Bending moment capacity of round mortise and tenon furniture joints

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Abstract

Tests were conducted to determine the effect of cross pinning the tenons of round mortise and tenon joints on the bending moment capacity of the joints. Tenon diameters ranged from a nominal 0.6 to 1.0 inches. Cross-pins were about one-half the diameter of the tenons. Both wood and steel cross-pins were included. Cross pinning was found to reduce the bending moment capacity of red oak joints by 33 percent and the capacity of yellow-poplar joints by 38 percent. Smaller cross-pins had less effect than larger cross-pins, and offsetting the pins toward the tip of the tenon also caused less reduction in bending moment capacity. Results also tend to indicate that the form factor for round beams, i.e., 1.18, should be incorporated into the flexure formula when estimating the bending moment capacity of round tenons. Finally, the results indicate that the shoulders on tenons significantly increase the bending moment capacity of a joint when the shoulders of the tenon fit firmly against the side of the member in which the tenon is inserted.

Cross-pins have been used to reinforce furniture joints for many years in the belief that they both strengthen the joints and enhance their reliability. In the case of round mortise and tenon joints, however, cross-pins might actually reduce the bending moment capacity of the joints since they could induce parallel to grain shear failures in the tenons. It is essential, therefore to obtain estimates of the weakening effect, if any, of cross-pins on the bending moment capacity of round mortise and tenon joints that will allow informed judgments to be made concerning their use in the construction of furniture.

Objectives

Exploratory studies were conducted to determine the bending moment capacities of various configurations of round mortise and tenon joints, but especially, cross-pinned joints. The primary objective of these tests was to determine whether cross-pins, and their position along the length of a tenon, affect the moment capacities of the joints.

A second objective was to obtain background data on the bending moment capacity of tenons without shoulders and corresponding information concerning the bending moment capacity of small-diameter round beams. This information is needed to determine whether the form factor used in the flexure formula to calculate the moment capacity of round beams also applies to the tenons in round mortise and tenon joints (Markwardt and Wilson 1935, Wangaard 1950).

A third objective was to determine how closely the bending moment capacity of a number of glued joints taken from prototype furniture frames compared to the capacity of joints constructed in the laboratory. Tests of these joints provide an indication of whether joint strengths obtained in practice are

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comparable to those obtained under laboratory conditions. These tests also provided the opportunity to evaluate the performance of joints constructed with two important Central American wood species.

A final objective was to determine the bending moment capacities of joints fabricated using "green wood" construction. These joints were provided by contributor John Alexander.

Specimen construction

Most of the specimen sets were constructed of yellow-poplar (*Liriodendron tulipifera*) and red oak (*Quercus rubra*). Additional sets, as noted, were constructed of loblolly pine (*Pinus taeda*), southern pine (*Pinus* sp.), hickory (*Carya* sp.), caobilla (*Carapa guianensis*), and gmelina (*Gmelina arborea*). Cross-pin species included red oak, ramin (*Gonystylus bancanus*), sugar maple (*Acer saccharum*), white birch (*Betula papyrifera*), and yellow birch (*Betula alleghaniensis*). All of the material except for that supplied by the contributor and the dowel stock came from a common pool that was used in previous tests of school furniture (Eckelman et al. 2001; Haviarova et al. 2001a, 2001b). Unless otherwise noted, the nominal moisture content (MC) of the material was 7 percent.

Unglued joints with shoulders, both pinned and unpinned, were constructed of yellow-poplar and red oak as shown in **Figures 1a and 1b**. Dimensions of the members, mortises, and tenons are given in **Table 1**. All tenons were centered on the ends of the members so that shoulder width, *w*, was equal to the (*member width – tenon diameter*) divided by 2.

Unglued joints with shoulders and cross-pins, both centered and offset, were constructed of yellow-poplar. These tests were conducted in order to determine the effect of cross-pin placement on the bending moment capacities of the joints. Member width was 1.5 inches, tenon diameter was 0.720 inch, so that shoulder width was 0.39 inch. Three specimens were constructed with a 0.25-inch diameter ramin cross-pin centered in each tenon (**Fig. 1b**), three were constructed with the cross-pin offset 0.25-inch toward the tip (out) of the tenon (**Fig. 1c**), and three were constructed with the cross-pin offset 0.25-inch toward the root (in) of the tenon (**Fig. 1d**). Another three specimens were constructed without cross-pins (**Fig. 1a**).

Unglued joints without shoulders were prepared from yellow-poplar, red

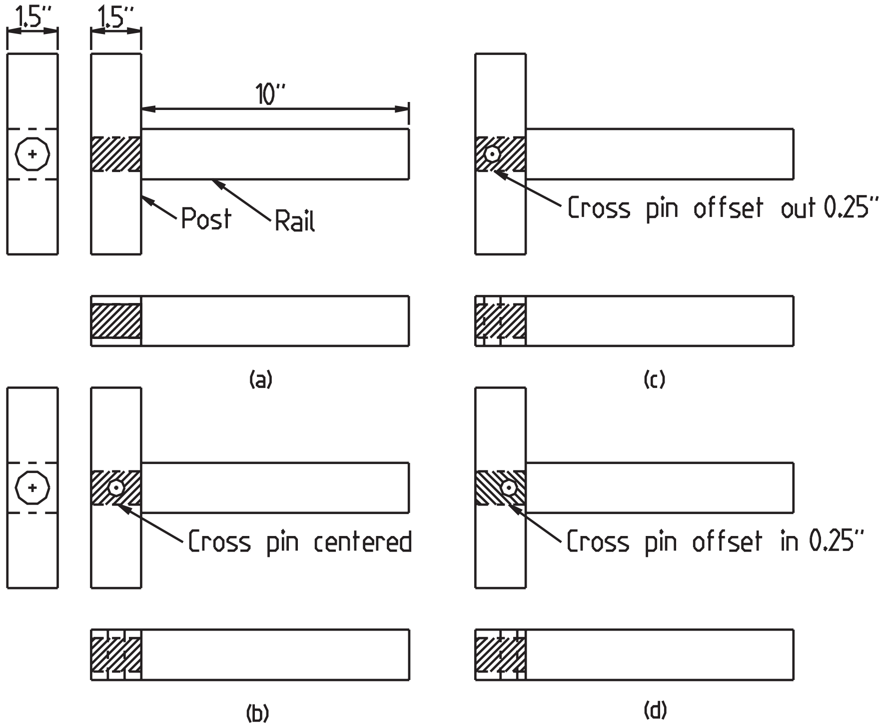

Figure 1. — Typical configurations of the round mortise and tenon joint specimens used in bending moment tests.

Table 1. — Bending moment capacity of unglued joints with and without cross-pins. Three specimens each.

Species	Tenon member dimension	Tenon diameter	Mortise drill diameter	Cross-pin species	Cross-pin diameter	Bending moment capacity					Estimated Equation [**2**]	Ratio estimated/Eq. [**2**] test
						Cross-pin		Unpinned				
						Average	SD[a]	Average	SD[a]	Ratio		
	(in. by in.)	- - - - - (in.) - - - - -			(in.)	- - - - - - - - - - - (in.-lb.) - - - - - - - - - - -				(%)	(in.-lb.)	
Yellow-poplar	1.5	1.087	1.031	sugar maple	0.5	998	221	1,877	93	53	1,878	1.00
	1.5	0.970	0.906	sugar maple	0.4375	1,007	179	1,670	104	60	1,623	0.97
	1.5	0.843	0.813	sugar maple	0.375	602	72	1,150	0	52	1,356	0.18
	0.875	0.719	0.688	sugar maple	0.3125	450	23	625	51	72	645	1.03
	0.875	0.607	0.578	sugar maple	0.25	378	99	520	67	73	520	1.00
Red oak	1.5	1.087	1.031	red oak	0.5	1,947	403	2,615	282	74	2,628	1.01
	1.5	0.970	0.906	red oak	0.4375	1,155	291	2,237	381	52	2,271	1.02
	1.5	0.843	0.813	red oak	0.375	1,062	262	2,025	346	52	898	0.94
	0.875	0.719	0.688	red oak	0.3125	718	98	968	93	74	903	0.93
	0.875	0.607	0.578	red oak	0.25	608	66	713	123	85	727	1.02

[a] SD = standard deviation.

oak, loblolly pine, and gmelina. All of the members were 1.5 in.^{2} The tenons measured 0.75-inch in diameter by 3 inches long. Hence, 1.5 inches of the tenon extended to the outside of the mortise so that any possible shoulder reinforcement was eliminated (**Fig. 2**).

Round beam specimens were prepared from both 0.75-inch and 1-inch diameter by 36-inch long red oak dowel stock obtained from a commercial supplier. These dowels were cut into nominal 18-inch lengths and conditioned to 7.5 percent MC. Average diameters of the rods were 0.746 and 0.999 inches, respectively. Specific gravity (SG) of the rods based on ovendry weight and volume at 12 percent averaged 0.65 and 0.62 for the 0.75-inch and 1-inch diameter dowel rods, respectively. Six specimens of each diameter were prepared.

Glued joints salvaged from existing prototype furniture frames included joints from bookcase frames and chairs constructed of tropical woods. The bookcase joints were constructed of red oak and yellow poplar. Red oak tenon stock measured 0.906 in.^{2} with a MC of 7 percent, whereas the yellow-poplar stock measure 0.813 inches with a MC of 7.5 percent. Tenon diameters measured a nominal 0.720 inches. Ten red oak and 18 yellow-poplar samples were prepared.

Twelve chair joints were cut from frames constructed at the Institute of Technology of Costa Rica. The tenon members were constructed of 0.8-in.^{2} caobilla, whereas the mortised members were constructed of gmelina. MC averaged 8 percent. Tenon diameter and length were 0.607 and 1.25 inches, respectively. Half the joints were cross-pinned with small 0.08-inch diameter steel pins that were centered along the length of the tenons.

Another 34 joints were salvaged from chair frames constructed with 0.720-inch tenons (machined on 0.875-in.^{2} yellow-poplar stretchers) and 1.5- by 1.5-inch southern pine posts. MC averaged 9.3 percent All joints were constructed with an aliphatic resin adhesive.

Glued and unglued "green wood" joints (**Fig. 3**) without cross-pins were prepared from unseasoned wood using a construction technique described by Alexander (1994). Parts for these joints were cut from "green" wood. Tenons on the hickory stretchers were cut oversize and then dried until they fit in the oak mortises. Completed assemblies were then allowed to dry naturally. Nominal unseasoned tenon diameter was 0.630 inch; the corresponding mortise diameter was 0.620 inch. MC at time of test was 7 percent.

Table 2. — Bending moment capacity of yellow-poplar joints with centered and offset cross-pins. Three specimens each were tested.

Joint construction	Bending moment capacity Average	Bending moment capacity Standard deviation	Fraction of no cross-pin strength
	------- (in.-lb.) -------		(%)
No cross-pin	1,030	70	
Cross-pin offset to tip	720	30	70
Centered cross-pin	620	30	60
Cross-pin offset to root	590	87	57

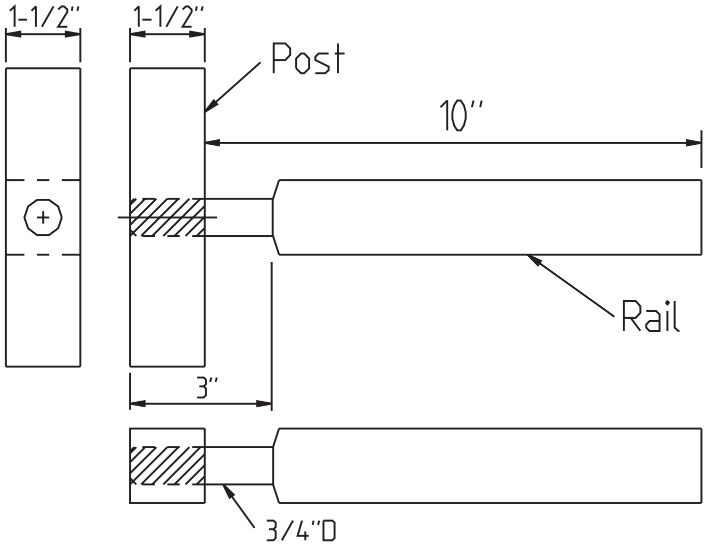

Figure 2. — Configuration of specimens without shoulders.

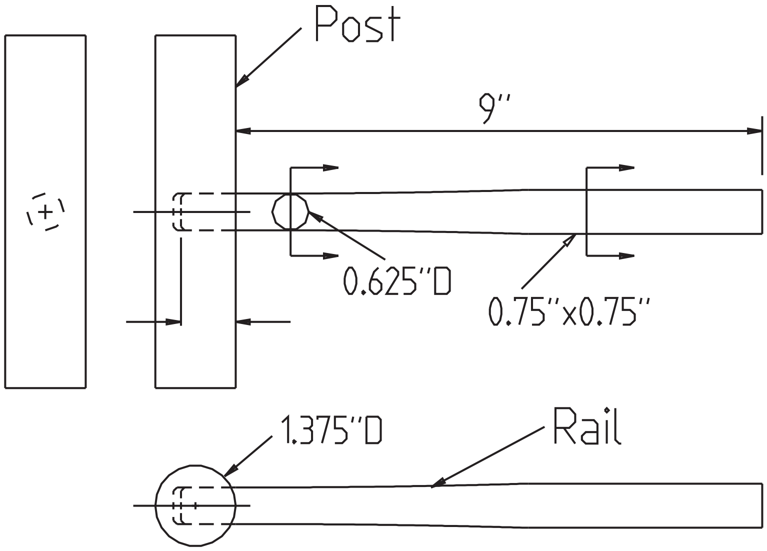

Figure 3. — Configuration of "green wood" specimens.

Description of tests

All of the bending tests were carried out in a universal testing machine with the jig shown in **Figure 4**. The moment arm (L = 8 in.) was measured from the point of load application to the face of the joint. Bending moment capacity, f_4, was calculated as:

$$f_4 = 8 \times F \cdot \text{in.-lb.}$$

where:

F = applied load (lb.).

Tests were conducted at a rate of 0.15 in./minute. Ultimate load was taken as the point of failure.

Static bending tests of the small-diameter round beams were carried out with conventional test equipment. A span of 15 inches was used in all tests with a single point load applied at mid-span. Rate of loading was 0.15 in./minute. Ultimate load was taken as the point of failure.

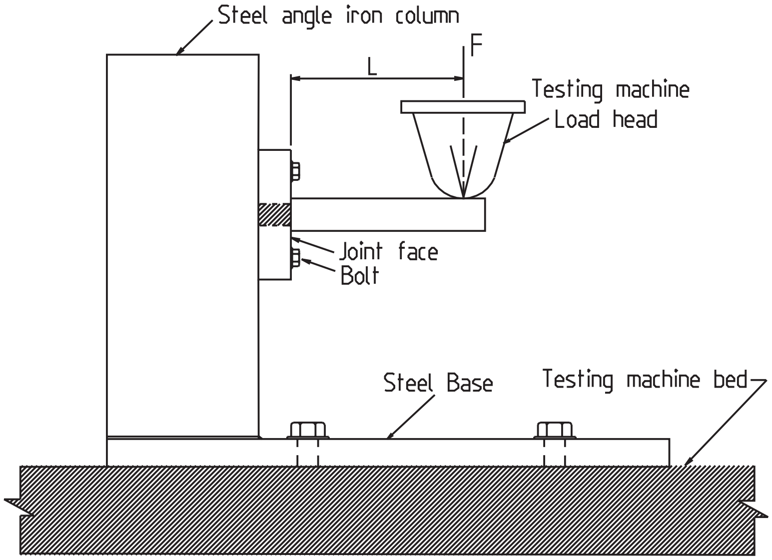

Figure 4. — Jig used to mount specimens in testing machine.

Discussion of results

Bending moment capacities of the unglued joints, both pinned and unpinned, with shoulders, are given in **Table 1**. Normal mode of failure was tension fracture of the tenon at its point of entry into the mortise. In joints with cross-pins, a shear failure in the plane of the tenon preceded the tension fracture, **Figure 5**. Linear representations of the data are given in **Figure 6**. As can be seen in **Figure 6**, the pinned joints had significantly less moment capacity than the unpinned, i.e., on average, the pinned red oak joints had 67 percent and the pinned yellow-poplar joints had 62 percent of the capacity of the corresponding unpinned joints. Overall, therefore, use of cross-pins resulted in a significant reduction in bending moment capacity. The smaller diameter tenons were weakened the least – possibly because the shear plane length parallel to the neutral axis is longer. Subsequent research is needed to define the relationship between pin diameter and bending moment capacity for a specific tenon diameter.

Presumably, the bending moment capacities of the joints without cross-pins can be estimated by means of a modified form of the flexure formula that includes a form factor for round tenons and a shoulder effect factor. Wangaard (1950) indicates that the bending moment capacity, f_4, of round beams may be estimated by means of the following form of the flexure formula, i.e.,

$$f_4 = 1.18 \times \frac{\pi D^3 s_4}{32} \cdot \text{in.-lb.} \qquad [1]$$

where:

s_4 = bending strength of the wood (psi),

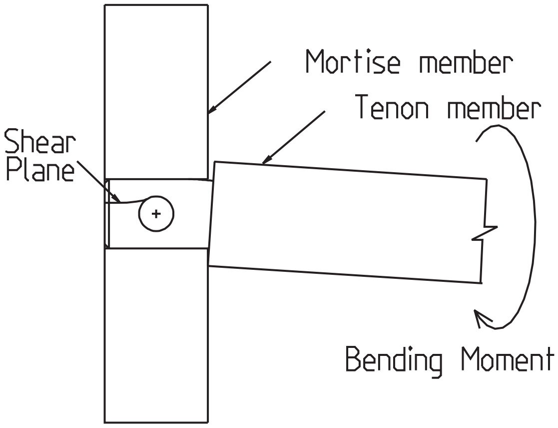

Figure 5. — Longitudinal shear failures developed in tenons with cross-pins prior to tension fracture of the tenon.

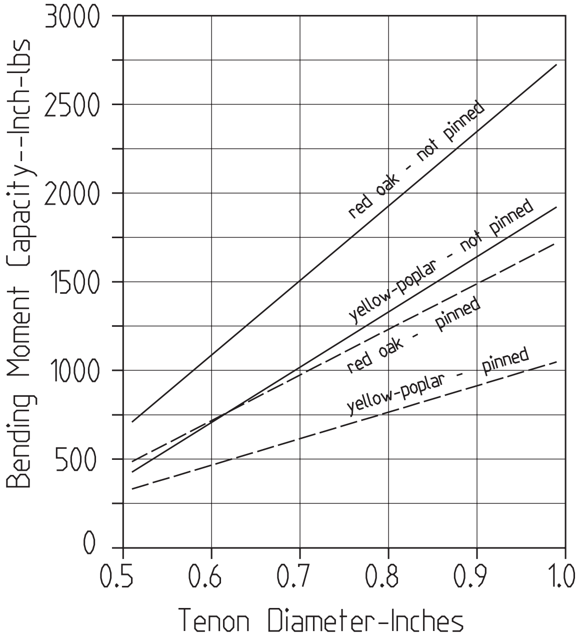

Figure 6. — Linear representations of bending moment capacity of round mortise and tenon joints with and without cross-pins.

D = diameter of the tenon (in.), and

1.18 = a form factor for round beams (Newlin and Trayer 1924, Markwardt and Wilson 1935).

Work in progress (Eckelman et al.) indicates that the reinforcing effect of shoulders may be estimated by an expression of the form:

$$\alpha \times \frac{(D+2w)}{D^{\beta}}$$

where:

w = width of the shoulder (in.),

D = diameter of the tenon (in.), and

α and β = constants.

Incorporating this modification into the flexure formula gives

$$f_4 = 1.18 \times \frac{\pi D^3 s_4}{32} \times \frac{\alpha \cdot (D = 2w)}{D^{\beta}} \cdot \text{in.-lb.} \qquad [\mathbf{2}]$$

The *Wood Handbook* (USDA 1999) values for the modulus of rupture (MOR) of red oak and yellow-poplar adjusted to 7 percent MC are 17,268 psi and 12,340 psi, respectively. Based on these values, a regression analysis of the test results gives α = 0.79 and β =1.72 with an r^2 of 94.3 percent. Estimates of bending moment capacity based on these coefficients and the *Wood Handbook* values are also given in **Table 1**. The averages of the estimated values divided by the test values were 1.04 and 0.98 for yellow-poplar and red oak, respectively, with corresponding standard deviations (SDs) of 0.08 and 0.05.

The bending moment capacities of the yellow-poplar joints with centered and offset cross-pins are given in **Table 2**. As can be seen, joints with the cross-pin offset toward the tip of the tenon had the highest bending moment capacity (70%) relative to the joints without cross-pins; likewise, joints with the tip offset toward the root of the tenon had the least capacity (57%). Of particular interest, the joints with centered cross-pins developed 60 percent of the bending moment capacity of the joints without cross-pins.

The average capacity of the joints without cross-pins was higher than that shown in **Table 1** for comparable joints, i.e., 1,030 in.-lb. compared to 625 in.-lb. in the previous test. If this result is examined with respect to shoulder effects, the ratio of these two values, 1.65, should be equal to the ratio of the shoulder factors for the two sets of specimens. Forming this ratio gives $(1.5/0.720^{1.72})/(0.875/0.719^{1.72})$, or, 1.71. As the small difference between ratios indicates, good agreement exists between the two sets of specimens when shoulder effects are taken into account.

Bending moment capacities of unglued joints without shoulders are given in **Table 3**. Estimates of bending moment capacity, based on Equation [**1**], are also presented for each species. The average of the ratios formed by dividing the estimated bending moment capacities by the corresponding test values was 1.0 with a SD of 0.04. This result provides additional support for the use of the form factor for round beams when using the flexure formula to estimate the bending moment capacities of round tenons.

The average bending moment capacities of the 0.75- and 1.0-inch diameter round oak beams were 822 in.-lb. and 1,992 in.-lb., respectively, with corresponding SDs of 137 and 280 in.-lb. The *Wood Handbook* value for the MOR of red oak converted to 7.5 percent MC amounts to 17,263 psi. Based on this value, the Wangaard (1950) form of the flexure formula estimates bending moment capacities 830 in.-lb. and 1,994 in.-lb. Thus, the estimated values were 1.01 and 1.00 times as great as the test values. These results, therefore, also tend to support the use of the form factor, 1.18, in determining the bending moment capacity of small round beams, and, by extension, round tenons.

Average bending moment capacity of the glued red oak joints with 0.720-inch-diameter tenons cut from the furniture cabinet frames was 967 in.-lb. with a SD of 139 in.-lb. This value is essentially the same as that obtained in the previous bending tests, i.e., 968 in.-lb. (**Table 1**). Furthermore, the *Wood Handbook* MOR for red oak adjusted to 7 percent is 17,160 psi. Based on this value and a tenon diameter of 0.720 inches, Equation [**2**] estimates a bending moment capacity of 950 in.-lb. Thus, the estimated value is 98 percent as great as the test value.

Average and SD values for the yellow-poplar tenons were 558 in.-lb. and 80 in.-lb., respectively. The *Wood Handbook* MOR for yellow-poplar adjusted to 7.5 percent is 11,918 psi. Based on this value and a tenon diameter of 0.720 inches, Equation [**2**] estimates a bending moment capacity of 582 in.-lb. Thus the estimated value is 5 percent greater than the test value. Both of these results indicate that the bending moment capacities of the joints obtained from prototype cabinet frames were about the same as those of the laboratory samples. The results also tend to indicate that the bending moment capacities of joints constructed without adhesives is about the same as for those constructed with adhesives.

Average bending moment capacities of the caobilla tenons cut from chairs were 546 and 413 in.-lb. for the unpinned and pinned tenons, respectively. Thus, the pinned joints had 76 percent of the moment capacity of the unpinned

Table 3. — Bending moment capacity of joints without shoulders and estimated bending moment capacity of tenons.

Tenon species	Number of specimens	Moisture content	Specific gravity	*Wood Handbook* specific gravity	*Wood Handbook* MOR @ given MC	Bending moment Average	SD[a]	Estimated[b]	Ratio est.[b]/test
		(%)	------ (12%) ------		(psi)				
Yellow-poplar	11	6.44	0.47	0.42	12,346	607	44	604	1.00
Red oak	5	6.09	0.66	0.63	17,680	872	205	864	0.99
Loblolly pine	5	7.22	0.57	0.51	15,247	781	85	745	0.95
Gmelina	3	8.22	0.38	0.41	9,958[c]	464	18	487	1.05

[a] SD = standard deviation.

[b] Estimated: $f_4 = 1.18 \times \pi D^3 \times \text{MOR} / 32$.

[c] Determined by test.

tenons. This result supports the concept that small cross-pins reduce bending moment capacity less than do large pins. Based on an adjusted MOR value of 17,200 psi (Junta del Acuerdo de Cartagena 1981), Equation [**2**] estimates a bending moment capacity of 641 in.-lb. Thus, the estimated values were 17 percent greater than the test values.

Average bending moment capacity of the 34 joints cut from chairs was 584 in.-lb. with a SD of 67 in.-lb. The *Wood Handbook* MOR value for yellow-poplar at 9.3 percent MC is 11,254 psi. Based on this value and a shoulder width of 0.078 inch, Equation [**2**] estimates a bending moment capacity of 616 in.-lb. The estimated value, accordingly, was 5 percent greater than the test value.

Bending moment capacity of the unglued "greenwood construction" joints averaged 727 in.-lb. with a standard deviation of 94 in.-lb. The *Wood Handbook* MOR for shagbark hickory at 12 percent MC is 20,200 psi. Based on this value and a tenon diameter of 0.630 inch, Equation [**1**] estimates a bending moment capacity of 702 in.-lb. Thus, the test result was only slightly greater than the estimated value. Bending moment capacity of the glued joints averaged 738 in.-lb. with a SD of 29 in.-lb. Hence, the unglued "shrink-fit" tenons had essentially the same moment capacity as the glued tenons.

Conclusions

Tests of joints with and without cross-pins indicate that cross-pins substantially reduce the bending moment capacity of round mortise and tenon joints. Placement of the cross-pin away from the root of the tenon reduces the loss in bending moment capacity.

Tests of joints without shoulders on the tenons along with the results of static beam bending tests on small-diameter round beams indicates that the form factor of 1.18 suggested by Newlin and Trayer (1924), Markwardt and Wilson (1935), and Wangaard (1950) may be used in estimating the bending moment capacity of round tenons. Thus, k should be set equal to 1.18 when using the flexure formula to estimate the bending moment capacity of round mortise and tenon joints.

Tests of joints with shoulders indicates that the shoulders have a substantial effect on the bending moment capacity of the joints. In general, the larger the shoulder, the greater the effect. To be fully effective, the shoulder must "butt" up against the wall of the member containing the mortise.

Tests of joints cut from prototype cabinet and chair frame constructions indicate that the bending moment capacity of both glued and unglued round mortise and tenon joints is essentially the same. In addition, the results indicate that joint capacities obtained under laboratory conditions are readily obtained in practice.

Joints constructed using "green wood" techniques yielded usable bending moment capacity values. Although tests have not been conducted on chairs constructed using these techniques without adhesives or cross-pins, chairs constructed with adhesives have performed well. Whether these joints will retain their bending moment capacity under repetitive loading as well as fluctuating relative humidity conditions remains to be determined, however.

Overall, the use of cross-pins in round mortise and tenon furniture joints appears to provide a rational alternative, or, a useful redundant backup construction, to adhesives in those cases where adhesives are either unobtainable or long-term adhesive joint strength is questionable. Furniture containing cross-pins, however, must be designed to ensure that the bending moment capacities of the pinned joints are not exceeded.

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