Mortise and Tenon Joints

Round Mortise and Tenon Joints

Round mortise and tenon joints are similar in character to rectangular mortise and tenon joints but differ in that the end of a member is machined to form a round rather than a rectangular tenon, which, in turn, fits into a round rather than a rectangular mortise, Figure 6-17.

Round mortise and tenon joints may be used for a variety of furniture constructions. Most commonly, however, they are used in stretcher to

front post and stretcher to back post joints, in front post to arm joints, Figure 6-18, and for spindle to arm, backrest and seat joints in chairs, as well as for analogous joints in other furniture. Depth of embedment is particularly important in leg to seat constructions since the leg is dependent on the joint alone for strength should the supporting stretcher connections fail.

The strength of this type of connection depends on the diameter of the tenon, its depth of insertion in the second member, and also upon the inherent strength properties of the woods used. In most cases, the tenons should be machined to the largest diameter possible. (An exception would be when the mortise drilled into the second member would be so large that it would seriously weaken it).

The rational design of round mortise and tenon joints to resist withdrawal loads is essential in several types of furniture. In Windsor and captain’s type chairs, for example, the structural integrity of the seat support system depends on the ability of the stretchers to hold the four legs together to form an integral unit. Failure of one of the stretcher to leg joints—which is almost always a round mortise and tenon joint—will eventually result in the collapse of the chair. Strict quality control, accordingly, is called for in the construction of these joints.

Withdrawal Strength

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Presumably, the withdrawal strength of round mortise and tenon joints can be predicted by means of equation (6-1) since a round tenon is actually nothing more than a large dowel. Test results (Eckelman et al, 2003) indicate that the withdrawal strength of close-fitting joints may be predicted by means of equation (6-1).

Obtaining a close fit between tenon and mortise becomes progressively more difficult as tenon sizes increase, however, in part because the tenons tend to become oval in shape. A "loose fit" between tenon and mortise substantially reduces withdrawal strength so that caution should be exercised to ensure that a "tight," or, at least "snug fit" exists between tenon and mortise in estimating the withdrawal strength of large diameter tenons.

Problem for Discussion

To illustrate the use of the above expression, let us calculate the withdrawal strength of a 3/4-inch diameter sugar maple round tenon embedded 7/8 inches in the side grain of a sugar maple leg.

Soln.  \( S_1 = S_2 = 1.15 \times 2,330 = 2,680 \text{ psi} \). Thus, \( F_2 = 0.834 \times (0.75) \times (0.875)^{0.89} \times (0.95 \times 2,680 + 2,680) = 2,900 \text{ lb} \).

Calculate the withdrawal strength if red alder were used.

Soln.  \( S_1 = S_2 = 1.15 \times 1,080 = 1,242 \text{ psi} \). Thus \( F_2 = 0.834 \times (0.75) \times (0.875)^{0.89} \times (0.95 \times 1,242 + 1,242) = 1,340 \text{ lb} \).

Bending Moment Resistance of Round Mortise and Tenon Joints

In determining the bending moment resistance of round mortise and tenon joints, two cases must be considered. In the first case, it is assumed that the shoulder that is formed on the end of a stretcher or spindle does not bear up against the member in which the tenon is inserted, Figure 6-17a, whereas in the second case, it is assumed that it does, Figure 6-17b. The first case represents a typical condition for stretchers and spindles, whereas the second case represents the typical condition for legs. Presumably, the shoulder on a stretcher or leg reinforces the joint so that a round tenon with a shoulder should form a stronger joint than one without. Recent test results (Eckelman et al, 2003) indicate that in the case of rectangular members, the reinforcing effect of a shoulder may be estimated by the expression

\[
F_s = 0.97 \times \frac{W}{D^{1.3}} \times F
\]

where \( F_s \) refers to the bending moment capacity of tenons with shoulders, in-lb; \( F \) to the bending moment capacity of tenons without shoulders, in-lb; \( W \) refers to the depth of the member, in; and \( D \) refers to the diameter of the tenon, in.
In practice it is difficult to ensure that the shoulders always effectively butt up against the adjoining member. Unless contact can be ensured, potential shoulder reinforcement effects should be disregarded.

To develop the full bending moment resistance of a round tenon, the tenon should be inserted to a depth which is at least equal to its diameter and greater if possible. In tests carried out by Eckelman (1970a), it was found that round tenons (3/4 inches in diameter) would develop their full calculated bending moment resistance when depth of insertion in the second member was equal to the diameter of the pin.

The bending moment resistance of round mortise and tenon joints may be calculated by means of the expression

\[ F_4 = k \times \frac{3.14 \times D^3}{32} \times S_4 \]  

(6-13)

where \( S_4 \) = the modulus of rupture of the material of which the tenon is constructed, psi; \( F_4 \) = the bending moment resistance of the joint, in-lb; \( D \) = the diameter of the tenon, in; and \( k = 1 \). As can be seen from the above expression, the bending moment resistance of the joint is directly related to the bending strength of the wood, i.e., the MOR. To a lesser extent, the strength of such joints will also depend on the closeness of the fit between the tenon and mortise. From a manufacturing point of view, this is important because round tenons tend to shrink and swell as atmospheric conditions change, and as a result, it is difficult to obtain and maintain a good fit between these parts. The amount of adhesive used and how it was applied will also affect performance. For maximum strength, adhesives should be spread liberally over the walls of the mortise and also over the surface of the round tenon end.

Recent research (Eckelman, 2003) tends to support the inclusion of the form factor of \( k = 1.18 \) in the above expression in keeping with results obtained for the bending moment resistance of round beams (Wolfe et al, 2001; Markwardt and Wilson, 1935; Newlin and Trayer, 1924). This expression may not hold for large tenons in "softer" woods, however, owing to crushing of the tenon on the compression side.

To obtain a feeling for the potential bending moment resistance of round mortise and tenon joints, let us calculate the bending moment resistance of a red oak stretcher with a tenon diameter of 3/4 inches. Let us assume that the material has a moisture content of 7 percent.

The modulus of rupture of red oak at 12 percent moisture content is 14,300 psi, Appendix 6-I. The bending moment resistance of wood increases 4 percent for each percent decrease in moisture content below 12 percent (Wood Handbook, 1972). Thus the bending moment resistance of the red oak becomes \( 14,300 \times 1.20 \) = 17,160 psi. Substituting these values into equation (6-13) gives

\[ F_4 = 3.14 \times (0.75)^3 \times (14,300) \times (1.20) / 32 = 710.7 \text{ in-lb} , \]

or, if the form factor is applied, \( F_4 = 1.18 \times 710.7 = 839 \text{ in-lb} \)

This calculation indicates that such joints have considerable strength for their size, and their potential contribution to the strength of a furniture construction should be taken into consideration and utilized.

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Furthermore, if this tenon were cut on the end of a 1-inch square member so that a shoulder were left on the tenon, which butted up against the member in which the tenon was inserted, the bending moment resistance of the round mortise and tenon joint would be estimated to be

\[ F_y = 0.97 \times \frac{1}{(0.75)^{1.5}} \times 839 = 1,252 \text{ in-lb} . \]

As can be seen, the shoulder substantially increases the bending moment resistance of the joint.

**Wedging**

The ends of legs that frame into the underside of solid wood chair seats are often wedged. Presumably, this wedging action helps to hold the leg in place. “Wedging” likely provides some pressure as the adhesive in the joint dries, but the overall value of this construction is somewhat doubtful because wedging may cause the tenon to split and thereby severely weaken it.

**Diameter Effects**

Equation (6-13) indicates that the bending moment resistance of these joints is quite sensitive to the diameter of the tenons. For this reason, the diameter of the tenon should always be left as large as possible.

As an example, (ignoring the form factor for simplicity) if the tenon on the stretcher in the previous example had been machined to 7/8 inches instead of 3/4 inches, its strength would have been

\[ 710.7 \times (\frac{7}{8})^3 / (\frac{3}{4})^3 = 1128.6 \text{ in-lb} . \]

In this case, joint strength would be increased by a factor of 1128.6/710.7, or 58.8 percent simply by increasing the diameter of the tenon by only 1/8 inch. Likewise, if the diameter of the tenon had been reduced to 1/2 inch--which is a common practice--its resistance would have been reduced to 710.7x(1/2)^3/(3/4)^3 = 210.6 in-lb; i.e., the bending moment resistance of a 1/2 inch diameter tenon is only 29.6 percent as great as that of one 3/4 inches in diameter. As these calculations indicate, it is advantageous to use the largest possible diameter tenon on the end of a member.

To further illustrate the use of the above expression, let us calculate the bending moment resistance of the round mortise and tenon joint shown in Figure 6-19. Assume that the front spindle must be able to resist the entire front to back force exerted on the arm. In order to show this graphically, the arm is shown cut between the stump and second spindles.

The ultimate bending strength of sugar maple at 12 percent moisture content is 15,800 psi. Since bending strength increases 4 percent for each percent decrease in moisture content, at 7 percent its bending strength, \( S_4 \), would be

\[ S_4(7) = 15,800 \times [1 + 0.04 \times (12 - 7)] = 18,960 \text{ psi} . \]

Substituting the appropriate values into equation (6-13) and simplifying gives

\[ F_4 = 1.18 \times 3.14 \times (0.875)^3 \times 18960 / 32 = 1,471 \text{ in-lb} . \]
Since \( F_4 = 8 \cdot F_H \), this spindle could be expected, accordingly, to withstand an ultimate front to back force, \( F_H \), applied to the arm in the magnitude of 
\[ F_H = 1.471 \div 8 = 184 \text{ lb}. \]

Had the tenon been turned to a 5/8-inch diameter, which is a common practice, the strength of the joint would have been reduced by the ratio of 
\[ \frac{(5/8)^3}{(7/8)^3}. \]
The bending moment resistance, accordingly, would have been reduced to 
\[ F_4 = 1.18 \times 3.14 \times (0.625)^3 \times 18,960 / 32 = 536 \text{ in-lb}. \]
This example demonstrates the importance of using the largest possible tenon on the end of a member rather than arbitrarily machining it to a smaller diameter.

Problems for discussion

Calculate the bending moment resistance of the tenon on the end of a chair leg constructed of red alder. Assume the diameter of the tenon is 1-1/8 inches and that the moisture content of the material is 7 percent.

\[ \text{Ans. } F_4 = 1.18 \times 3.14 \times (9/8)^3 \times (9,800) \times (1.20) / 32 = 1,940 \text{ in-lb}. \]

Rectangular Mortise and Tenon Joints

Bending Moment Resistance

Mortise-and-tenon joints have been used for centuries, and despite the increasing use of dowel joints, they are still favored for many types of construction. Numerous variations of the basic joint exist including the blind, barefaced, stub, keyed, pinned or pegged, open or slip, and haunched mortise-and-tenon.

Early versions of mortise-and-tenon joints were often constructed without adhesives. Tenons were first cut so that they fit snugly into the mortises. Drawbar pins were then run crossways through the joint which pulled the tenon tightly into the mortise and locked it in place. When properly made, this type of construction produced a strong and durable joint. The blind type of mortise-and-tenon joint, Figure 6-20, is used most commonly in furniture construction today, and adhesives necessarily must be used to develop needed strength because of the relatively small size of the tenon.

Over a period of years, a number of investigations concerning mortise-and-tenon joints have been made, and these studies have contributed to our knowledge of the factors which affect their strength. Milham (1949), for example, demonstrated that strongest joints are obtained when
a close tolerance is maintained between the tenon and mortise, and furthermore, that the shoulder has a pronounced effect on the bending moment resistance of the joint. Dupont (1963) further emphasized the importance of maintaining close tolerances when machining these joints. He also showed that optimum joint strength was obtained when glue was applied to both the tenon and sides of the mortise. He also concluded that wood moisture contents of 7 to 9 percent were most appropriate for fabricating these joints. Willard (1966, 1967) investigated joints with compressed tenons and concluded that this type of construction was no stronger than conventional methods of assembly. A comprehensive study concerning mortise-and-tenon joints was carried out by Sparkes (1968). He concluded that square-end mortise-and-tenon or round-end mortise-and-tenon joints were equally effective but that a square-end tenon fitting into a round-end mortise produced joints that were 15 percent weaker than either of the other two. He also investigated the effect of joint geometry on ultimate bending moment resistance and found that as tenon width and length were increased, the resistance of the joint improved correspondingly.

### Structural Behavior of Moment Resisting Mortise and Tenon Joints

The construction and structural behavior of mortise and tenon joints in resisting bending forces can be divided into three categories:

a) A rectangular tenon fits into a tight fitting mortise. In this case, the top and bottom of the tenon are supported by the tops and bottoms of the mortise; the sides of the tenon are bonded to the sides of the mortise; and the sides of the tenon are bonded to the walls of the mortise. Assuming the tenon is of sufficient length, this construction behaves as a mechanical joint.

The strength of this joint is limited by the bending moment resistance of the tenon itself. Thus, the strength of the joint may be calculated by calculating the bending moment resistance of the tenon. In the case of rectangular tenons, bending moment resistance may be determined by means of the expression

\[ F_4 = \frac{td^2}{6} \times S_4 \]  

(6-14)

where

- \( F_4 \) = the bending moment resistance of the tenon, lb-in;
- \( t \) = thickness of the tenon, in;
- \( d \) = the depth of the tenon, in;
- \( S_4 \) = the modulus of rupture of the material of which the tenon is constructed, psi.

This expression would apply primarily to those cases in which tenon depth equals member depth.

To illustrate the use of this expression, consider a joint in which a 3/8-inch thick tenon is cut across the full width of a sugar maple rail which measures 1 by 2 inches in cross section, Figure 6-21. Length of
the tenon is 2 inches. Assume a tight fit is maintained between tenon and mortise.

At 7 percent moisture content, the bending strength (modulus of rupture) of sugar maple is equal to 15,800 x (1.20), or, 18,960 psi. Substituting the appropriate values into equation (6-14) and solving gives

\[ F_4 = 0.375 \times (2)^2 \times (18,960)/6 = 4,740 \text{ in} - \text{lb}. \]

This value indicates the high strengths that can be obtained with tight-fitting mortise and tenon joints when tenons are of sufficient length to develop the full bending moment resistance of the tenon. Presumably, this is the strongest type of mortise and tenon joint that can be constructed.

b) A rectangular tenon fits into a mortise in which the tops and bottoms are rounded. Only the sides of the tenon contact the walls of the mortise and are bonded to it, Figure 6-22.

In this case, where the top and bottom of the mortise are rounded so that the tenon contacts the walls of the mortise only on the sides, the bending moments applied to the joint are resisted by torsional shear stresses developed in the glue line between the sides of the tenon and the walls of the mortise. Under these conditions, joint strength is proportional to the length and width of the tenon but is independent of the thickness of the tenon so long as the tenon does not fail in bending. In effect, this joint forms a double lap joint. It might also be compared to a corner mortise and tenon joint or a multiple mortise and tenon joint. Its bending moment resistance is limited by the torsional shear strength of the adhesive bond between the sides of the tenon and the side walls of the mortise. An equation cannot be given at this time for estimating the strength of this type of joint.

c) The tenon and mortise mate poorly so that the top and bottom of the mortise do not support the tenon firmly or the tenon is so short that it is able to withdraw owing to crushing of its fibers. When the tenon is quite short, Figure 6-23, the joint depends solely on the adhesive for its strength.

In this latter case, the action of the mortise and tenon joint in resisting bending forces may be understood by comparing it with a dowel joint. If the wood along the longitudinal axis of the tenon were removed, essentially two rectangular dowels would be left. Under this condition, a mor-
tise and tenon joint might be expected to behave similar to a dowel joint, Figure 6-24, up to the point that the adhesive fails. Furthermore, since the material along the longitudinal axis of the tenon (that is, along the neutral axis) is only lightly stressed, a mortise and tenon joint would not be expected to be a great deal stronger than a comparable dowel joint. This analogy would be expected to hold, for example, for a concealed joint in which the tenon fits closely in the mortise on all sides. Presumably, estimates of the strength of such a joint could be obtained by replacing the tenon with two “equivalent” dowels. Utilizing this concept, Hill and Eckelman (1973), developed the following equation for estimating the bending moment resistance of mortise and tenon joints constructed with 3/8-inch thick tenons

\[ F_4 = 0.7 \times (0.57T_w + 0.24R_w) \times S_3 \times B \times C \times D \]  

(6-15a)

where \( T_w \) refers to tenon width and \( R_w \) refers to rail width; \( B \) is a tenon length factor; \( C \) is an adhesive factor; \( D \) is a tenon fit factor, all in Table 6-6; and \( S_3 \) is the shear strength parallel to the grain of the material of which the joint is constructed, Appendix 6-1. This expression may be simplified to read

\[ F_4 = 0.7 \cdot S_3 \times A \times B \times C \times D \]  

(6-15b)

where \( A \) is a tenon-rail dimension factor, Table 6-5.

As these expressions show, joint strength is highly dependent on the width (as opposed to thickness) of the tenon. Furthermore, strength is nearly proportional to tenon length up to about an inch and then decreases to a ratio of about 0.55. Since significant amounts of material are removed from structural members in cutting mortises, it is better, to use a tenon that is thin but with a width as great as possible, Figure 6-21, than to use a thicker tenon with less width.

To illustrate the use of this expression, let us find the estimated bending moment resistance of a joint constructed with a black walnut rail which measures one-inch thick by 2 1/2 inches wide, Figure 6-25. Assume the tenon has a thickness of 3/8 inches, a width of 2 inches, and a length of 1 inch. Moisture content of the wood is 7 percent. The joint is joined together with a high solids content PVA adhesive, and the tenon/mortise clearance is less than 0.002 inches.

The shear strength parallel to the grain of black walnut at 7 percent moisture content is 1,825 x (1.15) psi. Substituting this along with the other appropriate values into the above equation gives

\[ F_4 = 0.7 \times (1,825) \times (1.15) \times (1.74) \times (1.0) \times (1.32) \times (1.0) = 3,374.3 \text{ in lb}. \]
To further illustrate the use of this expression, let us find the predicted bending moment resistance of a mortise-and-tenon joint constructed of American beech, Figure 6-26. Let us assume that the width of the rail is 3 inches, tenon width is 2-1/4 inches, and tenon length and thickness are 2 inches and 3/8 inches, respectively. Let us further assume that the moisture content of the joint is 7 percent, that a urea-formaldehyde resin is used to assemble the joint, and that the tenon clearance is 0.003 inches.

**Soln.** The shear strength of American beech at 12 percent moisture content is 2,010 so that its shear strength at 7 percent is

\[ S_{7}(7\%) = 2,010 \times [1 + 0.03 \times (12 - 7)] = 2,312 \text{ psi} \]

Substituting the appropriate values into equation (6-15b) gives

\[ F_4 = 0.7 \times 2,312 \times 2.003 \times 1.66 \times 1.24 \times 0.94 = 6,263 \text{ in} - \text{lb} \]

Another application of the predictive expression can be illustrated by considering the table support frame shown in Figure 6-27a. Let us assume that a mortise-and-tenon joint will be used to connect the top rail and leg. We will further assume that the top rail and leg will be constructed of 3-inch wide by 1-inch thick sugar maple which has a moisture content of 7 percent, that PVA glue (65 percent solids) will be used, and that the tenon-mortise clearance is 0.006-inch. Each top-rail to leg joint of the frame is to be designed to withstand the external forces illustrated in Figure 6-27a. Therefore, each joint must resist an external bending moment of

\[ F_4 = 100 \times 300 = 3,000 \text{ in} - \text{lb} \]

as shown in Figure 6-27b. Let us now assume that a 0.75-inch tenon length will be used for this joint, Figure 6-27c. We must then determine what tenon width could be used to provide the required strength.

**Ans.** The shear strength of sugar maple at 12 percent moisture content is 2,330 psi so that its shear strength at 7 percent is

\[ S_{7} = 2,330[1 + .03x(12-7)] = 2,680 \text{ psi} \]

Substituting the appropriate values into equation 6-15 we obtain

\[ F_4 = 3,000 = 0.7 \times 2,680 \times A \times 0.8 \times 1.32 \times 0.89 \]

Solving for \( A \) gives, \( A = 1.70 \). By consulting Table 6-5 we find that a tenon width of 1.75-inch is required.

We could also have assumed that tenon width was fixed at 1.5 inches, Figure 6-27d, and find what tenon length is required. Substituting into the expression we now find

\[ F_4 = 3,000 = 0.7 \times 2,680 \times 1.575 \times B \times 1.32 \times 0.89 \]
or, $B = 0.864$. Consulting Table 6-6, we find that a tenon length of 7/8-inch could be used. It should be noted that the preceding calculations are based on the ultimate strength of the joint and no factor of safety is considered. If, for example, a safety factor of 2 were desired, then the tenon length factor would have been 1.728 and a tenon length of greater than two inches would be required for a 1-1/2-inch tenon width. A better solution in this case might be to use a 2-inch wide tenon. Under these conditions

$$F_4 = 2 \times 3,000 = 0.7 \times 2,680 \times 1.575 \times B \times 1.32 \times 0.89$$

or, $B = 1.464$, so that the required tenon length is 1-7/8-inch.

Figure 6-27. Table support frame subjected to two 200 pound external forces. The floor reaction forces are equally distributed to the four legs.

Table 6-5. A-factors to be used in equation (6-15). These factors are calculated values of $(.57Tw + .24Rw)$ where “Tw” refers to tenon width and “Rw” to rail width.

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Problems

©C.A. Eckelman/Purdue University 6-33
The top rail of a bed has a width of 3 inches where it joins the bedpost, Figure 6-28. Width of the tenon is 2 1/2 inches; thickness of the tenon is 3/8 inches, and length is 1 inch. Rail and post, which are constructed of white pine, have a moisture content of 7 percent. A high solids content PVA is used in construction of the joint; tenon/mortise clearance is between 0.003 and 0.005 inches. What is the bending moment resistance of the joint?

\[ F_4 = 0.7x(900)x(1.15)x(2.145)x(1.0)x(1.32)x(0.94) = 1,928.3 \text{ lb-in.} \]

Pinned Mortise and Tenon Joints

Pinned mortise and tenon joints are also used in several types of furniture construction. In some cases, a single pin is used which passes through the exposed end of the tenon. In other cases, two smaller pins pass through the hidden tenon along with the member in which the mortise is cut. This type of construction has been used for connecting aprons to legs in tables, for example. Systematic scientific studies have not been carried out to determine the strength of this latter type of construction, but it may be predicted that the strength of the joint can be determined by assuming that the top cross pin carries all of the tensile force acting on the joint while the resisting compression force vector acts at a point midway between the longitudinal axis of the lower cross pin and the lower edge of the rail in which the tenon is cut, Figure 6-29. This relationship may be expressed in the form

\[ F_4 = 2 \times a \times t \times \left[ j + \frac{(Rw - j)}{4} \right] \quad (6-16) \]

where

- \( F_4 \) = the bending moment resistance of the joint, lb-in;
- \( t \) = the thickness of the tenon, in;
- \( a \) = the distance from the longitudinal axis of the pin hole to the front edge of the tenon.
- \( j \) = the distance between the longitudinal axis of the pin holes, in;
- \( Rw \) = the width of the rail in which the tenon is cut.

To illustrate the use of the above expression, consider the following problem. Let us say that a 4-inch wide rail frames into a post, Figure 6-30. The tenon measures 3/8 inches thick by 3 inches deep, and it is pinned into the post by means of two 1/4-inch diameter pins.
pins which are spaced 2-1/4 inches apart. The tenon is 1 inch long; the pin holes are located 1/2 inch on center from the front edge of the tenon. The rail and post are constructed of white pine with a moisture content of 7 percent; the pins are constructed of sugar maple.

The shear strength parallel to the grain of white pine at 7 percent moisture content is 900 (1.15) psi, Appendix 6-1. Substituting this along with the other appropriate values into the above equation gives

\[ F_4 = 2 \times \left( \frac{1}{8} \times \frac{1}{2} \right) \times (900 \times 1.15) \times \left[ 2.25 + \frac{(4 - 2.25)}{4} \right] = 1,043 \text{ in-lb}. \]

As can be seen from the above result, the shear area together with the shear strength of the wood of which the tenon is constructed are the principal factors limiting joint strength. For example, the strength of the joint, according to the above equation, could have been increased 50 percent simply by relocating the cross pins 3/4 inches back from the front edge of the tenon instead of 1/2 inch. To do so, however, might cause the pins to split out of the edge of the post. A better solution might be to increase the length of the tenon by one quarter inch so that the same hole to edge distance in the post could be maintained.

**Multiple Mortise and Tenon Joints**

Multiple mortise and tenon joints, **Figure 6-31** may be used in exposed frames, particularly for front and rear post to arm joints in chairs. These joints develop high strength when well made. Again, a good fit of the parts and adequate gluing are essential. Principal problem with this joint is that the fingers tend to “grab” one another as the joint is being assembled.

A simple multiple mortise-and-tenon joint is shown in **Figure 6-32**. In effect, this type of joint is similar in appearance and action to a lock-corner box joint. In this type of construction, one-half of the material is removed from each of two members framing together so that the joint would not be expected to develop more than 50 percent of the strength of the members framing into it. The ratio of tenon length to tenon thickness is of critical importance in this type of joint. Richards (1962) indicates that a ratio of at least 7 to 1 is needed to develop full strength, but he also points out that joints made in sweetgum with a ratio of only 3 to 1 developed nearly 50 percent of the strength of the members.

**Finger Joints**

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A finger joint is essentially a multiple mortise-and-tenon joint, Figure 6-33, in which the fingers are tapered rather than straight. The ends of the tenons, or, fingers as they are called, may be pointed or they may be blunted. Although finger joints are regularly used in the furniture industry to fabricate curved members from woods that cannot be readily steam-bent, finger jointing has not, for the most part, been used extensively in furniture construction.

In particular, it has not been used to produce long straight structural material from short pieces as has been done in the building construction industries. Furthermore, this type of joint has not been extensively investigated as a potential furniture joint except by one researcher (Richards, 1962) so that there is little information available which can be used in designing finger joints for furniture. The information that is available, however, indicates that this is one of the strongest and most efficient methods that can be used to join wood together and certainly deserves a great deal more consideration for high strength furniture joints.

90 Degree Finger Joints

Research strength tests carried out by Richards (1962) on 90 degree corner joints fabricated with fingers which had 0.016 inch thick tips, a 1 to 8 slope, and a length of 0.984 inch indicated that these joints could be expected to develop at least 50 percent of the strength of the wood itself.

On the basis of the tests carried out by Richards (1962), it seems reasonable to assume, at least for now, that well-made multiple mortise-and-tenon joints as well as tapered finger type joints can develop 50 percent of the strength of the members framing into the joint. It should be pointed out as a word of caution, however, that the joints used in these tests were of high quality so that the values reported are likely to be the highest that can be obtained rather than an average for finger joints in general. In particular, it is questionable whether or not other finger jointing methods such as micro-finger jointing techniques can produce joints equal in strength to those produced by Richards. Such questions obviously must remain unanswered until tests are carried out to resolve the issue.

Straight Finger Joints

In contrast to the very limited use of finger jointing for corner joints, finger jointing has been widely used for joining flat stock, particularly in the building construction industries. Finger joints have been widely used, for example, to fabricate the long members that are needed in large laminated beams. They have also been used to fabricate the clear wood members that are needed in millwork. Their use in the furniture industry, however, has been largely limited to construction of curved members as was previously stated.
Numerous variations in the design of the fingers are possible. Some are long and pointed whereas others are blunt, Figure 6-34a, and Figure 6-34b. In some cases, rather short fingers are used. Usually, the fingers are machined into the ends of the members, but in some cases they are molded by pressing the end of the member against a hot die (Strickler, 1967). This process is referred to as impression finger jointing. A combination of both methods has also been used.

The bending moment resistances reported for this type of joint vary considerably depending upon the shape of the fingers and other joint parameters. Test values usually range from a low of about 50 percent to a high of about 90 percent of the strength of the wood. In tests carried out on actual furniture parts, the author obtained bending moment resistance values that averaged 50 percent of the strength of the wood. There are obviously many factors that can affect this type of joint as it is used in furniture construction, and until more research has been carried out to evaluate the various parameters which affect its strength and the strength values of joints produced on a production line basis, these joints should be conservatively designed. Since tests conducted on actual furniture parts gave results that averaged about 50 percent of the strength of the wood, however, it seems reasonable to accept this value as the upper strength bound, at least for the present time, that can be expected from this type of joint.

Example: To illustrate the use of a finger type corner joint in furniture construction, let us consider the design of the table side frame shown in Figure 6-35 in which the legs are connected to the front apron of the table by means of finger joints. If the depth, \( d \), of the leg and apron at this point where the two are joined together is 2 inches, what must be their thickness, \( w \), if each leg is to be able to resist a 100 pound side thrust which is applied as shown?

Solving for the bending moment on the joint gives

\[
F_4 = 100 \text{ lb} \times 30 \text{ in} = 3,000 \text{ in} \cdot \text{lb}.
\]

The stress developed in the joint material is given by the expression

\[
S_4 = \frac{6 \times F_4}{w \times d^2} \text{ psi}
\]

Referring to Appendix 6-1, we see that the ultimate bending strength of sugar maple at 12 percent mc is 15,800 psi. Taking half this value gives 7,900 psi. Substituting the appropriate values into the stress equation given above and solving for \( w \) gives

\[
w = 6 \times 3000/(7900 \times 4) = 0.57 \text{ in}.
\]

This result indicates that a thickness of 0.57 inch is sufficient. There is no factor of safety included in these calculations, however. If we fol-
low the convention of taking allowable strength values as equal to 1/3 the ultimate values given in Appendix 6-1 then this value should be multiplied by a factor of 3, i.e., the thickness should be increased to 1.71 inches, or, about 1-3/4 inches.

Additional Research
Findings on 90 Degree Mortise, Multiple Mortise, and Finger Joints

Biniek and Maciejewski (1981) investigated the bending moment resistance of finger joints and mortise and tenon joints constructed of pine. The joints were constructed with fingers which measured 7.5 mm (0.295 in.) long with a tip thickness of 0.2 mm (0.079); spacing between fingers was 2.05 mm. The members in which the fingers were cut measured 2.05 mm.

They found that miter joints constructed with fingers produced strong joints when the fingers were cut along the length of the miters, Figure 6-36. It was also found that such joints are much stronger when loaded in compression than in tension. As expected, joints constructed with the teeth cut across the miter, Figure 6-37, gave poor results.

Butt joints constructed with fingers, Figure 6-38 gave much lower strength values than did miter joints. This occurs because the member in which the teeth are cut into the side grain tends to split along the grain owing to failure of the wood in tension perpendicular to the grain. This same phenomena is observed in both dowel joints and mortise and tenon joints in which the dowels or tenons do not penetrate deeply into the side grain of the one member.

Mortise and tenon joints consisting of one tenon were also constructed for comparison, Figure 6-39. These joints gave nearly identical strengths in both tension and compression, Figure 6-40. Strength values for these joints were less than for finger joints along the miter in compression but greater than for the finger joints in tension.

The members used in the tests measured 1.57 inches square. Bending strength of the pine wood of which the joints were constructed was not given, but if it is assumed that it had a modulus of rupture of 10,000 psi,
then the stresses developed in the joints expressed as percentages of the bending strength of the wood are as given in Table 6-7.

In tests in which the joints were loaded in tension (joints tend to open under load) so that the ends of the side grain members cannot split, Rabiej (1979) obtained essentially the same strength values for both one/two-tenon and finger joints in butt joints. The fingers in these joints had a length of 35 mm, Figure 6-41.

By way of comparison, tests with two/three-tenon joints, Figure 6-42, showed that the use of two tenons instead of one in joints of identical size increases joint strength about 42 percent. It is interesting to note here that the gluing surface is doubled.

In comparing the types of joints constructed by Biniek and Maciejewski (1981) with those of Rabiej (1979), it again seems evident that longer fingers should be used when butt joints are constructed in order to prevent splitting of the side grain member.

### Table 6-7. Bending stresses developed in joints expressed as a percentage of bending strength of the wood. Biniek and Maciejewski (1981)

<table>
<thead>
<tr>
<th>Type of Joint</th>
<th>Bending moment resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compression (%)</td>
</tr>
<tr>
<td>Miter Finger</td>
<td>59.7</td>
</tr>
<tr>
<td>Butt Type Finger</td>
<td>11.0</td>
</tr>
<tr>
<td>Mortise and Tenon</td>
<td>22.3</td>
</tr>
</tbody>
</table>

![Figure 6-38](image1.png)

![Figure 6-39](image2.png)
Figure 6-40.

Figure 6-41.

Figure 6-42.