WITHDRAWAL AND COMPRESSION FORCE CAPACITY OF PINNED END-TO-END ROUND MORTISE-AND-TENON WOODEN JOINTS

C. A. Eckelman

Professor of Wood Science Technology
E-mail: eckelmac@purdue.edu

*E. Haviarova**†

Associate Professor of Wood Science Technology
Wood Research Laboratory
Department of Forestry and Natural Resources
Purdue University, West Lafayette, IN 47907
E-mail: ehaviar@purdue.edu

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Abstract. Tests were conducted to determine the withdrawal and compression force capacity of end-to-end round mortise-and-tenon joints constructed of nominal 88.9- by 88.9-mm Hem-Fir studs with tenons cross pinned with either one or two pins. For specimens with one tenon cross pin, withdrawal force capacities increased from 9.1 to 14.4 kN as tenon diameters increased from 31.8 to 50.8 mm. Comparable values for joints constructed with two (smaller) cross pins ranged from 15 to 21.9 kN. Capacities of comparable joints with a single 12.7-mm tenon cross pin loaded in compression decreased from 220 to 165.7 kN as tenon diameters increased from 31.8 to 50.8 mm. In the case of compression specimens, cross mortises cut through the follower member of the joint substantially decreased compression force capacity from 172.8 to 113.2 kN as tenon and cross-mortise diameters increased from 31.8 to 50.8 mm. Compression force capacities for comparable specimens with 19.1-mm cross mortises in the follower members ranged from 157.5 to 122.3 kN for tenon diameters ranging from 31.8 to 50.8 mm.

Keywords: Building construction, round mortise-and-tenon joints, pinned end-to-end joints, withdrawal and compression force capacity.

INTRODUCTION

Light timber frames constructed with round mortise-and-tenon joints provide a unique approach to erecting structures, such as houses, farms, and light industrial buildings in developing countries, with members cut from locally grown timber, as well as erecting commonplace domestic suburban structures such as backyard barns. Various aspects of round mortise-and-tenon joinery have been reported (Akcay et al 2005; Eckelman et al 2006b, 2007, 2008) along with the structural behavior of two backyard barn frames (1.8 × 3.6 and 2.4 × 3.0 m) constructed with round mortise-and-tenon joints (Eckelman et al 2002, 2006a). But an important aspect of round mortise-and-tenon joint construction that remains to be investigated is end-to-end joining of members. Such joining would be useful in constructions in which longer members (such as purlins) are needed but especially in constructions in which the members may be subjected to substantial compressive forces, such as corner posts, where it would allow the joining of nondurable aboveground corner posts to durable foundation posts.

Examples of the use of end-to-end jointing of members with round mortise-and-tenon joints were not found in a search of the literature, but examples of end-to-end jointing with dowels were found. For example, a diagram of end-to-end construction is given by Karlsen (1967) that shows an "oak pin" embedded in an end-to-end joint of two vertical members in a Shukhov

* Corresponding author
† SWST member

wooden lattice tower. Likewise, Jacoby (1914) shows a dowel that "holds the tip of the follower pile in place on the butt of the lower pile."

Numerous examples of end-to-end connections using other self-contained joinery were found including those used in barn construction by Ensminger (1992), Fink (1987), and Sobon (2002); in the construction of structures such as water tank towers by Dewell (1917) and Karlsen (1967); in general carpentry in structures such as steeples, spires, and towers by Hodgson (1916) and Townsend (1908); in heavy timber construction by Elliott and Wallas (1977); in general construction by Holtman (1929); and in the design of wooden-covered bridges by Pierce et al (2005).

Other research of particular interest (Andrews 2006) on rectangular mortise-and-tenon joints indicated that the withdrawal capacity of end-to-end round mortise-and-tenon joints would probably depend primarily on the relative relish areas of the tenon-and-mortise wall and the tensile capacity of the tenon adjacent to the cross-pin hole. Likewise, information provided by FPL (1940) concerning bolted joints indicated that the use of larger rather than smaller diameter pins ($L/d < 4$) in cross-pinning tenons is desirable but risks decreasing the optimum residual tenon cross section. Also, the research conducted by Eckelman and Senft (1995) along with Wolfe et al (2000) on the use of dowel nuts, which function in a manner somewhat similar to tenon cross pins, indicated that cross pins placed in existing end splits (or in areas where splits might subsequently develop) decreases joint capacity but that "clamping" the end of the member substantially decreases the loss of capacity (Eckelman 2004). Finally, Moss (1997) indicated that in a multipinned tension joint, the end pins carry most of the load; thus, use of more than two pins may not be appropriate.

In the case of compression specimens, Seeley and Smith (1952), Smith (1944), and FPL (1951, 1956) provide information concerning the stresses around a hole in a wide plate subjected to a uniform compression stress, which provides insight into the nature of the stresses around cross-pin holes and cross mortises in round mortise-and-tenon joints. Specifically, the sides of a cross-pin hole or cross mortise are loaded in compression parallel to the grain, whereas the top and bottom of the hole are loaded in tension perpendicular to the grain, with the perpendicular-to-grain stress equal but opposite in sign to the parallel-to-grain stress. Thus, given the limited perpendicular-to-grain strength of wood (relative to longitudinal strength), splits might be expected to form at the top and bottom of a cross-pin hole with a corresponding decrease in load capacity of the post. Because the magnitude of tension perpendicular-to-grain stresses at these points is a function of the axial stress resulting from applied loads, cross-mortise diameters should be minimized as much as possible.

The protean nature of round mortise-and-tenon light timber frame construction (including the ease with which emergency structures can be erected under difficult circumstances with a minimum of tools by local labor with little technical experience and the ability to fabricate durable modular constructions in disadvantaged areas of the world with members sawn from locally grown woods) justifies a preliminary exploratory study of the basic properties of such joints including their modes of failure and their estimated load capacity. An exploratory program was undertaken, accordingly, to obtain insights into the various modes of failure of these joints and to obtain first estimates of their withdrawal and compression capacities.

The objectives of the study were to

1. Obtain estimates of the ultimate end-to-end withdrawal force capacities of round mortise-and-tenon joints in nominal 88.9×88.9 mm members cross-pinned with either one or two pins.
2. Obtain estimates of the ultimate end-to-end compression force capacities of round mortise-and-tenon joints in nominal 88.9×88.9 mm members with tenons cross-pinned with one

steel pin and with or without a secondary cross mortise in the follower (tenoned) member.

MATERIALS AND METHODS

Design of Experiments

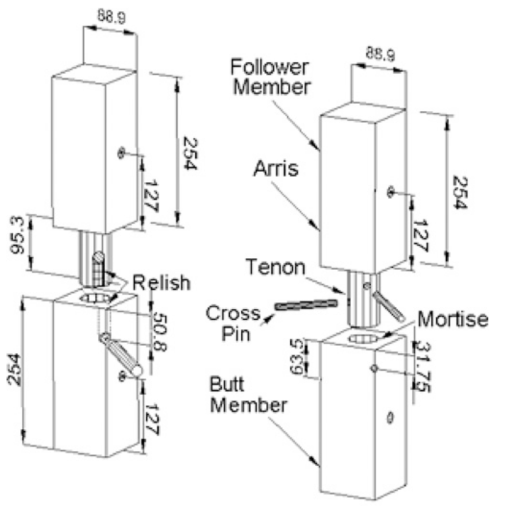
Specimen set 1. Five tension specimens each with tenon diameters of 31.8, 34.9, and 41.3 mm and one tenon cross pin with a diameter of 12.7 mm for 15 specimens.

Five tension specimens each with a tenon diameter of 44.5 mm and one tenon cross pin with a diameter of 15.9 mm for five specimens.

Five tension specimens each with a tenon diameter of 50.8 mm and one tenon cross pin with a diameter of 19.1 mm for five specimens (Fig 1a).

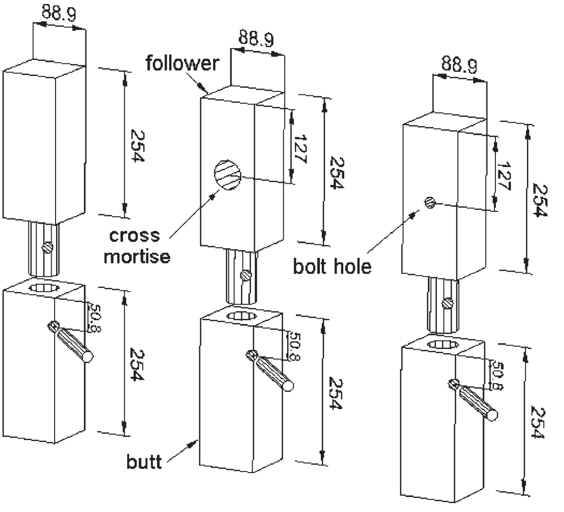
Specimen set 2. Five tension specimens each with tenon diameters of 31.8, 34.9, 41.3, 44.5, and 50.8 mm and two tenon cross pins with diameters of 11.1 mm for 25 specimens (Fig 1b).

Specimen set 3. Five compression specimens each with tenon diameters of 31.8, 34.9, 41.3, 44.5, and 50.8 mm and a tenon cross-pin diameter of 12.7 mm for 25 specimens (Fig 2a).



(a) (b)

Figure 1. Typical withdrawal specimens (a) single cross pin (b) two cross pins. All dimension in millimeters.



(a) (b) (c)

Figure 2. Typical compression specimens (a) without cross mortise in follower, (b) with cross mortise equal to tenon diameter, (c) with 19.1-mm-diameter bolt hole (cross mortise). All dimensions in millimeters.

Specimen set 4. Five compression specimens each with tenon diameters of 31.8, 34.9, 41.3, 44.5, and 50.8 mm and a tenon cross-pin diameter of 12.7 mm and corresponding cross mortises in the follower of 31.8, 34.9, 41.3, 44.5, and 50.8 mm for 25 specimens (Fig 2b).

Specimen set 5. Five compression specimens each with tenon diameters of 31.8, 34.9, 41.3, 44.5, and 50.8 mm and a tenon cross-pin diameter of 12.7- and 19.1-mm cross mortises in the follower for 25 specimens (Fig 2c).

Specimen Configurations and Construction

Configurations of the withdrawal specimens are illustrated in Fig 1a-b, and compression specimen configurations are illustrated in Fig 2a-c. Tenon and cross-pin diameters are given in Table 1. Tenon length was fixed at 95.3 mm, whereas mortise depth was fixed at 101.6 mm. All specimens were constructed of 88.9 mm (nominal 100 mm) square Hem-Fir stud-grade (standard grade) material that was conditioned to 8% MC.

Withdrawal specimens—one cross pin. In withdrawal specimens with one cross pin, the

Table 1. Joint geometry details (Replications: 5 each; Tenon length: 95.3 mm; Mortise depth: 101.6 mm).

				Distance to root of tenon		
Specimen set number	Tenon diameter (mm)	Number of cross pins	Cross-pin diameter (mm)	Pin 1 (mm)	Pin 2 (mm)	Cross-mortise diameter (mm)
			Tension—one pin			
1	31.8	1	12.7	50.8		
	34.9	1	12.7	50.8		
	41.3	1	12.7	50.8		
	44.5	1	15.9	50.8		
	50.8	1	19.1	50.8		
			Tension—two pin			
2	31.8	2	11.1	31.8	63.5	
	34.9	2	11.1	31.8	63.5	
	41.3	2	11.1	31.8	63.5	
	44.5	2	11.1	31.8	63.5	
	50.8	2	11.1	31.8	63.5	
			Compression without cross mortise			
3	31.8	1	12.7	50.8		
	34.9	1	12.7	50.8		
	41.3	1	12.7	50.8		
	44.5	1	12.7	50.8		
	50.8	1	12.7	50.8		
			Compression with cross mortise = tenon diameter			
4	31.8	1	12.7	50.8		31.8
	34.9	1	12.7	50.8		34.9
	41.3	1	12.7	50.8		41.3
	44.5	1	12.7	50.8		44.5
	50.8	1	12.7	50.8		50.8
			Compression with cross mortise = 19.1 mm			
5	31.8	1	12.7	50.8		19.1
	34.9	1	12.7	50.8		19.1
	41.3	1	12.7	50.8		19.1
	44.5	1	12.7	50.8		19.1
	50.8	1	12.7	50.8		19.1

cross-pin axis was located 50.8 mm away from the root of the tenon (44.5 mm from the tip) for all tenon diameters. 12.7-mm-diameter cross pins were used in specimens with 31.8- to 41.3-mm tenon diameters, whereas 15.9- and 19.1-mm cross pins were used in specimens with 44.5- and 50.8-mm diameter tenons, respectively, to maintain a low-tenon diameter to cross-pin diameter ratio. Holes for load straps (19-mm diameter) were located at the center of the side face of the follower and the corresponding side face of the butt section at the center points of the faces (Fig 1).

Withdrawal specimens—two cross pins. Loss of residual tenon cross section was of concern in specimens with two cross pins, and it was also speculated that the use of smaller pins might result in a more uniform distribution of pin forces. Thus, joints were constructed with 11.1-mm-diameter rather than 12.7-mm-diameter cross pins Also, the use of more than two pins did not appear to be feasible for tenons of this length (Moss 1997). Lacking information concerning optimum placement, cross pins were arbitrarily located at the third points along the length of the tenon (31.75 and 63.5 mm away from the root of the tenon—31.75-mm spacing) with the axis of the second pin rotated 90° from the axis of the first pin.

Compression specimens—no cross mortise in follower. The tenon cross-pin hole diameter (12.7 mm) was held constant in the compression specimens to minimize size-associated effects in the mortise wall. To evaluate tenon diameter effects, specimens (without follower cross holes or cross mortises) were constructed for each of the five tenon diameters, namely, 31.8, 34.9, 41.3, 44.5, and 50.8 mm.

Compression specimens with equal cross-mortise and tenon diameters. Specimens with cross mortises in the follower (with cross-mortise diameters identical to the corresponding specimen tenon diameters) were constructed to investigate the weakening effect of cross mortises drilled in the follower such as that might occur when a horizontal member is attached to the face of the post by means of an end-to-side grain joint. Holes for pinning potential cross tenons were not drilled in the followers.

Compression specimens with 12.7-mm cross mortise in follower. In a similar manner, compression specimens with 19.1-mm cross holes in the followers were constructed for each of the five tenon diameters to investigate the weakening effect of holes drilled through the follower to accommodate members bolted to the face of a post.

Construction. Each 2440-mm length of material was first cut into four 610-mm lengths. Each 610-mm length was then cut into a 254- and a 356-mm length. A tenon was then machined on the end of the 356-mm length, and a mortise was machined in the corresponding matching end of the 254-mm length as shown in Figs 1 and 2. Tenons were machined to a length of 101.6 mm and then trimmed to 95.3 mm, whereas end mortises were machined to a depth of 101.6 mm.

Tenons and member end mortises were machined on a horizontal drill press with commercially available tenon cutters and Forstner bits, respectively. Cross mortises and cross-pin holes were machined on a vertical drill press with Forstner and standard wood bits, respectively. Diameter tolerances for both tenons and mortises were ±0.13 mm.

Following machining of the tenon and corresponding mortise, the tenon was inserted into the mortise, the resulting assembly was clamped together lengthwise with a bar clamp to assure firm shoulder-to-shoulder contact, and the hole for the cross pin was drilled.

In withdrawal specimens with one cross pin, the cross-pin hole was drilled from one corner (arris) to the opposite corner (arris) of the butt potion of a specimen (through the mortise walls) (Fig 1a). In specimens with two cross pins (Fig 1b), the cross-pin holes were drilled 90° to one another. Holes for load straps were bored from face to face through the side face of the follower and butt sections (Fig 1).

In compression specimens (Fig 2), cross mortises and holes in the face of the followers were machined at the center point of a face (Fig 2b-c). All cross-pin holes in the butt sections were machined from corner (aris) to corner (aris).

Test Procedures

All tests were conducted in a Riehle Universal Testing machine with a precision of ±1% of load. The compression specimens were loaded as shown in Fig 3a. Tension specimens were fitted with straps for loading and tested as shown in Fig 3b. Rate of loading was 1.27 mm/min. Specimen MC was maintained at 8%. Testing of

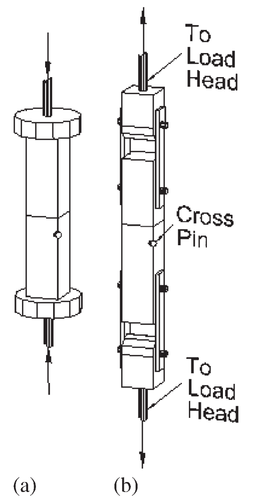


Figure 3. Methods of loading specimens (a) in compression and (b) in withdrawal.

Table 2. Withdrawal force capacity of one- and two-pin specimens.

	One pin			Two pins		
Tenon diameter (mm)	Number of specimen	Mean (kN)	SD (kN)	Number of specimen	Mean (kN)	SD (kN)
31.8	5	9.1	1.3	5	15.0	1.1
34.9	5	10.0	3.1	5	15.1	2.0
41.3	5	15.1	3.0	5	19.5	3.4
44.5	5	16.0	2.8	5	20.6	3.6
50.8	5	14.5	4.8	5	21.9	3.8

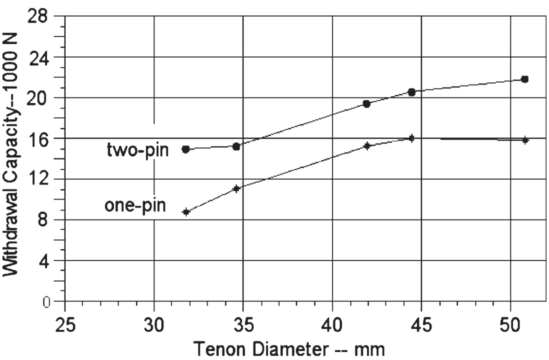


Figure 4. Results of withdrawal tests.

specimens was continued until a nonrecoverable drop-off in load occurred.

RESULTS AND DISCUSSION

Withdrawal Force Capacity

Results of the withdrawal tests are given in Table 2 and illustrated in Fig 4. As Fig 4 shows, withdrawal force capacity increased by a factor of 1.76 as tenon diameter increased from 31.8 to 44.5 mm (a factor of 1.4). However, withdrawal force capacity decreased to 14.5 kN as tenon diameter increased to 50.1 mm. In keeping with this result, specimens with 31.8- to 41.3-mm-diameter tenons experienced tenon relish failures, with the exception of one tenon tension failure through the cross-pin hole, whereas both tenon-wall and mortise-wall relish failures occurred in specimens with 50.8-mm-diameter tenons, which presumably reflects the decrease in mortise relish area with larger tenon diameter.

Results of the withdrawal tests of the two-pin specimens are also given in Table 2 and Fig 4. As can be seen, the two-pin specimens had substantially greater withdrawal force capacity than the one-pin specimens, 43% greater on average. Overall, withdrawal force capacity increased by a factor of 1.46 as tenon diameter increased from 31.8 to 50.8 mm (a factor of 1.6). Observations made during the course of testing indicated that the relish on the tip of the tenon ordinarily failed first followed by the mortise wall relish nearest the shoulder of the butt member.

Compression Force Capacity

Results of the compression tests of specimens with identical cross-mortise-and-tenon diameters are given in Table 3 and shown in Fig 5. The compression force capacity of specimens with the tenon cross-pinned with a 12.7-mm-diameter cross pin (but without a cross mortise in the follower) decreased from 219.6 kN for joints with 31.8-mm-diameter tenons to 165.7 kN for joints with 50.8-mm-diameter tenons.

Compression force capacities of joints with a cross mortise in the follower equal in diameter to the tenon ranged from a high of 172.8 kN for 31.8-mm cross holes to a low of 114 kN for 50.8-mm cross holes, for an average of 137.5 kN. Comparable values for specimens with 19.1-mm

Table 3. Compression force capacity with and without cross mortise and with a 19.1-mm cross hole.

	Without cross mortise			With cross mortise			With 19.1-mm cross hole		
Tenon diameter (mm)	Number of specimen	Mean (kN)	SD (kN)	Number of specimen	Mean (kN)	SD (kN)	Number of specimen	Mean (kN)	SD (kN)
31.8	5	219.6	27.1	5	172.8	24.2	5	157.5	16.7
34.9	5	207.1	25.6	5	147.6	22.9	5	149.2	10.8
41.3	5	182.4	27.1	5	126.0	8.5	5	141.1	20.2
44.5	5	182.7	11.3	5	127.2	20.8	5	125.5	17.8
50.8	5	165.7	27.5	5	114.0	34.8	5	122.3	30.7

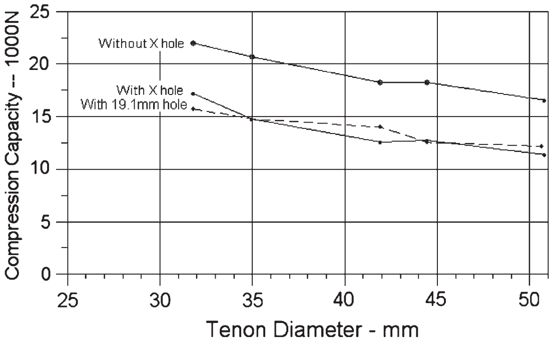


Figure 5. Results of compression tests.

cross holes ranged from a high of 157.5 kN for specimens with 31.8-mm tenons to 122.3 kN for specimens with 50.8-mm tenons, for an average of 139.1 kN. Overall, joints with equal tenon and follower cross-mortise diameters averaged 72% of the load capacity of joints without cross mortises. Likewise, joints with comparable 19.1-mm-diameter follower holes averaged 72.7% of the capacity of the joints without follower cross holes. Thus, holes or cross mortises in the follower used for the attachment of other members are expected to substantially decrease the load capacity of round mortise-and-tenon end-to-end joints.

In the case of specimens without cross mortises in the follower, splits first occurred in the mortise walls of the butt member on a line coincident with the center of the cross-pin hole at the top and bottom surfaces of the hole. In some cases, as loading continued, compression failure of the mortise wall occurred on a plane coincident with the center of the cross-pin holes. In other cases, the split in the butt member widened and a corresponding split then formed on the face of the tenon member.

In the case of specimens with cross mortises in the follower, a longitudinal split first developed on the upper and lower rim of the cross mortise in the follower. As this split developed, the walls of the mortise bulged outward with corresponding drop-off in load. In the case of followers with large-diameter cross mortises, crushing of the mortise walls also occurred. Overall, observations of the modes of failure indicated that for equal diameter cross and end mortises, the butt member had greater compressive capacity than the follower.

The capacity of specimens with 19.1-mm cross mortises in the follower essentially paralleled that of specimens with equal tenon and cross-mortise diameters, which indicates that the ultimate load capacity of the specimens depended on the residual shoulder area of the members regardless of the cross-hole diameter, at least up to the point that compression or buckling failure of the walls of the cross mortise occurred.

Statistical Analysis

Analysis of variance results indicated that tenon diameter and cross-mortise diameter had significant effects on both compression load and tension load of end-to-end joints. In compression testing, 69% ($R^2 = 0.6877$) of the variability was explained by the model. In the same way, in tension test, 65% ($R^2 = 0.6491$) of the variability was explained by the model. On the basis of statistical analysis, it could be concluded that there were strong relationships between tenon diameter and cross-mortise diameter and both compression and tension load of end-to-end joints.

CONCLUSION

The withdrawal force capacity of end-to-end round mortise-and-tenon joints constructed with 95.3-mm-long by 31.8- to 50.8-mm-diameter tenons in 88.9-mm square Hem-Fir studs cross pinned with 12.7- to 19.1-mm cross pins ranged from 9.1 to 16 kN. Withdrawal force capacity increased when tenons were cross pinned with two rather than one cross pin. Withdrawal capacity of comparable joints with two 11.1-mm-diameter cross pins located at the third points of the tenon with their axes positioned 90° to one another ranged from 15 to 21.9 kN.

The compression force capacity of comparable specimens with tenons cross pinned with 12.7-mm-diameter pins ranged from 219.6 kN for joints with 31.8-mm-diameter tenons to 165.7 kN for joints with 50.8-mm-diameter tenons. Cross mortises or holes located in the follower member above the joint interface substantially decreased the load capacity of the joint. Joints with equal tenon and follower cross-mortise diameters averaged 72% of the force capacity of joints without cross mortises. Similarly, joints with comparable 19.1-mm-diameter follower holes averaged 72.7% of the capacity of the joints without follower cross holes. Thus, holes or cross mortises in the follower used for the attachment of other members must be expected to substantially decrease the force capacity of round mortise-and-tenon end-to-end joints.

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