Effect of the Panel Type and Panel Thickness on Moment Resistance of Screw-Jointed Corner Joints and Stiffness of Four-Member Cabinets

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The objective of this study was to investigate the effects of panel type and panel thickness on moment resistance of L-type corner joints and deflection characteristics of four-member cabinets. Three different wood based panels, namely particleboard (PB), medium density fiberboard (MDF), and okoume (*Aucoumea klaineana*) plywood (PW) were utilized in two different thickness levels for constructing the four-member cabinets. All corner joints and cases were assembled with 4 x 50 mm screws without adhesive. The four member cabinets were tested under static load by supporting at three points. Furthermore, moment resistances of the same type jointed L-type corner joints were tested under static compression and tension loads. Test results indicated that the highest stiffness values were observed with 15 mm PW. This showed that 15 mm plywood could be used instead of 18 mm PW. 16 mm PB and MDF cabinets yielded higher stiffness values than those of 18 mm MDF, PW, and PB. Test results also indicated that 15 mm and 16 mm thick panels can have nearly the same stiffness as 18 mm thick panel.

Keywords: Medium density fiberboard; Particleboard; Stiffness; Four-sided cabinets; L-type corner joints

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INTRODUCTION

Case-type furniture is one of the most important categories of furniture produced and used today. It is used comprehensively in homes, offices, and industrial buildings for storage purposes. Due to increasing liability costs associated with the manufacture of poorly designed case furniture, the use of rational design methods for furniture cases will become a primary concern, especially in the case-type furniture industry where large quantities of the same design are sold to each customer.

In contrast to a rigid frame structure, which derives its strength and rigidity from the bending stiffness of its beams and columns, the strength and rigidity of a panel structure is almost totally dependent upon the torsional rigidity of its plates (Eckelman 1967).

Nowadays, joints without adhesives are common in furniture construction because their use allows furniture to be shipped in the knock-down condition and assembled on site, and this approach greatly reduces shipping costs. In spite of their widespread use, limited studies have been conducted on the strength and stiffness of screw joints.

Screws have been employed in furniture construction for two to three hundred years, primarily to reinforce other constructions or to attach parts such as glue blocks.

They may also be used as the principal connectors. Their ability to resist both withdrawal and lateral loads makes screws excellent furniture fasteners. They are still widely used to fasten hardware to furniture, but they are also extensively used in place of other fasteners such as dowels and nails to form structural, load-bearing joints.

Screw-type fasteners are widely used to construct corner joints of the furniture cases with or without glue. The rational design of case type furniture constructed with screws requires information on the rigidity of these in particleboard (PB) and medium density fiberboard (MDF).

Kotas (1957, 1958a,b) carried out the first known studies of the structural characteristics of case furniture; the results of his research were later incorporated into a small design manual. Lin and Eckelman (1987) carried out a study to determine the effect of joint rigidity on case stiffness; they indicated that joints do have a significant effect on stiffness, and manufacturers may want to use joints that provide the greatest stiffness in their constructions. Kasal *et al.* (2008) studied the effects of screw size on load-bearing capacity and stiffness of five-sided furniture cases constructed of MDF and PB. Five-sided cases were tested under static load by supporting at three points, and it was found that MDF cases yielded significantly higher load-bearing capacity than PB cases, but the significance of MDF cases stiffness over PB cases depended on screw diameter. The stiffness of corner joints affects the strength of case furniture. The deflection of case furniture containing shelves could be reduced by increasing the stiffness of the corner joints (Cai and Wang 1993).

As much as 90% (or more) of all furniture made in Europe is based on wood-based panels, especially using particleboards and MDFs (BioMatNet 2003). It became evident that the moment resistance of the joints is influenced by panel material, type of adhesive, and joints (Tankut and Tankut 2009). Samples with edge banding, which is used to cover the exposed sides of materials, gave higher diagonal tension and compression strength than control samples. LamMDF (laminated medium density fiberboard) corner joints were stronger than LamPB (laminated particleboard) corner joints. As for the type of edge banding, melamine type edge banding material gave more diagonal tension and compression strength than others. The lowest tension and compression strength was obtained in PVC edge banding material (Tankut and Tankut 2010).

This exploratory study aimed to determine the effect of panel type and panel thickness on moment resistance of L-type corner joints and stiffness of four-member cabinets by keeping all other factors (screw size, screw type and etc.) constant.

EXPERIMENTAL

In this study, three different panel types (PB, MDF, PW) and two different panel thicknesses (18 mm to 16 mm for PB&MDF, 18 mm to 15 mm for PW), were used. These are the most commonly used panel types and panel thicknesses in the furniture industry (BioMatNet 2003).

There were 5 replications each. Accordingly, a total of 60 L-type corner joint specimens (30 for compression, 30 for tension) and 30 four-member cabinets were constructed for static moment resistance and stiffness tests. In total, 90 specimens were prepared and tested in this study.

Table 1. Experimental Design of Study

Panel Type	Panel Thickness (mm)	Compression Test (L-type specimens)	Tension Test (L-type specimens	Stiffness Test (Four-member cabinets)	Total
PB	18	5	5	5	15
	16	5	5	5	15
MDF	18	5	5	5	15
	16	5	5	5	15
PW	18	5	5	5	15
	15	5	5	5	15
Total		30	30	30	90

Preparation and Construction of the Specimens

L-type corner joints

Each specimen had two members named face and butt. Dimensions of the face member were 320 ×200 mm for all panel thickness, while dimensions of the butt member were 320 ×182 mm for 18 mm thick panels, 320 x 184 mm for 16 mm thick panels, and 320 x 185 mm for 15 mm thick PW panel (Fig. 1). Members were combined to each other with 3 screws. 4 x 50 mm steel Phillips-head wood screws with 40 ± 3 degree thread angle were used for constructing the corner joints of four-member cabinets, following what is commonly used in the furniture industry. Root diameter, outside diameter, and thread per pitch were 2.4 ± 0.25, 4.0 ± 0.3, and 1.8 mm for screws, respectively.

Screws were driven to the center of thickness of butt member that had pre-drilled pilot holes. Figure 1 shows a typical placement of screws in the L-type corner joints used in this study. The diameters of the pilot holes were equal to approximately 80% of the root diameter of the screws, and depths of the pilot holes were equal to approximately 75% of the penetration of the screws (Eckelman 2003). L-type corner joint specimens were kept in a conditioning chamber at 20 ºC ± 2 and 65 ± 3 % relative humidity prior to test in order to avoid moisture content variations.

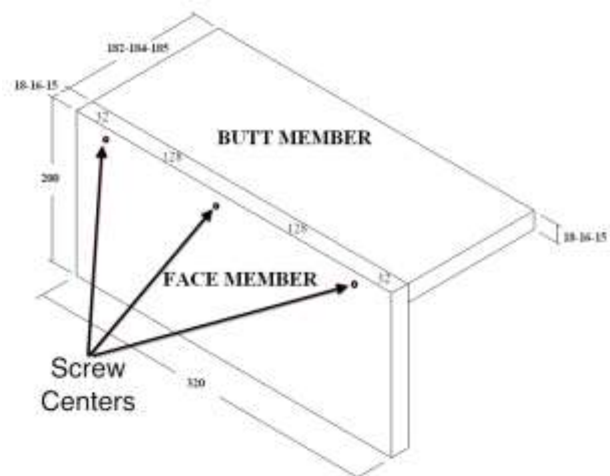

Fig. 1. General configuration of the L-type corner joint specimen and typical placement of screws (measurements in mm)

Four-member cabinets

The general configuration of four-member cabinets used in this study is shown in Fig. 2. Four-member cabinets were constructed of 16 mm and 18 mm thick PB and MDF, and 15 mm and 18 mm thick okoume (*Aucoumea klaineana*) PW panels. A four-sided cabinet consists of a top panel, a bottom panel, and side panels of the same material. Four-member cabinets were constructed by assembling of the side panels to top and bottom panels. In construction of the test cabinets, 3660 x 1830 mm full-size sheets of 18 mm thick PB and MDF, 2800 x 2100 mm full size sheets of 16 mm thick PB, 2440 x 2100 mm full size sheets of 16 mm thick MDF, 2200 x1700 mm full size sheets of 16 and 18 mm thick PW were cut into the top, bottom, and side panels; then these panels were dimensioned into the final member width and lengths. The final measurements of each four-sided case were based on commonly used wall cabinet size of 650 mm height by 320 mm depth by 650 mm width. All construction and assembling procedures were the same as assembling of the L-type corner joints in order to provide reasonable comparisons.

Similarly, four-member cabinets were stored in a conditioning chamber at 20 ºC ± 2 and 65 ± 3 % relative humidity prior to test in order to avoid moisture content variations, too.

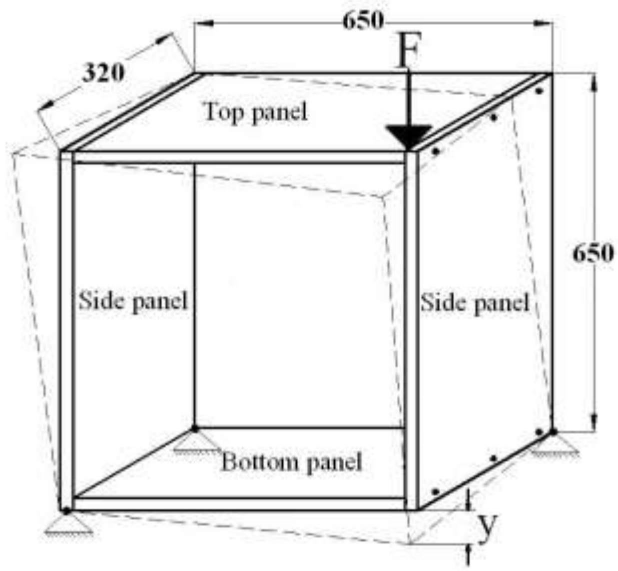

Fig. 2. General configuration and deformation diagram of a four-member cabinet supported at three points under the static test (measurements in mm)

Methods of Testing and Loading

Physical and mechanical properties of PB, MDF, and PW were tested in accordance with the procedures described in ASTM D 4442 (2003) and ASTM D 1037 (2001). Furthermore, screw-holding strengths of PB, MDF, and PW panels from edge and face were determined according to procedures set by Erdil *et al.* (2002). The diameters and depth of penetration of the pilot holes were all the same as the assembly of L-type corner joint and four-member cabinets in order to provide a reasonable comparison. All screw holding tests were carried out on a 50 kN capacity universal testing machine. The rate of loading was 2 mm/min. Ultimate loads were taken as the screw holding strength of the materials.

Moment resistance tests

All of the tests were carried out on a 50 kN capacity universal testing machine at a loading rate of 6 mm/min (Fig. 3). In the tension test setup, 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 and remain free of restraint as the joint was loaded. The loading was continued until a failure or full separation occurred in the specimens. Ultimate applied load values, *F*, measured in N, were converted to corresponding moment resistance values by means of the expressions $M_c = L_c \times F$ and $M_t = L_t \times F/2$, for compression and tension, respectively. M_c and M_t measured in Nm are the moment resistances for specimens subjected to compression and tension loads, respectively. Moment arms (L_c, L_t) were calculated as 0.129 m (18 mm thick panel), 0.130 m (16 mm thick panel), and 0.131 m (15 mm thick panel) and used as a constant value, respectively for compression and tension loading.

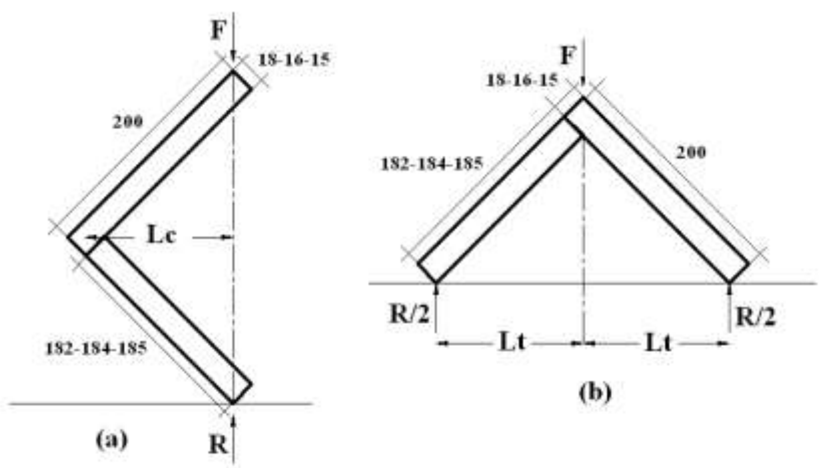

Fig. 3. Diagram showing loading forms of specimens subjected to compression (a) and tension (b). The letter "R" refers to the reaction force (measurements in mm).

Static tests of four-member cabinets

Four-member cabinets were tested under static loads, and force-deflection diagrams were drawn for evaluating the stiffness of four-member cabinets. Figure 2 shows loading and supporting conditions of the four-member cabinets.

All tests were carried out on a 50 kN capacity universal testing machine at a loading rate of 6 mm/min. Load was applied from the free corner. The four-sided cabinet itself was fixed on this main frame by the help of three supports. These supporters were assembled on the table by nuts and bolts. At first, some cases were tested to determine the ultimate failure loads. Cases force and deflection values were recorded until the 70% - 80% of these ultimate failure loads. During the static tests, failure modes, and deflections in vertical (*Y*) direction were recorded. Stiffness values were calculated in N/mm by taking several measurements of load *vs.* deflection in the elastic, apparently linear range and then fitting them into a regression line by least squares method.

Statistical analysis of data

Even though three distinct types of panels were utilized in the study, six levels for a single factor (panel type) was described in the analysis to practically nest the thickness effect to the panel type factor; *i.e,* instead of two factor (panel type and panel thickness), one way ANOVA procedure was utilized. The main reason leading to the use of this approach was the fact that the thicknesses of PW panels were different from the others. To summarize, one-way ANOVA general linear model procedures were performed for individual data for moment resistances of L-type corner joints under compression and tension loads and stiffness values of four-member cabinets in order to analyze the effect of panel type on moment resistance of L-type corner joints and stiffness values of four-member cabinets.

ANOVA results indicated that moment resistances of L-type corner joints and stiffness of four-member cabinets were statistically different at the 5% significance level (Table 2).

The least significant difference (LSD) multiple comparisons procedure at 5% significance level were performed to determine the mean differences of moment resistances of corner joints and stiffness values of four-member cabinets tested considering the ANOVA results mentioned above.

Table 2. ANOVA Results for Moment Resistances under Compression and Tension Loads and Stiffness Values

Sources	Degrees of freedom	F value	Probability ($p<0.05$)
Within groups	4	0,7413	
Between groups	5	59,8123	0,0000
Error	20		
Total	29		
Within groups	4	1,0104	0,4256
Between groups	5	71,8990	0,0000
Error	20		
Total	29		
Within groups	4	1,1473	0,3632
Between groups	5	11,1936	0,0000
Error	20		
Total	29		

RESULTS AND DISCUSSION

Physical and mechanical properties of materials used in the tests are given in Table 3**.** Shear modulus of MDF panels yielded higher values than those of PW and PB panels. Stiffness of four-member cabinets was affected by the shear modulus of the panels. The highest shear modulus values were observed with 18 mm MDF, while the lowest values were obtained with 18 mm PB. Except for the MDF panels for shear modulus values, it was determined that the less thick panels gave higher rigidity than those of thicker panels in terms of both shear modulus and IB (internal bonding) strength values.

For MDF panels, 18 mm panels averaged approximately 8% greater than those of 16 mm panels. In a similar study on bending moment resistance of corner joints, it was shown that the elastic modulus and modulus of rigidity values of MDF was higher than PB (Maleki *et al.* 2012), as expected.

Table 3. Physical and Mechanical Properties of the Panels used in the Study

Panel Type	MC (%)	Density (g/cm^3)	MOR (N/mm^2)	MOE (N/mm^2)	G (N/mm^2)	IB (N/mm^2)
18 mm PB	7.01	0.58	11.20	2,031	1,110	0.27
16 mm PB	6.25	0.66	20.82	2,611	1,826	0.47
18 mm MDF	6.28	0.75	37.32	2,563	2,017	0.75
16 mm MDF	5.81	0.73	35.44	3,303	1,858	0.97
18 mm PW	7.29	0.59	54.23	5,173	1,513	0.85
15 mm PW	7.50	0.59	74.71	8,413	1,797	1.14

Screw holding strengths (from edge and face) from the PB, MDF, and PW used in the tests are presented in Table 4. The 16 mm PB and 15 mm PW gave higher screw holding strength from the edge than 18 mm PB and PW, respectively. For MDF panels, the differences between the screw holding strength from edge of 16 mm and 18 mm panels were not significant. It can be clearly seen that according to the results, screw holding strength of the panels from edge and IB strength of the panels were found to have considerably more effect on stiffness of four-member cabinets than on the shear modulus of the panels. Therefore, it can be stated that stiffness of four-member cabinets were affected by the joint rigidity more than the individual panel properties such as MOE and shear modulus. According to results given in Table 3, 15 mm PW panels showed 34% higher IB strength than those of 18 mm PW panels, and according to the Table 4, 15 mm PW panels yielded 20% higher screw holding strength from edge than those of 18 mm PW panels.

It is logically expected that the screw holding strength from the edge and IB strength of panels represent the rigidity of the joints. Screw holding strength of 18 mm MDF and PW panels from the face yielded higher values than 16 mm MDF and 15 mm PW, respectively. On the contrary, for PB panels, 16 mm panels gave higher screw holding strength from the face than 18 mm panels. Vassiliou (2005) similarly found that the MDF have higher screw holding strength than the PB. They compared different kinds of screws and determined that MDF gives up to 40% higher screw holding strength than PB for the same type of screws.

Table 4. Screw Holding Strength of Panels Utilized in the Construction of Specimens

Panel Type	Screw Holding Strength from the Edge (N)	Screw Holding Strength from the Face (N)
18 mm PB	1139 (21)	912 (13)
16 mm PB	1711 (9)	1030 (6)
18 mm MDF	2774 (8)	1779 (8)
16 mm MDF	2623 (4)	1420 (10)
18 mm PW	3017 (14)	2367 (9)
15 mm PW	3614 (22)	2151 (16)

*Values in parenthesis are coefficients of variation (COV)

It was determined that the failure modes of L-type corner joints were similar. All joint failures occurred between 60 and 90 seconds. L-type corner joints opened up slowly, not suddenly. Failures of joints constructed of PB, MDF, and PW started with the screw heads crushing into the face member, followed by screw withdrawal from the butt members along with some core material together, with edge splitting around the screws. PB specimens showed more core material attached on screws than MDF and PW ones. The splitting around the screws of MDF specimens was larger than ones of PB.

In the rigidity tests, static loads were applied to cases until 70% to 80% of the ultimate failure loads; therefore, expected typical deflections in the individual panels and entire cases occurred.

Table 5. Mean Moment Resistance of L-type Corner Joints and Stiffness of Four-Member Cabinets

Panel Type	Moment Resistance under Tension (Nm)			Moment Resistance under Compression (Nm)			Stiffness (N/mm)		
	Mean (Nm)	COV (%)	HG*	Mean (Nm)	COV (%)	HG	Mean (N/mm)	COV (%)	HG
18 mm PB	47.49	14	C	36.68	10	E	68.91	26	B
16 mm PB	58.06	12	B	56.00	6	D	83.25	5.1	B
18 mm MDF	91.60	6	A	88.41	6	B	99.18	39	B
16 mm MDF	96.19	3	A	82.36	8	C	103.1	25	B
18 mm PW	96.18	6	A	99.48	10	A	79.53	19	B
15 mm PW	99.00	6	A	79.61	11	C	196.6	28	A

LSD critical value for tension=7,849 *Nm,* for compression=8,826, for stiffness=41.21 *N/mm*, HG: Homogenous group

Average moment resistance values of L-type corner joints and stiffness values of four-member cabinets and their coefficients of variation are given in Table 5. Test results showed that moment resistances of L-type corner joints and stiffness values of four-member cabinets were significantly affected by the panel type and panel thickness. In general, L-type corner joints and four-member cabinets constructed of 15 mm PW showed the highest values.

The significant difference between the 15 mm and 18 mm PW can be explained based on the thickness differences. It is also can be assumed 15 mm PW has higher production quality where 15 mm PW mostly showed higher mechanical properties (MOE, MOR, & IB) than the 18 mm PW. The specimens constructed of MDF showed higher values than those of the specimens constructed of PB for two thickness levels. These differences in moment resistance and stiffness values could be explained by differences in density and mechanical properties such as bending strength (*MOR*), internal bond strength (*IB*), shear modulus (*G*), and screw holding strength of the panels. It is a fact that the most strength properties especially screw holding strength of PW are higher than those of MDF, similarly density and most strength properties of MDF are higher than those of PB.

Moment Resistance of L-type Corner Joints

Table 5 gives ranked mean comparisons of moment resistance of L-type corner joints under tension and compression regarding the effect of panel type-panel thickness interaction. The highest moment resistances were obtained from the 15 mm PW, 16 mm MDF, 18 mm PW, and 18 mm MDF specimens under tension loads. However, the differences of moment resistances between the specimens constructed of mentioned panels were not statistically significant. The lowest moment resistances were obtained from 18 mm PB specimens. Under compression loads, the highest moment resistances were observed from the 18 mm PW specimens. The lowest moment resistance values were obtained from 18 mm PB specimens under both tension and compression loads.

Grouping data for joints subjected tension loading test, yielded a mean moment resistance of 81.42 Nm while grouping data of joints tested in compression loading resulted in a mean ultimate moment resistance of 73.70 Nm.

Stiffness of Four-Member Cabinets

Table 5 shows the ranked mean comparisons of stiffness values of four-member cabinets tested with respect to the material type-thickness interaction. Results showed that the highest stiffness values were obtained in the 15 mm PW four-member cabinets, 196.6 N/mm, which is 52.4% higher than the next highest stiffness valued material, 16 mm MDF. It is assumed that, some differences occurred at rigidity of connections while preparing the cases. The lowest stiffness values were obtained in the 18 mm PB four-member cabinets.

According to the test results, 15 mm or 16 mm four-member cabinets yielded considerably higher stiffness values compared to the 18 mm thick panels. Stiffness values of 16 mm PB four-member cabinets were higher than 18 mm PW four-member cabinets. The best material is PW and the optimum thickness is 15 mm. As it might be expected, the modulus of rigidity values of the individual panels and full four-member cabinets had a strong relationship.

In general, thickness was found to have a greater effect on stiffness of four-member cabinets. When the thickness of panels was increased the stiffness of the four-member cabinets decreased significantly.

CONCLUSIONS

In this exploratory study, the effect of panel type and panel thickness on moment resistance of L-type corner joints and stiffness values of four-member cabinets were investigated by assuming all L-type corner joints and four-member cabinets were assembled and manufactured homogeneously.

Results indicated that four-member cabinets constructed of 15 mm or 16 mm thickness yield higher moment resistance and stiffness values than those of 18 mm thickness panels. Also, it was determined that, among the materials, PW gave higher performance than MDF and PB as expected. Therefore, in the production of the cases, 15 mm PW could be recommended as a panel type instead of the 18 mm and MDF, PB. However, production costs and the uncovered surfaces of the PW are the issues that need to be overcome to be used in furniture industry.

Finally, it can be deduced that corner joint construction of screwed four-member cabinets' mechanical properties are strongly dependent on the panel type and thickness when the other factors (screw size, screw types, screw centers, *etc*.) kept constant. This study provides key information about how the case furniture corner joints and stiffness properties were affected by the panel type and thickness. Future work will include investigating the potential solutions to use PW four-sided cabinets in furniture industry.

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