Advanced Composite Material Applications in Structural Engineering

Advances and Challenges

By

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OUTLINE

- Introduction: What are Composite Materials?
- Bridge Applications
- Final Remarks
What are Composite Materials?

- Composite structures are often called fiber reinforced polymer (FRP) structures, and polymer matrix composites (PMC).
- Composite materials are man-made, and must contain at least two constituents that are distinct chemically and physically.
- Intended to achieve an increase in certain properties such as stiffness, strength, fracture toughness among others, or decrease certain properties such as weight and corrosion. Composites in general can be categorized in two groups as follows:
Composites Architecture

- **Matrix**
- **Interface**
- **Reinforcement**

Diagram showing the components of a composite material:
- Polymer Matrix
  - Y
  - Si(CH₂)ₙ
  - X₃
- Glass Fiber Surface
  - Fiber
  - Coating or Size
Reinforcement

- **Long continuous bundles**
  - $l/d > 10$ by definition, (typical dia for a fiber $\sim 6-15 \, \mu m$)
  - unidirectional
  - multidirectional
  - woven or braided Continuous fibers

- **Short chopped fibers**
  - randomly oriented

- **Whiskers**
  - long thin crystals $d< 1 \, \text{micron}$ length in the order of 100 microns used in ceramic matrix composites (CMC) and metal matrix composites (MMC)

- **Particulates**
  - Near spherical
  - not usually used for strength
  - increase the toughness of the material

- **Flakes**
  - metallic, electrical/heating applications
  - 2-D in nature, not usually used for strength
Reinforcement (cont’d)

Glass (E-, S-, C-glass fibers)
- E-glass: Young’s modulus ~ 72 GPa, $\sigma_u = 3450$ MPa (500 ksi), strain to failure 1-2%
- Carbon
  - EL: 250-517 GPa, ET=12-20 GPa
  - $\sigma_u = 2000-2900$ MPa (290-435 ksi), strain to failure 0.5-1%
- Kevlar, Spectra (organic)
  - E: 62-131 GPa
  - $\sigma_u = 2500-3790$ MPa (360-550 ksi), strain to failure 2-5%
- Ceramic fibers: high strength, stiffness and temperature stability
  - Alumina ($\text{Al}_2\text{O}_3$)
    - E: 370 GPa
    - $\sigma_u = 1380$ MPa (200 ksi)
  - SiC
  - Boron (toxic material), typically large diameter
Matrix

- Metallic
- Ceramic
- Polymeric
  - Thermoplastic
  - Thermoset
### Polymer Matrix

**Polymer**

- Linear
- Branched

### Some Properties of Thermoset & Thermoplastic

<table>
<thead>
<tr>
<th>Property</th>
<th>Epoxy</th>
<th>Polycarbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sigma_u$ (MPa)</td>
<td>50-130</td>
<td>60</td>
</tr>
<tr>
<td>$E$ (GPa)</td>
<td>3-4</td>
<td>2.2</td>
</tr>
<tr>
<td>$\alpha_L$ (10$^{-6}$/°C)</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>1-8</td>
<td>50-100</td>
</tr>
</tbody>
</table>
Composites Categories

**Reinforced Plastics**
- Low strength and stiffness
- Inexpensive
- Glass fibers is primary reinforcement
- Applications:
  - Boat Hulls
  - Corrugated sheets
  - Piping
  - Automotive panels
  - Sporting goods

**Advanced Composites**
- High strength and stiffness
- Expensive
- High performance reinforcement such as: graphite, aramid, kevlar
- Applications:
  - Aerospace industry
Typical Applications in Structural Engineering

- Retrofitting of beams and columns
- Seismic Retrofitting
- New applications
  - Bridge Deck
  - Bridge Superstructure
FRP COMPOSITES IN STRUCTURAL APPLICATIONS

- **Advantages**
  - High specific strength and stiffness
  - Corrosion resistance
  - Tailored properties
  - Enhanced fatigue life
  - Lightweight
  - Ease of installation
  - Lower life-cycle costs

- **Factors preventing FRP from being widely accepted**
  - High initial costs
  - No specifications
  - No widely accepted structural components and systems
  - Insufficient data on long-term environmental durability
28% of 590,000 public bridges are classified as “deficient”.

The annual cost to improve bridge conditions is estimated to be $10.6 billion.

Need for bridge systems that have long-term durability and require less maintenance.

(Source: National Bridge Inventory)
Is it necessary to use expensive FRP materials for bridge renewal?

Given the massive investment to renew deficient bridges (28% of all bridges are deficient), repeating the same designs, materials, etc. may not be a prudent approach.

Consider the fact that the average life span of a bridge in the U.S. is less than 50 years.

FRP materials, if designed properly, could provide new bridges that last over 100 years.
GLASS FIBER REINFORCED POLYMER (GFRP) BOX SECTIONS

- The compressive flange is weaker than the tensile flange.
- A failure of a GFRP box section usually occurs in a catastrophic manner.
- The design of a GFRP box section is usually governed by stiffness instead of strength.

Hybrid design or Special structural system
BRIDGE APPLICATIONS – 1
(TOM’S CREEK BRIDGE)

- Virginia Tech and Strongwell
- Pultruded composite beam (hybrid design of glass and carbon fibers and vinyl ester matrix)
- Span: 5.33 m, Width: 7.32 m
BRIDGE APPLICATIONS – 2
(TECH 21 BRIDGE)

- LJB Engineers & Architects, Inc. and Martin Marietta Materials
- Length : 10.1 m, Width : 7.3 m
- E-glass fiber reinforcement and polyester matrix
- Deck : pultruded trapezoidal tubes between two face sheets (tubes run parallel with the traffic direction)
- Stringer : three U-shaped structural beams

838 mm
**BRIDGE APPLICATIONS – 3**
*(KINGS STORMWATER CHANNEL BRIDGE)*

- UC San Diego, Alliant TechSystems, Inc., and Martin Marietta
- Span: 2 x 10 m, Width: 13 m
- Six longitudinal concrete filled carbon tube girders (carbon/epoxy system)
- GFRP deck panel (pultruded trapezoidal E-glass/epoxy tubes with a top skin layer)
BRIDGE APPLICATIONS – 4
(TOOOWOOMBA BRIDGE)

- University of Southern Queensland, Wagners Composite Fibre Technologies, and Huntsman Composites
- Span : 10 m, Width : 5.0 m
- Hybrid box beams : prefabricated concrete, GFRP, and CFRP

![Diagram with dimensions in mm]

concrete

GFRP

CFRP

(dimensions in mm)
Market Share (FRP Composites)

- Transportation: 31%
- Consumer: 20%
- Corrosion: 12%
- Marine: 10%
- Electrical: 10%
- Appliance: 6%
- Other: 3%
- Aerospace: 1%
FRP Composite Shipments

U.S. Composite Shipments

- Aerospace
- Appliance
- Construction
- Consumer
- Corrosion
- Electrical
- Marine
- Transportation
- Other

Shipments (Thousands of Metric Tons)

Year

60 65 70 75 80 85 90 95 00
Recent Development of FRP Bridge Deck and Superstructure Systems
Hybrid-FRP-Concrete Bridge Deck and Superstructure System

- The system is developed at UB by an optimum selection of concrete and FRP.
- The system is validated analytically and experimentally to assess the feasibility of the proposed hybrid bridge superstructure and deck.
- Simple methods of analysis for the proposed hybrid bridge superstructure were developed.
BASIC CONCEPT OF PROPOSED HYBRID FRP-CONCRETE BRIDGE

- Single span with a span length of 18.3 m
- AASHTO LRFD Bridge Specifications
  - Live load deflection check
    \[ d_{LL} < \frac{L}{800} \text{ under (1+IM)Truck} \]
  - Service I limit
    \[ DC + DW + Lane + (1 + IM)\text{Truck} \]
  - Strength I limit
    \[ 1.25DC + 1.5DW + 1.75[Lane + (1 + IM)\text{Truck}] \]
- Concrete should fail first in flexure.
- A strength reduction factor for GFRP was taken as 0.4.

Simple-span one-lane hybrid bridge
PROPOSED HYBRID BRIDGE SUPERSTRUCTURE

Advantages include:

– Increase in stiffness
– Corrosion resistance
– Cost-effectiveness
– Lightweight
– Local deformation reduction
– High torsional rigidity
– Pre-fabrication
– Short construction period
**DISPLACEMENT AND STRENGTH CHECKS**

- Deflection check: $0.61 \times L/800$
- Max. failure index: $0.107$ (safety factor = 3.1)

(a) Live load deflection check  
(b) Tsai-Hill Failure index under Strength I limit
**TSAI-HILL FAILURE INDEX**

\[
I_{TH} = \frac{\sigma_1^2}{X^2} - \frac{\sigma_1\sigma_2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\sigma_6^2}{S^2}
\]

Failure condition : \(I_{TH} = 1.0\)

where

\[
\{\sigma_1 \sigma_2 \sigma_6\} = \{\sigma_{11} \sigma_{22} \tau_{12}\}
\]

\[
X = \begin{cases} 
X^T & \text{for } \sigma_1 > 0 \\
X^C & \text{otherwise}
\end{cases}
\]

\[
Y = \begin{cases} 
Y^T & \text{for } \sigma_2 > 0 \\
Y^C & \text{otherwise}
\end{cases}
\]

\(X, Y, \text{ and } S\) : Strengths in the principal 1 and 2 directions and in-plane shear

\(T\) and \(C\) : Tensile and compressive directions
EXPERIMENTAL PROGRAM

- Materials
  - GFRP
  - Concrete
- Non-destructive tests
  - Flexure
  - Off-axis flexure
- Fatigue test
- Destructive tests
  - Flexure
  - Shear
  - Bearing
TEST SPECIMEN

- One-fifth scale model
- Span length = 3658 mm

(dimensions in mm)
Stacking Sequences

- Thickness of one layer = 0.33-0.40 mm
FABRICATION – 1
FABRICATION – 2
Shear Keys

Shear keys

(dimensions in mm)

Longitudinal direction
MATERIALS – GFRP

- E-glass woven fabric reinforcement
  - Cheaper than carbon fiber reinforcement
  - Impact resistance
- Vinyl ester
  - High durability
  - Extremely high corrosion resistance
  - Thermal stability

Material Properties

<table>
<thead>
<tr>
<th>Test</th>
<th>Dir.</th>
<th>E or G (GPa)</th>
<th>v</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tens</td>
<td>Fill</td>
<td>16.6</td>
<td>0.129</td>
<td>285</td>
</tr>
<tr>
<td></td>
<td>Warp</td>
<td>17.9</td>
<td>0.131</td>
<td>335</td>
</tr>
<tr>
<td>Comp</td>
<td>Fill</td>
<td>15.9</td>
<td>0.099</td>
<td>-241</td>
</tr>
<tr>
<td></td>
<td>Warp</td>
<td>22.5</td>
<td>0.254</td>
<td>-265</td>
</tr>
<tr>
<td>Shear</td>
<td>Fill</td>
<td>2.72</td>
<td>--</td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>Warp</td>
<td>2.45</td>
<td>--</td>
<td>63.8</td>
</tr>
</tbody>
</table>
GFRP – COMPRESSION
GFRP – SHEAR

Shear Stress (MPa)

Shear Strain

- S0-1
- S0-2
- S0-3
MATERIALS - CONCRETE

- No coarse aggregates
- water : cement : aggregate = 0.46 : 1.0 : 3.4 by weight

Compressive Properties

<table>
<thead>
<tr>
<th>Young’s Modulus (GPa)</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.38</td>
<td>37.9</td>
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</tbody>
</table>
TEST SETUP

Actuator
Load Cell
Swivel
Spreader Beam
Bridge Model
Elastomeric Bearing Pad
Concrete Block
FLEXURAL LOADING CONFIGURATION

(a) Elevation

(b) Cross section (flexure)

(c) Cross section (off-axis flexure)

(dimensions in mm)
NONDESTRUCTIVE FLEXURE (TEST PROTOCOL)

- To examine elastic behavior of the bridge under the flexural loading
- Displacement control
- Max applied displ. = \( \frac{L}{480} \) (\( L \): span length)
NONDESTRUCTIVE FLEXURE (FORCE-DISPLACEMENT)

- **Applied Load (X Tandem Load)**
  - G-BOT-C: 19% increase
  - FRP Only: 40% for the prototype

**Graph Details:**
- Vertical Displacement (X Span/800)
- Applied Load (X Tandem Load)
- Hybrid
- FRP Only

**Notes:**
- University at Buffalo: The State University of New York
NONDESTRUCTIVE FLEXURE (TOP SURFACE DEFORMATION)
NONDESTRUCTIVE FLEXURE (STRAIN RESULTS)

(a) Bottom surface along the center-line

(b) Exterior web over height
FATIGUE LOADING (TEST PROTOCOL)

- To examine fatigue characteristics
- Flexural loading
- Force control
- $2 \times 10^6$ cycles
- $\text{Freq.} = 3.0 \text{ Hz}$
- Max. load
  $= 2.0 \times \text{Tandem}$
- Stiffness evaluation
  every 0.2 million cycles
FATIGUE LOADING
(TEST RESULTS)

5.9% degradation

Stiffness Ratio vs. Applied Load Cycles

- Average (top)
- Average (bottom)
- Average (black line)
DESTRUCTIVE FLEXURE
(TEST PROTOCOL)

- To examine the strength of the bridge and failure modes
- Flexural loading
- Displacement control
- Two stages
  - Step I (displacement history #1)
  - Step II (displacement history #2)
DESTRUCTIVE FLEXURE
(TEST RESULTS – 1)

- Failure load = 35 x Tandem load
CHANGE OF A LOADING CONDITION

- From four point loads to two line loads

contact
DESTRUCTIVE FLEXURE
(test results – 2)

- Failure modes
  - Concrete crushing
  - Failure of GFRP in compression
DESTRUCTIVE FLEXURE (FAILURE MODES)
**Shear Test**

- **Actuator**
- **Beams contacted the specimen**
**BEARING TEST**

![Bearing Test Setup Image]

**Graph:**
- **Applied Load (x Tandem Load):** 0 to 140 kN
- **Vertical Displacement (x Span/800):** 0 to 35 mm

- **Failure** indicated on the graph.

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**Annotations:**
- Applied Load vs. Vertical Displacement
- Scale markers for Applied Load and Vertical Displacement
- Failure point marked on the graph.
BEARING TEST
(Failure Mode)
FINITE ELEMENT ANALYSIS

- ABAQUS
- Four-noded general shell element, S4R, for GFRP laminates
- Eight-noded general 3D solid element, C3D8, for concrete
- Assumed a perfect bonding between concrete and GFRP
- Linear analysis
- Nonlinear analysis
FINITE ELEMENT DISCRETIZATION (LINEAR ANALYSIS)

- Number of nodes: 31,857
- Number of elements: 38,892 (22,764 for S4R and 16,128 for C3D8)
**LINEAR FEA RESULTS**

(FLEXURE − 1)

- Stiffness was predicted by FEA within 5% error.
LINEAR FEA RESULTS  
(FLEXURE – 2)

(a) Top surface  
(b) Bottom surface
LINEAR FEA RESULTS
(FLEXURE – 3)

(a) Bottom surface
along the center-line

(b) Exterior web over height
FINITE ELEMENT DISCRETIZATION (NONLINEAR ANALYSIS)

- A quarter model

Loading point
NONLINEAR FEA RESULTS – 1

Vertical Displacement (X Span/800)

Applied Load (X Tandem Load)

- G-BOT-C
- Flexural Test
- Failure
- FRP only (Linear)
- Hybrid (Linear)
- FRP only (Nonlinear)
- Hybrid (Nonlinear)
NONLINEAR FEA RESULTS – 2
(DAMAGED AREA)

(a) FEA

(b) Experiment

failure section
Simple Methods of Analysis

- Simple methods
  - Beam analysis
  - Orthotropic plate analysis
- Classical lamination theory
- Use of effective engineering properties of laminates
- Perfect bonding between concrete and GFRP was assumed.
- Shear deformation was neglected
- Primary objective is to obtain deflection under design loads.
The bridge is modeled as a beam with a span length, $L$, effective flexural rigidity, $EI_{eff}$, and effective torsional rigidity, $GJ_{eff}$.

$$EI_{eff} = \int_{Ay} \overline{E}_y \overline{z}^2 dA$$

$$GJ_{eff} = \frac{4A_{encl}^2}{\int \int \overline{G}_{xy} ds}$$

where

- $\overline{E}_y$: Effective modulus
- $\overline{G}_{xy}$: Effective shear modulus
- $\overline{z}$: Vertical coord. from the neutral axis
- $A_{encl}$: Area enclosed by median lines of the top and bot. flanges and exterior webs
- $s$: Axis along the median line of a component
ORTHOTROPIC PLATE ANALYSIS

- The bridge is modeled as an orthotropic plate with span length of $L$ and width of $W$.

$$D_x \frac{\partial^4 w_0}{\partial x^4} + 2H \frac{\partial^4 w_0}{\partial x^2 \partial y^2} + D_y \frac{\partial^4 w_0}{\partial y^4} = q(x, y)$$

where

- $w_0$ : Vertical displacement
- $q$ : Distributed load on the plate
- $D_x$, $D_y$, and $H$ : Rigidities that can be obtained by using the classical lamination theory
**Representative Units for the Plate Analysis**

(a) Longitudinal direction

(b) Transverse direction

Section A-A
**SIMPLE METHODS OF ANALYSIS**
(UNDER TANDEM LOAD ONLY)

(a) Transverse direction

(b) Longitudinal direction
Summary

- Composite materials hold great promise for effective renewal of deficient bridges.
- The hybrid FRP-concrete bridge superstructure is highly feasible from the structural engineering point of view.
- GFRP used in this study has revealed that its stress-strain relationship is not perfectly linear-elastic. However, for design purposes, the equivalent linear model can be used.
As is often the case with all-composite bridges, the design of the hybrid bridge superstructure is also stiffness driven.

Results from a series of quasi-static tests have shown an excellent performance of the proposed hybrid bridge under live loads.

The beam and orthotropic plate simplified analyses have proven to be effective to accurately predict the deflection of the hybrid bridge under design loads.
Challenges

- A systematic way to determine design parameters should be developed. It is also important to propose and optimize the design based on life-cycle cost as well as performance.
- Long-term performance of FRP bridges is not yet established and should be investigated: *creep, fatigue, and material degradation.*
- Thermal effects on FRP bridges is still unknown and should be investigated.
- Quality control concerns— the material properties are highly dependent on the manufacturing process.
Several practical aspects of FRP applications in bridges need to be addressed by researchers. The following are some of the outstanding issues:

- Methods to expand lanes
- Methods to cast concrete
- Considerations for negative moments
- Concrete barrier or steel parapet
- Support conditions
Challenges (CONT’D)

- There are benefits in using light FRP deck or superstructure in bridges located in moderate and seismic regions.

- Automated fabrication process must be used to fabricate the FRP parts of the superstructure or deck.
AUTOMATED FABRICATION PROCESSES

- Pultrusion
- RTM
- VARTM
- Use of braided fabrics
- Filament Winding
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