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Externally bonded FRP reinforcement for RC structures: post strengthening

Book Composite for Construction, L. C. Bank, Chapter 8

Reasons for strengthening

- Deterioration due to ageing
- Crashing of vehicles into bridge components
- Degradation such as corrosion of steel reinforcement
- Poor initial design and/or construction
- Lack of maintenance
- Accidental events such as earthquakes
- Increase in service loads
- Change to the structural system
- Large crack widths
- Large deformations

Advantages of FRP as compared with steel

- Low weight and therefore easier application
- Unlimited availability in FRP sizes
- Very flexible during installation
- High strength (although this strength cannot be exploited in unstressed applications)
- Good fatigue resistance
- Immunity to corrosion

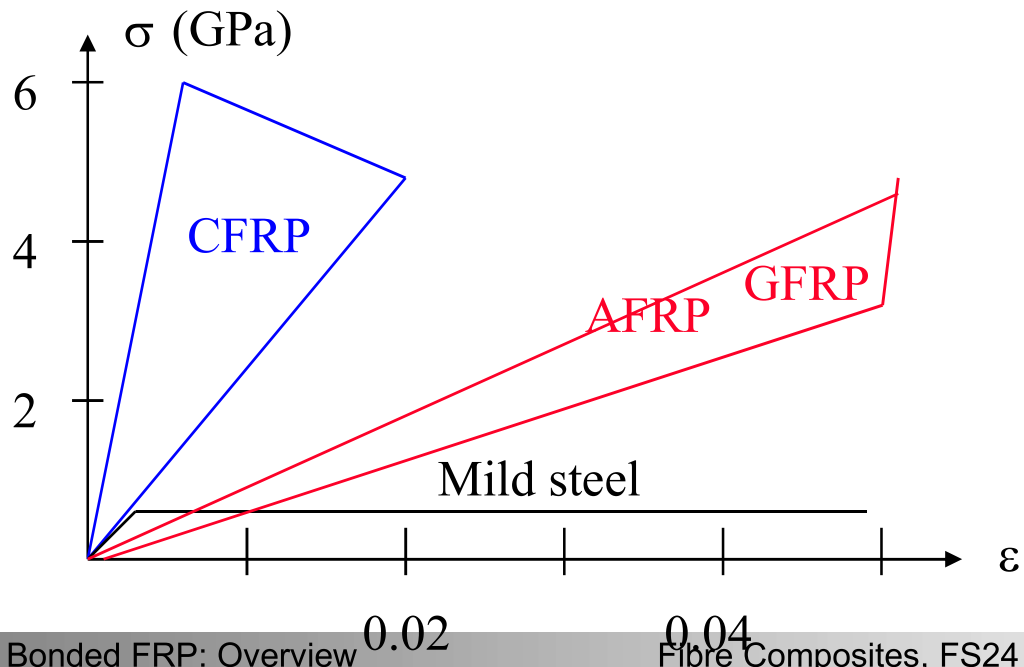
→ Life cycle cost can be competitive to steel

Disadvantages

- Performance under elevated temperatures
- Effect of UV radiation
- Application of FRP and adhesives need qualified personnel
- Adhesives are dangerous for people and environment
- Material behaviour: linear elastic to failure

Strengthening materials are available mainly in following forms:

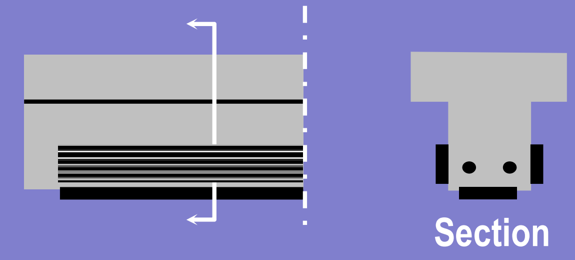
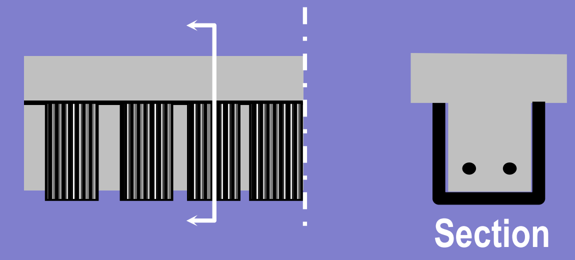
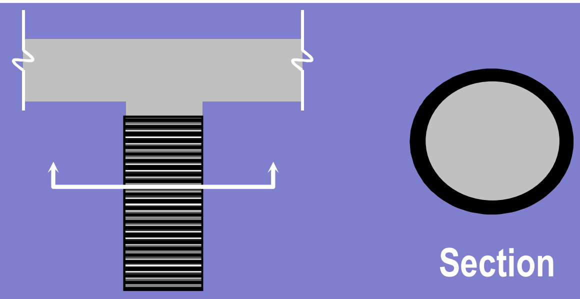
- **UD-Strips (thickness appr. 1 mm) made by pultrusion,**
- **Flexible sheets or fabrics (in one or two directions) and sometimes pre-impregnated with resin.**



FRP Strengthening may replace:

- **Steel plate strengthening,**
- **Concrete cast in-place or shotcrete jackets around existing elements,**
- **Steel jackets.**

FRP-Strengthening Applications

Type	Application	Fibre Dir.	Schematic
Flexural	Tension and/or side face of beam	Along long. axis of beam	
Shear	Side face of beam (u-wrap)	Perpendicular to long. axis of beam	
Confinement	Around column	Circumferential	

Typical FRP applications as strengthening material:

- **Flexural strengthening of slab (strips, sheets),**
- **Flexural strengthening of beam (strips, sheets, fabrics),**
- **Shear strengthening of beam (angles, sheets, fabrics),**
- **Shear strengthening and confinement of column (sheets, fabrics, shells),**
- **Wrapping of concrete tank (sheets, fabrics),**
- **Shear strengthening of beam-column joint (strips, sheets, fabrics).**

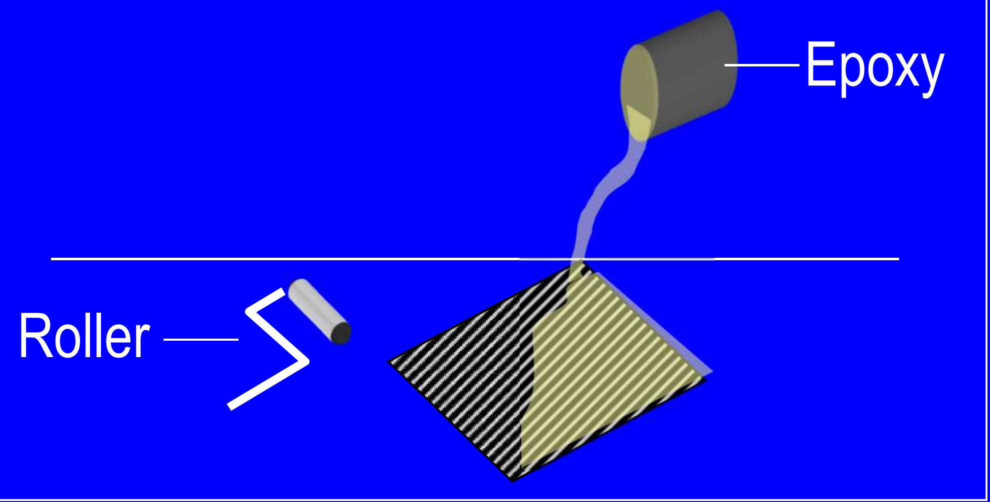
FRP Materials

❶ Wet lay-up

Used with flexible sheets

Saturate sheets with epoxy adhesive

Place on concrete surface



Resin acts as adhesive AND matrix

FRP Materials

Installation Techniques

❷ Pre-cured

Used with rigid, pre-cured strips

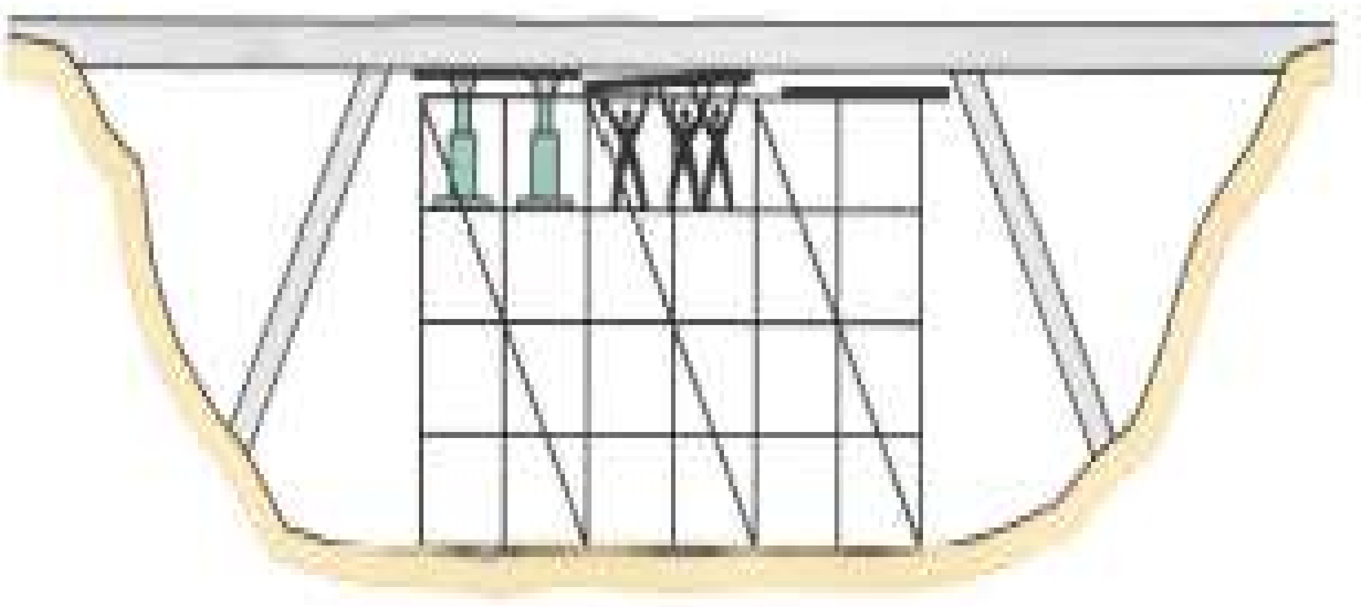
Apply adhesive to strip backing

Place on concrete surface

Not as flexible for variable structural shapes

Resin acts as adhesive

Post Strengthening using Steel Strips

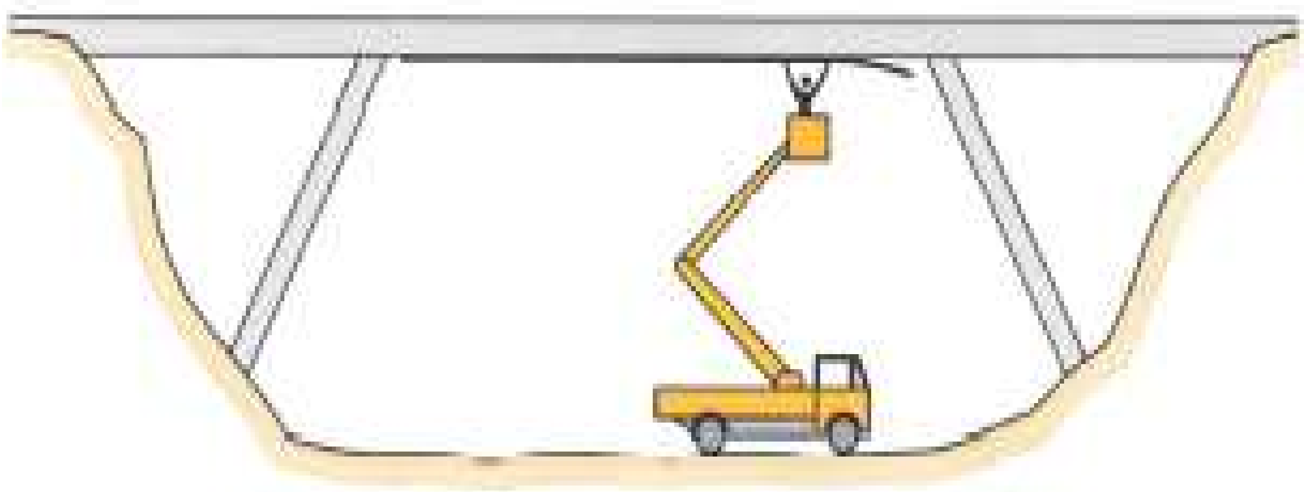


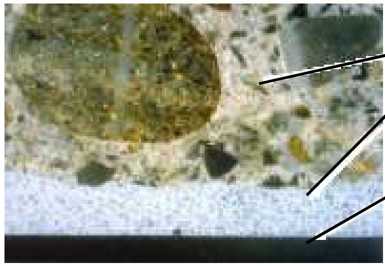
- Heavy
- Corrosion

- Requires scaffold
- Requires many joints

Post Strengthening using CFRP Strips

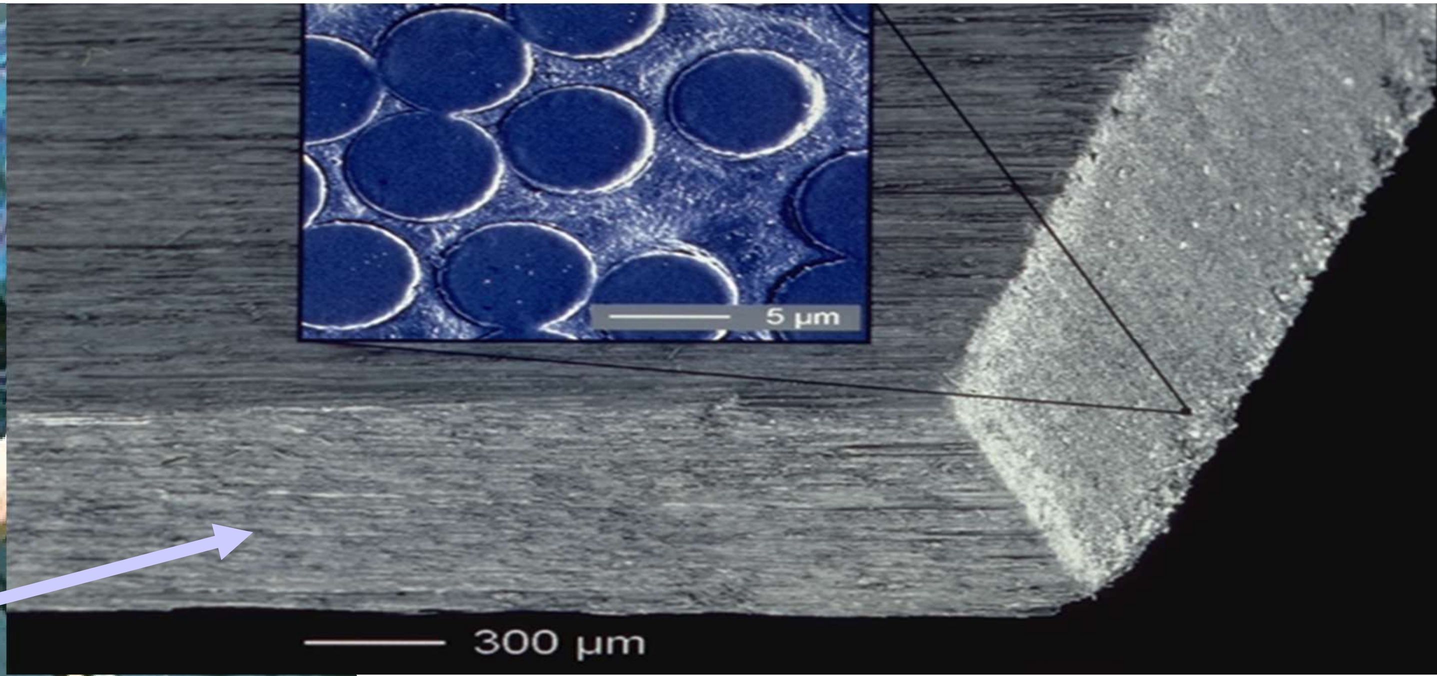
Introduced by Prof. Urs Meier (EMPA Switzerland) in 80's





- **Light weight**
- **Corrosion resistant**

- **No scaffold**
- **No joints**



CFRP Fibers:
65….72 vol%

Strength:
2500….3300 MPa

E-Modul:
150…300 GPa

CFRP Laminates (UD-Strips) for Post-Strengthening

Ibach Bridge, Switzerland 1991

Ibach Beridge, Switzerland 1991

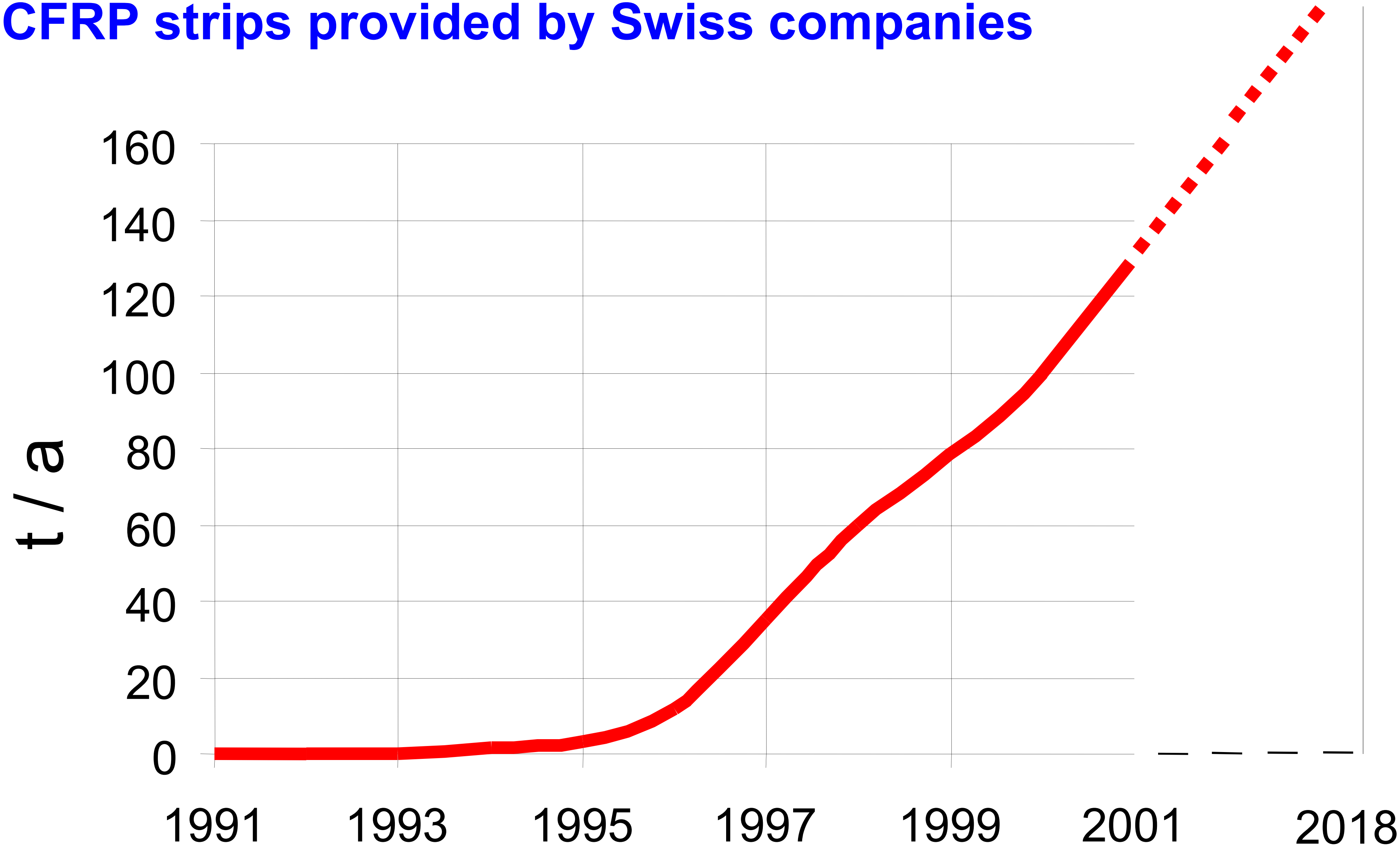
Flexural strengthening of RC structures

Strengthening of a concrete deck using
CFRP strips on the top and underside of the deck

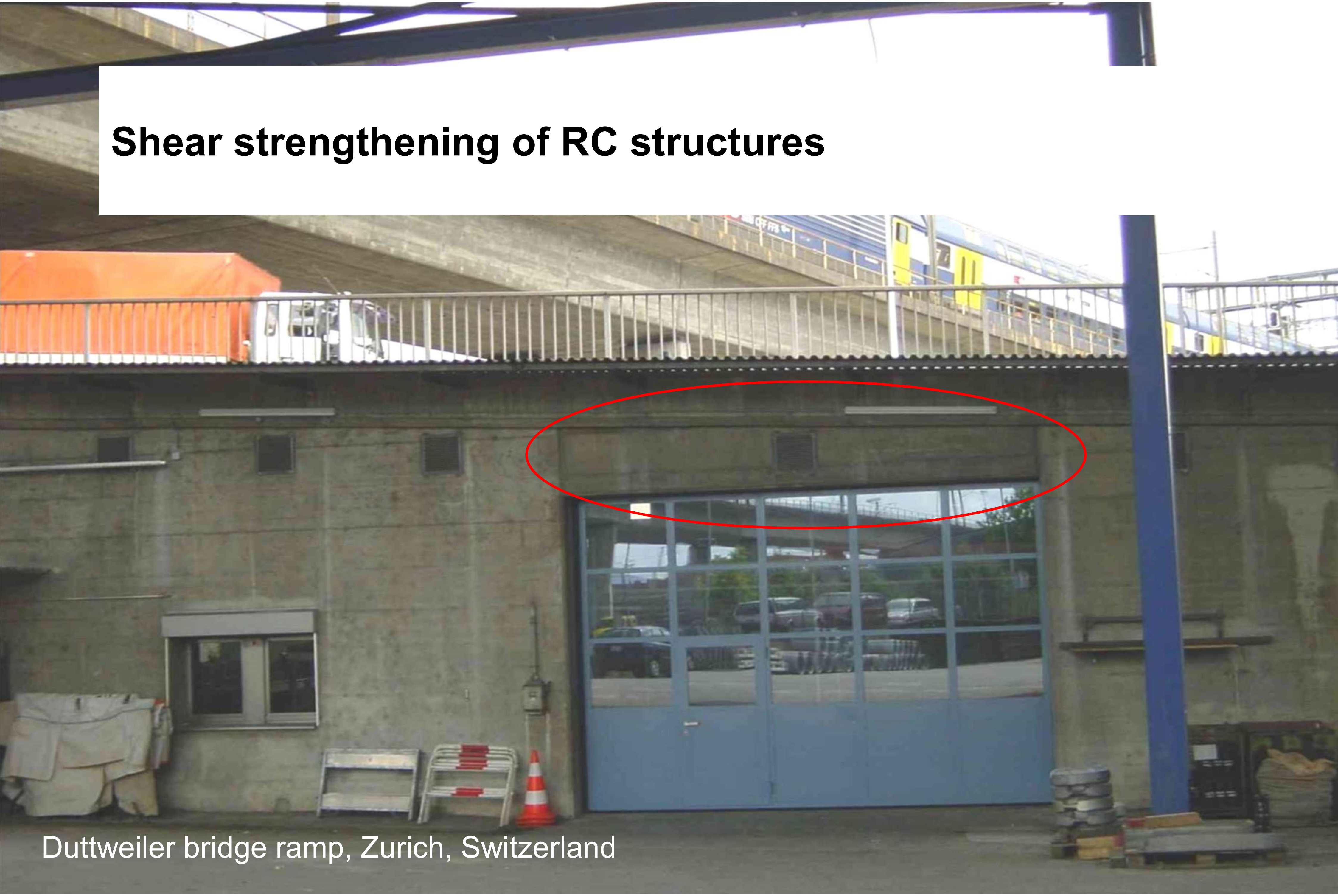
Flexural strengthening using CFRP strips of concrete girders in a Cement manufacturing building in Poland

Daily Job

CFRP strips provided by Swiss companies



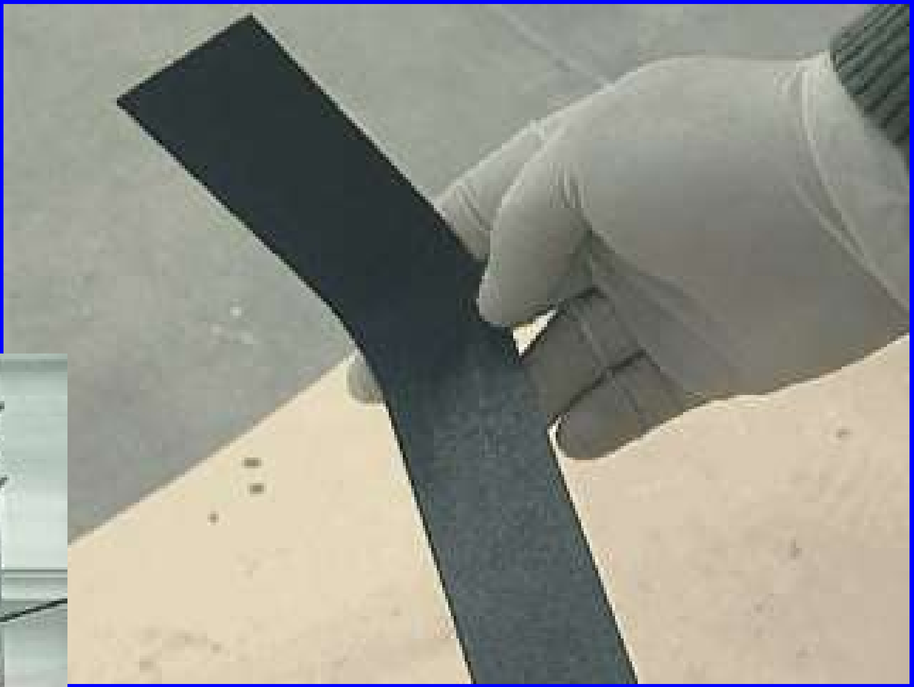
Shear strengthening of RC structures

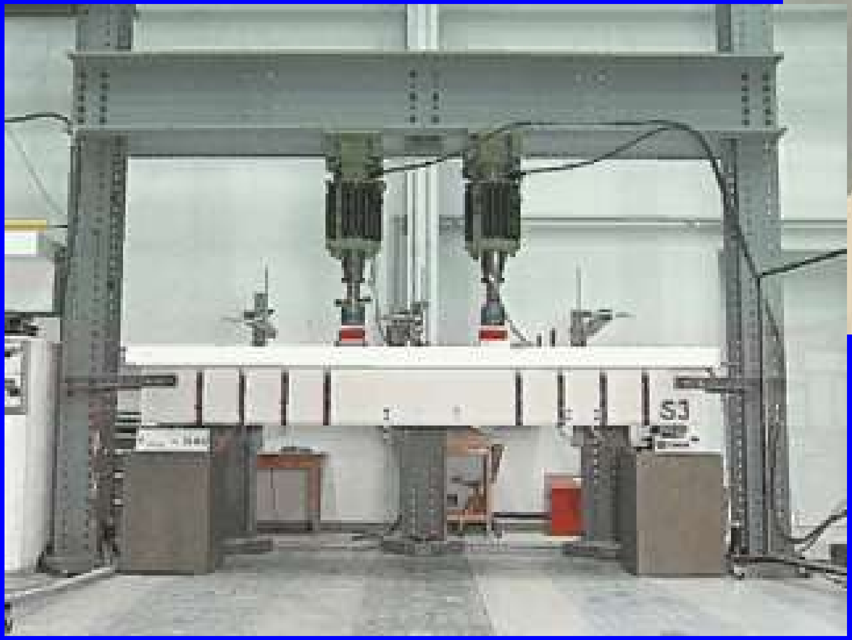


Duttweiler bridge ramp, Zurich, Switzerland

Installation of prefabricated CFRP L-shaped plates (shear strengthening) over existing CFRP strips (flexural strengthening)

Shear Strenghtening of Reinforced Concrete Structures Using CFRP-Laminates





Placing of CFRP fabrics for shear strengthening of DK 81 bridge above railway to Laziska power plant in Poland

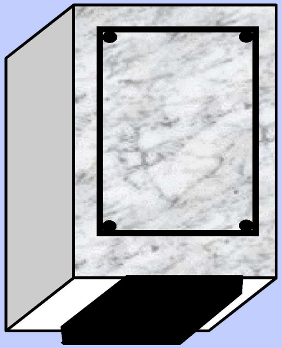
OBJECTIVES

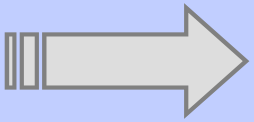
INCREASE EFFICIENCY OF STRENGTHENING BY APPLYING NEAR SURFACE MOUNTED REINFORCEMENT (NSMR)

ε_f = 6÷7‰

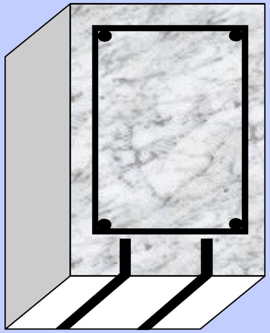
ε_f = ?

EXTERNAL BONDING





NSMR CFRP BONDING



Near Surface Mounting Reinforcement (NSMR)

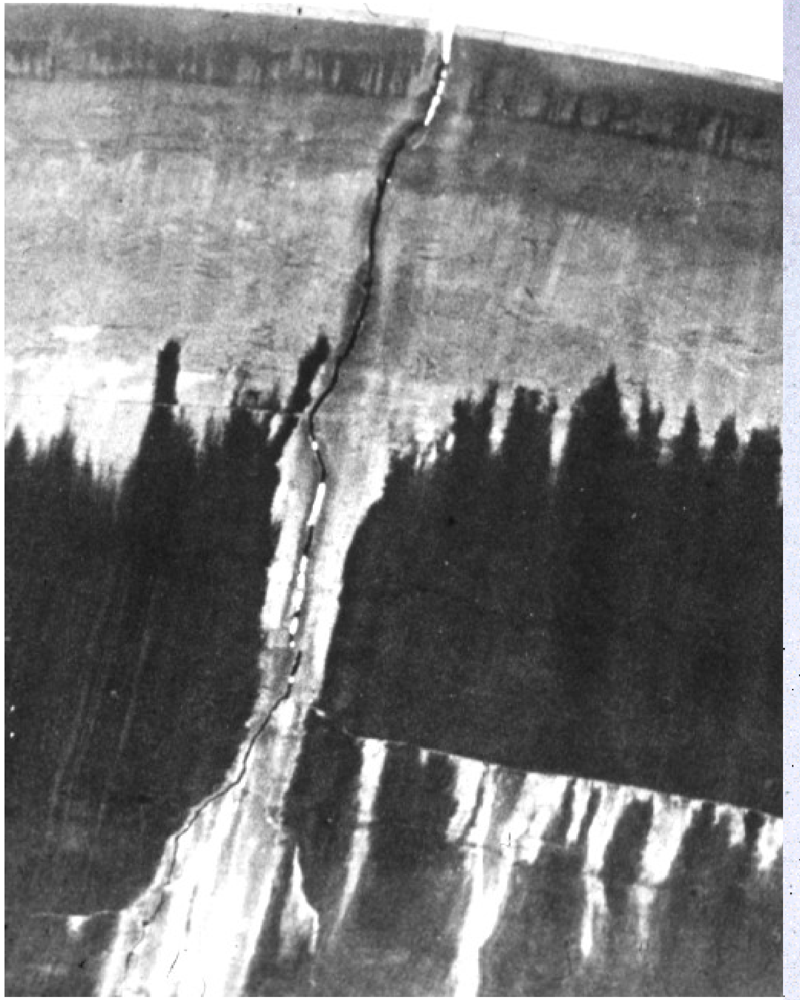
Flexural strengthening of a concrete deck in the region of negative bending moment using Near Surface Mounting Reinforcement (NSMR) technique by cutting a slot in the concrete deck and placing the CFRP into the slots; industry plant, Stuttgart, Germany

Seismic retrofitting

Application of CFRP fabrics to concrete columns for seismic retrofitting of Reggio Emilia football stadium, Italy

Seismic retrofitting of column-beam joints of Aigaleo football stadium in Athens, Greece, using CFRP fabrics with steel anchorages

Cooling Towers



Swiss Code SIA 166 (2004)

fib CEP-FIB, Bulletin 90, Externally applied FRP reinforcement for concrete structures, Technical Report, Task group 5.1, May 2019

ACI 440.2R-02

Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

Reported by ACI Committee 440

Basis of design and safety concept

- Determination of the state of the (repaired) structure prior to strengthening:
  - Field inspection
  - Reviewing existing documents
  - Structural analysis
- Identification of deficiencies and a proper repair concept
- Verification of Ultimate Limit State (ULS)
- Verification of Serviceability Limit State (SLS)

Evaluation of Existing Structures

- Evaluation is important to (e.g. SIA 162/5 “Erhaltung von Betontragwerken”):
  - Determine concrete condition
  - Identify the cause of the deficiency
  - Establish the current load capacity
  - Evaluate the feasibility of FRP strengthening

Evaluation of Existing Structures

- Evaluation should include:
  - All past modifications
  - Actual size of elements
  - Actual material properties
  - Location, size and cause of cracks, spalling
  - Location, extent of corrosion
  - Quantity, location of rebar

Evaluation of Existing Structures

- One of the key aspects of strengthening: → State of concrete substrate
- Concrete must transfer load from the elements to the FRPs through shear in the adhesive
- Surface modification required where surface flaws exist

Basis of design and safety concept

- **Accidental situation such as loss of FRP due to impact, vandalism or fire: assuming unstrengthened member with materials safety factors equal to 1.0 at ULS,**

- **Special design considerations: impact resistance, fire resistance, cyclic loading, extra bond stresses due to the difference in thermal expansion coeff between FRP and concrete,**

Basis of design and safety concept

- **Design should be such that brittle failure modes, such as shear and torsion are excluded.**

- **It should be guaranteed that:**

  the internal steel is sufficiently yielding in ULS , so that the strengthened member will fail in a ductile manner, despite the brittle nature of concrete crushing, FRP rupture or bond failure.

The design strength of the concrete:

$$\alpha . f_{cd} = \frac{\alpha . f_{ck}}{\gamma_c}$$

Where:

f_{ck} : characteristic value of the compressive strength.

α : reduce compressive strength under long term loading (=0.85).

γ_c : partial safety factor (=1.5).

For the steel reinforcement, a bilinear stress-strain relationship is considered:

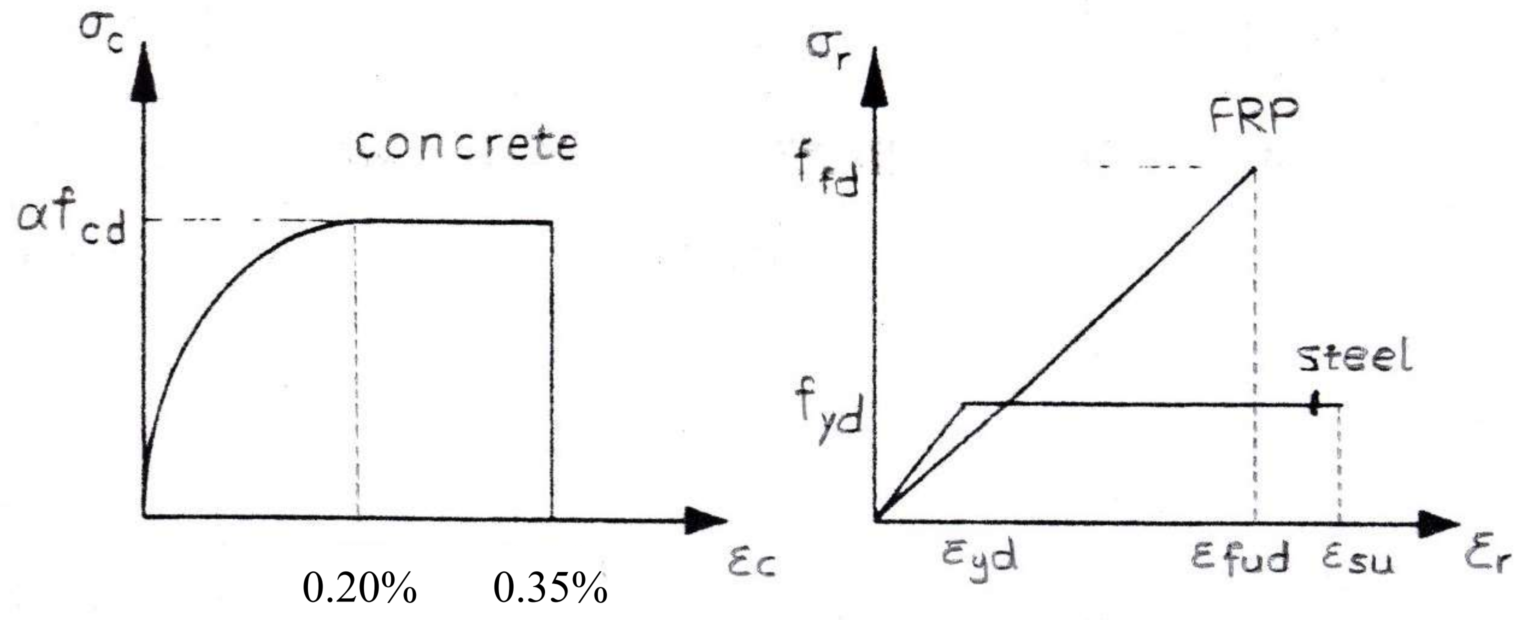
$$f_{yd} = \frac{f_{yk}}{\gamma_s}$$

Where:

f_{yd} : design yield strength.

f_{yk} : characteristic yield strength.

γ_s : material safety factor (=1.15).



Design stress-strain curves of constitutive materials at ULS

"List of Symbols"

<Externally bonded FRP reinforcement for RC structures>

γ_M : Material partial safety factor

σ_f : FRP stress ; ε_f : FRP strain, or (ε_{FRP})

E_{fk} or (E_{FRP}) : characteristic value of the secant modulus of FRP

$\alpha \cdot f_{cd} = \dfrac{\alpha \cdot f_{ck}}{\gamma_c}$
- f_{ck} : characteristic value of the compressive strength
- α : reduction factor for long term loading (= 0.85)
- γ_c : Partial safety factor (= 1.5)
- f_{cd} : design strength of concrete

$f_{yd} = \dfrac{f_{yk}}{\gamma_s}$
- f_{yd} : design yield strength of steel
- f_{yk} : characteristic yield strength
- γ_s : material safety factor (= 1.15)

$f_{fd} = \dfrac{f_{fk}}{\gamma_f}$
- f_{fd} : design FRP failure strength
- f_{fk} : characteristic FRP failure strength
- γ_f : FRP material safety factor (= 1.20 to 1.50)

φ_s ; φ_c , φ_{frp} : resistance factors for steel; concrete, FRP (following Canadian code)

$\gamma_{cb} = 1.5$: material safety factor for the shear strength of the concrete in the case of debonding

$\gamma_a = 1.5$: material safety factor for the shear strength of adhesive in the case of debonding

$\varepsilon_{fu,c}$: FRP strain in the critical section at Ultimate, or (ε_{FRPu})

ε_0 : initial strain prior to strengthening

$\varepsilon_{su,c}$: steel strain in the critical section at Ultimate