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DEPARTAMENTO DE ENGENHARIA
CIVIL, ARQUITETURA E GEORRECURSOS
TÉCNICO LISBOA

European Council
of
Civil Engineers

The New FRP Materials for Civil Engineering Structural Applications

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57th Meeting of the European Council of Civil Engineers (ECCE)
Ordem dos Engenheiros, Lisboa, 31/05/2013

HISTORICAL CONTEXT

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)

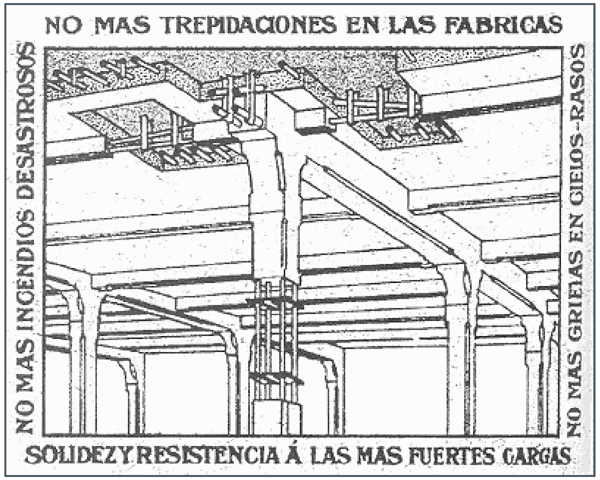
HISTORICAL CONTEXT

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**

Monsanto House of the Future

Futuro House

Icoshedron Classroom

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

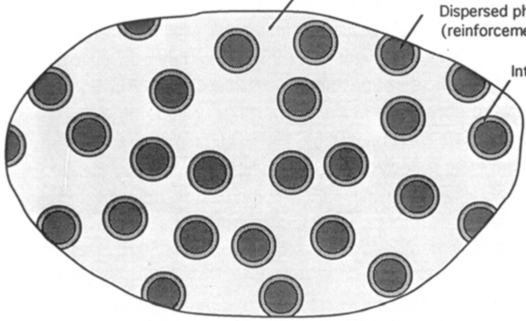
→ Durability

OUTLINE

1. FIBRE REINFORCED POLYMER (FRP) MATERIALS

1.1. CONSTITUTION AND GENERAL PROPERTIES OF FRPS

Fibre Reinforced Polymer (FRP) materials - 2 phases:



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

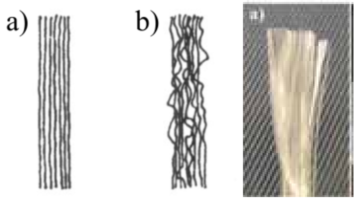
→ Keeping the fibres in position (and preventing their buckling when compressed)

1.1. CONSTITUTION AND GENERAL PROPERTIES OF FRPs

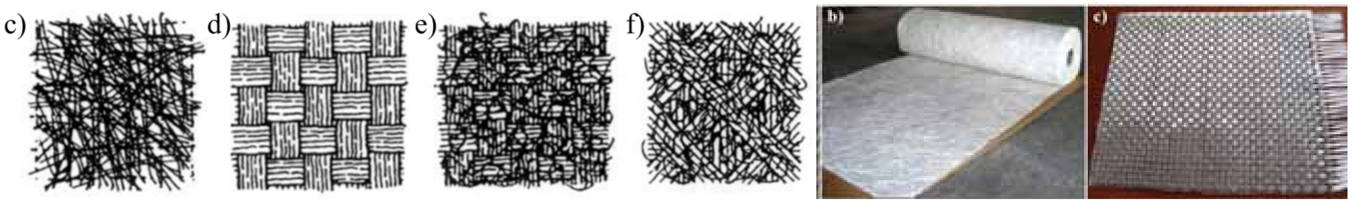
Properties and forms of reinforcing fibres

Property	E - Glass	Carbon	Aramid
Strength [MPa]	2350 - 4600	2600 - 3600	2800 - 4100
Elasticity modulus [GPa]	73 - 88	200 - 400	70 - 190
Strain at failure [%]	2.5 - 4.5	0.6 - 1.5	2.0 - 4.0
Density [g/cm^3]	2.6	1.7 - 1.9	1.4

- **Rovings (or tows) - bundles of continuous filaments**
- **Mats (*mats, veils, fabrics*) with short or continuous filaments, randomly oriented or oriented, woven or non-woven**



Rovings



Mats, fabrics

1.1. CONSTITUTION AND GENERAL PROPERTIES OF FRPS

Properties of polymeric matrixes

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

Property	Polyester	Vinylester	Epoxy
Strength [MPa]	20 - 70	68 - 82	60 - 80
Elasticity modulus [GPa]	2 - 3	3.5	2 - 4
Strain at failure [%]	1 - 5	3 - 4	1 - 8
Density [g/cm^3]	1.2 - 1.3	1.12 - 1.16	1.2 - 1.3
Glass transition temperature [ºC]	70 - 120	102 - 150	100 - 270

1.2 Manufacturing Processes for FRP Materials

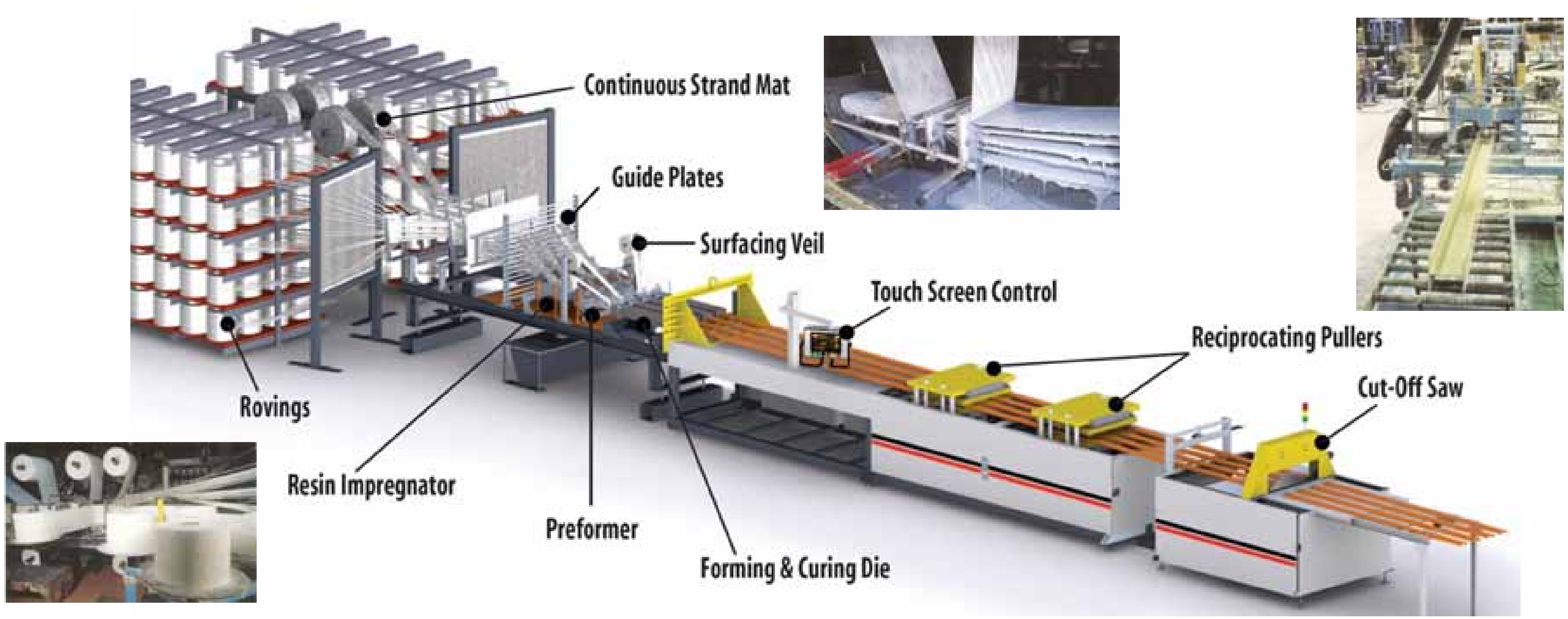
- **Pultrusion**
- **Hand layup**
- Filament winding
- Centrifugation
- Resin transfer moulding (RTM)
- Resin infusion moulding (RIM)
- Compression moulding
- Vacuum assisted resin transfer moulding (VARTM)
- Vacuum infusion

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 in a moulding table of a GFRP laminate

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**

Hybrid profile
(C and G fibres)

→ **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

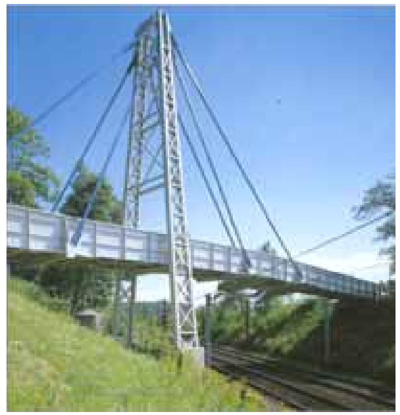
2.1. STRUCTURAL APPLICATION OF FRP MATERIALS

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

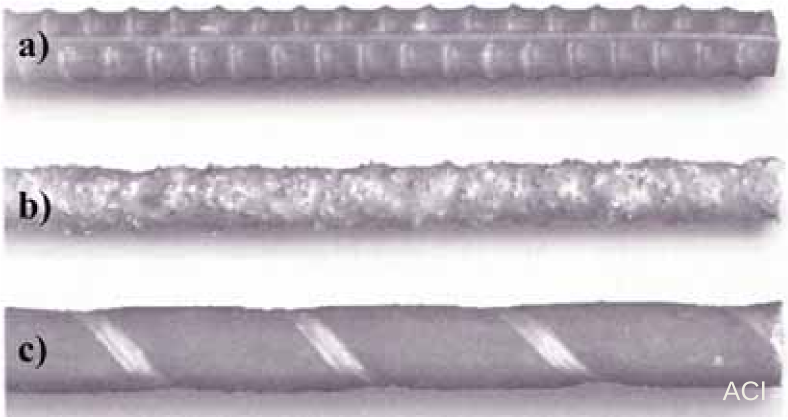
FRP laminates and sheets

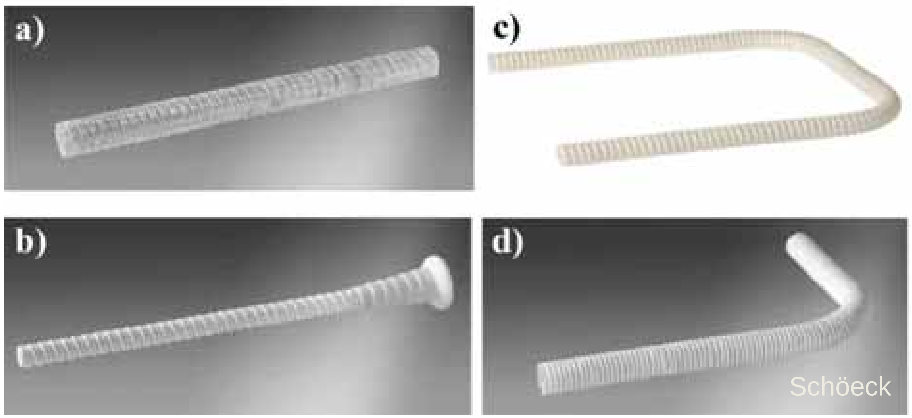


FRP profiles and panels

2.2. FRP REBARS – GEOMETRY AND PROPERTIES

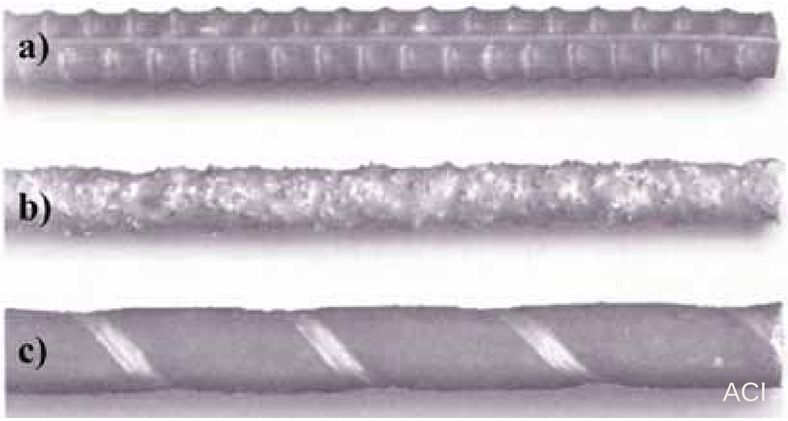
- **Constitution:** polymer matrix (vinylester) and rovings (axial fibre reinforcement)
- **Available diameters:** 6 to 36 mm
- **Surface finishing:** a) ribbed; b) sand coating; c) exterior wound fibres and sand coating
- **Geometry:** a) straight; b) with anchorage heads; and bent c) in U or d) hooked

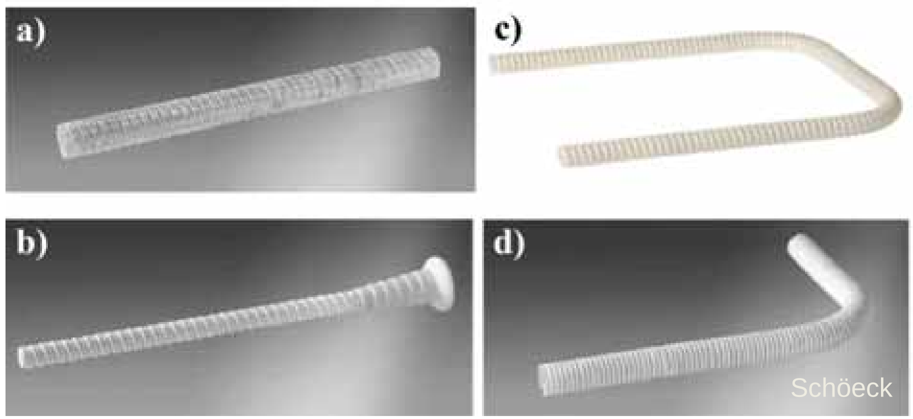




2.2. FRP REBARS – GEOMETRY AND PROPERTIES

Property		GFRP	CFRP	AFRP
Density [g/cm³]		1,25 - 2,10	1,50 - 1,60	1,25 - 1,40
Fibre content [%]		50 - 60	50 – 60	-
Thermal expansion coefficient [$\times 10^{-6}$/ºC]	Axial	6,0 - 10,0	-9,0 a 0,0	-6,0 a -2,0
	Transversal	21,0 - 23,0	74,0 - 104,0	60,0 - 80,0
Axial tensile strength [MPa]		**483 - 1600**	600 - 3690	1720 - 2540
Axial elasiticity modulus [GPa]		**35 - 60**	120 - 580	41 - 125
Axial strain at failure [%]		**1,2 - 3,1**	0,5 - 1,7	1,9 - 4,4





2.2. FRP REBARS – APPLICATIONS

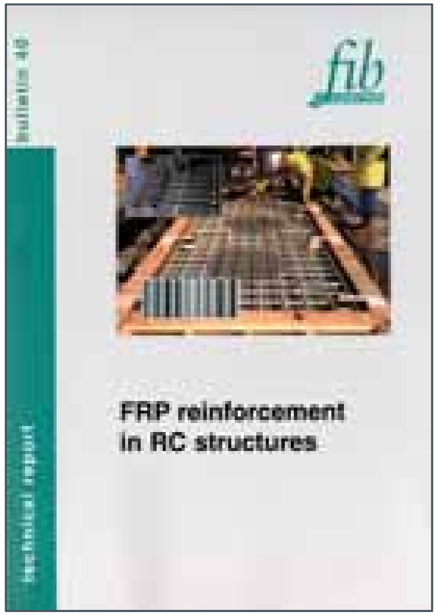
Reinforcement of bridge deck

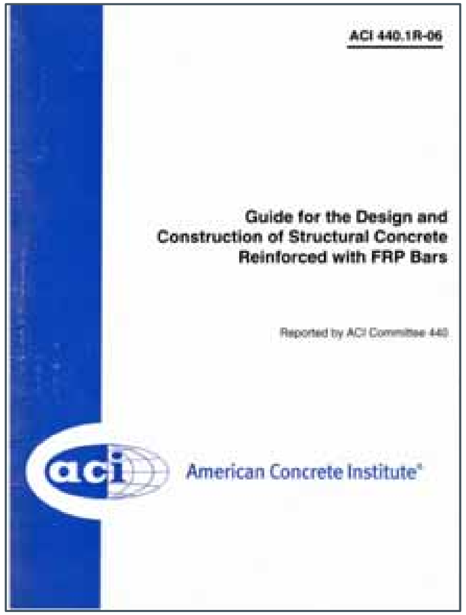
Aquaculture (Acuinova, Mira)

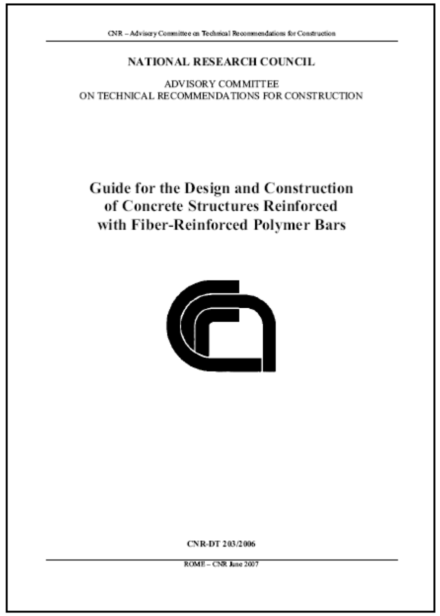
Repair of maritime structures, dock and pier

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



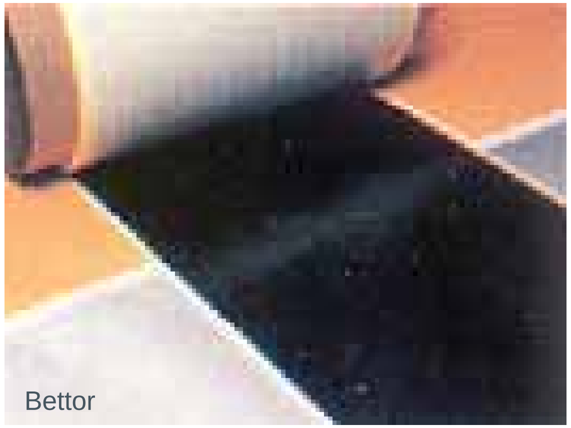




2.3. FRP STRENGTHENING SYSTEMS - TYPOLOGIES

- **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.

CFRP laminates



CFRP sheets

NOTE: There are also **rebars** and **cables/tendons**

2.3. FRP STRENGTHENING SYSTEMS - PROPERTIES

Laminates:

- E = 165 to 300 GPa
- σ_u = 1500 to 3000 MPa
- ε_u = 0,5 a 1,7%

a)

b)

Sheets:

- E = 240 to 640 GPa (typically, 240 to 300 GPa)
- σ_u = 2500 to 3000 MPa
- ε_u = 0,4 a 1,55 %

2.3. FRP STRENGTHENING SYSTEMS - APPLICATIONS

Flexural strengthening of beams and slabs

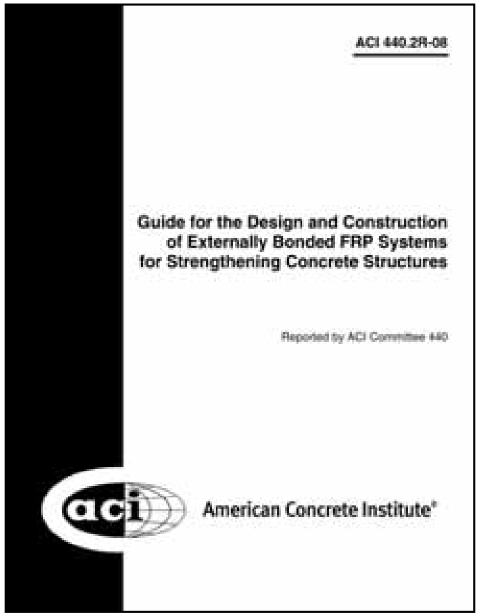
Shear strengthening of beam

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
- **CNR-DT (2004):** Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures



2.4. FRP PROFILES – GEOMETRIES AND CONSTITUTION

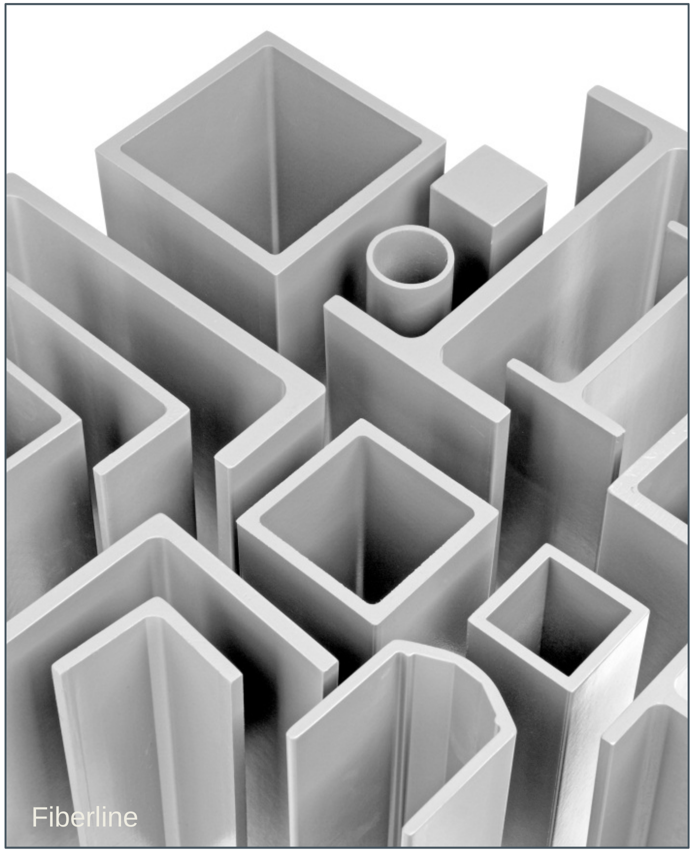
First generation profiles

Thin-walled cross-sections

mimicking metallic construction

- High deformability
- Susceptibility to instability phenomena under compression

→ **Limited exploitation of material potential**



First generation profiles

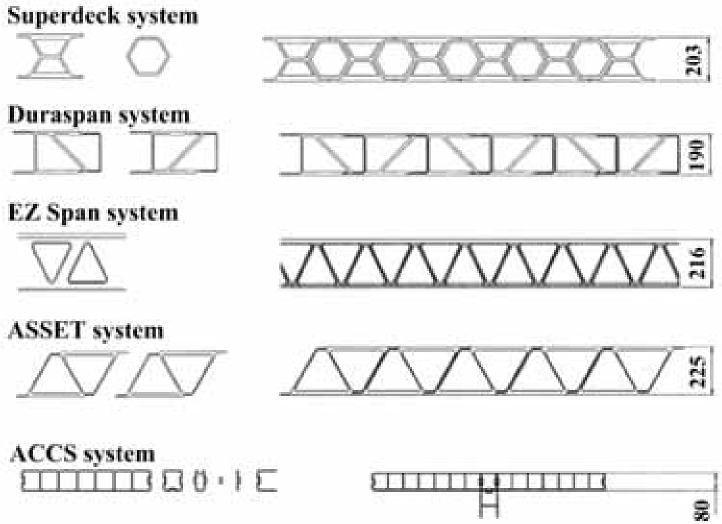
2.4. FRP PROFILES – GEOMETRIES AND CONSTITUTION

New generation profiles

Multi-cellular deck panels for new construction or rehabilitation

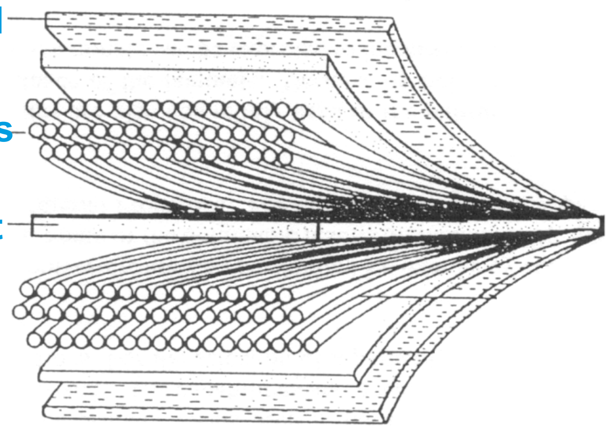
- **Panel-to-panel connection:** adhesive bonding or snap-fit
- **Panel-to-girder connection:** bolting/bonding

→ Lightness
→ Quick installation
→ High durability
→ Low maintenance



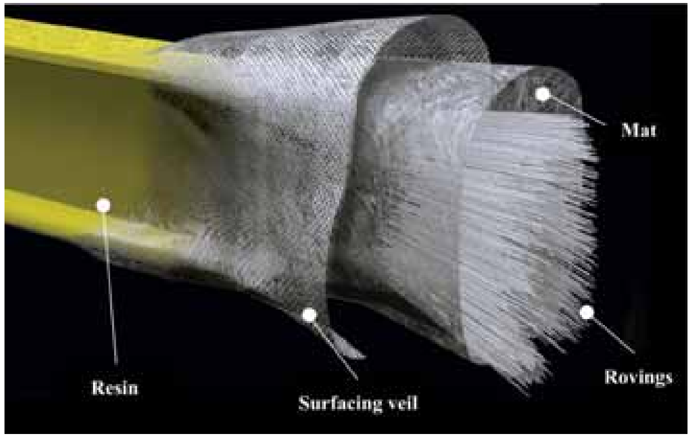
2.4. FRP PROFILES – GEOMETRIES AND CONSTITUTION

- **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

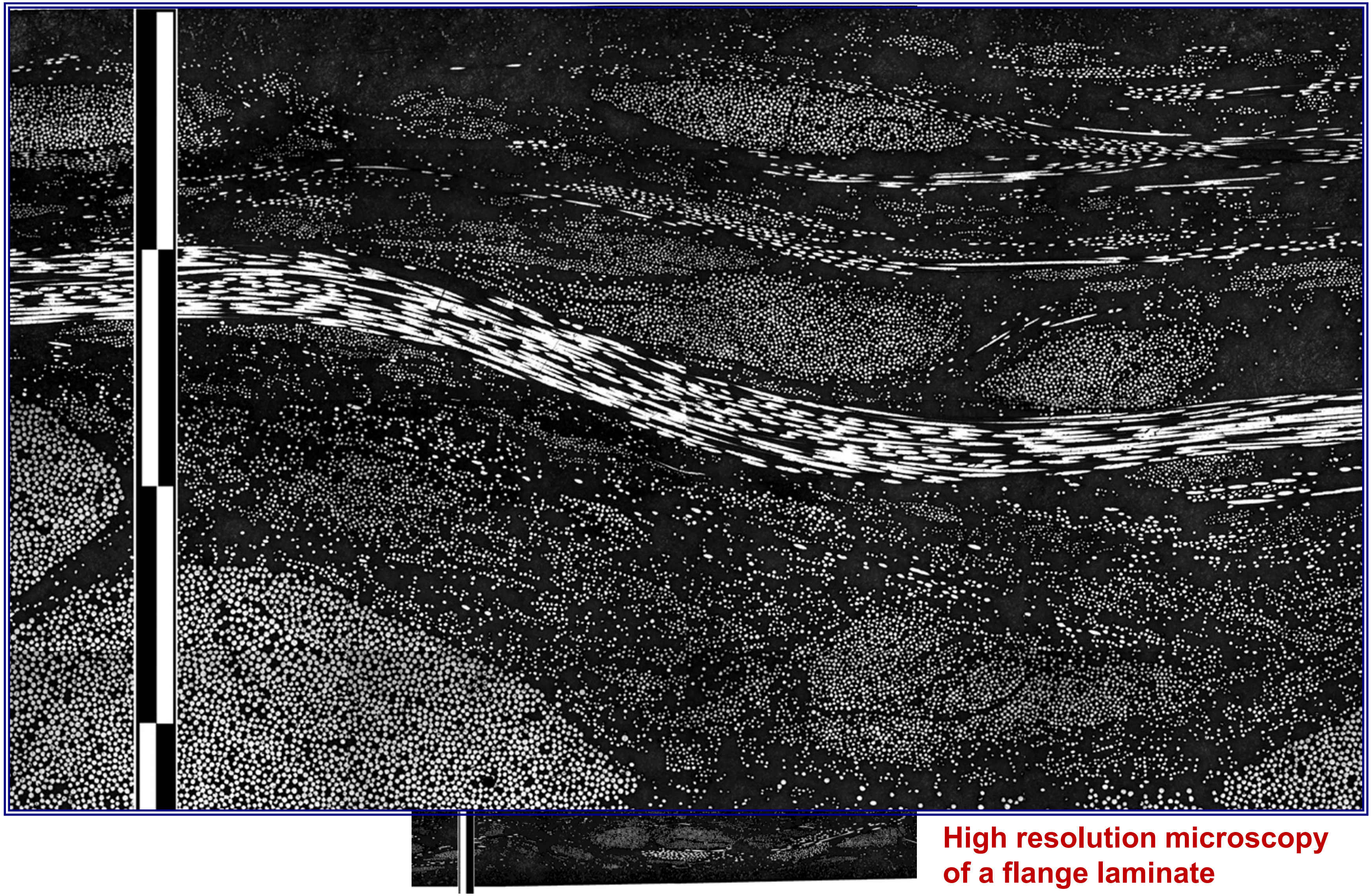


Fibre architecture of a laminate

- **Polymeric matrix:**
  - Resin (polyester, vinylester, epoxy)
  - Fillers
  - Additives



2.4. FRP PROFILES – GEOMETRIES AND CONSTITUTION



High resolution microscopy of a flange laminate

2.4. FRP PROFILES – PROPERTIES (GFRP)

Property	Longitudinal	Transverse
Tensile/compressive strength [MPa]	200 - 400	50 - 60
Shear strength [MPa]	20 - 30	
Elasticity modulus [GPa]	20 - 40	5 - 9
Shear modulus [GPa]	3 - 4	
Density [g/cm^3]	1.8 - 1.9	
Fibre content [%]	50 - 70	

→ 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)

2.4. 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

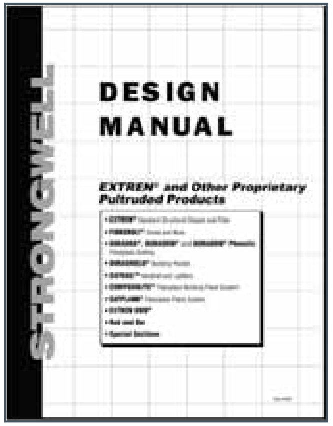
2.4. FRP PROFILES – DESIGN GUIDELINES

→ There is still **no specific official regulation**

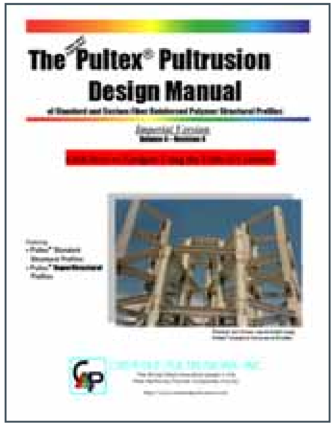
→ Design often based on **manufacturers manuals** – design tables (information provided limited)

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

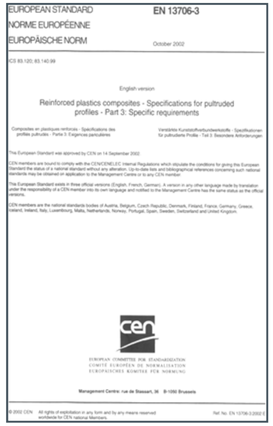
Fiberline Composites



Strongwell



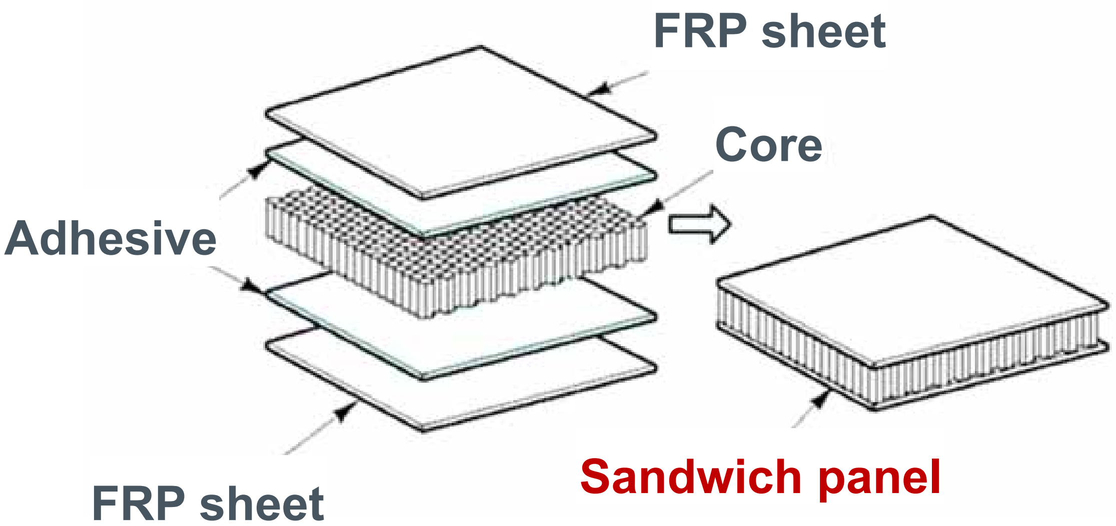
Creative Pultrusions



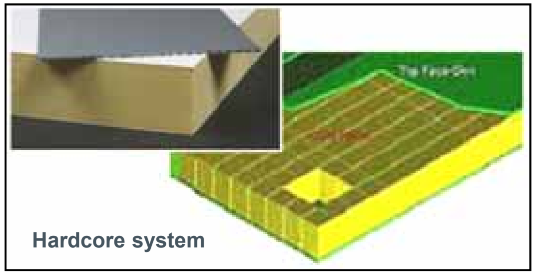
EN 13706

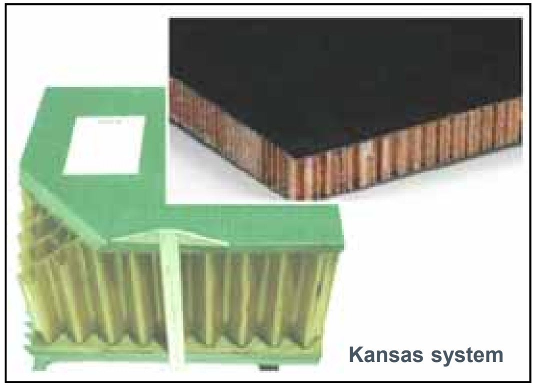
2.5. FRP SANDWICH PANELS – CONSTITUTION

- **FRP outer skins** - thin, stiff, resistant
- **Core** - thick, light, more flexible, less resistant (rigid foam, balsa wood, etc.)
- **Adhesive**



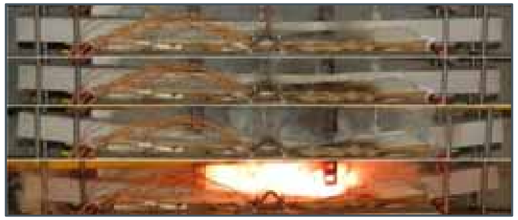
Sandwich panel



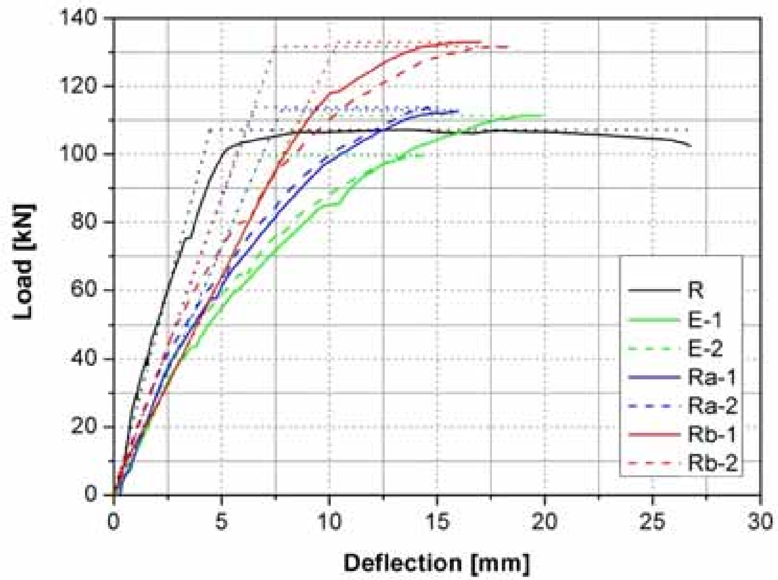


Commercial systems

3. CURRENT RESEARCH PROJECTS AT IST



3.1. STRUCTURAL BEHAVIOUR OF GFRP-RC BEAMS [1]

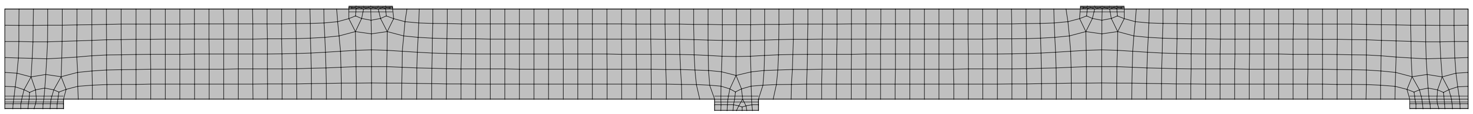


Flexural tests on 2-span beams

R – reference beam (steel reinforced);

Rb-1 – GFRP reinforced beam with concrete confinement in critical cross-sections

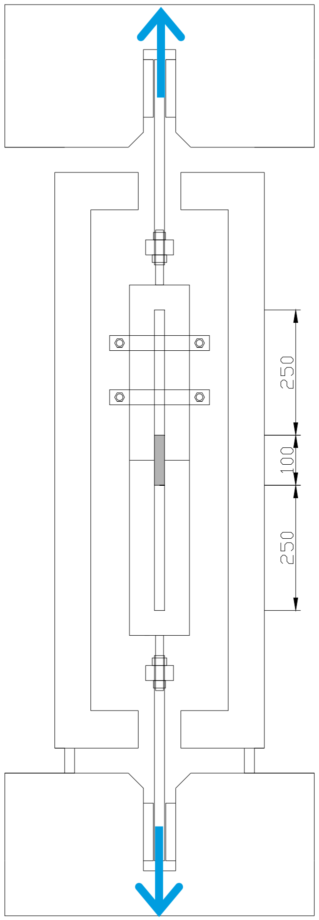
Load vs. deflection curves



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

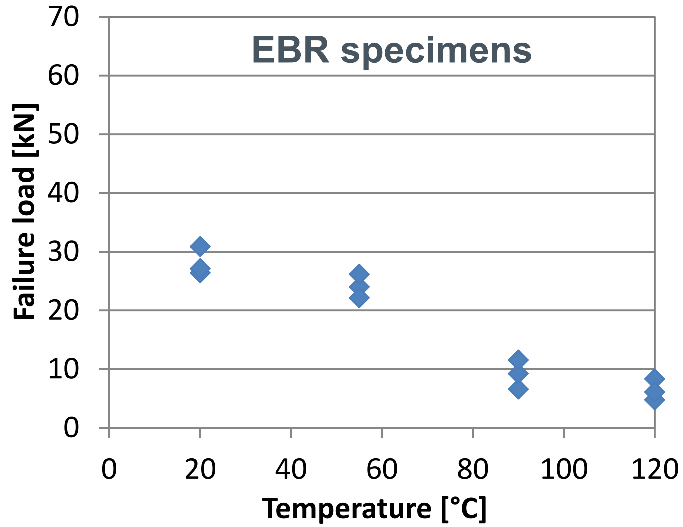
[1] Matos *et al*. (2012), *Composite Structures*

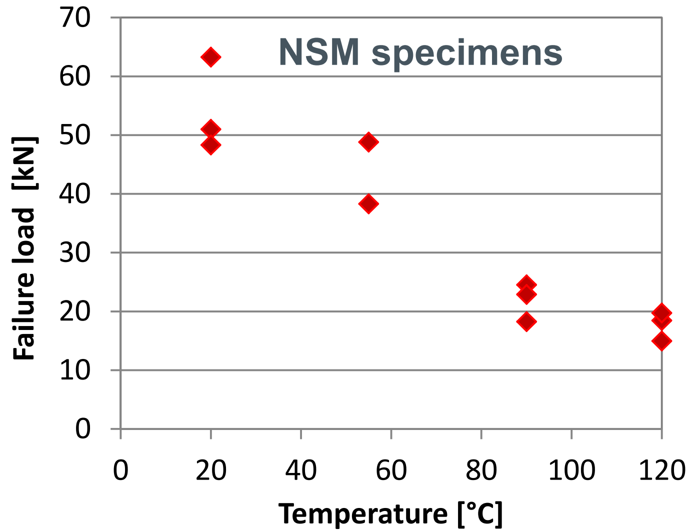
3.2. FIRE BEHAVIOUR OF CFRP-STRENGTHENED RC [2,3]



EBR specimen

NSM specimen





CFRP-concrete bond tests at elevated temperature

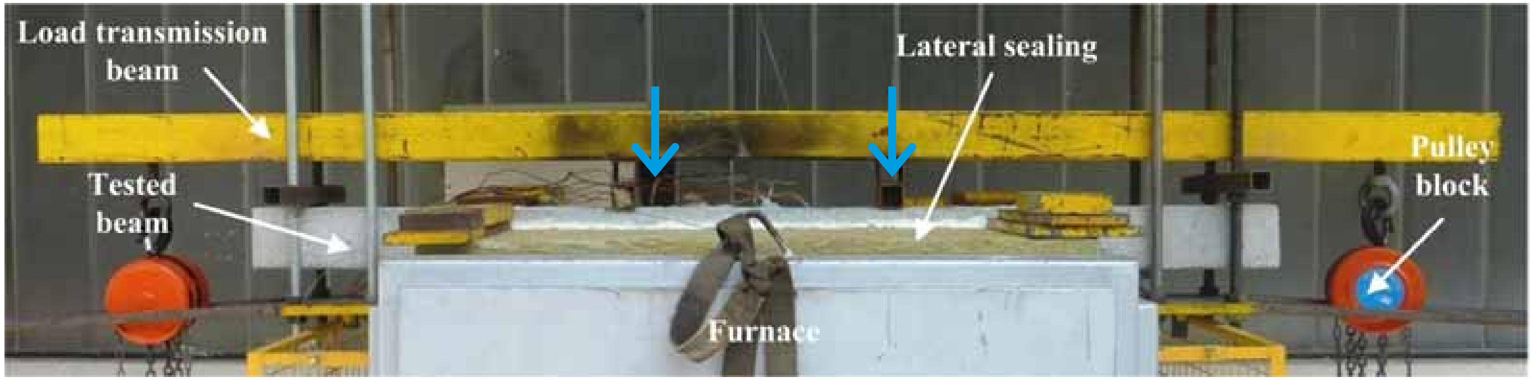
EBR – externally bonded reinforcement

NSM – near surface mounted

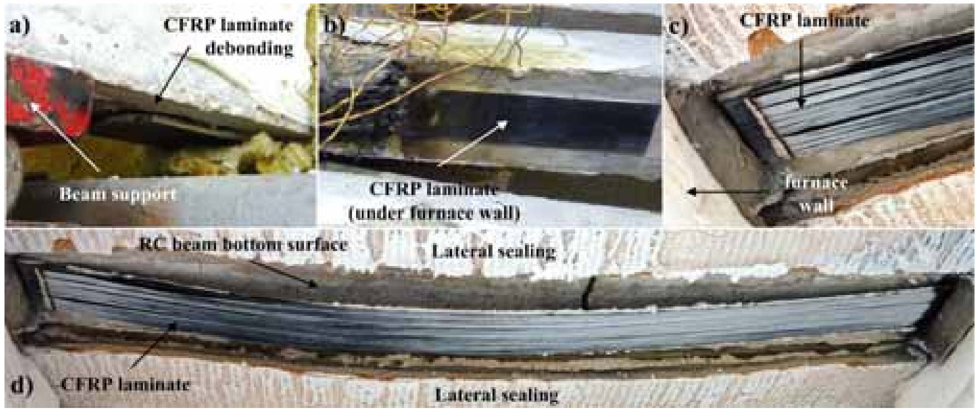
[2] Firmo *et al.* (2012), *Composites Part B: Engineering*

[3] López et al. (2013), *Construction and Building Materials*

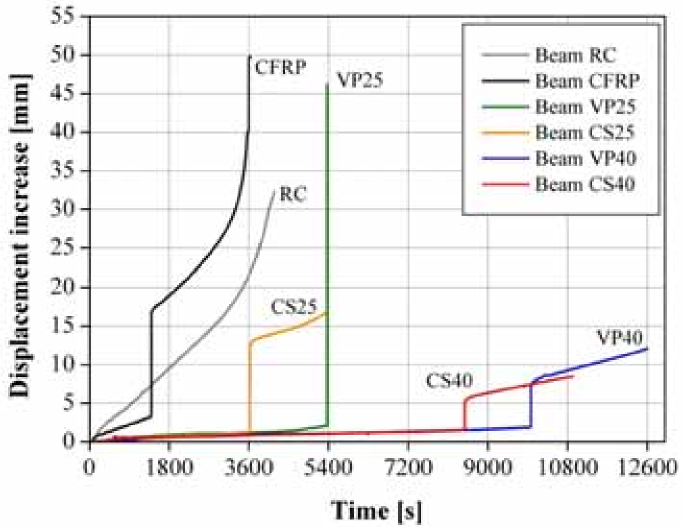
3.2. FIRE BEHAVIOUR OF CFRP-STRENGTHENED RC [2,3]



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



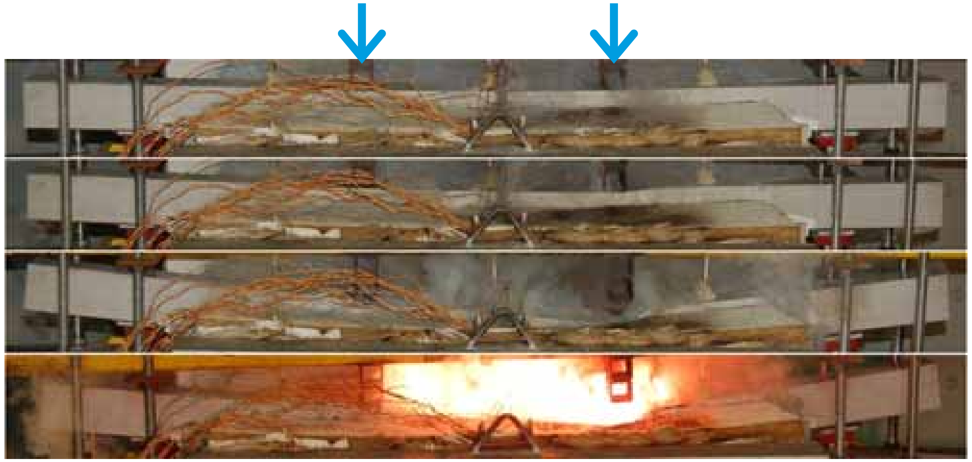
Failure of beam CFRP (unprotected)



Displacement increase *vs*. time

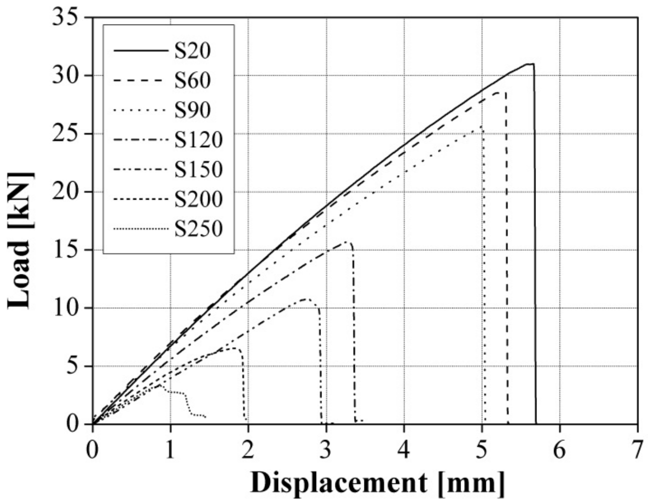
[2] Firmo *et al*. (2012), *Composites Part B: Engineering*
[3] López et al. (2013), *Construction and Building Materials*

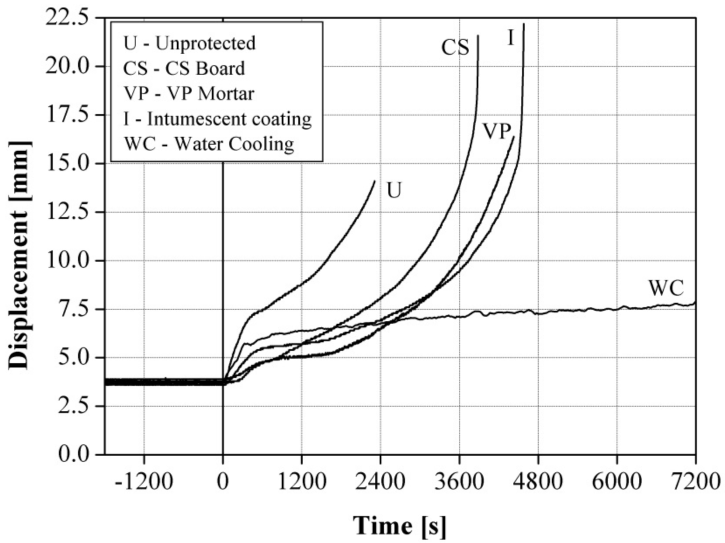
3.3. FIRE BEHAVIOUR OF GFRP PULTRUDED PROFILES [4,5]

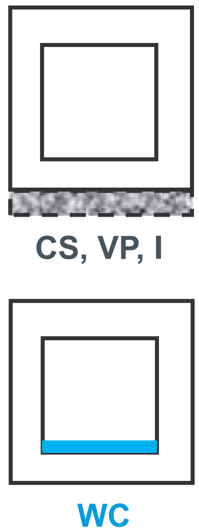


Shear tests on GFRP laminates (20-250ºC)

Fire resistance tests in GFRP profiles (ISO 834)



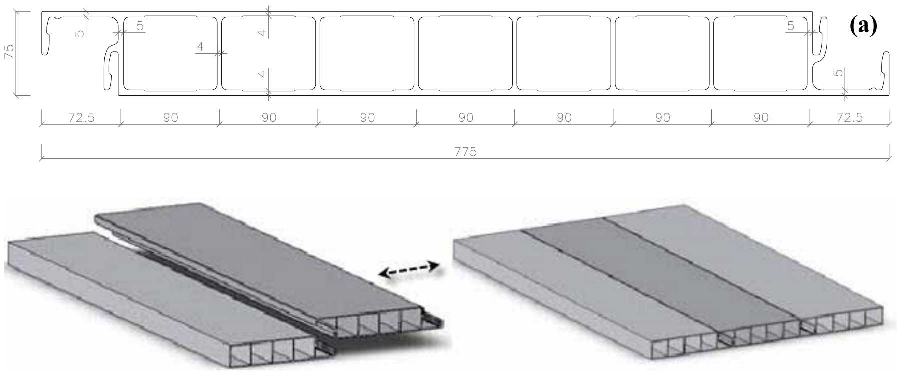




[4] Correia *et al.* (2013), *Composite Structures*

[5] Correia *et al.* (2012), *Composites Part B: Engineering*

3.4. BEHAVIOUR OF GFRP SNAP-FIT BRIDGE PANELS

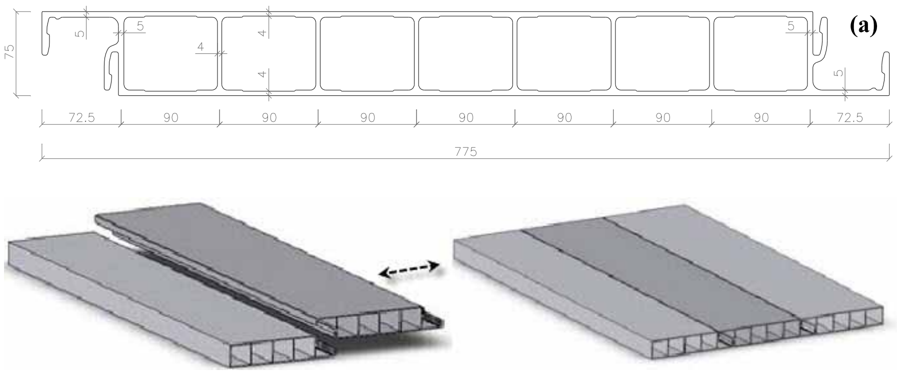


Cross-section and functioning principle of snap-fit GFRP panels

Flexural test on GFRP panel

Pedestrian bridge project (Feira de S. Mateus, Viseu)

3.4. BEHAVIOUR OF GFRP SNAP-FIT BRIDGE PANELS

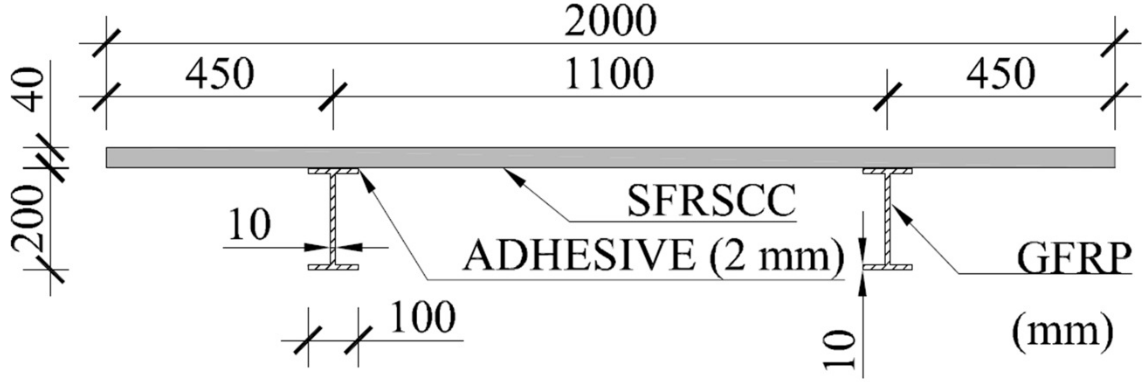


Cross-section and functioning principle of snap-fit GFRP panels

Flexural test on GFRP panel

Pedestrian bridge project (Feira de S. Mateus, Viseu)

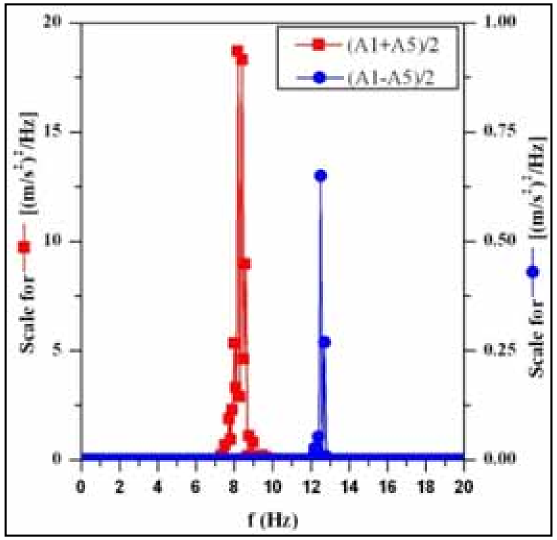
3.5. DEVELOPMENT OF GFRP-CONCRETE BRIDGES



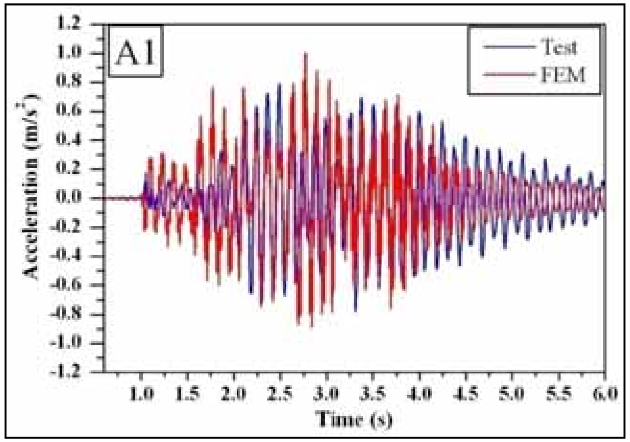
Geometry of the GFRP-SFRSCC cross-section

Small-scale pedestrian bridge prototype (6.0 m long)

3.5. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

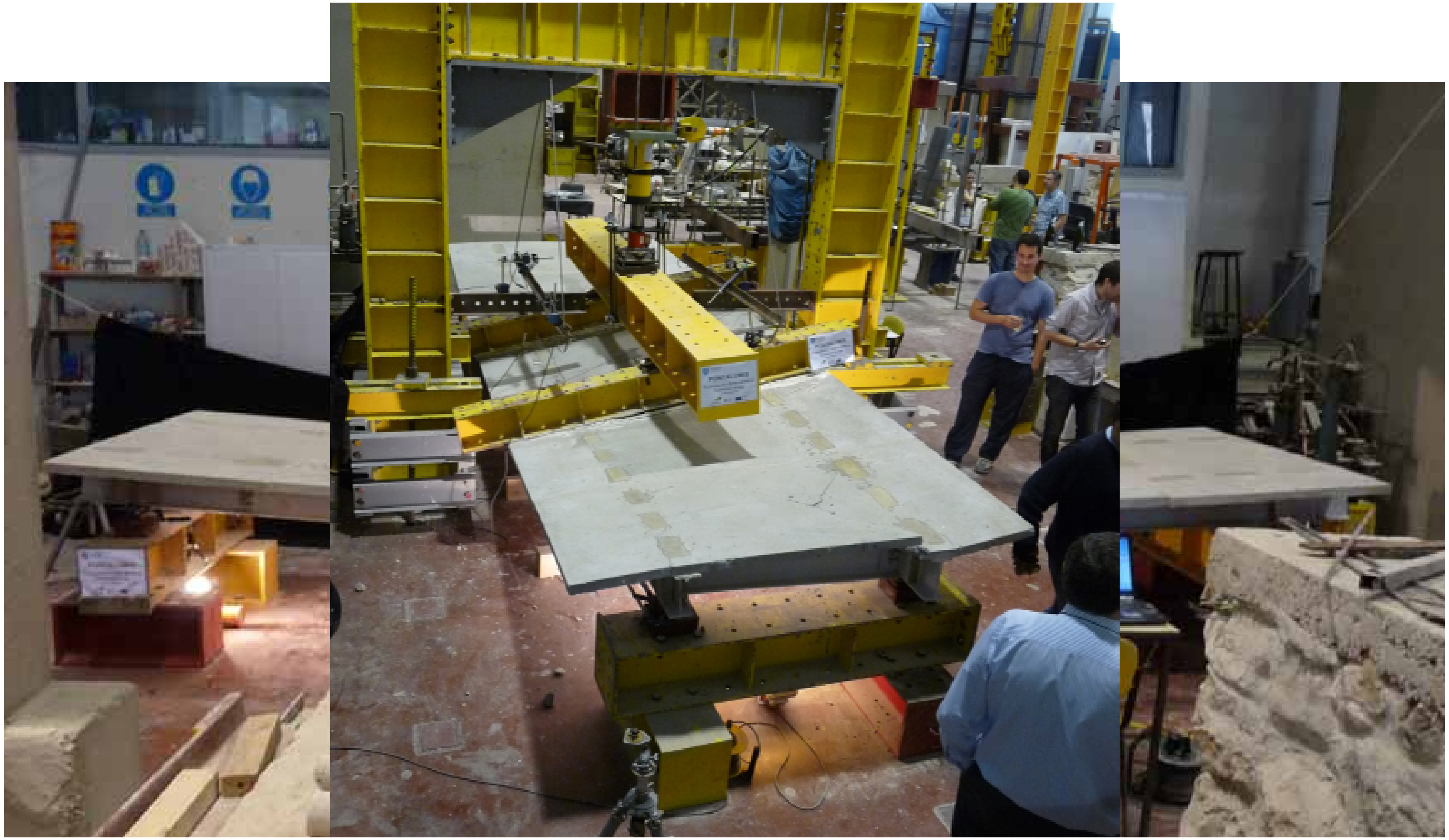


Modal identification tests



Pedestrian comfort dynamic tests and FE modelling

3.5. DEVELOPMENT OF GFRP-CONCRETE BRIDGES [6,7]



Flexural tests up to failure (F_u ~ 240 kN)

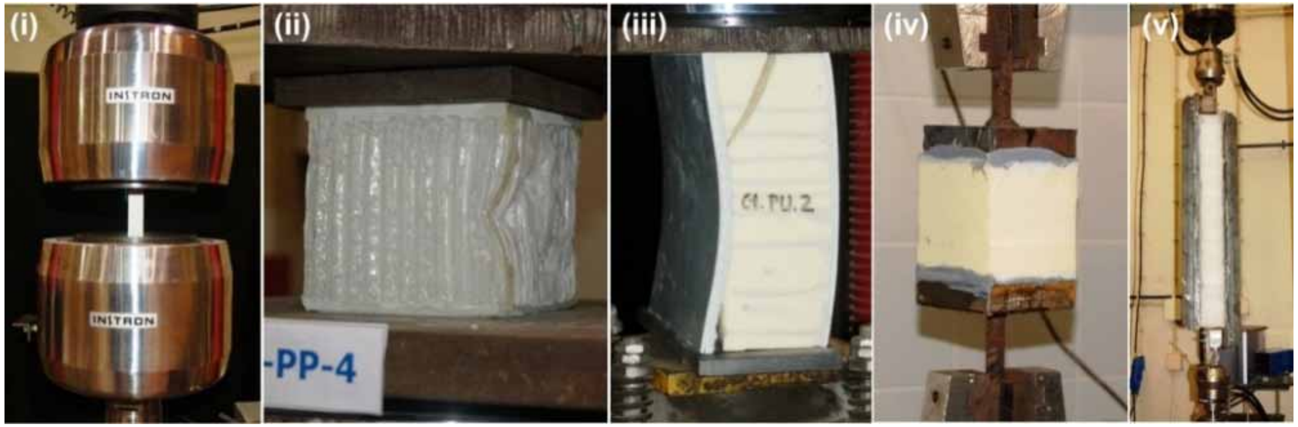
[6] Gonilha *et al*. (2013), *Composite Structures*

[7] Gonilha *et al*. (2013), *Composites Part B: Engineering*

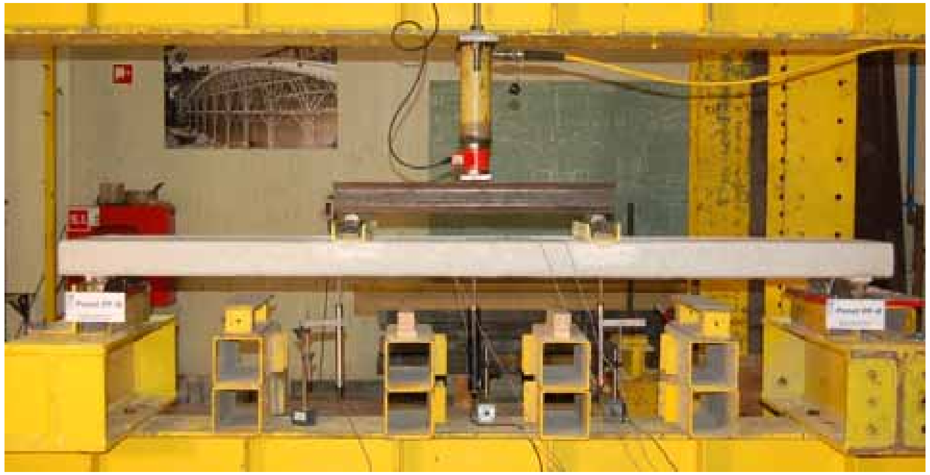
3.5. DEVELOPMENT OF GFRP-CONCRETE BRIDGES

Full-scale pedestrian bridge prototype (11.0 m long) – construction and load tests

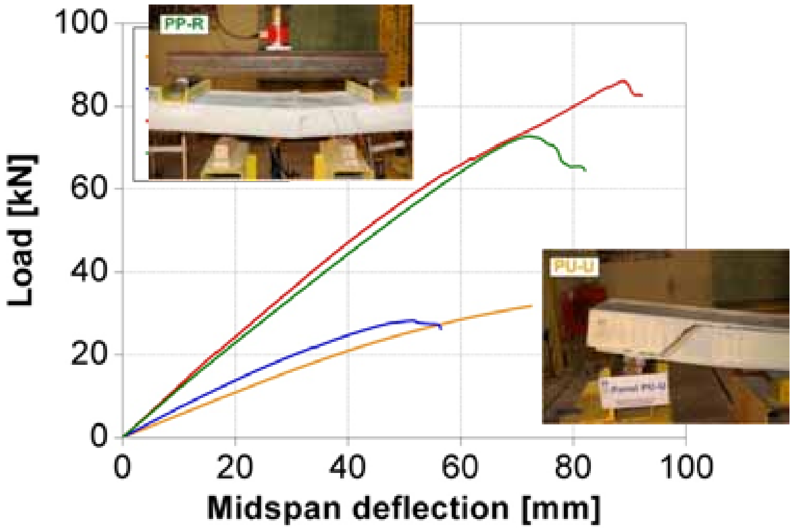
3.6. DEVELOPMENT OF GFRP SANDWICH PANELS[8]



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



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



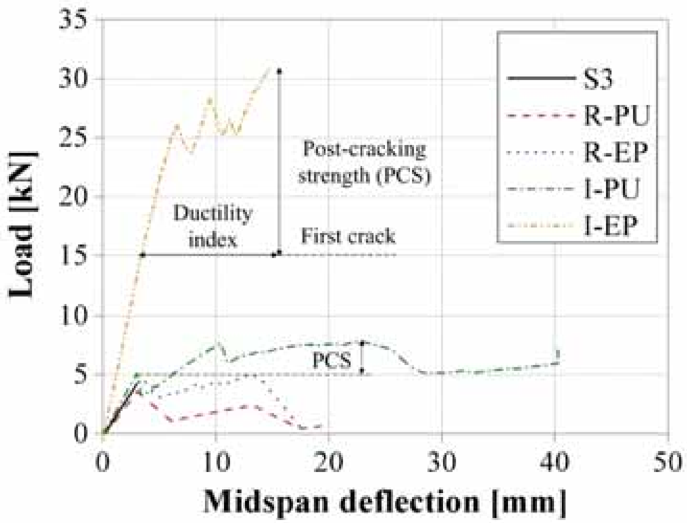
Load vs. deflection behaviour

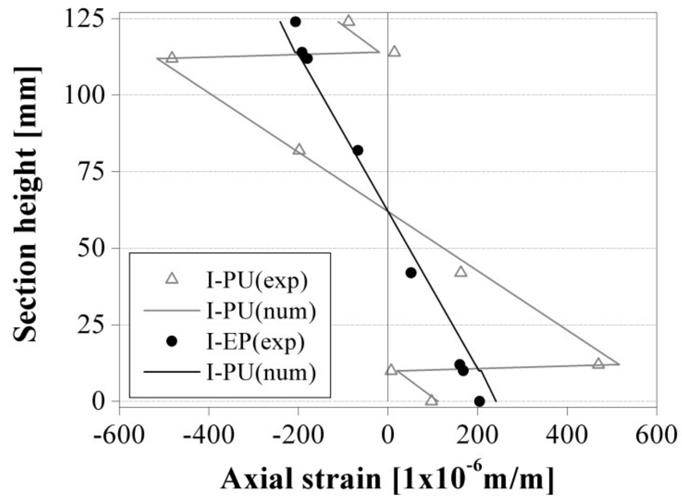
[8] Correia *et al*. (2012), *International Journal of Structural Integrity*

3.7. STRUCTURAL GLASS [9,10]

Glass-GFRP hybrid beam – EP adhesive

Glass-GFRP hybrid beam – PU adhesive





[9] Correia *et al*. (2012), *Composite Structures*

[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!