Design and testing of wall cabinet frames constructed with round mortise-and-tenon joints

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Abstract

This study investigated the design, construction, testing, and performance characteristics of wall cabinets constructed with round mortise-and-tenon joints that are suitable for use in classrooms, school libraries, and homes. Four wall cabinets, utilizing round mortise-and-tenon joints, were constructed to evaluate their performance. Tests indicated that the attachment of back plywood panels to the frames increased overall cabinet stiffness by 62 and 70 percent for red oak and yellow-poplar wall cabinets, respectively. Also, wood species was found to affect creep deflection. Overall, this study clearly demonstrated that wall cabinets constructed with round mortise-and-tenon joints were able to withstand normal service loads without loss of structural integrity or function.

In those underdeveloped and developing countries of the world with limited resources, severe shortages of school and library furniture exist along with shortages of domestic and other institutional furniture. In the case of schools, expenditures for furniture represents a large percentage of most governments' educational budgets, yet much of this furniture tends to be of low quality and of poor structural design, with accompanying high maintenance costs and short service lives. Thus, there is a pressing need for simple, durable furniture that can be produced from local resources using low-technology techniques that are appropriate for cottage as well as conventional industries.

In this paper, the design and testing of wall cabinets suitable for school or home use in developing countries are discussed—specifically, wall cabinets that could be produced using high-quality materials from locally available small-diameter tree species and relatively inexpensive panel materials. A specific objective of this research was to assess the ability of wall cabinet frames and panel-on-frame cabinets based on these frames to carry loads that might be anticipated in service. A second objective was to determine the behavior of panel-on-frame cabinets constructed with these frames and thin plywood panels. A final objective was to observe the creep characteristics of both the frames and the cabinet constructions.

Design and construction

The cabinets are designed in such a way that low-investment production technology can be used in their con-

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Construction. This design allows locally available small diameter wood species, wood residues, or semiprocessed woody materials to be used in construction of the cabinets.

All of the material used in the tests came from ungraded yellow-poplar (Liriodendron tulipifera) and red oak (Quercus rubra) lumber cut from locally grown trees by means of a portable band mill. Once cut, the lumber was air dried. It was then brought indoors, where it obtained a nominal MC of 7 percent.

The complete frames measured 30.5 inches (77.5 cm) high by 48 (121.5 cm) inches wide by 16 inches (40.6 cm) deep, Figure 1. All of the rails, except for the center cross rail and the door frame rails, were framed into the sides of the corner posts. The corner posts were cut to a length of 30.5 (77.5 cm) inches so that the minimum wall thickness of the mortises at the top and bottom of the posts was 0.438 inches (11.1 mm). The front frames and back were constructed with top and bottom rails, center stile, and end posts that measured 1.5 inches (38.1 mm) square. The side frames were constructed with top, bottom, and center side rails that measured 0.75 inches (19.1 mm) thick by 1.5 inches (19.1 mm) in depth. Center side rails along with a mid-frame center rail were included to provide support for an optional removable solid shelf.

The tenons on the ends of the rails were cut off-center in order to avoid interference between the tenons on the side rails with those of the front and back rails. By cutting the tenons off-center, the top surfaces of the side rails could be made flush with the front and back rails (Fig. 1).

The top and bottom shelves of the cabinets were constructed of 0.188-inch (4.8 mm) thick plywood with the face grain of the plywood aligned in the front to back direction of the shelves. The center shelf was constructed of 0.375-inch (9.5 mm) plywood with the face grain aligned parallel with the front of the cabinet.

Tenons, 0.6 inches (15.2 mm) in diameter by 1.5 inches (38.1 mm) long, were cut on the ends of the rails. Mortises were drilled in the posts with a 19/32-inch (15 mm) drill bit so that a tight shrink-fit could be obtained when the tenons were inserted in the holes. Side and back panels were 0.188 inch (4.8 mm) thick. Each side panel measured 13.5 inches (34.3 cm) wide by 30 inches (76.2 cm) long, whereas the back panel measured 45.5 inches (115.6 cm) wide and 30 inches (76.2 cm) long.

The walls of the mortises for the side frame tenons were thoroughly coated with PVA adhesive before the tenons were inserted. Bar or pipe clamps were used to pull the frames together until the desired dimensions were obtained. After the frame was assembled, the top and bottom shelf panels were placed on top of the rails and were secured to the rails with small brads.

The door frame stiles and rails measured 1 inch (25.4 mm) by 1.5 inches (38.1 mm) in cross section. In this construction, tenons were cut on the ends of the two door stiles (located adjacent to the front posts of the cabinet). Slightly larger matching holes, 0.625 inches (15.9 mm) in diameter, were drilled in the top and the bottom rails of the frame. When inserted into these holes, the tenons on the ends of the door stiles formed hinges for the cabinet doors. The stiles of the door frame measured 26.75 inches (67.9 cm) long, which allowed a clearance of 0.125 inch (3.2 mm) above and below the door rails. A similar clearance was allowed between the door stiles and frame posts. Washers, which served as both thrust bearings and spacers, were slipped over the ends of the door-stile tenons before the tenons were inserted into the mortises in the top and bottom front face rails. Tenons on the ends of the door rails were 0.5 inches (12.7 mm) in diameter.

Frame analyses

Finite element analyses were conducted on the frames in order to obtain estimates of critical bending moments and deflections (Tankut, 2001). The magnitude of the shelf loads was estimated by calculating the approximate weight of the expected contents of the cabinets. In the case of schools, books would be expected to be the heaviest items stored in the cabinets. A line load of 3 pound/in (5.4 N/cm) for books of mixed size is reasonable for most bookshelves. By way of comparison (ALA 1990, 1998), the proof load for 9- by 36-inch (22.9- by 91.4-cm) metal library shelving is about 4 pound/in (7.1 N/cm). For purposes of analysis, a line load of 4 pound/in (7.1 N/cm) was chosen.

Analyses of the side frames indicate that when the side frames are constructed with only one intermediate rail, in this case a center end-rail, the bending moment carried by the ends of the center end-rail is somewhat greater than that carried by the top and bottom end-rails. This is significant because it reduces the bending moment on the critical top and bottom end-rail to post joints. Use of two rather than one intermediate rails will also reduce the bending moments acting on these joints by some 30 percent. Finally, use of 0.75-inch (19.1 mm) rather than 0.6-inch (15.2 mm) diameter tenons on the ends of the center end-rail would also reduce bending moments on the top and bottom joints by more than 30 percent. As previously stated, these options are important because of the limited wall thickness of the mortises of the top and bottom post joints.
Analysis of side frame

For a line load of 4 pound/in (7.1 N/cm) applied along the centerline of a shelf, it can be assumed that 48 pounds (213.4 N) are transferred to each of the four corner posts by each shelf for a total of 144 pounds (640.1 N) for three shelves. Assuming that the joints behave as if they were semirigid (Lothers, 1960) with semirigid connection factors of $\pi = 1.5 \times 10^{-5}$ radians/in-lb (1.3 $\times$ 10$^{-4}$ radians/N-m), where $\pi$ is the angle change at a joint due to yield in a semirigid connection divided by the bending moment acting on the joint, the maximum bending moment (which acts on the center rail to rear post joint) amounts to 461 in-lb (4,079.9 N-m). The corresponding deflection of the bottom of the front post amounts to 0.142 inches (3.6 mm). The tenons measure 0.6 inches (15.2 mm) in diameter, so the corresponding estimated flexural stress, $s_d$, developed in the tenons (independent of shoulder effects) would be

$$s_d = \frac{32 \times f_i}{1.18 \times \pi \times D^3} = \frac{32 \times 461}{1.18 \times \pi \times (0.6)^3} = 18,415 \text{ psi} (1.27 \times 10^6 \text{ Pa}),$$

where 1.18 is a form factor for round beams, and $f_i$ is the bending moment acting on the joint. When shoulder effects (Eckelmann et al. 2004) are taken into account, however, this value is reduced to

$$s_d = \frac{0.6}{1.08 \times 0.75} \times 18,415 = 13,640 \text{ psi} (9.4 \times 10^6 \text{ Pa}).$$

This result indicates that a line load of 4 pound/in (7.1 N/cm) is likely a near maximum load for this construction when using yellow-poplar.

Analysis of front frame

Analyses of the front frame indicate that for a 4 pound/in (7.1 N/cm) line load acting along the centerlines of a thin plywood top, a center shelf, and a bottom shelf of a frame that is attached to a wall, the bending moments acting on the ends of the top and bottom rails could approach 338 in-lb (2,991.3 N-m) for a semirigid rail to post joint condition of $\pi = 1.5 \times 10^{-5}$ radians/in-lb (1.3 $\times$ 10$^{-4}$ radians/N-m). The corresponding deflection of the bottom rail at midspan would amount to about 0.108 inches (2.7 mm). Hence, for a total door frame clearance of 0.25 inches (6.4 mm), this design would allow the doors to open and close freely. Considering the mode of deflection, however, it seems reasonable that a clearance of 0.188 inch (4.8 mm) be provided above the door and 0.063 inch (1.6 mm) below.

Method of test

The test consisted of determining the short- and long-term deflection characteristics of wall cabinet frames and panel-on-frame wall cabinets that use round mortise-and-tenon joints in their construction. Thus, one bare cabinet frame constructed with yellow-poplar members and an identical frame fitted with 0.188-inch (4.8 mm) thick plywood panels were tested. Likewise, one bare frame constructed with red oak members and an identical frame fitted with 0.188-inch (4.8 mm) thick plywood panels were tested. These tests were conducted both to evaluate the deflection characteristics of the frames themselves and to determine the effect of the plywood panels on overall construction stiffness and creep deflection.

In testing the cabinets, two 2- by 4-inch nominal (5.1-by 10.2-cm) studs were mounted vertically on a wall; the back posts of the cabinet frames were then secured to the studs with four screws—two in each rear post at the third points. The cabinets were checked to see that they were square and level and fit against the studs with no gaps.

As discussed above, a line load of 3 to 4 pound/in (5.4 to 7.1 N/cm) appears appropriate for bookshelves. It is worthwhile, however, to consider other possible loads that might be stored in the cabinets such as dishes. To obtain an estimate of the load imposed by large dishes, a stack of dishes 11 inches (27.9 cm) in diameter by 12 inches (30.5 cm) high was weighed. The weight of dishes was about 20 pounds (8.7 kg). Assuming that 4 stacks of dishes could be stored in the cabinet, these dishes would produce an equivalent line load of 80/48 (348.2 N/122 cm), or, 1.67 pound/in (2.9 N/cm). Thus, even if the dishes were stacked 24 high, they would produce a line load of only 3.33 pound/in (6.0 N/cm). This result tended to indicate that a line load of 3 to 4 pound/in (5.4 to 7.1 N/cm) would be appropriate for cabinets used in schools or in homes.

Concrete bricks were used to load the frames and cabinets. The bricks averaged 5 pounds (2.2 kg) in weight and measured approximately 2.25 inches (5.7 cm) in thickness by 3.5 inches (8.9 cm) in width by 7.5 inches (19.1 cm) in length. Thirty-six bricks were stacked 3 high at 12 locations along the lengths of each shelf for a total load of 180 pounds (81.6 kg) per shelf, or, 3.75 pound/in (6.7 N/cm) of shelf. This appeared to be a reasonable loading based on the preceding discussion. The top, bottom, and midshelf of the cabinets were loaded as described so that the total load applied to the cabinet was 540 pound (244.9 kg). Deflections were measured at the bottom front corners of each cabinet frame, Figure 1, by means of dial gages with 0.001-inch (0.025 mm) sensitivity. Readings were taken immediately after loading and were continued over a 28-day period. The gages were not removed during testing but were left in place throughout each test.

Results and discussion

There were no joint or member failures during the course of the test, which indicates that the joints and members have sufficient strength to resist substantial service loads. Furthermore, the doors of both the bare frames and of the cabinets could be opened and closed freely during the course of the test. The initial deflection of the bottoms of the front posts amounted to 0.172 inches (4.4 mm) and 0.151 inches (3.8 mm) for the yellow-poplar and red oak frames, respectively. Corresponding deflections after 28 days amounted to 0.243 and 0.206 inches (6.2 and 5.2 mm). Thus, the frames themselves are sufficiently stiff to be used alone, i.e., without plywood panels, and could be covered with screen or perhaps burlap and used for food storage should that be desirable.

Comparable deflections of the panel-on-frame wall cabinets are also presented in Table 1. The paneled red oak cabinet deflected only 62 percent as much as its bare frame counterpart, whereas the yellow-poplar cabinet deflected 70 percent as much. These results indicate that the panels were only partially effective in reinforcing the frame. Lower deflection ratios would be expected if the edges of the panels were more effectively attached to the frame members because the panels are very rigid in their own plane and act as shear walls that
transmit the resisting forces from the frame to the panel. For this action to occur, the panels must be securely attached to the frame.

Also, results of the study indicated that the wall cabinet constructed with red oak was 9 percent stiffer than the one built with yellow-poplar. Overall, wood species and, therefore, wood properties, as expected, have a significant effect on the stiffness of the wall cabinets.

Creep deflection of wall cabinets

No failures occurred during the 28-day creep tests of the wall cabinets. Table 1 summarizes the initial, final, and creep deflection (final minus initial deflection). As seen from this table, the initial deflections of the panel-on-frame cabinets were less than those of the corresponding bare frames. Similarly, the creep of the cabinets was less than those of the frames, and, strikingly, the creep of the cabinets expressed as a percentage of initial deflection was much less than that of the frames. Creep deflection of the bare frames alone was equal to 36 and 41 percent of the elastic deflection for the red oak and yellow-poplar frames, respectively. However, creep deflection of the panel-on-frame cabinets was only 7.5 and 9 percent of the elastic deflection of the red oak and yellow-poplar cabinets, respectively.

Creep deflection of the frames and cabinets are presented graphically in Figures 2 and 3. In the case of panel-on-frame wall cabinets, as shown in Figure 2, creep had essentially ceased after the third day. In the case of the bare frames, however, substantial creep occurred until about the 21st day, Figure 3. This action can be explained by the panel effect. In the panel-on-frame construction, the frame deflected until the reinforcing action of the panels came into effect. Since panels have great stiffness in their own plane, a constant rate of creep deflection was reached quickly, and a lower creep deflection was observed.

Conclusions

Results of the study indicate that high-quality wall cabinet frames can be constructed with round mortise-and-tenon joints using only simple construction techniques.

The wall cabinets were tested with and without panels in order to define the panel contribution to overall cabinet stiffness. Results of the study showed that panels increased overall panel-on-frame wall cabinet stiffness. Attachment of the panel to the carcass frame is a critical factor since the glue line or the fasteners between the panel and frame transmit the resisting forces from frame to panel. Overall, wood species and, therefore, wood properties have significant effect on stiffness as well as creep deflection characteristics of the panel on frame wall cabinets. Also, yellow-poplar cabinets tended to creep more than the red oak cabinets.

Because the stiffness of the panel in its own plane is much greater than the frame itself, a constant rate of creep deflection was reached quickly, and a lower creep deflection was observed on panel-on-frame wall cabinets. Therefore, the panels have a considerable effect on both elastic and creep deflection of panel-on-frame wall cabinets.

Literature cited


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