Design and testing of environmentally friendly wood school chairs for developing countries

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Abstract

In many of the developing countries of the world, school chairs are poorly designed, of low quality, and often unfit for school use, yet they are costly and consume a disproportionate share of limited educational budgets. This situation need not continue. Attractive, well-designed, durable, maintenance-free chairs can be produced by local industry from locally available wood materials including plantation thinnings and semi-processed materials such as pallet deckboards. Only the simplest machining and joinery processes are required to construct the chairs. Cost of the chairs is generally less than that of competing products, yet performance tests indicate that the chairs produced are very durable.

In many developing countries, school furniture is poorly designed, of low quality, and often unfit for school use, yet it is costly and consumes a disproportionate share of limited educational budgets. Our past research experience led us to believe that this situation need not continue. Specifically, we believe that attractive, well-designed, durable, maintenance-free furniture can be produced from locally available woody residues using only the simplest machining and joinery processes.

The intent of this study was to design, construct, and evaluate one or more types of chair construction that would satisfy the necessary criteria. Two types of construction were selected: solid wood construction and laminated cross-lap construction. In the solid wood construction, the stretchers, rails, and posts were constructed of solid wood. In the laminated cross-lap construction, the cross stretchers and cross rails were constructed of solid wood, but the side frames, consisting of the side rails, side stretchers, and front and back posts, were of laminated construction.

The configuration of the chair that served as a basic model for the construction of all the chairs used in the study is shown in Figure 1. Individual chairs differed in detail – some chairs had straight back posts, for example, and the number of stretchers varied – but in general, all of the chairs were more or less the same size and of similar configuration. Overall, sizes of the chairs were such that they would be suitable for children in the 8- to 9-year-old age group.

All of the wood used in the study was cut from green logs by means of a portable band mill. Chair parts were subsequently cut from the lumber procured from the logs. Parts were visually inspected to eliminate severe defects, but in general, an attempt was made to avoid sorting for quality.

Solid wood chair construction

The stretchers and back rails of the solid wood chairs (Fig. 2) were first ripped from 7/8-inch-thick stock. After they were cut to length, round tenons were machined on the ends of each part with a 3/4-inch outside diameter hole saw. These saw cut tenons with a nominal diameter of about 19/32 inch. Excess material was removed from around the tenons as needed.

Front rails were constructed of 7/8-inch-thick by 1-3/4-inch-wide material. Round tenons were cut off-center on the ends of this member to allow the matching mortises in the front posts to be bored slightly further down from the top of the posts. The top backrest rail was
also constructed of 7/8-inch-thick by 1-3/4-inch-wide material, but the tenons were centered on the ends of this member. Holes (mortises) to receive tenons for stretchers or rails were drilled completely through the posts. The drill used to bore the mortises in the construction of the furniture described in this paper was chosen to provide a "shrink and swell" fit between hole and tenon. The back posts in the chairs with sloping back legs were either "creep bent" or bandsawn to shape (4).

From this point, assembly techniques varied as a "best" method of assembling the chairs was sought, but, in general, the side frames were constructed first. Walls of the holes and tenons were first coated with adhesive. The tenons on the ends of the stretchers were then inserted in the holes, and the assembly was pulled together by means of bar clamps until the desired front-to-back side-frame dimensions were obtained. Because of the slant of the back legs, a close fit between the shoulders of the tenons and the walls of the posts was not always obtained. The side frame assemblies were then allowed to dry, and the holes for the front and back stretchers, etc., were then bored in the sides of the front and back posts. The walls of the holes were coated with adhesive, the ends of the tenons inserted, and the assembly pulled together as described for the side frame assemblies. A 42 percent solids content PVA adhesive was used in the construction of all chairs. Frames were allowed to cure for several days before testing.

Moisture content (MC) of the wood at the time the chairs were constructed varied from 12 to 16 percent. Before assembly, however, the stretchers were dried to 4 to 5 percent MC. The completed chairs were then conditioned to an MC of 7 percent.

Chairs 1 and 2 were constructed of yellow-poplar (Liriodendron tulipifera), whereas chair 3 was constructed entirely of hickory (Carya spp.). These species were chosen to obtain estimates of the strengths of chairs constructed of a relatively low-strength hardwood as well as a high-strength hardwood. In the case of chair 4, the posts were constructed of yellow-poplar, whereas the stretchers were constructed of hickory. This chair was constructed to determine if high strength could be obtained when a weaker wood was used in the posts in combination with a high-strength wood in the stretchers.

Chair 5 (Fig. 3) was unique in that it was constructed of white ash (Fraxinus americana) with hand tools alone by a cooperator in the study. It differs somewhat in configuration from the other chairs because this was the cooperator's design.

Chairs 6a through 6d were of identical design (Fig. 2) and were constructed of yellow-poplar. These chairs had straight backposts and as a result, a close fit was obtained between the shoulders of the tenons and the sides of the posts, in contrast to chairs 1 through 4.

**Tenon-mortise fit**

All of the stretchers were attached to the posts or side frames with round mortise and tenon joints. A tight fit between the tenon and mortise is essential to the construction of robust durable joints. A simple procedure that can be used to produce such joints is to drill the mortise to a diameter slightly less than that of the tenon. The tenon is then dried prior to assembly, which causes it to shrink. Once the tenon has shrunk to a smaller diameter than that of the mortise, it is inserted into the mortise. As the tenon regains moisture, either from the adhesive on the walls of the mortise or the atmo-
sphere, it swells and a tight “shrink and swell” fit is obtained.

**BENDING GREEN BACK POSTS TO SHAPE**

The back posts used in chair 1 were bent to shape while they were in the green condition. In this process, the back post, while green, was supported at each end and subjected to a load perpendicular to its longitudinal axis at mid span (Fig. 4). The back post was bent as much as possible without fracturing and allowed to creep under load. The clamping nut, shown in Figure 4, was periodically tightened and the back post allowed to creep an additional amount. This process was repeated until the desired degree of curvature in the backpost, including an allowance for “spring back,” was obtained.

**SEATS**

The seats used with these chair frames were constructed of 1/2-inch-thick plywood. This material was used largely as a matter of convenience because the primary focus of this study was chair frames, but it is likely that such seats would be specified by many schools.

**CROSS-LAP JOINT CHAIR CONSTRUCTION**

Laminated cross-lap joint construction provides one of the simplest and most straightforward methods of constructing strong and dimensionally accurate side frames from either thick or thin slats. The three-member joints used in this study are symmetrical in construction and therefore well suited for use in chair side frames and similar constructions where their principal function is to resist the front-to-back loads acting on the chair. In this respect, cross-lap construction may be used to form both L-shaped corner joints and T-shaped rail to post joints. In form and function, these joints are equivalent to corresponding mortise and tenon or multiple mortise and tenon joints.

Construction of chair 7, a three-lamination cross-lap joint chair constructed of yellow-poplar, is shown in Figure 5. To obtain a sloping back leg, back posts were sawn to shape after the side frames had been assembled.

In constructing the laminated side frames, the joint centers of the frame were first located on a flat plywood panel. Holes were then drilled through these points, and bolts were inserted through the holes. Corresponding holes
were drilled through the joint centers of the various laminations. The lap areas of the laminations were then coated with adhesive, and the pre-drilled laminations slipped over the ends of the bolts. Large washers were then slipped over the ends of the bolts, and the nuts were then threaded onto the ends of the bolts and tightened to apply pressure to the lap joint areas. Shorter lengths of material were glued in place in the slots between laminations in the front and back posts in order to produce solid legs. Thus, the front and back post consisted of three laminations each, whereas the side rail and side stretcher consisted of only one lamination each. After the adhesive had dried, the frames were removed from the forms. The holes at the joint centers were then redrilled to accommodate the round tenons of the front and back rails and stretchers, and the side frames were joined together in essentially the same manner as with the solid wood chairs.

Chair 8 was identical to chair 7 except that the chair was constructed of gmelina (Gmelina arborea), a Central American wood species (2). Construction of chair 9, a seven-lamination cross-lap chair, is shown in Figure 6. This was an experimental chair in which the spaces between laminations were left open. Overall, the chair was somewhat larger than the others and was constructed of black ash (Fraxinus nigra).

**Front-to-back load and side load performance tests**

The front-to-back load test on seats as defined in the performance test method for library chairs developed by the American Library Association (ALA) (3) was used to evaluate the strength and durability of the chairs in the critical front-to-back direction. Likewise, the side load test was used to evaluate strength and durability in the side direction.

The front-to-back load test consists of pushing from front to back on the seat of a chair (or on the front rail). This action produces internal resisting forces in the side frame of the chair similar to those caused by the action of someone sitting backward. A strap passes over the seat and is pulled backward by an air cylinder (or by a similar loading mechanism) located behind the chair, which tends to tip the chair backward. As the chair begins to tilt slightly, however, it is prevented from overturning by that portion of the strap that hangs vertically over the front edge of the seat and is anchored below.

The chair is mounted for testing as shown in Figure 7. Reaction brackets are placed behind each of the back legs to prevent the chair from sliding backwards. Loads are applied to the chair seat in a front-to-back direction at a rate of 20 cycles per minute. For the purposes of this test, i.e., based on a consideration of the anticipated size of the users, testing of the chairs was begun at the 50-pound load level. Loads were increased in increments of 25 pounds after 25,000 cycles were completed at each preceding load level. Tests were conducted until a chair suffered disabling damage.

The horizontal side load test on seats is identical to the front-to-back load test except that the load is applied to the seat in a sideways direction. In addition, the reaction brackets are placed on one side of the chair rather than behind.

**Results and discussion**

**Front-to-back tests**

Chairs 1 and 2 failed at 200 and 250 pounds, respectively (Table 1). An examination of chair 1 after testing disclosed some discoloration of the wood.

![Figure 7. — Front-to-back load test on seats.](image_url)

**Table 1.** — Results of front-to-back and side load seat tests.

<table>
<thead>
<tr>
<th>Chair</th>
<th>Type of test</th>
<th>Initial load (lb)</th>
<th>Load increase (lb)</th>
<th>Ultimate loads (lb)</th>
<th>Cycles completed at ultimate load</th>
<th>Total cycles completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Front to back</td>
<td>50</td>
<td>25</td>
<td>200</td>
<td>469</td>
<td>150,469</td>
</tr>
<tr>
<td>2</td>
<td>Front to back</td>
<td>50</td>
<td>25</td>
<td>250</td>
<td>14,000</td>
<td>214,000</td>
</tr>
<tr>
<td>3</td>
<td>Front to back</td>
<td>50</td>
<td>25</td>
<td>425</td>
<td>22,000</td>
<td>397,000</td>
</tr>
<tr>
<td>4</td>
<td>Side load</td>
<td>50</td>
<td>25</td>
<td>450</td>
<td>3,956</td>
<td>403,956</td>
</tr>
<tr>
<td>5</td>
<td>Front to back</td>
<td>50</td>
<td>25</td>
<td>400</td>
<td>7,500</td>
<td>375,000</td>
</tr>
<tr>
<td>6a</td>
<td>Front to back</td>
<td>50</td>
<td>25</td>
<td>250</td>
<td>21,000</td>
<td>196,000</td>
</tr>
<tr>
<td>6b</td>
<td>Front to back</td>
<td>275</td>
<td></td>
<td></td>
<td>23,000</td>
<td>248,000</td>
</tr>
<tr>
<td>6c</td>
<td>Front to back</td>
<td>350</td>
<td></td>
<td></td>
<td>150</td>
<td>300,150</td>
</tr>
<tr>
<td>6d</td>
<td>Front to back</td>
<td>275</td>
<td></td>
<td></td>
<td>1,000</td>
<td>226,000</td>
</tr>
<tr>
<td>7</td>
<td>Front to back</td>
<td>350</td>
<td></td>
<td></td>
<td>3,800</td>
<td>303,800</td>
</tr>
<tr>
<td>8</td>
<td>Side load</td>
<td>50</td>
<td>25</td>
<td>250</td>
<td>100</td>
<td>200,100</td>
</tr>
<tr>
<td>6</td>
<td>Front to back</td>
<td>450</td>
<td></td>
<td></td>
<td>24,500</td>
<td>424,500</td>
</tr>
<tr>
<td>6</td>
<td>Front to back</td>
<td>50</td>
<td>25</td>
<td>600</td>
<td>25,000</td>
<td>600,000</td>
</tr>
</tbody>
</table>

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in two stretchers. Thus, there may have been some type of fungal activity that weakened the wood before it was processed. Nonetheless, as subsequently discussed, the chairs developed acceptable levels of strength.

Chairs 3 and 4 failed at 425 and 400 pounds, respectively. The small difference in performance between these two chairs indicates that chairs constructed with high-strength stretchers but low-strength posts may be expected to perform as well as chairs constructed with all high-strength material.

Chair 5 failed at 250 pounds. Cause of failure was fracture of the side stretcher to post joints. This chair had only two side stretchers so that its performance was regarded as quite good. Diameter of the tenons on the ends of the stretchers was 0.657 inch compared to 0.59 inch for chairs 1 through 4. Because the bending strengths of the tenons are related to the cube of their diameters, even this small difference in diameter could account for a 38 percent increase in tenon bending strength.

Chairs 6a and 6c failed at a load level of 275 pounds; similarly, chairs 6b and 6d failed at 350 pounds. The reason for their better performance compared to chairs 1 and 2 may be a result of the close fit between the shoulders of the tenon and the walls of the posts. In all four chairs, the walls of the posts were indented by the shoulders of the tenons during testing. This action indicates that the strength of the joints was a function of both tenon strength and shoulder width, i.e., the joint behaved as a conventional mortise and tenon joint. It may also be, however, that the material used in the latter chairs was simply of better quality.

Chair 7 failed at 425 pounds. The adhesive in the joints on the left side of the chair after a few cycles had been completed at the 400-pound load level. Importantly, the left side frame continued to carry load although it deflected more than the right. The adhesive in the right side frame also failed, but at the 425-pound load level. Finally, the tenons in both side frames fractured and the test was stopped after 15,780 cycles had been completed at the 425-pound load level. These results indicate that even if the adhesive in the joints fails, the joints will continue to carry load by mechanical action alone up to the point that the tenons fracture.

Chair 8 failed at 450 pounds. Cause of failure was fracture of the side stretchers at the stretcher to front and back post joints and fracture of the side rails at the rail to back post joint. This result indicates that chairs constructed of gmelina, considered to be a relatively weak wood, could be expected to be as strong as chairs constructed of yellow-poplar.

In the case of both laminated chair frames, chairs 7 and 8, the holes for the tenons of the front and back stretchers were drilled through the centers of the cross-lap joints in the side frames. Once the adhesive in a joint failed, the corresponding side frame tenon tended to rotate about the round stretcher tenon that framed into the side of the joint. As this action occurred, there was also a tendency for the side frame tenon to withdraw from the mortise. This action caused the central area of the tenon to fail in shear along lines corresponding to the outside diameter of the round tenon in a manner similar to that illustrated in Figure 8 and the remaining portion of the tenon to fracture as shown.

Chair 9 was tested through the 600-pound load level without failure. Testing was discontinued at this point owing to the very high load level obtained.

**Acceptance Levels**

To provide a basis for an intuitive feeling for the strength of the chairs evaluated in this study, it is useful to compare the strength values obtained with the acceptance levels specified in the ALA test method for chairs used in library reading rooms, a severe use environment (3). In the case of front-to-back load tests, values of 250, 350, and 450 pounds are specified. Essentially, these values correspond to what are regarded as light, medium, and heavy duty. Experience indicates that if chairs do not have at least a 250-pound front-to-back strength, a significant number will fail during the first 2 years in an adult library environment. Few chairs with a strength of at least 350 pounds ever fail, however. Comparable values for the side load test are 200, 250, and 300 pounds for low, medium, and high categories, respectively. The higher values tend to reflect the strength of chairs produced rather than strength needed to survive in service.

A comparison of the strength values obtained for the chairs in this study with the acceptance levels specified by the ALA (3) indicates that the solid wood chairs constructed of "weaker" woods essentially satisfied the "low" front-to-back load test acceptance level, whereas the chairs constructed of "high-strength" wood stretchers nearly satisfied the "high" acceptance level. In the case of the side load tests, the laminated chair constructed of yellow-poplar satisfied the "low" acceptance level, whereas the solid chair constructed of hickory far surpassed the "high" acceptance level.

To put these comparisons into perspective, it must be realized that adult library reading rooms (especially those located at universities) represent a severe use environment and acceptance levels, accordingly, are set high relative to other use environments. Chairs that meet only the "low" ALA acceptance level, for example, have given good service in fast-food restaurants. Furthermore, chairs intended for home use often fall considerably short of satisfying the "low" ALA acceptance level. Thus, a very high level of strength was achieved in the test chairs, which presumably can be attributed both to their design and method of construction.

**Structural Analysis: Solid Wood Chairs**

Following testing, structural analyses were conducted to determine the distribution of forces in the side frames under the action of the ultimate loads reached in the tests. Once these bending forces were determined, the corresponding bending stresses were determined and compared to the modulus of rupture (MOR) values of the materials used.

In evaluating results, the cyclic, as opposed to static, loading of the chairs
must be taken into account. Of particular interest, the peak load in each load cycle was held for less than a second. According to the Wood Handbook (6), "the load required to cause failure in a wood member in one second is approximately 25 percent higher than that obtained in ASTM (1) standard strength tests." Thus, calculated stresses at ultimate load levels in some cases may be considerably higher than published MOR values.

Fatigue may also have influenced the results. The number of cycles completed in these tests may not have been high enough for fatigue to be a factor, but the fatigue characteristics of the wood when subjected to a stepped load schedule, particularly at high percentages of ultimate strength, is unknown.

Analyses of the chairs were carried out with commercially available finite element software: MICROSAFE™, a product of the Microstress Corporation (5). Bending forces acting on the ends of the stretcher at their points of entry into the posts at the ultimate load levels achieved by the frames were calculated and the corresponding bending stresses determined.

In the case of chairs 1 and 2, the lowest calculated breaking stress was 9,324 psi; the highest was 12,461 psi. Compared to the corresponding MOR values shown in Table 2 for static and cyclic loading, these values appear reasonable; however, there was a question concerning the quality of this material, as previously discussed.

In the case of chairs 3 and 4 (hickory stretchers), the calculated ultimate stresses developed in the tenons ranged from a low of 18,152 psi to a high of 21,183 psi. Again, these values compare favorably with the static and cyclic MOR values given in Table 2 and indicate that the tenons developed a relatively high percentage of the strength of the materials of construction.

In the case of the cooperator chair, chair 5 (white ash stretchers), calculated ultimate stress values varied from 18,184 to 18,992 psi. These values compare well with those given in Table 2 for static MOR and cyclic MOR, respectively. This chair is of particular interest because the tenons had no shoulders. Hence, the strength of the joint would be expected to be governed by the bending strength of the tenon alone. Thus, the results obtained in this test give a more unbiased picture of the stresses developed in the tenons.

In the case of chairs 6a through 6d (yellow-poplar stretchers), the calculated stresses developed in the tenons ranged from a low of 12,479 psi to a high of 17,445 psi. In general, the values obtained with these chairs were higher than would be expected, even when cyclic loading is taken into account (Table 2). The back legs on these chairs were straight rather than curved, however, so that a close fit was obtained between the shoulder of the tenon and the wall of the post. As a result, the shoulder likely contributed to the strength of the connection so that the bending strength of the joint was greater than the predicted bending strength of the tenon acting alone.

**TABLE 2. — Modulus of rupture of each of the woods included in the study.**

<table>
<thead>
<tr>
<th>Species</th>
<th>12% MC</th>
<th>7% MC</th>
<th>Cyclic</th>
</tr>
</thead>
<tbody>
<tr>
<td>White ash (F. americana)</td>
<td>15,400</td>
<td>18,480</td>
<td>23,100</td>
</tr>
<tr>
<td>Yellow-poplar (L. tulipifera)</td>
<td>10,100</td>
<td>12,120</td>
<td>15,150</td>
</tr>
<tr>
<td>Hickory (Carya spp.)</td>
<td>20,200</td>
<td>23,230</td>
<td>29,038</td>
</tr>
<tr>
<td>Northern red oak (Q. rubra)</td>
<td>14,300</td>
<td>16,445</td>
<td>20,556</td>
</tr>
<tr>
<td>Gmelina (G. aborea)</td>
<td>9,375</td>
<td>11,250</td>
<td>14,063</td>
</tr>
</tbody>
</table>

**STRAIGHTENING:**

Structural analyses were also conducted on the cross-lap chairs of the type shown in Figure 5. In the case of chair 7, the rectangular tenons failed at calculated stress levels ranging from 3,762 to 4,153 psi. It should be noted that the L-shaped front post to side rail joints tend to fail first in this type of construction. When this occurs, these joints, in effect, become pinned joints and the bending forces they normally carry are redistributed to the other joints. Calculated stresses corresponding to the redistributed forces vary from 3,115 to 6,372 psi.

In the case of chair 8, the tenons failed at calculated stress levels ranging from 3,982 to 4,338 psi. When forces are redistributed as just described, calculated bending stresses range from 3,293 to 6,748 psi.

The mode of failure of the joints during testing is of interest because of possible weakening of the laminated joints in service owing to shrinking and swelling of the wood. Should the L-shaped front post to side rail joint fail, it would become, in effect, a pinned joint. Nonetheless, it would be held in place by the round tenon of the front rail that mates with it and passes through its center. Should the adhesive bonds in the remaining T-shaped joints fail, they would behave as mechanical mortise and tenon joints rather than adhesive-based cross-lap joints. Assuming that a close fit is maintained between the side rail or stretcher and post laminates during construction of the side frames, these joints would be expected to develop a high percentage of the ultimate strength of the side rails and stretchers.

At first glance, the rectangular side rails and stretchers used in chair 7 do not appear to be as efficient load carriers as the round tenons in the solid wood chairs. However, the cross hole drilled through the center of the rectangular tenon to accommodate the cross member considerably altered the mechanical characteristics of the section and weakened it. Hence, calculated stress values based on an undisturbed full tenon cross section would be expected to be lower than the actual stresses developed in the modified tenons.

**CONCLUSIONS**

Strong, durable school chair frames can be constructed using the simple techniques employed in the construction of the chairs evaluated in this study. The high strength of the chairs results both from the favorable distribution of internal resisting forces among the stretchers and rails and from the strength of the round mortise and tenon joints and the cross-lap joints. Deep hole sockets provide a convenient method of cutting round tenons of uniform diameter without the need for close quality control. The shrink and swell method of assembling joints provides a means of producing uniformly tight-fitting round mortise and tenon joints. Green bending provides a low-technology method of pro-
ducing curved back posts. Similar techniques can also be used to produce curved top rails. Structural analyses indicate that round tenons fail at apparent stress levels relatively consistent with their MORs. These analyses also indicate that the shoulders on the ends of the stretchers greatly contribute to the strength of the connection when the shoulders fit closely against the walls of the legs.

Overall, the study confirms that strong, durable school furniture can be produced by local industry in developing countries from largely local woody materials by means of low-technology processes.

LITERATURE CITED