Design Guidance for Strengthening Concrete Structures using Fibre Composite Materials (TR55)

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Topics Covered Today

- What are fibre composite materials?
- History of use
- Design guidance
- Plans for TR55 3rd edition
What are fibre reinforced polymer composites?

- Modern high strength, durable materials
- Extensively used in the aeronautical, automotive and sports goods industries
- External reinforcement for strengthening structures
What are Composites?

- Composites are a mixture of hardened matrix and a reinforcement.
- In traditional construction, the matrix is concrete and the reinforcement is steel.
- With fibre reinforced composites, the matrix is a resin (like epoxy) and a fibre or fabric (like carbon, aramid or glass).
- Different composites have different properties.
Fibres

- Aramid - Expensive, absorbs water, tough, good in impact situations, good in vibration damping, relatively high creep, very light
- Carbon - The BEST fibre, expensive, virtually inert, very low creep, limited availability, extreme temperature resistance, most brittle of the three
- Glass - the ECONOMIC choice, low creep, good temperature resistance, susceptible to strong acids and bases, very inexpensive. Subject to stress corrosion, readily available
Resins

There are five basic resin types used in composites

- Phenolics - good fibre resistance - poor mechanics
- Polyurethanes - good abrasion resistance - poor temperature performance, toxicity problems
- Polyesters - workhouse of the trade - inexpensive - good general properties - VOC and odour problems
- Vinylesters - good fatigue, moderate price, good chemical resistance, VCO and odour problems
- Epoxies - best resistance, adhesion, fatigue - more expensive, low odour and VOC
Laminates

- Pultruded carbon fibres
  - 5 microns diameter
- Epoxy resin
- Oven baked
- Surface preparation
Wraps - Hand lay-up

- Fabrics of Carbon, Glass, Aramid (Kevlar)
- Woven Mats
- Wet Applied or Dry Applied
Strengthening with Fibre Composite Materials

Calverley River Bridge, Leeds - Shear

Loudwater Viaduct, Wycombe - Flexural
Strengthening with Fibre Composite Materials

A30 Bible Christian Bridge, Bodmin – Axial
History of Use in UK

- Buildings - Kings College Hospital - 1996
- Highway structures – Jarrow Subways - 1996
- Rail Bridges – The Glade, Surrey - 1998
History of Design Guidance

• Early research in Switzerland (Prof. Urs Meier) - 1990
• Fib and ACI 440
• Technical Report 55 1\textsuperscript{st} Edition - 2000
• Technical Report 55 2\textsuperscript{nd} Edition - 2004
• Technical Report 55 3\textsuperscript{rd} Edition - 2011 ?
Technical Report 55 Contents
Second Edition

• Background
• Material types and properties
• Review of applications
Technical Report 55 Contents
Second Edition

Topics covered include:

• Structural design of strengthened members
• Strengthening members in flexure
• Shear strengthening
• Strengthening axially loaded members
Technical Report 55 Contents
Second Edition

• Emerging technologies
• Workmanship and installation
• Long-term inspection, monitoring and maintenance
Structural design of members

Basis of design

- Elastic – brittle nature of externally applied FRP’s
- Compatible with BS8110 and BS5400
- Ultimate limit states – bending shear, compression, anchorage / plate separation
- Serviceability – Deflection, cracking, steel stress, fatigue, creep, stress rupture, durability
Mechanical Properties of Materials

**FRP composite**

Characteristic tensile strength \((f_{jk}) = f_{fm} - 2 \, S\)

- \(f_{fm}\) = mean
- \(S\) = standard deviation

**Steel**

\(f_y\) = Characteristic yield strength

**Concrete**

\(f_{cu}\) = Characteristic cube strength
Partial Safety Factors for Loads

- As BS8110, BS5400 or BD37 as appropriate
- BS EN 1990 and BS EN 1991 in the future
Design Values for FRP Material Properties

Factors for:

Youngs Modulus ($\gamma_E$) – material
System type ($\gamma_{mm}$) – method of manufacture
Strain at ultimate limit state ($\gamma_\varepsilon$) – material
Fibre Types
Partial Safety Factors

Partial safety factors for Young’s modulus at the ultimate limit state

<table>
<thead>
<tr>
<th>Material</th>
<th>Factor of Safety, $\gamma_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon FRP</td>
<td>1.1</td>
</tr>
<tr>
<td>Aramid FRP</td>
<td>1.1</td>
</tr>
<tr>
<td>AR glass FRP</td>
<td>1.6</td>
</tr>
<tr>
<td>E glass FRP</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Composite Types
## Partial Safety Factors

Recommended values of additional partial safety factors, to be applied to manufactured composites

<table>
<thead>
<tr>
<th>Type of system (and method of application or manufacture)</th>
<th>Additional partial safety factor, $\gamma_{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plates</strong></td>
<td></td>
</tr>
<tr>
<td>Pultruded</td>
<td>1.05</td>
</tr>
<tr>
<td>Prepreg</td>
<td>1.05</td>
</tr>
<tr>
<td>Preformed</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Sheets or tapes</strong></td>
<td></td>
</tr>
<tr>
<td>Machine-controlled application</td>
<td>1.05</td>
</tr>
<tr>
<td>Vacuum infusion</td>
<td>1.1</td>
</tr>
<tr>
<td>Wet lay-up</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Prefabricated (factory-made) shells</strong></td>
<td></td>
</tr>
<tr>
<td>Filament winding</td>
<td>1.05</td>
</tr>
<tr>
<td>Resin transfer moulding</td>
<td>1.1</td>
</tr>
<tr>
<td>Hand lay-up</td>
<td>1.2</td>
</tr>
<tr>
<td>Hand-held spray application</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Partial Safety Factors

Partial safety factor for strain at the ultimate limit state

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<tr>
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</tr>
<tr>
<td>Aramid FRP</td>
<td>1.35</td>
</tr>
<tr>
<td>AR glass FRP</td>
<td>1.85</td>
</tr>
<tr>
<td>E glass FRP</td>
<td>1.95</td>
</tr>
</tbody>
</table>
Design Ultimate Strength of FRP ($f_{fd}$)

$$f_f = \frac{E_{fk} \varepsilon_{fk}}{\gamma_E \gamma_c (\gamma_{mm})^2}$$

where $E_{fk}$ characteristic modulus of elasticity
$\varepsilon_{fk} =$ characteristic failure strain

Note: $E_{fk}$ incorrectly denoted as $E_f$ in equation 2
Extreme Loadings

- Fire – FRP assumed to have zero capacity and satisfy fire limit state (BS8110 Part 2)
- Seismic – outside scope of guidance (BD84)
- Impact – Highways Agency Guidance
- Blast loading – specialist guidance required
- Damage – Warn, protect, monitor
Strengthening members in flexure

Key points
• Conventional rectangular or parabolic stress block approach can be utilised
• Upper limit on design strain of 0.008 or $\varepsilon_{fk} / (\gamma_e \gamma_{mm})$
Beam Behaviour

Idealised Moment/Strain Behaviour

Applied bending moment (M)

- Ultimate M
- Working M
- Dead load M

FRP Composite

Steel Reinforcement

Strain

0.00184

0.008
Design Method

- Iterative method for determining cross sectional area of FRP in section 6.2.5
- Check for FRP separation failure
Flexural Strengthening with NSM

- Basis for design as for surface mounted flexural strengthening – except for curtailment
- More variability in surface preparation and less experimentation
- Modes at failure
  - Adhesive splitting
  - Concrete splitting
  - Shear crack induced separation
Shear Strengthening

- Shear reinforcement configurations

Shear reinforcement configurations

- Side Only $(n=2)$
- U-Wrapped $(n=1)$
- Fully-Wrapped $(n=0)$

Side only or U wrapped reinforcement is more prone to separation failure
Contribution of Fibre Reinforcement

\[ V_f = E_{fd} \varepsilon_{fse} A_{fs} \left[ \frac{d_f - \frac{n}{3} l_{t,\text{max}}}{s_f} \right] (\cos \beta + \sin \beta) \]

- \( E_{fd} \) = design tensile modulus of laminate
- \( \varepsilon_{fse} \) = effective strain in FRP for shear strengthening
- \( t_f \) = thickness of the FRP laminate
- \( l_{t,\text{max}} \) = anchorage length
Strain Limit

- Effective strain is the lesser of:
  \[ \varepsilon_{fd} / 2 \quad \text{- Average strain in FRP at fracture} \]
  \[ 0.64 \sqrt{f_{ctm}} / E_{fd} t_f \quad \text{- debonding} \]
  \[ 0.004 \quad \text{- historical limit from test data} \]

Where

- \( F_{ctm} \) = tensile strength of concrete
- \( \varepsilon_{fd} \) = design ultimate strain of FRP
Anchorage Length

\[ l_{t,\text{max}} = 0.7 \sqrt{\left( \frac{E_{fd} \, t_f}{f_{ctm}} \right)} \]

- \( E_{fd} \) = design tensile modulus of laminate
- \( t_f \) = thickness of laminate
- \( f_{ctm} \) = tensile strength of concrete
Strengthening Axially Loaded Members

Stress-strain model for confined concrete

\[ f_{ccd} = f_{c0} + 4.1f_r \]

where

- \( f_{ccd} \) = confined concrete compressive strength
- \( f_{c0} \) = unconfined concrete compressive strength
- \( f_r \) = confinement pressure
Confinement of Concrete Testing

Rupture of fabric
Compression in Circular Columns

\[ f_{ced} = f_{c0} + 0.05 \left( \frac{2t_f}{D} \right) E_{fd} \]

Where

\[ f_{c0} = 0.67 f_{cu} / \gamma_{mc} \]

\( D \) = diameter of column
\( t_f \) = thickness of FRP
\( E_{fd} \) = design tensile modulus of FRP
\( \gamma_{mc} \) = 1.5
\( f_{cu} \) = characteristic cube strength of concrete
Laps

Laps in columns

Lap should be > 200mm and in accordance with manufacturer’s recommendations
Flexure and Compression

- Solve by iteration
- Assume thickness of FRP
- Calculate failure strain in concrete
- Assume depth of neutral axis
- Check vertical capacity equals applied load
- Interate to confirm N.A. depth and check strains (0.0035 max in concrete)
Non-Circular Cross-Section

Extent of confinement

Assumed confined region for FRP-wrapped rectangular column

Aspect ratio of column sides $\leq 1.5$
corner radii $\geq 15\text{mm}$
Strength of Rectangular Columns

For small columns (less than 200mm smaller side)

\[ f_{ce} = f_{c0} + 2 g_s f_r \]

Shape factor \((g_s) = \frac{b}{h} \cdot \frac{A_e}{A_g}\)

\(A_e = \) effectively confined area
\(A_g = \) total cross – sectional area
\(f_r = \) equivalent confining pressure

\[ f_r = \frac{2 f_{fd} t_f}{\sqrt{b^2 + h^2}} \]

Lam and Teng
Why does TR55 need to be revised?

- Alignment with Eurocodes
- Improved analysis and design methods
- Improve areas of limited design guidance or applicability
- New materials and techniques
- Rationalise approaches
- Experience of practising engineers
- Maintain TR55 as a state-of-the-art document
Chapter 5. Structural Design of Strengthened Members

- Load factors according to Eurocodes
- Fire resistance and fire engineering
- Design principles for impact, blast and seismic retrofit
Behaviour of Structures in Fire

FRP strengthening after fire
Analysis of Structures in Fire

- 2nd edition suggests that a section is fine in fire provided that the unfactored service loading is greater than the ultimate load capacity of the unstrengthened section.
- Cannot be defended under Eurocode fire guidance.
- 3rd edition states that a proportion of the ultimate load must be resisted by the unstrengthened section capacity taking into account degradation of strength of the unstrengthened section during the fire.
Chapter 6.
Strengthening Members in Flexure

• Design procedures to conform to Eurocode approaches
• Revised debonding analysis
• NSM strengthening – addition of anchorage design for square and rectangular bars, consistent with circular bars
• Strengthening prestressed concrete beams
Debonding analysis

- Average longitudinal shear stress
- PLUS local shear stress at crack positions
Prestressed beams

- Must consider serviceability limit states – stress and decompression limits must be maintained
- Consider effect of lack of cracking on anchorage
NSM Anchorage

- Limitations to design guidance currently in TR55
  - Circular diameter
  - Groove spacing
  - Surface preparation
- Cautious approach

Are square/rectangular strips better than round bars?
Observed failure mechanisms

- Resin splitting
- Failure at the bar-resin interface
- Failure at the resin-concrete interface
- Catastrophic failure of the concrete cover
- Shearing off of the outer layer of CFRP bar
- Tensile rupture of CFRP bar
Limiting behaviour

- FRP rupture (for rectangular strips) - dependent on sectional area/perimeter ratio
- Concrete Cover Separation (circular and square bars) - dependent on concrete strength
Chapter 7. Shear Strengthening

- Design procedures to conform to Eurocode approach
- Add guidance on shear strengthening using NSM
- Add guidance on shear strengthening using deep embedment bars
• British standards use 45° truss. Eurocode allows angle $q$ between 22 and 45° - governed by strength of diagonal concrete strut. Use of lowest angle possible

• Eurocode – Only the vertical stirrups carry the shear – depends on $q$. BS allows stirrups plus a concrete contribution
Eurocode approach

Compromise Solution
Allow a variable angle truss for the existing section capacity and a 45° truss for the FRP strengthening. We end up superposing two trusses.
Chapter 7. Strengthening axially loaded members

• Design procedures to conform to Eurocode approaches
• Review ultimate stress and strain in circular confinement model
• Rationalise confinement model for combined bending and axial load
• Review rectangular column strengthening model, with respect to larger column tests and combined axial and flexural loading.
Rectangular columns

- Cautious approach
- Limits on size
- Limits on aspect ratio
- No guidance on combined axial load and bending
Eccentrically loaded column

We must not assume failure is always by FRP rupture – debonding and steel rupture can occur, and $P-\Delta$ effects become important.
Summary

• Some aspects of design are well understood and have appropriate design guidance.
• Now in a position to address some of the limitations imposed on some design guidance.
• Newer techniques have reached a level of maturity allowing explicit guidance to be written.
• Ensure conformity with Eurocode approaches where appropriate.