Structural Performance of Plain Concrete and Fiber-reinforced Concrete Crossties Prestressed with BFRP Rebars

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Why Concrete Crossties...?

Manufactured
- product Uniformity
- Better control of tolerances in rail seat leading to better track geometry
- Well adapted for elastic fasteners

Better track stability
- Weighs 790 pounds compared to 240 for hardwood tie
- Better elastic fasteners control longitudinal rail forces
- Stiffer track promotes better track geometry

Track renewal installation provides benefits
- High quality track with fewer occupancies
- Facilitates rail change in the process of tie replacement

50 Year Life Expectancy
Concrete ties in US Railway

First concrete tie manufactured & installed– 1978

Manufacturers (# of ties produced):
- Santa Fe / San Vel: 1978 to 1983 ~ 1.0 million
- Lonestar: 1983 to 1986 ~ 300 K
- Rocla: 1990 to 2000 ~ 1.3 million
  - 2012 ~ 60 K
  - 2013 ~ 100 K
  - 2014 ~ 70 K

• Total concrete crossties purchased to date ~ 3.6 million
• Total concrete ties in track
• 1056 miles in North East Corridor (NEC), and
• 114 miles in Harrisburg Line
Basalt FRP Rebar – the alternative to steel

- Made from volcanic rock, the basalt rebar has higher tensile strength properties than steel.
- Much lighter than steel, 89% in fact! One man can easily lift a 500 foot coil of 10 mm basalt rebar.
- Basalt rebar is naturally resistant to corrosion, alkali, and acids. Unlike steel, moisture penetration from concrete does not cause spalling. Do not need any special coating like fiberglass rods.
- Basalt rebar has a similar thermal coefficient as concrete!
- Basalt rebar is perfect for Marine environments and Chemical plants where corrosion is a major concern.
Challenges of Using Basalt FRP in Structural Application

- Strength depends on the polymer matrix or resin and environmental degradation of this polymer matrix may be highly unfavorable.
- Due to lower elastic modulus large service load deflections and larger crack widths occurs.
- After manufacturing as a bar it is difficult to bend

- The anisotropy of the FRP material makes design and analysis of the structure more difficult.
- May be susceptible to fire depending on matrix type and concrete cover thickness
Design Approach

• The ultimate strength of Basalt FRP bars is around 1100 Mpa (160 ksi) which is approximately three times that of Grade 60 steel rebars.

• Due to low modulus of Elasticity (8000 ksi), it shows high deformation at ultimate load. Therefore it is difficult to utilize its full capacity and meet the serviceability at the same time.

• To utilize the full strength of Basalt FRP rebars, **prestressing of Basalt rebars** is an optimum solution.

• The study has been conducted to check the feasibility of using prestressed Basalt FRP bars as **internal reinforcement in concrete crossties** replacing the prestressing steel wires.
**Code specification for Concrete crossties**

**AREMA specification for flexural properties of concrete crossties** *(Table 30-4-1)*

<table>
<thead>
<tr>
<th>Tie Length</th>
<th>Rail Seat Negative</th>
<th>Center Negative</th>
<th>Center Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>7'-9&quot; (2.360 m)</td>
<td>0.72M</td>
<td>1.13M</td>
<td>0.61M</td>
</tr>
<tr>
<td>8'-0&quot; (2.440 m)</td>
<td>0.64M</td>
<td>0.92M</td>
<td>0.56M</td>
</tr>
<tr>
<td>8'-3&quot; (2.520 m)</td>
<td>0.58M</td>
<td>0.77M</td>
<td>0.51M</td>
</tr>
<tr>
<td>8'-6&quot; (2.590 m)</td>
<td>0.53M</td>
<td>0.67M</td>
<td>0.47M</td>
</tr>
<tr>
<td>9'-0&quot; (2.740 m)</td>
<td>0.46M</td>
<td>0.57M</td>
<td>0.40M</td>
</tr>
</tbody>
</table>

Where M is the ultimate design moment and calculated as follows

\[ M = B \times V \times T \]

B: the bending moment in inch kips (kN-m)

V: is the speed factor obtained

T: the tonnage factor
I. Background and Motivation

• Prestressed concrete rail ties are increasingly being considered as a more sustainable and durable substitute for conventional wooden ties in current railroad construction projects.

• This type of crosstie can be twice as much as regular wooden ties in terms of service life.

• Despite the numerous advantages of prestressed concrete ties, refinements are required due to the increased weight and additional manufacturing costs.

• The use of fiber reinforced polymer (FRP) composites as prestressing material has been usually considered for mitigating corrosion issues that are evident in harsh environmental conditions.
I. Background and Motivation

• The study investigates the performance of concrete crossties that are prestressed with basalt-fiber reinforced polymer (BFRP) bars for plain concrete and fiber-reinforced concrete (FRC).

• Crosstie specimens were tested for center negative moment and rail seat positive moment tests in accordance with the AREMA Manual for Railway Engineering testing standards.
2. Crosstie Specimen Description

- The crossties consist of a trapezoidal cross section spanning 98 in.
- The height of the cross section at the ends of the cross tie and at the midspan is 10 in. and 9½ in., respectively.
2. Crosstie Specimen Description

The Prestressed reinforcement consists of
- Level 1: 5 #3 BFRP bars at 1¾ in
- Level 2: 5 #3 BFRP bars at 2 in.
- Level 3: 2 #3 BFRP bars at 7 ¼ in.
3. Material Selection

3.1 Mixture design and concrete strength

- FRC crossties included 6 lbs./yd³ of synthetic macro fibers.
- Air-entraining admixture was considered to increase freeze-thaw resistance as intended for concrete members subjected to harsh environmental conditions.

- The compressive strength results at release \((f'_{ci})\) was 5700 psi and the compressive strength at the date of testing \((f'_c)\) was 6250 psi.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Plain</th>
<th>FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, lb/yd³</td>
<td>Type I</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Fly Ash, lb/yd³</td>
<td>Class C</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Silica Fume, lb/yd³</td>
<td></td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Total CMC, lb/yd³</td>
<td></td>
<td>775</td>
<td>775</td>
</tr>
<tr>
<td>Fine Aggregate, lb/yd³</td>
<td>Combined Sand</td>
<td>1114</td>
<td>1114</td>
</tr>
<tr>
<td>Coarse Aggregate, lb/yd³</td>
<td>Crushed Limestone</td>
<td>1642</td>
<td>1642</td>
</tr>
<tr>
<td>Water, lb/yd³</td>
<td></td>
<td>288</td>
<td>288</td>
</tr>
<tr>
<td>w/cm</td>
<td></td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>AEA, fl. oz/cwt</td>
<td>AE 90</td>
<td>4.31</td>
<td>4.85</td>
</tr>
<tr>
<td>HRWR, fl. oz/cwt</td>
<td>MasterGlenium 7511</td>
<td>7.54</td>
<td>10.23</td>
</tr>
<tr>
<td>Total Volume, ft³</td>
<td></td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Synthetic Fibers, lb/yd³</td>
<td>STRUX 90/40</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

| Fresh Properties                  |               |       |     |
| Air content, %                    |               | 7.4   | 6.8 |
| Unit Weight, lb/ft³               |               | 139.92| 140.36|
3. Material Selection

3.2 Basalt fiber reinforced polymer (BFRP) bars

- The mechanical properties of #3 BFRP bars are shown in Table 2. These values are obtained from a study conducted by Issa et al. (2016) as per ASTM D7205 and ACI 440.3R.

<table>
<thead>
<tr>
<th>Bar Size, in</th>
<th>Ultimate Stress $f_{fu}$, ksi</th>
<th>Modulus of Elasticity $E_f$, ksi</th>
<th>Ultimate Strain $\varepsilon_{fu}$, $\mu\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>162.6</td>
<td>8,022</td>
<td>20,269</td>
</tr>
</tbody>
</table>

- BFRP flexural reinforcing bars characteristics:
  - Pultruded by impregnating bars with vinyl epoxy resin
  - Surface painted and sand-coated to improve bond strength
3. Material Selection

3.3 Synthetic fibers

- Synthetic macro fibers manufactured by W.R. Grace (STRUX® 90/40) was included in one crosstie specimen. The mechanical properties of this type of fibers is presented in the table below.

<table>
<thead>
<tr>
<th>Specific Gravity</th>
<th>Alkali and Chemical Resistance</th>
<th>Tensile Strength, ksi</th>
<th>Modulus of Elasticity, ksi</th>
<th>Length, in.</th>
<th>Aspect Ratio</th>
<th>Type</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>Excellent</td>
<td>90</td>
<td>1,378</td>
<td>1.55</td>
<td>90</td>
<td>flat</td>
<td>100% virgin polypro-pylene</td>
</tr>
</tbody>
</table>
Transfer Length in FRP (Issa et al., 1993)

• Issa et al. (1993) experimentally investigated transfer lengths of FRP prestressed concrete members which was found to range from 10 to 11 in. (254 to 279 mm).

Concrete strain variation vs. specimen length measured from both ends.
Transfer Length in FRP (Issa et al., 1993)

- Empirical relationships were established between steel and FRP prestressed members.
- The option of FRP prestressing can potentially reduce transfer lengths by around **28%** as the bond strength of the reinforcement/concrete interface was improved by **60%**.

\[
(L_T)_{ST} = \frac{d}{2\mu_{st}} (1 + m_c) \left( \frac{n}{m_s} - \frac{f_i}{E_s} \right) \left( \frac{f_e}{2f_i - f_e} \right)
\]

\[
\frac{(L_T)_{FG}}{(L_T)_{ST}} = \frac{\mu_{st}}{\mu_{fg}} \frac{E_{fg}}{E_{st}} \frac{m_{st}}{m_{fg}} \approx 0.72
\]

- \( m_c, m_s \) = Poisson’s ratio for concrete and steel, respectively
- \( f_i, f_e \) = initial and effective prestress in steel, respectively
- \( d \) = diameter of wire
- \( n \) = modular ratio
- \( \mu \) = coefficient of friction between concrete and steel

Concrete strain variation along specimen length measured from one end
4. BFRP Prestressing

• The crosstie consists of 12 #3 BFRP bars that were prestressed with an approximate force of 10,000 lbs. in each bar.

• The prestressing force corresponds to an effective stress of 95 ksi which represents to 58% of the ultimate tensile capacity of BFRP reinforcement.
4. BFRP Prestressing

Strain readings were monitored and collected throughout the prestressing operation until the time of releasing the prestressing force.

\[ f_{pu} = 162 \text{ ksi} \]
\[ \varepsilon_{pe} = 11.7 \times 10^{-3} \text{ after anchor set losses} \]
\[ f_{pe} = 94 \text{ ksi} \]
\[ Y = 8000 X \]
4. BFRP Prestressing

Strain gauge measurements at crosstie midspan

Concrete casting after prestress operations
5. Center rail negative moment test

Testing schematics for center negative moment
5. Center rail negative moment test
5. Center rail negative moment test

Test setup

- **Minimum design load** to be achieved as per AREMA standards: 14.5 kips.
- **Support span**: 60 in.
- **Loading Span**: 6 in.
- **Concrete top level instrumentation**: Displacement transducer (100 mm) and strain gauge.
- **Concrete bottom level instrumentation**: Displacement transducer (150 mm).
- **BFRP bars instrumentation at the bottom level**: Strain gauges at the left (BL), middle (BM), and right (BR) positions.
- **Specimen deflection**: One LVDT (100 mm) at the midspan and one LVDT (25 mm) near each support.
- **Testing Machine**: INSTRON 8500R servo loop control system (capacity of 50 kips).
5. Center rail negative moment test

Crack pattern at ultimate load (FRC Crosstie)
5. Center rail negative moment test

Load versus deflection for plain concrete crosstie, FRC crosstie, and finite element analysis

- The FRC crosstie achieved an ultimate load of about **62% greater** than the ultimate load of the plain concrete crosstie.
5. Center rail negative moment test

An observation of the results indicates a strain development with a **maximum strain value of around 1.6%** at failure.

- Strain values were below the ultimate strain of the BFRP material of about 2%.
5. Center rail negative moment test

The cracking loads were around **13.5 kips** and **12 kips** for the plain concrete specimen and FRC specimen, respectively.
5. Rail Seat Positive Moment Test

Rail seat positive moment testing summary:

- **Minimum design load** to be achieved as per AREMA standards: 43.6 kips.
- **Support span**: 30 in.
- **Loading span**: 4.5 in.
- **Testing machine**: Tinius Olsen Testing Machine (capacity of 400 kips).
5. Rail Seat Positive Moment Test

- Testing results proved to be satisfactory as per AREMA standards that require a minimum service load of 43.6 kips.
- The ultimate load was **79.4 kips for the plain concrete crosstie** while **FRC specimens reached 134 kips** (68% increase).
5. Rail Seat Positive Moment Test

- The plain concrete specimen cracked at 6 in. from the end of the bottom layer while FRC specimens cracked at 11 in. with no slippage of BFRP.
5. Rail Seat Positive Moment Test

Cracked End of rail seat positive moment test with at 9 inches with no BFRP slippage (FRC Crosstie)
Conclusion and future studies

• Prestressed BFRP rebars can be used as an alternative to steel reinforcement.

• Prestressing BFRP rebars is an effective way to utilize its ultimate strength as well as control the deformation within the allowable limits.

• 50% of ultimate strength is a good starting point for initial prestress. Effect of different prestress levels in concrete ties is under investigation.

• Investigation of the effect of different BFRP rebar sizes in concrete crossties is underway.
Alternative Solutions:

Basalt Fiber Reinforced Polymer for Remanufacturing Creosote-Railroad Ties
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Basalt Fiber Reinforced Polymer for Remanufacturing Creosote-Railroad Ties

Refurbished Ties with BFRP
Alternative Solutions

Recycled Plastic Railroad Road Ties
Recycled Plastic Railroad Road Ties, HDPE (Tangent Tech)
Task I – Experimental testing

Flexural

- 12 Specimens
- AREMA Part 2- Section 2.2.3 – Test 1B & C
- Span (30, 60)
- Rail system effect

Outcome

- Surpassed AREMA Specs
- Negated Literature Concerns (Reiff, R. and Trevizo, C., 2012)
- Identified rail system effect
Task I – Experimental testing

Temperature effect

- 20 Specimens
- Range investigated: (10°F to 125°F)

Outcome

- Isolative material – (10 to 12 hrs) to reach temp.
- Prolonged exposure
- Established scaling models for compliance prediction
- Recommended solutions and mitigation strategies
Task I – Experimental testing

**Fatigue test**

- 2 Specimens completed so far
- AREMA Part 2- 2.6.3 – Test 5C
  - Angle 22°
- L/V = 0.40
- 5 Strain gauges
- 6 LDVT’s
- 5000 lbs to 35,000 lbs
- 3 Hz
- 3,000,000 cycles
- Test duration: 12 days
Task II – Material Model

Includes calibration, Failure criteria, and proposed optimum modeling approach