This research investigated using fiberglass reinforcement to enhance the load-carrying capacity of bolted wood connections. Specimens were prepared from standard 51-by 102-mm (nominal 2- by 4-in.) lumber from the spruce-pine-fir lumber grouping. Matched specimens were reinforced with one, two, or three layers of bi-directional fiberglass cloth. Resulting test specimens were configured as a connection that was in accordance with current design specifications. A total of 80 single-bolt, double-shear connections were tested: 40 with parallel-to-grain and 40 with perpendicular-to-grain loading. Results indicate that connection strength increases as the number of layers of fiberglass reinforcement increases. The ultimate strength of a three-layer reinforced connection was 33 percent greater than the nonreinforced connection for parallel-to-grain loading, and more than twice the strength for perpendicular-to-grain loading. More importantly, the reinforcement changed the mode of failure from an abrupt, catastrophic failure associated with tension perpendicular-to-grain stresses to a ductile failure associated with bearing-type failures.

Failures in wood structures often occur at a connection. Bolted connections often fail by a shear plug or a splitting beneath the bolt caused by tension perpendicular-to-grain stresses as the bolt wedges its way through the wood. Preventing this type of failure would enhance bolted connection capacity and reliability, thus increasing the overall integrity of a timber structure and enabling wood to compete favorably with other engineering materials.

This study examined the technical feasibility of reinforcing the wood at bolted connections with fiberglass and epoxy resin. The scope was limited to one wood species, one type of fiberglass reinforcing system, one epoxy resin, one connection configuration, and three layer configurations. The limited scope was in keeping with the objective of determining technical feasibility.

Several studies have examined how various reinforcing systems contribute to the performance of wood members, exclusive of the connection. Initial studies used metal reinforcement. More recently, fiber-reinforced polymer (FRP) has been investigated. Triantafillou et al. (11) studied nonprestressed and prestressed FRP sheets bonded with epoxy to the tension zone of a wood beam. Rowlands et al. (9) studied tension and flexure of internally reinforced laminated wood. Ten adhesives and several types of fiber reinforcement were evaluated. Results showed an increase up to 45 percent in tensile strength compared to nonreinforced Douglas-fir beams by using 18 percent by volume glass reinforcement. They also noted that “fiber reinforcement could be advantageous in regions of stress concentration (bolted joints, etc.).”

Bulleit (2) reviewed past studies and concluded that reinforcing wood was technically feasible for improving strength and stiffness properties but economically unfeasible. Unidirectional fiberglass was the preferred reinforcing material of the pre-1984 studies that he reviewed. There was no consensus whether to use a woven or nonwoven, strand or mat, reinforcing system. In addition, there was no preferred resin. Most studies used epoxy, but acceptable results were also obtained using phenolic, polyester, and phenol-resorcinol-formaldehyde resins. Only two of the studies summarized by Bulleit related to connection reinforcing.

Spaun (10) tested composite members using western hemlock cores with Douglas-fir veneers and FRP layers between the core and veneers; the members were finger-jointed at midspan. Poplis and Mitzner (8) tested the bolted connection strength of plywood overlaid with FRP. They conducted bolt bearing tests that included varying the plywood thickness, bolt diameter, double- versus single-shear connections, FRP overlay type and glass content, edge distance, torque on fasteners, wet versus dry panel, clean joint versus joint with mastic, and face

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grain direction of the plywood. The use of FRP typically increased strength and stiffness.

Several aspects of the Poplis and Mitzner study are significant for comparison to our study. The FRP wet overlays, of equal thickness on both sides, were polyester resin, and two weights of woven roving fiberglass were used. Three plywood thicknesses and three bolt diameters were tested. The overlaid reinforcement increased the ultimate strength of the connections 54 to 117 percent.

There are several recent studies on FRP-reinforced connections. Meierhofer (6) tested tension and bending of small FRP-spliced specimens; splices were made using three lengths of carbon fibers. No strength increase information was given. Miyatake and Fujii (7) studied the use of FRP-reinforced internal gusset plates for timber structures. Test results indicated that strength increased with length of gusset plate.

Haller et al. (4) studied reinforced bolted connections of densified wood (wood that is thermo-mechanically treated to increase its density). The glass fiber fabric reinforcement was about half the weight of that used in our study and was placed at 45 and 90 degrees to the load direction. Haller et al. found that ultimate strength and ductility were increased about two times.

Larsen et al. (5) studied doweled and nailed connections reinforced with glass fibers glued to the side of the main member. They observed more ductile connection behavior, with some increase in ultimate strength, when compared with nonreinforced connections. They concluded that spacings and end distances can be reduced.

**EXPERIMENTAL PROCEDURE**

A total of 80 single-bolt, double-shear connections were tested; 40 connections were tested with parallel-to-grain loading and 40 with perpendicular-to-grain loading in accordance with ASTM D 5652-95 (1). Each set of 40 tests consisted of 10 replications of four types of reinforced connections: a control having no reinforcement, and one, two, and three layers of fiberglass cloth reinforcement bonded to both wide faces of the specimens (Fig. 1).

The lumber used for the connections was cut from twenty 51-mm by 102-mm by 4.9-m (2-in. by 4-in. by 16-ft.) spruce-pine-fir No. 2 or better species-grouped boards. Anatomical examination determined the species to be lodgepole pine. A transverse vibration nondestructive
method determined the flatwise modulus of elasticity (MOE) of each board. The boards were ranked by MOE and divided into 2 groups of 10 each for the parallel- and perpendicular-to-grain tests. Four matched specimens were cut from each board for the four types of reinforced connections. The boards were cut such that the connection area had no defects.

Both the fiberglass cloth and epoxy adhesive system are commercially available products. The bi-directional woven fiberglass cloth had a unit weight of $6.2 \times 10^{-3}$ kg/mm$^2$ (6 oz./yd.$^2$), an MOE of $46.19 \times 10^3$ MPa (6.7 × 10$^3$ ksi), and a tensile strength of $35.0 \text{ N/mm\, width}$, according to the manufacturer’s technical data. The reinforcing system (adhesive and cloth) was applied in accordance with the manufacturer’s recommendations. One, two, and three layers of fiberglass increased the volume of the specimen by 2.2, 3.3, and 4.6 percent, respectively. The cloth was oriented perpendicular to load direction for all tests.

The bolts were 25.4 mm (1 in.) in diameter for the parallel-to-grain tests and 12.7 mm (0.5 in.) in diameter for the perpendicular-to-grain tests. The smaller diameter bolts were necessary to have adequate end distance in the perpendicular-to-grain tests. All bolts were low carbon steel conforming to SAE 1020 steel, with a minimum yield tensile stress of 310.3 MPa (45 ksi). Bolt lengths were selected to ensure that threads were excluded from bearing against the wood. The ratio of member thickness to bolt diameter was small enough to induce failure in the wood, with minimal bending displacement of the bolt.

Prior to testing, the specimens were stored in a constant temperature and relative humidity room to equilibrate at approximately 12 percent moisture content. Specific gravity of the specimens varied from 0.46 to 0.48. Tension parallel-to-grain (Fig. 2) and compression perpendicular-to-grain (Fig. 3) connection tests were in accordance with ASTM D 5652 (1). Rates of load were applied to achieve failure in 5 to 15 minutes. Two linear variable differential transformers continuously monitored and averaged displacements on both sides of the connection. One of the following defined failures was recorded for each specimen:

- Specimen split under the bolt;
- Load resistance of the connection steadily decreased;
- Displacement of the bolt exceeded 7.62 mm (0.3 in.) or 5.08 mm (0.2 in.) for parallel- and perpendicular-to-grain loading, respectively.

**Results and Discussion**

Load versus displacement curves were generated for each test. We were primarily interested in data on ultimate strength, strength at 5 percent offset, and failure mode. Strength at 5 percent offset is the load at the point where the load versus displacement curve intersects a line that is parallel to the initial part of the plot. This line is offset from the linear part of the plot by 5 percent of the fastener diameter. The 5 percent offset is the current U.S. method for defining the yield strength of a timber connection.

Table 1 summarizes average 5 percent offset and ultimate strength values; Figure 4 shows the complete data for each of the four types of reinforced connections.

![Figure 4a](image)

**Figure 4a.** – Five-percent offset strength of 10 replications for each of 4 types of reinforced connections loaded parallel to the grain.

![Figure 4b](image)

**Figure 4b.** – Ultimate strength of 10 replications for each of 4 types of reinforced connections loaded parallel to the grain.

Average strength increased as the number of fiberglass layers increased. This is particularly significant for those specimens loaded perpendicular to the grain. A comparison of ultimate strength results of three layers of reinforcement with nonreinforced specimens shows an increase of 33 percent for parallel-to-grain loading and more than double for perpendicular-to-grain loading.

The increase in ultimate strength as a result of fiberglass reinforcement was more for the perpendicular-to-grain loading and less for parallel-to-grain loading than that reported by Poplis and Mitzner (8). However, a comparison with our study is not justified because they used 2 to 11 times more fiberglass by weight per unit thickness to reinforce plywood that had plies in both grain directions.

Table 2 summarizes the increase in 5 percent offset and ultimate strength val-

![Figure 4c](image)

**Figure 4c.** – Five-percent offset strength of 10 replications for each of 4 types of reinforced connections loaded perpendicular to the grain.

![Figure 4d](image)

**Figure 4d.** – Ultimate strength of 10 replications for each of 4 types of reinforced connections loaded perpendicular to the grain.
TABLE 1. – Average 5 percent offset and ultimate strength for parallel- and perpendicular-to-grain connection tests.

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Parallel-to-grain</th>
<th>Perpendicular-to-grain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5% offset (kN) Cov</td>
<td>Ultimate (kN) Cov</td>
</tr>
<tr>
<td>None</td>
<td>31.3 (0.14)</td>
<td>7.5 (0.18)</td>
</tr>
<tr>
<td>One layer</td>
<td>35.2 (0.14)</td>
<td>9.6 (0.14)</td>
</tr>
<tr>
<td>Two layers</td>
<td>37.5 (0.15)</td>
<td>10.6 (0.14)</td>
</tr>
<tr>
<td>Three layers</td>
<td>39.4 (0.14)</td>
<td>11.6 (0.13)</td>
</tr>
</tbody>
</table>

a COV = coefficient of variation.

The observed failure modes for specimens loaded parallel to the grain varied, depending on the number of fiberglass layers. All nonreinforced specimens failed by a split beneath the bolt. Approximately half the specimens reinforced with one layer failed by a combination of splitting of the wood and tearing the fiberglass along the split. The remainder of the specimens reinforced with one layer and all the specimens with two or three layers failed by crushing of the wood beneath the bolt.

The observed failure mode for specimens loaded perpendicular to the grain was crushing of the wood under the bolt, for all types of reinforcement.

The fiberglass reinforcement increased the ductility of the connection in both grain directions. This increased ductility is apparent from the load versus displacement curves (Fig. 5).

The effect of the amount of epoxy resin was not studied. Datoo (3) concluded that resins alone contribute little to load-bearing capacity.

CONCLUSIONS

Eighty single-bolt connections were tested using parallel- and perpendicular-to-grain loading. Ten replications were tested for specimens with no reinforcement and one, two, and three layers of fiberglass reinforcing. Test results indicate that connection strength and ductility increase as the number of layers of reinforcement increase.

The largest incremental increase occurred when adding the initial layer of reinforcement to the nonreinforced connection. Additional layers of reinforcement further increased strength, but at a decreasing rate. Average ultimate strength of a three-layer reinforced connection was 33 percent greater than the nonreinforced connection for parallel-to-grain loading and more than double for perpendicular-to-grain loading.

More importantly for parallel-to-grain loading, fiberglass reinforcement changed the mode of failure from an abrupt, catastrophic-type failure associated with tension perpendicular-to-grain stress to a ductile-type failure associated with bearing stress. Two layers of reinforcement were necessary to achieve this change in failure mode. For perpendicular-to-grain loading, no difference in failure mode was observed, but a large increase in strength and ductility did occur.
TABLE 2 – Increase in average strength with each additional layer of reinforcement.

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Parallel-to-grain</th>
<th>Perpendicular-to-grain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5% offset</td>
<td>Ultimate</td>
</tr>
<tr>
<td>1 layer versus none</td>
<td>12.5</td>
<td>14.4</td>
</tr>
<tr>
<td>2 layers versus 1 layer</td>
<td>6.3</td>
<td>8.1</td>
</tr>
<tr>
<td>3 layers versus 2 layers</td>
<td>5.2</td>
<td>7.4</td>
</tr>
</tbody>
</table>

LITERATURE CITED


