise-and-tenon joint; bending moment; joint angle; tenon length*

SAŽETAK • *U radu je proučavan moment savijanja spojeva na križnoj potkonstrukciji sjedala stolice. Krajnji momenti savijanja (najveći moment), izračunani na temelju izmjerenih najvećih opterećenja (najveća sila), uspoređeni su za spojeve prednjih i stražnjih nogu križne potkonstrukcije sjedala stolice. Spojevi su imali različite kutove između poveznika i noge (kut spoja), kao i različitu duljinu čepova (30 i 32 mm). Rezultati ispitivanja pokazali su da je za različitu konfiguraciju ispitnih uzoraka, ali za istu geometriju čepa i rupe, najveća sila bila veća za spojeve s manjim kutom (spojevi prednjih nogu) nego za spojeve s većim kutom (spojevi stražnjih nogu), i to za čepove obiju duljina. Rezultati su također pokazali manju razliku između izračunanih momenata savijanja analiziranih grupa spojeva. Nije utvrđena značajna razlika momenata savijanja spojeva s manjim i većim kutom za čepove obiju duljina. Značajna razlika između momenata savijanja za čepove dužine 30 i 32 mm utvrđena je za spojeve stražnjih nogu, ali ne i za spojeve prednjih nogu stolice. Prikazani pristup analize čvrstoće spojeva ispitivanjem uzoraka različitih oblika i dimenzija primjenjiv je u istraživanju i u praksi.*

KLJUČNE RIJEČI: *stolica; spoj s čepom i rupom; moment savijanja; kut spoja; duljina čepa*

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1 INTRODUCTION
1. UVOD

Different forms of mortise-and-tenon joints are still the most common solutions for connecting elements of wood chairs. The mechanical properties of tenon joints are widely researched in order to improve the quality of joints and chair structure, and hence different factors that affect the strength, stiffness and load-carrying capacity have been investigated.

The tenon size is well known to be the main factor affecting the moment capacity of a mortise-and-tenon joint. The bending-moment capacity is strongly affected by the length and width of the tenon, while the width has a slight lower influence (Kasal *et al.,* 2015; Likos *et al.,* 2012; Derikvand *et al.,* 2014; Hajdarevic *et al.,* 2020). Elek *et al.* (2020) investigated the effects of fitting for pairing of open full-width mortise-and-tenon-joint elements on the strength of joints, and this type of joint was found to be the strongest at a tight fit of 0.1 mm. The mortise-and-tenon joint, in combination with PVAc, provided the best strength for all investigated wood species (Vassiliou *et al*., 2016; Bardak *et al*., 2017), while PU glue has appropriate strength in comparison with PVAc, and can completely fill and cover the gaps between the elements of a joint (Hrovatin *et al*., 2013). The suitable construction type of chairs, constructed with defined tenon dimensions, has been determined based on the required load-carrying capacity (Kiliç *et al.,* 2018; Hitka *et al.,* 2018; Kasal *et al.,* 2016; Ayrilmis *et al.,* 2020). Different chair structures and chair joints were analysed with the finite-element method to obtain the stress and strain states under loading, and the results showed good agreement with experimental tests to determine the mechanical properties of such constructions and joints (Smardzewski, 2008; Horman *et al.,* 2010; Hajdarevic and Martinovic, 2014; Hajdarevic and Busuladzic, 2015; Kasal *et al*., 2016).

The strength of the joints represents the strength of the entire system of a chair frame and, as the most critical parts of a chair, these should have adequate strength (Kiliç *et al.,* 2018). However, there is a problem in joint strength testing of real chair structures. The analysis of such joints should enable obtaining realistic and comparable values of joint strength regardless of the conditioned shape and dimensions of the tested sample, although the shape and dimensions of the tested samples depend on the shape and dimensions of the structure from which they were cut.

The aim of the study was, therefore, to explore the capabilities of the test method to obtain a comparable joint strength of two different sets of specimens that were cut from specific wooden frame configurations. The objective of the present study was to determine the effects of joint angle and length of the tenon in the joints of the crossed chair base in bending.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

This study investigated the bending moment of the crossed chair-base joints taken from an industrial manufacturing process. The front and rear leg joints of the crossed chair base had different angles, i.e. the positions of the stretcher and the front leg and the stretcher and the rear leg were different and asymmetric. In addition, all joints had the same geometry configuration with two different tenon lengths (30 mm and 32 mm).

Each crossed chair base was assembled from two frames and four corner blocks and supplied from furniture manufacturers (Figure 1a), and specimens for the bending test of the mortise-and-tenon joint were prepared using these chair bases by cutting the frames into two parts and shortening the leg length (Figure 1b-c). All parts of the crossed chair base were made of com-
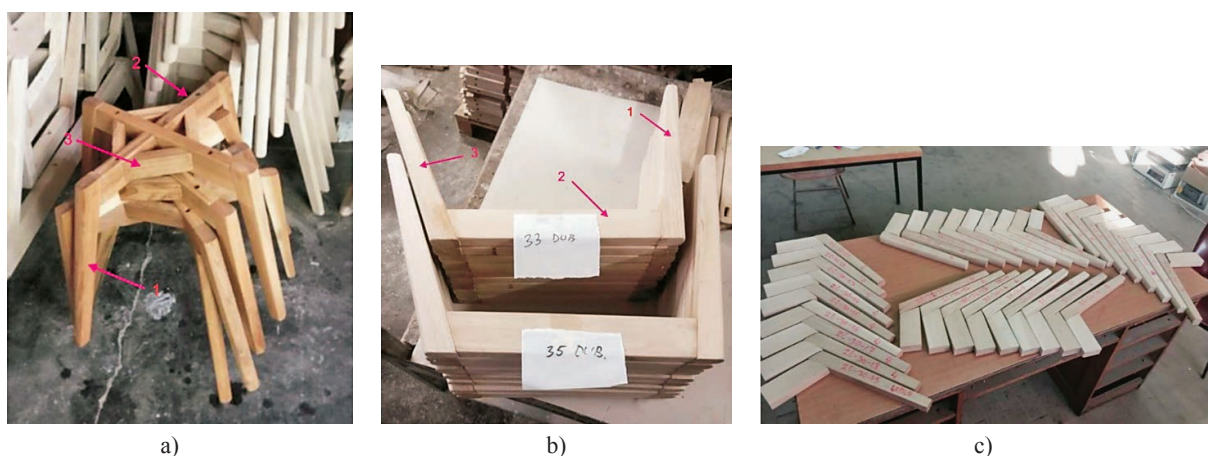

| a) | b) | c) |

Figure 1 Crossed chair base: a) assembled structure (1 – leg; 2 – stretcher; 3 – corner block), b) frame of two chair legs (1 – front leg; 3 – rear leg) and stretcher (2), c) specimens prepared for bending test of mortise-and-tenon joint
Slika 1. Križna potkonstrukcija sjedala stolice: a) sastavljena konstrukcija (1 – noga; 2 – poveznik; 3 – kutni poveznik); b) okvir dviju nogu stolice (1 – prednja noga; 3 – stražnja noga) i poveznik (2); c) uzorci spojeni čepom i rupom pripremljeni za ispitivanje
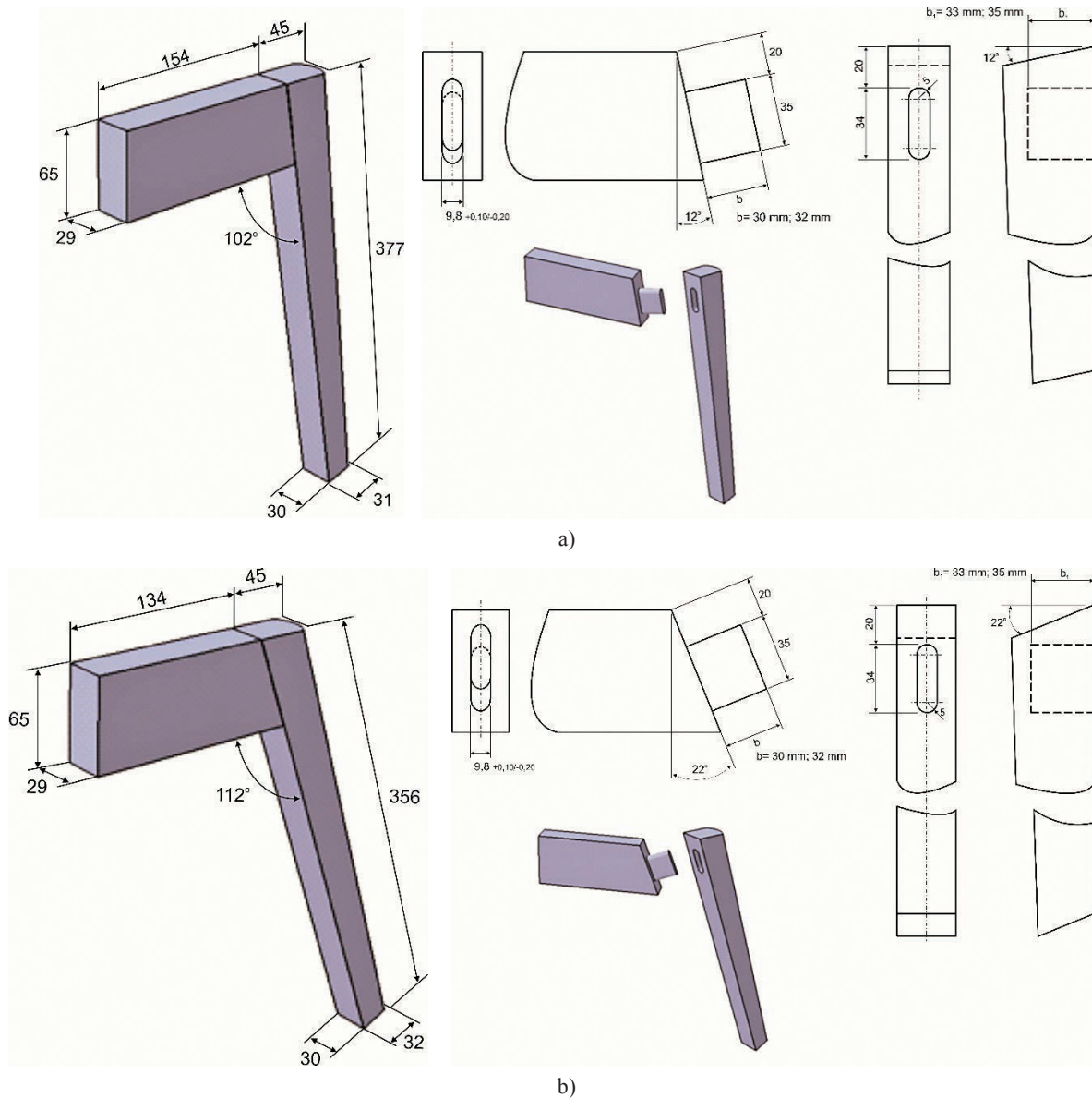
a)

b)

Figure 2 Configuration of test specimens: a) front leg joint (left) and configuration of mortise-and-tenon (right); b) rear leg joint (left) and configuration of mortise-and-tenon (right)
Slika 2. Konfiguracija ispitnih uzoraka: a) spoj prednje noge (lijevo) i konfiguracija čepa i rupe (desno); b) spoj stražnje noge (lijevo) i konfiguracija čepa i rupe (desno)

mon oak wood (*Quercus robur* L.). The moisture content and density of oak wood were evaluated in accordance with the procedures described in ISO 13061-1 (2014) and ISO 13061-2 (2014) after testing. The average value of moisture content and density of the wood specimens were 12.1 % and 0.77 g/cm³, respectively.

Each frame was composed of two chair legs and a stretcher. PVA-c adhesive (Kleiberit 303.0, Klebchemie, Weingarten, Germany) was used to bond the frame elements together at ambient conditions and with applied pressure. The adhesive met the requirements of stress group D3 according to DIN/EN 204,

Table 1 Test set-up and description of specimens (see Figure 2)
Tablica 1. Postavke ispitivanja i opis uzoraka (v. sl. 2.)

Specimen group No. *Broj skupine uzoraka*	Specimen group mark *Oznaka skupine uzoraka*	Position *Pozicija*	Angle between stretcher and leg, ° *Kut između poveznika i noge, °*	No. of specimens *Broj uzoraka*	Tenon length, mm *Duljina čepa, mm*
1	FL – T30	Front leg / *prednja noga*	102	9	30
2	FL – T32	Front leg / *prednja noga*	102	9	32
3	RL – T30	Rear leg / *stražnja noga*	112	9	30
4	RL – T32	Rear leg / *stražnja noga*	112	9	32

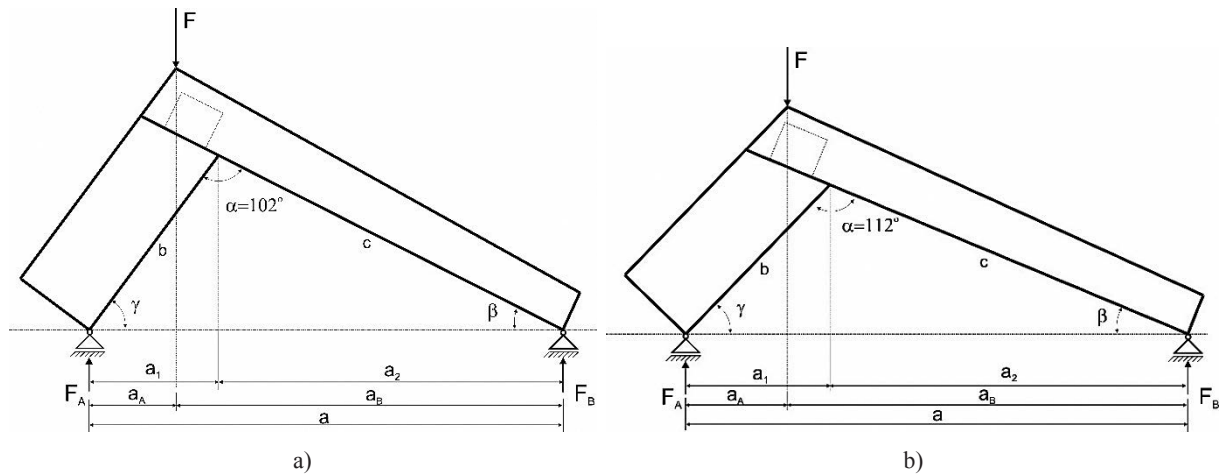a)   b)

Figure 3 Diagram of joint loading: a) front leg joint, b) rear leg joint. Notation used: F – force (load), F_A and F_B – support reactions, a_A and a_B – moment arms, i.e. perpendicular distances from support reaction line to force line, sides (a, b and c), angles (α, β and γ) and base distances to height (a_1 and a_2) of a scalene triangle
Slika 3. Dijagram opterećenja spoja: a) spoj prednje noge; b) spoj stražnje noge. Oznake: F – sila (opterećenje), F_A i F_B – reakcije oslonca, a_A i a_B – krakovi momenta, tj. okomiti razmaci od osi reakcije oslonca do osi sila, stranice (a, b i c), kutovi (α, β i γ) i udaljenosti baza do visine (a_1 i a_2) razmjernog trokuta.

with the density of 1.1 g/cm³, pH approx. 3 and viscosity at 20 °C of about 13.000 mPa·s. The stretcher joined and supported a front leg and a rear leg of the chair by mortise-and-tenon joints. All joints were of mortise-and-tenon type with rounded tenons.

Configurations of specimens of front and rear leg joints for the bending test of the mortise-and-tenon joint are shown in Figure 2. The geometry and dimensions of the specimens were different, i.e. the front leg joint had a smaller angle between the stretcher and leg (102°) than the test specimens of the rear leg joint (112°). The test set-up is presented in Table 1.

The loading diagrams of the front leg joints and rear leg joints are shown in Figure 3. The supports were set up on the edges of the leg and stretcher cross-section. The load was applied to the joint in a manner that corresponded to the tension of the specimen. The test was carried out on a universal testing machine Zwick 1282 (Zwick Roell Group, Ulm, Germany), as shown in Figure 4. The force (load cell RSCC-C3/1t HBM, Darmstadt, Germany) and displacement (inductive displacement transducer WI10 HBM, Darmstadt, Germany) along the force line were measured simultaneously until a joint failure and large fall in the load occurred.

The applied load values and the corresponding displacement along the force line were ascertained using the data collected by the software. Working diagrams of the 36 tested specimens were then created.

The ultimate (maximum) bending moment of the joints, based on the ultimate applied load values, were calculated both for front leg joints and rear leg joints by:

$$M_{max} = F_{(A\,max)} \cdot a_A = F_{(B\,max)} \cdot a_B \qquad (1)$$

Where M_{max} is maximum bending moment, $F_{(A\,max)}$ and $F_{(B\,max)}$ are support reactions and, a_A and a_B

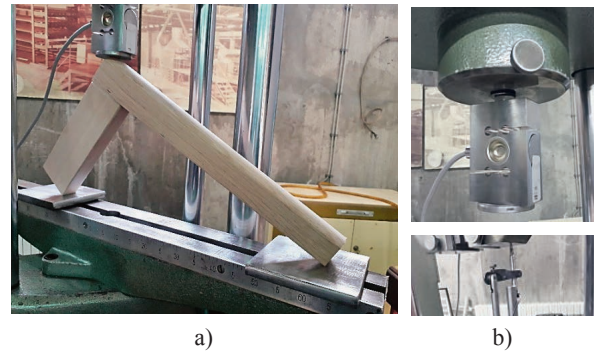a)   b)

Figure 4 Joint testing: a) set-up of joints in testing machine, b) load cell and inductive displacement transducer
Slika 4. Ispitivanje spoja: a) postavljanje spojeva u ispitni uređaj; b) davač sile i induktivni davač pomaka

are moment arms. Support reactions were obtained based on the trigonometric analysis and static conditions.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Figure 5 shows the force-displacement diagrams of the tested specimens. All joints had a wide defined elastic region, *i.e.* proportional zones. The initial wood or bond-line fractures occurred at load values higher than 4000 N for all specimens. There was a noticeable difference among the ultimate loads of the front and rear leg joints, although the differences were not apparent among the ultimate loads of the front or rear leg joints with different tenon lengths. The values of displacements at ultimate load ranged from 8 to 12 mm.

The results of maximum force (F_{max}) and maximum moment (M_{max}) of the front leg joints and rear
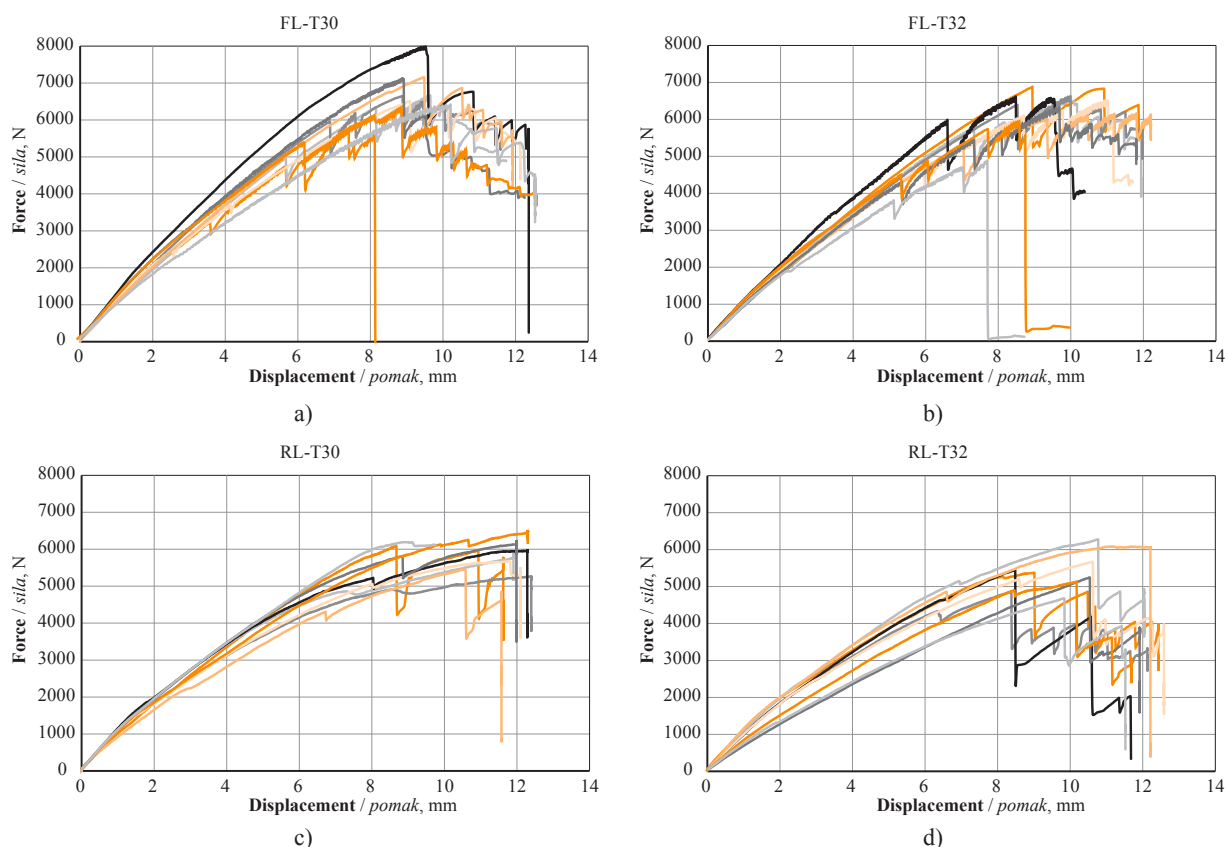
Figure 5 Force-displacement diagram of joint strength testing for front leg joints with tenon length of a) 30 mm and b) 32 mm, and rear leg joints with tenon length of c) 30 mm and d) 32 mm
Slika 5. Dijagram sila-pomak pri ispitivanju čvrstoće spojeva prednje noge s čepom duljine: a) 30 mm i b) 32 mm, te stražnje noge s čepom duljine: c) 30 mm i d) 32 mm

joints with two different tenon lengths are given in Tables 2 and 3, respectively.

The characteristic pattern of the ultimate fractures of joints is shown in Figure 6. The tenon started to take the load after the bond-line failed, and then the tenon was partially pulled out from the mortise, while fracture of mortise wood occurred. This typical fracture mode of L-shape mortise and tenon joints glued with PVA-c glue was also described in (Kasal *et al.*, 2015).

Table 2 Results of forces and bending moments of front leg joints
Tablica 2. Rezultati sila i momenata savijanja spojeva prednjih nogu

No. of specimen *Broj uzorka*	Tenon length 30 mm / *Duljina čepa 30* mm		Tenon length 32 mm / *Duljina čepa 32* mm	
	Max force, N *Najveća sila, N*	**Max moment, Nm** *Moment savijanja, Nm*	**Max force, N** *Najveća sila, N*	**Max moment, Nm** *Moment savijanja, Nm*
1	6421.1	359.0	4891.8	273.5
2	6329.1	353.8	5940.1	332.1
3	7136.9	399.0	6336.9	354.3
4	7155.9	400.1	6165.2	344.7
5	6511.0	364.0	6514.8	364.2
6	7986.0	446.5	6622.2	370.2
7	6647.7	371.7	6631.4	370.7
8	6670.1	372.9	6496.1	363.2
9	5736.1	320.7	6881.9	384.7
Mean / *srednja vrijednost*	6732.7	376.4	6275.6	350.8
Median / *medijan*	6647.7	371.6	6496.1	363.2
Standard deviation *standardna devijacija*	635.1	35.5	587.7	32.9
Coefficient of variation *koeficijent varijacije*	9.4 %	9.4 %	9.4 %	9.4 %

Table 3 Results of forces and bending moments of rear leg joints
Tablica 3. Rezultati sila i momenata savijanja spojeva stražnjih nogu

No. of specimen *Broj uzorka*	Tenon length 30 mm *Duljina čepa 30 mm*		Tenon length 32 mm *Duljina čepa 32 mm*	
	Max force, N *Najveća sila, N*	Max moment, Nm *Moment savijanja, Nm*	Max force, N *Najveća sila, N*	Max moment, Nm *Moment savijanja, Nm*
1	6194.4	386.0	4682.0	291.8
2	6503.6	405.3	5131.5	319.8
3	6222.6	387.8	5248.6	327.1
4	5452.7	339.8	6088.4	379.4
5	5670.8	353.4	5670.9	353.4
6	5969.5	372.0	5451.6	339.7
7	5261.7	327.9	4863.4	303.1
8	5931.4	369.6	6282.1	391.5
9	6080.2	378.9	5372.8	334.8
Mean / *srednja vrijednost*	5920.8	369.0	5421.3	337.9
Median / *medijan*	5969.5	372.0	5372.8	334.8
Standard deviation *standardna devijacija*	395.2	24.6	527.2	32.9
Coefficient of variation *koeficijent varijacije*	6.7 %	6.7 %	9.7 %	9.7 %

Generally, the results indicated that the maximum force mean values of front leg joints with a smaller angle between the stretcher and leg were higher than the mean values of rear leg joints for all tenon lengths. The mean maximum force of the front leg joints (angle 102°) with a tenon length of 30 mm was 13.7 %, and with a tenon length of 32 mm 15.7 %, higher than the rear leg joints (angle 112°) with the same tenon length. The differences are partly the result of different configurations of test specimens of the front and rear leg joints, e.g. the different lengths of the specimen elements that were obtained during their construction.

Consequently, the values of maximum force were not comparable due to dimensional differences of these two groups of joints and, in this case, the maximum force cannot be an indicator of the joint strength.

Moreover, the results show differences among the mean values of the maximum force of joints constructed using two different tenon lengths (30 and 32 mm). The mean values of maximum force increased by 7.3 % (front leg joints – 102°) and 9.2 % (rear leg joints — 112°) as the tenon length decreased from 32 mm to 30 mm. These results contradict the data in the literature, which claim that joints became stronger as tenon
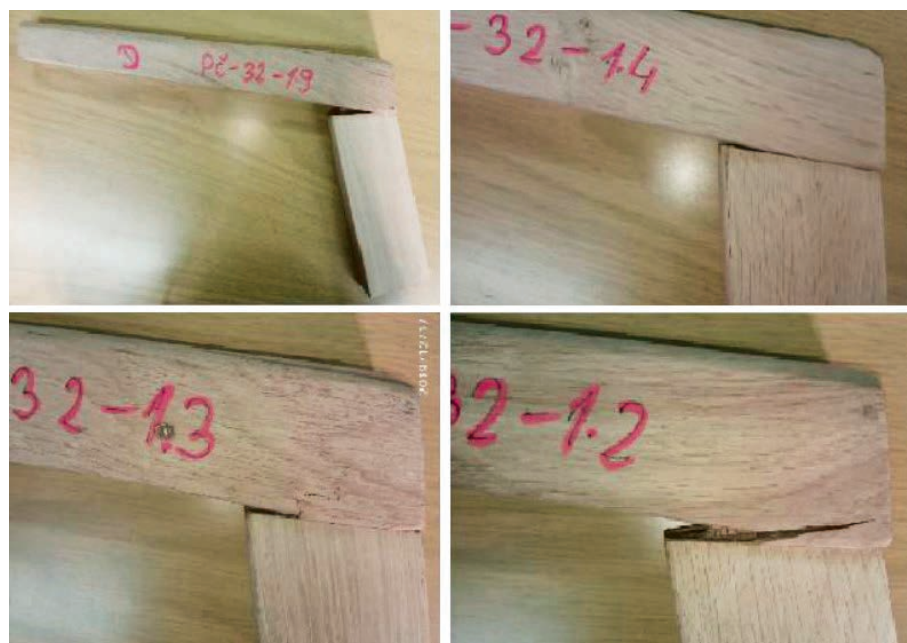

Figure 6 Characteristic joint failures
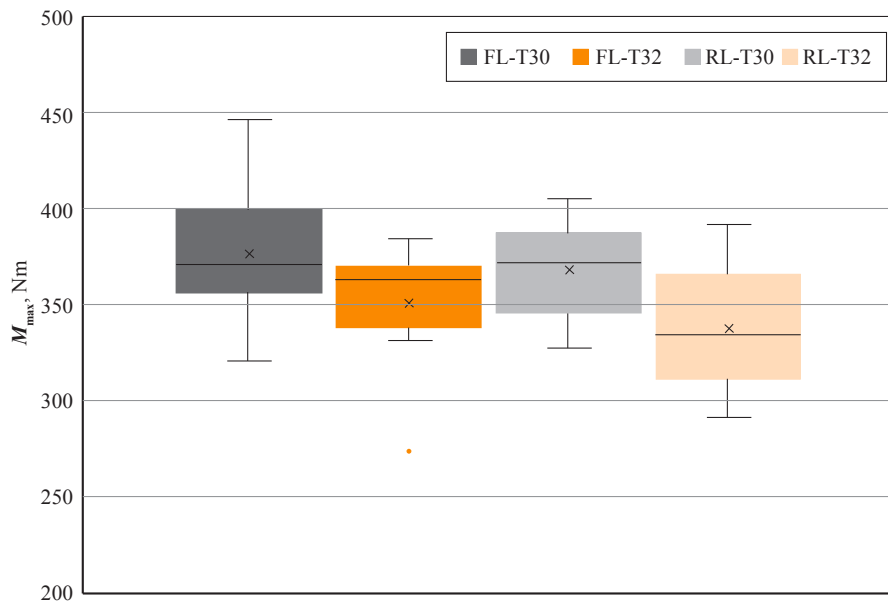**Slika 6.** Karakteristični lomovi spoja

Figure 7 Box and whisker plot – distribution of maximum moment results of front leg joints (FL) and rear leg joints (RL) for tenon length of 30 mm and 32 mm (T30 and T32)
Slika 7. Dijagram raspodjele rezultata najvećeg momenta spojeva prednjih nogu (FL) i spojeva stražnjih nogu (RL) za duljinu čepa 30 i 32 mm (T30 i T32)

length increased. It is assumed that the results of the current work were influenced by a small difference between the examined tenon lengths (2 mm).

The left support reactions were $F_{Amax}=0.842 \cdot F_{max}$ and $F_{Amax}=0.802 \cdot F_{max}$ for front and rear leg joints, respectively. The values of the ultimate bending moment of the joints were calculated using the moment arm (1), i.e. the distance from the left support reaction to the force line, $a_A=66.39$ mm for front leg joints and the distance $a_A=77.66$ mm for rear leg joints.

Certainly, the percentages of the ratio of maximum moments of the joints with tenon lengths of 30 and 32 mm had the same values as the differences among the mean values of maximum force of the joints constructed using those two tenon lengths. However, the front leg joints (angle 102°) with a tenon length of 30 mm had only 2.0 %, and with tenon length of 32 mm only 3.8 %, higher mean maximum moments than the rear leg joints (angle 112°) with the same tenon length. The differences between the ratio of maximum force with two tenon lengths and the ratio of maximum moment with the same tenon lengths were the results of the specimen configuration of front and rear leg joints. Unlike maximum force, the values of maximum moment were comparable and, in this case, they can be an indicator of the strength of the front and rear leg joints.

The basic descriptive statistics of the maximum moment results of front and rear leg joints are presented in Tables 2 and 3. The coefficients of variation (CV) indicate the extent of variability in relation to the mean values of the maximum moment results of the four tested groups of joints. The front leg joints with tenon lengths of 30 mm (CV 9.4 %) and 32 mm (CV 9.4 %),

as well the rear leg joints with a tenon length of 32 mm (CV 9.7 %), turned out to exhibit the highest and similar variability, whereas the rear leg joints with a tenon length of 30 mm (CV 6.7 %) were characterised by the lowest variability.

Comparative distributions of the maximum moment results of the tested groups of joints, i.e. the front and rear leg joints for two tenon lengths, are shown in a Box and Whisker plot (Figure 7). The median line of the RL – T32 box lies outside of all three other comparison boxes and indicates that there is a difference between this group of joints and the other tested joint groups. The interquartile range of the data group FL – T32 (with an outlier) is smaller compared to the other box lengths and indicates that the maximum moment results are less dispersed. Larger ranges for the group FL – T30 (the extreme values) indicate a wider distribution of the maximum moment results. The groups of maximum moment results show different kinds of asymmetry, i.e. skewness.

The t-test was used to determine if the means of two sets of maximum moment results were significantly different from each other. The *p*-values, shown in Table 4, are used to determine statistical significance in the hypothesis tests.

A significant difference (*p* = 0.1326) was not demonstrated with a 95 % level of confidence (α=0.05) between bending moments for the tenon lengths of 30 mm and 32 mm for the front leg joints, while a significant difference (*p* = 0.0371) was demonstrated between the bending moments for tenon lengths of 30 mm and 32 mm for the rear leg joints. According to the literature (Hajdarevic *et al.,* 2020), increasing the tenon

Table 4 *P*-values to determine statistical significance of difference between bending moments for front and rear leg joints with tenon lengths of 30 mm and 32 mm
Tablica 4. *p*-vrijednosti za određivanje statistički značajne razlike između momenata savijanja za spojeve prednjih i stražnjih nogu s čepovima duljine 30 mm i 32 mm

Data source *Izvor podataka*	Variable 1 *Varijabla 1.*	Variable 2 *Varijabla 2.*	*p*-value *p-vrijednost*
Front leg *prednja noga*	Tenon length 30 mm *duljina čepa 30* mm	Tenon length 32 mm *duljina čepa 32* mm	0.1326
Rear leg *stražnja noga*	Tenon length 30 mm *duljina čepa 30* mm	Tenon length 32 mm *duljina čepa 32* mm	0.0371
Tenon length 30 mm *duljina čepa 30* mm	Front leg joint *prednja noga*	Rear leg joint *stražnja noga*	0.6137
Tenon length 32 mm *duljina čepa 32* mm	Front leg joint *prednja noga*	Rear leg joint *stražnja noga*	0.4138

length increases the maximum moment and proportional moment of the mortise-and-tenon joints. The results in this paper indicate that the effect of tenon length is not always clear when there are small changes in it (the difference in tenon length was 2 mm).

A significant difference was not found between the bending moments for front and rear leg joints (different angles between the stretcher and leg) for the tenon length of 30 mm ($p = 0.6137$) or tenon length of 32 mm ($p = 0.4138$). In both cases, the bending moments of the front and rear leg joint specimens were analysed with the same tenon-and-mortise configuration of geometry.

The axial force and transversal force (internal, cross-section forces) of the front and rear leg joint specimens had significantly different values. However, these internal forces are not dominant, and in this case, it can be assumed that they had little effect on the stress state of loaded joints, i.e. joint strength.

4 CONCLUSIONS
4. ZAKLJUČAK

This paper analysed the joint strengths of two sets of specimens with different shapes and dimensions that were cut from real wooden frame constructions. The maximum applied load and bending moment of the front and rear leg joints of the crossed chair base were investigated. All specimens had the same tenon-and-mortise geometry, while the difference in the joint angles was 10°.

The results showed that the joints with a smaller value of joint angle (front leg joints) had greater maximum force than those with a larger joint angle (rear leg joints). The results of maximum force were not completely comparable due to different lengths of specimen elements of front and rear joints. The maximum force increased less than 10 % as the tenon length decreased by 2 mm for both the front and rear leg joints.

The result of calculations showed that the joints with a smaller value of joint angle (front leg joints) had

a higher maximum bending moment than those with a larger joint angle (rear leg joints). However, the differences among the values of bending moment were only 2.0 % and 3.8 % for the tenon lengths of 30 mm and 32 mm, respectively. A significant difference was not revealed between the bending moments of joints with a smaller value of joint angle and the bending moments of joints with a larger angle for all tenon lengths. Significant differences between bending moments for the different tenon lengths were determined for rear leg joints, but not for front leg joints.

The approach presented here to determine and compare joint strength through testing different types of specimens is applicable to research and practice.

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