THE NEW FRP MATERIALS FOR CIVIL ENGINEERING STRUCTURAL APPLICATIONS

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

**HISTORICAL CONTEXT**

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 increasing 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 IN CIVIL ENGINEERING APPLICATIONS

3. CURRENT RESEARCH PROJECTS AT IST

4. 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</th>
<th>Vinylester</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength [MPa]</td>
<td>20 - 70</td>
<td>68 - 82</td>
<td>60 - 80</td>
</tr>
<tr>
<td>Elasticity modulus [GPa]</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 [ºC]</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.
1.3. PHILOSOPHY IN FRP DEVELOPMENT

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

- **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
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)
- Fully-composite structures

FRP rebars
FRP laminates 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 ([\text{g/cm}^3])</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 ([\times10^{-6}/°\text{C}])</td>
<td>Axial</td>
<td>-9.0 a 0,0</td>
<td>-6.0 a -2,0</td>
</tr>
<tr>
<td></td>
<td>Transversal</td>
<td>74.0 - 104,0</td>
<td>60,0 - 80,0</td>
</tr>
<tr>
<td>Axial tensile strength ([\text{MPa}])</td>
<td>483 - 1600</td>
<td>600 - 3690</td>
<td>1720 - 2540</td>
</tr>
<tr>
<td>Axial elasticity modulus ([\text{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>
2.2. FRP Rebars – Applications

- Reinforcement of bridge deck
- Aquaculture (Acuinova, Mira)
- Repair of maritime structures, dock and pier
2.2. FRP REBARS – DESIGN GUIDELINES

- **FIB (2007):** Fib Bulletin 40 - FRP reinforcement in RC structures
- **ACI (2006):** ACI 440.1R-06 - Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars
- **CNR-DT (2007):** Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars
2.3. FRP STRENGTHENING SYSTEMS - TYPOLoGIES

- **Laminates**: unidirectional *precured* (carbon) fibre strips, 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

Laminates:
- $E = 165$ 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)
2.3. FRP STRENGTHENING SYSTEMS - GUIDELINES

- **FIB (2001):** Externally bonded FRP reinforcement for RC structures
- **ACI (2008):** ACI 440.2R-08 - Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures
First generation profiles

Thin-walled cross-sections mimicking metallic construction

- High deformability
- Susceptibility to instability phenomena under compression

Limited exploitation of material potential
2. FRP MATERIALS FOR CIVIL ENGINEERING APPLICATIONS

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 – Geometries and Constitution

High resolution microscopy of a flange laminate
2. FRP MATERIALS FOR CIVIL ENGINEERING APPLICATIONS

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>20 - 30</td>
<td></td>
</tr>
<tr>
<td>Elasticity modulus [GPa]</td>
<td>20 - 40</td>
<td>5 - 9</td>
</tr>
<tr>
<td>Shear modulus [GPa]</td>
<td>3 - 4</td>
<td></td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>1.8 - 1.9</td>
<td></td>
</tr>
<tr>
<td>Fibre content [%]</td>
<td>50 - 70</td>
<td></td>
</tr>
</tbody>
</table>

→ **Linear elastic** behaviour up to failure (no ductility!)
→ **Orthotropic** behaviour
→ **High longitudinal strength** (similar to steel)
→ **Low elasticity** (10-20% of steel) and **shear moduli**
→ **Low density** (20-25% of steel)
2. FRP MATERIALS FOR CIVIL ENGINEERING APPLICATIONS

2.4. FRP PROFILES – APPLICATIONS

New construction

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

Kolding Bridge, Denmark
2.4. FRP PROFILES – APPLICATIONS

Rehabilitation

Replacement of bridge decks

Rehabilitation of timber floors
2.4. FRP Profiles – Design Guidelines

→ There is still no specific official regulation

→ Design often based on manufacturers manuals – design tables
  (information provided limited)

→ EN 13706 (2002), “Reinforced plastics composites – Specifications for pultruded profiles” - 2 material classes, specifications for minimum material properties and tests

Fiberline Composites
Strongwell
Creative Pultrusions
EN 13706
2.5. FRP SANDWICH PANELS – CONSTITUTION

- FRP outer skins - thin, stiff, resistant
- Core - thick, light, more flexible, less resistant (rigid foam, balsa wood, etc.)
- Adhesive
3. CURRENT RESEARCH PROJECTS AT IST
3. Current Research Projects at IST

3.1. 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)

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1 Matos et al. (2012), Composite Structures
3.2. Fire Behaviour of CFRP-Strengthened RC $^2,^3$

CFRP-concrete bond tests at elevated temperature

EBR – externally bonded reinforcement
NSM – near surface mounted

2 Firmo et al. (2012), Composites Part B: Engineering
3 López et al. (2013), Construction and Building Materials
3.2. Fire Behaviour of CFRP-Strengthened RC

Fire resistance tests in CFRP-strengthened beams (ISO 834)
Different fire protection systems (thick insulation at the anchorage zones)

Failure of beam CFRP (unprotected)

Displacement increase vs. time

2 Firmo et al. (2012), Composites Part B: Engineering
3 López et al. (2013), Construction and Building Materials
3. Current Research Projects at IST

3.3. Fire Behaviour of GFRP Pultruded Profiles \(^4,5\)

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

Fire resistance tests in GFRP profiles (ISO 834)

\(^4\) Correia et al. (2013), Composite Structures

\(^5\) Correia et al. (2012), Composites Part B: Engineering
3.4. **Behaviour of GFRP Snap-Fit Bridge Panels**

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

Flexural test on GFRP panel

Pedestrian bridge project (Feira de S. Mateus, Viseu)
3. CURRENT RESEARCH PROJECTS AT IST

3.4. BEHAVIOUR OF GFRP SNAP-FIT BRIDGE PANELS

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

Flexural test on GFRP panel

Pedestrian bridge project (Feira de S. Mateus, Viseu)
3. CURRENT RESEARCH PROJECTS AT IST

3.5. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

Geometry of the GFRP-SFRSCC cross-section

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

Modal identification tests

Pedestrian comfort dynamic tests and FE modelling
3.5. Development of GFRP-Concrete Bridges

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

6 Gonilha et al. (2013), Composite Structures
7 Gonilha et al. (2013), Composites Part B: Engineering
3. CURRENT RESEARCH PROJECTS AT IST

3.5. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

Full-scale pedestrian bridge prototype (11.0 m long) – construction and load tests
3.6. DEVELOPMENT OF GFRP SANDWICH PANELS

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

Flexural tests in full-scale panels
(different cores / lateral ribs)

Load vs. deflection behaviour

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8 Correia et al. (2012), *International Journal of Structural Integrity*
3.7. STRUCTURAL GLASS\textsuperscript{9,10}

Glass-GFRP hybrid beam – EP adhesive

Glass-GFRP hybrid beam – PU adhesive

\textsuperscript{9} Correia et al. (2012), Composite Structures

\textsuperscript{10} Valarinho et al. (2013), Construction and Building Materials
4. 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

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