Knee Braces for Bents Constructed with Round Mortise and Tenon Joints

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Abstract

Tests were conducted to determine the axial load capacities of knee braces suitable for use in light timber frames constructed with round mortise and tenon joints. To make the knee braces consistent with typical frame construction, the ends of the knee braces were tenoned and did not require machining equipment that was different or more complex than that used for a typical frame. Knee braces with tenons machined perpendicular to the faces of the ends of the braces satisfied these requirements. Three types of braces were investigated; specifically, braces with tenons centrally located on the end-faces of flush-fitting braces, braces with tenons located on the outer edge of the end-faces of flush-fitting braces, and finally, braces with the tenon centrally located on the end-faces of ''housed braces,'' i.e., braces with the end-faces housed in the sides of the connecting members. Results indicated that all three types of construction had sufficient load capacity to be useful in timber frames constructed with round mortise and tenon joints, but braces with tenons offset toward the outer edge of the end-faces had better structural characteristics than braces with flush ends and centrally located tenons. Finally, knee braces with centrally located tenons and housed ends had substantially greater load capacity than those with unhoused ends.

Knee braces are important structural elements in timber bents constructed with round mortise and tenon joints, as shown in Figure 1, not only because they provide resistance to horizontal wind loads (Karlsen 1967) but also because they can improve distribution of forces in the frame and permit the use of wider spans. In reinforcing frames with knee braces, it is desirable, both from an esthetic and a manufacturing point of view, that the knee brace construction be consistent with that used throughout the frame. In general, this implies that the braces should be constructed with round mortise and tenon joints and should not require machining equipment that is different or more complex than that used in constructing the frame itself.

Ideally, knee braces should be able to resist both compression and tension loads (Karlsen 1967). Bulleit et al. (1999) evaluated the behavior of pegged knee braces under both compressive and tensile loading and generally found that knee brace behavior in axial compression was ''highly dependent'' on the fit between the end of the knee brace and the face of the post or joint. In tension, the capacity of the knee brace joints was limited by either peg failure or by relish failure (i.e., block shear failure of the wood between the peg hole and the end of the tenon). The behavior of knee brace joints was also discussed by Sandberg et al. (2000), who indicated that peg failure is the primary cause of knee brace failure in knee braces loaded in tension.

In practice, knee braces are often designed to resist force in only one direction (Sobon and Schroeder 1984). Hence, they are commonly used in opposing matched sets. Pierce et al. (2005), however, point out that such ''compression-only'' systems may lead to unwanted distortion of the frame.

Elliott and Wallas (1977) suggest that braces should be about half as long as the posts into which they frame. This convention results in a construction in which the upper and lower knee brace joints are located at the third points of the post.

Inclusion of knee braces (with end tenons) into frames constructed with round mortise and tenon joints can be difficult because the tenons on the ends of the knee braces along with the tenon on one of the members (usually a beam or post) must be inserted simultaneously into their associated mortises—a problem also encountered in conventional rectangular mortise and tenon joint construction (Chappell 1983). To allow such insertions, tenons on the ends of the braces should be machined with their longitudinal axes perpendicular to the faces of the knee braces such as those shown in Figure 2. This construction is in principle similar to that used in rectangular mortise and tenon construction such as that shown by Chappell (1983)

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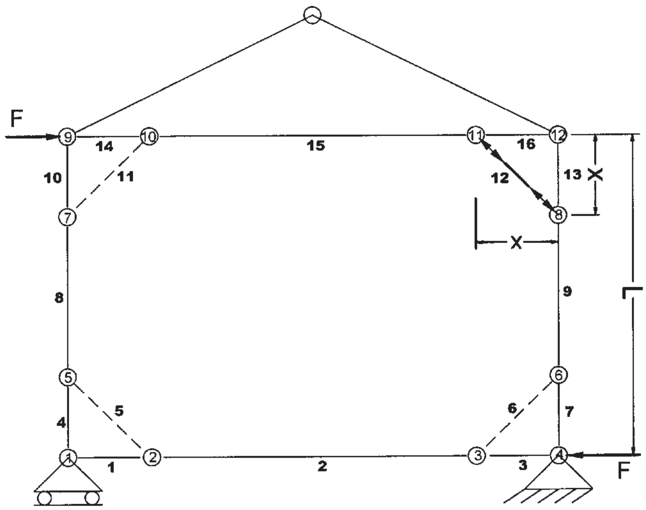

Figure 1.—Diagram of frame used in analysis. Dashed braces are inactive.

among others. In assembling the joint shown in Figure 2a, for example, the tenon on the upper end of the brace is inserted into its corresponding joist mortise and the tenons on the ends of the resulting knee brace to joist assemblage—one on the end of the joist and the other on the lower end of the knee brace—are then simultaneously inserted into their corresponding mortises in the post.

Three variations of this basic construction appear to be of interest. In the first construction (Fig. 2a), the shoulders of the brace are flush with the post and beam surfaces and the tenons are centered on the ends of the brace; in the second type (Fig. 2b), the shoulders are again flush, but the tenon is offset toward the outside edge of the brace (bullnose tenon). Finally, in the third type (Fig. 2c), shallow dadoes are machined in the sides of the post and joist in order to house the ends of the brace, and the tenons are centered on the ends of the brace.

Based on the considerations given above, exploratory tests were conducted to determine the capacity of knee braces with these three types of end connections. Results of the tests are given in this article.

Discussion of Estimated Required Knee Brace Capacity

Useful initial estimates of required axial knee brace capacities can be obtained by considering the bending moment capacities of the joists and posts in braced constructions as shown in Figure 1 and the withdrawal and shear capacities of the joist-to-post connections. In the case of a frame with yellow poplar (*Liriodendron tulipifera*) posts, for example, based on a typical modulus of rupture of 12,000 psi at 7 percent moisture content, the calculated bending moment capacities of 3.5-, 3.625-, and 6-inch square posts are 85,750, 95,270, and 432,000 pound-inches, respectively. For a typical frame (Fig. 1) in which $L = 96$ inches and $X = 24$ inches, the corresponding side-thrust forces, F, needed to develop these bending moments at joint 8 amount to 1,191, 1,323, and 6,000 pounds for 3.5-, 3.625-, and 6-inch posts, respectively. Analyses of the frame (Fig. 1) indicate that the axial forces developed in the knee braces corresponding to these side-thrust forces amount to 6,740, 7,740, and 33,900 pounds, respectively.

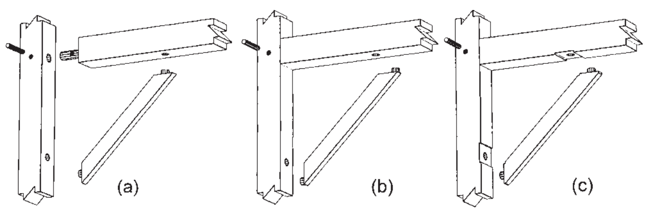

Figure 2.—Diagram showing (a) centered tenon with flush end, (b) offset tenon with flush end, and (c) centered tenon with mortised end.

These results, of course, are based on a modulus of rupture strength value rather than a design strength value, but they do provide initial insight into the magnitudes of knee brace capacities needed to correspond with given post capacities. Also, although maximum capacity is obtained with housed knee braces (Sobon 1994), it should be noted that material removed from members for housing can substantially reduce moment resistance. A half-inch housing dado cut into a 3.5-inch square post, for example, reduces moment capacity by 37 percent.

Aside from the bending moment capacities of the posts, the capacities of the joist-to-post joints also indicate the limits of potentially needed knee brace capacity. Results of tests carried out by Akcay et al. (2005), for example, show that the withdrawal strengths of 2- and 3-inch round tenons with a single wood cross pin are about 3,500 and 5,000 pounds, respectively. Analogous values for joints with comparable size pipe cross pins amount to about 5,000 and 10,000 pounds, respectively. Analysis of the frame shown in Figure 1 indicates that for a withdrawal force of 5,000 pounds (corresponding to the value given above for a 2-in. tenon with pipe cross pin) acting on the joist-to-post joint (members 16 and 13, joint 12), the accompanying axial knee brace force is 9,400 pounds. Similarly, for a maximum withdrawal capacity of 10,000 pounds (corresponding to the value given above for a 3-in. tenon with pipe cross pin), the accompanying knee brace force is 18,800 pounds.

Similarly, Akcay et al. (2005) found the lateral shear capacities of 2- and 3-inch-diameter tenons to be about 3,600 and 7,500 pounds, respectively. Analysis of the frame shown in Figure 1 indicates that for a limiting lateral shear force of 3,600 pounds acting on the joist-to-post joint (members 16 and 13, joint 12), the corresponding axial knee brace force is 6,100 pounds. Similarly, for a limiting lateral shear force value of 7,500 pounds, the corresponding knee brace force is 12,700 pounds.

These sets of values, though somewhat abstract in nature, provide initial estimates of knee brace capacities consistent with either joint or post capacities.

Pinning of the knee brace tenons was not addressed in this study. Ideally, the tenons should be free to withdraw slightly from the mortises when a brace is loaded in tension so that the brace and tenon, in particular, do not carry axial forces. But the tenons must not withdraw completely from the mortises because they must reseat themselves when the brace is loaded in compression—otherwise, some form of pinning may, in fact, be necessary.

Finally, though not discussed in this article, this type of construction potentially has other uses such as attaching rafters to ridge beams and wall plates in roofs with a high pitch.

Specimen Design and Construction

The general configuration of the test specimens used to evaluate the three types of knee brace end connections shown in Figure 2 is illustrated in Figure 3. In these specimens, the mortise and tenon joist-to-post joint shown in Figure 2 has been replaced by a ''pinned'' joint that is secured by means of what is essentially a ''through bolt with dowel nut.'' This construction was used in order to avoid premature failures of the joist-to-post joint and thereby allow the knee braces to be loaded to failure. Three specimens with each type of knee brace end-connection were constructed with each of the following member sizes: 3.5 by 3.5-inch southern yellow pine (*Pinus echinata*) post and beam with 1.75 by 3.5-inch southern yellow pine brace and 1.75-inch diameter tenons; 3.625 by 3.625-inch yellow poplar post and beam with 1.875 by 3.875-inch yellow poplar brace and 1.875-inch diameter tenons; and finally, 6 by 6-inch yellow poplar post and beam with 3 by 5.5-inch yellow poplar brace and 3-inch tenons. All braces were a nominal 34 inches in length and were installed at an angle of 45 degrees relative to the beam and post. Tenon lengths were limited to 1 inch in order to reduce the amount of material removed from the post and beam. Anchor holes were provided in the posts (Fig. 3) to allow securing a specimen to the upright of the testing jig with bolts. All of the specimens were conditioned to and maintained at 7 percent moisture content.

Method of Test and Analysis

The specimens were mounted for testing as shown in Figure 4. Tests were carried out on a 30,000-pound capacity Riehle universal testing machine at a constant cross head movement of 0.5 inch per minute. Ultimate load was taken as that point at which some type of catastrophic fracture of the knee brace or tenon occurred with accompanying major loss of applied load.

Each specimen was treated as a four-member structure with pinned knee brace-to-joist joint (Fig. 5, joint 3), pinned knee brace-to-post joint (Fig. 5, joint 1), and pinned joist-to-post joint (Fig. 5, joint 2) and analyzed to determine the axial load acting on the knee brace at the time of failure, which was taken as the ultimate load capacity of the knee brace construction. To provide a standard basis for comparison, all force calculations were based on distances measured from the intersections of the longitudinal axes of the members (Fig. 5).

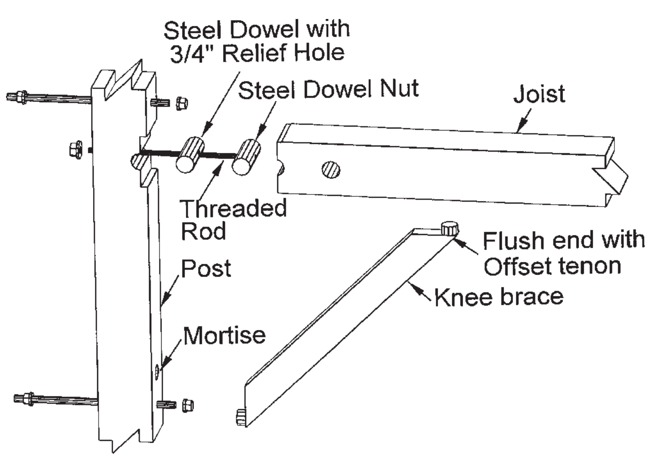

Figure 3.—Specimen configuration.

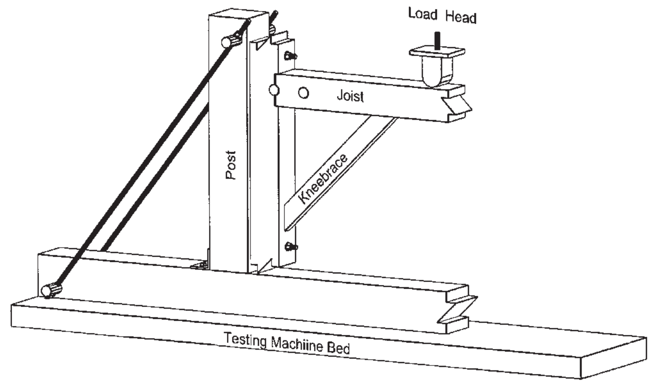

Figure 4.—Test setup.

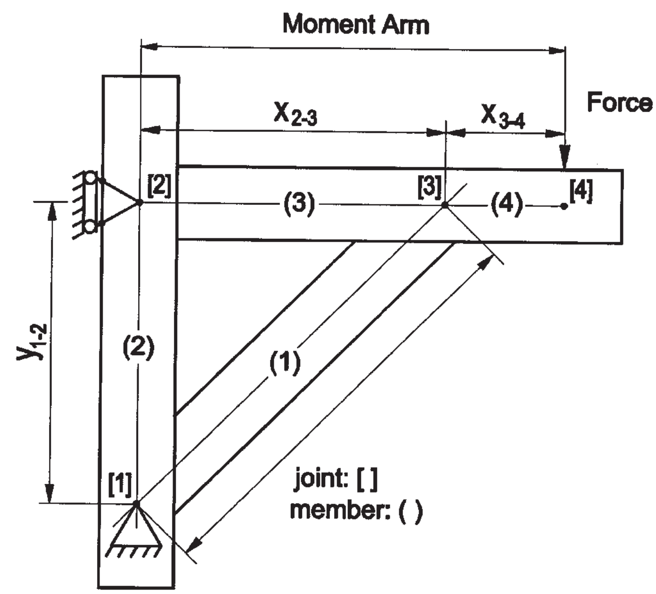

Figure 5.—Labeling of specimen for analysis.

Results and Discussion

Results of the tests are given in Table 1. To facilitate comparisons, results are also presented graphically in Figure 6.

Overall, as can be seen in Figure 6, the knee braces with offset tenons and flush ends had greater load capacity than did braces with centered tenons and flush ends in both the 1.75 by 3.5-inch and the 1.875 by 3.875-inch knee braces but had essentially identical strengths in the 3 by 6-inch knee braces. Knee braces with centered tenons and housed ends, however, had substantially greater strengths than the knee braces with flush ends in all three cases.

In the specimens with centered tenons and flush ends (Fig. 2a), splits first developed along the grain adjacent to the outside edges of the tenons. These splits lengthened as loadings increased until, in some cases, they extended the entire length of the brace; this action was then followed (sometimes concurrently) by fracture of the wood at the root of the tenon on its tension side. These splits occurred because the joists tended to rotate slightly (relative to the

Table 1.—Specimen description and test load results.

No. of reps.	Specimen: Post/joist cross section (in.)	Knee brace: Wood species[a]	Knee brace: End type	Knee brace: Width (in.)	Knee brace: Depth (in.)	Knee brace: Tenon diam. (in.)	Knee brace: Mach load (in.)	Test results: Ultimate test load (SD) (lb)[b]	Test results: Axial knee brace force (SD) (lb)[c]
3	3.5	SYP	Center/flush	1.75	3.5	1.75	1.0	3,110 (269)	4,599 (383)
3	3.5	SYP	Right/flush	1.75	3.5	1.75	1.0	4,100 (1,186)	6,374 (1,819)
3	3.5	SYP	Center/dado	1.75	3.5	1.75	1.0	6,667 (946)	11,416 (2,212)
3	3.625	YP	Center/flush	1.875	3.875	1.875	1.0	6,250 (901)	11,200 (1,664)
3	3.625	YP	Right/flush	1.875	3.875	1.875	1.0	6,467 (1,570)	13,636 (919)
3	3.626	YP	Center/dado	1.875	3.875	1.875	1.0	11,267 (1,429)	20,785 (2,637)
3	6.0	YP	Center/flush	3.0	5.5	3.0	1.0	13,417 (382)	22,808 (649)
3	6.0	YP	Right/flush	3.0	5.5	3.0	1.0	13,213 (1,957)	22,036 (3,013)
3	6.0	YP	Center/dado	3.0	5.5	3.0	1.0	21,000 (1,000)	35,913 (2,026)

[a] SYP = southern yellow pine; YP = yellow poplar.
[b] SD = standard deviation.
[c] Calculated axial knee brace force (based on Fig. 5).

posts) under load so that the noses of the braces were loaded rather than the entire face. This loading caused forces perpendicular to the grain to be exerted on the ends of the knee braces, which caused splits to develop adjacent to the outside edges of the roots of the tenons. Once these splits occurred, the knee braces essentially behaved like those with offset tenons in that the tenons alone carried the shear forces acting parallel to the faces of the brace. Specimens with offset tenons and flush ends failed owing to fracture of the root of the tenon at either nose of the knee brace. Some splitting of the knee brace along the grain occurred in a few specimens but to a much lesser degree than with the flush centered tenons.

The specimens with centered tenons and housed ends failed owing to crushing of the nose of the knee brace along with shearing of the tenon. Basically, these specimens carried load until a sudden major type of fracture of the knee brace occurred. Presumably, the blunted noses of the knee brace and the tenons act together to resist the load imposed on the joint; however, the substantial increase in capacity obtained in specimens with housed ends indicate that the blunted noses of the knee brace carry a large part of the load. Thus, use of thicker knee braces might be expected to substantially increase knee brace capacity.

The previously estimated axial knee brace forces corresponding to the construction shown in Figure 1 are

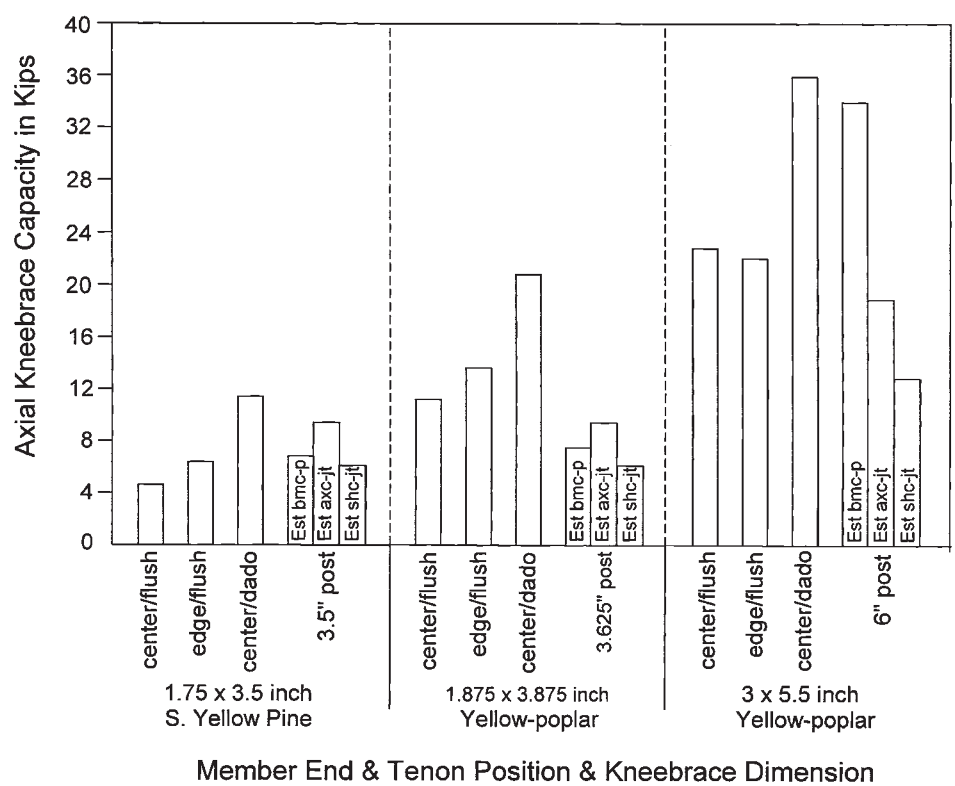

Figure 6.—Bar graph showing mean axial load capacities for knee brace configurations included in the study. "Est" bars refer to estimated values discussed in text.

also shown in Figure 6. As can be seen, all of the housed (center/dado) knee braces had greater axial capacities than the corresponding estimated capacities based on bending moment capacities of the posts (Fig. 6, Est bmc-p). In the case of centered and offset flush braces, however, only the 1.875 by 3.875-inch yellow poplar braces had greater equivalent capacity than that estimated for corresponding posts.

In the case of joint withdrawal capacities, only the knee braces with flush ends and 1.75-inch diameter centered and edge tenons had less axial capacities than the corresponding previously estimated values (Fig. 6, Est axc-jt).

Finally, in the case of lateral shear capacities of joist-to-post joints, only the knee braces with flush ends and 1.75-inch-diameter centered and edge tenons had lower capacities (Fig. 6, Est shc-jt) than the corresponding previously estimated values. It should be noted, however, that in multiple story constructions, lateral shear strength can be substantially increased by inletting the end of the joist into the post.

Conclusions

Knee braces with round tenons cut perpendicular to the ends of the braces provide a means of reinforcing light timber frame bents constructed with round mortise and tenon joints that are both structurally sound and consistent with the overall method of construction. Knee braces with flush ends and either centered or offset tenons would be expected to provide the capacity needed for most constructions, whereas knee braces with housed ends would provide added capacity for demanding constructions.

In knee braces with flush ends and centered tenons, the knee brace tends to split along a line from the forward edge of one tenon to the forward edge of the other. In the case of braces with ''unhoused ends,'' braces with flush ends and offset tenons should likely be considered when braces are cut from small tree stems because the tenon would be located further away from reaction wood.

Maximum capacity is obtained when the ends of the knee brace are ''housed'' in the faces of the beam and post, subject to the constraint or consideration that the housing dado reduces the bending moment capacity of these members. Use of thicker knee braces than those used in this study would presumably increase carrying capacity.

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