FRP COMPOSITES FOR NEW CONSTRUCTION AND STRENGTHENING: PROPERTIES, APPLICATIONS & RESEARCH AT IST

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Kaunas University of Technology (KTU), Lithuania, 27/4/2015
Instituto Superior Técnico, founded in 1911, is the Engineering, Science and Technology School of Lisbon University.

- 11,000 students (42% MSc and PhD, ~20% international)
- 33 MSc and 31 PhD programs
- ~1000 faculty and staff
- 8 Departments and 28 R&D Centers
  (Civil Engineering, Architecture and Georesources)
Development of Civil Engineering has been intimately connected to innovation in structural materials.

**Development of mud bricks reinforced with straw (Mesopotamia)**

- Reduction of construction to human scale
- Architecture with partition walls
HISTORICAL CONTEXT

Development of Civil Engineering has been intimately connected to innovation in structural materials

Development of *cast iron, wrought iron and steel*
- Decisive factor for industrial revolution
- Development of long span bridges

**Alcantara Bridge, Toledo**  **The Iron Bridge, Shropshire (1779-1781)**
HISTORICAL CONTEXT

Development of Civil Engineering has been intimately connected to innovation in structural materials.

Development of reinforced concrete:
- Rapid reconstruction after World War II

Lambot’s boat (1848)  Hennebique system (1892)  Burj Dubai Tower
OVERVIEW OF COMPOSITES DEVELOPMENT

- **5000 a.C.** – Use of straw in the reinforcement of mud bricks to reduce shrinkage cracks (Mesopotamia)
- **1940** – First structural applications of modern composites in naval and aerospace industries
- **1950** – Introduction of composites in automotive and oil industries
- **1960** – Development of advanced composites (defence industries) and first applications in construction industry
OVERVIEW OF COMPOSITES DEVELOPMENT

- **1970** – Effort to reduce manufacturing costs enables extension to new markets (e.g. sports goods)

- **1980 and 1990s:**
  - Technological development of manufacturing processes (e.g. pultrusion)
  - Increasing need to rehabilitate civil infrastructure (limited durability of traditional materials; increase of loads)
  - Requirement of higher construction speed

  ➔ Increasing acceptance from construction industry

(Growing research and pilot projects)

- High strength
- Low self-weight
- Durability
OUTLINE

1. FIBRE REINFORCED POLYMER (FRP) MATERIALS
2. FRP MATERIALS FOR CIVIL ENGINEERING
3. STRENGTHENING SYSTEMS AT HIGH TEMPERATURE
4. OTHER RESEARCH PROJECTS AT IST
5. CONCLUDING REMARKS
1. FIBRE REINFORCED POLYMER (FRP) MATERIALS
1. Fibre reinforcement
   → High resistance
   → Brittle behaviour

2. Polymeric matrix (resin + filler + additives)
   → Very low resistance
   → Load transfer and stress distribution between fibres
   → Protection of fibres from environmental agents
   → Keeping the fibres in position (and preventing their buckling when compressed)
1.1. Constitution and General Properties of FRPs

Properties and forms of reinforcing fibres

<table>
<thead>
<tr>
<th>Property</th>
<th>E - Glass</th>
<th>Carbon</th>
<th>Aramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength [MPa]</td>
<td>2350 - 4600</td>
<td>2600 - 3600</td>
<td>2800 - 4100</td>
</tr>
<tr>
<td>Elasticity modulus [GPa]</td>
<td>73 - 88</td>
<td>200 - 400</td>
<td>70 - 190</td>
</tr>
<tr>
<td>Strain at failure [%]</td>
<td>2.5 - 4.5</td>
<td>0.6 - 1.5</td>
<td>2.0 - 4.0</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>2.6</td>
<td>1.7 - 1.9</td>
<td>1.4</td>
</tr>
</tbody>
</table>

- Rovings (or tows) - bundles of continuous filaments
- Mats (mats, veils, fabrics) with short or continuous filaments, randomly oriented or oriented, woven or non-woven
1.1. CONSTITUTION AND GENERAL PROPERTIES OF FRPs

Properties of polymeric matrixes

- **Thermoset** (polyester, vinylester, epoxy)
- Thermoplastic (polyethylene, polypropylene)

<table>
<thead>
<tr>
<th>Property</th>
<th>Polyester [MPa]</th>
<th>Vinylester [GPa]</th>
<th>Epoxy [ºC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>20 - 70</td>
<td>68 - 82</td>
<td>60 - 80</td>
</tr>
<tr>
<td>Elasticity modulus</td>
<td>2 - 3</td>
<td>3.5</td>
<td>2 - 4</td>
</tr>
<tr>
<td>Strain at failure</td>
<td>1 - 5</td>
<td>3 - 4</td>
<td>1 - 8</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>1.2 - 1.3</td>
<td>1.12 - 1.16</td>
<td>1.2 - 1.3</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>70 - 120</td>
<td>102 - 150</td>
<td>100 - 270</td>
</tr>
</tbody>
</table>
1.2 MANUFACTURING PROCESSES FOR FRP MATERIALS

- Pultrusion
- Hand layup
- Filament winding
- Centrifugation
- Resin transfer moulding (RTM)
- Resin infusion moulding (RIM)
- Compression moulding
- Vacuum assisted resin transfer moulding (VARTM)
- Vacuum infusion
1.2 Manufacturing Processes for FRP Materials

Pultrusion

Phase 1: Impregnation of glass fibres by liquid resin inside a heated mould, with the shape of the cross-section to be produced

Phase 2: Curing/solidification of the resin matrix inside the mould, resulting in a profile with the intended cross-section
1.2 MANUFACTURING PROCESSES FOR FRP MATERIALS

Hand layup

Consecutive application of layers of fibre reinforcement and subsequent impregnation by the polymeric matrix, which cures (i) in a mould or (ii) over a member to be strengthened.

Hand layup of a GFRP laminate in a moulding table

Moulding of CFRP sheets over reinforced concrete elements
1.3. PHILOSOPHY IN FRP DEVELOPMENT

 ⇒ Depending on the specific application requirements, it is possible to combine:

 Several manufacturing processes

 → Diversity of fibre reinforcement
   (type, orientation, position, content)

 → Variety of polymers as matrix

 → Additives and fillers in the matrix (specific properties)
2. FRP MATERIALS FOR CIVIL ENGINEERING APPLICATIONS
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2.1. STRUCTURAL APPLICATION OF FRP MATERIALS

Field of application of FRP materials

- Internal reinforcement of RC structures
- External strengthening of RC structures
- Hybrid structures (with traditional)
- All-composite structures

FRP rebars
FRP strips and sheets
FRP profiles and panels
2.2. FRP REBARS – GEOMETRY AND PROPERTIES

- **Constitution**: polymer matrix (vinylester) and rovings (axial fibre reinforcement)
- **Available diameters**: 6 to 36 mm
- **Surface finishing**: a) ribbed; b) sand coating; c) exterior wound fibres and sand coating
- **Geometry**: a) straight; b) with anchorage heads; and bent c) in U or d) hooked
2.2. FRP REBARS – GEOMETRY AND PROPERTIES

<table>
<thead>
<tr>
<th>Property</th>
<th>GFRP</th>
<th>CFRP</th>
<th>AFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</td>
<td>1.25 - 2.10</td>
<td>1.50 - 1.60</td>
<td>1.25 - 1.40</td>
</tr>
<tr>
<td>Fibre content [%]</td>
<td>50 - 60</td>
<td>50 – 60</td>
<td>-</td>
</tr>
<tr>
<td>Thermal expansion coefficient ([× 10^{-6}/°C])</td>
<td>Axial</td>
<td>-9.0 a 0.0</td>
<td>-6.0 a -2.0</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>74.0 - 104.0</td>
<td>60.0 - 80.0</td>
</tr>
<tr>
<td>Axial tensile strength [MPa]</td>
<td>483 - 1600</td>
<td>600 - 3690</td>
<td>1720 - 2540</td>
</tr>
<tr>
<td>Axial elasticity modulus* [GPa]</td>
<td>35 - 60</td>
<td>120 - 580</td>
<td>41 - 125</td>
</tr>
<tr>
<td>Axial strain at failure [%]</td>
<td>1.2 - 3.1</td>
<td>0.5 - 1.7</td>
<td>1.9 - 4.4</td>
</tr>
</tbody>
</table>

* Linear elastic up to failure

Images of FRP rebars:
2.2. FRP Rebars – Applications

- Reinforcement of bridge deck
- Repair of maritime structures, dock and pier
- Aquaculture (Acuinova, Mira)
2.3. FRP STRENGTHENING SYSTEMS - TYPOLOGIES

• **Strips**: unidirectional *precured* (carbon) fibre laminates, adhesively bonded with epoxy adhesive.

• **Sheets**: uni/multi-directional mats of continuous (carbon) fibres, *moulded and cured in situ*, impregnated and bonded with an epoxy matrix.

NOTE: There are also rebars and cables/tendons
2.3. FRP Strengthening Systems - Properties

Strips:
- $E = 165$ to $300$ GPa
- $\sigma_u = 1500$ to $3000$ MPa
- $\varepsilon_u = 0.5$ to $1.7\%$

Sheets:
- $E = 240$ to $640$ GPa (typically, $240$ to $300$ GPa)
- $\sigma_u = 2500$ to $3000$ MPa
- $\varepsilon_u = 0.4$ to $1.55\%$
2.3. FRP STRENGTHENING SYSTEMS - APPLICATIONS

- Flexural strengthening of beams and slabs
- Shear strengthening of beam
- Flexural and shear strengthening of beam
- Column strengthening (confinement)
2.4. FRP Profiles – Geometries and Constitution

First generation profiles
Thin-walled cross-sections mimicking metallic construction

- High deformability
- Susceptibility to instability phenomena under compression

Limited exploitation of material potential

First generation GFRP profiles
2.4. FRP Profiles – Geometries and Constitution

New generation profiles
Multi-cellular deck panels for new construction or rehabilitation

- Panel-to-panel connection: adhesive bonding or snap-fit
- Panel-to-girder connection: bolting/bonding

→ Lightness
→ Quick installation
→ High durability
→ Low maintenance
2.4. FRP Profiles – Geometries and Constitution

- **Fibre reinforcement:**
  - **Rovings** - bundles of longitudinal continuous fibres
  - **Mats** - (non-)woven chopped or continuous fibres in several directions
  - **Surface veil** with randomly oriented chopped fibres

- **Polymeric matrix:**
  - **Resin** (polyester, vinylester, epoxy)
  - **Fillers**
  - **Additives**
2.4. FRP PROFILES – PROPERTIES (GFRP)

<table>
<thead>
<tr>
<th>Property</th>
<th>Longitudinal</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile/compressive strength [MPa]</td>
<td>200 - 400</td>
<td>50 - 60</td>
</tr>
<tr>
<td>Shear strength [MPa]</td>
<td></td>
<td>20 - 30</td>
</tr>
<tr>
<td>Elasticity modulus [GPa]</td>
<td>20 - 40</td>
<td>5 - 9</td>
</tr>
<tr>
<td>Shear modulus [GPa]</td>
<td></td>
<td>3 - 4</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td></td>
<td>1.8 - 1.9</td>
</tr>
<tr>
<td>Fibre content [%]</td>
<td></td>
<td>50 - 70</td>
</tr>
</tbody>
</table>

→ Linear elastic behaviour up to failure (no ductility!)
→ Orthotropic behaviour
→ High longitudinal strength (similar to steel)
→ Low transverse and shear strengths
→ Low elasticity (10-20% of steel) and shear moduli
→ Low density (20-25% of steel)
2.4. FRP Profiles – Applications

New construction

*Eyecatcher* building (5 storeys), Basel, Switzerland

Kolding Bridge, Denmark
2.4. FRP Profiles – Applications

Rehabilitation

Rehabilitation of timber floors

Replacement of bridge decks
2.5. FRP SANDWICH PANELS – CONSTITUTION

- **FRP outer skins** - thin, stiff, resistant
- **Core** - thick, light, more flexible, less resistant (polymeric foam, honeycomb, balsa wood, etc.)
- **Adhesive**
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.1. MOTIVATION

- Polymeric materials are ignitable, releasing heat and smoke.
- Mechanical properties of strengthening materials (CFRP and epoxy adhesive) are reduced when approaching $T_g$.
- CFRP-concrete bond highly affected when approaching $T_g$.

Concern about loss of structural effectiveness of strengthening system, particularly in buildings (fire).

![Graph showing tensile strength vs. temperature for CFRP and epoxy adhesive.](image-url)
3.2. Objectives

1. Study the effect of elevated temperature on the bond behaviour of CFRP-concrete interfaces (double-lap shear tests):

- Study the influence of (i) strengthening technique (EBR vs. NSM), (ii) mechanical anchorage (EBR), and (iii) type of adhesive (NSM – epoxy vs. mixed grout);
- Define “bond-slip” relationships vs. temperature.

Typical “bond-slip” relationship

EBR – externally bonded reinforcement
NSM – near surface mounted

Double-lap shear tests performed at elevated temperatures
3.2. OBJECTIVES

- II. Study the fire behaviour of RC beams strengthened with CFRP strips (fire resistance tests):
  - Study the influence of (i) strengthening technique (EBR vs. NSM), (ii) mechanical anchorage (EBR), and (ii) type of adhesive (NSM – epoxy vs. mixed grout);
  - Develop fire protection solutions that allow achieving appropriate fire ratings.

Fire resistance tests
3.3. PROJECT OVERVIEW

I. CFRP-concrete bond at elevated temperature

II. Fire resistance of RC beams strengthened with CFRP

Fire resistance tests on CFRP-strengthened beams (3.6)

FEM simulation (3.7)
3.4. **Bond Tests at High Temperature**

a) Objectives and test series (1/2)

→ **Objectives**: Behaviour of CFRP-concrete interfaces vs. *temperature*:
  
  - Stiffness
  - Strength
  - Failure modes

→ **Test series**: *Double-lap shear tests* on concrete specimens strengthened with CFRP strips:

  - **Series 1** – *Steady state tests*: constant temperature (20, 40, 55, 90, 120, 150°C) with increasing load

<table>
<thead>
<tr>
<th>EBR</th>
<th>Simply bonded</th>
<th>Mechanical anchor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSM</td>
<td>Epoxy adhesive</td>
<td>Mixed epoxy-grout adhesive</td>
</tr>
</tbody>
</table>
3.4. **BOND TESTS AT HIGH TEMPERATURE**

a) Objectives and test series (2/2)

→ **Objectives**: Behaviour of CFRP-concrete interfaces vs. temperature:
   - Stiffness
   - Strength
   - Failure modes

Bond-slip relationship

→ **Test series**: Double-lap shear tests on concrete specimens strengthened with CFRP strips:

- **Series 2** – **Transient state**: constant load (25, 50 or 75% of ultimate load)
  
  with increasing temperature

  only **EBR** – simply bonded
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.4. BOND TESTS @ HIGH TEMPERATURE

b) General view of the specimens (1/2)

Steel plates to confine the concrete

Unbonded length

Instrumented side of the specimens

EBR specimen

NSM specimen
b) General view of the specimens (2/2)

- EBR simply bonded (epoxy adhesive)
- EBR mechanical anchorage (epoxy adhesive)
- NSM (epoxy adhesive)
- NSM (mixed epoxy-grout adhesive)
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.4. BOND TESTS @ HIGH TEMPERATURE

c) Test setup - double-lap shear tests

Test setup for EBR (displacement control)

EBR test at 20ºC

EBR test at elevated temperature
d) Instrumentation

- **2 LVDTs** for measuring the CFRP-concrete slip
- **11 Electrical strain gauges** glued on the CFRP along the bonded length
- **Thermocouples type K** in the adhesive for temperature measurement
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.4. Bond Tests @ High Temperature

e) Results – Total load vs. displacement (cross-head)

• Reduction of stiffness and strength with increasing temperature
• NSM technique (vs. EBR): better performance for all temperatures
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.4. Bond Tests @ High Temperature

e) Results – Failure modes at ambient temperature

EBR (simple)  
Cohesive failure (thin concrete layer)

EBR (anchorage)  
Concrete failure (at the anchorage zone)

NSM (epoxy)  
Concrete failure

NSM (mixed)  
Adhesive failure @ CFRP-adhesive interface
e) Results – Failure modes at high temperature

EBR (simple)  EBR (anchorage)  NSM (epoxy)  NSM (mixed)

Slip under the anchorage

Adhesive failure @ concrete-adhesive interfaces

Adhesive failure @ CFRP-adhesive interfaces
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.4. BOND TESTS @ HIGH TEMPERATURE

e) Results – Bond strength vs. temperature (series 1+2)

**EBR specimens**

- **EBR**: agreement between results obtained in series 1 and 2
- **EBR**: beneficial effect of applying a mechanical anchorage

**NSM specimens**

- **NSM**: better performance of epoxy adhesive
- **Considerable** bond strength retention for \( T > T_g \)

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**Graphs:**

- **EBR (simple) - S1**
- **EBR (simple) - S2**
- **EBR (anchorage) - S1**
- **NSM (epoxy) - S1**
- **NSM (mixed) - S1**
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.4. BOND TESTS @ HIGH TEMPERATURE

e) Results – Bond-slip curves vs. temperature

![EBR simple Bond-slip curves](image1)

![NSM epoxy Bond-slip curves](image2)

(*) curves obtained between consecutive strain gauges on CFRP

In both EBR and NSM specimens:

- Remarkable **stiffness reduction** with temperature (85% @ 55°C)
- Massive **reduction** of the maximum **shear stress** (85% @ 120°C)
- Considerable **scatter**
e) Results – Bond-slip curves vs. temperature

<table>
<thead>
<tr>
<th></th>
<th>EBR simple</th>
<th>NSM epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EBR-T20</td>
<td>NSM-T20</td>
</tr>
<tr>
<td></td>
<td>EBR-T55</td>
<td>NSM-T55</td>
</tr>
<tr>
<td></td>
<td>EBR-T90</td>
<td>NSM-T90</td>
</tr>
<tr>
<td></td>
<td>EBR-T120</td>
<td>NSM-T120</td>
</tr>
<tr>
<td></td>
<td>EBR-T150</td>
<td>NSM-T150</td>
</tr>
</tbody>
</table>

(*) curves obtained between consecutive strain gauges on CFRP

**Question:** Which curves are representative of the global behaviour of the CFRP-concrete bond for each temperature?
3.5. NUMERICAL SIMULATION OF BOND TESTS

a) Objectives and assumptions

- **Objective**: calibrate bond-slip laws for EBR and NSM for each temperature
- **Assumption**: global behaviour of CFRP-concrete bond described by a bilinear relationship
b) Description of the models

- **Software:** ABAQUS
- **Geometry:** 3D models of half specimens
- **Linear elastic behaviour**
  - CFRP (isotropic)
  - Steel (isotropic)
- **Damage plasticity model - Concrete**
- **Material properties:** constant with temperature
- **CFRP-concrete interaction modelled with cohesive damage behaviour (bilinear law)**

NSM specimens mesh
c) Methodology for calibration of bond-slip laws

→ Inverse analysis for determination of bond-slip relationships

Range of evaluated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EBR</th>
<th>NSM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>$K$ [MPa/mm]</td>
<td>1</td>
<td>1500</td>
</tr>
<tr>
<td>$\tau_{LM}$ [MPa]</td>
<td>0.5</td>
<td>25</td>
</tr>
<tr>
<td>$s_{L0}$ [mm]</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

→ Bond-slip laws defined according to the agreement between experimental and numerical data:

- Failure loads
- Load vs. strain relationships
- Load vs. relative displacement relationships
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.5. NUMERICAL SIMULATION OF BOND TESTS

**d) Results – Proposed global bond-slip laws***

<table>
<thead>
<tr>
<th>Parameter</th>
<th>20°C</th>
<th>55°C</th>
<th>90°C</th>
<th>120°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>K [MPa/mm]</td>
<td>350</td>
<td>10</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>τₗ₀ [mm]</td>
<td>9</td>
<td>4</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>s₀ [mm]</td>
<td>0.20</td>
<td>0.45</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>20°C</th>
<th>55°C</th>
<th>90°C</th>
<th>120°C</th>
<th>150°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>K [MPa/mm]</td>
<td>300</td>
<td>10</td>
<td>3.5</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>τₗ₀ [mm]</td>
<td>15</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1.75</td>
</tr>
<tr>
<td>s₀ [mm]</td>
<td>0.50</td>
<td>0.9</td>
<td>0.95</td>
<td>1.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*Note: bond-slip laws proposed (for “overall” joint behaviour) are not directly comparable with experimental curves (“measured” at CFRP-adhesive interface)
d) Results – Load vs. slip relationships

Reasonable agreement in terms of:

- Failure loads
- Total force vs. slip relationships
- Strain distributions
d) Results – Strain distributions (EBR)

3.5. NUMERICAL SIMULATION OF BOND TESTS
d) Results – Strain distributions (NSM)

20°C

- 24% - 24%
- 46% - 46%
- 64% - 64%
- 80% - 80%
- 92% - 92%

55°C

- 14% - 14%
- 28% - 28%
- 41% - 41%
- 82% - 82%
- 95% - 95%

90°C

- 16% - 16%
- 32% - 32%
- 48% - 48%
- 64% - 64%
- 79% - 79%

120°C

- 15% - 15%
- 29% - 29%
- 44% - 44%
- 58% - 58%
- 73% - 73%

3.5. NUMERICAL SIMULATION OF BOND TESTS
3.6. Fire Tests on CFRP-Strengthened RC Beams

a) Preliminary fire resistance tests

CFRP strip transformed into a “cable” fixed at the (cool) anchorage zones

Temperatures at the concrete-CFRP interface when the strengthening system failed

- Midspan: $T_{av.} = 146 \, ^\circ C$
- Anchorage zone: $T_{av.} = 52 \, ^\circ C$

1 Firmo (2010), MSc Dissertation, IST.
b) Concept for fire protection design

Promote the CFRP strip “cable” behaviour during a fire event

Requirements for the design of fire protection systems

<table>
<thead>
<tr>
<th>Current zone (span)</th>
<th>Anchorage zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of CFRP strip below a certain critical temperature, based on the stress level and residual strength vs. temperature</td>
<td>Temperature of the CFRP-concrete interface &lt; $T_g$ of adhesive used in strengthening system</td>
</tr>
<tr>
<td>Prevent tensile rupture of the CFRP strip</td>
<td>Prevent debonding of CFRP strengthening system</td>
</tr>
</tbody>
</table>
c) Preliminary numerical (thermal) modelling (3D)

¼ of the slab sector modeled

Calcium Silicate boards

anchorage length

Detail of the insulation system at the anchorage zone

Dimensions L, T and W varying between 2 cm and 10 cm.

Minimum thickness of 2 cm defined based on a simple criterion:

\[ T_{CFRP} < 500^\circ C \] (after 90 min of fire exposure)

\[ f_{u,500^\circ C} \approx 45\% \ f_{u,20^\circ C} \]

(Wang et al. 2011)
c) Preliminary numerical (thermal) modelling (3D)

Influence of the total thickness of the protection system (dimension T)

Failure criterion: temperature at anchorage zone = \( T_g \) of epoxy.

35 min of fire endurance

52 min of fire endurance
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.6. FIRE RESISTANCE TESTS ON CFRP-RC BEAMS

d) Test setup

- Supports
- Tested beam
- CFRP strip
- Oven
  \[ T(t) = \text{ISO 834} \]
- Load transmission beam
- Weights
- Reaction frame

Action according to Eurocode 1, part 1-2
3.6. FIRE RESISTANCE TESTS ON CFRP-RC BEAMS

e) Characteristics of tested beams

- **Total length**: 1.50 m; **Span**: 1.26 m; **Cross-section**: 0.10 m x 0.12 m;
- **CFRP strips**: 1.10 m long;
- **Thermal insulation**: Calcium silicate boards (25 mm to 75 mm);
- **Types of strengthening systems**:

  - Simply bonded
  - Mechanical anchor
  - Epoxy adhesive
  - Epoxy-cement adhesive

![Diagram showing CFRP strengthening systems and dimensions](image)
### e) Characteristics of tested beams - nomenclature

<table>
<thead>
<tr>
<th>Name</th>
<th>Strength. technique</th>
<th>Adhesive type</th>
<th>Insulation thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anchorage zone</td>
</tr>
<tr>
<td>RC</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EBR-U</td>
<td>EBR</td>
<td>Epoxy (S&amp;P 220)</td>
<td>-</td>
</tr>
<tr>
<td>EBR-25-0</td>
<td>EBR</td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>EBR-25-25</td>
<td>EBR</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>EBR-50-25</td>
<td>EBR</td>
<td>75 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>EBR-75-25</td>
<td>EBR</td>
<td>75 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>EBR-75-50</td>
<td>EBR</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>EBR-50-25</td>
<td>Araldite 2014</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>EBR-50-25</td>
<td>Araldite 2014+S&amp;P</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>EBR-A-U</td>
<td>EBR+A</td>
<td>Epoxy (S&amp;P 220)</td>
<td>-</td>
</tr>
<tr>
<td>EBR-A-50-25</td>
<td>EBR+A</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>NSM-U</td>
<td>NSM</td>
<td>Epoxy (S&amp;P 220)</td>
<td>-</td>
</tr>
<tr>
<td>NSM-25-0</td>
<td>NSM</td>
<td>25 mm</td>
<td>-</td>
</tr>
<tr>
<td>NSM-25-25</td>
<td>NSM</td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>NSM-50-25</td>
<td>NSM</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>NSM-C-U</td>
<td>NSM</td>
<td>Mixed epoxy-cement</td>
<td>-</td>
</tr>
<tr>
<td>NSM-C-25-0</td>
<td>NSM</td>
<td>25 mm</td>
<td>-</td>
</tr>
<tr>
<td>NSM-C-25-25</td>
<td>NSM</td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>NSM-C-50-25</td>
<td>NSM</td>
<td>50 mm</td>
<td>25 mm</td>
</tr>
</tbody>
</table>

A – anchorage (EBR);  
C – mixed epoxy-cement grout (NSM).
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.6. FIRE RESISTANCE TESTS ON CFRP-RC BEAMS

e) Examples of insulation schemes tested

Specimen U (unprotected)

Specimen 25-0

Specimen 25-25

Specimen 50-25

Specimen 25-0 - Anchorage: 25 mm; central: 0 mm

Specimen 25-25 - Anchorage: 25 mm; central: 25 mm

Specimen 50-25 - Anchorage: 50 mm; central: 25 mm
f) Instrumentation – specimens EBR

- 1 Displacement transducer (midspan section);
- 15 Thermocouples type K.
f) Instrumentation – specimens NSM

- 1 Displacement transducer (midspan section);
- 17 Thermocouples type K.

7 (air temperature at the top surface)
g) Results for EBR - temperature distributions (specimen EBR 25-0)
g) Results – midspan displacement increase

**EBR**

**NSM**

![Graphs showing midspan displacement increase vs. time of fire exposure for EBR and NSM systems.](image-url)
g) Results – adhesive temperature at debonding instant

**EBR**

- EBR-U
- EBR-25-0
- EBR-25-25
- EBR-50-25
- EBR-50-25-Araldite
- EBR-50-25-Araldite+S&P
- EBR-75-25
- EBR-75-50
- EBR-A-25-U
- EBR-A-50-25
- Tg (55°C)

**NSM**

- NSM-U
- NSM-25-0
- NSM-25-25
- NSM-50-25
- NSM-C-U
- NSM-C-25-0
- NSM-C-25-25
- NSM-C-50-25
- Tg (55°C)
g) Results – average adhesive temperature at anchorage (debonding)

**EBR**

Anchorage: \( T_{\text{max}} = 1.2 - 1.5 \ T_g \)
Current zone: \( T_{\text{max}} = 410 \ °C \)

**NSM**

Anchorage: \( T_{\text{max}} = 2.2 - 5.6 \ T_g \)
Current zone: \( T_{\text{max}} = 630 \ °C \)

Average temperature in the anchorage at the debonding instant [°C]
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.6. FIRE RESISTANCE TESTS ON CFRP-RC BEAMS

3.6. FIRE RESISTANCE TESTS ON CFRP-RC BEAMS

g) Results for EBR - post-fire observations

Specimen EBR-U

Specimen EBR-25-0

Specimen EBR-A-U

Debonding of CFRP strip at anchorage zone
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.6. FIRE RESISTANCE TESTS ON CFRP-RC BEAMS

g) Results for NSM - post-fire observations

Specimen NSM-U

Slippage of CFRP strip along slit
(although in one of the CFRP strips some broken fibres are also visible)

Specimen NSM-25-0
h) Time to the loss of the CFRP strengthening system

The diagram shows the time to the loss of the CFRP strengthening system in minutes. The systems are categorized into two groups: EBR and NSM, with further subcategories such as EBR-A and NSM-C. The values indicate the time in minutes for each condition.
3.7. NUMERICAL SIMULATION OF FIRE TESTS

a) Description of the models

- **Software**: ABAQUS
- **Geometry**: 2D, half specimens
- **CFRP**: linear elastic model
- **Steel**: elasto-plastic model
- **Concrete**: damage plasticity model
- **Material properties**: temperature dependent
- **CFRP-concrete interaction**: cohesive damage model

- **Uncoupled analysis**: Thermal → Mechanical
3. FRP STRENGTHENING SYSTEMS SUBJECT TO HIGH TEMPERATURE AND FIRE

3.7. NUMERICAL SIMULATION OF FIRE RESISTANCE TESTS

b) Results
4. OTHER ONGOING RESEARCH PROJECTS AT IST
4.1. STRUCTURAL BEHAVIOUR OF GFRP PROFILES

Lateral-torsional buckling of cantilevers

Local buckling of beams

Correia et al. (2010), Structural Engineering International
Correia et al. (2011), Computers and Structures
Silva et al. (2011), Computers and Structures
4.1. STRUCTURAL BEHAVIOUR OF GFRP PROFILES

Local buckling of short GFRP and C+GFRP columns

Correia et al. (2013), *Journal of Composites for Construction*
Nunes et al. (2013), *Thin-Walled Structures*

Euler buckling of long columns
4.1. Structural Behaviour of GFRP Profiles

Web crippling of transversely loaded GFRP members

Fernandes et al. (2015a,b), Composite Structures
4.2. Structural Behaviour of GFRP-RC Beams

Flexural tests on 2-span beams
R – reference beam (steel reinforced);
Rb-1 – GFRP reinforced beam with concrete confinement in critical cross-sections

Load vs. deflection curves

FEM in commercial package ATENA (non-linear analyses, cracking/crushing)

Matos et al. (2012), Composite Structures
Santos et al. (2013), Construction and Building Materials
4.3. Structural Behaviour of FRP Sandwich Panels

Material characterisation tests
(GFRP laminates, PU and PET foams, balsa, PP honeycomb cores)

Flexural tests in full-scale panels (different core materials / lateral ribs / trusses)

Correia et al. (2012), International Journal of Structural Integrity
4.3. STRUCTURAL BEHAVIOUR OF FRP SANDWICH PANELS

Shear creep tests on PU foam cores

Composed creep model (CCM)

Flexural creep tests on full-scale panels

\[
\delta_{\text{mid-span}}(\sigma, \tau, t) = \frac{5}{384} \frac{pL^4}{E(\sigma,t)I} + \frac{1}{8} \frac{pL^2}{G(\tau,t)A_y}
\]

Garrido et al. (2014), Journal of Composite Materials
4.3. STRUCTURAL BEHAVIOUR OF FRP SANDWICH PANELS

Creep tests on PU foam cores, sandwich panels and GFRP laminates at different temperatures (20°C, 24°C and 28°C)

Garrido et al. (2015), Construction and Building Materials
### 4.4. DURABILITY OF GFRP PROFILES / BONDED JOINTS

<table>
<thead>
<tr>
<th>Type of exposure</th>
<th>Duration</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immersion in demineralised water (W-20, W-40 W-60)</td>
<td>3, 6, 9, 12, 18, 24 months</td>
<td>Temperatures: 20 (±2) °C, 40 (±1) °C and 60 (±1) °C</td>
</tr>
<tr>
<td>Immersion in salt-water (S-20, S-40, S-60)</td>
<td></td>
<td>Composition: 35 g/l NaCl Temperatures: 20 (±2) °C, 40 (±1) °C and 60 (±1) °C</td>
</tr>
<tr>
<td>Continuous condensation (CC-40)</td>
<td>200, 400, 600 cycles</td>
<td>Temperature: 40 (±2) °C Relative humidity: 100 %</td>
</tr>
<tr>
<td>Temperature cycles</td>
<td>2000, 4000, 6000 cycles</td>
<td>6 hours at -5 ºC + 6 hours at +40 ºC</td>
</tr>
<tr>
<td>Salt fog chamber</td>
<td>1000, 2000, 3000 hours</td>
<td>Neutral salt spray, according to ISO 7253</td>
</tr>
<tr>
<td>QUV chamber</td>
<td>1000, 2000, 3000, 6000 hours</td>
<td>4 hours with UV radiation at 50 ºC (dry cycle) + 4 hours without UV radiation at 60 ºC and moisture (wet cycle), according to ISO 4892</td>
</tr>
<tr>
<td>Natural weathering exposure</td>
<td>1, 2, 5, 10 years</td>
<td>Roof of LNEC building, with continuous monitoring of temperature, relative humidity and UV radiation</td>
</tr>
</tbody>
</table>

*Cabral-Fonseca et al. (2012), Strain*
*Correia et al. (2014), Experimental Techniques*
4.5. FIRE BEHAVIOUR OF GFRP PULTRUDED PROFILES

Shear tests on GFRP laminates (20-250°C)

Fire resistance tests in GFRP profiles (ISO 834)

Correia et al. (2013), Composite Structures

Correia et al. (2012), Composites Part B: Engineering
4.6. Behaviour of GFRP Snap-Fit Bridge Panels

Cross-section and functioning principle of snap-fit GFRP panels

Flexural test on GFRP panel

Design and construction of a pedestrian bridge (Feira de S. Mateus, Viseu)
4.6. BEHAVIOUR OF GFRP SNAP-FIT BRIDGE PANELS

Cross-section and functioning principle of snap-fit GFRP panels

Flexural test on GFRP panel

Design and construction of a pedestrian bridge (Feira de S. Mateus, Viseu)
4.6. Behaviour of GFRP Snap-Fit Bridge Panels

Transportation, lifting and connection to the abutments of the metallic structure

Panel-to-panel and panel-to-girder connections (epoxy+bolted)

Application of wear layer
4.6. Behaviour of GFRP Snap-Fit Bridge Panels

Design and construction of a pedestrian bridge (Feira de S. Mateus, Viseu)
4.6. Behaviour of GFRP Snap-Fit Bridge Panels

Design and construction of a pedestrian bridge (Feira de S. Mateus, Viseu)
4.7. Development of GFRP-Concrete Bridges

Geometry of the GFRP-SFRSCC cross-section

Small-scale pedestrian bridge prototype (6.0 m long)
4.7. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

Modal identification tests

Pedestrian comfort dynamic tests and FE modelling

Gonilha et al. (2013a, 2013b), Composite Structures
4.7. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

Creep tests (different load levels and ambient temperatures)

Analytical modelling of creep response

Gonilha et al. (2013), Composites Part B
4.7. Development of GFRP-Concrete Bridges

Flexural tests up to failure ($F_u \sim 240$ kN)

Gonilha et al. (2014), *Engineering Structures*
4.7. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

Full-scale pedestrian bridge prototype (11.0 m long) – construction and load tests
Gonilha et al. (2015), Composite Structures
5. CONCLUDING REMARKS
CONCLUDING REMARKS

• The development of Civil Engineering has been intimately connected to the innovation in structural materials

• FRP composites are promising materials, presenting several advantages over traditional materials for both new construction and rehabilitation: strength, lightness, ease of application, durability under aggressive environments and low maintenance

• CFRP strengthening systems are an already well-established “standard” solution for RC strengthening, with several advantages over alternative techniques, but poor performance at elevated temperature and under fire exposure

• The limitations of FRP materials are the motivation for seeking “material adapted” structural solutions, the main goal of the on-going research projects at IST
THANK YOU!

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