Evaluation of the gluability of pressure steam-dried wood

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Abstract
Yellow-poplar and red oak blanks were kiln-dried using conventional schedules and a relatively new, high-temperature, pressure steam-drying process. The blanks for each species and drying process were manufactured into five types of furniture joints. These include dowel, mortise and tenon, cross lap, edge-, and finger-joints. Differences in strength for each joint type and drying process were not significant at the 5 percent level. A shear block and bending specimen for each joint produced were also tested. Strength values for the pressure steam-dried specimens were similar to those for the conventionally dried specimens at the as-tested moisture content (MC). However, when adjusted to a common MC, the strength properties of the pressure steam-dried wood were lower than those for the conventionally dried wood, probably due to a loss of hygroscopicity of the steam-dried wood.

Drying wood at temperatures over 212°F at atmospheric pressure has been shown to be an effective way of reducing the moisture content (MC) of some species to levels acceptable for subsequent processing (12, 7). The severe conditions used in such drying, however, may have deleterious, though not necessarily unacceptable, effects on the properties of the wood. It is known, for example, that the treatment darkens the surface of the wood, causes knots to loosen, and causes exudation of resin (14). Koch has shown that for southern yellow pine, the mechanical properties are not significantly affected (13); Kozlik, however, has demonstrated a significant effect with Douglas-fir (15).

Rosen has developed a high-temperature drying method called pressure steam-drying (PSD) whereby wood is dried above atmospheric pressure in steam generated from the wood itself (18). This process holds potential for the drying of hardwoods which cannot be dried by conventional high-temperature methods. In this process, lumber is dried in a steam-heated atmosphere to temperatures as high as 300°F at pressures to 35 pounds per square inch (psi). The use of elevated pressures allows higher equilibrium moisture content (EMC) conditions to be attained in the chamber than are possible in conventional high-temperature drying so that moisture gradients in the lumber are not as steep. Advantages of the high-pressure steam-drying process include rapid drying of the wood and a significant potential for energy savings. For example, using this process, yellow-poplar lumber, 5/4 inches thick, may be dried from 110 to 5 percent MC in 30 hours.

Exposure of wood to these conditions may cause degradation of the wood structure itself with consequent reduction in mechanical strength properties (19). If it is assumed that significant changes in the structure and surface reactivity of the wood may occur during PSD, it follows that the strength of adhesive-based joints constructed from such material may also be affected. Since much of the wood produced by PSD could be used in furniture construction, it is important to evaluate the strength characteristics of joints constructed from material dried by this process. The objective of this study, accordingly, was to determine if there is a significant difference in the strength of typical furniture joints constructed of wood dried by the PSD method compared to joints constructed of wood dried by conventional methods in a standard kiln. The joint types...

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tested included mortise and tenon, finger, dowel, cross lap, and edge.

Materials

The wood species selected for evaluation were red oak and yellow-poplar. Trees of these two species, harvested in the Carbondale, Ill., area, were sawn to provide the 5/4 lumber needed. Boards for the study were then randomly selected from this common supply of lumber. The oak lumber was then air-dried to 28 percent MC. One-half of the boards of each species were kiln-dried according to conventional schedules; the other half of the boards were pressure steam-dried according to the following schedule: a temperature of 260°F and a pressure of 19 psi for 26 hours for yellow-poplar and 22 hours for red oak, followed by 4 hours of conditioning at 215°F and 15 psi. Thus, four sets of dried material resulted; kiln-dried red oak, PSD red oak, kiln-dried yellow-poplar, and PSD yellow-poplar. The kiln-dried yellow-poplar and red oak averaged 9-1/2 and 7-1/2 percent MC, respectively; the PSD yellow-poplar and red oak averaged 12 and 8 percent, respectively. The lower MC of the PSD oak resulted from a small leak in the drier which caused the pressure in the drying chamber to drop below 19 psi as the run progressed. Some honeycombing of the oak occurred as a result of the decreased pressure, but a sufficient number of satisfactory boards were found to fulfill the needs of the study.

Clear blanks, 1 by 6 inches in cross section by either 6 or 7-1/4 feet long were then cut from boards randomly selected from each of the four sets of dried material. Each blank provided the material for one complete joint along with a bending, shear, and specific gravity specimen (Figs. 1 through 5).

Specific gravity determinations (oven-dry weight and volume at current MC) were made immediately after the blanks were cut into specimens. Parts cut from blanks in which the specific gravity differed by more than 10 percent from Wood Handbook (24) values were discarded and replaced with other material.

Preparation of specimens

All of the specimens were machined to size at the Forest Sciences Laboratory in Carbondale. Parts for 25 sets each of dowel, mortise and tenon, finger-, and cross lap joints, and 50 sets of edge-glued joints were machined from each of the 4 sets of blanks. After the parts had been machined, they were transported to Purdue University where they were stored at a temperature of 72°F and a relative humidity of 40 percent.

Assembly of the joints was carried out at Purdue. All of the joints were assembled with a 60 percent solids content polyvinyl adhesive furnished by Franklin Chemical Industries. Double-gluing techniques in which glue is applied to both mating surfaces were used in assembling all of the joints. Details of the construction of each joint type follow.

Dowel joints — The configuration of the dowel joint specimens used in the tests is given in Figure 1. There are no standard test methods for dowel joints; hence a joint configuration was used which has previously been reported in the literature (8, 10, 20, 21, 22, 25). Hole diameters were determined and recorded; maximum allowable tolerance was +/− 0.003 inch.

Only straight-grained, spiral-grooved, yellow birch dowels, 2-1/4 inches long, procured from Saunders Brothers of Westbrook, Maine, were used in fabricating the joints. Nominal diameter of the dowels was 3/8 inch. Dowel-hole clearances averaged 0.003 inch for the red oak and 0.005 inch for the yellow-poplar.

To obtain exactly 1-inch depth of penetration of the dowel into the test block, a dowel was first started into the hole in the load block. A 1-inch-long spacer was placed over the dowel and the dowel was then forced into the hole in the load block in a press. This procedure ensured that the free end of the dowel protruded exactly 1 inch from the end of the load block after the dowel was seated.

The assembly was allowed to cure briefly to ensure that the dowel would not move in the hole. A piece of wax paper with a 3/8-inch-diameter hole cut in it was slipped over the end of the dowel to prevent any possibility of the load and test block adhering to one another. The free end of the dowel was then inserted into the hole in the test block and seated.

Mortise and tenon joints — The configuration of the mortise and tenon joints is shown in Figure 2. Standard test methods have not been developed for these joints; hence, a joint configuration was chosen which had been used in other studies (1, 2, 11, 23). Initially, it was planned that mortise and tenon clearances would not exceed 0.003 inch. Actual tolerances were significantly larger; however, tolerances were consistent from one set to another so that test results are comparable. A jig was used in assembling the joints which allowed the tenon to be forced into the side of the mortise and held in place for 1 minute.

Figure 1. — Diagram of the dowel joint specimen and a diagram showing how the dowel joint, shear, and bending specimens were cut from one blank.
**Finger-joints** — The configuration of the finger-joint specimens is shown in Figure 3. Each finger of the joints measured 3/4 inch long and was 1/8 inch wide at the root; all of the fingers were sharp-pointed. The fingers of the joints were machined with a cutterhead available at the Forest Sciences Laboratory. A jig was constructed so that a pressure of 450 psi, based on the cross section of the part, was applied to each joint to ensure that the parts mated properly. This force was maintained for 1 minute.

**Edge-joints** — The edge-glued joint components were assembled in a press in which a pressure of 100 psi was applied for a period of 2 hours (Fig. 4). One set of conventionally dried parts and one set of PSD parts were assembled simultaneously so that each of the two joint specimens received the same glue line pressure. Two glue line shear block specimens were cut from each blank (4).

**Cross lap joints** — The configuration of the cross lap joints is shown in Figure 5. Pairs of joints of conventionally dried and PSD wood were assembled and clamped simultaneously in a press so that joints of both materials were subjected to the same clamping pressure. A pressure of 100 psi was applied and held for 24 hours in assembling the joints.

**Testing of specimens**
All mechanical tests were carried out on a 60,000-pound capacity Tinius-Olsen universal testing machine which was equipped with a standard differential transformer-type deflection measuring device and an X-Y recorder. Ultimate strength was taken as the limit of strength in all tests. Shear strength and modulus of rupture (MOR) were determined as recommended in ASTM D 905-49 (4).

**Dowel joints** — Testing of the dowel joints was done by means of the equipment shown in Figure 6. The purpose of the brackets shown is to ensure that loads are applied to the joint along the line of the longitudinal axis of the dowel, free of eccentricity. The rate of loading used was 0.05 inch per minute of crosshead travel.

**Mortise and tenon joints** — The mortise and tenon joints were tested as shown in Figure 7. A vertical load was applied to the horizontal leg of the joint at a point exactly 12 inches in front of the nearest edge of the vertical member of the fixture. The rate of loading used was 0.1 inch per minute.

**Finger-joints** — Tests of the finger-joint specimens were carried out as shown in Figure 8. This test is similar to that used in ASTM D 198-76 for static tests of timbers in structural sizes (3). The supports were spaced 30 inches apart on center. Two-point loading was used as recommended in ASTM D 3110-72 (6). The loads were applied at points 5 inches on either side of the center point of the specimen. All specimens were tested in the flat position. The rate of loading was 0.25 inch per minute.

**Edge-glued joints** — Glue line shear block tests were carried out with a standard shear block test fixture as recommended in ASTM D 905-49 (4). Glue line shear block specimens were cut from the edge-glued joints in a manner similar to that shown in ASTM D 905-49 (4).
One-half of the specimens were soaked in accordance with the provisions given in ASTM D 3110-72 (6). All tests were carried out at a speed of 0.015 inch per minute.

Cross lap joints — Testing of the cross lap joints was carried out with the fixture shown in Figure 9. Rate of loading was 0.05 inch per minute.

Results and discussion

Results of the shear strength tests are given in Table 1 and the results of the bending strength tests in Table 2. Actual test results have been adjusted to 12 percent MC in both tables to permit comparisons with Wood Handbook (24) values. The values obtained for the soaked shear block specimens are not shown in Table 1 since they received a special treatment. The mean strength value obtained for the soaked specimens, however, was identical to that obtained for the unsoaked specimens.

As can be seen in Table 1, the shear strength values obtained for kiln-dried and PSD material are quite close. When the values are adjusted to 12 percent MC, however, a substantial difference results between the values for kiln-dried and PSD oak. The adjusted values for the kiln-dried oak is about 2 percent less than the published value, but the value for the PSD oak is about 10 percent lower. This difference results from the low MC recorded for the oak. Adjusted values for the yellow-poplar in which the MCs differed only slightly are about 8 percent less than the published value.

Figure 5. — Diagram showing the configuration of the cross lap joints and a diagram showing how the joint parts, shear, and bending specimens were cut from one blank.

Figure 6. — Diagram showing apparatus used to test the dowel joints.

Figure 9. — Diagram showing the fixture used to evaluate the cross lap specimens.
TABLE 1. — Average shear strength results for conventionally kiln-dried and PSD samples of red oak and yellow-poplar based on MC at time of testing (shear) and adjusted to 12 percent (shear 6% 12%).

<table>
<thead>
<tr>
<th>Wood type</th>
<th>Treatment</th>
<th>No. of specimens</th>
<th>MC (%)</th>
<th>Shear (psi)</th>
<th>Shear (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red oak</td>
<td>Kiln</td>
<td>132</td>
<td>7.31</td>
<td>1,964</td>
<td>1,742</td>
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<tr>
<td>Red oak</td>
<td>PSD</td>
<td>93</td>
<td>5.17</td>
<td>1,932</td>
<td>1,603</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>128</td>
<td>8.03</td>
<td>1,227</td>
<td>1,096</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>PSD</td>
<td>129</td>
<td>8.44</td>
<td>1,220</td>
<td>1,102</td>
</tr>
</tbody>
</table>

TABLE 2. — Average MOR values for conventionally kiln-dried and PSD samples of red oak and yellow-poplar based on MC at time of testing (MOR) and when adjusted to 12 percent (MOR 6% 12%).

<table>
<thead>
<tr>
<th>Wood type</th>
<th>Treatment</th>
<th>No. of specimens</th>
<th>MC (%)</th>
<th>MOR (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red oak</td>
<td>Kiln</td>
<td>132</td>
<td>7.09</td>
<td>14,640</td>
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<tr>
<td>Red oak</td>
<td>PSD</td>
<td>95</td>
<td>5.10</td>
<td>14,320</td>
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<tr>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>127</td>
<td>7.80</td>
<td>11,440</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>PSD</td>
<td>127</td>
<td>7.32</td>
<td>10,880</td>
</tr>
</tbody>
</table>

TABLE 3. — Mean strength values, MCs, statistical significance, and number of samples tested for five joint types constructed from conventionally kiln-dried and PSD red oak and yellow-poplar.

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Wood species</th>
<th>Treatment</th>
<th>No. of specimens</th>
<th>MC (%)</th>
<th>Mean strength (lb.)</th>
<th>F-value</th>
<th>Significance of F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dowel</td>
<td>Red oak</td>
<td>Kiln</td>
<td>27</td>
<td>7.0</td>
<td>927</td>
<td>1.974</td>
<td>0.167</td>
</tr>
<tr>
<td></td>
<td>Red oak</td>
<td>PSD</td>
<td>25</td>
<td>5.1</td>
<td>914</td>
<td>802</td>
<td>0.033</td>
</tr>
<tr>
<td></td>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>26</td>
<td>7.6</td>
<td>817</td>
<td>867</td>
<td>0.436</td>
</tr>
<tr>
<td></td>
<td>Yellow-poplar</td>
<td>PSD</td>
<td>25</td>
<td>7.2</td>
<td>749</td>
<td>(lb-m)</td>
<td></td>
</tr>
<tr>
<td>Mortise</td>
<td>Red oak</td>
<td>Kiln</td>
<td>25</td>
<td>6.7</td>
<td>1768</td>
<td>1.720</td>
<td>0.197</td>
</tr>
<tr>
<td></td>
<td>Red oak</td>
<td>PSD</td>
<td>24</td>
<td>4.9</td>
<td>1913</td>
<td>1382</td>
<td>0.932</td>
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<tr>
<td></td>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>24</td>
<td>7.2</td>
<td>1297</td>
<td>1257</td>
<td>0.593</td>
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<tr>
<td></td>
<td>Yellow-poplar</td>
<td>PSD</td>
<td>25</td>
<td>7.1</td>
<td>1082</td>
<td>(psi)</td>
<td></td>
</tr>
<tr>
<td>Cross lap</td>
<td>Red oak</td>
<td>Kiln</td>
<td>27</td>
<td>7.0</td>
<td>303</td>
<td>3.847</td>
<td>0.055</td>
</tr>
<tr>
<td></td>
<td>Red oak</td>
<td>PSD</td>
<td>31</td>
<td>4.9</td>
<td>291</td>
<td>355</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>25</td>
<td>7.7</td>
<td>308</td>
<td>2122</td>
<td>0.152</td>
</tr>
<tr>
<td></td>
<td>Yellow-poplar</td>
<td>PSD</td>
<td>25</td>
<td>7.1</td>
<td>308</td>
<td>(psi)</td>
<td></td>
</tr>
<tr>
<td>Finger-</td>
<td>Red oak</td>
<td>Kiln</td>
<td>28</td>
<td>7.0</td>
<td>802</td>
<td>802</td>
<td>0.055</td>
</tr>
<tr>
<td></td>
<td>Red oak</td>
<td>PSD</td>
<td>22</td>
<td>5.2</td>
<td>8063</td>
<td>2.209</td>
<td>0.144</td>
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<tr>
<td></td>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>27</td>
<td>7.4</td>
<td>6889</td>
<td>6889</td>
<td>0.039</td>
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<tr>
<td></td>
<td>Yellow-poplar</td>
<td>PSD</td>
<td>29</td>
<td>7.1</td>
<td>6961</td>
<td>(psi)</td>
<td></td>
</tr>
<tr>
<td>Edge-</td>
<td>Red oak</td>
<td>Kiln</td>
<td>81</td>
<td>5.6</td>
<td>1939</td>
<td>2.175</td>
<td>0.142</td>
</tr>
<tr>
<td></td>
<td>Red oak</td>
<td>PSD</td>
<td>66</td>
<td>3.9</td>
<td>1641</td>
<td>1148</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>Yellow-poplar</td>
<td>Kiln</td>
<td>76</td>
<td>4.9</td>
<td>1148</td>
<td>1148</td>
<td>0.018</td>
</tr>
</tbody>
</table>

The lower MC value for the PSD red oak is a consequence of its being subjected to severe drying conditions at high temperature which causes a loss in hygroscopicity (16). A corresponding shift in strength properties does not accompany this shift in hygroscopicity, however. Thus, even though the EMC of the oak has been reduced, the shear strength and bending strength of the wood remain consistent with the values expected for the normal EMC of the wood.

Similar comments hold for the bending strength values given in Table 2. The unadjusted values for kiln-dried and PSD wood in both wood species do not differ greatly. The adjusted value for the PSD oak is considerably less than that of the kiln-dried oak, however, because of its lower initial MC. Finally, adjusted values for the kiln-dried red oak and yellow-poplar were about 14 and 3 percent less, respectively, than published values.

The unadjusted mean strength values obtained in the various joint tests are given in Table 3. As can be seen, differences in strength between joints produced from conventionally kiln-dried and PSD wood have little practical significance. In six cases, joints produced from conventionally kiln-dried material were stronger than joints produced from PSD material; in three cases, the opposite was true; in one case identical results were obtained.

Although these results indicate that the effect of the PSD treatment on joint strength is minimal, analyses of variance were carried out on the results of matched sets of specimens in order to test for statistical significance. In these evaluations, it was hypothesized that there were no treatment differences within one species by joint type combination. Results of these analyses are given in Table 3. The F-values and the significance of F for each of these analyses are also given in Table 3. As shown, the highest F-value obtained was 3.847. Furthermore, the probability levels shown under the column "Significance of F" indicate that there is not sufficient evidence at the 0.05 level to reject the hypothesis that all treatments belong to a population with a common mean. Or, we conclude that the experiment does not provide evidence of real differences among treatment means.

The actual strength values obtained during the study are of interest in terms of what they add to the discipline of furniture engineering. In the case of the dowel joints, expected withdrawal strengths under the
conditions of the test (9) would be 1,078 pounds for the oak and 843 pounds for the yellow-poplar. The test values obtained, accordingly, were 86 percent as great as predicted for the oak and 95 percent as great as predicted for the yellow-poplar.

Expressions do not exist for predicting the strength of L-shaped mortise and tenon joints although one expression does exist for predicting the strength of T-shaped joints (9). Hence, the results of these tests are of value in estimating the strength of similar joints. Owing to the relatively loose fit of the parts, however, it would be expected that well-fitting joints of similar construction might develop greater strength than did the joints in this study.

Similarly, there are no well established values to which the results obtained with the cross lap joints can be compared. The results obtained in this study, accordingly, provide useful estimates of the values that can be expected.

Expressions are also lacking which can be used to predict the strength of finger-joints. Published results, however, indicate that these joints can develop a high percentage of the strength of the wood itself. In this study, the joints constructed from kiln-dried red oak developed 64 percent of the bending strength of the wood; similarly, the joints constructed of kiln-dried yellow-poplar developed 70 percent of the strength of the wood. Higher strength ratios have been reported (17); however, in practice, the ratios obtained in this study would translate into very high strength furniture joints.

The strength values obtained in the edge-glued joints can be compared to the values obtained for the wood itself in the shear block tests. In general, the values obtained are only slightly weaker than those obtained for the wood itself. This result indicates simply that edge-joints can be obtained which are as strong as the wood itself when the proper adhesive and gluing techniques are used.

Literature cited