FRP-Glulam Beams
Modeling and Code Approval

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Summary

- What is FRP-Glulam?
- Brief overview of computer model for FRP-Glulams: ReLAM.
- FHWA test program for medium and long-span FRP-Glulams at AEWC.
- ICC Acceptance Criteria (AC280)
- ASTM Standard for FRP-Glulam (D7199-06)
- Draft AASHTO Specification
What is FRP-Glulam?

- FRP-Glulam is traditional glue-laminated (Glulam) wood beams, reinforced with Fiber-Reinforced Polymers (FRP)

- Why reinforce wood?
Why Reinforce Glulam?

- Top in Compression
- Bottom in Tension
Why Reinforce Glulam?

- Lower laminating grades are significantly stronger in compression than in tension.
- Traditional glulam failure is almost always in the tension face (knot or finger-joint).
- Reinforcing glulam with small amounts (1% to 3% by volume) of FRP in tension can double beam bending strength.
Advantages of FRP-Glulam

Glulam

- Strength is defect-driven
- Deflections are a concern

FRP-reinforced glulam

- Greatly improved flexural strength
- Higher strength beams possible using lower grade wood
FRP-Glulam Computer Model: ReLAM

- Non-linear model accounting for progressive failure of laminations.
- Does **not** assume tension or compression failure.
- Calculates bending properties of reinforced glulam beams with various layups, reinforcing levels, wood species, types of reinforcement.

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Orono, ME 04469-5793
Why ReLAM?

3% GRP: MOR=9,465 DUCT=3.1

1% GRP: MOR=7,229 DUCT=1.7

CONTROL: MOR=4,013 DUCTL=1
ReLAM Computer Model

- Beta version of Windows™-based pre/post processor is completed.
Features of Windows™-based ReLAM

- Allows user to build and view FRP-glulam beam layup graphically
- Easy to modify layup, span, and materials for repetitive analyses
Features of Windows™-based ReLAM

- Uses a database of wood and FRP laminating stock
- User may easily add to or modify database
Features of Windows™-based ReLAM

- Can simulate from 100 to 10000 beams in an analysis run.
- Incorporates published moisture content adjustments for wood mechanical properties. User may choose between:
  - ASTM D1990 methods
  - Quadratic Surface Model developed by the USDA Forest Products Laboratory
- Option to calculate load-deflection plots to failure.
Load-Deflection Plots
Windows™-based ReLAM
Modeling of FRP-Glulam

- **Required Input: Mean and COV**
  - Lumber and Reinforcement MOE
  - Lumber and Reinforcement Tensile Strength
  - Lumber Compression Strength
  - Beam Layup

- **Using Monte Carlo Simulation Methods**
  - Predicts Mean, COV of Beam MOR
  - Predicts Mean, COV of Beam MOE
  - Calculate MOE & $F_b$ for given layup

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Tension Test of 12 ft Wood Specimen
Compression Test of 1 ft. Wood Specimen
Step 1: Simulate Cross Section Layup

Properties to simulate for each lamination:

- MOE
- Ultimate Tensile Strength
- Ultimate Compression Strength

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Step 2: Analyze cross section under unit load

\[ \varepsilon(y) \]

\[ \sigma(y) \]

N.A. b d Y y C Arm

\[ \varepsilon_c \]

\[ \phi \]

\[ f_{\text{yield}} \]
Step 3: Apply Increasing Load to Beam until Failure

- End Result is a Load-Deflection Relationship for the beam until complete failure
  - Ultimate Bending Moment & Stress
  - Beam MOE
Step 4: Repeat #1 to #3

- End up with a distribution of Ultimate Bending Stress ($F_{ult}$), and Beam MOE
- Allowable Bending Stress ($F_b$) = $5\%\text{LTL}/2.1$
- $\text{MOE} = \text{Mean MOE}$
Early Validation of ReLAM

- In 1996, 90 Reinforced Glulam beams were tested by APA & UMaine in cooperation with Willamette Industries.
- One beam size: 5 in. x 12 in. x 21 ft span
- Two species of lumber (Doug-fir & Western Hemlock), L2/L3 grade
- Three levels of reinforcement (0%, 1%, & 3% by volume)
Early Validation Results

- For the 4 sets of 15 reinforced glulams tested, on average:
  - ReLAM $F_b$ was within 4% of the $F_b$ calculated from the test beams.
  - ReLAM MOE was within 1% of the mean MOE from the test beams.

- Although further “fine-tuning” of ReLAM was required, the analysis methodology had proven itself.
Test Program to Finish ReLAM Validation

- FHWA contract with the AEWC Center to develop AASHTO Standards and Specifications for FRP-Glulams Bridges.
- Task Order 1: Quasi-static testing of 114 FRP-Glulam beams to failure in third-point bending.
Test Program

- 114 Full-scale quasi-static beam tests - COMPLETED
- Two span lengths: 36 ft and 48 ft
- Two beam depths: 21 in. and 28.5 in.
- Two beam widths: 5.125 in. and 6.75 in.
- Douglas-fir grade L1 and L2/L3 laminating stock
- Three reinforcement ratios: 0% (Layup A), 1.2% (Layup B), and 2.4% (Layup C) E-Glass FRP by volume.

<table>
<thead>
<tr>
<th>TO 1 Category</th>
<th>Layup</th>
<th>Species</th>
<th>Grades</th>
<th>Core &amp; Tension Zone</th>
<th>Reinf Ratio</th>
<th>No. Beams</th>
<th>Width (in.)</th>
<th>Depth (in.)</th>
<th>Span (ft)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>Douglas-fir</td>
<td>L2/L3 (100%)</td>
<td></td>
<td>0%</td>
<td>6</td>
<td>5.125</td>
<td>21</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>Douglas-fir</td>
<td></td>
<td></td>
<td>0%</td>
<td>6</td>
<td>6.75</td>
<td>28.5</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>Douglas-fir</td>
<td>L1 (25%)</td>
<td>L2/L3 (73.8%)</td>
<td>1.2%</td>
<td>30</td>
<td>5.125</td>
<td>21</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>Douglas-fir</td>
<td>L1 (25%)</td>
<td>L2/L3 (73.8%)</td>
<td>1.2%</td>
<td>21</td>
<td>6.75</td>
<td>28.5</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>Douglas-fir</td>
<td>L1 (25%)</td>
<td>L2/L3 (72.6%)</td>
<td>2.4%</td>
<td>30</td>
<td>5.125</td>
<td>21</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>Douglas-fir</td>
<td>L1 (25%)</td>
<td>L2/L3 (72.6%)</td>
<td>2.4%</td>
<td>21</td>
<td>6.75</td>
<td>28.5</td>
<td>48</td>
</tr>
</tbody>
</table>
Comparison of ReLAM Predictions to Test Data

- At mean MOR: ReLAM prediction was within 3.8% of Test Data
- At 5% Lower Tolerance Limit (LTL) MOR: ReLAM prediction was within 6% of Test Data

<table>
<thead>
<tr>
<th>Span (ft)</th>
<th>% GFRP</th>
<th>Sample Size</th>
<th>Mean MOR (psi)</th>
<th>5% LTL MOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test</td>
<td>ReLAM</td>
<td>Test</td>
</tr>
<tr>
<td>36</td>
<td>1.2%</td>
<td>30</td>
<td>1000</td>
<td>6372</td>
</tr>
<tr>
<td>36</td>
<td>2.4%</td>
<td>30</td>
<td>1000</td>
<td>7244</td>
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<tr>
<td>48</td>
<td>1.2%</td>
<td>21</td>
<td>1000</td>
<td>6237</td>
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<tr>
<td>48</td>
<td>2.4%</td>
<td>21</td>
<td>1000</td>
<td>7113</td>
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</tbody>
</table>
FRP-Glulam Code Approval

- AC 280 approved by the International Code Council (ICC) in February, 2005.
ASTM Standard


- ASTM D7199-06 approved in 2006.
AASHTO Code Modification

• AASHTO LRFD Code, Section 8 (Wood Structures)
• Section 8.4.1.2 – Structural Glued Laminated Timber.
• Section 8.4.1.3 (New Section) – Tension-Reinforced Glulam
AASHTO Code Modification

- **8.4.1.3.1 – General**
  - Description/limitations for tension-reinforced glulam.
  - Description of typical reinforcements (E-glass, carbon, kevlar, steel) and reinforcement ratios ($\rho$).
  - Addresses only tension-reinforced glulams in bending.
  - Secondary properties determined as in conventional glulam (ASTM D3737)
AASHTO Code Modification

• 8.4.1.3.2 – Dimensions
  • Actual net dimensions used (full depth and width).
  • MOE and Fb calculated using gross cross-section properties.
    • $I = b \cdot d^3/12$
    • $S = b \cdot d^2/6$
AASHTO Code Modification

- 8.4.1.3.3 – Fatigue
  - Tension reinforcement must extend for full length of beam.
  - For beams reinforced with pultruded reinforcement, fatigue will not govern design.
  - For non-pultruded reinforcement, fatigue testing of coupon specimens is required.
  - When reinforcement increases beam strength by more than 75%, full-scale fatigue testing is required.
## AASHTO Code Modification

### 8.4.1.3.4 – Reference Design Values (ksi)

<table>
<thead>
<tr>
<th>Combination Symbol</th>
<th>Species (Outer/Core)</th>
<th>Bending about X-Axis</th>
<th>Shear</th>
<th>Modulus of Elasticity</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Extreme Fiber in Bending</td>
<td>Compression Perpendicular to Grain</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tension zone stressed in tension $F_{bx0}$ +</td>
<td>Compression zone stressed in tension $F_{bx0}$ -</td>
<td>Tension face</td>
</tr>
<tr>
<td>30F-1.9E</td>
<td></td>
<td>3.000</td>
<td>2.000</td>
<td>0.56</td>
</tr>
<tr>
<td>30F-V1R</td>
<td>DF/DF</td>
<td>3.000</td>
<td>2.000</td>
<td>0.56</td>
</tr>
<tr>
<td>30F-2.0E</td>
<td></td>
<td>3.000</td>
<td>2.000</td>
<td>0.56</td>
</tr>
<tr>
<td>30F-V4R</td>
<td>DF/DF</td>
<td>3.000</td>
<td>2.000</td>
<td>0.56</td>
</tr>
<tr>
<td>30F-2.1E</td>
<td></td>
<td>3.200</td>
<td>2.100</td>
<td>0.56</td>
</tr>
<tr>
<td>32F-V1R</td>
<td>DF/DF</td>
<td>3.400</td>
<td>2.100</td>
<td>0.56</td>
</tr>
</tbody>
</table>

**Note:** Values are in units of ksi.
AASHTO Code Modification

8.4.1.3.5 – Volume effect

- Volume factors for tension reinforced glulams in bending are built into the reference design value, except with the unreinforced compression zone is stressed in tension.

- Tests and modeling have shown that the volume effect disappears with 1.5% to 3% GFRP reinforcement in tension.
AASHTO Code Modification

- 8.4.1.3.6 – Preservative treatment
  - Effects of preservative treatment on FRP and bond shall be evaluated per ASTM D7199.
  - Preservative treatment shall be applied after the bonding of the reinforcement.
  - GFRP reinforced beams shall not be post-treated with CCA.