THE PENNSYLVANIA STATE UNIVERSITY
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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

MOMENT TIMBER FRAME CONNECTIONS
LOCALLY REINFORCED WITH GLASS FIBER RODS

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Wood has a high strength to weight ratio and the capacity to absorb large amounts of energy because it can undergo large deformations before seeing a decline in strength. This gives it great potential for seismic areas, where it can perform better than concrete or steel. The biggest constraint of the material is the strength of the connections, where large distances must be maintained between connectors in order to prevent wood from failing in tension perpendicular to the grain. This paper investigates the effectiveness of glass fiber rods in reinforcing wood and the importance of dowel spacing in reinforced wood connections.
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Chapter 1

Introduction

Timber construction offers numerous benefits for structural applications. It is a lightweight material and has a high strength to weight ratio, and can undergo large deformations while retaining significant structural strength. This allows wood structures to dissipate large amounts of energy, which makes them especially effective for seismic areas. In addition, heavy timber structures, which are made with fewer and larger members than the light timber framing commonly found in the United States, have superior fireproof characteristics. Wood’s main weakness is in tension perpendicular to the grain, where it is weak and fails in a brittle manner. Connections in heavy timber structures are heavily stressed and subject to significant bending moments, so they limit the strength of the structure.

While increasing the number of dowels improves connection strength, dowel spacings are limited because the holes drilled for them weaken the wood and allow for failure. Minimum spacings, edge distances, and end distances have been set using known wood strength, but because local reinforcement of the connections improves both the strength and the ductility of wood, it is expected that reduced spacings could be permitted when the connections are reinforced. (American Forest and Paper Association 2005)

Wood can fail in direct tension parallel to the grain and in group tear out, where it fails in shear in line with pins and in tension between them. The controlling failure modes are normally splitting in tension perpendicular to the fibers or dowel bearing, where the dowels crush the wood without causing it to fracture. See Figure 1-1 on the following page for a diagram of typical wood
failure modes. In order to permit reduced dowel spacings, the reinforcement must improve wood’s strength in failure modes where it normally performs the worst: dowel bearing and tension perpendicular to the fibers.

![Typical wood failure modes](image)

*Figure 1-1: Typical wood failure modes (Heiduschke 2006, 5).*

This thesis examines reinforced wood L connections consisting of 6.4 and 9.5 mm dowels spaced 15.9 and 12.7 mm apart, respectively. It evaluates the effectiveness of reinforcement in connections with each dowel diameter and compares the performance of connections with different dowel diameters both with reinforcement and without. Hysteresis curves and envelopes, cumulative energy dissipated plots, and T tests were all used to evaluate the tests.
Chapter 2

Literature Review

Wood’s high strength weight ratio and its ability to undergo large deflections without losing structural capacity give it favorable structural properties. Its most significant weakness is the low strength in tension perpendicular to the grain. Wood will often fail catastrophically in this mode. The strength of wooden moment frames is usually limited by that of the connections, which are weakened by the presence of holes drilled for connectors and subject to tensile loads perpendicular to the grain in order to resist moments. The number of bolts or dowel pins that can be placed is limited by spacings required to prevent the wood from splitting. Wider bolt spacings will allow higher loading per dowel and more ductile failure, but will also require larger connections, which is a problem aesthetically and economically (Madsen 2000). The National Design Specification (NDS) reports spacing requirements in terms of the diameter of dowels, or D. It requires an edge distance of 1.5D for loading parallel to the grain and for the unloaded edge with loading perpendicular to the grain, and 4D for the loaded edge in the latter case. It requires an end distance of 7D for tension members loaded parallel to the grain and 4D for compression members and members loaded perpendicular to the grain. (American Forest and Paper Association 2005).

The simplest solution to this problem conceptually is to increase the cross section of the frame members in the vicinity of the connections, although this is costly and often aesthetically unacceptable. As a result, various methods are being tested to reinforce the wood in order to give it higher bearing strength and a more ductile behavior, such as providing reinforcement in order to prevent splitting in tension perpendicular to the grain. The primary goal of this is to allow
smaller edge and end distances to be employed so that greater strength and stiffness can be achieved with a smaller connection.

Wood exhibits brittle failure in tension perpendicular to the grain in the form of splitting. This characteristic can be improved by reinforcing the wood with a number of materials, the most common being plywood or steel, to make the wood both stronger and more ductile. One method investigated by Heimeshoff (1977) involved simply placing screws through timber members perpendicular to the grain. Recent investigations have explored the use of glass fiber and carbon fiber composites in fabrics glued to the surface of wooden structural members.

**Plywood Reinforced Joints**

Bouhaïr et al. (2007) investigated doweled moment-resisting timber joints reinforced with plywood panels. Reinforcement was found to increase strength of the connections by about 35%. Load in the dowels was found to be perpendicular to the radius of the circle about which the dowels are placed, and loads for all dowels were found to be uniformly distributed in spite of the orthotropy of the wood. This means that the center of the connection can be taken to be the center of rotation.

Guan and Rodd (2001) investigated local reinforcement of timber joints with densified veneer plywood. It was found that ductility was good for single-dowel tension joints, but that stiffness was low. Stiffness was improved with the addition of densified veneer wood, although this reduced ductility. Densified veneer wood had a significant improvement on the performance of moment-resisting joints, however, as action between the dowels caused failure in connections made with unreinforced wood. 12 millimeter thick plywood was necessary in order to provide adequate transfer of shear forces from the plywood to the hollow dowels used in the experiments, which exhibit a ductile failure similar to a configuration with multiple smaller dowels.
Bouchair et al. (1996) found that reinforcing joints with 12 mm thick plywood can double ultimate capacity. High stiffness \( E/K_0 \) was found to be more important to strength of wood than the ratio of \( K_0 \) to \( K_90 \), or the stiffness parallel and perpendicular to the grain, respectively.

**Glass Fiber Textile Reinforced Joints**

Kasal et al. (2004) investigated the seismic performance of laminated timber frames with fiber-reinforced joints. Ordinary wood frames, frames with fiber reinforcement, and frames with fiber and densified wood reinforcement were tested using one-directional sinusoidal sweeps, free harmonic vibration, and 2-directional arbitrary loading simulating seismic conditions. Specimens were found to have good load bearing capacity at displacements beyond those acceptable for steel or concrete structures. They also exhibited high structural damping due to the hysteretic behavior of the connections. The connections with densified wood maintained stiffness better.

Heiduschke (2006) investigated seismic performance of moment-resisting timber frames with densified and textile reinforced connections. He found that textile reinforcement was effective in reinforcing wood to make it undergo larger loads and fail in a more ductile manner. In addition, the connections retained favorable load carrying capacity after the maximum moment was reached. Densification increased strength, stiffness, and energy dissipation capacity. (Heiduschke 2006)

Small-scale and full-scale joints failed at similar rotations and with similar failure modes. The materials are non-linear and one-to-one mapping is impossible, so a mapping function was used that produced error at small displacements. The mapping functions were relatively accurate for larger displacements and the overall amount of energy dissipated, for which small displacements are unimportant. (Heiduschke, 2006) Small-scale specimens, while not a perfect
indicator of the performance of a large-scale specimen, were found to fail in similar modes and at similar loadings to larger ones, which makes them useful for preliminary testing such as to determine joint configuration and for model validation.

Haller et. al. (2006) investigated textile reinforcements for wood composites. Fiberglass was woven or stitch-bonded into textiles, which were then applied to the surface of wooden members using an epoxy resin in the area of the joints. It was found that highly reinforced connections failed in the wood-textile interface, making the adhesive the limiting material for this configuration. Textiles with a loop structure were found to be less ductile than knitted ones, though they also had a higher stiffness. Densified and undensified wood were used, and the combination of densification and reinforcement tripled capacity compared to the undensified, unreinforced reference specimens. Thick sections needed to be laminated with multiple layers of textile within the specimen in order for it to effectively reinforce the wood.

Haller et al. (1998) found that both reinforcement and densification improve the dowel bearing strength of wood in compression and tension parallel and perpendicular to the grain. Densification and reinforcement combined were found to be far more effective than either treatment alone. Densified unreinforced wood was found to be less ductile than ordinary wood, but all other configurations showed improvements in ductility as well as strength.

Chen et al. (1994) tested a connection in a warren truss which, when unreinforced, failed at stress levels well below the allowable stress by splitting from tension perpendicular to the grain. They applied fiberglass fabrics to the truss members with an epoxy resin. This technique was successful in reinforcing the connections, yielding greater stiffness and ductility, and a 70% increase in ultimate strength. When optimally reinforced, the truss connection failed by yielding of the dowel joints.

Kharouf et al. (1999) performed fracture modeling of bolted connections in wood and composites. This report found that there is currently no fracture model for orthotropic materials
that works for all cases. Models currently used are semi-empirical and are only valid for specific cases.

Johansen’s theory (1949) does not consider failure modes such as splitting or withdrawal resistance. The former can allow loads to be higher than those predicted by Johansen’s theory because placing the rods in direct tension increases their shear resistance. On the other hand, splitting in the wood will cause wood to fail before the failure modes Johansen considered and at lower loads than he predicted. Full plastic behavior of both timber and steel components is only achieved in dowelled joints when other failure modes, such as splitting are excluded. (Madsen 2000)

Chen (1998) found that for textile reinforced wood, an end distance of 5 d displayed no decrease in strength, while at 2.5 d the connection failed before the design capacity was reached. This indicates that current spacing requirements are in fact overly conservative, but the influence connection geometry has on strength needs to be studied more.

An important consideration for fiber reinforced wood composites is the bond between the two materials. According to Richter et al. (2005), polyurethane and epoxy adhesives are both effective in bonding dissimilar materials with high strength bonds. Advantages of polyurethane adhesives are their low cost, viscosity, and ease of use.

While prior research has established the effectiveness of reinforcement in improving strength and ductility and in permitting closer dowel spacing, it was not clearly established what dowel spacings can be achieved using the reinforcement or at what dowel spacing reinforcement would be most effective.
Chapter 3

Materials

This thesis investigates the strength of wood frame connections using 6.4 mm and 9.5 mm (1/4 inch and 3/8 inch) steel dowels, reinforced with 3.18 mm (1/8 inch) glass fiber rods placed perpendicular to the fibers in the wooden frame members. Wood used is fast-grown southern yellow pine. This wood has a brittle failure mode that is favorable for this investigation.

Southern Yellow Pine

Southern yellow pine was tested to determine modulus of elasticity and yield strength in tension perpendicular and parallel to the grain, and for dowel bearing strength and modulus. The tensile tests did not produce realistic values for modulus of elasticity or exhibit a true failure, so they are not reported. The USDA Forest Products Laboratory (1987) reports a modulus of elasticity of 1370 MPa (1980 ksi) See Appendix A for results from the dowel bearing tests.

Glass Fiber Rods

According to TAP Plastics (n.d.), the glass fiber rods used for this experiment contain 75% glass by weight and have a tensile strength of 827 MPa (120 ksi) and a tensile modulus of 41000 MPa (6000 ksi).
Polyurethane adhesive

Vick and Okkonen (1998) found that polyurethane adhesives were found to have minimum shear strength of 11.38 MPa (1650 psi). These adhesives function by bonding with free hydrogen groups and by having a small particle size that can flow into porous materials, while also readily forming hydrogen bonds with drastically different materials (Richter and Steiger 2005). One-part polyurethane adhesives are becoming the most common because these are simpler to use than 2-part polyurethanes and epoxies, and because they react with moisture. Directions indicate that surfaces should be dampened before applying these adhesives, but they can also draw out and react with moisture naturally occurring in wood. The strength of polyurethane adhesives decreases when they bond across gaps, limiting acceptable gap width to 0.3 mm. (Richter and Steiger 2005) The specimens used for this paper had gaps of 0.20 mm (1/128 inches), so use of polyurethane adhesive is acceptable.
Chapter 4

Methodology

Specimen Configurations

Specimens have six (6) pins each with diameters of either 6.4 mm (1/4 inch) or 9.5 mm (3/8 inch), arranged with their center points equally spaced about a 22.2 mm (0.875 in) radius circle. Six specimens with each pin diameter were tested both with and without reinforcement, for a total of 24 specimens. The four configurations were numbered as follows: Configuration 1 with 9.5 mm dowels and reinforcement, Configuration 2 with 9.5 mm dowels and no reinforcement, Configuration 3 with 6.4 mm dowels and reinforcement, and Configuration 4 with 6.4 mm dowels and no reinforcement.

The specimens with 6.4 mm dowels have a dowel spacing of 15.9 mm (0.625 in), while the 9.5 mm dowels have a spacing of 12.7 mm (0.5 in). Glass fiber rods were placed through specimens with one located in each space between two dowels. See Figures 4-1 and 4-2 on the following pages for detailed views of the connections, and Appendix G for complete shop drawings. These figures show the placement of dowels and glass fiber rods. In these figures, the central members are placed horizontally and have 6 rods placed through them, while the side members have four. It can be seen that the rods are centered between dowels, and that the 9.5 mm dowel configuration does not have adequate clearances between the pins to provide space for a rod to pass through intact.
Figure 4-1: Layout of reinforcement for connections with 9.5 mm dowels (dimensions in mm).

Figure 4-2: Layout of reinforcement for connections with 6.4 mm dowels (dimensions in mm).
The specimens were attached to an MTS load frame as seen below and loaded vertically in order to induce a moment in the joint.

Figure 4-3: View of specimen on MTS load frame.
Test Method

The ASTM E-2126-09 (2010) test method C, otherwise known as the CUREE protocol, was used for this test. All displacements in the protocol are set in proportion to the first major event, or $\Delta$, which was set at the displacement at which the weakest connection configuration, unreinforced with 9.5 mm dowels, failed. This displacement was determined to be 4.163 mm (0.1639 in). A maximum displacement of 2.5 $\Delta$ or 10.41 mm (0.4098 in) was reached with the test protocol. Triangular waveforms were programmed using a constant rate of 8.326 mm (0.3278 inches) per second, with maximum displacements increasing from 5% to 250% of $\Delta$. See Table 4-1 for amplitudes and rates used for this test.

Table 4-1: Rate and amplitude values used for cyclic load protocol.

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</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3</td>
<td>200</td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>33.65</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>3</td>
<td>250</td>
<td>5</td>
<td>7.5</td>
<td>12.5</td>
<td>46.15</td>
</tr>
</tbody>
</table>
**Instrumentation**

Load was measured from an LVDT attached to the MTS. Displacement was measured from the MTS and from a Celesco string potentiometer. It was expected that the string potentiometer would provide more accurate data because it was closer to the joints and rigidly attached to the specimens, but error in the string potentiometer readings made the MTS displacement readings more valid. Custom cables were made for the tests, and schematic drawings of these can be found in Appendix G.

**Data Processing**

Data was retrieved for a minimum of 6 specimens per configuration. The effects of the dowel size and of the reinforcement were then evaluated by comparing the envelopes of hysteresis curves within each configuration and the average envelopes between different configurations, and by comparing cumulative energy dissipated versus time in the same manner. A t-test was performed to evaluate the significance of the variation between different cumulative energy dissipated values.

![Figure 4-3: Schematic connection diagram showing positive (left) neutral (center) and negative (right) rotations.](image)
The diagram above shows a schematic view of the corner specimens in a neutral position and with positive and negative rotations. The connections are fixed to the MTS at points A and B, and the center of the joint, taken as the center of rotation, is located at point C. The connection at point A remains fixed during the test, while that at point B moves up and down. The distance \( d \) is given as MTS displacement, and \( c \) is a fixed value, the length of one side of the connection.

Angle \( e \) is known to be 45 degrees because the joint angle is 90 degrees and the connection is symmetrical. When length \( d \) is positive, the angle \( e' \) closes, and when it is negative the angle opens. The lengths of \( a \) and \( a' \) can be found using the following equations:

\[
a = \frac{\sqrt{2}}{2} \times c
\]

\[
a' = a - \frac{d}{2}
\]

Load is applied vertically at points A and B’. The angle \( e' \) (half of the joint angle) can now be found using trigonometry and the moment arm \( b' \) can be determined using the Pythagorean Theorem as seen below:

\[
e = \sin^{-1} \left( \frac{a}{c} \right)
\]

\[
b' = \sqrt{c^2 - a'^2}
\]

Cumulative energy was determined by calculating the area under the hysteresis (moment-rotation) curves using the trapezoidal rule as seen below:

\[
E = \sum \frac{m_1 + m_2}{2} \times \Delta \phi
\]

Where \( m_1 \) and \( m_2 \) are energy at two data points and \( \Delta \phi \) is the change in the rotation angle between these two points.
Specimen Construction

Placing the glass fiber rods for these specimens was difficult because in the central members clearances between the pins were sometimes as narrow as 1.59 mm (1/16 inch). The rods have a diameter of 3.18 mm (1/8 inch), which means that if placed perfectly through the center of the space between the pins, a quarter of its diameter would be cut when the holes were drilled for the dowels. However, the jigs used to place the holes did not place the steel pins and the glass fiber rods simultaneously and they did not align perfectly with each other. As a result, many rods were cut even where clearances were wider than the diameter of the dowels. In addition, southern yellow pine has a large difference in density between early wood and late wood, and the grain was rarely aligned perpendicular to the holes being drilled. As a result, the drills shifted parallel to the grain lines and produced holes that moved far off center on the side where they exited the specimens.
Chapter 5

Results

Hysteresis Curves

See Figure 5-1 below for a typical hysteresis curve. Note that this curve shows increasing strength as the test progresses, although some specimens show declines early in testing. See Appendix B for all hysteresis curve plots.

Figure 5-1: Typical hysteresis curve.
Hysteresis Envelopes

Envelopes were formed to determine the distribution of hysteresis curves within the samples of each configuration. Envelopes for all specimens can be found in Appendix C. An average was determined for each configuration in order to compare results between different configurations. These averages can be seen below in Figure 5-2. It is evident that the larger diameter dowels provide greater stiffness at low displacements, while the smaller diameter provides greater ductility. The 6.4 mm reinforced connections also carry higher loads at larger displacements than their unreinforced counterparts.

Figure 5-2: Comparison of average hysteresis envelopes for Configurations 1-4.
Cumulative Energy Dissipated

The average cumulative energy dissipated values can be seen below in Figure 5-3. Cumulative energy dissipated plots for all specimens can be found in Appendix D. Note that reinforcement appears to provide a modest increase in energy dissipated for both configurations at larger displacements, although between about 15 and 30 seconds the 6.4 mm unreinforced specimens perform better. The same is true for 9.5 mm pins from 25 to 35 seconds. At small displacements toward the beginning of the test, T values are very close for connections with the same dowel diameter, especially for the 9.5 mm configurations.

Figure 5-3: Average cumulative energy dissipated for Configurations 1-4.
As seen above, differences in energy dissipation between different specimen configurations are minor. Reinforcement had a negligible effect especially in the 9.5 mm specimens at smaller displacements. In the larger specimens, reinforcement appears to have adversely affected energy dissipation until displacements are large.

Table 5-1 below shows the times, step numbers, and amplitude at which the specimen failed. Note that all specimens are not shown because the test did not fail all specimens used. No specimens with reinforcement and 6.4 mm (1/4 inch) dowels failed in the original cyclic tests. Specimens 1-1, 1-2, and 1-4 failed in approximately the same amounts of time, and in the same steps, as specimens 2-1 through 2-5. In fact, 1-1 failed earlier than the others although this specimen is reinforced. As a result, this test fails to show an improvement in behavior due to reinforcement for specimens with 9.5 mm dowels. Of the 6.4 mm dowel specimens, only specimen 4-2 was failed successfully, as 4-1, 4-3, and 4-4 were tested with displacements only reaching the first major event ($\Delta$, or 0.1639 mm).

Table 5-1: Time, Cycle number, and Displacement values at failure.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Failure Time (sec)</th>
<th>Failure Cycle</th>
<th>Amplitude (% FME)</th>
<th>Amplitude (mm)</th>
<th>Angle (deg)</th>
<th>Moment (kN*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1 (9.5 mm R)</td>
<td>11.8</td>
<td>8</td>
<td>100</td>
<td>4</td>
<td>1.20</td>
<td>336</td>
</tr>
<tr>
<td>1-2 (9.5 mm R)</td>
<td>18.6</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>607</td>
</tr>
<tr>
<td>1-3 (9.5 mm R)</td>
<td>18.6</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>513</td>
</tr>
<tr>
<td>1-4 (9.5 mm R)</td>
<td>18.5</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>581</td>
</tr>
<tr>
<td>1-5 (9.5 mm R)</td>
<td>18.5</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>427</td>
</tr>
<tr>
<td>1-6 (9.5 mm R)</td>
<td>18.6</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>359</td>
</tr>
<tr>
<td>2-1 (9.5 mm UR)</td>
<td>18.5</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>234</td>
</tr>
<tr>
<td>2-2 (9.5 mm UR)</td>
<td>18.3</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>374</td>
</tr>
<tr>
<td>2-3 (9.5 mm UR)</td>
<td>18.4</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>590</td>
</tr>
<tr>
<td>2-5 (9.5 mm UR)</td>
<td>16.9</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>543</td>
</tr>
<tr>
<td>2-6 (9.5 mm UR)</td>
<td>18.2</td>
<td>9</td>
<td>150</td>
<td>6</td>
<td>1.79</td>
<td>410</td>
</tr>
<tr>
<td>4-2 (6.35 mm UR)</td>
<td>24.6</td>
<td>10</td>
<td>200</td>
<td>8</td>
<td>2.38</td>
<td>449</td>
</tr>
<tr>
<td><strong>9.5 mm R Avg</strong></td>
<td><strong>17.4</strong></td>
<td><strong>9</strong></td>
<td><strong>142</strong></td>
<td><strong>6</strong></td>
<td><strong>1.69</strong></td>
<td><strong>471</strong></td>
</tr>
<tr>
<td><strong>9.5 mm UR Avg</strong></td>
<td><strong>18.0</strong></td>
<td><strong>9</strong></td>
<td><strong>150</strong></td>
<td><strong>6</strong></td>
<td><strong>1.79</strong></td>
<td><strong>430</strong></td>
</tr>
</tbody>
</table>
While the reinforced and unreinforced specimens with 9.5 mm dowels all failed at similar
displacements, the loadings of the reinforced ones are higher. The failure moments for 9.5 mm
specimens have a T value of 0.512, which is far short of the value of 1.476 required for a 90%
confidence interval. Thus no significant difference was found. As insufficient data was produced
for failures in the specimens with 6.4 mm dowels, more investigation will be required to
determine the impact of reinforcement on failure loads for this configuration.

Failure modes summary

As seen in the photo above, Specimen 2-2 failed by splitting along the grain, but at an
angle between pins. The other side member and the main member failed purely in tension

Figure 5-4: Connection failure on Specimen 2-2.
perpendicular to the grain. Below is Specimen 2-6, which exhibited a failure behavior in tension perpendicular to the grain. Specimen 2-1 failed both in tension perpendicular and parallel to the grain, a mode more typical of the reinforced specimens with the same dowel configuration. Specimens 2-4 and 2-5 split in the main member, while specimen 2-3 failed in both the main member and one of the side members, and exhibited failure planes along the grain and angled to run between dowels.

As seen below, Specimen 1-6 failed in the side members only, in tension parallel to the grain only. Reinforcement of this specimen was effective in changing the failure mode, but did not provide a notable increase in strength. Specimen 1-4, on the other hand, failed in the main member only, in tension perpendicular to the grain, and withdrawal of the reinforcing rods is
evident. Similar behavior was seen in Specimens 1-1, 1-2, 1-3. Specimen 1-5 failed along a complex bent surface that ran between pins and sometimes involved tension parallel to the grain.

Specimens 4-2 and 4-5 both failed in tension parallel to the grain. Unlike the similar specimens with smaller dowel pins, failure planes were aligned with the grain and did not bend to pass through more dowel holes. Note that Specimen 4-5 was a misfabrication whose connections were loose. This makes the energy dissipated inconsistent with other specimens, although the ultimate failure mode was consistent. As a result it is worth examining due to the limited number of specimens in this configuration that were tested to failure.
X-ray Imaging

X-ray images were taken of all specimens showing the locations of steel dowel pins after testing and are listed in Appendix E. As can be seen there, only the Configuration 3 connections, or those with 6.4 mm dowels and reinforcement, showed dowel yielding. These specimens did not fail, but there is clear evidence of a plastic hinge in them.

T Test Plots

T tests were performed comparing the cumulative energy dissipated between reinforced and unreinforced specimens with the same diameter dowels, and between both reinforced and both unreinforced configurations. Reinforced connections were expected to perform better than unreinforced ones and those with 6.4 mm dowels to perform better than those with 9.5 mm dowels, and the T-test was calculated such that the values will be positive when this is the case. The T test formula was entered according to the equation below:

\[
t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_1^2}{m} + \frac{s_2^2}{n}}}
\]

where:

- \( t = \) T value
- \( \bar{x} = \) Sample 1 mean
- \( \bar{y} = \) Sample 2 mean
- \( s_1 = \) Sample 1 variance
- \( s_2 = \) Sample 2 variance
- \( m = \) Number of specimens in sample 1
- \( n = \) Number of specimens in sample 2
T values for 90 and 95% confidence intervals were chosen from a T table (Devore 2004) using the number of degrees of freedom \( \nu \) determined with the following equation:

\[
\nu = \frac{(\frac{s^2_1}{m} + \frac{s^2_2}{n})^2}{\left(\frac{s^2_1}{m}\right)^2 + \left(\frac{s^2_2}{n}\right)^2}
\]

The T value plots are seen below in Figures 5-7 through 5-10.

Figure 5-7: Comparison of 9.5 mm specimens.

As shown above, the effectiveness of reinforcement is highly variable at low displacements, and does not indicate a consistent improvement in structural performance.
This T-test indicates that reinforcement of this configuration degrades the structure slightly at low displacements, while improving the performance significantly at higher ones.

Figure 5-8: Comparison of 6.4 mm specimens.

Figure 5-9: Comparison of reinforced specimens.
As might be expected, this test shows that reinforced specimens with larger dowels perform better at lower displacements, while those with smaller ones, and thus larger dowel spacings, perform better at higher displacements. It shows with 95% confidence that the performance of reinforced specimens with 9.5 mm dowels was better from about 5 to 25 seconds, or at amplitudes from about 30% to 150% of the first major event.

Figure 5-10: Comparison of unreinforced specimens.

A comparison of unreinforced specimens shows a similar trend to the previous T-test. Usable T values were not determined beyond 100% of the first major event, but the 9.5 mm dowels perform better starting at approximately 8 seconds, at a displacement of 70% of the first major event.
Below is a summary table of T values by amplitude in percent of First Major Event. Because T values fluctuate significantly within steps, the minimum and the maximum of the absolute values of the T values were both reported. Failure times were determined from the Moment-time plots found in Appendix F. The minimum T value for any configurations and steps in which the sign of the T value changed was taken as 0. Values that are above the critical T value for 90% confidence are shaded light grey, while those that satisfy 95% confidence are shaded dark grey.

Table 5-2: Summary of T Values.

<table>
<thead>
<tr>
<th>% FME</th>
<th>Condition Held Constant</th>
<th>Reinforced</th>
<th>Unreinforced</th>
<th>9.5 mm</th>
<th>6.4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>min</td>
<td>0.93</td>
<td>0</td>
<td>0.87</td>
<td>0.21</td>
</tr>
<tr>
<td>5</td>
<td>max</td>
<td>0.10</td>
<td>1.20</td>
<td>1.52</td>
<td>0.89</td>
</tr>
<tr>
<td>7.5</td>
<td>min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7.5</td>
<td>max</td>
<td>2.08</td>
<td>1.72</td>
<td>1.86</td>
<td>1.58</td>
</tr>
<tr>
<td>10</td>
<td>min</td>
<td>0</td>
<td>0</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>max</td>
<td>1.68</td>
<td>1.78</td>
<td>1.57</td>
<td>1.37</td>
</tr>
<tr>
<td>20</td>
<td>min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>20</td>
<td>max</td>
<td>3.38</td>
<td>2.17</td>
<td>1.49</td>
<td>1.55</td>
</tr>
<tr>
<td>30</td>
<td>min</td>
<td>1.13</td>
<td>0</td>
<td>0</td>
<td>0.96</td>
</tr>
<tr>
<td>30</td>
<td>max</td>
<td>5.48</td>
<td>2.32</td>
<td>1.67</td>
<td>4.47</td>
</tr>
<tr>
<td>40</td>
<td>min</td>
<td>1.59</td>
<td>0</td>
<td>0</td>
<td>1.11</td>
</tr>
<tr>
<td>40</td>
<td>max</td>
<td>5.30</td>
<td>3.49</td>
<td>2.36</td>
<td>3.28</td>
</tr>
<tr>
<td>70</td>
<td>min</td>
<td>1.95</td>
<td>0</td>
<td>0</td>
<td>0.39</td>
</tr>
<tr>
<td>70</td>
<td>max</td>
<td>5.36</td>
<td>5.62</td>
<td>1.93</td>
<td>3.34</td>
</tr>
<tr>
<td>100</td>
<td>min</td>
<td>3.13</td>
<td>2.97</td>
<td>0</td>
<td>0.32</td>
</tr>
<tr>
<td>100</td>
<td>max</td>
<td>5.03</td>
<td>7.38</td>
<td>1.13</td>
<td>1.97</td>
</tr>
<tr>
<td>150</td>
<td>min</td>
<td>2.88</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>150</td>
<td>max</td>
<td>4.70</td>
<td>N/A</td>
<td>0.62</td>
<td>N/A</td>
</tr>
<tr>
<td>200</td>
<td>min</td>
<td>0.78</td>
<td>N/A</td>
<td>0.23</td>
<td>N/A</td>
</tr>
<tr>
<td>200</td>
<td>max</td>
<td>3.07</td>
<td>N/A</td>
<td>1.23</td>
<td>N/A</td>
</tr>
<tr>
<td>250</td>
<td>min</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>250</td>
<td>max</td>
<td>1.40</td>
<td>N/A</td>
<td>1.18</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Chapter 6

Conclusion and Recommendations

The expected result of this test was that reinforcement would improve the performance of connections with both 6.35 and 9.5 mm dowels, and that the improvement would be more significant with the larger dowels as a primary benefit of reinforcement is allowing reduced dowel spacings. The tests employed here indicate that increasing dowel spacing is significantly more effective than adding reinforcement. No significant differences were found due to the reinforcement. The only comparison that did produce a significant difference was that the larger dowels performed better starting at 40% to 70% of the first major event, and in the reinforced case, up to 150%. More testing will be necessary to determine the upper limit at which this is the case for the 6.4 mm dowels, and to produce meaningful data with which to compare these frames at failure loadings.

The fact that Specimen 4-2 failed at a higher displacement than the specimens with larger dowels suggests that edge distance and end distance have more of an effect at these configurations than the reinforcement does, although one specimen is inadequate to verify this.

Recommendations

A number of conditions could have been improved in these tests. Continuing the cyclic loading to larger displacement values that would have failed all specimens would give more information about ultimate load-carrying capacity. In addition, joint configurations could have been modified in order to prevent cutting of the glass fiber reinforcing rods. While a four-pin connection easily provides clearances through which the rods can be placed, the six-pin
configurations did not. Limited precision of drills and the tendency of the drill bits to deflect in order to avoid denser latewood further exacerbated this problem. In addition, some reinforced specimens failed at the bond between the wood and the reinforcement. This could be due to insufficient structural properties of the polyurethane adhesive or gaps in the bond. Refining the installation of glass fiber rods to improve this bond would help to make the reinforcement more effective.
References


TAP Plastics. Fiberglass reinforced plastic pultruded rod and bar. 


Appendix A

Material Testing Results

Dowel Bearing Tests

Dowel bearing tests were performed according to ASTM D-5764-97A (2007). Holes were drilled through wood from the same source as that which made the connection specimens, and then it was cut through the center of the hole to create a semicircular groove. These grooves were sized at 6.35 and 9.53 mm to match the diameters of the rods used in the corner connections. Rods were then placed in the grooves and they were loaded at a rate of 18.26 mm (0.72 in) per second. See Figure F-1 below for a typical test setup.

Figure A-1: Typical dowel bearing test configuration.
Two variations on the test were used. In one, the specimens were loaded in the longitudinal direction, and in the other, they were loaded perpendicular to it. Seven specimens were loaded in the longitudinal direction, labeled A through G, of which A through C have 6.35 mm dowels and D through G have 9.53 mm dowels. Photographs of these specimens can be seen below in Figures F-2 through F-8.

Figure A-2: Longitudinal dowel bearing specimen A (6.35 mm dowels).
Figure A-3: Longitudinal dowel bearing specimen B (6.35 mm dowels).

Figure A-4: Longitudinal dowel bearing specimen C (6.35 mm dowels).
Figure A-5: Longitudinal dowel bearing specimen D (9.53 mm dowels).

Figure A-6: Longitudinal dowel bearing specimen E (9.53 mm dowels).
Figure A-7: Longitudinal dowel bearing specimen F (9.53 mm dowels).

Figure A-8: Longitudinal dowel bearing specimen G (9.53 mm dowels).
Five specimens were loaded perpendicular to the longitudinal direction, labeled 1 through 5. Of these, Specimens 1 through 3 had 9.53 mm dowels and specimens 4 and 5 had 6.35 mm dowels. Figures F-9 through F-13 show these specimens.

Figure A-9: Transverse dowel bearing specimen 1 (9.53 mm dowels).

Figure A-10: Transverse dowel bearing specimen 2 (9.53 mm dowels).
Figure A-11: Transverse dowel bearing specimen 3 (9.53 mm dowels).

Figure A-12: Transverse dowel bearing specimen 4 (6.35 mm dowels).
The stress-displacement curves can be found below in Figures F-14 and F-15. The dowel bearing moduli were found by plotting a linear regression on the linear portion of the average stress-displacement curve. The dowel bearing moduli were found to be 15.5 N/mm$^3$ perpendicular to the longitudinal direction and 35.3 N/mm$^3$ in the longitudinal direction.

Figure A-13: Transverse dowel bearing specimen 5 (6.35 mm dowels).
Figure A-14: Results from dowel bearing test perpendicular to longitudinal direction.

Figure A-15: Results from dowel bearing test in longitudinal direction.
Appendix B

Hysteresis Curves

Figure B-1: Hysteresis Curve for Specimen 1-1 (9.53 mm R).

Figure B-2: Hysteresis Curve for Specimen 1-2 (9.53 mm R).
Figure B-3: Hysteresis Curve for Specimen 1-3 (9.53 mm R).

Figure B-4: Hysteresis Curve for Specimen 1-4 (9.53 mm R).
Figure B-5: Hysteresis Curve for Specimen 1-5 (9.53 mm R).

Figure B-6: Hysteresis Curve for Specimen 1-6 (9.53 mm R).
Figure B-7: Hysteresis Curve for Specimen 2-1 (9.53 mm UR).

Figure B-8: Hysteresis Curve for Specimen 2-2 (9.53 mm UR).
Figure B-9: Hysteresis Curve for Specimen 2-3 (9.53 mm UR).

Figure B-10: Hysteresis Curve for Specimen 2-4 (9.53 mm UR).
Figure **B-11**: Hysteresis Curve for Specimen 2-5 (9.53 mm UR).

Figure **B-12**: Hysteresis Curve for Specimen 2-6 (9.53 mm UR).
Figure B-13: Hysteresis Curve for Specimen 3-1 (6.35 mm R).

Figure B-14: Hysteresis Curve for Specimen 3-2 (6.35 mm R).
Figure B-15: Hysteresis Curve for Specimen 3-3 (6.35 mm R).

Figure B-16: Hysteresis Curve for Specimen 3-4 (6.35 mm R).
Figure B-17: Hysteresis Curve for Specimen 3-6 (6.35 mm R).

Figure B-18: Hysteresis Curve for Specimen 4-1 (6.35 mm UR).
Figure B-19: Hysteresis Curve for Specimen 4-2 (6.35 mm UR).

Figure B-20: Hysteresis Curve for Specimen 4-3 (6.35 mm UR).
Figure B-21: Hysteresis Curve for Specimen 4-4 (6.35 mm UR).
Appendix C

Hysteresis Envelopes

Figure C-1: Hysteresis envelopes for Configuration 1 (9.53 mm R).

Figure C-2: Hysteresis envelopes for Configuration 2 (9.53 mm UR).
Figure C-3: Hysteresis envelopes for Configuration 3 (6.35 mm R).

Figure C-4: Hysteresis envelopes for Configuration 4 (6.35 mm UR).
Appendix D

Cumulative Energy Dissipated Plots

Figure D-1: Cumulative energy plots for Configuration 1 (9.53 mm R).

Figure D-2: Cumulative energy plots for Configuration 2 (9.53 mm UR).
Figure D-3: Cumulative energy plots for Configuration 3 (6.35 mm R).

Figure D-4: Cumulative energy plots for Configuration 4 (6.35 mm UR).
Appendix E

X-ray Images

Figure E-1: X-ray image of Specimen 1-1 (9.53 mm R).

Figure E-2: X-ray image of Specimen 1-2 (9.53 mm R).
Figure E-3: X-ray image of Specimen 1-3 (9.53 mm R).

Figure E-4: X-ray image of Specimen 1-4 (9.53 mm R).
Figure E-5: X-ray image of Specimen 1-5 (9.53 mm R).

Figure E-6: X-ray image of Specimen 1-6 (9.53 mm R).
Figure E-7: X-ray image of Specimen 2-1 (9.53 mm UR).

Figure E-8: X-ray image of Specimen 2-2 (9.53 mm UR).
Figure E-9: X-ray image of Specimen 2-3 (9.53 mm UR).

Figure E-10: X-ray image of Specimen 2-5 (9.53 mm UR).
Figure **E-11**: X-ray image of Specimen 2-6 (9.53 mm UR).

Figure **E-12**: X-ray image of Specimen 3-1 (6.35 mm R).
Figure E-13: X-ray image of Specimen 3-2 (6.35 mm R).

Figure E-14: X-ray image of Specimen 3-3 (6.35 mm R).
Figure **E-15**: X-ray image of Specimen 3-4 (6.35 mm R).

Figure **E-16**: X-ray image of Specimen 3-5 (6.35 mm R).
Figure E-17: X-ray image of Specimen 3-6 (6.35 mm R).

Figure E-18: X-ray image of Specimen 4-1 (6.35 mm UR).
Figure E-19: X-ray image of Specimen 4-2 (6.35 mm UR).

Figure E-20: X-ray image of Specimen 4-3 (6.35 mm UR).
Figure E-21: X-ray image of Specimen 4-4 (6.35 mm UR).
Appendix F

Moment-Time Plots

Figure F-1: Moment-Time plot for Specimen 1-1 (9.53 mm R).

Figure F-2: Moment-Time plot for Specimen 1-2 (9.53 mm R).
Figure F-3: Moment-Time plot for Specimen 1-3 (9.53 mm R).

Figure F-4: Moment-Time plot for Specimen 1-4 (9.53 mm R).
Figure F-5: Moment-Time plot for Specimen 1-5 (9.53 mm R).

Figure F-6: Moment-Time plot for Specimen 1-6 (9.53 mm R).
Figure F-7: Moment-Time plot for Specimen 2-1 (9.53 mm UR).

Figure F-8: Moment-Time plot for Specimen 2-2 (9.53 mm UR).
Figure F-9: Moment-Time plot for Specimen 2-3 (9.53 mm UR).

Figure F-10: Moment-Time plot for Specimen 2-4 (9.53 mm UR).
Figure F-11: Moment-Time plot for Specimen 2-5 (9.53 mm UR).

Figure F-12: Moment-Time plot for Specimen 2-6 (9.53 mm UR).
Figure F-13: Moment-Time plot for Specimen 3-2 (6.35 mm R).

Figure F-14: Moment-Time plot for Specimen 3-3 (6.35 mm R).
Figure F-15: Moment-Time plot for Specimen 3-4 (6.35 mm R).

Figure F-16: Moment-Time plot for Specimen 3-6 (6.35 mm R).
Figure F-17: Moment-Time plot for Specimen 4-1 (6.35 mm UR).

Figure F-18: Moment-Time plot for Specimen 4-2 (6.35 mm UR).
Figure F-19: Moment-Time plot for Specimen 4-3 (6.35 mm UR).

Figure F-20: Moment-Time plot for Specimen 4-4 (6.35 mm UR).
Appendix G

Shop Drawings and Cabling Diagrams

Connections with 6.35 mm Dowels. ................................................................. 1/8
Connections with 9.53 mm Dowels. ................................................................. 2/8
Steel Templates. ................................................................................................. 3/8
Celesco String Potentiometer. ......................................................................... 4/8
USB 6221 Data Acquisition Device. ................................................................. 5/8
MTS Chassis Backplane J40. ........................................................................... 6/8
MTS Chassis Backplane J48. ........................................................................... 7/8
MTS Chassis Backplane J66. ........................................................................... 8/8
4 PIN CIRCULAR PLASTIC CONNECTOR GOES TO CELESCO MTA 2E 5 KW STRING PLOT

AT USB 6221

96  GREEN (+5V)
94   WHITE (GROUND)

AI 10 (8)  BLACK (OUTPUT)
AI  2 (7)  RED (OUTPUT, AI2)
MTS 458 CHASSIS BACK PLANE
J40 (LOAD, LVIT, STRING PLOT,
CONDITIONAL SIGNALS)

MTS 458 CHASSIS BACK PLANE
J4B (MTS START AND STOP BUTTONS)

MTS STOP

MTS RUN

LVIT
WHITE
BLACK
LOAD
RED
GREEN
STRING
RED
POT
BLACK

RED
WHITE
BLACK

GREEN
BLACK

WHITE
GREEN
STRING
POT

NC = No Connect
ACADEMIC VITA

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Penn State University, Spring 2010
Minor in International Studies
Honors in Civil Engineering
Thesis Title: Moment Timber Frame Connections Locally Reinforced with
Glass Fiber Rods
Thesis Supervisor: Bohumil Kasal

Related Experience:
Internship at Pennoni Associates, Summer 2006 and 2007
Supervisor: Tom Friese
Internship at Boles Smyth Associates, Summer 2008
Supervisor: Mike Boles
Internship at AECOM, Summer 2009
Supervisor: Jon Schmidt

Awards:
Dean’s List
National Honor Society

Activities:
Organized Make a Difference Day 2006
Volunteer at City Team Ministries
Fundraising Director for Penn State Circle K