Bending Moment Capacities of L-Shaped Mortise and Tenon Joints under Compression and Tension Loadings

Ali Kasal,[a] Carl A. Eckelman,[b] Eva Haviarova,[b,]* Yusuf Z. Erdil,[a] and Ibrahim Yalcin [a]

Tests were carried out to determine the bending moment capacities of L-shaped mortise and tenon furniture joints under both compression and tension loadings. The effects of wood species (Turkish beech and Scotch pine), adhesive type (polyvinylacetate and polyurethane), and tenon size (width and length) on the static bending moment capacity of joints under the same loading conditions were investigated. The results of the tests indicated that the moment capacity increased as either tenon width or length increased. The results also indicated that tenon length had a greater effect on the moment capacity than tenon width. In both compression and tension tests, Turkish beech joints were stronger than Scotch pine joints, and PU joints were stronger than PVA joints. An empirically derived expression was developed to estimate the average ultimate bending moment capacity of joints under compression and tension loads as functions of the wood species, the adhesive type, and the tenon size.

Keywords: L-shaped furniture joints; Mortise and tenon joints; Tenon size; Moment capacity; Compression load; Tension load

*Contact Information: a: Department of Wood Science & Industrial Engineering, 48000 Muğla University, Turkey; b: Department of Forestry and Natural Resources, Purdue University, 175 Marsteller Str., 47907 West Lafayette, IN, USA; *Corresponding author: ehaviar@purdue.edu*

INTRODUCTION

Mortise and tenon joints have a long history of use in furniture frame construction, and despite the development of other means of fastening, they continue to be widely used today. To design furniture with mortise and tenon joints that are able to resist the loads imposed on them during service, the ultimate capacity, and especially the moment capacity, of the joints must be known.

Important factors that affect the moment capacity of mortise and tenon joints include tenon length, width, and thickness; closeness of fit between tenon sides and mortise walls; shape of tenon and mortise; properties wood species; and type of adhesive used in construction of the joints, (Smardzewski 2002; Dzincic and Skakic 2012; Dzincic and Zıvanic 2014). A universally accepted design formula that takes these factors into account has not been developed, but useful studies that add to the body of knowledge of the effects of these factors have been conducted. One of the earliest studies was conducted by Milham (1949), who showed that highest capacities are obtained when a close tolerance between the tenon and mortise is obtained and that tenon shoulders have a positive effect on joint capacity. Dupont (1963) also demonstrated the importance of maintaining close tolerances and showed that optimum capacity was obtained when glue was applied to both the sides of the tenon and the walls of the mortise. Sparkes (1968) showed that square-end and round-end mortise and tenon joints were equally effective, but that a square-end tenon fitted into a round-end mortise had 15% less capacity than joints with matched components. Hill and Eckelman (1973) found that moment capacity was directly related to the shear strength of the wood species. An important study by Wilczynski and Warmbier (2003) carried out to determine the effect of tenon dimensions on the bending strength and stiffness of mortise and tenon joints indicated that moment capacity was related to tenon length to the 0.743 power and tenon width to the 0.648 power for beech specimens constructed with a polyvinyl acetate adhesive. Tankut and Tankut (2005) showed that rectangular-edge mortise and tenon joints were approximately 15% stronger than round-edge mortise and tenon joints, or joints constructed with rectangular-end tenons fitted into round-end mortises. Ratnasingam *et al.* (2010) compared the bending and fatigue strengths of rectangular mortise and tenon joints made from oil palm (*Elaeis guineensis*) against woods such as rubberwood (*Hevea brasiliensis*), Nyatoh (*Pallaquim* sp.), Meranti (*Shorea* sp.), and Sepetir (*Sindora* sp.) and found that the bending moment capacity of the oil palm joints was half that of the capacity of the joints constructed with the other woods. Finally, Kasal *et al*. (2013) developed a predictive expression for round-edge rectangular mortise and tenon joints as a function of wood species, adhesives, and tenon geometry.

In contrast to the studies conducted on T-shaped mortise and tenon joints, there is limited information available concerning the bending moment capacity of L-shaped mortise and tenon joints. In service, L-shaped joints would be expected to be loaded either in tension or compression, or both, so it is important to evaluate the moment capacity of these joints under both types of loading. Assuming that differences exist, the lower capacity, whether in tension or compression, would be used for general design purposes. Another factor of interest is whether or not the coefficients of variation of the moment capacities associated with the two types of loading differ substantially.

This study was carried out to investigate the relationship of the bending moment capacities of L-shaped, round-edge mortise and tenon joints to joint geometry, wood species, and type of adhesive used in their construction. An additional objective was to develop expressions that could estimate the bending moment capacity of L-shaped joints that were loaded in either tension or compression.

EXPERIMENTAL

Experimental Plan of Study

Altogether, 360 specimens {(180 compression and 180 tension) x 5 replications x 2 wood species (Turkish beech and Scotch pine) x 2 adhesive types (PVA and PU) x 3 tenon widths (30, 40, and 50 mm) x 3 tenon lengths (30, 40, and 50 mm)} were prepared and tested to determine the joint bending moment capacity.

Full linear models, represented by Eqs. 1 and 2, for the four-way factorial experiments were considered to determine the effects of the wood species, adhesive type, tenon depth, and tenon length on the bending moment capacity of L-shaped joints under static compression and tension loads. The form models are,

$$MC_{ijklm} = \mu_1 + A_i + B_j + C_k + D_l + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (AD)_{il} + (BD)_{jl} + (CD)_{kl} + (ABC)_{ijk} + (ABD)_{ijl} + (ACD)_{ikl} + (BCD)_{jkl} + (ABCD)_{ijkl} + \varepsilon_{ijklm} \quad (1)$$

$$MT_{ijklm} = \mu_2 + A_i + B_j + C_k + D_l + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (AD)_{il} + (BD)_{jl} + (CD)_{kl} + (ABC)_{ijk} + (ABD)_{ijl} + (ACD)_{ikl} + (BCD)_{jkl} + (ABCD)_{ijkl} + \varepsilon_{ijklm} \quad (2)$$

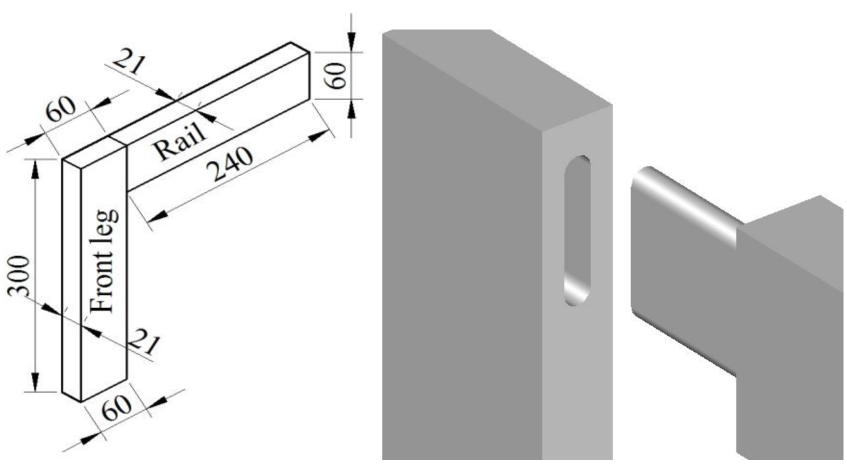
where MC_{ijklm} and MT_{ijklm} are the bending moment capacities (N·m) under compression and tension, respectively; μ_1 and μ_2 are the population mean bending moment capacities (N·m) for all wood species-adhesive, type-tenon, and width-tenon length combinations, respectively; A is the discrete variable representing the effect of the wood species; B is the discrete variable representing the effect of the adhesive type; C is the discrete variable representing the effect of the tenon width; D is the discrete variable representing the effect of the tenon length; (AB), (AC), (BC) , (AD), (BD), and (CD) are the effects of the two-way interactions among the four variables; (ABC), (ABD), (ACD), and (BCD) are the effects of the three-way interactions among the four variables; $(ABCD)$ is the effect of the four-way interaction among the four variables; ε is a random error term; i is an index for the wood species, 1 or 2; j is an index for the adhesive type, 1 or 2; k is and index for the tenon width, 1, 2, or 3; l is an index for tenon length, 1, 2, or 3; and m is and index for the replication, 1 to 5.

Test Materials

All of the joints were constructed of Turkish beech (*Fagus orientalis* L.) or Scotch pine (*Pinus sylvestris* L.) lumber obtained from commercial suppliers. The moisture content (MC), density, compression, tension, shear, bending strength (MOR), and modulus of elasticity (MOE) of the woods were evaluated in accordance with the procedures described in ASTM D 4442 (2001) and ASTM D 143-94 (2000), respectively. The average density values were 0.60 and 0.45 g/cm^3 at 10.8% and 11.2% MC for Turkish beech and Scotch pine, respectively. Specimens were conditioned to and tested at 12 ± 0.2% moisture at a dry bulb temperature of 22 °C. To assemble the specimens, 65%-solids content polyvinyl acetate and one component solvent free polyurethane adhesives were used.

Description of Specimens

The configuration of the specimens is shown in Fig. 1a and 1b.



a. b.

Fig. 1. General configuration of the L-shaped joint specimen used (a) and detail of the round-edge (b) mortise and tenon (measurements in mm)

Each L-shaped joint consisted of two members, namely, a post (front leg) and a rail. Each post measured 300 mm long by 60 mm wide by 21 mm thick, whereas each rail measured 240 mm long by 60 mm wide by 21 mm thick.

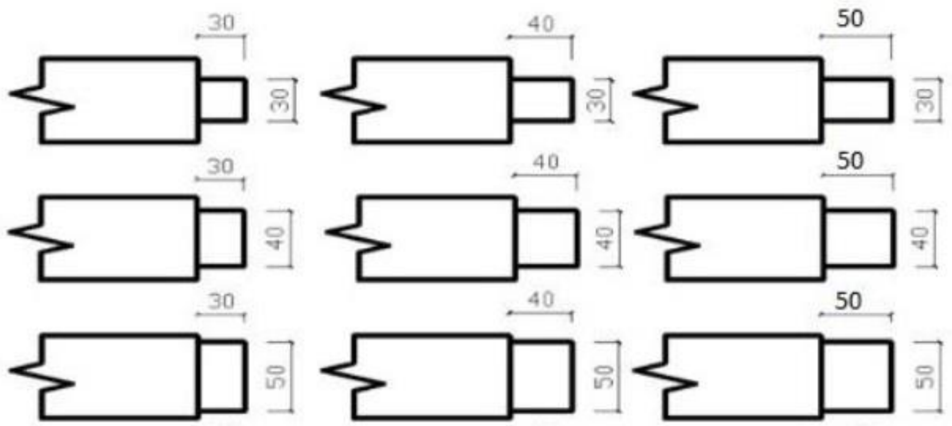


Fig. 2. Geometries of the various sizes of mortise and tenon joints (measurements in mm) showing width (vertical) and tenon length (horizontal)

A mortising machine and a tenoning machine were used to machine the round-edge mortises and to cut the round-edge tenons. Tenon configurations are given in Fig. 2. As can be seen, the tenons measured 30, 40, or 50 mm long by 30, 40, or 50 mm wide. All tenons were 7 mm thick. The clearance and type of fit were not observed according to a standard or a norm. However, in this study a snug fit (average mortise-tenon clearance of 0.076 ± 0.025 mm) was obtained between the tenons and mortises. Adhesive was applied liberally to the tenon faces (cheeks) and the walls of the mortises. Pieces of wax paper (with openings to accommodate the tenons) were placed between the ends of the rails and the walls of the posts to prevent the tenon shoulders from adhering to the walls of the posts.

After the initial insertion of a tenon into its corresponding mortise, a bar clamp was used to fully seat the tenon. Following assembly, the specimens were allowed to cure for at least one month before being tested in an environmentally controlled conditioning room set to produce an average equilibrium moisture content of 12% at 22 °C.

Testing

Loads were applied to the joints as shown in Fig. 3a and 3b. All tests were carried out on a 50-kN-capacity universal testing machine. The moment arm was 0.170 m for both compression and tension loading. The rate of static loading was 6 mm/min. In the tension tests, as shown in Fig. 3b, the bottoms of each of the two legs of the joints were placed on rollers so that the two joint members were free to move outward as the joint was loaded.

The loading was continued until a non-recoverable drop in load occurred. Both the mode of failure of the joints and the ultimate load values were recorded. Specimens were cut from the rails and weighed immediately after each test. A total of 360 joint specimens were tested, 180 in compression and 180 in tension.

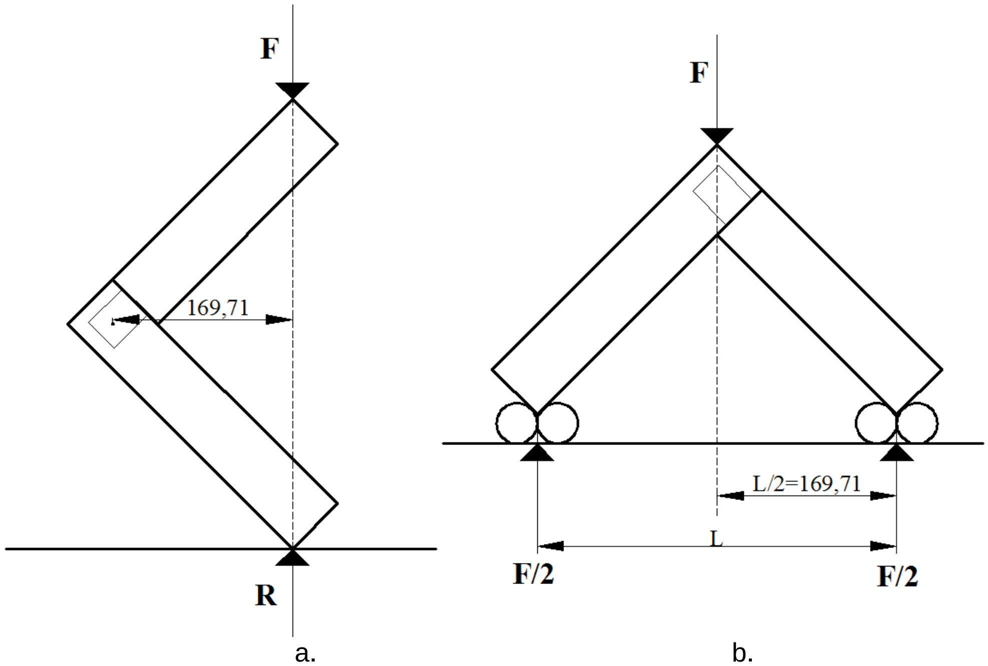


Fig. 3. Diagram showing loading forms of specimens subjected to compression (a) and tension (b). The letter "R" refers to the reaction force (measurements in mm)

The ultimate applied load values, *F*, measured in N, were converted to corresponding bending moment values by means of the expressions $M_C = 0.170\ F$ and $M_T = 0.085\ F$ for compression and tension, respectively, where M_C and M_T were measured in N·m and are the ultimate bending moments for specimens subjected to compression and tension loads, respectively.

Statistical Analysis

Four-way analysis of variance (ANOVA) linear model procedures were performed for the bending moment capacity data for both compression and tension loads to analyze the main effects and interaction factors affecting the ultimate bending moments.

The least significant difference (LSD) multiple comparisons procedure at the 5% significance level was performed to determine the mean differences in the bending moment capacity under compression and tension of the L-shaped joints tested, considering some of the significant factors and interactions in the ANOVA results mentioned above. For both compression and tension data, average comparisons for the main factors (wood species, adhesive type, tenon width, and tenon length) and four-way interactions were analyzed.

RESULTS AND DISCUSSION

Material Properties

The physical and mechanical properties of the materials, as determined according to the procedures described in ASTM D 4442 (2001) and ASTM D 143-94 (2000), respectively, are given in Table 1.

Table 1. Physical and Mechanical Properties of Wood Species Used in the Study

Wood species	MOE * (N/mm^2)	Tension strength (N/mm^2)	Compression strength (N/mm^2)	Shear strength (N/mm^2)	MOR* (N/mm^2)	Density (g/cm^3)	MC* (%)
Turkish Beech	11183	118.4	60.7	10.3	115.9	0.60	10.8
Scotch Pine	10289	65.5	57.2	6.2	88.3	0.45	11.2
* MOE: Modulus of elasticity; MOR: Modulus of rupture; MC: Moisture content							

Failure Modes

A rapid drop in the applied load occurred when the ultimate value was reached in both compression and tension loadings. In general, joints with tenons 30 mm in length failed as a result of glue-line fractures, whereas joints with tenons 40 and 50 mm in length failed as a result of splitting of the post or fracture of the tenon (Fig. 4a, b, and c). When joints were loaded in compression, the top of the mortise failed in tension perpendicular to the grain, especially in the Scotch pine specimens with large tenons, whereas in joints loaded in tension, the top portion of the mortise member failed in shear parallel to the grain.

a. b. c.

Fig. 4. Failure modes of the specimens including the glue-line fracture (a), splitting of the post (b), and fracture of the tenon (c).

Bending Moment Capacities

For the compression test data, ANOVA results indicated that the four-factor interaction, all three-factor interactions, all two-factor interactions (except for the adhesive type-tenon length interaction), and all main factors were statistically significant at the 5% significance level. For the tension data, ANOVA results indicated that the four-factor interaction, all two-factor and three-factor interactions, and all main factors were significant.

Tables 2 and 3 show the mean comparisons of the bending moment capacity under compression and tension for wood species and adhesive type, respectively. The single LSD values were 3.641 Nm for compression and 3.696 Nm for tension. Thus, the bending moment capacities of the joints under both compression and tension were significantly affected by the joint member wood species and the adhesive type. Specimens glued with the PU adhesive had approximately 16% higher capacity than the specimens glued with PVA in both compression and tension. Overall, the specimens constructed of Turkish beech had 33% and 16% higher moment capacities than the specimens constructed of Scotch pine when loaded in compression and tension, respectively. These differences in the moment capacities could be explained by the differences in shear strength parallel to the grain of the wood of which the joints were constructed. Tests have shown (Hill and Eckelman 1973) that a positive linear relationship exists between the bending moment capacity of mortise and tenon joints and the shear strength parallel to the grain of the wood in which the mortise is cut.

Table 2. Mean Comparisons for Wood Species on Bending Moment Capacity under Compression and Tension Loads*

Wood Species	Moment under Compression (N·m)		Moment under Tension (N·m)	
	X	HG	X	HG
Turkish beech	187	A	165	A
Scotch pine	140	B	142	B
	LSD ± 3.641 N·m		LSD ± 3.696 N·m	

* Values followed by the same capital letter are not significantly different.

Table 3. Mean Comparisons for Adhesive Type on Bending Moment Capacity under Compression and Tension Loads

Adhesive Type	Moment under Compression (N·m)		Moment under Tension (N·m)	
	X	HG	X	HG
PU	178	A	163	A
PVAc	149	B	143	B
	LSD ± 3.641 N·m		LSD ± 3.696 N·m	

Figures 5a and 5b give comparisons of the mean bending moment capacities of the joints for tenon width and length, respectively. The single LSD values were 4.46 N·m for compression and 4.526 N·m for tension. Results indicated that the bending moment capacity of the joints increased as either tenon width or tenon length increased. However, tenon length had a greater effect on the moment capacity of the joints under tension than tenon width. Maximum increases were obtained when tenon width increased from 30 to 40 mm in compression loadings; however, increasing the tenon width from 30 to 40 mm had no significant effect on the bending moment capacity in tension loadings.

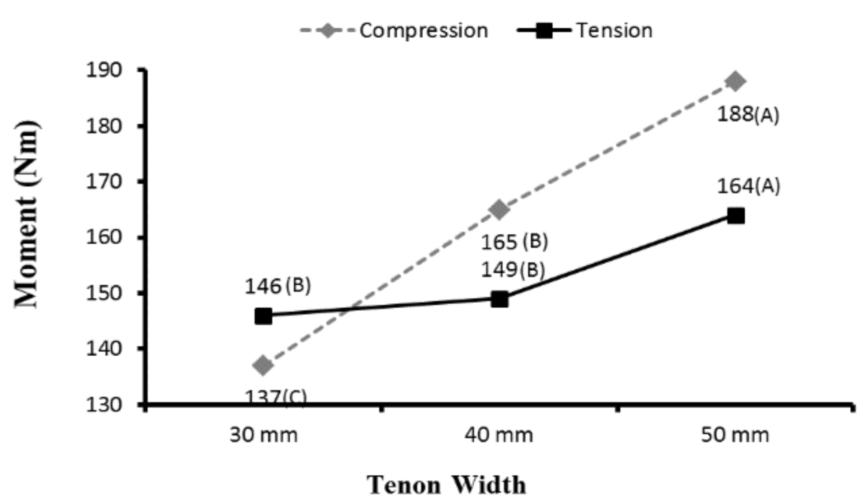


Fig. 5a. Mean comparisons for tenon width and length under compression and tension loads

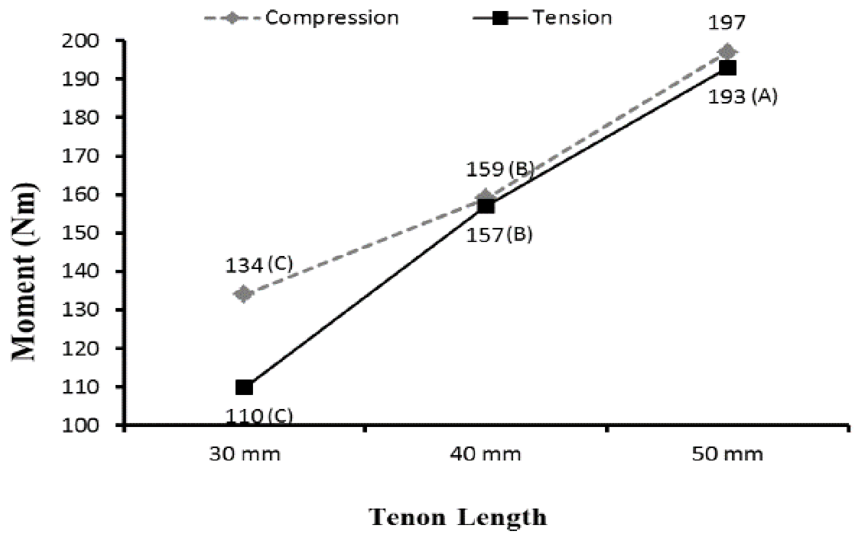


Fig. 5b. Mean comparisons for tenon width on bending moment capacity under compression and tension loads

Increasing the tenon width from 40 to 50 mm increased the bending moment capacity of the joints by approximately 12% under both loading conditions. The bending moment capacity increased by 19% and 24%, respectively, as tenon length increased from 30 to 40 mm and from 40 to 50 mm for joints loaded in compression, whereas it increased by 43% and 23%, respectively, for joints loaded in tension.

The average bending moment capacities for both compression and tension loadings, along with coefficients of variation and LSD comparison test results for four-way interaction, are given in Tables 4 and 5, respectively. The single LSD values were 15.45 N·m for compression and 15.68 N·m for tension. As can be seen in Table 4, in the case of compression loading, the beech joints glued with PU with 50-by-50 mm tenons had the highest bending moment capacity (279 N·m); in contrast, the pine joints glued with PVA with 30-by-30 mm tenons had the lowest bending moment capacity (70 N·m). In the case of tension loading (Table 5), the beech joints glued with PU with 40-by-50 mm tenons had the highest bending moment capacities (270 N·m), whereas the pine joints glued with PVA with 40-by-30 mm tenons had the lowest capacities (70 N·m).

Overall, the joints subjected to compression loading had an average moment capacity of 163.33 N·m, whereas the joints loaded in tension had an average ultimate moment capacity of 153.28 N·m. Thus, the moment capacity of the joints loaded in compression was, on average, 7% higher than the average for the joints loaded in tension. In terms of the COVs, 27 sets (75%) of the tensioned specimens had COVs less than 10%, whereas the compression specimens had 30 sets (83%) with COVs less than 10%. Likewise, 9 tension sets had COVs between 11% and 20% as compared to 6 sets for the compression specimens. Overall, these results indicate that the capacity in tension was somewhat more variable than that in compression, particularly in the 0% to 10% COV range.

Finally, in considering "working design" values, it is also useful to consider the performance of the joints as a fraction of the average capacity of each group. None of the joints failed at a capacity below 70% of the average capacity for their group. Likewise, only seven (9.7%) specimens had less capacity than 75% of their group's average. Only 8 specimens (11.1%) had capacities less than 80% of their group's average.

Table 4. Mean Moment Capacities, LSD Results, and Comparison of Test and Predicted Values of L-Shaped Joints under Compression Loads

Wood Sp.	Tenon width (*mm*)	Tenon length (*mm*)	Moment capacity under compression (*Nm*)									
			PVAc					PU				
			Test value (*Nm*)	COV *(%)*	HG	Pred. value (*Nm*)	Ave. / Pred. Ratio	Test value (*Nm*)	COV *(%)*	HG	Pred. value (*Nm*)	Ave. / Pred. Ratio
Turkish beech	30	30	123	3.89	KL	108	1.14	157	7.59	HI	127	1.24
		40	145	3.74	IJ	144	1.01	155	5.75	HI	169	0.92
		50	197	5.59	EF	180	1.10	197	5.59	EF	211	0.93
	40	30	164	11.18	H	126	1.30	169	1.45	GH	148	1.14
		40	155	5.94	HI	168	0.92	147	9.28	IJ	198	0.74
		50	238	11.53	B	210	1.13	223	9.11	C	247	0.90
	50	30	154	7.52	HI	135	1.14	194	3.96	EF	159	1.22
		40	215	8.18	CD	180	1.19	225	6.58	BC	212	1.06
		50	221	4.00	C	225	0.98	279	6.50	A	265	1.05
Scotch pine	30	30	70	2.92	P	87	0.80	105	9.35	MN	103	1.02
		40	95	9.44	NO	116	0.82	113	3.36	LM	137	0.83
		50	133	16.22	JK	145	0.92	158	11.00	HI	171	0.92
	40	30	85	5.42	OP	102	0.83	156	4.83	HI	120	1.30
		40	129	7.09	K	136	0.95	190	2.35	EF	160	1.19
		50	132	10.19	JK	170	0.78	191	5.31	EF	200	0.96
	50	30	112	10.97	LM	109	1.02	121	4.84	KL	129	0.94
		40	129	4.52	K	146	0.89	205	8.11	DE	171	1.20
		50	183	2.28	FG	182	1.00	214	5.29	CD	214	1.00
			LSD ± 15.45 *Nm*									

Non-Linear Regression Expression

In developing a regression expression for estimating the bending moment capacity of these joints, the position of the neutral axis is unknown, but the sum of the tensile forces (*T*) on one side of the neutral axis must equal the sum of the compressive forces (*C*) on the opposite side (Fairman and Cutshall 1953). The internal resisting moment developed, *M*, is equal to the product of the resultant force, *T*, multiplied by the distance between the resultant tension and compressive forces, (*i.e.*, the internal moment arm). If the resultant force, *T*, is represented by the term a_0WL, and the internal moment arm by the term a_1W+d, the following expression is obtained for the compression and tension, respectively,

$$M = a_0WL \times (a_1W + d) \tag{3}$$

where *M* refers to the moment capacity of the joint under compression or tension in N·m; *W* refers to the width and *L* to the length of the tenon in mm; *d* refers to the width of the shoulder (for these specimens, d = (60 – tenon width)/2) in mm; and a_0 and a_1 are regression coefficients (Fig. 6). To this expression must be added a term for the shear strength of the wood, S^{a_2} (N/mm^2).

Table 5. Mean Moment Capacities, LSD Results, and Comparison of Test and Predicted Values of L-Shaped Joints under Tension Loads

Wood Species	Tenon width (*mm*)	Tenon length (*mm*)	Moment capacity under tension (*Nm*)									
			PVAc					PU				
			Test Value (*Nm*)	COV *(%)*	HG	Pred. Value (*Nm*)	Ave./ Pred. Ratio	Test Value (*Nm*)	COV *(%)*	HG	Pred. Value (*Nm*)	Ave. / Pred. Ratio
Turkish beech	30	30	140	11.76	LM	101	1.38	104	4.63	RS	119	0.87
		40	178	13.35	HI	135	1.32	195	5.56	FG	159	1.23
		50	246	6.45	B	169	1.46	225	3.17	DE	198	1.13
	40	30	111	5.67	QR	118	0.94	95	6.68	ST	139	0.68
		40	160	6.82	JK	158	1.02	135	11.16	MNOP	185	0.73
		50	172	8.66	IJ	197	0.87	270	4.21	A	232	1.17
	50	30	93	14.65	ST	127	0.73	105	8.32	RS	149	0.70
		40	156	6.19	KL	169	0.92	131	9.11	MNOP	199	0.66
		50	209	3.53	EF	211	0.99	241	8.97	BC	249	0.97
Scotch pine	30	30	89	11.21	T	82	1.09	97	10.98	RST	96	1.01
		40	121	11.00	PQ	109	1.11	134	5.82	MNOP	128	1.04
		50	139	12.91	MN	136	1.02	145	7.58	T	160	0.90
	40	30	70	8.66	U	96	0.73	132	6.74	MNOP	112	1.17
		40	123	7.06	OPQ	127	0.97	215	6.77	DE	150	1.43
		50	137	9.25	MNO	159	0.86	174	8.59	IJ	187	0.93
	50	30	125	15.53	MNOP	103	1.22	155	7.79	KL	121	1.29
		40	123	9.50	NOPQ	137	0.90	214	5.02	DE	161	1.33
		50	191	4.45	GH	171	1.12	229	5.27	CD	201	1.14
			LSD ± 15.68 *Nm*									

In addition, terms are needed to account for the adhesive, *PVA* or *PU*. When these terms are added, the following expression is obtained,

$$M = a_0(WL)(a_1W + d)S^{a_2}(a_3T + a_4C)(a_5\,pva + a_6\,pu) \qquad (4)$$

where a_1 to a_6 are regression coefficients, T and C refer to tension or compression loading, respectively, *PVA* and *PU* refer to the polyvinyl acetate and polyurethane adhesives, respectively, and the remaining variables are defined above. When fitted to the test results (where *T*, *C*, *PVA*, and *PU* have values of either 0 or 1), the following expression results,

$$M = 0.00227(WL)(0.229W + d)S^{0.42}\mathrm{k}_1\mathrm{k}_2 \qquad (5)$$

where k_1 refers to the type of loading: k_1 (tension) = 1 or k_1 (compression) = 1.066; and k_2 refers to the adhesive: k_2 (PU) = 1.0 or k_2 (PVA) = 0.85. The R^2 value for this expression was 61.6%. The standard deviation of the percentage differences between the observed and predicted values, expressed as a fraction of the observed values, was 23.0. The values estimated by the above expression are given in Tables 4 and 5.

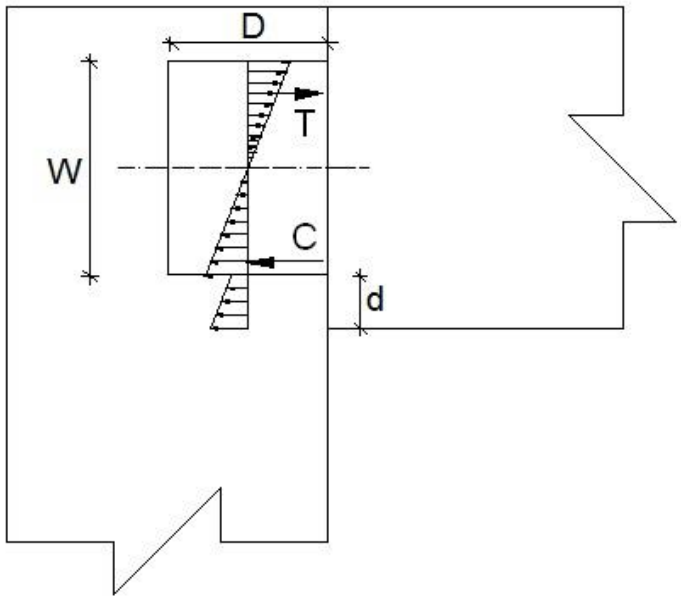


Fig. 6. Dimension nomenclature of a mortise and tenon joint

"Working Design" Considerations

The ratios of the average test values for each joint configuration divided by the corresponding estimated values are also given in Tables 4 and 5. The ratios of test values-to-estimated values ranged from a minimum of 0.66 to a maximum of 1.46. Given the minimum ratio of 0.66, it follows that "working" design values must be taken as only a fraction of the estimated value. If the working level were taken as 70% of the estimated level, for example, none of the test samples would have had capacities less than the predicted values.

CONCLUSIONS

This study provides furniture frame manufacturers with useful information concerning the effects of several joint construction factors, such as the wood species, adhesive type, tenon width, and tenon length, on the bending moment capacities of L-shaped mortise and tenon joints under compression and tension loadings. Specifically, results of the study indicate that the shear strength of the wood parallel to the grain has a substantial effect on the moment capacity of mortise and tenon joints. Specimens constructed of Turkish beech (which has a shear strength of 10.3 N/mm^2 at 12% MC) had higher bending moment capacities than those constructed of Scotch pine (which has a shear strength of 6.2 N/mm^2). The adhesives also had a measurable effect on the joint capacity. Joints constructed with the PVA adhesive had only 85% the capacity of those constructed with the PU adhesive. Moment capacity increased as either the tenon width or tenon length increased but was most affected by tenon length.

Finally, the empirically derived predictive expression, which estimates the ultimate bending moment capacity of mortise and tenon joints under compression and tension loads, provides furniture designers with a design tool that makes it possible to estimate the average strength of joints of similar construction.

REFERENCES CITED

ASTM D143-94 (2000). "Standard test methods for small clear specimens of timber," ASTM International, West Conshohocken, PA.

ASTM D4442-92 (2001). "Standard test methods for direct moisture content measurement of wood and wood-base materials," ASTM International, West Conshohocken, PA.

Dzincic, I., and Skakic, D. (2012). "Influence of type of fit on strength and deformation of oval tenon-mortise joint," *Wood Research* 57 (3), 469-477.

Dzincic, I., and Zivanic, D. (2014). "The influence of fit on the distribution of glue in oval tenon/mortise joint," *Wood Research* 59 (2), 297-302.

Dupont, W. (1963). "Rationalization of glued joints in the woodworking industries," Dept. of Forestry, Forest Products Laboratory, Canada.

Fairman, S., and Cutshall, C. (1953). *Mechanics of Materials*, John Wiley and Sons, Hoboken, NJ.

Hill, M., and Eckelman, C. (1973). "Flexibility and bending strength of mortise and tenon joints," *Furniture Design and Manufacturing* 45(1), 54-61.

Kasal, A., Haviarova, E., Efe, H., Eckelman, C., and Erdil, Y. (2013). "Effect of adhesive type and tenon size on bending moment capacity and rigidity of t-shaped furniture joints constructed of Turkish beech and Scots pine," *Wood and Fiber Science* 45(3), 287-293.

Milham, R. (1949). *A Comparison of Strength Characteristics of the Mortise and Tenon Joint and Dowel Joint*, M.S. thesis, University of Michigan, Ann Arbor, MI.

Ratnasingam, J., Ioras, F., and McNulty, T. (2010). "Fatigue strength of mortise and tenon furniture joints made from oil palm lumber and some Malaysian timbers," *Journal of Applied Sciences* 10(22), 2869-2874. DOI: 10.3923/jas.2010.2869.2874

Smardzewski, J. (2002). "Strength of profile-adhesive joints," *Wood Science and Technology* 36 (2), 173-183.

Sparkes, A. (1968). *The Strength of Mortise and Tenon Joints*, Furniture Industry Research Association, Stevenage, Hertfordshire, UK.

Tankut, A. N., and Tankut, N. (2005). "The effects of joint forms (shape) and dimensions on the strengths of mortise and tenon joints," *Turkish Journal of Agriculture and Forestry* 29, 493-498.

Wilczyński, A., and Warmbier, K. (2003). "Effect of joint dimensions on strength and stiffness of tenon joints," *Folia Forestalia Polonica Seria B* 34, 53-66.

Article submitted: April 17, 2015; Peer review completed: July 20, 2015; Revised version received and accepted: July 27, 2015; Published: September 1, 2015.
DOI: 10.15376/biores.10.4.7009-7020