FRP composites in bridge design

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Introduction

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FRP Composites in bridge design

Agenda

What is NGCC?
What are FRP Composites?
Why use them in bridges?
What have we learned so far?
What challenges remain?
Recent developments in design guidance
Future opportunities
What is NGCC?

FRP Composites in bridge design

Encourages effective use of FRP
Partnering + collaboration
Raise profile
Provide information
Training and events
What is NGCC?

FRP Composites in bridge design

Our members include:
clients, designers, architects,
contractors, suppliers, manufacturers,
academics...

Benefits:
• Networking with professionals across industry and academia
• Collaboration and research opportunities
• Technical information in website members area
• Exhibition opportunities
• Special rates at events
What is NGCC?

**FRP Composites in bridge design**

NGCC

- provides representation on the European working group to develop eurocodes for FRP composites
- Has set up a bridge design group developing design guidance
- Has set up subgroups to coordinate FRP research and development and training
FRP Composites in bridge design

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FRP Composites

Benefits
- Non-corroding
- Do not need painting
- Light weight
- Strong
- Able to resist harsh environments
- Can be non-conductive and non-magnetic

Image courtesy of Parsons Brinckerhoff
FRP Composites

Fibres
- Glass
- Carbon (standard and high modulus)
- Aramid
- Basalt

Resin matrix
- Polyesters
- Vinyl esters
- Epoxies
- Phenolics
- Thermoplastics (eg polyamides)

Additives
What are FRP Composites?

**FRP Composites**

**Properties**

<table>
<thead>
<tr>
<th></th>
<th>E-GLASS</th>
<th>ARAMID (Kevlar 49)</th>
<th>HIGH STRENGTH CARBON</th>
<th>HIGH MODULUS CARBON</th>
<th>STEEL (Grade S275)</th>
<th>CONCRETE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>650</td>
<td>900</td>
<td>1000-1900</td>
<td>800-1400</td>
<td>275 Yield 430 Ultimate</td>
<td>2-5</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>550</td>
<td>250</td>
<td>~1000</td>
<td>~600</td>
<td>275 Yield 430 Ultimate</td>
<td>25-60</td>
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<tr>
<td>Tensile Modulus (GPa)</td>
<td>30</td>
<td>50</td>
<td>100-120</td>
<td>140-240</td>
<td>205</td>
<td>25-36</td>
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<tr>
<td>Tensile Failure Strain (%)</td>
<td>2.3</td>
<td>2.2</td>
<td>1.5-2.2</td>
<td>0.6-1.4</td>
<td>20</td>
<td>0.01</td>
</tr>
<tr>
<td>Density (Kg/m³)</td>
<td>1700</td>
<td>1300</td>
<td>1440</td>
<td>1480</td>
<td>7900</td>
<td>2400</td>
</tr>
<tr>
<td>Coefficient of Thermal Exp (10⁶/°C)</td>
<td>10</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>7-12</td>
</tr>
</tbody>
</table>

Undirectional Laminate Fibre Volume Fraction Vf = 40%. Properties in longitudinal direction.

Properties are typical values but are highly dependant on laminate quality, fibre volume fraction, etc...
FRP Composites

Manufacturing processes

- Pultrusion

- Variety of moulding processes
  - Open moulding (hand or spray lamination)
  - Vacuum infusion
  - Resin transfer moulding
  - Vacuum bag or press moulding
FRP Composites

Manufacturing processes

• Pultruded components
  – Prismatic sections
  – Standard profiles (off the shelf)
  – Lower partial factors for design
  – Limited geometries

• Moulded components / structures
  – Unlimited geometric possibilities
  – Optimised fibre layouts
  – Can reduce need for joints
  – Bespoke tooling
FRP Composites in bridge design

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Why use them in bridges?

Non-corroding
No need to paint
Light weight – installation advantages

Cost?
Not always the best solution

Particular situations
- Difficult access
- Corrosive environments
- Need to minimise weight on supporting structure
- Quick installation over existing road / railway
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Bridge applications
FRP Composites in bridge design

- Overview of FRP bridges
- Case Study: St Austell Footbridge
• Motorway overbridges using hybrid system
• Short span road bridges
FRP Composites in bridge design

- Lifting bridges
• Footbridges
• Case study: St Austell Footbridge Design
St Austell Footbridge Design

Laser survey of old footbridge
St Austell Footbridge Design
St Austell Footbridge Design

St Austell Footbridge Design

- The first bridge on the UK rail network to be entirely constructed from FRP
- Pultruded main elements
- Moulded exterior skin
St Austell Footbridge Design

- Pultruded panels bonded and secured with additional mechanical connection

- Design philosophy developed for robustness

- Unexpected joint failure would cause reduction of stiffness, not collapse
St Austell Footbridge Design

- Bridge is very light (central span is 5 tonnes)
- Potential for vibration caused by train buffeting
- Low mass might result in high accelerations – uncomfortable for pedestrians?
- Magnitude of train buffeting loading?
Vibration research

- Goring temporary footbridge
- A very lively structure
Vibration research

- Dynamic testing carried out with Sheffield University
Vibration research

- Accelerometers positioned on structure
Vibration research

- Determination of modal properties
- Measurement of structure response
• Comparison of theoretical response with actual response
Vibration research

- Comparison of theoretical response with actual response
Vibration research

- Derivation of revised loading model based on measurements
- PB-derived loads used to design St Austell Footbridge
- Research provides data to allow lightweight footbridges to be used over railway lines
Testing and monitoring

- Before fabrication
  - Material testing
  - Component testing

- After fabrication
  - Structure load testing

- After installation
  - Dynamic testing & monitoring
Testing and monitoring

- Static load testing
- Water load - uniform
- Linear behaviour
- Small deflections
Testing and monitoring

- Dynamic testing
- Modal properties
- Pedestrian-induced vibrations
- Train buffeting vibrations
Testing and monitoring

- Ongoing monitoring of structure
- Philosophy developed for dynamic monitoring of natural frequencies and modeshapes
FRP Composites in bridge design

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Challenges

Gaps in codes
Clients unfamiliar with materials?
Costs need to be competitive at construction
Recyclability of materials
Design issues – eg flexibility, fire, robustness
"Failure is central to engineering … every single calculation that an engineer makes is a failure calculation.

Successful engineering is all about understanding how things break or fail."

Henry Petroski
Collapse of the (steel) I-35W Highway Bridge, Minnesota, Aug 2007
I-35W Highway Bridge, Minnesota, Aug 2007

North

Collapse Video - Frame #6
I-35W Highway Bridge, Minnesota, Aug 2007

Collapse Video - Frame #11

North
Collapse of the (concrete) De la Concorde Overpass, Montreal, 2006
Inquiries recommended improvements to:

- robustness in design
- and management of vulnerable structures
How do we apply principles of robustness to FRP structures?
How do we apply principles of robustness to FRP structures?

Not Plastic!

Gaps in design standards
2.1
(2) A structure shall be designed to have adequate:
• structural resistance,
• serviceability, and
• durability.
2.4

(2) A structure shall be designed and executed in a way that it will not be damaged by events such as:

- explosion
- impact, and
- the consequences of human errors, to an extent disproportionate to the original cause
General design principles

ULS
In ductile structures, we often rely on a very useful theorem that allows us to make simplifications in the analysis...
If the load has a magnitude such that it is possible to find a stress distribution corresponding to stresses within the yield surface and satisfying the equilibrium conditions and the statical boundary conditions for the actual load, then this load will not be able to cause collapse of the body.
If the load has a magnitude such that it is possible to find a stress distribution corresponding to stresses within the yield surface and satisfying the equilibrium conditions and the statical boundary conditions for the actual load, then this load will not be able to cause collapse of the body.

The Lower Bound Theorem of Limit Analysis
If the load has a magnitude such that it is possible to find a stress distribution corresponding to stresses within the yield surface and satisfying the equilibrium conditions and the statical boundary conditions for the actual load, then this load will not be able to cause collapse of the body.

The Lower Bound Theorem of Limit Analysis

Not valid without ductility!
We can not rely on the lower bound theorem for FRP design
General design principles

ULS

We can not rely on the lower bound theorem for FRP design

No shortcuts!

Relative stiffness effects
- Anisotropy
- Shear flexibility
- “Cosmetic” components

Self equilibrating stresses
- Thermal effects
- Differential settlement
But FRP structure designs are very often governed by SLS criteria
SLS – driven design is quite unusual in bridge design

It provides safety and robustness benefits
Consider a simply supported beam, subject to excessive load
Consider a simply supported beam, subject to excessive load

Steel design, governed by ULS - collapse with almost no warning
- ULS factor of safety $R_k/E_k$ about 1.6
Consider a simply supported beam, subject to excessive load

Steel design, governed by ULS
- collapse with almost no warning
- ULS factor of safety $R_k/E_k \approx 1.6$

FRP design, governed by SLS
- large deflections before collapse
- ULS factor of safety $R_k/E_k \approx 5-10$
So how do we design for robustness?

What would happen next if there was some local damage / overstress?
(5) For unconventional structures (e.g. very large structures, those with new design concepts, those using new materials) the probability of having some unspecified cause of failure should be considered as substantial. A combined approach of the methods described in B.9.1(2) and B.9.1(3) should be taken into account.
BS EN 1991-1-7 B.9.1

(5) For unconventional structures (e.g. very large structures, those with new design concepts, those using new materials) the probability of having some unspecified cause of failure should be considered as substantial. A combined approach of the methods described in B.9.1(2) and B.9.1(3) should be taken into account.

(a)  
(b)  
(c)
General design principles

Designing for robustness

The undamaged structure is designed for SLS and ULS.

Vulnerable details are identified

A vulnerable detail is chosen for further investigation

The structure is modelled with this detail removed using the combination of actions for the accidental design situation

The effects from this analysis are compared with the ULS design resistance for short term effects.

If the damaged structure has insufficient resistance, the design is revised to improve robustness.
General design principles

Designing for robustness

Philosophy developed for St Austell Footbridge

- Exterior skin comprising moulded panels
- Longitudinal elements comprising ACCS panels built up into U-shape
- Transverse frames to provide lateral stiffness and stability
- Lower part of structure can resist “frequent” loading if vulnerable joints fail
Designing for robustness

General design principles

Hybrid joints
- Bonded and bolted
Robustness needs to be considered in ALL designs

Challenges are different with FRP

High strain to failure – SLS governs

Framework for design proposed at paper at FRP Bridges 2012.

“Successful engineering is all about understanding how things break or fail.”

Henry Petroski
FRP Composites in bridge design

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Most previous designs carried out using combination of:

- (previously) BD37
- (now) Eurocodes for loading and basis of design
- BD90,
- Eurocomp Design Code,
- Product design manuals,
- Project-specific “aspects not covered” or departures (often developed by designers).

Currently no Eurocode for FRP design (there are plans for one eventually).

There is a need for a more coordinated and comprehensive set of design rules and principles.
NGCC has an FRP Bridge Design Group

Producing design guidance on FRP bridge design

- Eurocode aligned

- Aims to plug the gaps in current standards and provide best practice guidance

- Focus on principles and failure criteria to be covered.
Technical Report No. 55
Design guidance for strengthening concrete structures using fibre composite materials
Third Edition

Strengthening using FRP: new edition of TR55
What does TR55 cover?

How has it changed in 3\textsuperscript{rd} edition?
What does TR55 cover?

How has it changed in 3rd edition?
What does TR55 cover?

1. Introduction
2. Background
3. Material types and properties
4. Review of applications
5. Structural design of strengthened members
6. Strengthening members in flexure
7. Shear strengthening
8. Strengthening axially loaded members
9. Emerging technologies
10. Workmanship and installation
11. Long term inspection and monitoring
What does TR55 cover?

2 Background

• Advantages
• Disadvantages
What does TR55 cover?

3 Material types and properties

- Fibres
- Fabrics
- Plates
- Rods and strips
- Preformed shells
- Specials
- Adhesives and resins
What does TR55 cover?

5 Structural design of strengthened members

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>Serviceability</th>
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</thead>
<tbody>
<tr>
<td>Structural strength</td>
<td>Deflection</td>
</tr>
<tr>
<td>Bending</td>
<td>Concrete crack widths</td>
</tr>
<tr>
<td>Shear</td>
<td>Stress limitations</td>
</tr>
<tr>
<td>Compression</td>
<td>Vibration</td>
</tr>
<tr>
<td>Anchorage–plate separation</td>
<td></td>
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<tr>
<td>FRP stress rupture</td>
<td></td>
</tr>
<tr>
<td>Fatigue</td>
<td></td>
</tr>
<tr>
<td>Fire</td>
<td></td>
</tr>
</tbody>
</table>
What does TR55 cover?
What does TR55 cover?

7 Shear strengthening
What does TR55 cover?

8 Strengthening axially loaded members
What does TR55 cover?

8 Strengthening axially loaded members
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8 Strengthening axially loaded members
Square and rectangular columns:

- Axial strain
- Corner confining force
- Hoop FRP strain
- Shear stress, $\tau$

$\varepsilon_{cc,\text{max}} = 0.001$
What does TR55 cover?

How has it changed in 3rd edition?
How has it changed in the 3\textsuperscript{rd} edition?

- Eurocode alignment
- Research advances
- Further experience of materials
- Links to CompClass & CSWIP
How has it changed in the 3rd edition?

- Fire design
- Improvements and rationalisation of design processes
- Deep embedment bars
- Emerging technologies
How has it changed in the 3\textsuperscript{rd} edition?

- Eurocode alignment
  - Eurocodes have effectively replaced British Standards for design.
  - FRP outside scope of Eurocodes

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BS EN 1990

BS EN 1991

BS EN 1992

TR55
3\textsuperscript{rd} Ed
How has it changed in the 3rd edition?

- Eurocode alignment
- Particular impact on:
  - Basis of design
  - Load models
  - Concrete
How has it changed in the 3\textsuperscript{rd} edition?

- Eurocode alignment
- Particular impact on:
  - Combinations of actions
  - Robustness
  - Initial strain
  - SLS criteria

Characteristic

Frequent

Quasi-permanent
How has it changed in the 3rd edition?

- Eurocode alignment
- Particular impact on:
  - Fire design
  - Shear strengthening
Conclusion

What does TR55 cover?

How has it changed in 3rd edition?
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Future opportunities

FRP Composites in bridge design

©Optima Projects
Mirabella V 75m long hull mould & on sea trials
(VT Shipbuilding)

75m long wind turbine blade
(Reinforced Plastics / Siemens)
Most conventional bridges would have 2 or more intermediate piers.

Piers are complex, expensive & time consuming to build.

FRP design to have 300m clear span to avoid the need for piers.
Future opportunities

FRP Composites in bridge design

Low laminate stresses (SLS driven design)
Future opportunities

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