Design and testing of bookcase frames constructed with round mortise and tenon joints

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Abstract

Previous work has shown that by using round mortise and tenon joints, durable maintenance-free school chairs and desks can be produced from largely waste local woody materials by cottage industries in remote regions of the world. Results of this previous work would suggest that by using this same method of construction, well-designed, durable, functional bookcases also could be produced from locally available small-diameter tree species and thin plywood or other thin panel materials. A number of panel and frame bookcases utilizing round mortise and tenon joints were constructed to evaluate their performance. Tests conducted on the resulting bookcase frames and shelves indicated that shelves constructed of thin plywood supported by small front and back shelf rails with ends joined to the corner posts with round mortise and tenon joints easily met critical shelf deflection criteria. The excellent deflection characteristics of the shelves were credited to the high degree of end fixity of the shelf rails that was obtained through the use of snug fitting round mortise and tenon joints.

In the underdeveloped and developing countries of the world, school furniture represents a large percentage of limited educational budgets. Yet much of the furniture tends to be of low quality and poorly designed structurally so that it has a short service life. Recyclable and renewable resources exist in those countries, however, that can be used in the production of affordable low-cost furniture. Specifically, in the case of bookcases, well-designed, durable, functional furniture can be produced from locally available small-diameter tree species and thin plywood or other thin panel materials. Such furniture can be used in libraries, governmental offices, and in homes, in addition to schools.

Studies in related areas (Haviarova et al. 2001a,b) indicated that round mortise and tenon joints may be used to construct strong durable school chairs and desk frames from small-diameter timber. Further, these studies showed that high quality round tenons can be machined with simple jigs and low-cost equipment. Complementary research (Eckelman et al. 2001) has shown that round mortise and tenon joints are efficient load carriers in bending and highly resistant to cyclic loading.

Round mortise and tenon joint construction provides the means for producing strong durable bookcase frames from locally available wood, wood residues, or semi-processed woody materials. In this paper, the design and testing of bookcases suitable for school or library use in developing countries are discussed. The specific objectives of this paper were to determine the performance of the bookcases constructed with round mortise and tenon joints and thin panel materials and to evaluate the performance of the constructions.

Construction

The general configurations of the bookcases used in the study are shown

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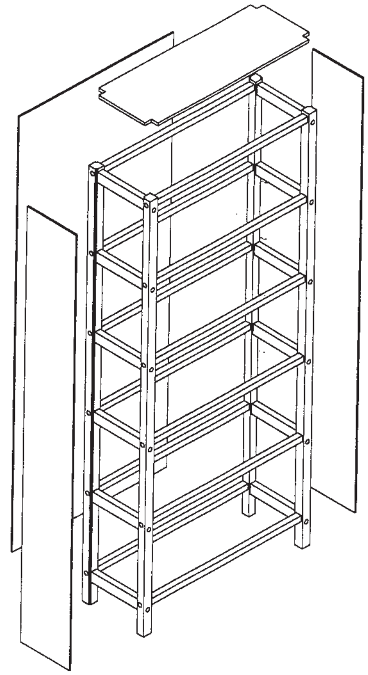

Figure 1. — Three-dimensional configuration of bookcase construction in which the panels fit into the rabbets cut into the posts.

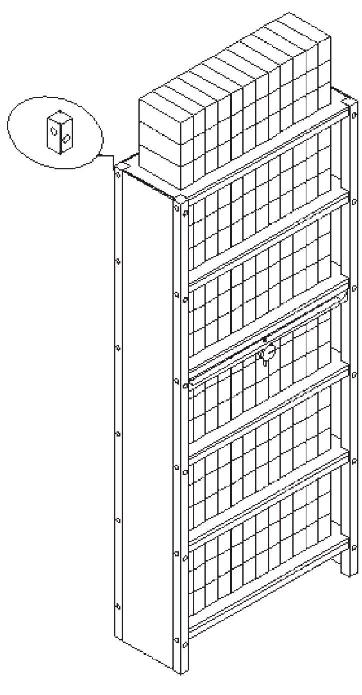

Figure 2. — Three-dimensional configuration of bookcase construction in which the panels fit into the grooves cut into the posts.

in **Figures 1** and **2**. Overall, the cases measured 73-1/2 inches high, 32 inches wide, and 12 inches deep. All of the posts measured 1-1/2 by 1-1/2 inches in cross section. The side rails measured 7/8 by 1-1/2 inches in cross section, whereas the front and the back rails measured 7/8 inch wide by 1 inch deep. The side rails were wider than the front and back rails so that off-center tenons could be cut on their ends. The shelves were constructed of 3/16-inch-thick plywood with the face grain of the plywood aligned in the front to back direction.

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 moisture content of 7 percent.

Construction of the bookshelves began with machining the parts to the proper lengths and cross sections. Tenons were then cut on the ends of the rails. All tenons were cut with a 7/8-inch hole saw and measured 0.720 inches in diameter by 1-1/2 inches long. The tenons on the ends of the side rails were cut off-center in order to avoid interference with the tenons on the ends of the front and back rails. Note that the tenons on the ends of the front and back rails also were cut slightly off-center so that the top surfaces of the side rails and the top surfaces of the front and back rails were identical.

A 23/32-inch drill bit was used to bore round mortises in the posts. The drill used was of such a size that a tight shrink-fit could be obtained when the tenons were inserted in the holes. The rails were dried in an oven (180°F) for 6 hours until the tenons on their ends shrank just enough to fit into the corresponding holes. It was found that some care was needed in drying since too rapid drying at high temperatures caused some tenons to check.

The end frames of the cases were assembled first. The walls of the holes in two end posts were thoroughly coated with adhesive and the side rail tenons inserted. Bar or pipe clamps were used to pull the assembly together until the desired dimensions were obtained. The other end frame was assembled in the same manner. A commercial aliphatic adhesive was used in the construction of all the frames.

Next, the walls of the mortises for the front and back rail tenons were thoroughly coated with adhesive and the tenons inserted. Bar or pipe clamps were again used to pull the frames together until the desired dimensions were obtained. In this stage of assembly, the frame was checked to ensure that it was square. Also, care was taken to ensure that the rails were properly aligned when their tenons were inserted in the mortises in the posts.

After the frame was assembled, the shelves were placed on top of the rails and secured to the rails at each end with brads. All of the sharp edges on the frame were lightly sanded; excessive dried glue on the various parts was removed by light sanding.

The sides and back of the frame were covered with 3/16-inch-thick plywood. One bookcase with red oak posts and rails and one with yellow-poplar posts and rails were constructed as shown in **Figure 1**. Rabbets were cut into the sides of the posts to receive the back and side panels. A back panel was fitted into the rabbets cut into the side of the back post and attached with small nails to the posts. The side panels were attached in a similar manner. Each side panel measured 9-3/4 inches wide by 69-3/8 inches long, whereas the back panel measured 29-3/4 inches wide by 68-7/8 inches long. All panels were 3/16 inch thick.

Another set of two bookcases was constructed as shown in **Figure 2**. In this construction, the panels fit into grooves cut into the posts. These cases have a somewhat better appearance than the other two because the edges of the panel are not visible and the nails on the ends of the cases are eliminated.

The grooves were cut with a router although a table saw could have been used. A router was preferred over a table saw because it was easier to maintain the desired groove to edge spacing over the entire length of the posts through the use of a guide fitted to the router. The panels in the end frames were secured with a small amount of glue inserted in the grooves. The back panel also was glued in a similar manner.

Method of test

In order to simulate common loading conditions, the shelves of the bookcases were uniformly loaded as shown in **Figure 2**. The individual weights used in this test were nominal 5-pound concrete bricks with dimensions of 3-5/8 by 7-1/2 by 2-1/4 inches in depth, length, and thickness, respectively. Thirty-six bricks were used per shelf, i.e., 3 rows of 12 bricks, for a total load of 180 pounds per shelf. The bricks were centered on the shelves, 2-1/4 inches from the front of the shelves and 1-3/4 inches from the interior faces of the side panels. All of the bookcases, i.e., two constructed of yellow-poplar and two constructed of red oak, were loaded in this manner. The load tests were performed at a constant temperature of 70° F.

Initial deflection measurements were made on the unloaded shelves at mid-span. As soon as a shelf was loaded, its mid-span deflection was measured again. Additional deflection measurements were then made on a regular basis over a 3-month period. A deflection yoke equipped with a dial gage was used to measure the center deflection of the shelves to the nearest 0.001 inch (**Fig. 2**).

After the tests had been completed, the stiffnesses of the front and back rails were determined in accordance with American Society for Testing and Materials (ASTM) standard D 143-94 (ASTM 1997). All of the samples were cut from the front and back rails of one bookcase frame of yellow-poplar and one frame of red oak.

Elastic deflection and joint rigidity of the shelves

All four bookcases were used in the elastic shelf deflection tests. The purpose of the tests was to determine both the mid-span elastic deflection of the shelves and the rigidity of the shelf rail to post joints. In this type of construction, the end rigidity of the front and back rails has an important influence on mid-span deflection since the deflection of a beam with fixed ends is only one-fifth as great as that of a simply supported beam. It is this beam characteristic that suggested that high performance bookshelves could be constructed from what is often "scrap" material in developing countries.

Creep deflection of shelves

Two bookcases were used in the creep deflection tests of the shelves, one constructed of red oak and one of yellow-poplar. Loads were maintained on the shelves for three months; deflection measurements were collected regularly during that time. At the end of the specified time, both cases were unloaded, the initial deflection recovery measured, and measurement of creep recovery continued for an additional three months.

Results and discussion

Elastic deflection and joint rigidity of the shelves

The average mid-span deflection of the shelves supported by oak rails was 0.068 inches with a standard deviation of 0.003 inches (**Table 1**). Comparable mid-span deflection for the shelves supported by yellow-poplar rails was 0.087 inches with a standard deviation of 0.002 inches (**Table 2**).

To put these values into perspective, one deflection criteria that has been applied to shelves (Suchova 1972) is that the mid-span deflection should be less than L/180 where L refers to the length of the span. In general, a deflection of L/180 is discernible but not objectionable. A deflection of L/160, on the other hand is not only discernible, but also borders on objectionable. An acceptance level of L/180, accordingly, appears to be satisfactory for bookcases used in schools.

For a 29-inch shelf, the L/180 ratio amounts to 29 inches/180, or 0.16 inches. Thus, the deflection of the red oak and yellow-poplar shelves were only 43 percent and 54 percent, respectively, as great as the criteria allows. This performance was noteworthy in that the shelves supported loads of 180 pounds, i.e., 6.2 pounds per inch of shelf length, or, almost 75 pounds per foot. The thin 3-ply plywood used to cover the rails was aligned with the surface grain in the front to back shelf direction. Thus, the plywood provided essentially no structural support along the length of the rails with the result that the entire load was carried by the two small (nominal 3/4 by 1 in.) front and back shelf rails. Rails of this small size are able to carry the loads and satisfy deflection criteria only because of their method of attachment to the case posts.

In the design of these bookcases, loads applied to the shelves are transferred to and carried by the front and back rails. These rails are attached to the corner posts by means of glued round mortise and tenon joints that provide attachments that, presumably, are rigid. In effect, therefore, the loads on the test shelves are transferred to and are carried by two wood beams that are rigidly supported at their ends. In reality, however, these joints are semi-rigid rather than rigid.

Elastic deflection of the shelves depends on the geometry of the rails, the mechanical properties of the rails, specifically their modulus of elasticity (MOE), and the rigidity of the rail to post joints. The deflection of a rigidly supported beam or rail at mid-span un-

Table 1. — Relationship of elastic deflection of front and back shelf rails to joint rigidity in the red oak bookcases.

Rail no.	Actual elastic deflection	Theoretical elastic deflection	Difference	Ratio for joint rigidity (actual/theoretical)
	- - - - - - - - - - - - (in.)	- - - - - - - - - - - -	(%)	
1	0.064	0.0593	7.9	1.079
2	0.067	0.0593	13.0	1.129
3	0.064	0.0593	7.9	1.079
4	0.072	0.0593	21.4	1.214
5	0.069	0.0593	16.4	1.163
6	0.071	0.0593	19.7	1.197
7	0.072	0.0593	21.4	1.214
8	0.066	0.0593	11.3	1.113
9	0.068	0.0593	14.7	1.146
10	0.069	0.0593	16.4	1.163
11	0.073	0.0593	23.1	1.231
12	0.064	0.0593	7.9	1.079
13	0.064	0.0593	7.9	1.079
14	0.072	0.0593	21.4	1.214
15	0.069	0.0593	16.4	1.163
16	0.068	0.0593	14.7	1.146
17	0.070	0.0593	18.0	1.180
18	0.071	0.0593	19.7	1.197
Average	0.068	0.0593	15.5	1.146

Table 2. — Relationship of elastic deflection of front and back shelf rails to joint rigidity in the yellow-poplar bookcases.

Rail no.	Actual elastic deflection	Theoretical elastic deflection	Difference	Ratio for joint rigidity (actual/theoretical)
	- - - - - - - - - - - - (in.)	- - - - - - - - - - - -	(%)	
1	0.082	0.077	6.5	1.065
2	0.089	0.077	15.6	1.155
3	0.092	0.077	19.5	1.194
4	0.085	0.077	10.4	1.104
5	0.086	0.077	11.7	1.116
6	0.088	0.077	14.3	1.142
7	0.090	0.077	16.9	1.168
8	0.084	0.077	9.1	1.090
9	0.091	0.077	18.2	1.181
10	0.086	0.077	11.7	1.116
11	0.087	0.077	13.0	1.129
12	0.085	0.077	10.4	1.103
13	0.088	0.077	14.3	1.142
14	0.086	0.077	11.7	1.116
15	0.090	0.077	16.9	1.168
16	0.084	0.077	9.1	1.090
17	0.087	0.077	13.0	1.129
18	0.089	0.077	15.6	1.155
Average	0.087	0.077	13.2	1.129

der the action of a uniform load may be estimated by means of the following expression:

$$y_c = \frac{kqL^4}{384EI}$$

where:

y_c = deflection of the beam or rail at mid-span

k = rigidity constant = 1 (k = 1 for truly fixed end support and k = 5 for simply supported beams)

q = the line load applied to the shelf (lb./in.)

L = length of the beam or rail (in.)

E = MOE of the material of which the rails are constructed (psi)

I = moment of inertia of the rail, i.e.,

$$I = \frac{wt^3}{12}$$

where:

w = width of the rail (in.)

t = thickness of the rail (in.)

In the case of the frames constructed of red oak, the MOE of the rails averaged 1,972,000 psi with a standard deviation of 138,000 psi at an average moisture content of 7.55 percent.

The front and back rails measured an average of 0.768 inches wide by 0.979 inch deep. The shelves were uniformly loaded with 180 pounds of bricks so that each rail carried 90 pounds, or 3.1 pounds per inch of rail length. Substituting these values into the expression given above and solving gives an estimated midspan deflection of:

$$y_c = \frac{3.1 \times (29)^4}{384 \times 1{,}972{,}00 \times \frac{0.768 \times (0.979)^3}{12}}$$

$$= 0.0482 \text{ in.}$$

for rigidly supported beams, and

$$y_c = 5 \times 0.0482 = 0.241 \text{ in.}$$

for simply supported beams

The other two bookcase frames were constructed of yellow-poplar, which had an average MOE of 1,500,000 psi with a standard deviation of 112,000 psi at an average 6.59 percent moisture content. The front and back rails measured an average of 0.768 inch wide by 0.983 inch deep. Again, the shelves were uniformly loaded with 180 pounds of bricks.

Substituting the appropriate values into the expression given above and solving gives the deflection of the shelf (front rail) at mid-span as:

$$y_c = \frac{3.1 \times (29)^4}{384 \times 1{,}500{,}000 \times \frac{0.768 \times (0.983)^3}{12}}$$

$$= 0.0626 \text{ in.}$$

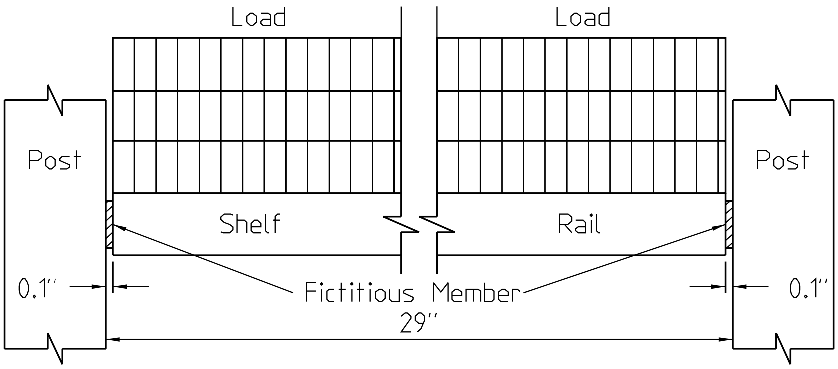

Figure 3. — Diagram illustrating the use of "fictitious" beams in computing the mid-span deflection of the shelf rails.

for rigidly supported beams, and

$$y_c = 5\times 0.0626 = 0.3131 \text{ in.}$$

for simply supported beams

Estimated deflections were computed for all of the rails as detailed above and the results compared with the corresponding test values in order to determine the joint rigidity of the front and back rails of the shelves. The average of measured elastic deflection of the red oak rails divided by the theoretical deflection of 0.0482 inch amounts to 0.068/0.0482, or 1.41. The corresponding ratio for the yellow-poplar rails amounted to 0.087/0.626, or 1.39. As can be seen, the rails deflected somewhat more than rigid joint theory predicts but much less than simply supported theory predicts. Specifically, the constant, *k*, in the above expression amounted to 1.41 for red oak rails and 1.39 for yellow-poplar rails. Thus, the results indicate that round mortise and tenon joints do, in fact, provide a high degree of joint rigidity.

Semi-rigid z-values (Lothers 1960) may be calculated for the joints from the results obtained on an iterative trial-and-error basis. According to Lothers (1960), a "z-value may be defined as that property of a semi-rigid connection which, when used in conjunction with the *E* and *I* of the connected member, becomes the necessary correction factor to render the ordinary methods of analysis applicable." It is zero for a rigid connection and infinite for a pin connection. Results of these analyses indicate a z-value of 1.4×10^{-5} rad./lb.-in. for the red oak tenons and a value of 1.7×10^{-5} rad./lb.-in. for the yellow-poplar tenons. Whether the difference in values is real or the product of experimental error remains to be determined. If an average z-value of 1.55×10^{-5} rad./lb.-in. is assumed, the predicted deflection of the red oak rails is 0.0699 inch (vs. 0.068 in.); likewise, the predicted deflection of the yellow-poplar rails is 0.0849 inch (vs. 0.087 in.). Thus, deflection of the red oak rails is overestimated by the ratio of 0.0699/0.068, or 2.8 percent, and underestimated for the yellow-poplar rails by 2.4 percent.

Semi-rigid joints can be introduced readily into matrix analyses of frames through the use of short fictitious members that reflect the characteristics of the semi-rigid joints in question. The relationship between the z-value of a joint and the properties of a fictitious member that reflect its behavior may be obtained from the relationship of the rotation of the end of a cantilever beam (ϕ) in response to a couple applied to the end of the beam:

$$\phi = \frac{M \times L}{E \times I},$$

where:

M = the couple (lb.-in.)

The following expression may then be written in order to express the MOE of the fictitious member in terms of its geometry and the z-value of the joint it represents:

$$\phi = \frac{M \times L}{E \times I} = Z \times M, or, E = \frac{L}{Z \times I}$$

To illustrate the use of this expression in computing the MOE of a fictitious member that is used to represent the characteristics of the round tenons used in construction of the bookcase frames, assume that $L = 0.1$. The moment of inertia of a 0.72-inch-diameter tenon is 0.01319 in.[4] Substituting these values into the above expression and solving for *E* gives:

$$E = \frac{0.1}{1.5 \times 10^{-5} \times 0.01319}$$
$$= 5.05 \times 10^{5} \text{ psi}$$

Analyzing a red oak rail with fictitious end members (**Fig. 3**) with the properties given above ($E = 5.05 \times 10^5$; $L = 0.1$ in.; $D = 0.72$ in.) yields an estimated mid-span deflection of 0.0679 inch (vs. 0.068 in.). Similarly, an estimated value of 0.0824 inch (vs. 0.087 in.) is obtained for yellow-poplar. As can be seen, this procedure can be used in matrix methods of structural analyses to obtain close estimates of deflections. The procedure as a whole is of interest largely because estimates of z-values can be obtained from relatively simple tests carried out on cantilever beams (Eckelman 1971, Zhang 2001).

Finally, it is worthwhile to compare the performance of these shelves with the performance of comparable solid shelves constructed of wood composites. In her study of the performance characteristics of bookcases constructed of composites, for identically loaded shelves, Denizli (2002) obtained deflections of 0.384, 0.116, and 0.104 inch for 12- by 30-inch solid composite shelves with restrained ends constructed of 5/8- and 3/4-inch-thick particleboard and 3/4-inch-thick medium density fiberboard, respectively (k = 1.75 for the 5/8-in. shelf and 1.5 for the 3/4-in. shelves). Thus, it can be seen that the shelves with rails, which had deflections of 0.069 and 0.087 inch for red oak and yellow-poplar rails, respectively, performed very well in comparison to the more conventional wood composite solid shelves.

Creep deflection of shelves

Table 3 shows the total deflection and creep deflection of the shelves for both red oak and yellow-poplar bookcases. Creep deflection is presented as a percentage of initial elastic deflection. In the case of red oak shelves, creep deflection averaged 49.5 percent of initial elastic deflection. In the case of yellow-poplar shelves, creep deflection averaged 54.2 percent of initial elastic deflection. It was concluded from this

Table 3. — Shelf deflection values of red oak and yellow-poplar bookcases.

	Red oak					Yellow-poplar			
	Total deflection					Total deflection			
Shelf no.	Initial	Final	Creep deflection	Percent of initial creep deflection	Shelf no.	Initial	Final	Creep deflection	Percent of initial creep deflection
	(in.)			(%)		(in.)			(%)
1	0.064	0.096	0.032	50.0	1	0.088	0.134	0.046	52.3
2	0.072	0.107	0.035	48.6	2	0.086	0.129	0.043	50.0
3	0.069	0.108	0.039	56.5	3	0.090	0.142	0.052	57.8
4	0.068	0.102	0.034	50.0	4	0.084	0.128	0.044	52.4
5	0.070	0.105	0.035	50.0	5	0.087	0.134	0.047	54.0
6	0.071	0.101	0.030	42.2	6	0.089	0.141	0.052	58.4

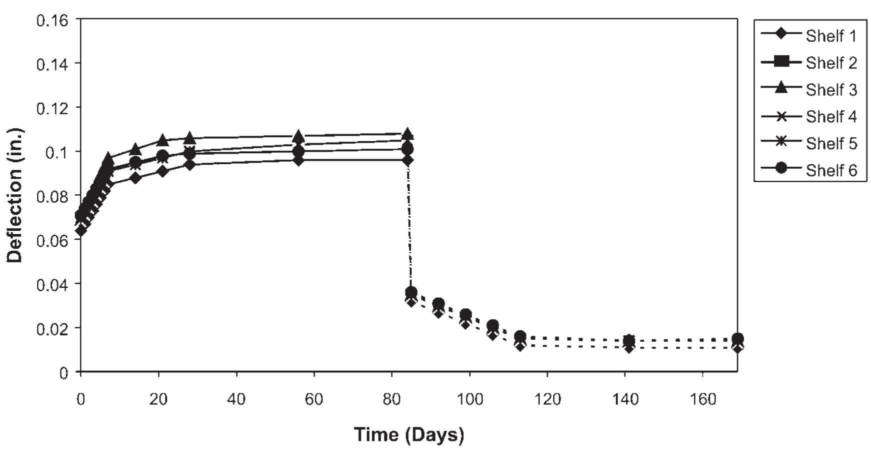

Figure 4. — Creep deflection (continuous lines) and recovery (dotted lines) of red oak bookcase shelves that were subjected to 3 months of uniform loading and 3 months of recovery monitoring.

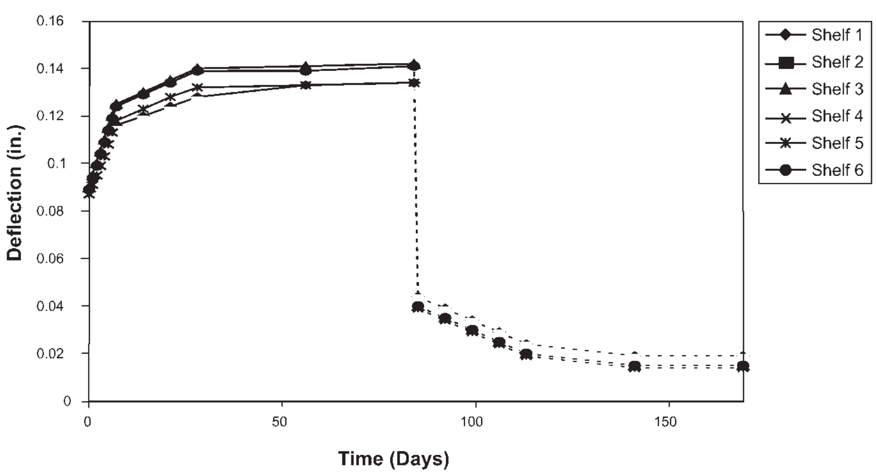

Figure 5. — Creep deflection (continuous lines) and recovery (dotted lines) of yellow-poplar bookcase shelves that were subjected to 3 months of uniform loading and 3 months of recovery monitoring.

study that the type of wood species used in construction of the bookcase frame has a significant effect on both elastic and creep deflection of the shelves because the red oak bookcase has lower elastic and creep shelf deflections than the one made of yellow-poplar.

The creep deflection and recovery measurements are presented graphically in **Figures 4** and **5**. In these figures, the continuous lines represent creep, whereas the dotted lines represent recovery of the shelves. According to the results of the study as shown in these figures, the instantaneous creep recovery was approximately equal to 50 percent of the magnitude of the instantaneous elastic deformation for red oak and yellow-poplar shelves. Overall, creep recovery averaged 86.8 and 87.3 percent of total shelf deflection for red oak and yellow-poplar shelves, respectively. These figures also showed that after a period of about a month, very low rates of creep deflection and recovery were reached for all shelves.

Again, it is worthwhile to compare the performance of these shelves with the performance of comparable solid shelves constructed of wood composites. Denizli (2002) obtained deflections of 0.583, 0.155, and 0.130 inch for 5/8- and 3/4-inch-thick particleboard and 3/4-inch-thick medium density fiberboard, respectively, for shelves with restrained ends after 6 months of loading. Comparable values for shelves with rails were 0.103 and 0.135 inch for the red oak and yellow-poplar rails, respectively. In keeping with the previous short-term results, the shelves with rails performed very well in comparison to the more conventional wood composite solid shelves.

Conclusions

Results of the study indicate that high quality bookcase frames can be constructed with round mortise and tenon joints using only simple construction techniques. Of particular interest, the study clearly demonstrated that shelf rails of relatively small cross section could be used to carry large shelf loads and still satisfy critical deflection criteria, provided the ends of the rails were joined to the posts with essentially rigid joints (in this case, round mortise and tenon joints). Overall, therefore, results of the tests indicate that local cottage industry should be able to produce quality bookcases from readily obtainable local woody materials in even remote regions of the world.

Results of the tests also indicate that round mortise and tenon joints provide a simple means of obtaining a high level of end fixity for shelf rails with resulting diminished mid-span shelf deflections. Specifically, the average mid-span deflections of the shelf rails rails were only 28.2 and 27.8 percent as great, respectively, as the estimated deflection values for simply supported red oak and yellow-poplar rails.

Finally, construction of the case frames demonstrated that tight tenon/mortise fits can be obtained readily through a shrink and swell technique that consists of drying a tenon until it shrinks just enough to fit into a mortise, and then once inserted in the mortise, allowing it to swell and thereby obtain a tight fit as it regains moisture.

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