Strengthening concrete structures with FRP laminates

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EUROCODES

EN 1992

Design
of concrete
structures

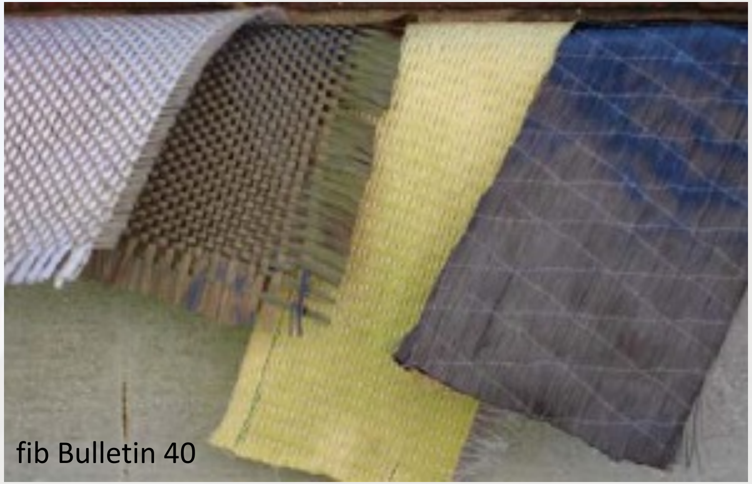
2nd generation of Eurocode 2 on concrete structures

Madrid, October 17th, 2023

Contents

1. INTRODUCTION

FIBRE REINFORCED POLYMER (FRP): Composite material formed by a polymeric matrix (resin) reinforced with continuous fibres



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GFRP
CFRP
BFRP
AFRP

Fibres:
G (glass), C (carbon), B (basalt), A (aramid)

Matrix:
Thermosetting; Thermoplastic

1. INTRODUCTION

STRENGTHENING STRUCTURES with FIBRE REINFORCED POLYMER (FRP) LAMINATES

to restore or increase their load bearing capacity

FRPs related to other industries

FRPs introduced in **construction sector** to overcome the drawbacks of steel bonded plates (corrosion and weight)

1. INTRODUCTION

STRENGTHENING STRUCTURES by ADHESIVELY BONDED REINFORCEMENT (ABR) with CARBON FIBRE REINFORCED POLYMER (CFRP) LAMINATES

Included in **ANNEX J** (informative) **of EUROCODE 2**

- 2 possible CONFIGURATIONS

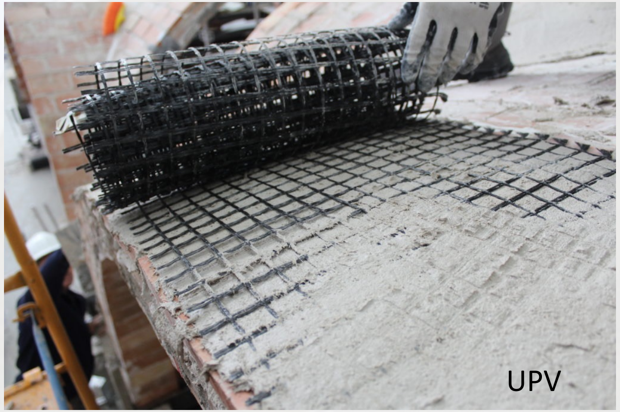
Externally bonded reinforcement (EBR)

Near surface mounted (NSM) reinforcement

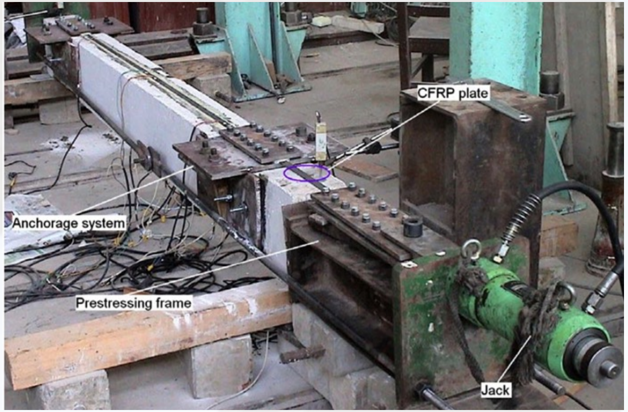
1. INTRODUCTION

STRENGTHENING STRUCTURES by ADHESIVELY BONDED REINFORCEMENT (ABR) with CARBON FIBRE REINFORCED POLYMER (CFRP) LAMINATES

NOT Included in **ANNEX J** (informative) **of EUROCODE 2**



Textile Reinforced Mortar (TRM)

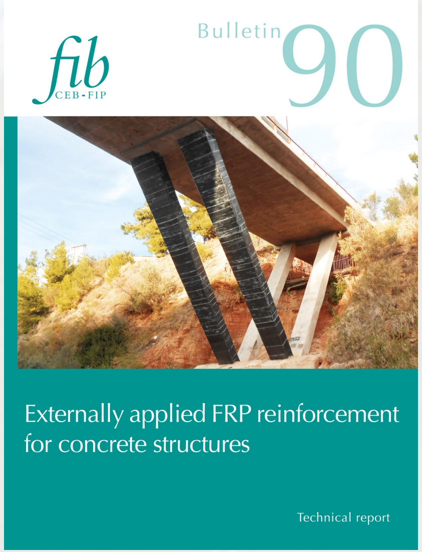


Prestressed adhesively bonded reinforcement

1. INTRODUCTION

STRENGTHENING STRUCTURES by ADHESIVELY BONDED REINFORCEMENT (ABR) with CARBON FIBRE REINFORCED POLYMER (CFRP) LAMINATES

Existing European guidelines

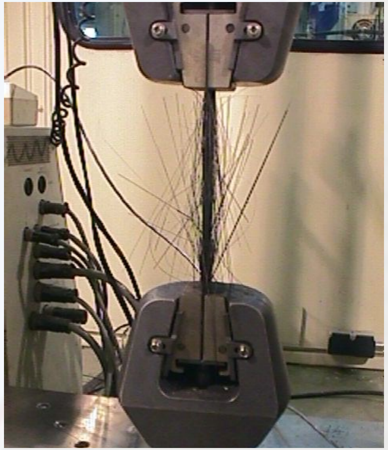


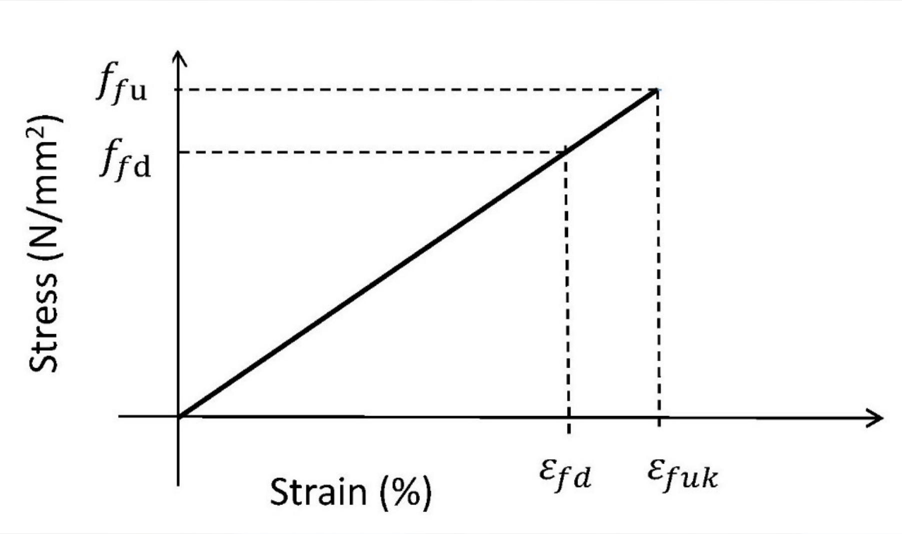
- DAfStb (2013)
- CNR-DT 200 R1/2013 (2013)
- TR-55 (2012)
- AFGC (2011)
- SIA (2004)
- GRECO (2013)

Additional background to Annex J

2. BASIS OF DESIGN, MATERIALS AND STRUCTURAL ANALYSIS

- **Linear elastic** up to failure





Design situation	Tensile strength		Bond strength
	CFRP strips and bars	In-situ lay-up CF sheets	Failure in concrete or adhesive
Designation	γ_f		γ_{BA}
Persistent and transient	1.30	1.40	1.50
Accidental	1.10	1.15	1.15
Serviceability	1.00	1.00	1.00
Fatigue	1.30	1.40	1.50

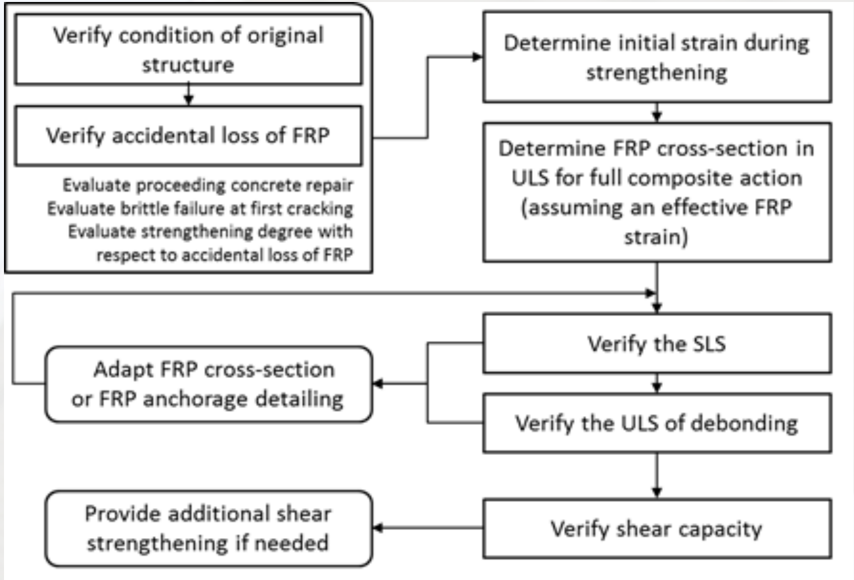
$$f_{fd} = \frac{\eta_f \cdot f_{fuk}}{\gamma_f}$$

η_f Reduction factor for relevant exposure conditions

Members strengthened with ABR should not be analysed using linear elastic analysis with limited redistribution or plastic analysis

3. ULTIMATE LIMIT STATES

Bending with or without axial forces



Design of flexural strengthening system by applying equilibrium + compatibility

CHECK **FRP DEBONDING**!!!

3. ULTIMATE LIMIT STATES

Confinement

FRPs apply an ever-increasing confinement pressure to the concrete core.

Ultimate capacity is governed by tensile failure of FRP (lower than standard tensile testing of FRP coupons).

based on **Lam and Teng** (2003)

For circular columns:

$$\Delta f_{cd} = 0 \qquad \text{for } \frac{t_f \cdot f_{fud}}{D \cdot f_{cd}} < 0.07$$

$$\Delta f_{cd} = k_{cc} \cdot \frac{t_f}{D} \cdot f_{fud} \qquad \text{for } \frac{t_f \cdot f_{fud}}{D \cdot f_{cd}} \geq 0.07$$

For rectangular columns:

$$\Delta f_{cd} = 0 \qquad \text{for } \left(\frac{b}{h}\right)^2 k_e \frac{t_f \cdot k_r \cdot f_{fud}}{D_{eq} \cdot f_{cd}} < 0.07$$

$$\Delta f_{cd} = k_{cc} \cdot \left(\frac{b}{h}\right)^2 \cdot k_e \cdot \frac{t_f}{D_{eq}} \cdot k_r \cdot f_{fud} \qquad \text{for } \left(\frac{b}{h}\right)^2 k_e \frac{t_f \cdot k_r \cdot f_{fud}}{D \cdot f_{cd}} \geq 0.07$$

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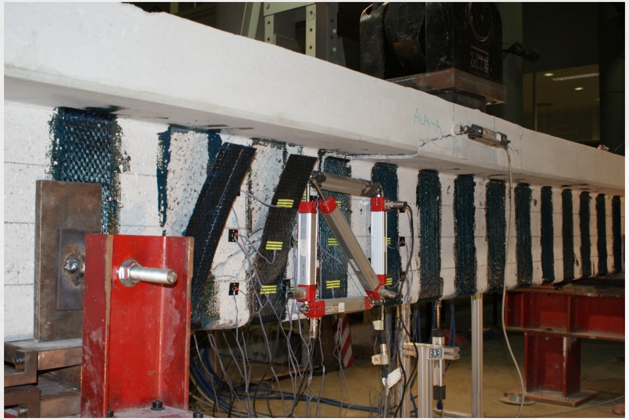
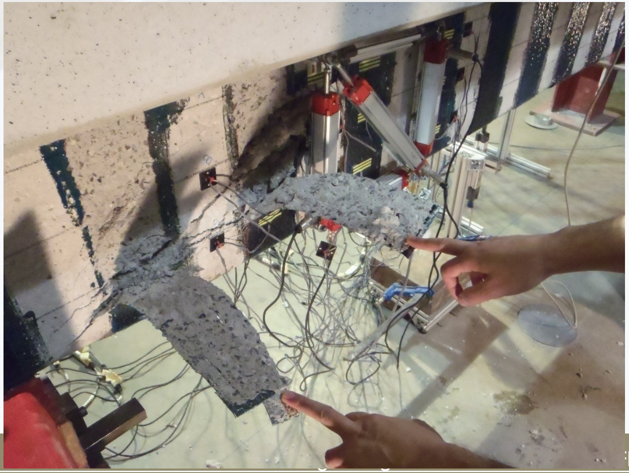
3. ULTIMATE LIMIT STATES

Problem: Debonding of FRP shear strengthening system

Shear

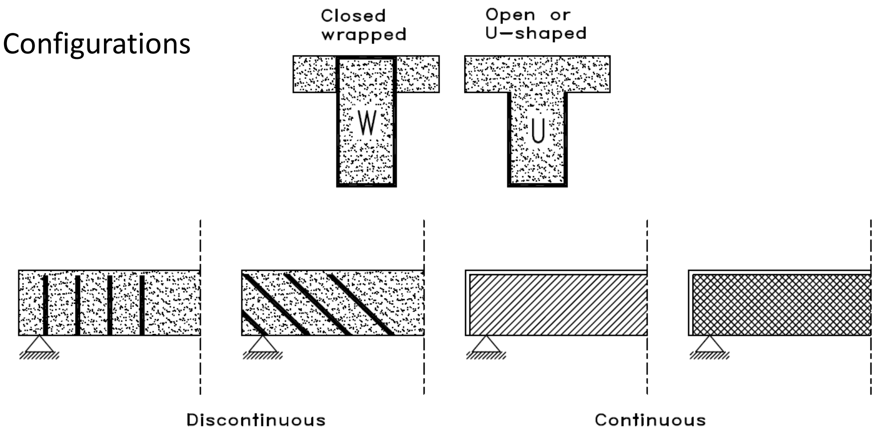


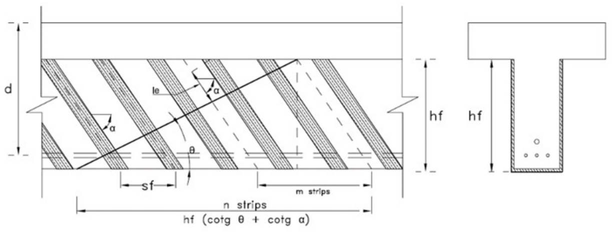


3. ULTIMATE LIMIT STATES

Shear

Configurations





Unstrengthened structure

$$\tau_{Rd,CFRP} = \boxed{\tau_{Rd}} + \tau_{Rd,f} \leq 0.5 \cdot \nu \cdot f_{cd}$$

$$\tau_{Rd,f} = \frac{A_f}{s_f} \cdot \frac{f_{fwd}}{b_w} \cdot (\cot\theta + \cot\alpha_f) \cdot \sin\alpha_f$$

$f_{fwd} = ????$ **FRP does not yield**

W Closed system $f_{fwd} = 0.8 \cdot k_r \cdot f_{fud}$

U Open system

CASE 1 $$f_{fwd} = \frac{2}{3} \cdot \frac{n \cdot s_f}{l_{bf,max,k} \cdot [(\cot\theta + \cot\alpha_f) \cdot \sin\alpha_f]} \cdot f_{bfRd}$$

CASE 2 $$f_{fwd} = \left[1 - \left(1 - \frac{2}{3}\frac{m \cdot s_f}{l_{bf,max,k} \cdot [(\cot\theta + \cot\alpha_f) \cdot \sin\alpha_f]}\right)\frac{m}{n}\right] \cdot f_{bfRd}$$

4. SERVICEABILITY LIMIT STATES

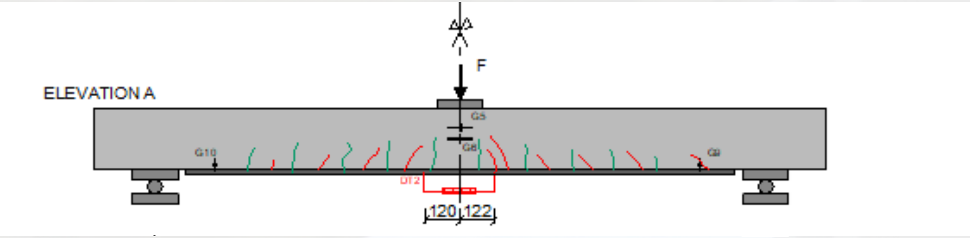
SLS (**control of deflections**) might govern the design of the strengthening system, even the main purpose was the strength increase.

Previous state of stresses and deflections should be considered in the verification of the SLS

$$\sigma_f \leq 0.8 \cdot f_{yk} \cdot \frac{E_f}{E_s}$$

Stress limitations due to compatibility reasons

Cracking:

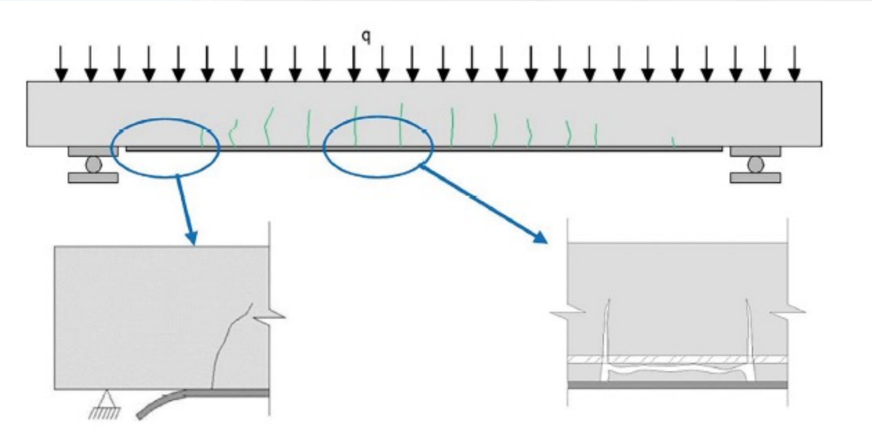


Deflections: Strengthened element should fulfil the deflection limitations given by the main EC2. Limited studies on the long-term behaviours.

6. BOND AND ANCHORAGE OF ADHESIVELY BONDED CFRP SYSTEMS

Anchorage of EBR

Flexural strengthening



End debonding Intermediate crack debonding

End debonding

Effective bonded length $l_{bf,max}$: the minimum length that ensures the transfer of the maximum force or stress between the CFRP laminate and the concrete substrate.

a) Refined method

b) Simplified method

$$l_{bf,max,k} = 1.5\sqrt{\frac{E_f \cdot t_f}{\left(f_{cm} \cdot f_{ctm,surf}\right)^{0.5}}}$$

EBR shall be anchored from the section where the existing structure is able to carry the design load forces without any additional strengthening system

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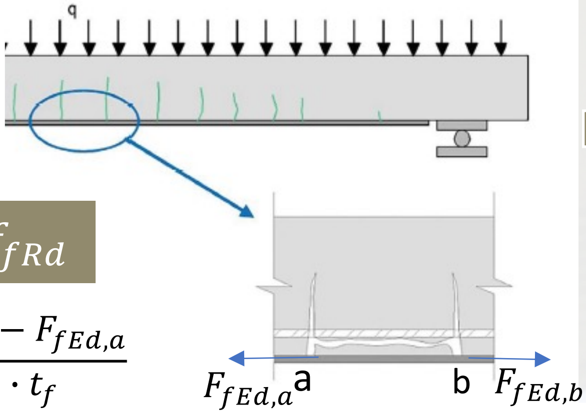
Flexural strengthening



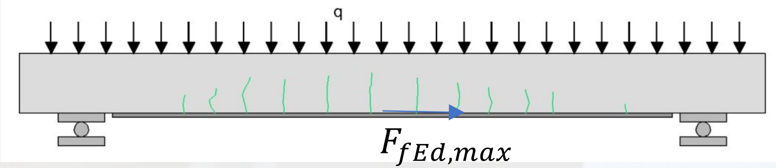
$$\Delta f_{fEd} \leq \Delta f_{fRd}$$

$$\Delta f_{fEd} = \frac{F_{fEd,b} - F_{fEd,a}}{b_f \cdot t_f}$$

$$\Delta f_{fRd} = \frac{1}{\gamma_{BA}} \cdot \left((\eta_{cc} \cdot k_{tc} \cdot k_{tt})^{0.5} \cdot \Delta f_{fk,B} + \Delta f_{fk,F} + \Delta f_{fk,C} \right)$$

Intermediate crack debonding

a) to limit the maximum CFRP strain or stress



b) to limit the increment of the tensile forces for each pair of adjacent cracks

Annex J is based on Finck and Zilch (2012) model included in the German guideline DAfStb (2013)

CONCLUSIONS

Strengthening existing concrete structures with CFRP adhesively bonded systems has been incorporated for the **first time** in **EC2 provisions** in an informative annex (Annex J).

- Design provisions for strengthening existing reinforced or prestressed concrete structures in flexure, shear or confinement with passive EB or NSM CFRP reinforcements are given considering:
  - ✓ CFRP laminates are **linear elastic up** to failure.
  - ✓ **Debonding** is a **premature failure** that should be considered when strengthening in flexure and shear.

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Thank you for your attention

Eva Oller