Preservation and Renewal of Civil Engineering Infrastructure Using FRP Composites

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OUTLINE OF THE PRESENTATION

1. Introduction
2. Current Challenges and Issues at Hand
3. Fiber-Reinforced Polymers (FRP)
4. Shear Strengthening
5. Softened Membrane Model
6. Concluding Remarks
WHERE IN THE WORLD ARE HOUSTON AND TEXAS?

• Texas is the second largest state in the USA.
  • It shares border with Mexico.
  • The capital city is Austin
  • 26 million people live in Texas.

TEXAS LANDSCAPE

★ Texas has a wide variety of landscapes, including coastal, mountains, planes, and desert.
TEXAS ECONOMY

Texas is an important part of the U.S. economy. It is the second wealthiest state in the country.

Important sectors of the Texas economy include oil and gas, agriculture and mining, energy, technology, and commerce.

Houston City - The Basics

- America’s 3rd/4th largest city
- Over 4 million residents
- Energy Capital of the World
- No ethnic majority
- 83 languages spoken
- “Houston” - First Word Spoken from the Moon
The University of Houston (UH) is a state research university and the flagship institution of the University of Houston System.

Founded in 1927
UH is the third largest university in Texas with more than 41,000 students.

UH is the second most ethnically diverse major research university in the United States.

Students come to UH from more than 137 nations

UH offers more than 120 undergraduate majors, 139 master’s, and 54 doctoral degrees.

UH has 980 ranked faculty, 1340 non-ranked faculty, and 1450 student teaching assistants.
The University of Houston comprises **12 academic colleges** and an interdisciplinary Honors College.

- Gerald D. Hines College of Architecture
- C.T. Bauer College of Business
- College of Education
- **Cullen College of Engineering**
- Honors College
- Conrad N. Hilton College of Hotel and
- UH Law Center
- College of Liberal Arts & Social Sciences
- College of Natural Sciences & Mathematics
- College of Optometry
- College of Pharmacy
- Graduate College of Social Work
- College of Technology

**UH Cullen College of Engineering**

- Dept. of Civil and Environmental Engineering
- Dept. of Electrical and Computer Engineering
- Dept. of Chemical Engineering
- Dept. of Petroleum Engineering
- Dept. of Biomedical Engineering
- Dept. of Industrial Engineering

**Interdisciplinary Graduate Programs in**

- Materials engineering
- Subsea Engineering
- Aerospace Engineering
- Geosensing Engineering
- Environmental Engineering

www.uh.edu
1- Introduction

Milestones of architecture and civil engineering

"If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death."

Code of Hammurabi – 1772 BC
1- Introduction

Conventional construction materials of today started to appear.
- Portland cement concrete
- Reinforced concrete
- Prestressed concrete
- Advanced composites and plastics
- What is next??

1- Introduction

The birth of reinforced Concrete

Reinforced Concrete details - Monier System 1867
Reinforced Concrete

The Burj Khalifa (United Arab Emirates) is the tallest man-made structure ever built (as of today). It is supported by a reinforced concrete core using a special concrete mix.

1- Introduction

Two centuries full of technological breakthrough

RC vs PC vs FRP

- Portland Cement
- Reinforced Concrete
- Prestressed Concrete
- ACI Building Code
- CEB/FIB
- PCI
- AASHTO
- ACI 440
- EuroCode

1824 J. Aspdin
1867 J. Monier
1871 Montasino
1933 E. Freyssinet
1957 Montasino
1967
1985
2000
2025
1824
1850
1875
1900
1925
1950
1975
2000
2025
2- Current Challenges and Issues at Hand

Man constructs,
Man destructs,
Man constructs...

Source: http://whateveryhappensny.bandcamp.com/releases

2- Current Challenges and Issues at Hand

WW II – Mass destruction of built environment and infrastructure of cities all around the world.

Hiroshima – Japan, 1945

Warsaw, Poland 1935-1945-2009
Reconstruction of the cities and boost of infrastructure started after WWII era in 1950s. Majority of structures today are reaching to their design life time.

- Boost in urbanization and accompanied infrastructure development. (Roads, bridges, sewers, buildings etc.)
- High demands, poor maintenance and aging bring accelerated deterioration.
2- Current Challenges and Issues at Hand

A great number of US bridges have become structurally deficient or functionally obsolete due to:

- Changing traffic demands

1950’s

2000’s

Change of use: Higher loads than originally designed
A great number of US bridges have become structurally deficient or functionally obsolete due to:

- Changing traffic demands
- Improvements in design standards
- Long-term deterioration
2- Current Challenges and Issues at Hand
A great number of US bridges have become structurally deficient or functionally obsolete due to:

- Changing traffic demands
- Improvements in design standards
- Long-term deterioration
- Man-made structural damage
2- Current Challenges and Issues at Hand

Bridge construction in the USA

About 1,000,000 bridges

Source: www.FHWA.DOT.GOV

2- Current Challenges and Issues at Hand

Wood, 3.7%
Prestressed Concrete, 24.0%
Steel, 30.1%
Concrete, 41.6%
Other, 0.6%

Source: www.FHWA.DOT.GOV
2- Current Challenges and Issues at Hand

ASCE 2013 Report Card for Bridges: **C+**

Need to invest $20.5 billion annually till 2028

Problem should be addressed and solutions should be proposed in the light of former experience and foresight:

- Traditional vs. new materials
- Economical solutions
- Immediate actions

ADVANCE COMPOSITE MATERIALS
2- Current Challenges and Issues at Hand

Find out more about any of these Grand Challenges:

- Advance health informatics
- Advance personalized medicine
- Engineer better medicines
- Engineer the tools of scientific discovery
- Manage the carbon cycle
- Provide energy from fusion
- Provide access to clean water
- Secure cyberspace
- Secure food and water
- Secure the nation
- Develop carbon capture and storage techniques
- Enhance virtual reality
- Prevent nuclear terror
- Restore and improve urban infrastructure

Nationally recognized need

3- Fiber-Reinforced Polymers (FRP)

FRPs are advanced composite materials consisting of high strength fibers such as aramid, carbon or glass embedded in a polymer resin.

Commercially available forms
- Reinforcing Bar and Prestressing Tendons
- Pre-cured laminate shells
- Grids
- Fiber sheets
Since 1970s FRP has been used in civil engineering application.

Among all the research about FRP, the study of the shear behavior still remains as a challenging debate.

3- Fiber-Reinforced Polymers (FRP)

- Flexural Strengthening
- Confinement
- Shear Strengthening

2- Fiber-Reinforced Polymers (FRP)

- 53rd Ave. Bridge, IA
- Mills Rd. Bridge, OH
- Franklin Co. Bridge, VA
- Trout River Bridge, Alcan Hwy.
3- Fiber-Reinforced Polymers (FRP)

- What is FRP?

  **Fibers**
  - Provide strength and stiffness
  - Carbon, glass, aramid

  **Matrix**
  - Protects and transfers load between fibres
  - Epoxy, polyester, vinylester

**Composite**

Creates a material with attributes superior to either component alone!

3- Fiber-Reinforced Polymers (FRP)

- Light weight
- High Strength
- Corrosion Resistant
- High Versatility

**Advanced Composite Materials – FRP**
FRP properties (compared to steel reinforcement):

- Linear elastic
- No yielding
- Higher ultimate strength
- Lower strain at failure

Limitations:
- Higher Cost
- Anisotropy
- Brittle Behavior
- Complex Characterization
- Lack of Comprehensive Standard Design Codes (emerging)
Global demand for CFRP in tonnes (2008 – 2020)

Civil Engineering = 6%

Global Carbon Fiber consumption per application (2012)


3- Fiber-Reinforced Polymers (FRP)

General use of FRP in Transportation

Aircrafts
- A380 Fiber Metal Laminate
- McLaren – Formula 1 CFRP Thermoset Car Body Structure

Race Cars
- GMT-Thermoplastic
- SMC Thermoset Parts for Driver Cabin
- SMC Thermoset Panels

Trucks
- GMT-Thermoplastic

Cars
- Innovative Moulded Thermoplastic Car Body

Helicopters
- Rotor Blade Erosion Protection

Sport Cars
- CFRP Thermoset Car Body Structure

Buses
- SMC Thermoset Panels

Concept Cars
- Injection Moulded Thermoplastic Car Body

Automotive/Railway and Aerospace
Proposal for a carbon fiber-reinforced composite bridge across the Strait of Gibraltar at its narrowest site according to Meier (1987) as a cable net structure.

Spans: 3,100 – 8,400 m.
The heights of the towers are approximately 850 and 1,250 m. above sea level.
A suspension bridge across the Strait of Taiwan with a main span of 3,500m.

FRP composites have various applications in bridge construction:

- Bridge deck
- Abutment panel
- Rebar or prestressing reinforcement
- Dowel bar
- Pole and post
- Signboard and signpost
- Guardrail system
3- Fiber-Reinforced Polymers (FRP)

Cases of structural strengthening

FRP Strengthening

- **Type**
  - Flexural
  - Axial
  - Shear

- **Location**
  - On surface (Tension side)
  - On periphery
  - On surface (Web side)

- **Fiber Orientation**
  - Parallel to long. axis
  - Circumferential
  - Perpendicular to long. axis

12/9/2016
3- Fiber-Reinforced Polymers (FRP)

Available Design Guidelines Worldwide

- ISIS Canada Design Manual
- CSA S806-12
- ACI 440.2R-08
- European fib TG9.3 (2001)

Emerging Technologies

Accepted Technologies
Analysis procedures are more empirical as compared to flexural and axial strengthening

Limited experimental knowledge base

Not all parameters affecting the shear behavior have been investigated
4-Shear Strengthening

**Schemes**

- Internal reinforcement
- FRP laminates

- Complete Wrapping
  - (Contact critical)

- U-Wrap
  - (Bond critical)

**Parameters Influencing the Behavior**

- Wrapping Schemes

![Bar chart showing FRP Wrapping Schemes](chart.png)

- Side Bonding: 82%
- U-Wrap: 65%
- Complete wrapping: 55%
Main Approaches

- **Truss Model Approach**
  - Triantafillou (1998)
  - Khalifa et al. (1998, 1999)
  - Triantafillou et al. (2000)
  - Chaallal et al. (2002)
  - Pellegrino et al. (2002)
  - Hsu et al. (2003); Zhang and Hsu (2005)

- **Mechanics-Based Model**
  - Cao et al. (2005)
  - Caroline and Talsten (2005)
  - Monti and Liotta (2005)

- **Non-Uniform Strain Distribution**
  - Khalifa et al. (1999)
  - Chen and Teng (2003)

Shear Mechanism Based on Truss Model

General Form of Design Equations:

\[ V_n = V_c + V_f + \psi_f V_f \]

- **Adopted from RC design**
- **Considered similar as steel**

The shear contribution of each component is derived separately. However, a high level of interaction exists between them.
4. Shear Strengthening

Analytical Models for Shear Resistance of FRP-Strengthened Specimens

\[ V_n = V_c + V_s + \psi_f V_f \]

- General formulation:
  \[ V_f = \frac{A_f E_f \varepsilon_{fe} d_f (\cot \theta \sin \beta + \cos \beta)}{s_f} \]

Strengthening with FRP can affect the shear contribution of concrete and transverse reinforcement.

The primary difference between existing relationships for \( V_f \) is in the calculation of the effective strain and the effective depth of the FRP reinforcement.

Analytical Models – Use of Fixed Value of Effective Strain \( \varepsilon_{fe} \)

- Chajes et al. (1995)
  \[ \varepsilon_{fe} = 0.005 \]
  (failure mode was not defined)

- Hutchinson and Rizkalla (1999)
  \[ \varepsilon_{fe} = 0.004 \]
  For peeling off of FRP observed especially in girder

  For other failure mode, Triantafillou (1998) and Khalifa (2000) were referred

- CSA S806-07 (2007)
  \[ \varepsilon_{fe} = 0.004 \]
  for U-wrap
  \[ \varepsilon_{fe} = 0.002 \]
  for Side-bonding

- ACI 440.2R-08 (2008)
  \[ \varepsilon_{fe} = 0.004 \leq 0.75 \varepsilon_p \]
  for full wrapped FRP

  For two-side bonding and U wrapped FRP, different equations are provided
Most of strain limits fall into this range.

Relation of active bond length $L_e$ to effective depth $d_{fe}$

- **U-wrapped**
  
  $d_{fe} = d_f - L_e$

- **2 sides only**
  
  $d_{fe} = d_f - 2L_e$
4-Shear Strengthening

Determination of active bond length $L_e$:

Effective bond length as specified by various Codes:

<table>
<thead>
<tr>
<th>Code</th>
<th>Year</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI 440.2R-08 (USA)</td>
<td>2008</td>
<td>$\frac{23300}{(nE_s f_y)^{0.1}}$</td>
</tr>
<tr>
<td>ISIS, CSA S806-02 (Canada)</td>
<td>2002</td>
<td>$\frac{25350}{(E_s f_y)^{0.12}}$</td>
</tr>
<tr>
<td>FIB B14- Appendix A1 (Europe)</td>
<td>2001</td>
<td>$L_e = \frac{f_y}{E_s} \cdot \frac{c_3}{c_2}$</td>
</tr>
<tr>
<td>FIB B14- Appendix A2 (Europe)</td>
<td>2001</td>
<td>$L_e = c_1 \cdot \frac{F_y}{E_s} \cdot \frac{c_3}{c_2}$ ; $c_3 = 1.44$</td>
</tr>
<tr>
<td>CS TR55 (UK)</td>
<td>2004</td>
<td>$L_e = 0.7 \frac{f_y}{E_s}$</td>
</tr>
<tr>
<td>CNR-DT 200/04 (Italy)</td>
<td>2005</td>
<td>$L_e = \frac{f_y}{E_s}$</td>
</tr>
<tr>
<td>Eurocode 8-3 (Europe)</td>
<td>2004</td>
<td>$L_e = \frac{f_y}{E_s}$</td>
</tr>
<tr>
<td>CIDAR (Australia)</td>
<td>2006</td>
<td>$L_e = \frac{f_y}{E_s}$</td>
</tr>
</tbody>
</table>

Mostly based on stiffness of FRP
**Influence of FRP Properties on Effective FRP Strain**

FRP stiffness increase → Effective FRP strain decrease

**Influence of FRP Properties on Shear Force Gain**

Slender beam without transverse steel reinforcement → debonding failure

Beyond this point, additional FRP does not translate into additional shear gain
Effect of Transverse Steel Reinforcement on Shear Force Gain

Slender beams – debonding failure

Shear force gain (%)

\[ \left( \frac{\rho_s f_s}{\rho_f f_e} \right) \text{ Increases } \Rightarrow \text{ Shear force gain decreases} \]

Effect of Shear Span to Depth Ratio (Slender vs. Deep Beam)

Beams without transverse steel reinforcement – debonding failure

Increases in shear force gain seem in general to be greater in slender beams (a/d>2.5) than in deep beams \(\Rightarrow\) arch action
4. Shear Strengthening

Scale Effect
Beams without transverse steel reinforcement – debonding failure

![Graph showing scale effect with practical values for AASHTO type girders](image)

Possible Shear Failure Modes

- Debonding of FRP sheet from substrate
Possible Shear Failure Modes

- Debonding of FRP sheet from substrate
- Loss of aggregate interlock (i.e., loss of $V_c$)

- Loss of web width/area
Possible Shear Failure Modes

- Debonding of FRP sheet from substrate
- Loss of aggregate interlock (i.e., loss of $V_c$)
- Loss of web width/area
- FRP rupture due to stress concentration
Analytical Models for Shear Resistance of FRP-Strengthened Specimens

NCHRP Report 678 (2011)

U-Wrapping

1 in. = 25.4 mm

1 ksi = 6.89 MPa

"All models are wrong; some models are useful."

George Box (Statistician)
5. Softened Membrane Model

- Element Behavior as Part of a Complete Structure

- Nuclear Containment Vessel
- Shell Structure
- Gravity Base Offshore Platform
- High-Rise Building Core (Shanghai Tower, 2,073 ft)
An efficient method to assess the overall shear response of a strengthened member is to study the behavior of an element constituting the structure.

On-Going Panel Tester Project

Universal Panel Tester

FRP strengthened RC Panel
5. Softened Membrane Model

- Softened Membrane Model (2002)
  - SMM-FRP

Governing Equations of SMM

- Stress equilibrium equations

\[
\begin{align*}
\sigma_1 &= \sigma_1^c \cos^2 \alpha_i + \sigma_2^c \sin^2 \alpha_i - \tau_{12} \cdot 2 \sin \alpha_i \cos \alpha_i + \rho_{1f} f_{1f} \cdot \rho_{nf} f_{nf} \\
\sigma_2 &= \sigma_1^c \sin^2 \alpha_i + \sigma_2^c \cos^2 \alpha_i + \tau_{12} \cdot 2 \sin \alpha_i \cos \alpha_i + \rho_{2f} f_{2f} + \rho_{nf} f_{nf} \\
\tau_{12} &= \left(\sigma_1^c - \sigma_2^c\right) \sin \alpha_i \cos \alpha_i + \tau_{12}^c \left(\cos^2 \alpha_i - \sin^2 \alpha_i\right)
\end{align*}
\]
Universal Panel Tester

Unique facility to test full scale panel elements under various combination of in-plane and out-of-plane stress conditions.

Softened Membrane Model (2002)

- Governing Equations of SMM

  - Strain transformation equations

\[
\begin{align*}
\epsilon_f &= \epsilon_1 \cos^2 \alpha_1 + \epsilon_2 \sin^2 \alpha_1 - \frac{Y_{12}}{2} \sin \alpha_1 \cos \alpha_1 \\
\epsilon_t &= \epsilon_1 \sin^2 \alpha_1 + \epsilon_2 \cos^2 \alpha_1 + \frac{Y_{12}}{2} \sin \alpha_1 \cos \alpha_1 \\
\frac{Y_{tt}}{2} &= (\epsilon_1 - \epsilon_2) \sin \alpha_1 \cos \alpha_1 + \frac{Y_{12}}{2} (\cos^2 \alpha_1 - \sin^2 \alpha_1)
\end{align*}
\]
5. Softened Membrane Model

- Softened Membrane Model (2002)
  - Governing Equations of SMM
    - Material laws
      \[ \begin{align*}
      (\sigma_1', \sigma_2', \tau_{12}', f_1', f_2') &= f(\varepsilon_{12}', \varepsilon_{13}', \varepsilon_{23}', \varepsilon_{13}, \varepsilon_{23}) \\
      \text{Smeared Stress} \quad \text{Smeared Strain} \quad \text{Poisson’s Ratio}
      \end{align*} \]

- Smeared Stress-Strain Curves of Concrete in Tension
  \[ \begin{align*}
  \sigma_1' &= E_c' \varepsilon_1' \left( \frac{\varepsilon_c}{\varepsilon_1'} \right)^{0.4} \frac{\varepsilon_1'}{\varepsilon_c} < 1 \quad \varepsilon_1' < \varepsilon_c = 0.00008 \\
  \sigma_2' &= f_{cr} \left( \frac{\varepsilon_c}{\varepsilon_1'} \right)^{0.4} \frac{\varepsilon_1'}{\varepsilon_c} \geq 1 \quad \varepsilon_1' \geq \varepsilon_c = 0.00008 \\
  \end{align*} \]

Due to the extra bond created by the FRP and the smaller crack distribution, the tension stiffening is expected to be increased.

- Concrete Softening under Biaxial Load
  \[ \begin{align*}
  \sigma_2' &= \zeta_2' \left[ 2 \left( \frac{\varepsilon_2}{\varepsilon_0} - \left( \frac{\varepsilon_2}{\varepsilon_0} \right)^2 \right) \right] \frac{\varepsilon_2}{\varepsilon_0} < 1 \\
  \sigma_2' &= \zeta_2' \left[ 1 - \left( \frac{\varepsilon_2}{\varepsilon_0} - \left( \frac{\varepsilon_2}{\varepsilon_0} \right)^2 \right) \right] \frac{\varepsilon_2}{\varepsilon_0} \geq 1 \\
  \end{align*} \]

Due to the confinement effect of FRP, concrete should be less “softened.”
5. Softened Membrane Model

- Softened Membrane Model (2002)
  - Governing Equations of SMM
    - Material laws
      \[ (\sigma_1', \sigma_2', \varepsilon_1', \varepsilon_2', f_1, f_2) = f(\varepsilon_{1u}, \varepsilon_{2u}, \varepsilon_{12}, \varepsilon_{21}) \]
      - Smear Stress
      - Smear Strain
      - Poisson's Ratio

-Smeared Stress-Strain Curves of Steel in Tension

\[ f_s = \frac{f_y}{E_s} \varepsilon_s \]
\[ f_s = (0.91 - 2B) f_y + (0.02 + 0.25B)E_s \varepsilon_s \]
\[ f_s = f_p - E_s (\varepsilon_{sp} - \varepsilon_{y}) \]
\[ \varepsilon_{sp} = \frac{f_y}{E_s} \]
\[ \varepsilon_{y} = (0.93 - 2B) f_y \]
\[ B = \left( \frac{f_{ys}}{f_y} \right)^{1.5} f_{sp} = 0.31 \sqrt{f_c} (MPa) \text{ and } \rho \geq 0.15\% \]

Shear Test Panels

- Specimen preparation
  - Grinded
  - Sandblasted
  - Power washed
  - Primer and putty
  - Wet lay up FRP application system

- Material tests
  - Concrete: ASTM C39
  - Steel: ASTM 8M-01
  - FRP: ASTM D3039

- \( f'c = 40 \text{ MPa } \) concrete strengths
- \( f'y = 420 \text{ MPa } \) steel reinforcements
### Shear Test Matrix

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Name</th>
<th>$\rho_{1}$ (%)</th>
<th>$\rho_{2}$ (%)</th>
<th>Wrapping Scheme</th>
<th>Anchorage method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>REF_P4</td>
<td>0.76</td>
<td>0.76</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>REF_P3</td>
<td>0.76</td>
<td>0.43</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>P4_040_SB</td>
<td>0.76</td>
<td>0.76</td>
<td>0.87</td>
<td>Side Bonding</td>
</tr>
<tr>
<td>4</td>
<td>P4_040_FA</td>
<td>0.76</td>
<td>0.76</td>
<td>0.87</td>
<td>U-Wrap CFRP anchor</td>
</tr>
<tr>
<td>5</td>
<td>P4_025_FW</td>
<td>0.76</td>
<td>0.76</td>
<td>0.54</td>
<td>Fully Wrap</td>
</tr>
<tr>
<td>6</td>
<td>P4_040_FW</td>
<td>0.76</td>
<td>0.76</td>
<td>0.87</td>
<td>Fully Wrap</td>
</tr>
<tr>
<td>7</td>
<td>P4_025_FA</td>
<td>0.76</td>
<td>0.76</td>
<td>0.54</td>
<td>U-Wrap CFRP anchor</td>
</tr>
<tr>
<td>8</td>
<td>P3_040_FW</td>
<td>0.76</td>
<td>0.43</td>
<td>0.87</td>
<td>Fully Wrap</td>
</tr>
<tr>
<td>9</td>
<td>P3_025_FW</td>
<td>0.76</td>
<td>0.43</td>
<td>0.54</td>
<td>Fully Wrap</td>
</tr>
<tr>
<td>10</td>
<td>P4_080_FW</td>
<td>0.76</td>
<td>0.76</td>
<td>1.74</td>
<td>Fully Wrap</td>
</tr>
</tbody>
</table>

The proposed equation for calculating Hsu/Zhu ratio for RC element significantly overestimated the Poisson effect for the FRP RC element. With the increase of FRP stiffness, the Poisson effect becomes less significant.
To develop a model based on SMM for FRP strengthened RC members, new material Laws have to be used:

- Smeared Stress-Strain Curves of Concrete in Tension
- Concrete Softening under Biaxial Load
- Smeared Stress-Strain Curves of Steel in Tension
- Poisson Ratio under Biaxial Load

New material models consider:

- Stiffness of FRP
- Wrapping scheme
- Spacing of External reinforcement
- Steel reinforcement ratio
- FRP reinforcement ratio
- Bond
6- Concluding Remarks

• Where do we stand in terms of level of knowledge regarding the shear behavior of FRP strengthened reinforced concrete members? How much do we know about shear behavior?

Preservation and Renewal of Civil Engineering Infrastructure Using FRP Composites

Thank you!

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