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Load-carrying capacity of mitered furniture corner joints with dovetail keys under diagonal tension load

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Abstract: The goal of this study was to introduce a method for estimating stress analysis as an efficient procedure for evaluating the strength of mitered corner joints in furniture structures. Tests were carried out to determine the effects of panel type, distance between the centers of dovetail holes and the edges of joints (10, 20, and 30 mm), and type of dovetail key on the load-carrying capacity of mitered corner joints under a diagonal tension load. Specimens were constructed of overlaid medium-density fiberboard (LamMDF) and particleboard (LamPb) and connected with butterfly and H-shaped dovetail keys. Polyvinyl acetate adhesive was used to assemble the joints. Specimens were tested under diagonal tension loads and the corresponding combined stress analysis was conducted using the following formulas:

Total stress at the outer edge, $= -(\sigma_b + \sigma_a) = -\left[\frac{3PL}{tb^2} + \frac{Pcos45}{2bt}\right]$

Total stress at the inner edge, $\sigma_b - \sigma_a = \frac{3PL}{tb^2} - \frac{P\cos 45}{2bt}$

where σb is bending stress, σa is axial stress, P is axial failure load, L is half of the span length, and t and b are the thickness and width of the joint members.

Test results showed that corner joints constructed of LamMDF were 13% stronger than joints constructed of LamPb. For the specimens constructed of both panel types, a 10-mm distance between the dovetail holes and the edges of joints gave better results than distances of 20 and 30 mm. No significant differences were observed between the 2 types of dovetail keys. Total compression stresses at the outer edge were 2 times greater than the total tension stresses at the inner edge of the joints.

Key words: Combined stress, dovetail keys, furniture, mitered joint

Introduction

Joints are the most critical parts of furniture construction. Thus, in discussing wood and wood-based panel furniture, proper design of the joints is the most important stage of the manufacturing process. In order to increase the stiffness and service life of furniture, it is necessary for producers to know what factors would play major roles in strengthening furniture joints. To date, various studies have been carried out in conjunction with strengthening furniture joints and some useful information has been compiled.

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Tankut and Tankut (2010) reported that in L-type corner joints, the diagonal tension is greater than the diagonal compression strength. Their results also showed that corner joints with overlaid medium-density fiberboard (MDF) members are stronger than the same type of joints with overlaid particleboard members. Eckelman and Rabiej (1985) analyzed case furniture using a comprehensive method. They developed an empirical equation that predicts deflection of an unsupported corner of a case, which may exist in both shelves and partitions. This equation showed that the deflection of the tops and bottoms of shelves are identical and a deflection at one location in a partition is equivalent to that of the other sides.

Atar et al. (2009) studied diagonal compression and tension performances of corner joints in case-type furniture constructed with wooden biscuits. They observed that the highest diagonal compression and tension strength are obtained in joints on melamine-coated fiberboards with polyurethane adhesive. Eckelman and Lin (1997) reported that high-strength joints can be fabricated using injection-molded splines, but the strength of such joints is highly dependent on the configuration of the spline itself. Furthermore, the strength of these joints was comparable with the expected strength of similar joints constructed with screws and dowels.

Considering the framed structure of furniture, there are several types of corner joints, such as mitered and butted joints, that are commonly used in the construction of furniture structures. Mitered corner joints are the most popular joints that are made with dovetail keys. Mitered corner joints with dovetail keys are widely used in kitchen cabinet construction. There are wooden and plastic dovetail keys, but butterfly and H-shaped keys made out of polyvinyl chloride are popular. The information available on the strength of mitered corner joints is limited. Ozkaya et al. (2010) studied the effects of the number of dovetail keys and the type of adhesive in frames constructed out of oriented strand board under diagonal tension load. They showed that the number of dovetail keys and the type of adhesive used have significant effects on the diagonal tension strength of tested joints. These investigators recommended application of dovetail keys in corner joints. According to their observations, a single dovetailed joint assembled with polyvinyl acetate (PVAc) is preferred. Altun et al. (2010) investigated the effect of adhesive type on the bending moment capacity of mitered corner joints containing a dovetail as well. Their results indicated that the highest bending moment capacity under tensile loading (46.09 Nm) was obtained in specimens bonded with cyanoacrylate adhesive, but specimens under diagonal compression had the highest bending moment capacity (72.04 Nm) when glued with PVAc. Kılıç et al. (2009) studied the bending moment capacities of mitered corner joints under diagonal tension and compression loadings. Their experimental joints were assembled with dovetails. They found that the best results are obtained with PVAc adhesive. They recommended applying adhesive when constructing joints with dovetails in order to achieve the highest bending moment capacity.

Furniture joints are subjected to various reactions under external loads. In furniture, racking and combined stresses are the most destructive ones to the joints. Most investigations thus far on the bending moment capacity of joints were conducted to observe the gross values of bending resistance of the test specimens (Zhang and Eckelman 1993; Ching and Yiren 1994; Kasal et al. 2005; Zhang et al. 2005; Tankut and Tankut 2009; Vassiliou and Barboutis 2009; Atar et al. 2010) and no effort has been made to analyze combined stresses that are applied to test joints.

The goal of this study was to introduce a method for efficiently evaluating the stress analysis of corner joints in conjunction with influential parameters by which the strength and stiffness of the joints are affected. Therefore, tests were done to analyze the effects of distance between the centers of dovetail holes and the inner and outer corners (edges) of a joint, type of dovetail key, and panel type on the strength of mitered joints constructed with dovetails under diagonal tension loads.

Materials and methods

The general configurations and dimensions of the plastic dovetail keys and the L-type joints used in this study are shown in Figures 1 and 2, respectively.

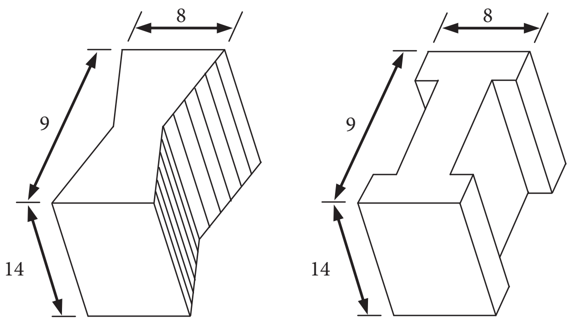

Figure 1. Configuration and dimensions (mm) of dovetail keys (left: butterfly key, right: H-shaped key).

Full-size commercially overlaid panels (3660 × 1830 × 16 mm) of MDF (LamMDF) and particleboard (LamPb) were used for preparing the specimens. The internal bond strength, modulus of rupture, and modulus of elasticity of the test panels were determined in accordance with the specifications of EN 310 (British Standards Institution 1993a) and EN 319 (British Standards Institution 1993b). Some technical properties of the test panels are given in Table 1.

Panels were cut into A and B members of 160 mm in length by 60 mm in width. The specimens were then constructed and trimmed to have the dimensions shown in Figure 2. Beveled cut and dovetail holes were made on the joint members prior to the assembly process. In assembling the test specimens, PVAc adhesive having a solid content of 60% and a density of 1.08 g cm^{-3} was used. The joints were then clamped for 24 h while the adhesive dried. The test specimens included 12 combinations of distance between the dovetail holes and the edges of the joint, type of dovetail keys, and panel type, and each combination had 5 replications. After the assembly process, the joints were kept in a climatic chamber at a relative humidity of 65 ± 3% and a temperature of 20 ± 2 °C for 21 days. It was balanced at 12% humidity so that the adhesive could achieve its full strength (Altinok et al. 2009). The corner joint specimens were tested on a computer-controlled Instron testing machine. The loading form is shown in Figure 3. The rate of loading was 5 mm min^{-1} during the tests.

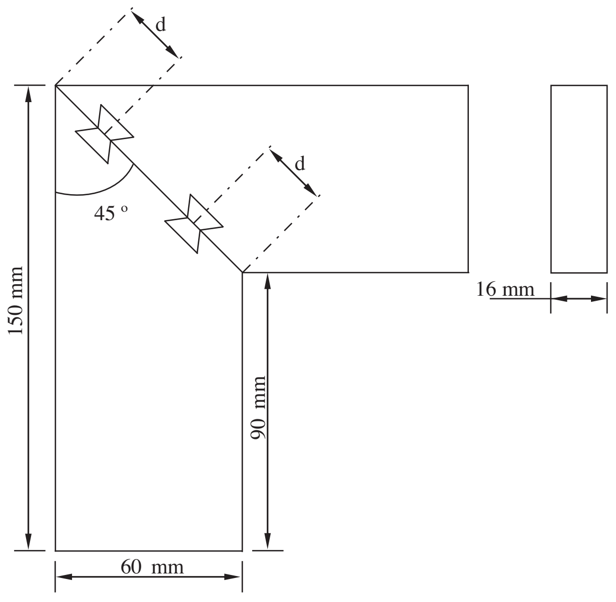

Figure 2. Configuration and dimensions of the corner joints used in the study. d = distance (mm) between the dovetail holes and the edges of the joints.

To analyze the collected data, the first step was to calculate the bending moments that occurred at the joints under diagonal tension loads using the following equation:

$$M_t = P/2 \times L, \tag{1}$$

where P is the ultimate failure load (N) and L is the moment arm (L = 0.06364 m).

Compression stress at the outer edge of the joint under load and the tension stress at the inner edge of joint were then calculated using the following equations:

Total stress at the outer edge

$$= -(\sigma_b + \sigma_a) = -\left[\frac{3PL}{tb^2} + \frac{P\cos 45}{2bt}\right] \tag{2}$$

Total stress at the inner edge

$$\sigma_b - \sigma_a = \frac{3PL}{tb^2} - \frac{P\cos 45}{2bt} \tag{3}$$

where σ_b is the bending stress (MPa) and σ_a is the axial stress. The bending stress (MPa), σ_b, is given by:

$$\sigma_b = \pm\frac{Mt}{S} = \pm\frac{3PL}{tb^2} \tag{4}$$

The axial stress (MPa), σ_a, is given by:

$$\sigma_a = \frac{-P_a}{2A} = \frac{P\cos 45}{2bt} \tag{5}$$

Table 1. Some technical properties of the panels used in this study.

Panel type	Density (g cm^{-3})	MOR (MPa)	MOE (MPa)	IB (MPa)
LamMDF	0.62	21.3	3574	0.55
LamPb	0.64	17.0	3641	0.80

MOR = modulus of rupture; MOE = modulus of elasticity; IB = internal bond strength; LamMDF = medium-density fiberboard; LamPb = particleboard.

where M_b is the calculated bending moment at the center point of the joint (Nm), S is the section modulus (mm^3), P is the measured ultimate load (N), L is the moment arm (mm), t is the thickness of the joint member (mm), b is the width of the joint member (mm), and A is the cross-sectional area of the joint member (mm^2) such that A = bt. The section modulus, S, is given by:

$$S = \frac{1}{6} t b^2 \quad (6)$$

The effect of internal friction between the surfaces and shear effects were ignored in calculating the combined stress. The collected data were statistically normalized and then analyzed. A multiple variance analysis was performed to determine differences among the variables. Duncan's test was used to determine the significant differences among the groups. All comparisons were made with a 5% significance level.

Results

The average values of the bending moment resistances and combined stresses at the inner and outer edges of the joints are given in Table 2. Analysis of variance (ANOVA) results related to determination of the bending moment resistance values of the tested joints are given in Table 3, which reveals that the difference between the groups was highly significant in terms of the panel type and distance factors. There was no significant difference in terms of dovetail key type.

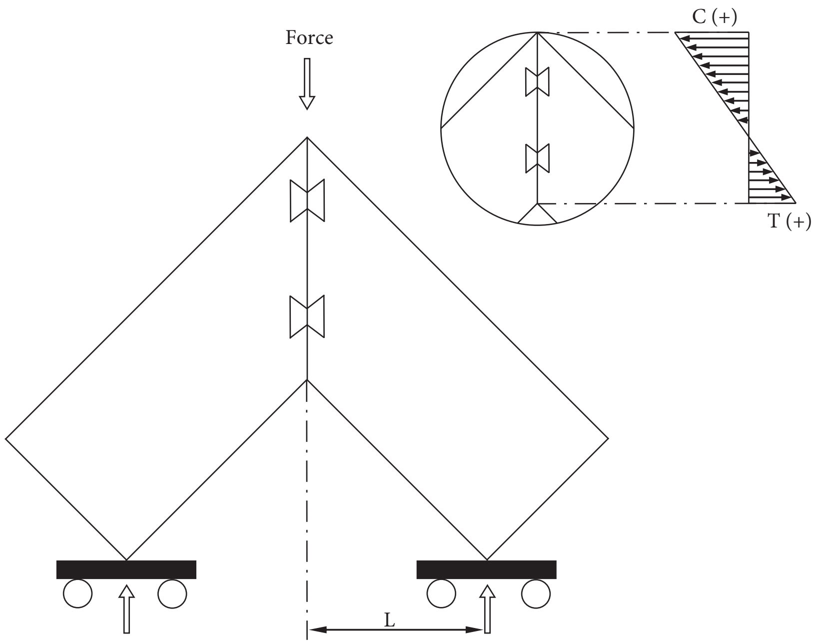

Figure 3. Loading form of diagonal tension test.

Table 2. Mean bending moment resistance and combined stress values of joints with their coefficients of variation (COVs) under diagonal tension.

Panel type	Type of dovetail key	Dovetail distance (mm)	Bending moment resistance (Nm)		Combined stresses (MPa)			
					Inner edge		Outer edge	
			x̄	COV (%)	x̄	COV (%)	x̄	COV (%)
LamMDF	Butterfly key	10	79.600	5.204	1.766	5.204	3.532	5.203
		20	71.772	9.682	1.592	9.683	3.184	9.676
		30	63.239	7.383	1.404	7.264	2.809	7.262
	H-shaped key	10	84.567	10.387	1.950	6.218	3.899	6.208
		20	70.982	3.870	1.619	0.854	3.237	0.849
		30	64.361	6.654	1.420	9.930	2.841	9.918
LamPb	Butterfly key	1	75.537	4.322	1.572	4.163	3.145	4.163
		2	62.263	9.023	1.352	9.260	2.704	9.253
		3	61.752	4.702	1.370	4.701	2.740	4.697
	H-shaped key	1	67.555	2.884	1.612	3.990	3.224	3.997
		2	61.327	8.966	1.368	8.933	2.736	8.905
		3	60.504	2.847	1.344	2.718	2.687	2.718

x̄: Arithmetic mean

Except for the group (dovetail key type × distance factor), the interactions between bilaterally different groups were statistically significance at the 5% level, and there was no significant difference between groups in terms of triple interactions.

The results of ANOVA for determining the combined stresses values in the joints showed that in both the inner and outer edge of joints, the difference between the groups was highly significant in terms of panel type and distance factors (Table 4).

The results of Duncan's test for the determination of significant difference between distance factor groups are given in Table 5. The highest bending moment resistance and stresses were obtained in

Table 3. Results of ANOVA for the bending moment resistance of the joints.

Variance source (symbol)	Sum of squares	SD	Average of squares	F-value	P-value
Panel type (A)	865.777	1	865.777	37.378	***
Dovetail key type (B)	9.870	1	9.870	0.426	NS
Distance factor (C)	2183.750	2	1091.875	47.140	***
A × B	99.647	1	99.647	4.302	*
A × C	184.178	2	92.089	3.976	*
B × C	5.235	2	2.617	0.113	NS
A × B × C	116.967	2	58.484	2.525	NS

$R^2 = 0.757$; NS = not significant; *** = highly significant at $P < 0.001$; * = significant at $P < 0.05$.

Table 4. Results of ANOVA for the amount of combined stress applied on the edges of the joints.

Variance source (symbol)	Dependent variable	Sum of squares	SD	Average of squares	F -value	P-value
Panel type (A)	Tension stress at inner edge	0.535	1	0.535	52.687	***
	Compression stress at outer edge	2.144	1	2.144	52.858	***
Dovetail key type (B)	Tension stress at inner edge	0.027	1	0.027	2.697	NS
	Compression stress at outer edge	0.109	1	0.109	2.683	NS
Distance factor (C)	Tension stress at inner edge	1.229	2	0.614	60.486	***
	Compression stress at outer edge	4.912	2	2.456	60.554	***
A × B	Tension stress at inner edge	0.016	1	0.016	1.596	NS
	Compression stress at outer edge	0.065	1	0.065	1.593	NS
A × C	Tension stress at inner edge	0.134	2	0.067	6.607	**
	Compression stress at outer edge	0.536	2	0.268	6.613	**
B × C	Tension stress at inner edge	0.037	2	0.019	1.843	NS
	Compression stress at outer edge	0.150	2	0.075	1.853	NS
A × B × C	Tension stress at inner edge	0.012	2	0.006	0.605	NS
	Compression stress at outer edge	0.049	2	0.024	.0602	NS

NS = not significant; *** = highly significant at $P < 0.001$; ** = significant at $P < 0.01$.

joints with a distance of 10 mm between the dovetail holes and the edges of the joints, and the lowest were in joints with a distance of 30 mm.

Discussion

As can be seen in Figure 4, under diagonal tension, the butterfly keys moved into the dovetail holes easier than the H-shaped keys. Presumably, the shelf section and the grooved surface of the butterfly key are the reasons for this phenomenon. Although there was no significant difference in term of dovetail key types, Table 2 shows that the H-shaped keys were stronger than the butterfly keys. The LamMDF specimens were about 13% stronger than the LamPb specimens (Table 2). These results are in agreement with those reported by Tankut and Tankut (2010).

Table 5 shows that in both the LamMDF and LamPb specimens, the 10-mm distance between

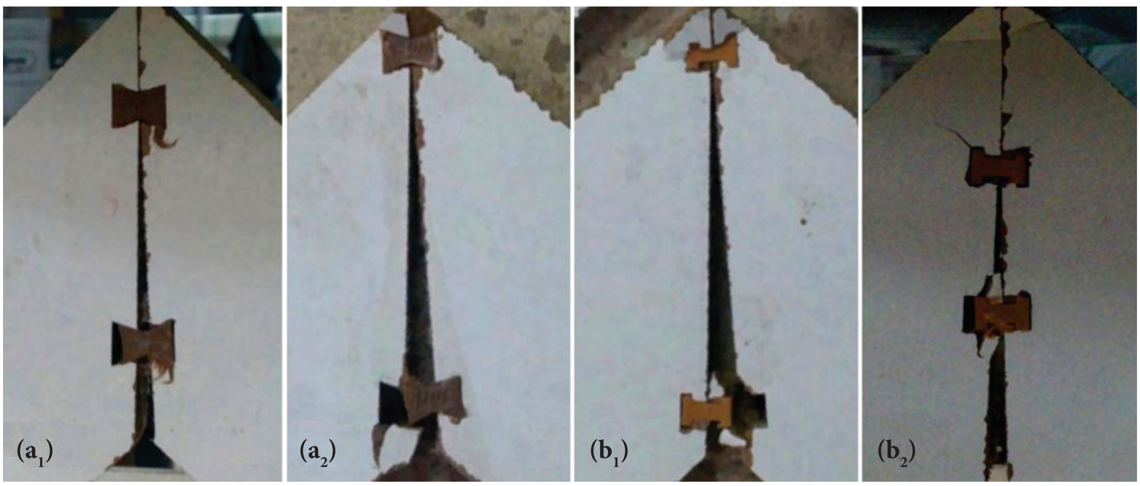

Figure 4. Some failure modes of the joints after the tension test: (a_1) and (a_2) are butterfly key fitted joints and (b_1) and (b_2) are H-shaped key fitted joints.

Table 5. Results of Duncan's test with respect to the distance between the centers of the dovetail holes and the inner and outer edges of the joints in tensile tests.

Panel type	Distance (mm)	Bending moment resistance		Tension stress at inner edge of joints		Compression stress at outer edge of joints	
		(MPa)	Duncan group	(MPa)	Duncan group	(MPa)	Duncan group
LamMDF	30	63.800	A	1.412	A	2.825	A
	20	71.377	B	1.605	B	3.211	B
	10	82.084	C	1.858	C	3.716	C
LamPb	30	61.128	A	1.357	A	2.714	A
	20	61.795	A	1.360	A	2.720	A
	10	71.546	B	1.592	B	3.184	B

the centers of the dovetail holes and the edges of the joint led to more bending moment resistance and stresses than the other 2 distances (20 and 30 mm). Accordingly, it can be said that the load-carrying capacity of the joints is greater when the dovetail holes are closer to the edges of the joints, due to the high stress concentration at the edges of the joints.

The average values of the compression stresses at the outer edges of the joints were about 2 times greater than those of the tension stresses at the inner edges. Under diagonal tension load the stress concentration was very high at the compression zone; the joint members were pressed tightly together at the outer edges of the joints and the edges of the panels split in this zone. The weak internal bonding strength of the panels can be one reason for this occurrence.

Data analysis indicated that under a diagonal tension load, stress concentration was very intensive at the outer edges of the joints. Accordingly, as Figure 4 illustrates, the edges of the panels split at the outside edges of the joints. Therefore, it is essential that the internal bonding strength of the wood composite panels be sufficient to resist this effect. Despite the fact that under a diagonal tension load the average value of the compression stresses at the outer edges of the joints was greater than that of the tension stresses at the inner edges, the strength of the mitered corner joints had the most dependence on the amount of tension stress at the inner edges of the joints, because of joint failures at the inner edges of the joints. However, under the diagonal comparison loads, it is more likely that the amount of combined stress would have more effect at the outer edges of the joints than at the inner edges. Thus, it is necessary for designers to create proper designs to make corner joints stronger. Based on the results, it can be suggested that a distance of 10 mm between the centers of dovetail holes and the edges of joints, H-shaped keys, and LamMDF can be used to prepare strong joints in the manufacturing of miter corner joints with dovetail keys.

Finally, although estimating bending moment resistance is a popular method used to compare the strength and stiffness of furniture corner joints, the analysis used in this study showed that a comparison of the amount of combined stress is a reasonable method to evaluate the effect of various influential factors on the strength of corner joints. Accordingly, for future studies, it can be recommended that estimation of stress analysis can be used in addition to estimation of bending moment resistance to determine the strength of L-shaped corner joints used in furniture frame construction.

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