EFFECT OF TENON GEOMETRY, GRAIN ORIENTATION, AND SHOULDER ON BENDING MOMENT CAPACITY AND MOMENT ROTATION CHARACTERISTICS OF MORTISE AND TENON JOINTS

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(Received January 2012)

Abstract. Bending moment capacity and moment rotation characteristics of mortise and tenon joints as a function of tenon geometry, grain orientation, length, and shoulder fit were examined. Bending moment capacity of all joints in which tenons were fully inserted in mortises was 54% greater than for joints in which tenons were not fully inserted. Joints with 25.4-mm-long diamond-shaped tenons had greater moment capacity than either rectangular or round tenon joints, whereas joints with 38- or 51-mm-long rectangular tenons had greater capacities than joints with diamond or round tenons. Similarly, for joints in which tenons were not fully inserted, rectangular tenons had the greatest moment capacity regardless of grain orientation or length.

Keywords: Mortise and tenon joints, bending moment capacity, semirigid rotation.

INTRODUCTION

Much of the furniture manufactured in Turkey, particularly that produced by smaller manufacturers, is constructed with mortise and tenon joints from softwood species, yet there is little information available concerning the bending moment capacity of joints constructed of softwoods of this and similar species. Also, information concerning stiffness characteristics of joints fabricated from such softwoods is lacking

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Wood and Fiber Science, 44(4), 2012, pp. 462-469
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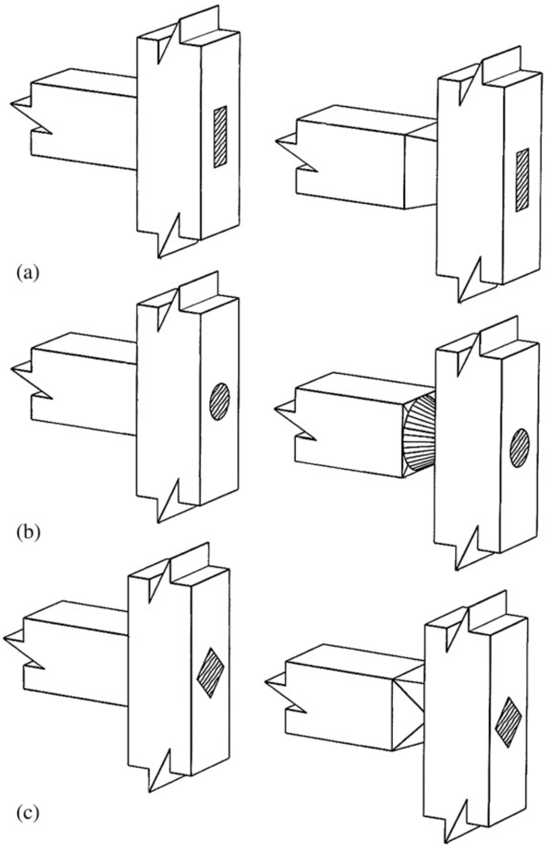

Figure 1. Mortise and tenon joint configuration of fully inserted (tight) and not fully inserted (loose) shoulder tenons: (a) rectangular, (b) round, and (c) diamond cross-sectional geometry.

(Eckelman et al 2001, 2003; Erdil 2002; Eckelman and Haviarova 2006). Furthermore, information concerning capacity of various tenon geometries is also lacking, ie information that would allow designers to select the tenon configuration best suited to their specific design. For example, tenons with rectangular configurations are probably best suited for structural members, such as seat rails, in chairs that have substantial width-to-thickness ratios, and round or square tenons may be better suited for smaller square members such as stretchers (Eckelman et al 2001, 2003; Erdil 2002; Eckelman and Haviarova 2006). Likewise, diamond-shaped tenons may be best suited for chairs subjected to frequent use (including tilting) to increase the shear area of the neutral plane of the tenon, as well as for aesthetic reasons when the ends are exposed (Fig 1). Another factor to consider is if grain orientation affects bending moment capacity. Finally, information is also lacking with respect to capacity of loose-shoulder "tenons," which do not have a shoulder that bears against the wall of the member in which they are inserted (Fig 1).

Given the need for such information, a study was undertaken to obtain information concerning performance characteristics of furniture joints constructed from structural-grade softwood comparable with those used in furniture construction in Turkey. The major objective of the study was to obtain information concerning bending moment capacity of joints of three cross-sectional

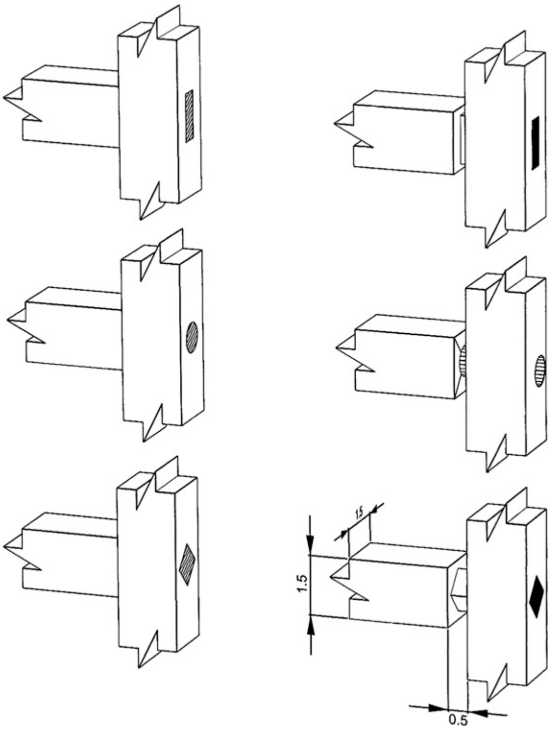

Figure 2. Actual joint specimen configurations of three cross-sectional geometries with tight vs loose tenon shoulder configuration.

geometries. Specific objectives were to determine the effect of the cross-sectional geometry of tenons, the effect of tight vs loose tenon shoulders (Fig 2), grain orientation effect, and tenon length effect on bending moment capacity of the joints. The final objective was to determine moment rotation characteristics of the joints as a function of tenon geometry and the contact geometry characteristics of the tenon shoulders (Fig 2).

PLAN OF STUDY

Four variables were considered, namely tenon length, tenon cross-section, grain orientation, and tight shoulders (fully inserted tenons) vs loose shoulders (nonfully inserted tenons). Five specimens were constructed for each combination of variables. Therefore, there were 5 replications × 3 tenon lengths × 3 tenon cross-sections × 3 grain orientations × 2 shoulder positions for a total of 270 specimens.

MATERIALS AND METHODS

Specimen Preparation

General configurations of the specimens included in this study are shown in Fig 2. All specimens were constructed of nominal 38- × 152-mm Loblolly pine (*Pinus teada*), which was conditioned to and maintained at 8% MC. Modulus of rupture of the wood species used in this study was 110.4 MPa, and modulus of elasticity was 9.05 GPa. Average specific gravity was 0.56 g/cm^3.

Dimensions of the tenon cross-sections are shown in Fig 3. The rectangular tenon was 12 mm wide × 30 mm deep, the diameter of the round tenon was 19 mm, and the diagonal tenon was 19 mm square. Tenon lengths were 25.4, 38.1, and 50.8 mm.

Specimens were constructed with three tenon grain orientations: radial (0°), tangential (90°), and rift (45°). For each grain orientation, half the tenons were fully inserted into their respective mortises (tight shoulders) (Fig 2), whereas the remaining half were not. Specifically, a 12.7-mm space was left between the tenon shoulder and the face of the post (loose shoulders).

All rails were 38 × 38 mm in cross-section. Posts were constructed of the same material as the rails and were 38 × 38 mm for 25.4- and 38.1-mm-long tenons and 38 × 50.8 mm for 50.8-mm-long tenons. Mortises were machined with standard mortising chisels on a drill press. Rectangular- and diamond-shaped tenons were cut with appropriate jigs on a band saw, and round tenons were cut with a deep hole saw. Prior to assembly, tenons and mortise walls were liberally coated with a polyvinyl acetate adhesive (40% solids content). All specimens were conditioned to

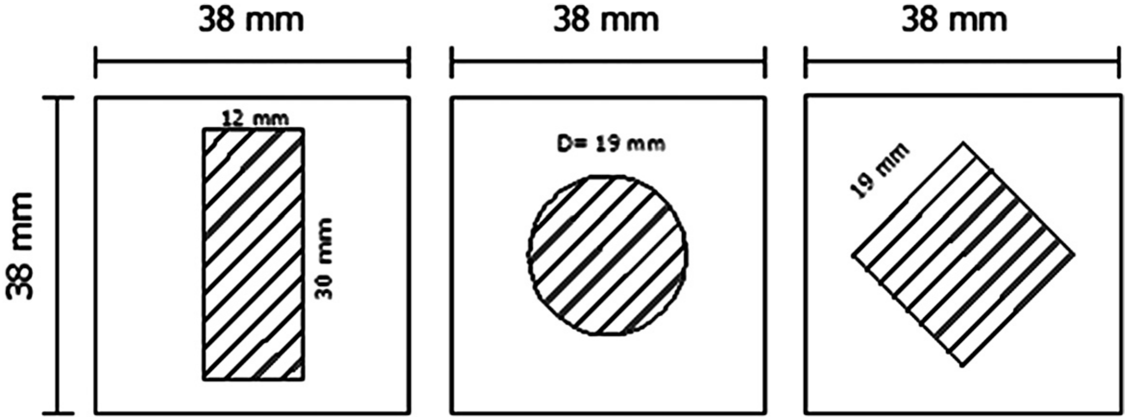

Figure 3. Cross-sectional geometry configurations and dimensions.

8% MC and were maintained at that moisture content throughout testing.

Test Method

All tests were conducted on a 133.4-kN capacity screw-powered Riehle universal testing machine. Specimens were attached to the testing jig with two bolts (Fig 4). Loads were applied to the rail at a point 254 mm from the front face of the specimen post. Joint rotations were measured by means of two dial gauges that were attached to the rail (Fig 4). Distance between dial gauges was 165 mm. Dial gauges were read at 22.2-N load intervals. Loading was continued until a nonrecoverable drop-off in load occurred.

RESULTS AND DISCUSSION

Bending Moment Capacity

Grain orientation. The effects of grain orientation are shown in Figs 5 and 6. In the case of joints with tight shoulders, joints with 45° grain orientation had 8.0 and 11% greater capacity than joints with radial and tangential grain orientation, respectively. Likewise, joints with loose shoulders and 45° grain orientation had 8.2 and 4.5% greater moment capacity than joints with radial and tangential grain orientation. Thus, in joints with both tight and loose shoulders, joints with tenons that had a 45° grain orientation had greater moment capacity than joints with either 0 or 90° grain orientations. In practice, however, these results were presumably too small to justify sorting wood members for grain orientation.

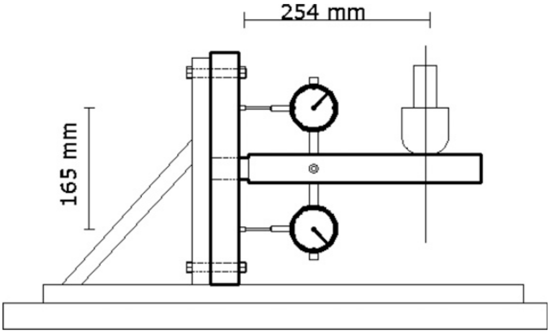

Figure 4. Testing jig for joint specimens and attachment of two dial gauges for joint rotation measurement.

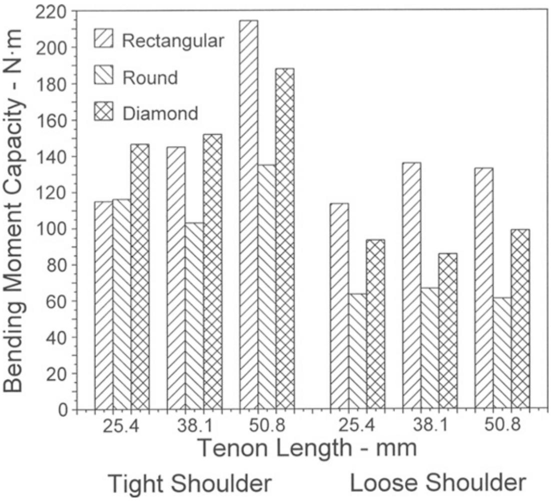

Figure 5. Bending moment capacity vs tenon length.

Shoulder effect. The effects of tenon shoulders on bending moment capacities of the joints are shown in Figs 5 and 6. Joints with shoulders had substantially greater moment capacity (1.58 times) than joints without shoulders. This result clearly illustrates the contribution of shoulders to the bending moment capacities of the joints and also indicates the loss in capacity incurred if glue joints loosen in service.

Cross-sectional geometry. The effects of tenon cross-sectional geometry on moment capacity are shown in Figs 5 and 6. Statistically, direct comparisons between capacities of cross-sections are not justified because of differences in cross-sectional area of the sections; however, the low value obtained for the 25.4-mm-long rectangular tenons probably indicates adhesive failure in the joint, whereas the increased value for the 38.1-mm-long tenons probably indicates a combination of adhesive failure and tenon fracture. Finally, the value for 50.8-mm-long tenons probably indicates primarily tenon fracture (Eckelman 1978).

Effect of tenon length. The effects of tenon length are shown in Figs 5 and 6. If capacities for each tenon length were averaged, bending

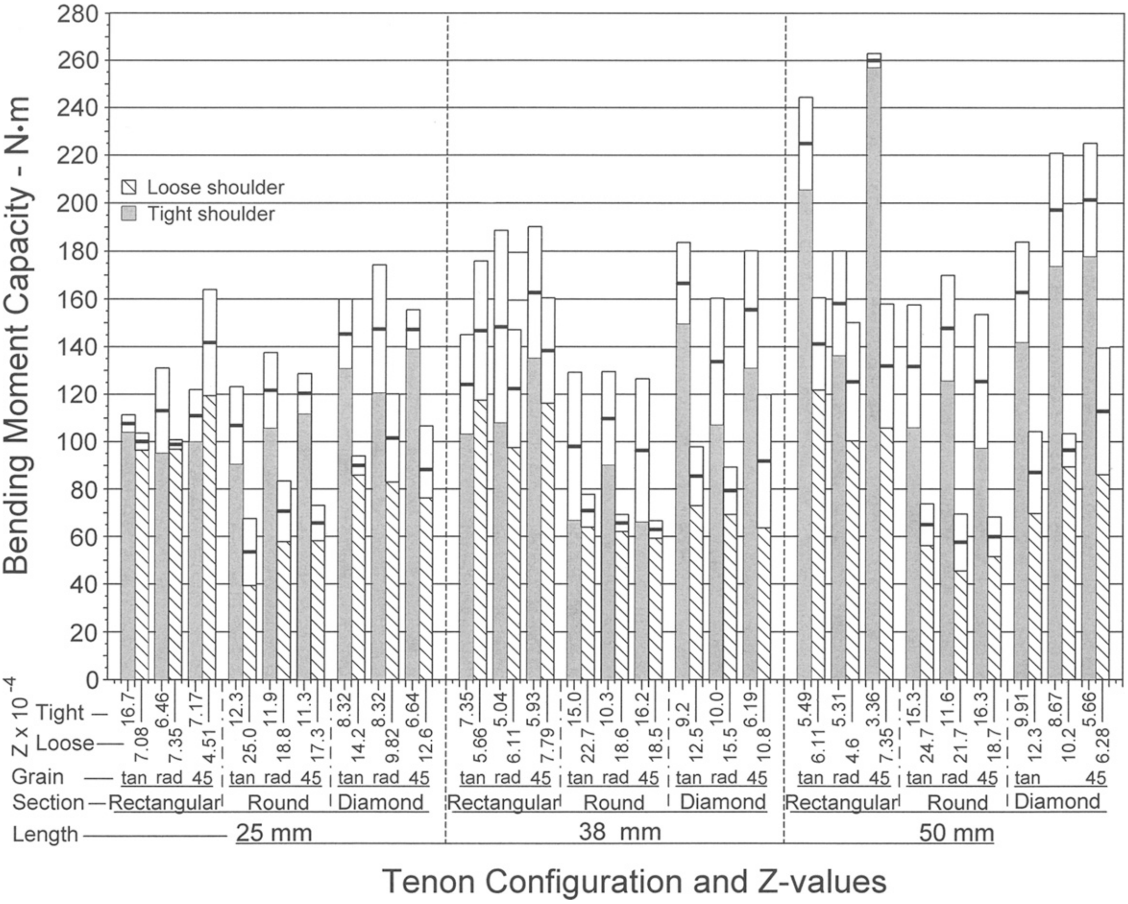

Figure 6. Bending moment capacity vs cross-sectional geometry, tenon length, grain orientation, and moment rotation characteristics (Z values).

moment capacities of the joints were 124.4, 132.7, and 178.8 N·m for 25.4-, 38.1-, and 50.8-mm tenons with tight shoulders and 90.0, 95.9, and 97.4 N·m for 25.4-, 38.1-, and 50.8-mm tenons with loose shoulders, respectively. In the case of specimens with tight shoulders, specimens with 50.8-mm tenons had 34.7 and 43.7% greater moment capacity than 38.1- and 25.4-mm tenons, respectively. Thus, as expected, tenon length had a substantial effect on joints with tight shoulders. In the case of joints with loose shoulders, however, tenon length had a much less pronounced effect.

Semirigid rotation factors. Semirigid connection factors were estimated through measurement of individual member rotations as shown in Fig 4. For this procedure,

$$Z = \frac{(|y_1| + |y_2|)}{x \cdot M} \tag{1}$$

where y_1 and y_2 refer to the deflections of the top and bottom gauges, respectively, mm; x refers to the distance between gauges, mm; and M is applied moment, N·m (Lothers 1960; Eckelman 1968).

Semirigid rotation coefficients computed as shown are given in Fig 6. The average semirigid rotation factor for all specimens with shoulders was 9.2×10^{-4} rad/N·m vs 12.8×10^{-4} rad/N·m for those without shoulders.

Table 1. Multiple variance analysis (ANOVA) results.

Source	df	F	Significance
Corrected model	53	13.055	0.000
Intercept	1	6229.984	0.000
Shoulder	1	261.265	0.000
Cross-section	2	101.128	0.000
Grain	2	3.904	0.022
Tenon length	2	29.798	0.000
Shoulder*cross-section	2	16.614	0.000
Shoulder*grain	2	0.276	0.759
Cross-section*grain	4	2.741	0.030
Shoulder*cross-section*grain	4	0.651	0.627
Shoulder*tenon	2	16.533	0.000
Cross-section*tenon length	4	8.498	0.000
Shoulder*cross-section*tenon length	4	2.739	0.030
Grain*tenon length	4	1.617	0.171
Shoulder*grain*tenon	4	1.256	0.288
Cross-section*grain*tenon length	8	0.982	0.451
Shoulder*cross-section*grain*tenon length	8	2.038	0.043
Error	216		
Total	270		
Corrected total	269		

Figure 6 also shows that variations based on tenon geometry were pronounced. Most notably, the semirigid connection factors for round tenons were substantially greater than for either rectangular or diagonal tenons. Figure 6 also shows that tight shoulders substantially decreased rotation factors. For semirigid rotation factors as a factor of grain orientation, results were mixed and differences were small between joints with different grain orientations. Tenon length had essentially no effect on semirigid coefficient factors for tenons with or without shoulders.

Statistical Analysis

According to the multiple variance analysis results (Table 1), the effects of shoulder type, cross-section, grain orientation, and tenon length factors were statistically significant on bending moment capacity. The two-way interactions of shoulder and cross-section, shoulder and tenon length, cross-section and tenon length, and cross-section and grain orientation were statistically significant. The three-way interaction of shoulder, tenon length, and cross-section was statistically significant. The four-way interaction of shoulder, tenon length, grain orientation, and cross-section was statistically significant. Differences between groups with respect to the effect of variance on bending moment capacity was meaningful (at 5% significance level). The results of the Duncan tests

Table 2. Duncan tests results.

Factor	Bending moment (N·m)	HG	Factor	Bending moment (N·m)	HG	Factor	Bending moment (N·m)	HG
B-O-2-I	53.4	A	B-□-1-I	98.8	D-K	B-□-2-III	141.1	M-U
B-O-1-III	57.5	AB	B-□-2-I	100.0	D-K	A-◇-2-I	145.3	N-U
B-O-3-III	59.9	A-C	B-◇-1-I	101.5	E-L	B-□-2-II	146.7	O-V
B-O-3-II	63.0	A-D	A-O-2-I	106.8	F-M	A-◇-3-I	147.1	O-V
B-O-2-III	65.0	A-E	A-□-2-I	107.6	F-N	A-◇-1-I	147.3	O-V
B-O-3-I	65.6	A-E	A-O-1-II	109.7	G-O	B-□-3-I	147.5	O-V
B-O-1-II	65.7	A-E	A-□-3-I	110.8	G-O	A-O-1-III	147.7	O-V
B-O-1-I	70.6	A-F	B-◇-3-III	112.8	G-P	A-□-1-II	148.3	O-V
B-O-2-II	70.8	A-F	A-□-1-I	113.0	G-P	A-□-2-II	149.6	P-V
B-◇-1-II	79.3	A-G	A-O-3-I	120.3	H-Q	A-◇-3-II	155.5	Q-V
B-◇-2-II	85.4	A-H	A-O-1-I	121.6	H-Q	A-□-3-II	162.6	R-V
B-◇-2-III	87.0	A-I	B-□-1-II	122.3	H-Q	A-◇-2-III	162.7	R-V
B-◇-3-I	88.1	A-I	A-O-3-III	125.3	İ-R	A-◇-2-II	166.6	S-V
B-◇-2-I	89.7	A-I	A-O-2-III	131.7	J-S	A-□-1-III	175.7	T-W
B-◇-3-II	91.8	B-I	B-□-3-III	131.9	J-S	A-◇-1-III	178.8	U-W
B-◇-1-III	96.3	C-I	A-◇-1-II	133.6	J-S	A-□-2-III	184.2	VW
A-O-3-II	96.3	C-I	B-□-1-III	136.8	K-S	A-◇-3-III	201.4	W
A-O-2-II	98.0	D-I	B-□-3-II	138.3	L-T	A-□-3-III	241.1	X

Shoulder type: tight Shoulder (A); loose shoulder (B).

Cross-section geometry: rectangular (□); round (O); diamond (◇).

Grain orientation: radial (1); tangential (2); rift (3).

Tenon length: 25.4 mm (I); 38 mm (II); 50 mm (III).

HG, homogeneity group.

were conducted to determine the importance of the differences between the groups (Table 2). The lowest value was obtained from the group of samples with round cross-section, loose shoulders, tangential grain, and 25.4-mm tenon length. The highest value was obtained from the group of samples with rectangular cross-section, shoulders, rift cut grain, and 50.8-mm tenon length.

APPLICATIONS

Results of these tests perhaps can best be interpreted through the use of a design example. Referring to the sample chair frame shown in Fig 7, if the seat depth, x, and the seat height, y, are 431.8 mm, then the horizontal force, FH, is related to the bending moments acting on the ends of the stretchers, f4 (assuming an identical moment acts on the ends of each stretcher in two side frames), by means of Eq 2.

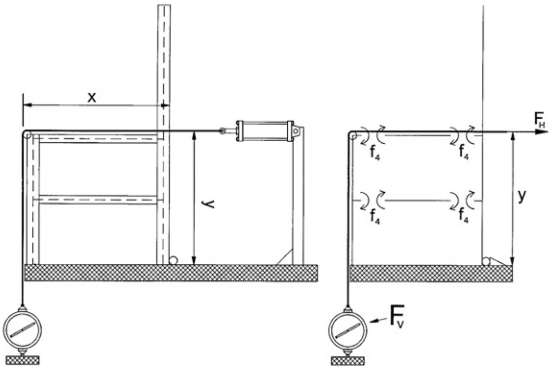

Figure 7. Schematics of chair frame performance testing.

Thus, for a 25.4-mm-long rectangular tenon with tight shoulders,

$$FH = (203.2 \times 4.4)/431.8 \text{ or, } 2.05\ kN \tag{2}$$

This value may be interpreted through the use of the American Library Association (ALA) standard for library chairs used in library reading rooms (Eckelman 1995), which relates cyclic load resistance to estimated light-, medium-, and heavy-duty library use categories. Specifically, this test method specifies cyclic front-to-back loads of 1.1, 1.6, and 2.0 kN for use categories that correspond to light, medium, and heavy duty.

Experience indicates that if chairs do not have at least 1.1 kN front-to-back strength, a significant number will fail during the first 2 yr in an adult library environment, which is a severe use environment, whereas chairs with strengths of at least 2.0 kN survive indefinitely. Furthermore, chairs that meet only the low ALA acceptance level have given good service in fast food restaurants, again indicating the severity of university library use and indicating that the load levels are higher than needed for domestic use. Ongoing research indicates that the cyclic strength of chairs of the type used in this study corresponds to about 75% of their static strength.

Table 3. Estimated static front-to-back load bending moment capacities.

		Shoulder			No shoulder		
Tenon length (mm)	Tenon type	Average bending moment (N·m)	Calculated front-to-back force (kN)	Equivalent cyclic load (kN)	Average bending moment (N·m)	Calculated front-to-back force (kN)	Equivalent cyclic load (kN)
25.4	Rectangular	110.5	2.05	1.53	113.4	2.1	1.58
38.1	Rectangular	145	2.69	2.02	135.7	2.51	1.89
50	Rectangular	214.2	3.97	2.98	132.8	2.46	1.85
	xbar=	120.1					
25.4	Round	116.3	2.15	1.61	63.3	1.17	0.88
38.1	Round	101.3	1.88	1.41	66.4	1.23	0.93
50.8	Round	134.9	2.5	1.88	60.8	1.13	0.845
	xbar=	128.7					
25.4	Diamond	145.4	2.72	2.04	93.2	1.73	1.29
38.1	Diamond	151.9	2.82	2.11	85.5	1.58	1.19
50.8	Diamond	187.1	3.47	2.6	98.7	1.83	1.37
	xbar=	161.5					

The estimated static front-to-back load capacities of the chairs in Fig 7 constructed with joints of the type investigated in this study are given in Table 3. As shown, chairs constructed with any of the three joint configurations would be satisfactory for domestic use, whereas those constructed with rectangular- and diamond-shaped tenons would be suitable for school or commercial use. However, the performance of chairs constructed with any of the joint configurations can be moved into a high-performance category simply by adding a third stretcher.

CONCLUSIONS

Overall, joints with tight-fitting shoulders had 158% greater bending moment capacity than those with loose fitting shoulders. In addition, tenon shoulders substantially decreased rotation factors.

Tenon cross-section also had a substantial effect on bending moment capacity. Joints with a round tenon configuration had only 50% of the capacity of those with a rectangular tenon configuration, whereas those with a diagonal configuration had 72.7% of the capacity of the rectangular. Likewise, joints with a round tenon configuration had only 68.8% of the capacity of joints with a diagonal configuration.

Bending moment capacity increased with tenon length in joints with rectangular- and diamond-shaped tenons but did not increase in joints with round tenons, whereas grain direction had little effect on bending moment capacity, regardless of whether the tenons had load-bearing shoulders.

Semirigid rotation factors were substantially affected by tenon geometry and shoulder effect. Overall, semirigid connection factors for joints with loose shoulders were 39% greater than for joints with tight shoulders. Connection factors for round tenons were substantially greater than for either rectangular- or diamond-shaped tenons. Also, differences were small among joints with different grain orientations, and tenon length had essentially no effect on semirigid coefficient factors for tenons with either tight or loose shoulders.

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