Advanced Composites in Engineering Structures

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Lecture VI: Strengthening of existing RC structures with FRP Composites

EPFL

GR MeC
Composite Mechanics Group

Outline

1. Introduction
2. Why do structures need repairing/strengthening?
3. Repairing/strengthening problematic
4. Traditional *vs*. innovative materials / strengthening techniques
5. Advanced strengthening techniques with composite materials

Section 1

Introduction

1. Introduction

❑ Types of structural materials to built structures

- Reinforced concrete
- Masonry
- Steel
- Timber
- Earth
- Glass
- Mixed
- …

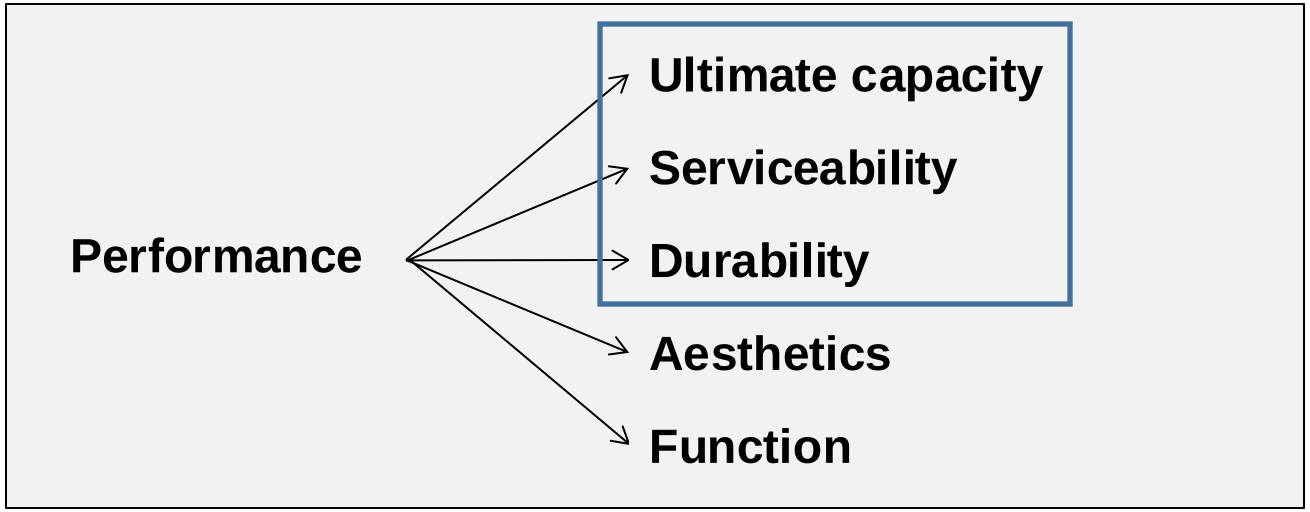
However: Over the time these structures faced different types of ”challenges”!!!

Source:
1. https://portosecreto.co/noite-sao-joao-circulacao-ponte-luis-i/
2. https://www.romapravoce.com/pantheon-de-roma/
3. https://hypebeast.com/2016/8/the-zhangjiajie-glass-bridge-in-china-open
4. https://eartharchitecture.org/?cat=78
5. https://www.youtube.com/watch?v=ELjvjg_41Yw&ab_channel=RodaaRodaNaEuropa
6. https://westernwoodstructures.com/timber-bridges/

1. Introduction

❑ Definitions

- **Maintenance**: to KEEP the structure performance at original level.
- **Repair**: to UPGRADE the structure performance to its original level.
- **Upgrading/Strengthening**: to INCREASE the structure performance.



Section 2

Why do structures need repairing/strengthening?

2. Why do structures need repairing/strengthening?

❑ Three main groups of reasons

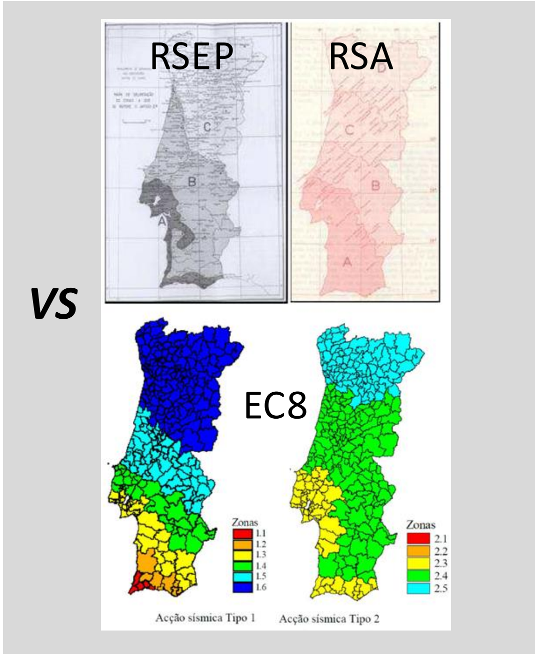
I. To **eliminate structural problems** or **distresses** which result from:

- unusual loading or exposure conditions;
- inadequate design;
- or poor construction practices.

Distresses may be caused by **overloads**, **fire**, **flood**, **foundation settlement**, **deterioration resulting from abrasion**, **fatigue effects**, **chemical attack**, **weathering**, **inadequate maintenance**, etc.

II. To be **conform to current codes** and **standards**.

III. To allow the feasibility of **changing the use** of a structure to accommodate a different use from the present one.



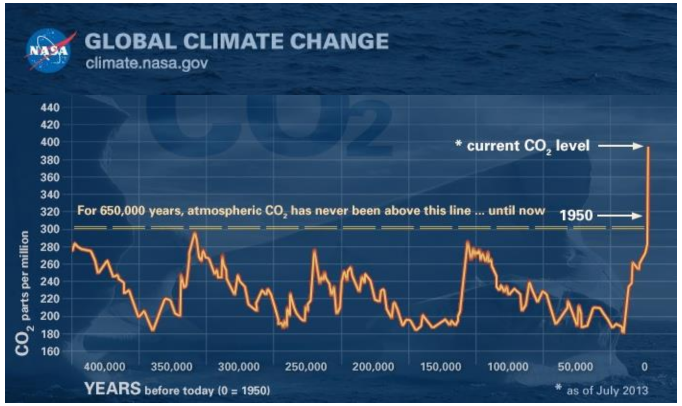
2. Why do structures need repairing/strengthening?

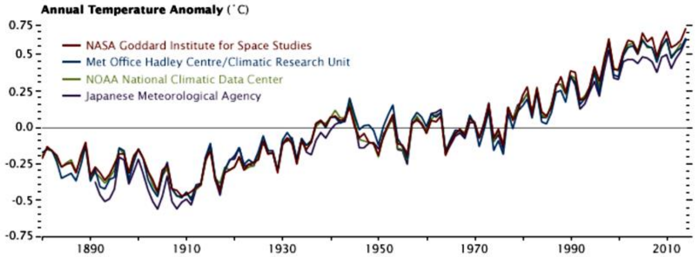
❑ Increased need of rehabilitation

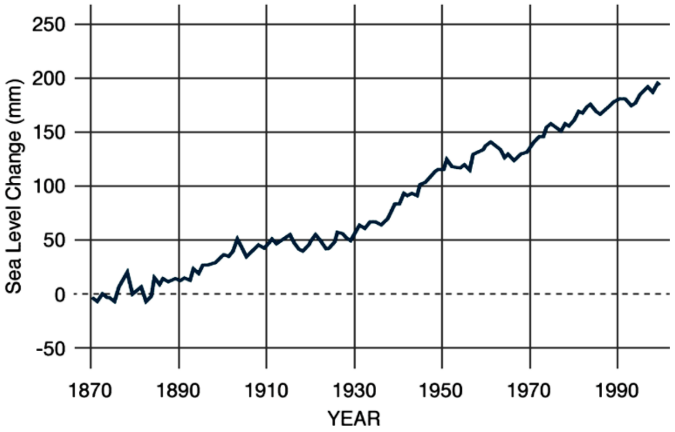
Increase in atmospheric CO_2 levels
- Increased Carbonation
- Increased Corrosion Rates

Increase in temperature by over 5 ˚C
- Increased Shrinkage
- Porous Microstructure and High Permeability
- Increased Corrosion Rates

Increased Water Levels
- Increased Saturation
- Greater Scour







2. Why do structures need repairing/strengthening?

❑ Increased need of rehabilitation

China, US and India

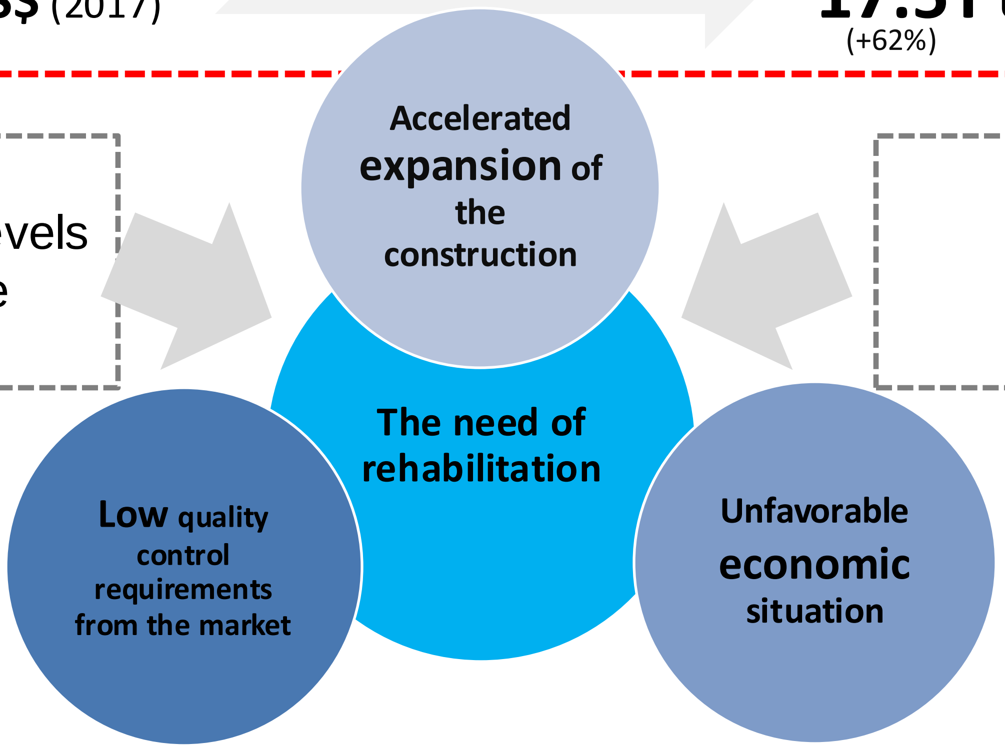
(57% of this investment)

Trends in the Construction Industry

10.8T US$** (2017) → GLOBAL INVESTMENT → **17.5T US$ (2030) (+62%)

Climatic changes:
Increase in atmospheric CO_2 levels
Increase in the temperature
Increase water levels

New policies/actions:
Green deal
Circular economy
Low-carbon economy



2. Why do structures need repairing/strengthening?

❑ Increased need of rehabilitation

In **2019**, total investment in construction in the EU27 amounted to €1,324 billion, which represented 9.5% of GDP. **The investments in rehabilitation and maintenance activities represented 28%** (€371 billion) of this total investment.

Source: European Construction Industry Federation

Based on the analysis of the U.S. Department of Transportation's **2019** National Bridge Inventory (NBI) database, nearly 231,000 U.S. bridges need major repair work or should be replaced (**46,000 are "structurally deficient" and in poor condition**). That figure represents 37% of all U.S. bridges. More than 46,000 of those bridges are "structurally deficient" and in poor condition. The ARTBA estimates a cost nearly $164 billion.

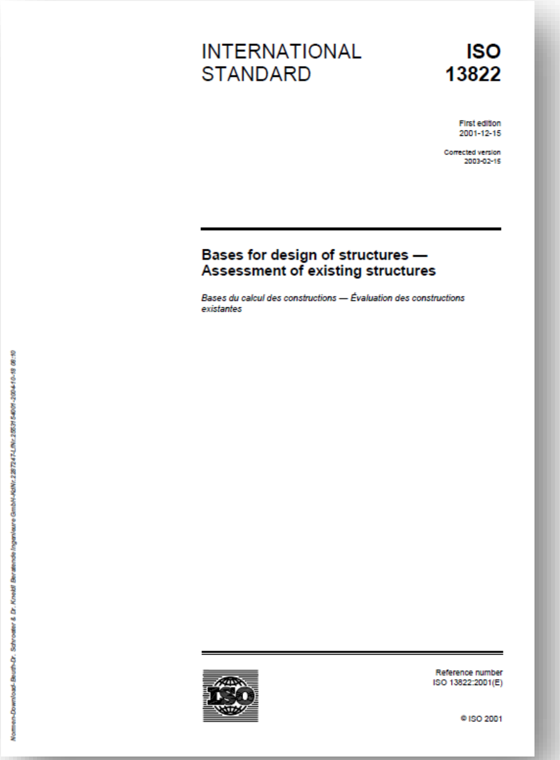
Source: American Road & Transportation Builders Association (ARTBA)

Section 3

Repairing/strengthening problematic

3. Repairing/strengthening problematic

❑ Assessment of existing structures



INTERNATIONAL STANDARD | ISO 13822

First edition 2001-12-15

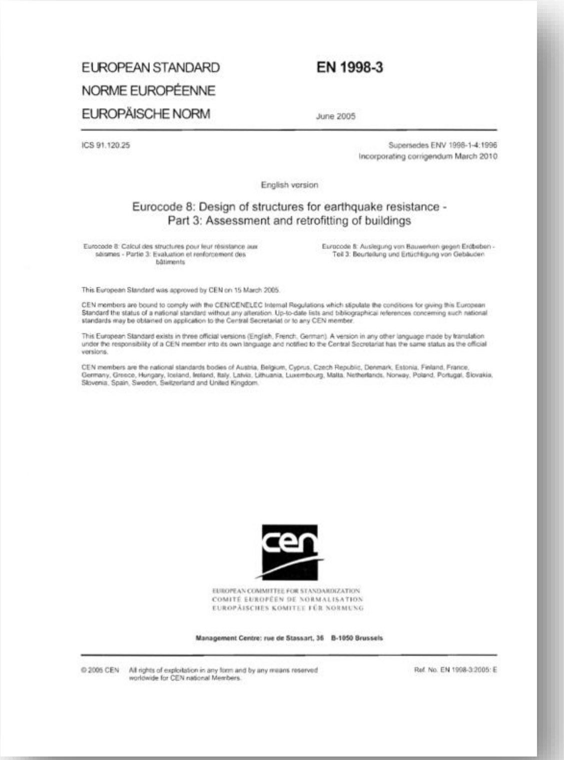
Corrected version 2003-02-15

Bases for design of structures — Assessment of existing structures

Bases du calcul des constructions — Évaluation des constructions existantes

Reference number ISO 13822:2001(E)

ISO 13822:2010



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1998-3

June 2005

ICS 91.120.25

Supersedes ENV 1998-1-4:1996
Incorporating corrigendum March 2010

English version

Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings

Eurocode 8: Calcul des structures pour leur résistance aux séismes - Partie 3: Evaluation et renforcement des bâtiments

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben - Teil 3: Beurteilung und Ertüchtigung von Gebäuden

This European Standard was approved by CEN on 15 March 2005.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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COMITÉ EUROPÉEN DE NORMALISATION
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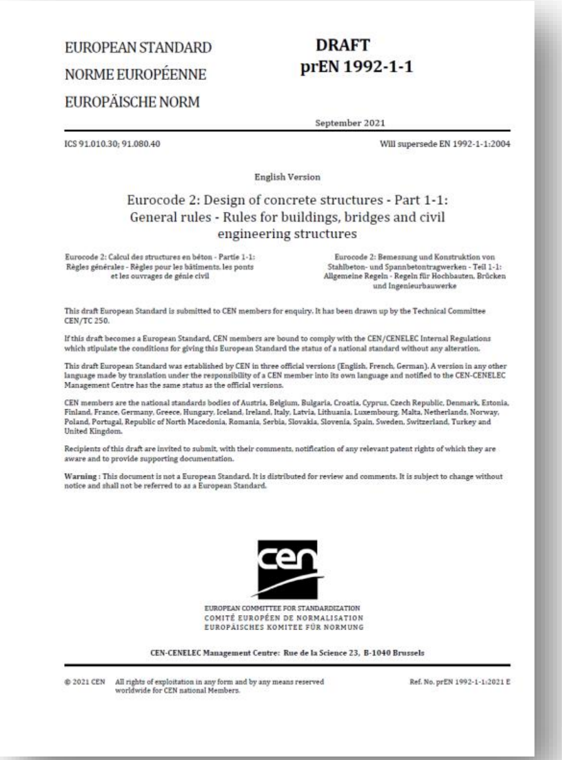
Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 1998-3:2005: E

EN 1998-3: 2005



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

DRAFT
prEN 1992-1-1

September 2021

ICS 91.010.30; 91.080.40

Will supersede EN 1992-1-1:2004

English Version

Eurocode 2: Design of concrete structures - Part 1-1: General rules - Rules for buildings, bridges and civil engineering structures

Eurocode 2: Calcul des structures en béton - Partie 1-1: Règles générales - Règles pour les bâtiments, les ponts et les ouvrages de génie civil

Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken - Teil 1-1: Allgemeine Regeln - Regeln für Hochbauten, Brücken und Ingenieurbauwerke

This draft European Standard is submitted to CEN members for enquiry. It has been drawn up by the Technical Committee CEN/TC 250.

If this draft becomes a European Standard, CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

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Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

Warning : This document is not a European Standard. It is distributed for review and comments. It is subject to change without notice and shall not be referred to as a European Standard.

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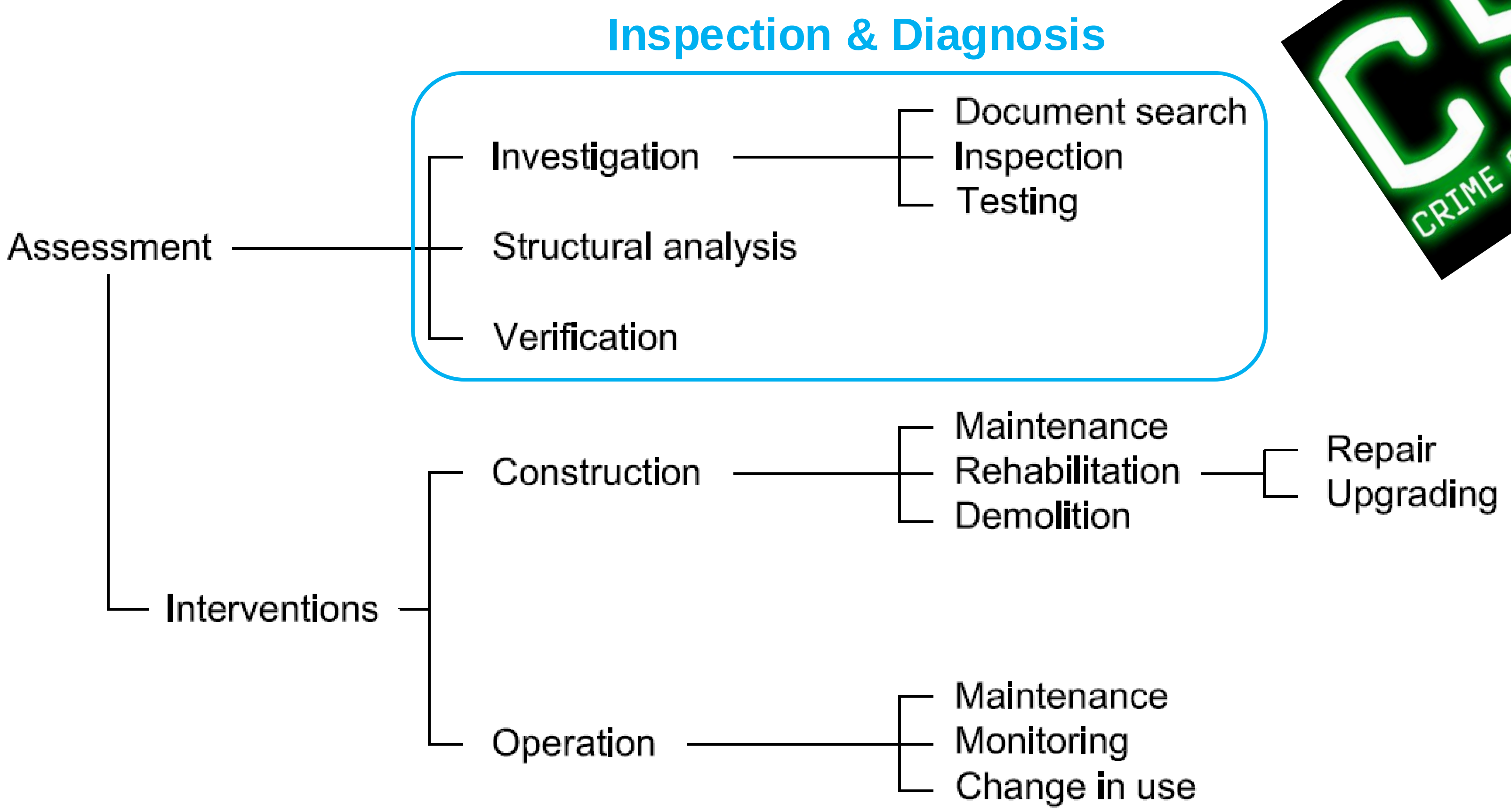
CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

Ref. No. prEN 1992-1-1:2021 E

prEN 1992-1-1

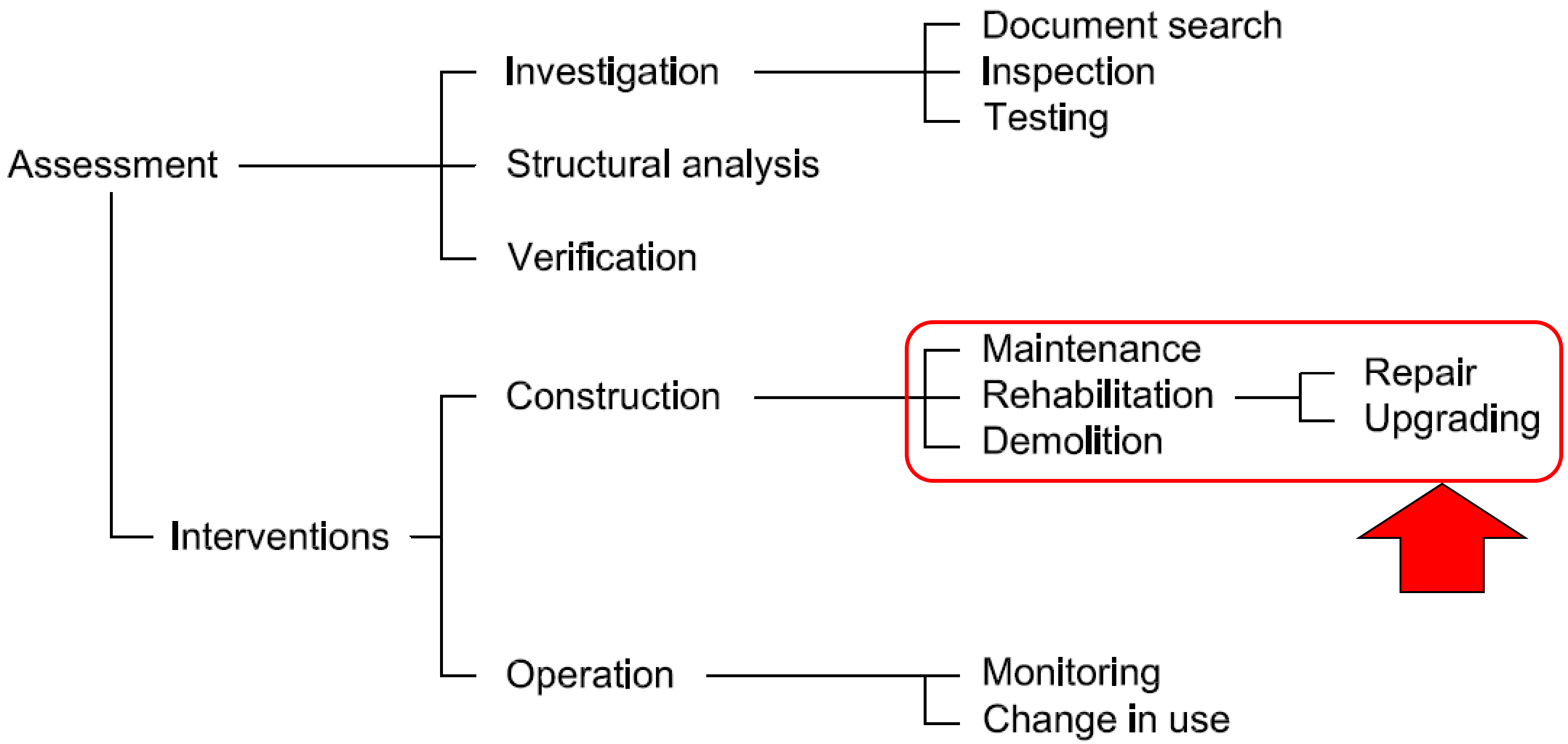
3. Repairing/strengthening problematic

- ❑ **Assessment of existing structures - Protocol**



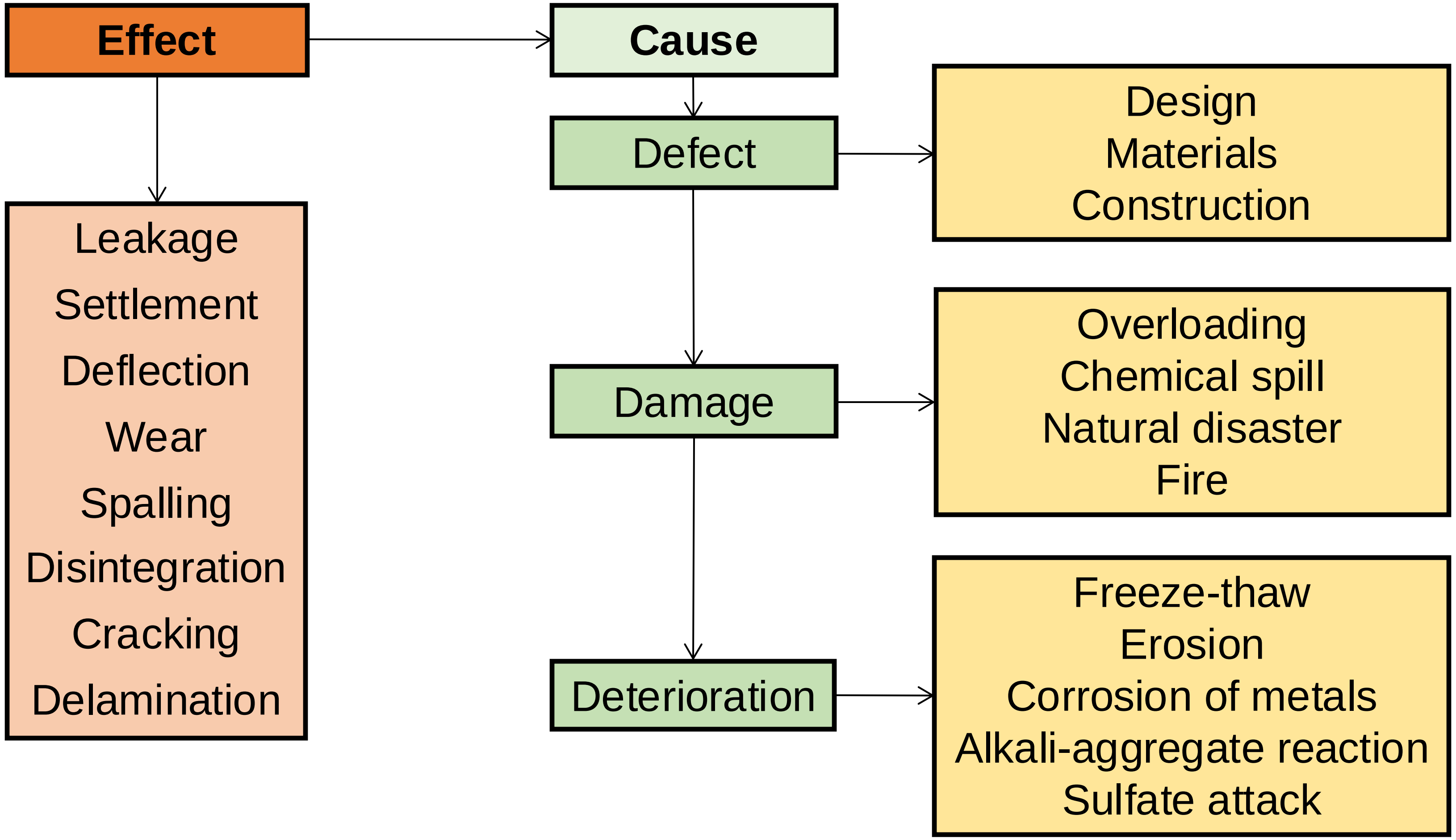
3. Repairing/strengthening problematic

❑ Intervention - Construction



3. Repairing/strengthening problematic

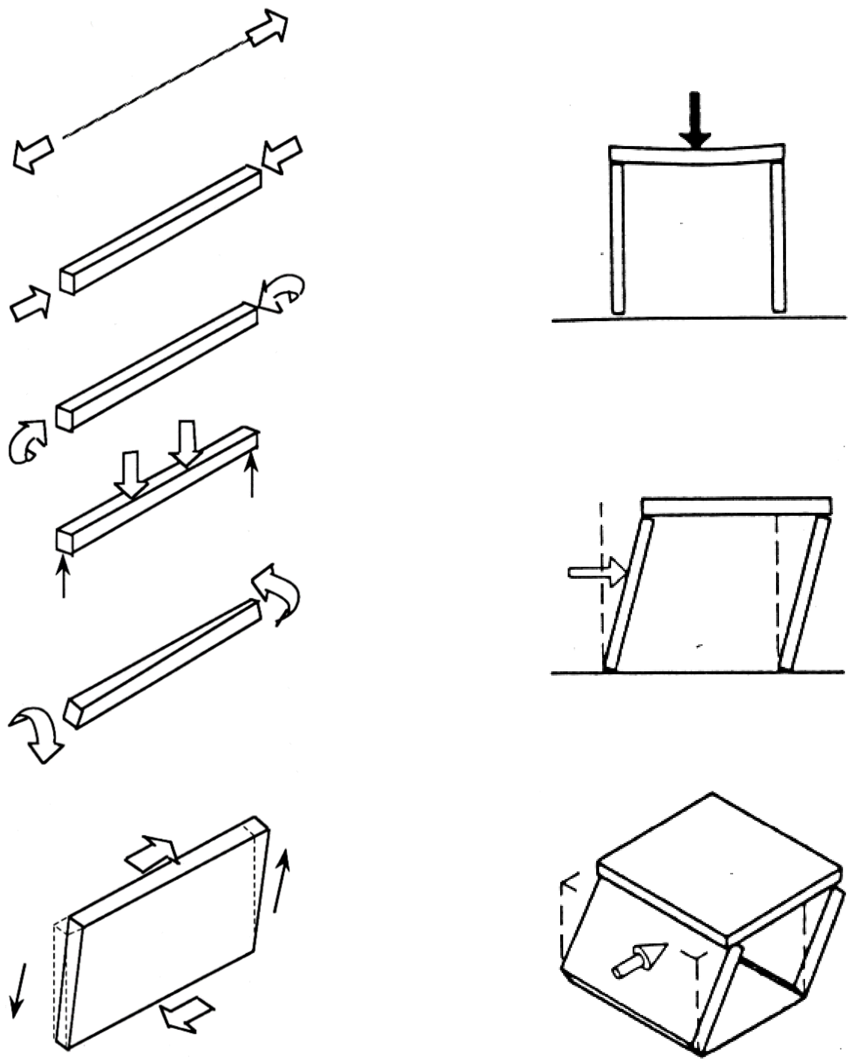
❑ Effects *vs.* causes



3. Repairing/strengthening problematic

❑ Targets

- Tensile capacity
- Compressive capacity
- Flexural capacity
- Torsional capacity
- Shear capacity
- Member stability (buckling)
- Ductility
- Stiffness



3. Repairing/strengthening problematic

❑ Repairing *vs*. strengthening

REPAIRING (causes):

- **Defects**
- **Deterioration**
- **Damage**

STRENGTHENING (causes):

- **Change in use**
- **Construction and/or design defects**
- **Code changes**
- **Seismic action**

3. Repairing/strengthening problematic

❑ Strategies

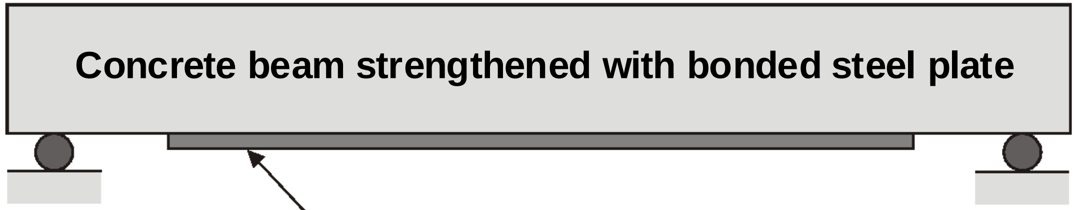
- **Passive** or **active** design?
- Using the **existing** structural elements or **addition of new** ones?
- **Total** (strength, stiffness, stability and ductility) or **selective**?

3. Repairing/strengthening problematic

❑ Passive *vs*. active techniques

Depends on how loads act on the additional components used to strengthen or stabilize the structure

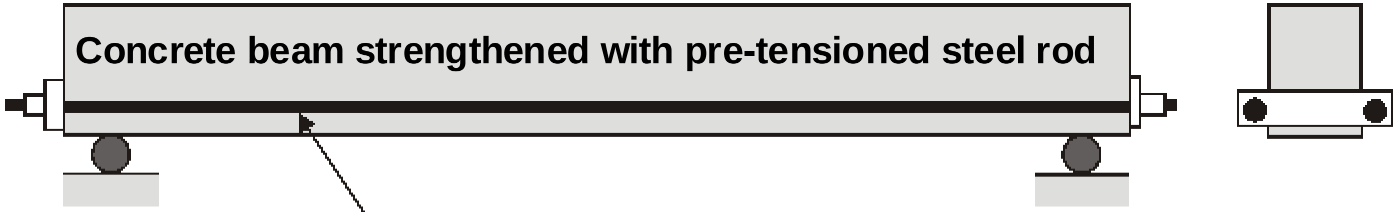
Passive



The steel plate is stress free until live loads are introduced. As the beam deflects, the steel plate will begin to share the tension loads.

Additional loads are required to engage the strengthening system

Active



Stressed tendon immediately allows the beam to carry loads

Immediate stress reduction and engagement of system

3. Repairing/strengthening problematic

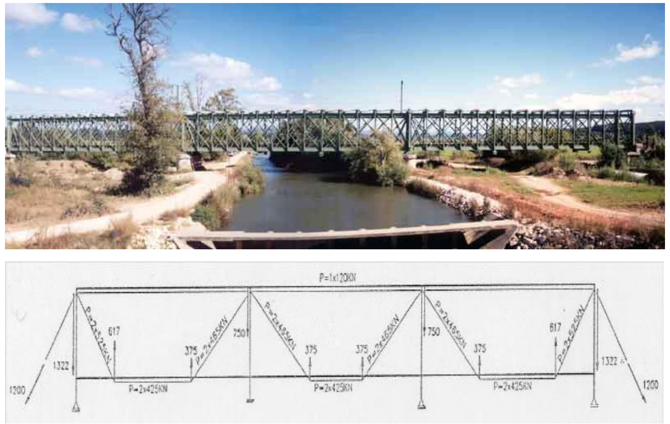
❑ Passive *vs*. active techniques

- **Active systems** require either **prestressing** the repaired elements or temporarily **removing loads** from the existent elements, or a combination of both.
- **Passive systems** are suitable when live load changes are anticipated (e.g. upgrading a bridge to sustain heavier loads may require only a passive system).

Luiz I bridge – Oporto city

GRID 1997/1998

• Replacement of the upper deck platform by a metallic railway platform
• **Strengthening** of the upper deck girders
• **Strengthening** of structural elements of the arch and metallic piers



Bridge over the Soure river

A2P 2005

• **External prestressing**
• Strengthening of the footings using micro-piles

3. Repairing/strengthening problematic

❑ Using the existing structural elements or addition of new ones

- RC walls
- Seismic bracing systems
- Buckling restrained braces
- **Dampers**
- …

London Millennium Footbridge

Type: Suspension bridge

Total length: 325 m

Width: 4 m

Engineering design: Arup

Architect: Norman Foster

Opened: 2000, Jun-10

Source: https://en.wikipedia.org/wiki/Millennium_Bridge,_London

3. Repairing/strengthening problematic

❑ Using the existing structural elements or addition of new ones

- RC walls
- Seismic bracing systems
- Buckling restrained braces
- **Dampers**
- …

London Millennium Footbridge

- Resonance problems
- The natural sway motion of people walking caused sideways oscillations in the bridge
- The vibrational modes **had not been anticipated by the designers**

Source:
https://en.wikipedia.org/wiki/Millennium_Bridge,_London

Video:
https://www.youtube.com/watch?v=eAXVa__XWZ8&ab_channel=mdepablo

3. Repairing/strengthening problematic

❑ Using the existing structural elements or addition of new ones

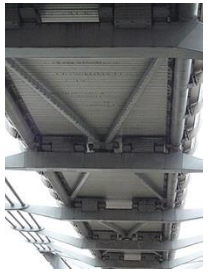
- RC walls
- Seismic bracing systems
- Buckling restrained braces
- **Dampers**
- …

London Millennium Footbridge

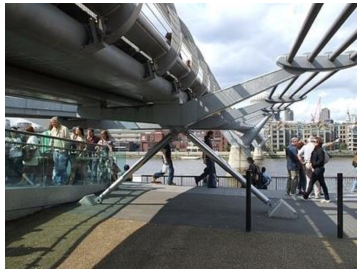
Mitigation

- Making the bridge stiffer (to move its resonant frequency out of the excitation range) was not feasible as it would greatly change its appearance.
- The resonance was controlled by retrofitting **37 viscous fluid dampers** to dissipate energy: 17 chevron dampers + 4 vertical to ground dampers + 16 pier damper
- **52 tuned mass dampers**

Chevron dampers



Vertical to ground dampers



Pier dampers

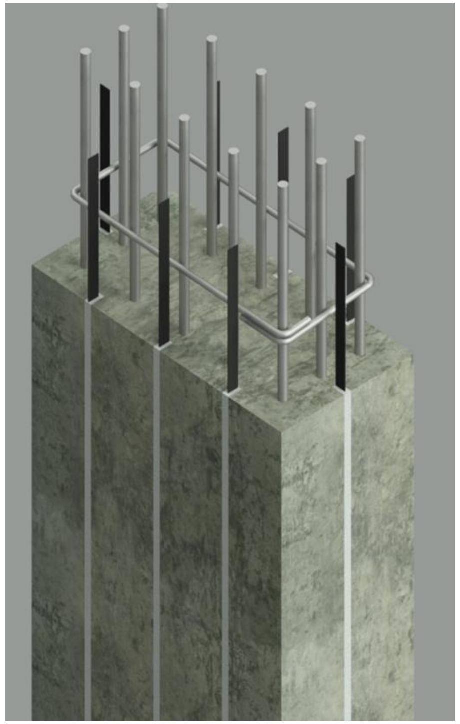
Moving end of pier damper

Tuned mass damper

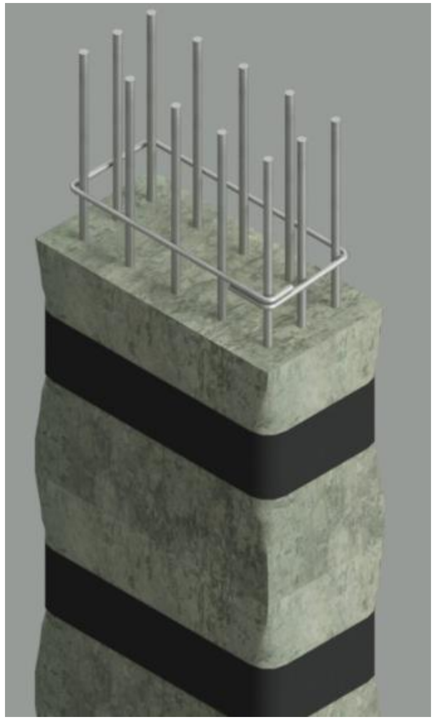
Source: https://en.wikipedia.org/wiki/Millennium_Bridge,_London

3. Repairing/strengthening problematic

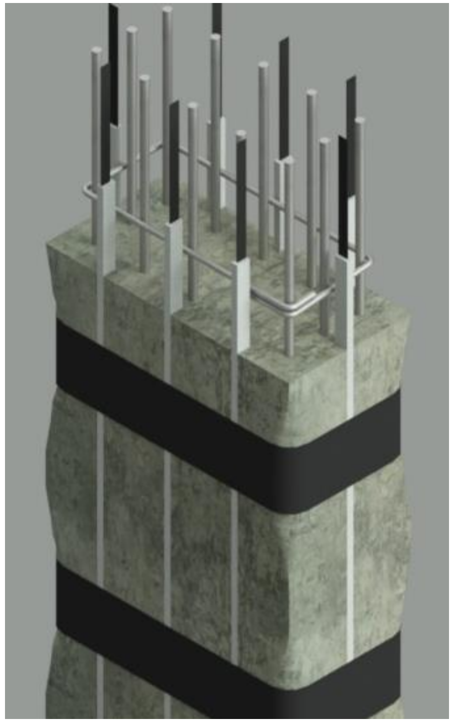
- Total *vs*. selective technique



Flexural strengthening



Shear + ductility strengthening



Flexural + shear + ductility strengthening

Section 4

Traditional *vs*. innovative materials / strengthening techniques

4. Traditional *vs*. innovative materials / strengthening techniques

- **Traditional techniques**
  - **Enlargements with concrete (total or partial)**
  - **Composite solutions (e.g. adding steel plates)**
  - **External prestressing**
  - **Span shortening**

- **Innovative techniques**
  - **Enlargements with new cementitious materials**
  - **Composite solutions with FRP**
  - **External prestressing with FRP**

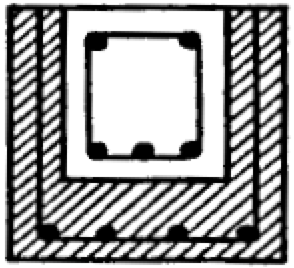
4. Traditional *vs*. innovative materials / strengthening techniques

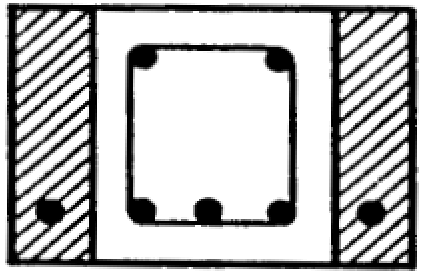
- **Traditional techniques: ADVANTAGES**
  - Use of materials **well-known**
  - In general, **qualified workers are not required!**
  - **Simple techniques and well-known**
  - In many cases the **existing codes can be used**
  - **Reduced initial cost**

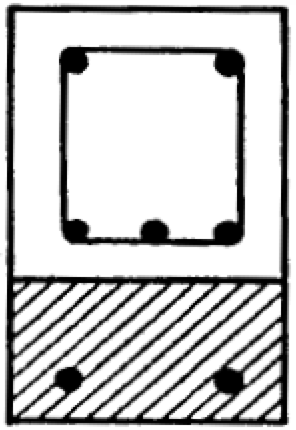
- **Traditional techniques: DISADVANTAGES**
  - **Very intrusive** with effective reduction of useful spaces
  - **Large amount of labor**
  - **Complicated logistics** during the strengthening phase
  - **Limited durability**

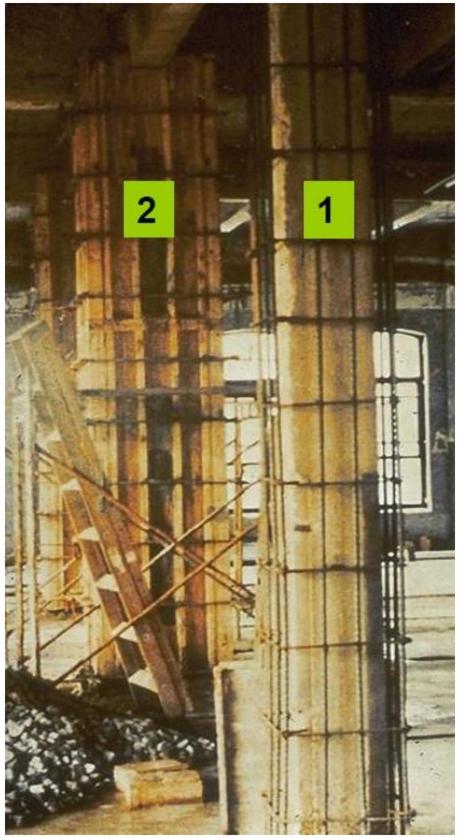
4. Traditional *vs*. innovative materials / strengthening techniques

- **Traditional techniques – Enlargements**



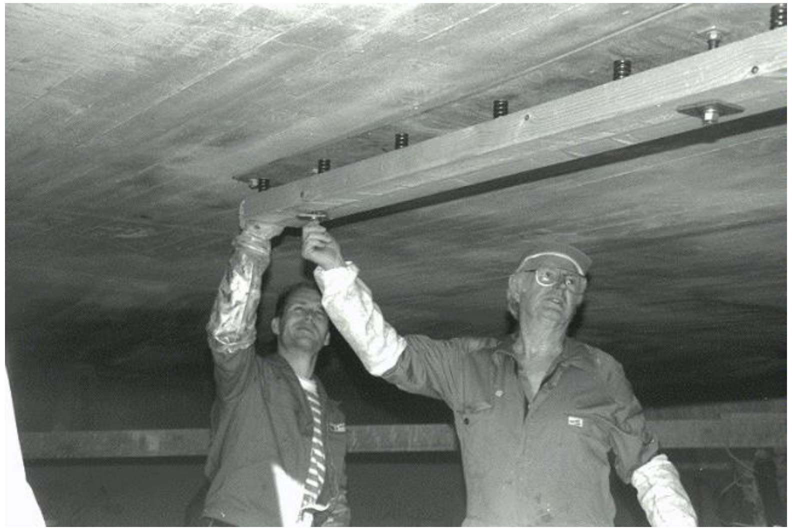






4. Traditional *vs*. innovative materials / strengthening techniques

- **Traditional techniques – Composites**

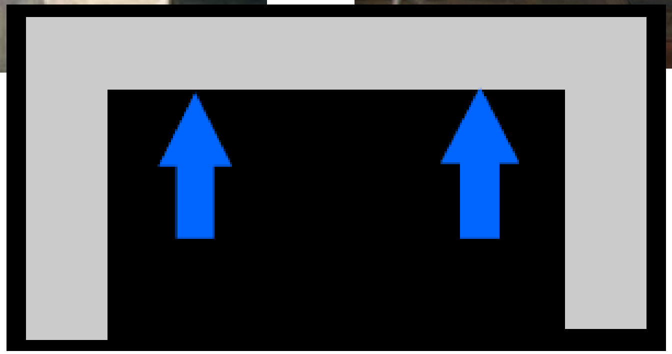


4. Traditional *vs*. innovative materials / strengthening techniques

- **Traditional techniques – Post-tensioning**

4. Traditional *vs*. innovative materials / strengthening techniques

- Traditional techniques – Span shortening



4. Traditional *vs.* innovative materials / strengthening techniques

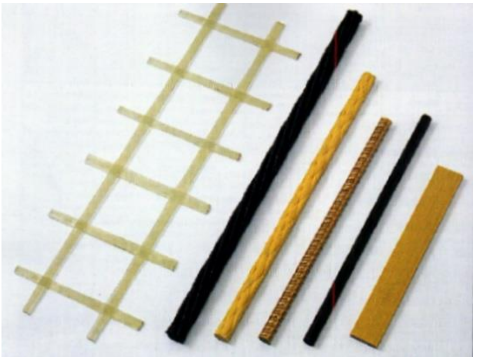
- **FRP composites**

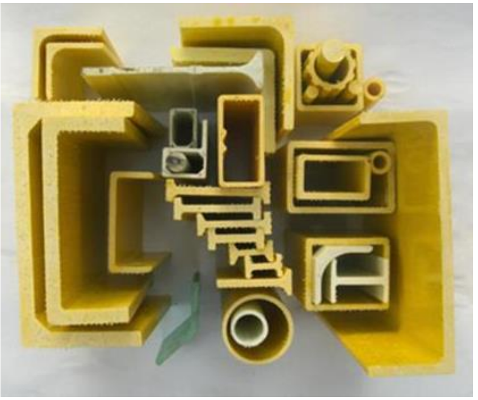
Fiber Reinforced Polymer (FRP)

- **Carbon (C)** → **CFRP**
- **Glass (G)** → **GFRP**
- **Aramid (A)** → **AFRP**
- **Basalt (B)** → **BFRP**

Sheet/Fabrics
- Uni-directional
- Multi-directional
- Dry sheet
- Pre-pregnated
- Strands

Bars
- Plate
- Rod
- Grid
- “Any” section





4. Traditional *vs*. innovative materials / strengthening techniques

- **Innovative techniques**

Shear strengthening

Flexural strengthening

Confinement

Confinement/Punching

Courtesy of S&P Company

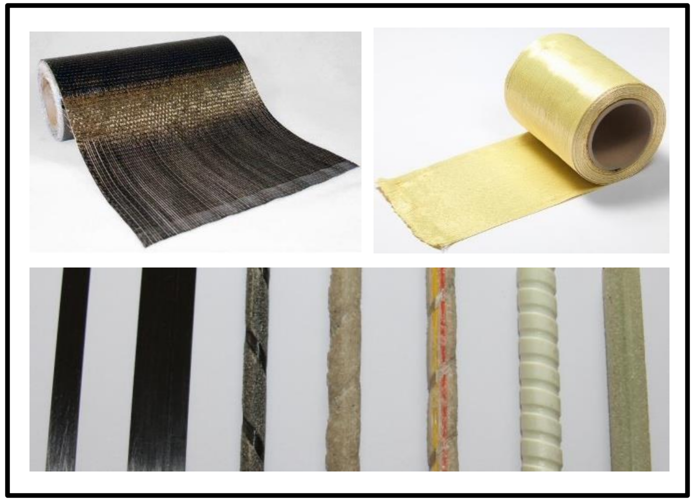
4. Traditional *vs.* innovative materials / strengthening techniques

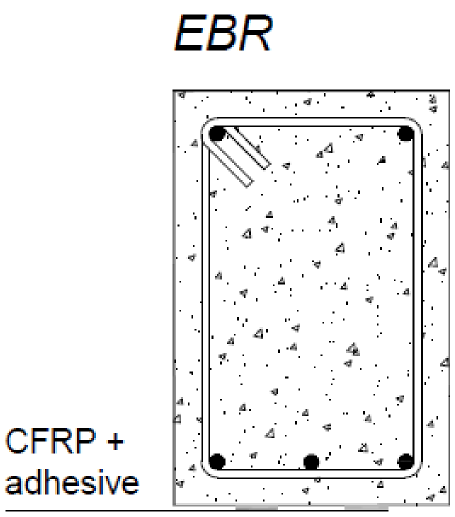
❑ Innovative techniques

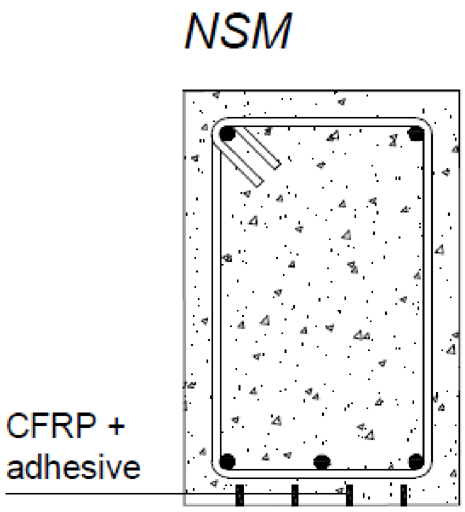
- EBR (***E**xternally **B**onded **R**einforcement*)
- NSM (***N**ear **S**urface **M**ounted*)

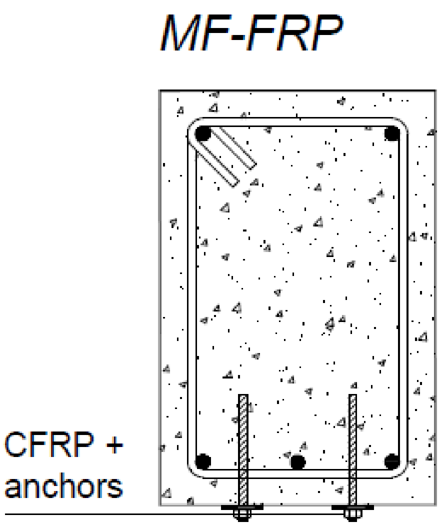
Active or passive systems

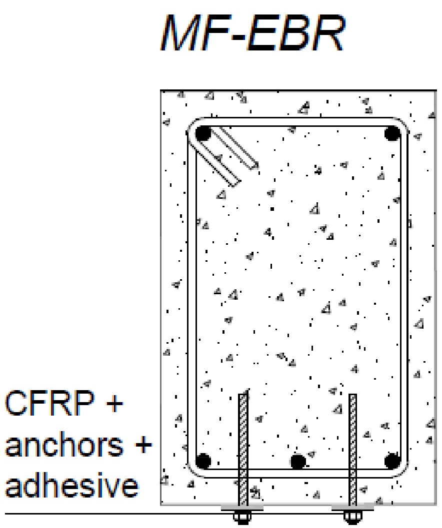
- MF-FRP (***M**echanically **F**astened **FRP***)
- MF-EBR (***M**echanically **F**astened and **E**xternally **B**onded **R**einforcement*)





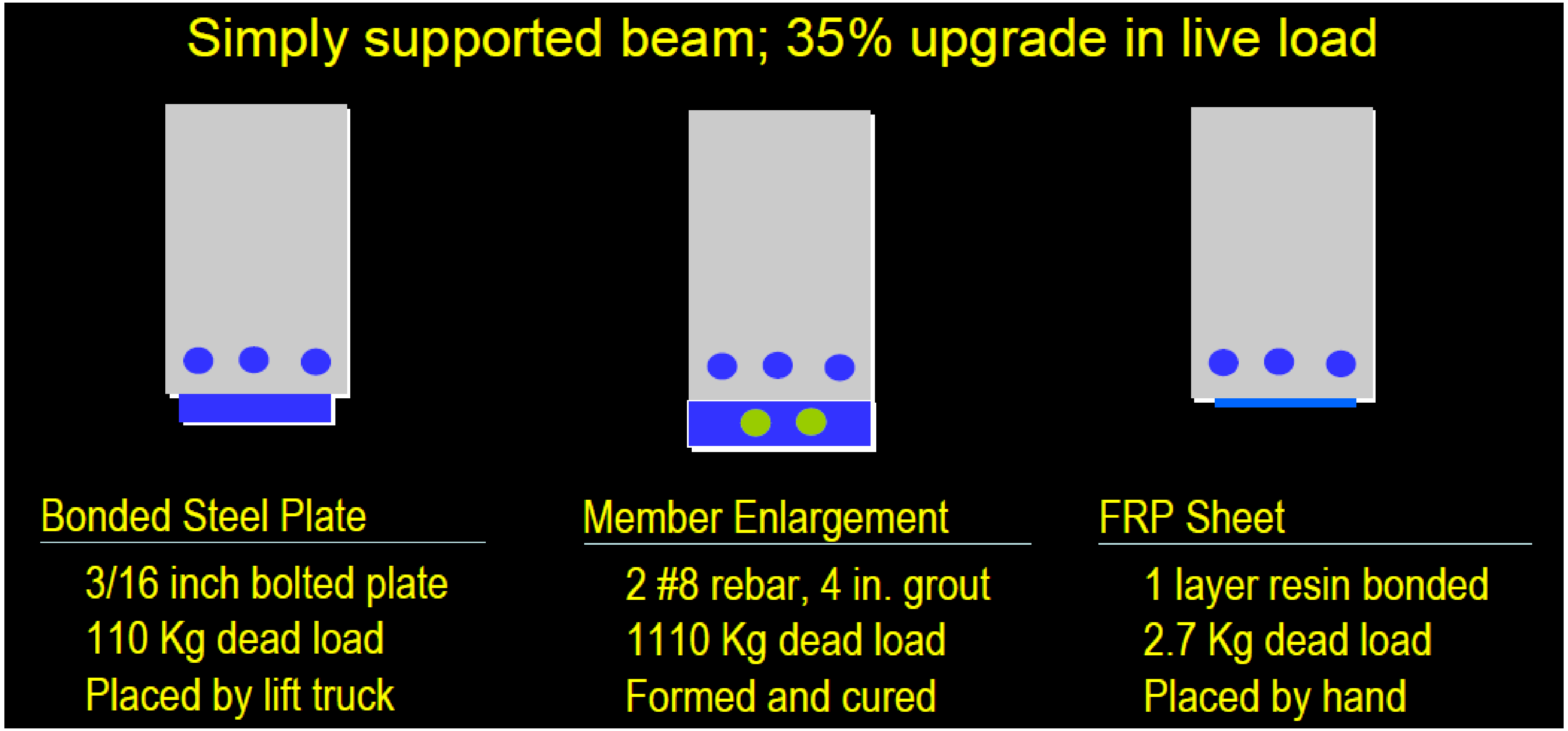






4. Traditional *vs*. innovative materials / strengthening techniques

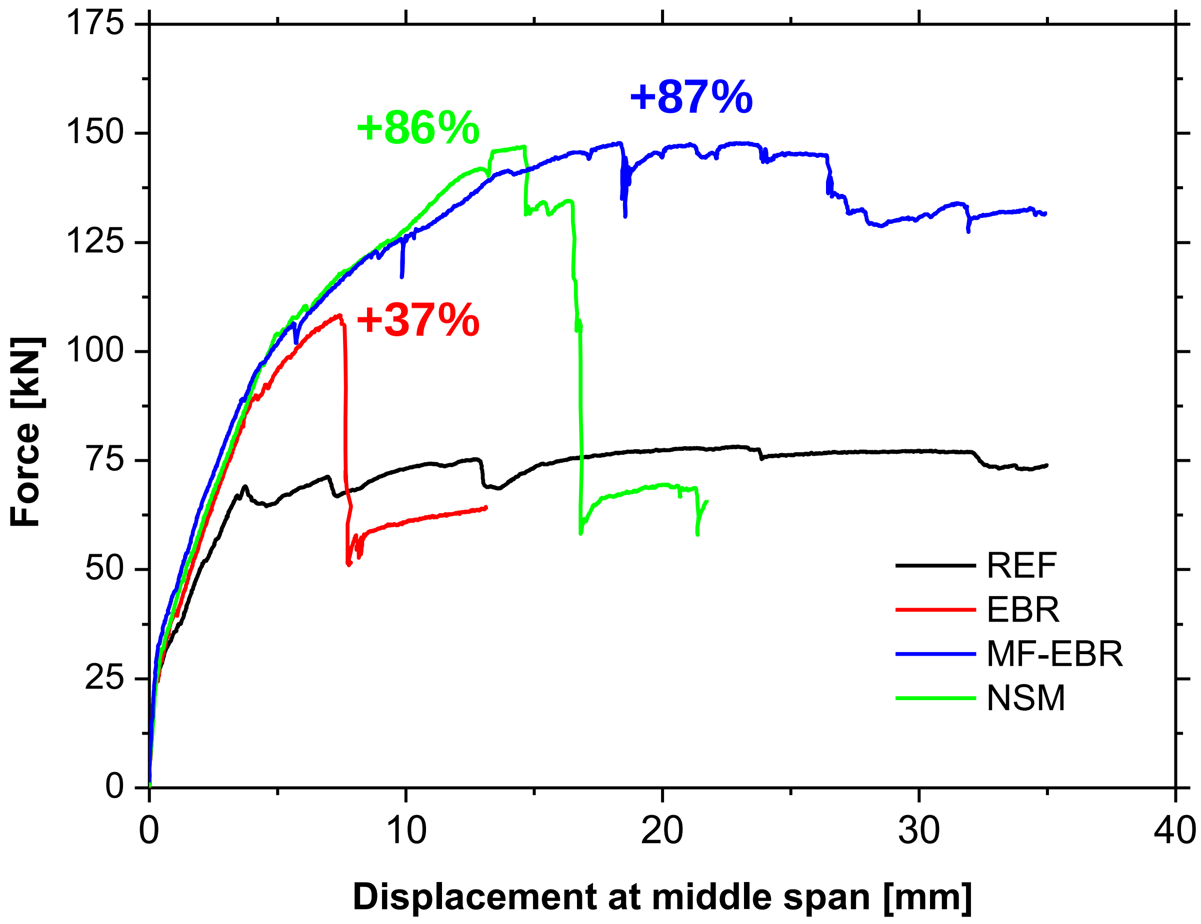
- **Bonded plate *vs*. enlargement *vs*. FRP sheet**

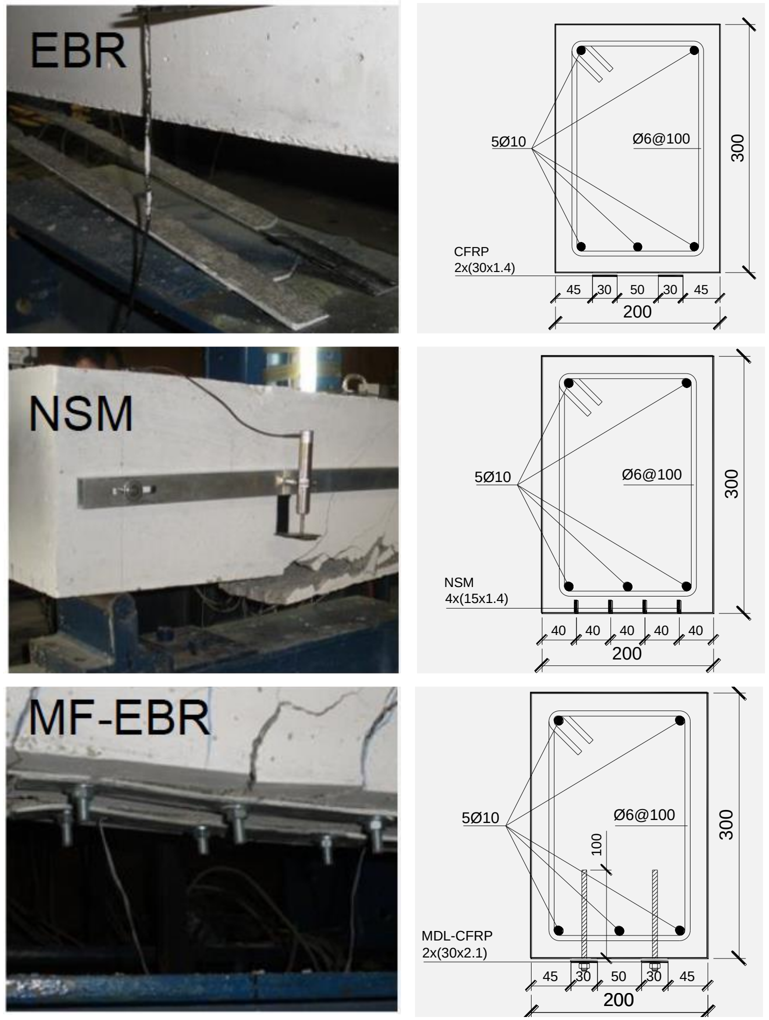


(Saleh Alsayed, Yousef Al-Salloum, and Tarek Almusallam)

4. Traditional *vs.* innovative materials / strengthening techniques

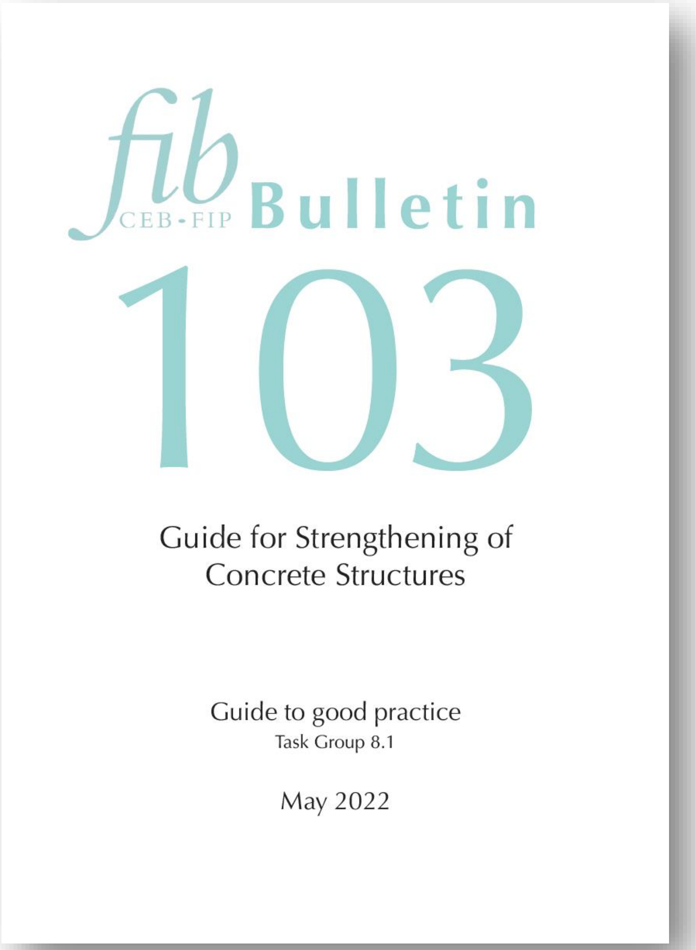
❑ Innovative techniques: EBR *vs.* NSM *vs.* MF-FRP





4. Traditional *vs*. innovative materials / strengthening techniques

❑ Externally applied or near surface mounted FRP



https://doi.org/10.35789/fib.BULL.0103.Ch07

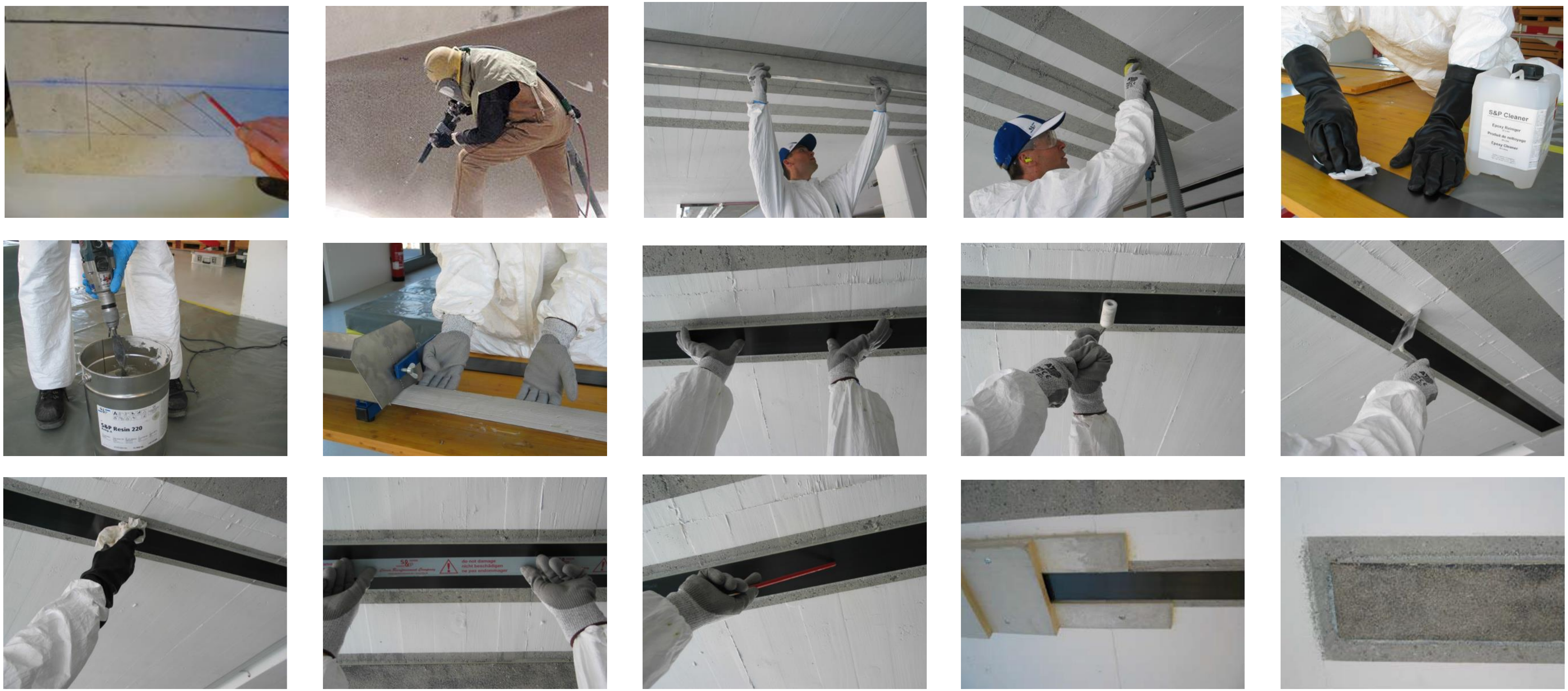
7. Externally applied or near surface mounted FRP
7.1 Foreword
7.2 Basics
7.3 Design
7.4 Stakeholders' roles and qualifications
7.5 Execution
7.6 Quality control
7.7 Monitoring and maintenance
7.8 Case study 1
7.9 Case study 2

Burtscher, Cabral Fonseca, Correia, Costa, Dourado, Ramoa Correia, Kotynia, Schmidt, **Sena Cruz***, Vorwagner
* Correspoding Author

4. Traditional *vs*. innovative materials / strengthening techniques

- **Externally bonded reinforcement – Main steps (*fib* bulletin 103)**

Courtesy of S&P Company



4. Traditional *vs*. innovative materials / strengthening techniques

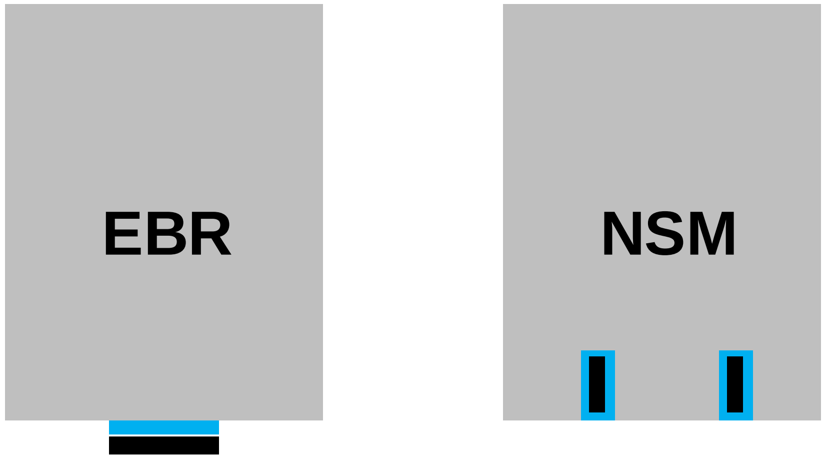
- **Near-surface mounted technique – Main steps (*fi*b bulletin 103)**

Courtesy of S&P Company

4. Traditional *vs*. innovative materials / strengthening techniques

❑ **Near-surface mounted technique *vs*. Externally bonded reinforcement**

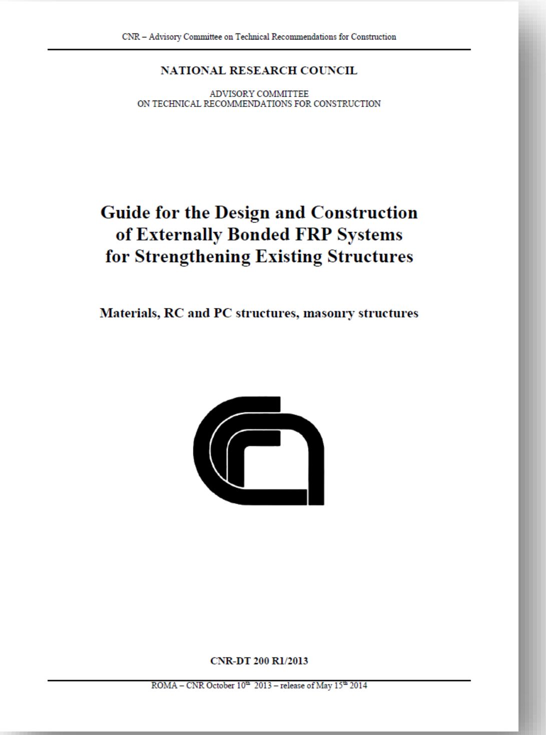
- Reduction of amount of site installation work
- Less prone to premature debonding
- Smaller visual impact
- Greater protection of the FRP against external aggression agents
- FRP failure can be achieved
- Easier to anchor into adjacent members to prevent debonding failures



4. Traditional *vs.* innovative materials / strengthening techniques

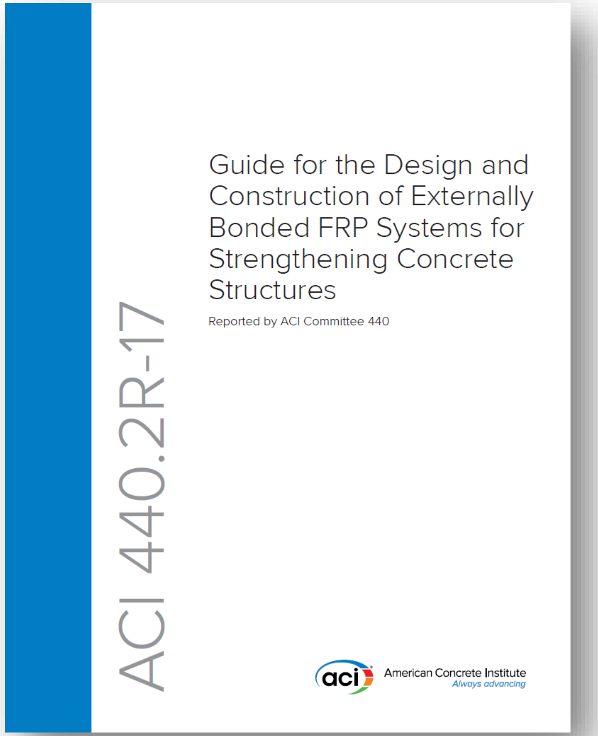
❑ Existing codes/guidelines

2004, 2013



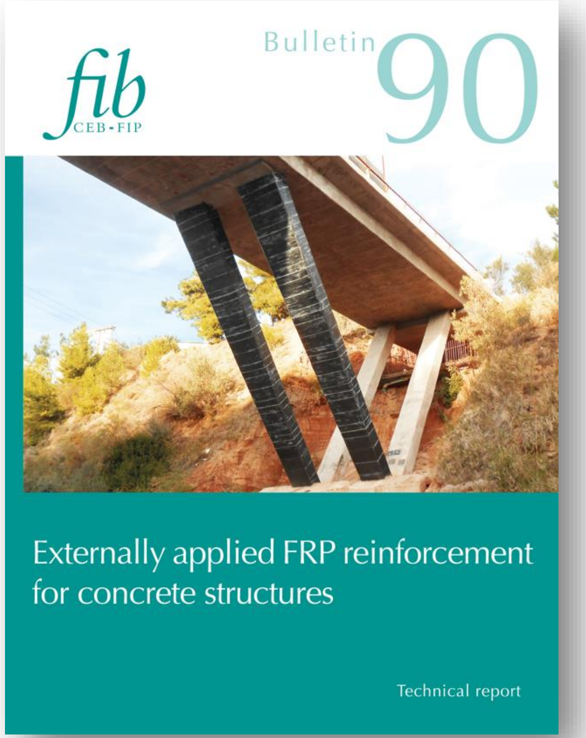
CNR-DT 200 R1

2002, 2008, 2017



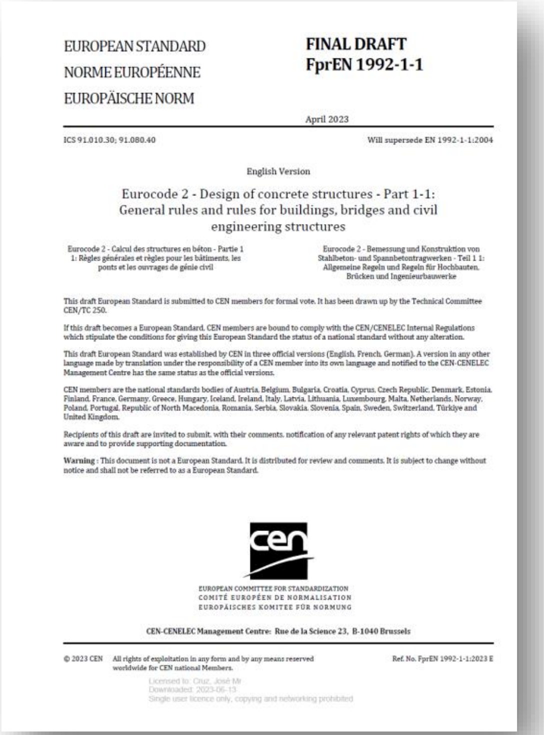
ACI 440.2R-17

2001, 2019



fib Bulletin 90

2024



EC2 – 2nd Generation

Section 5

Advanced strengthening techniques with composite materials

5. Advanced strengthening techniques with composite materials

❑ Introduction

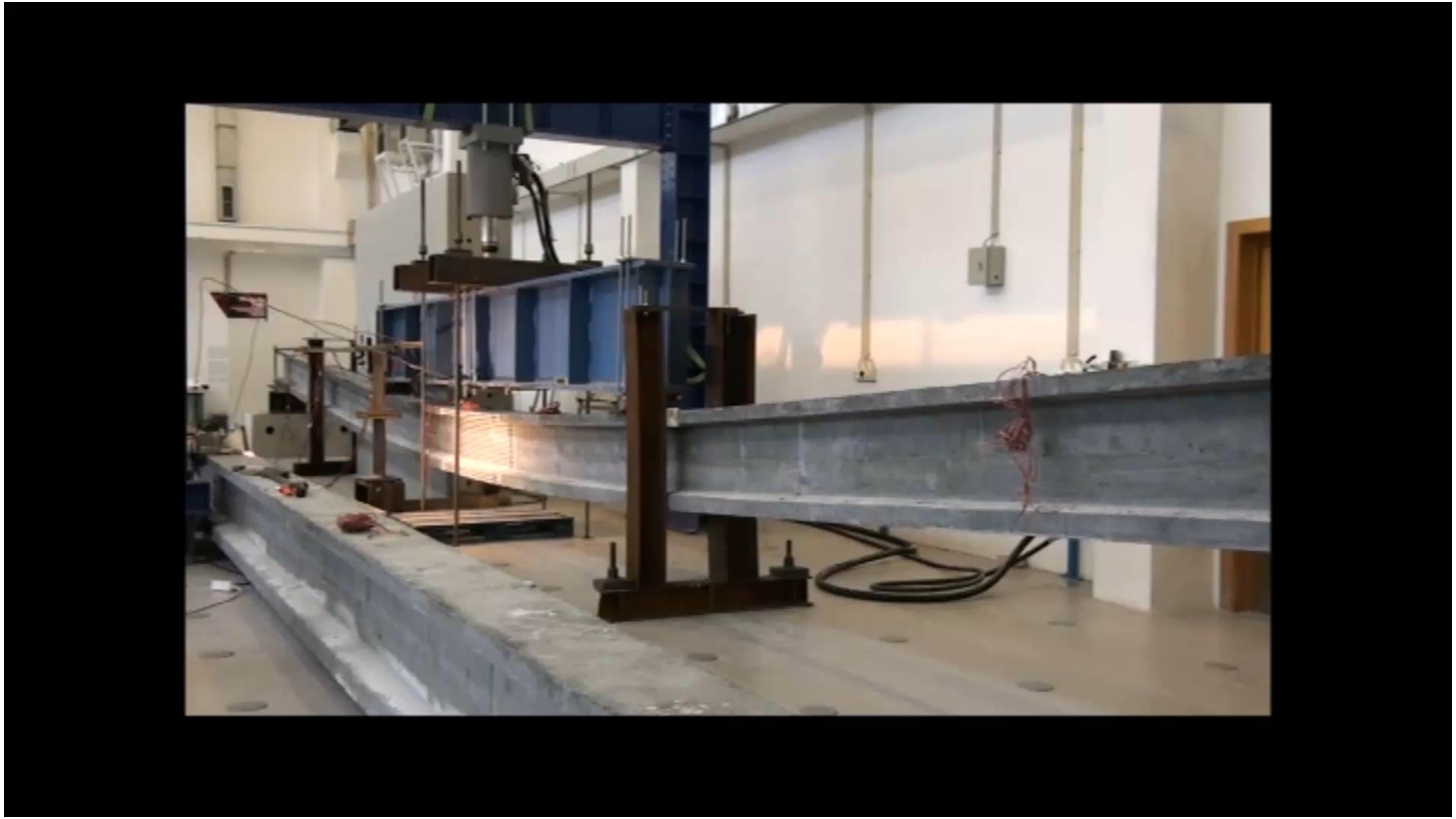
- Considerable research has been developed in the field of **strengthening of RC** with use of the **EBR technique** with **FRP materials.**

- The use of **prestressing** offers several advantages clearly identified by the literature.

- The use of **prestressed FRP** on the strengthening of RC structures **combines** the benefits of the **EBR technique** with the advantages associated with **external prestressing.**

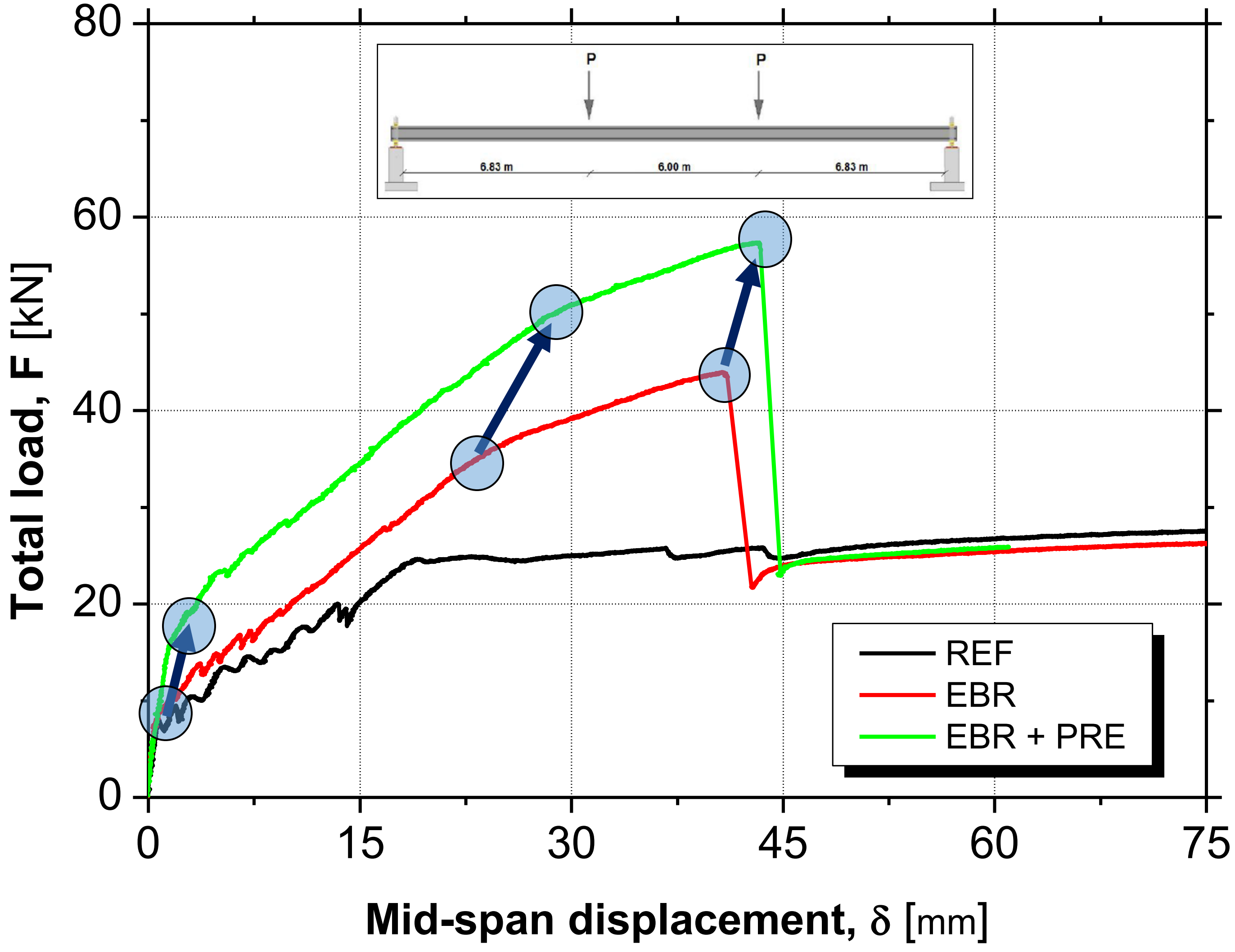
5. Advanced strengthening techniques with composite materials

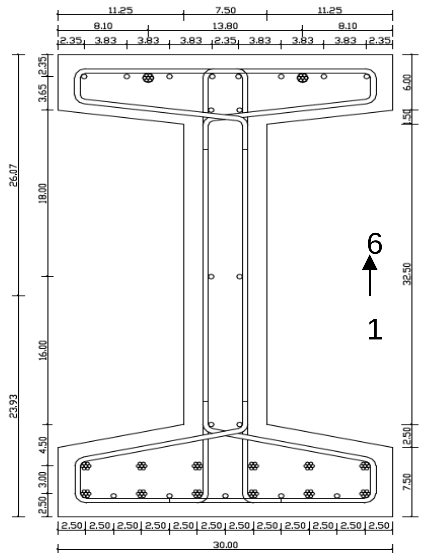
- Benefits of pre-stressing



5. Advanced strengthening techniques with composite materials

❑ Benefits of pre-stressing

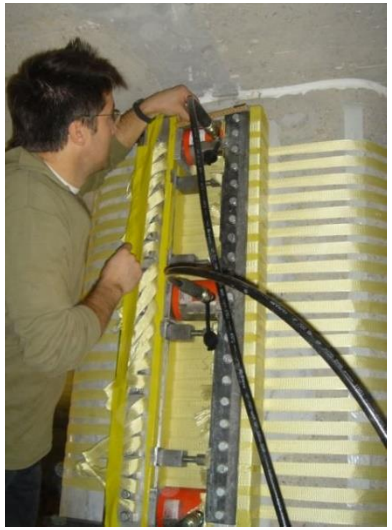




5. Advanced strengthening techniques with composite materials

❑ Benefits of pre-stressing

- Deflection reduction and acting against dead loads
- Crack widths reduction
- Delay in the onset of cracking
- Strain relief within the internal steel reinforcement
- Higher fatigue failure resistance
- Delay in yielding of the internal steel reinforcements
- More efficient use of concrete and FRP
- Reduction of premature debonding failure
- Increase in ultimate load-bearing capacity
- Increase in shear capacity



5. Advanced strengthening techniques with composite materials

❑ Flexural strengthening

S&P Clever Reinforcement

5. Advanced strengthening techniques with composite materials

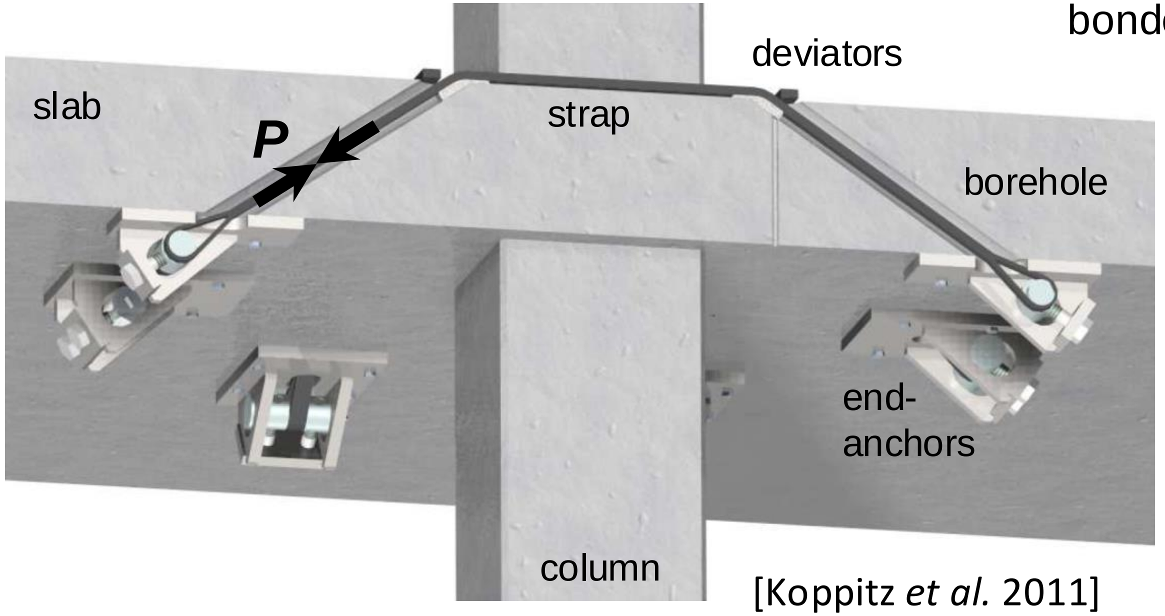
❑ Confinement

S&P Clever Reinforcement

5. Advanced strengthening techniques with composite materials

❑ Punching strengthening

bonded steel end-anchor



deviators on top surface

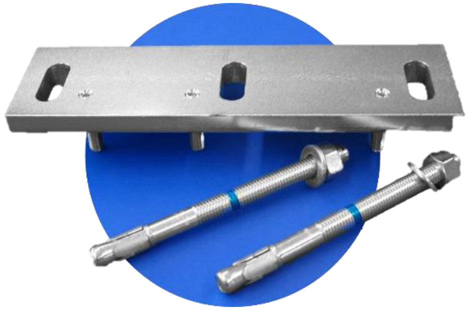
[Koppitz *et al.* 2011]

5. Advanced strengthening techniques with composite materials

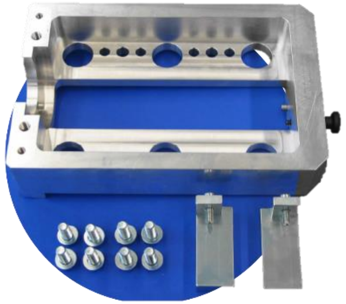
❑ Prestressing system from S&P

Clamp unit

Guides

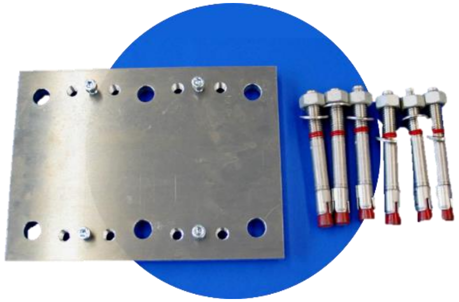


Frame

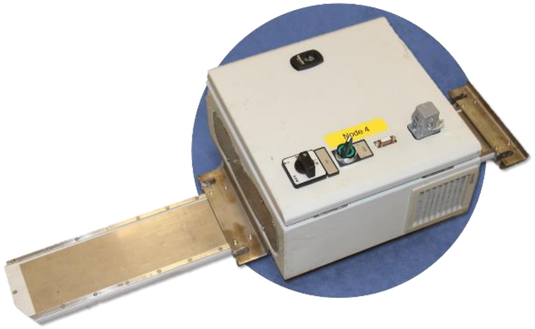


Hydraulic cylinder

Steel plate anchors (MA)



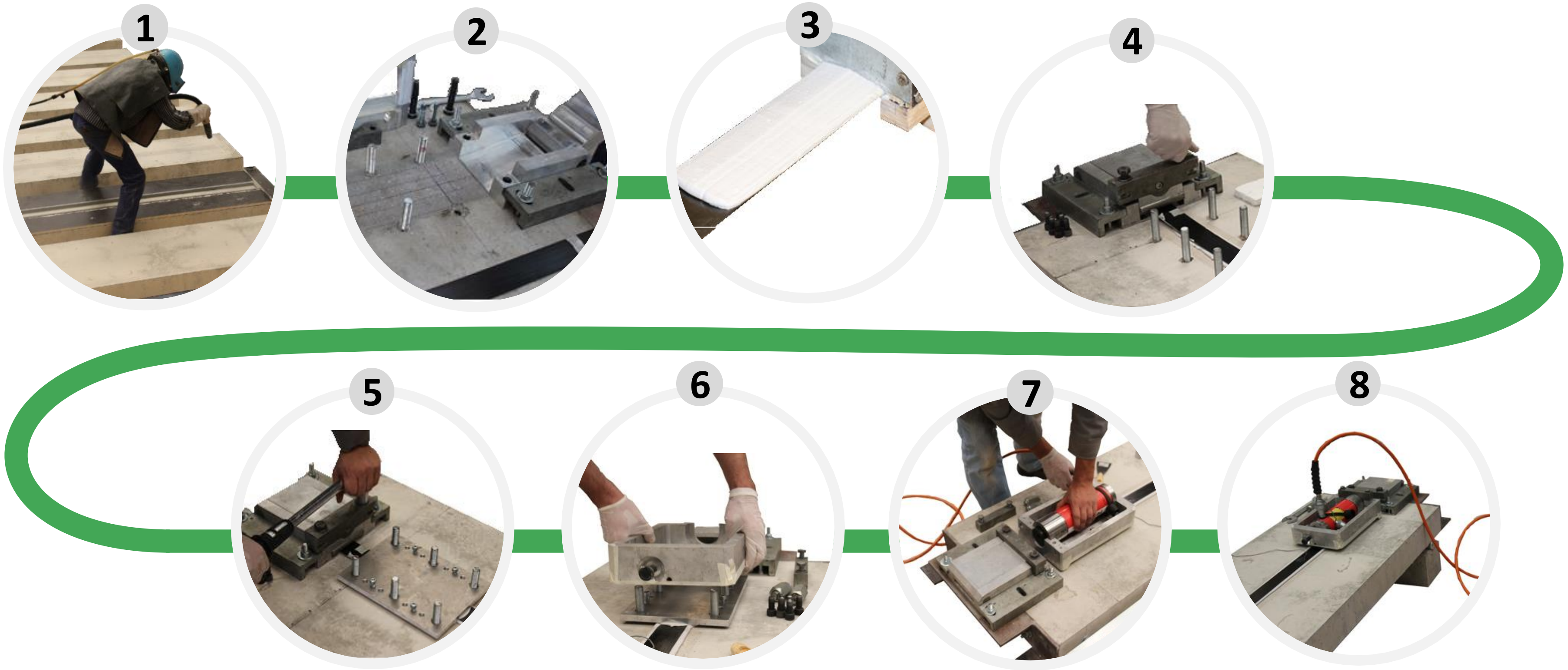
Heating device (GA)



Hydraulic pump

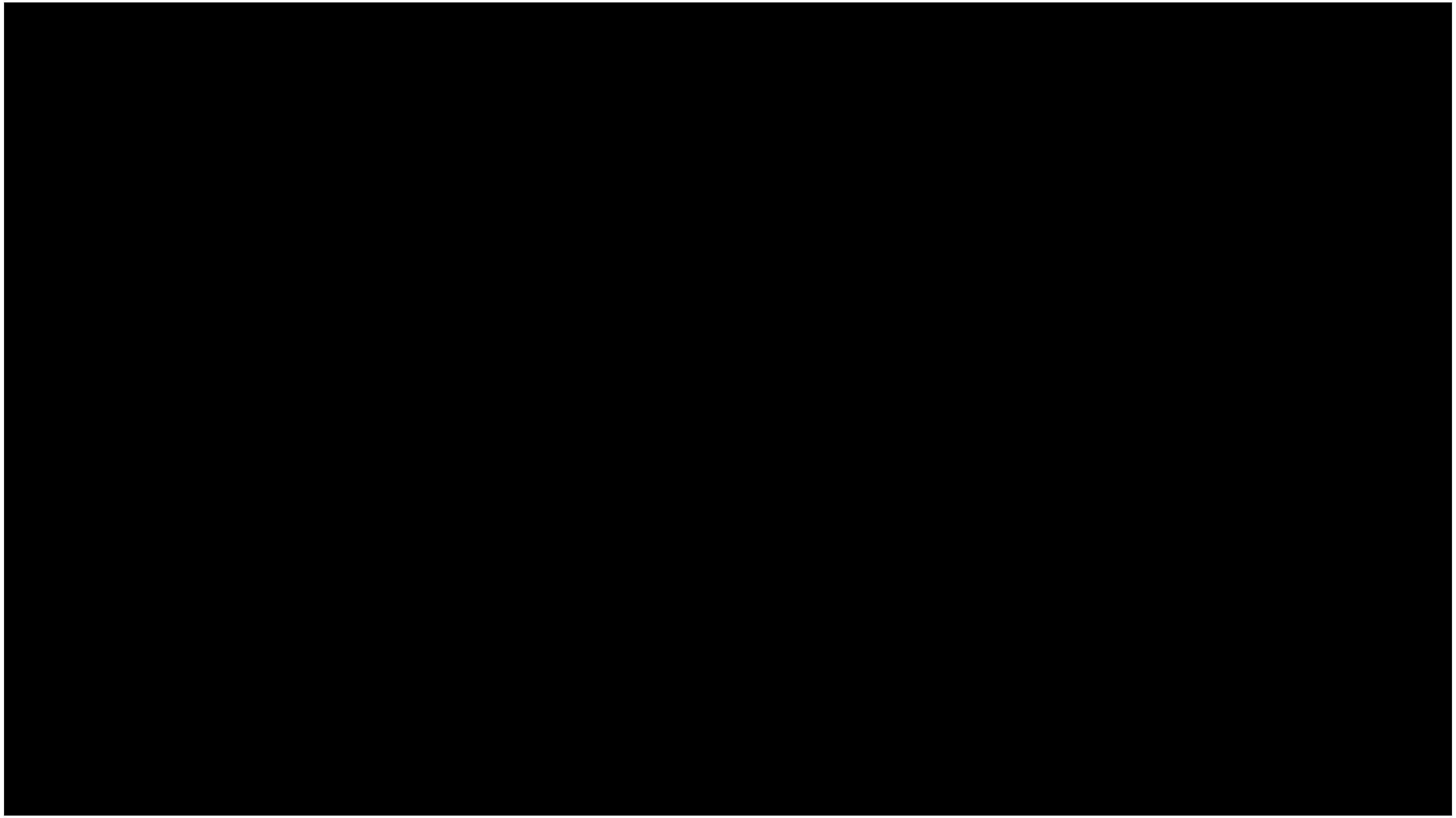
5. Advanced strengthening techniques with composite materials

❑ Prestressing system from S&P – Mechanical Anchorage (MA)



5. Advanced strengthening techniques with composite materials

❑ Prestressing system from S&P – Mechanical Anchorage (MA)

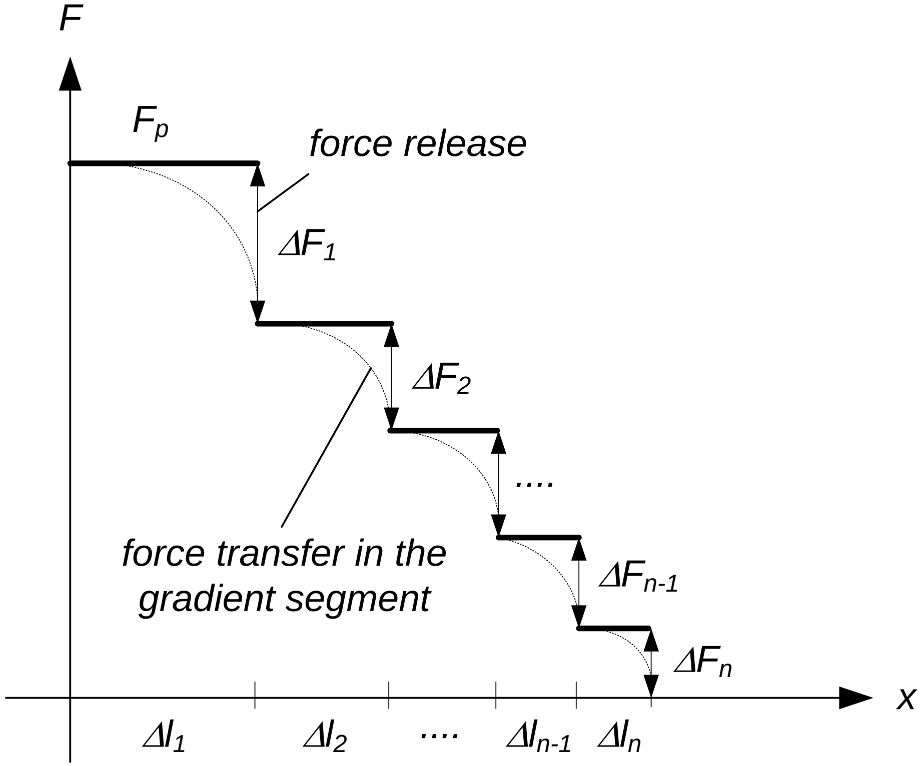


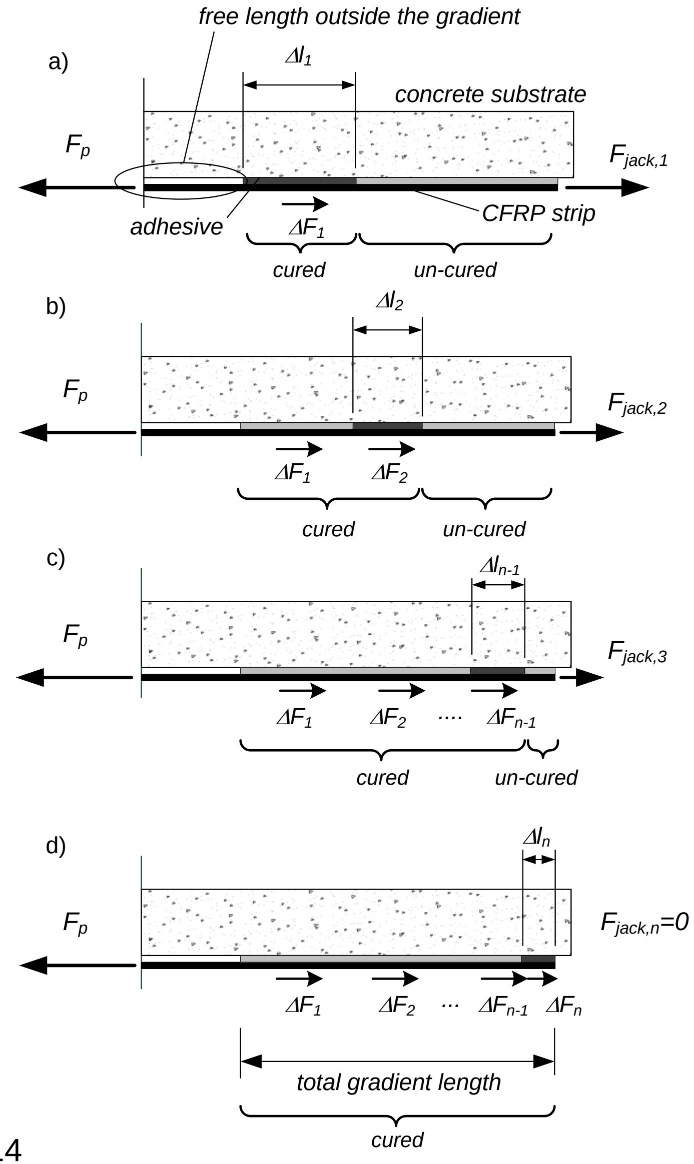
Courtesy of S&P Clever Reinforcement

5. Advanced strengthening techniques with composite materials

❑ Prestressing system from S&P – Gradient Anchorage (GA)

- **Non-mechanical** anchorage technique
- Based on the **epoxy's ability to cure faster under high temperatures**
- **Gradual releasing of the prestressing force over several sectors at the strip end**

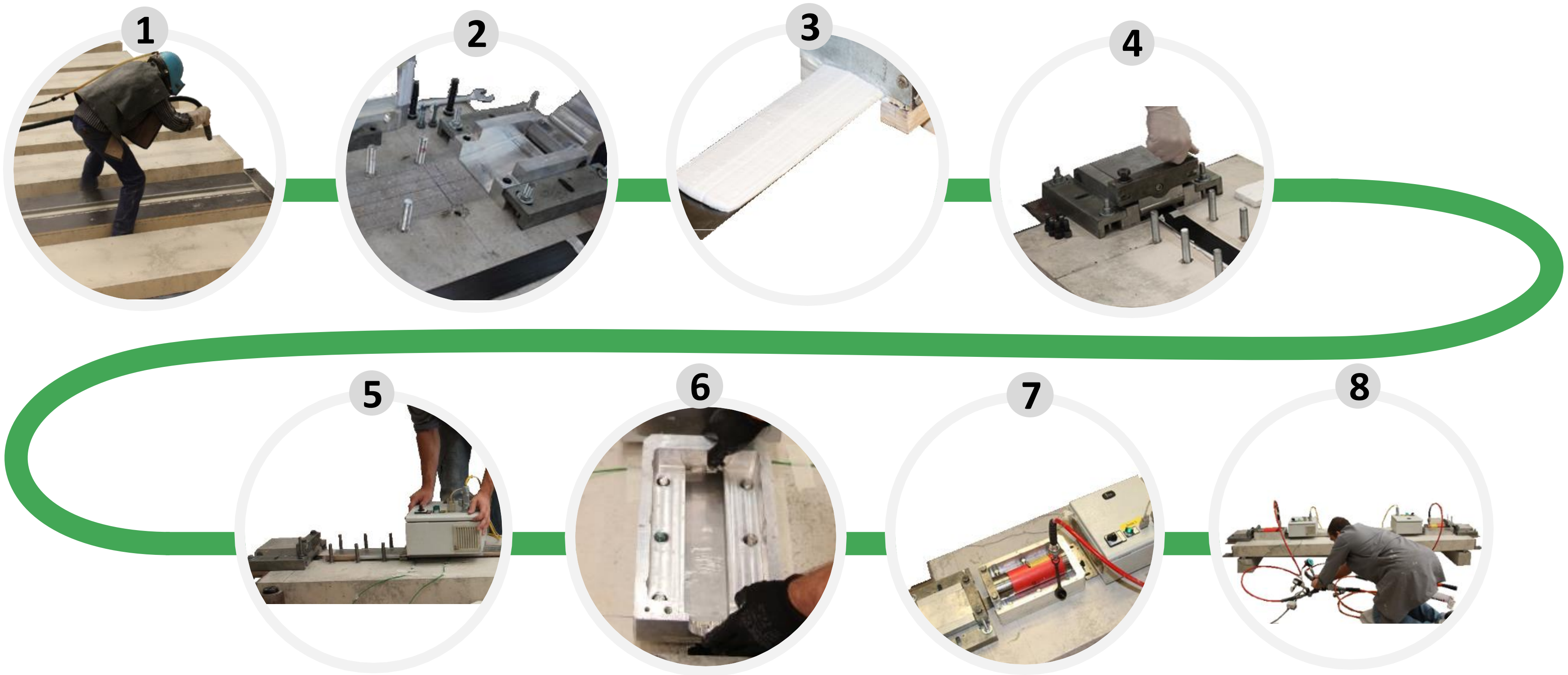




Source: Czaderski C. (2012) Strengthening of reinforced concrete members by prestressed externally bonded reinforcement with gradient method, PhD thesis No. 20504, ETH Zurich. http://dx.doi.org/10.3929/ethz-a-007569614

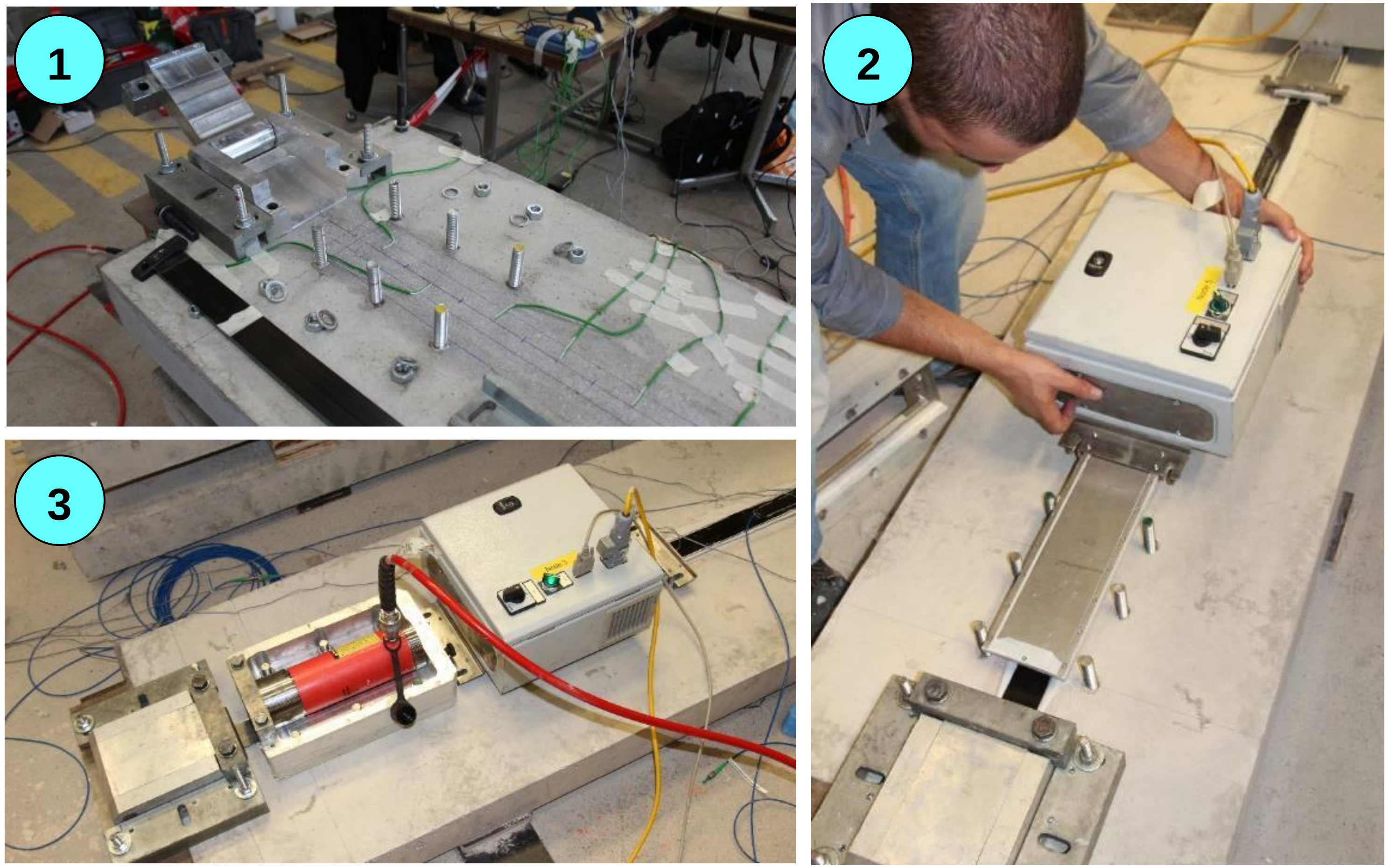
5. Advanced strengthening techniques with composite materials

- Prestressing system from S&P – Gradient Anchorage (GA)



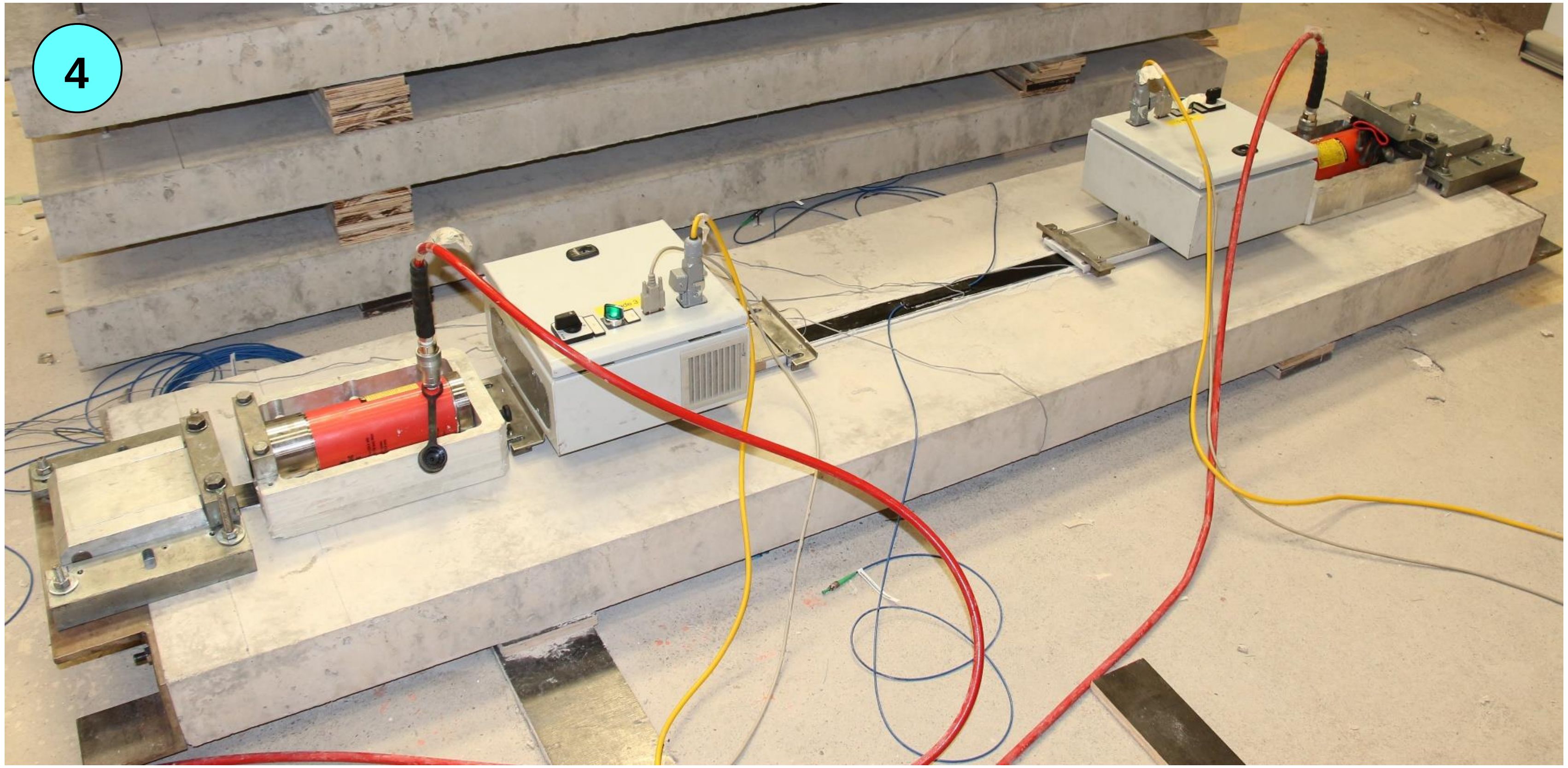
5. Advanced strengthening techniques with composite materials

❑ Prestressing system from S&P – Gradient Anchorage (GA)



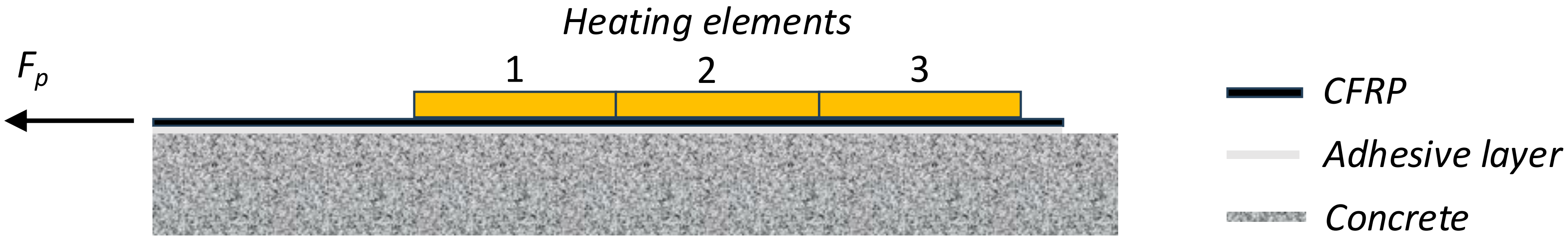
5. Advanced strengthening techniques with composite materials

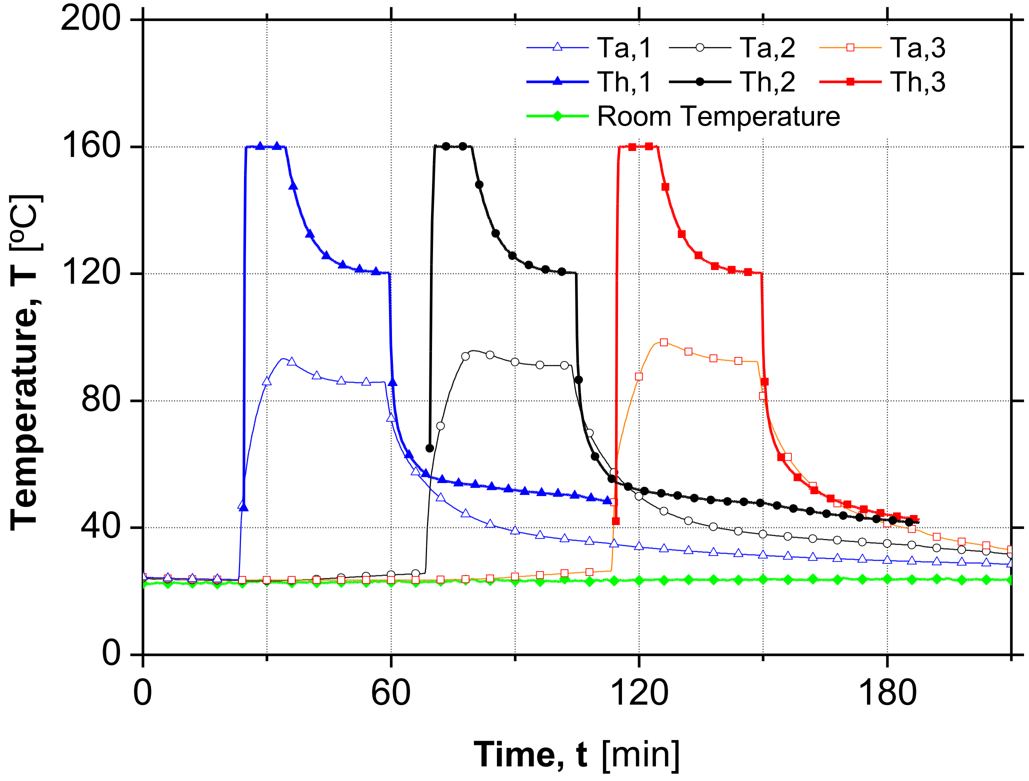
- Prestressing system from S&P – Gradient Anchorage (GA)

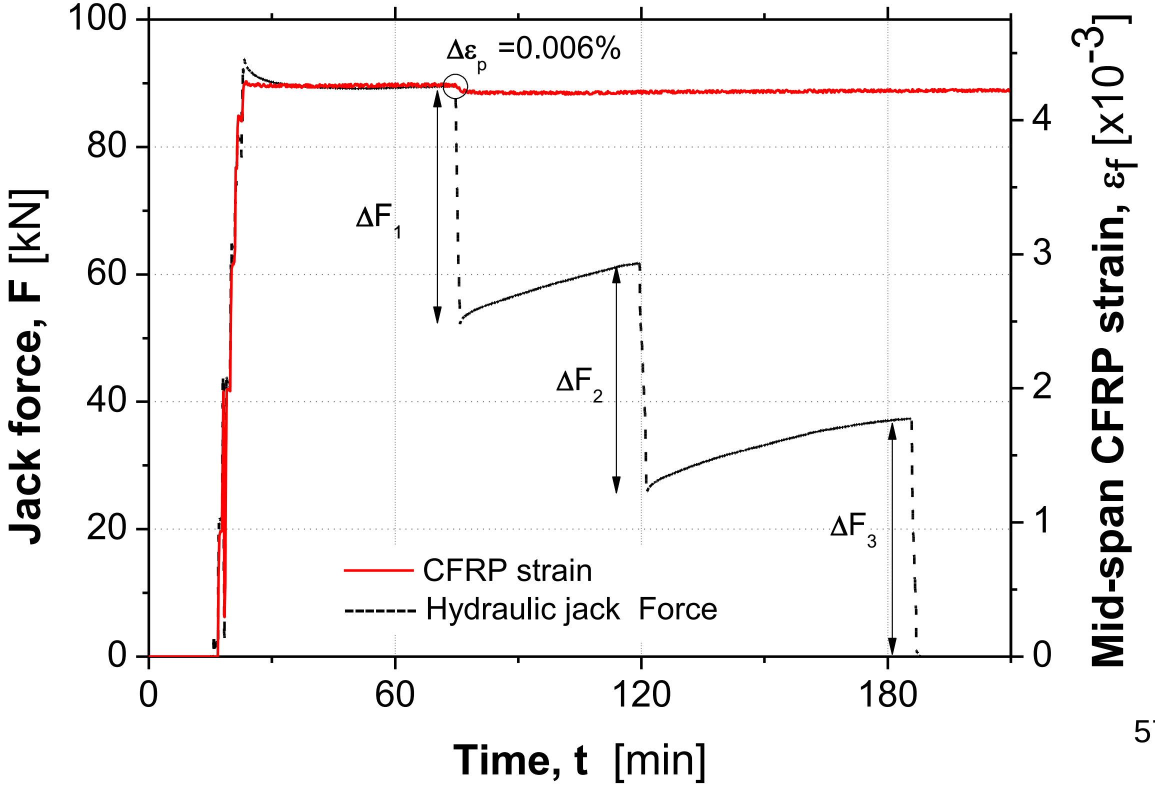


5. Advanced strengthening techniques with composite materials

❑ Prestressing system from S&P – Gradient Anchorage (GA)



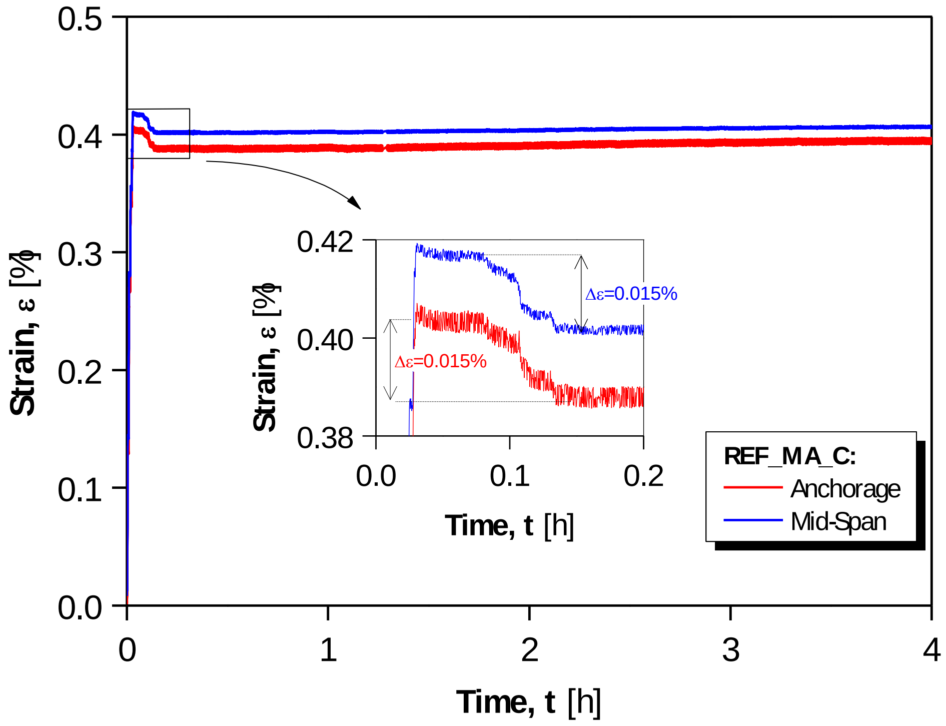




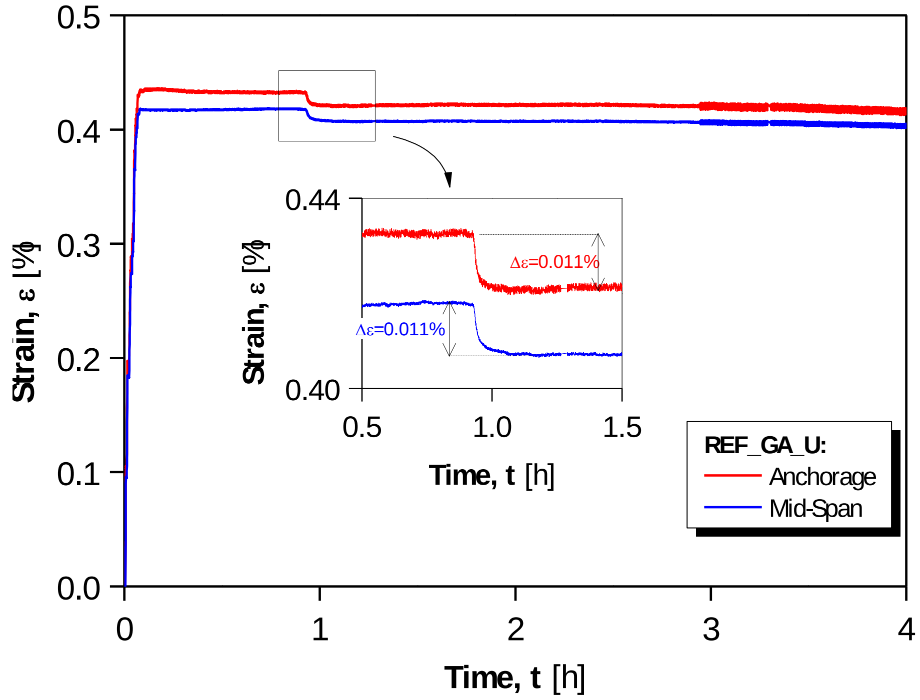
5. Advanced strengthening techniques with composite materials

❑ Prestressing system from S&P – Gradient Anchorage (GA)

Typical short-term losses



MA system

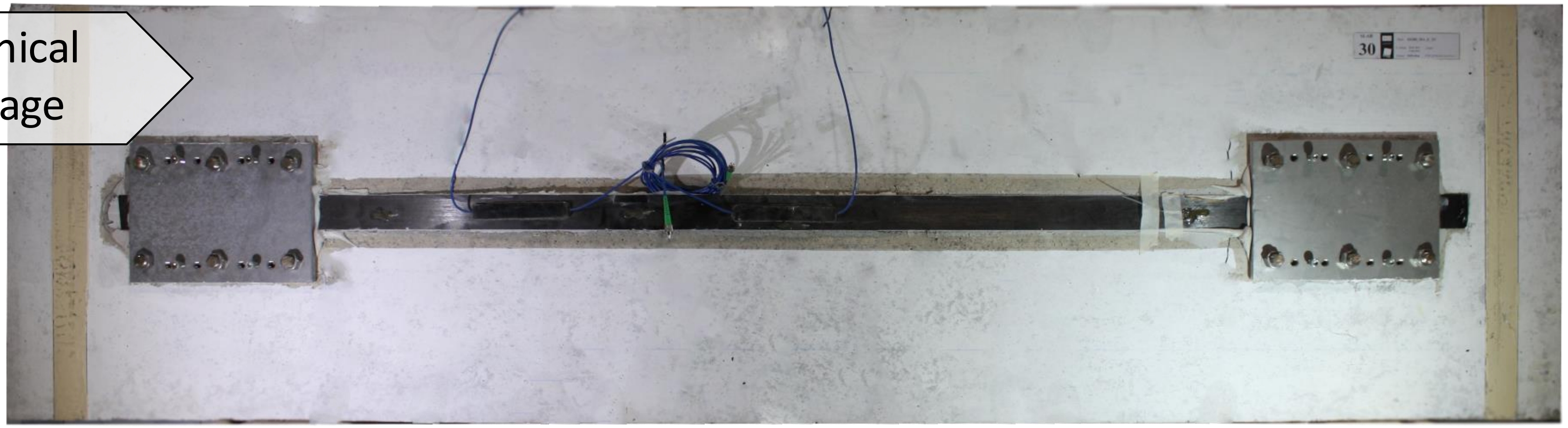


GA system

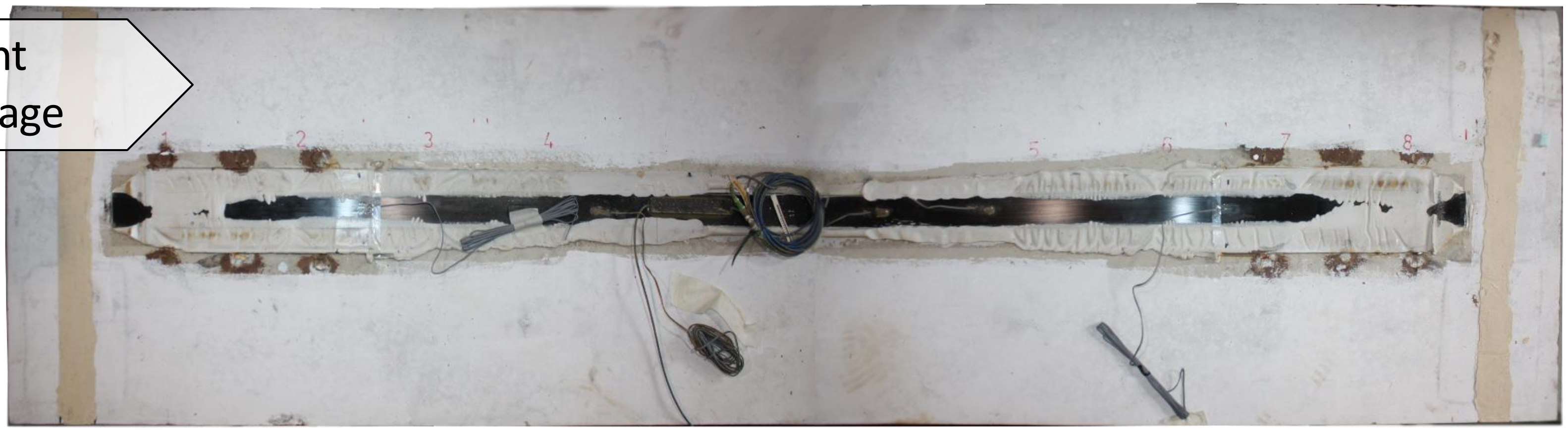
5. Advanced strengthening techniques with composite materials

❑ Mechanical Anchorage *vs*. Gradient Anchorage

Mechanical Anchorage



Gradient Anchorage

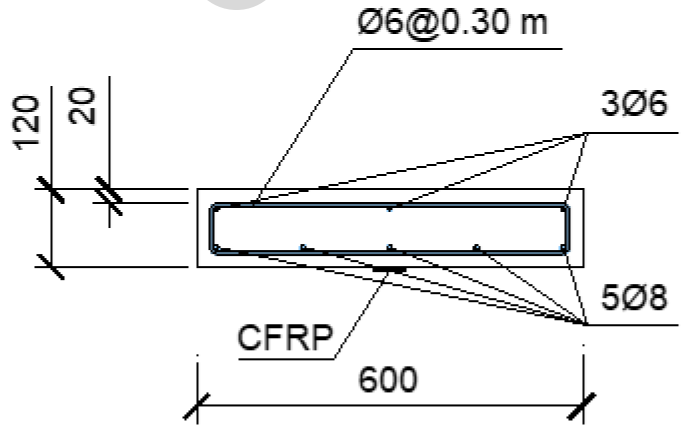


5. Advanced strengthening techniques with composite materials

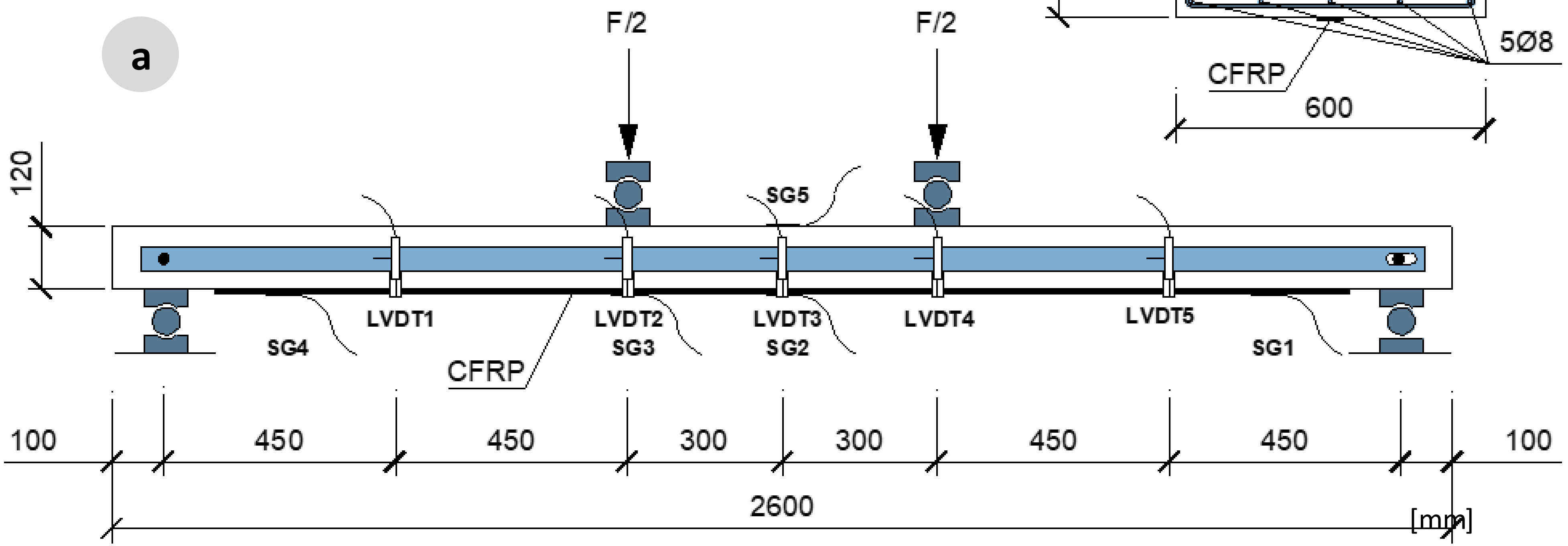
❑ Mechanical Anchorage *vs.* Gradient Anchorage

- **Displacement Control:** 1.2 mm/min
- **Deflections:** 5 LVDTs
- **CFRP & Steel & concrete strains:** Strain gauges
- **Cracking:** Handle microscope, DIC

b

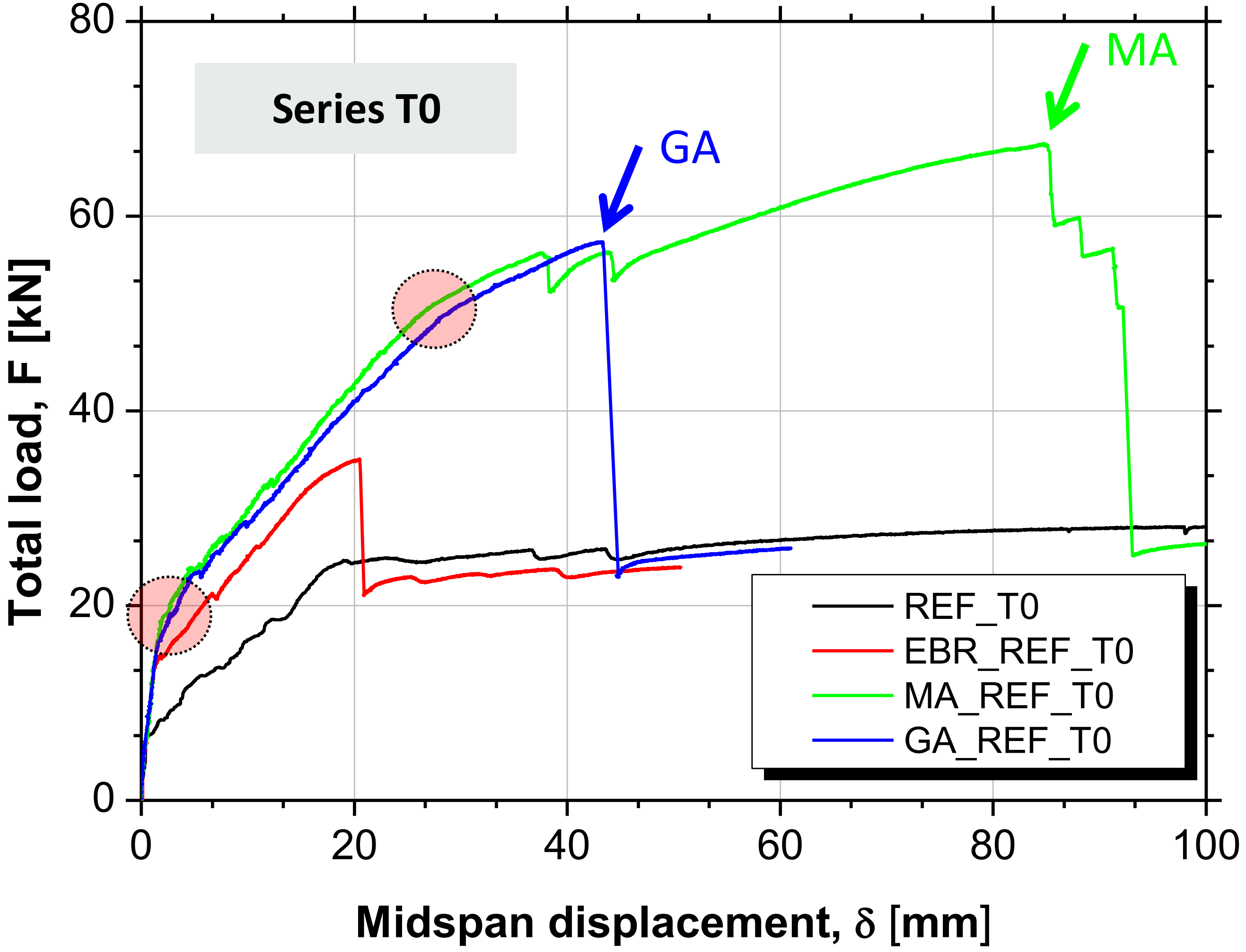


a



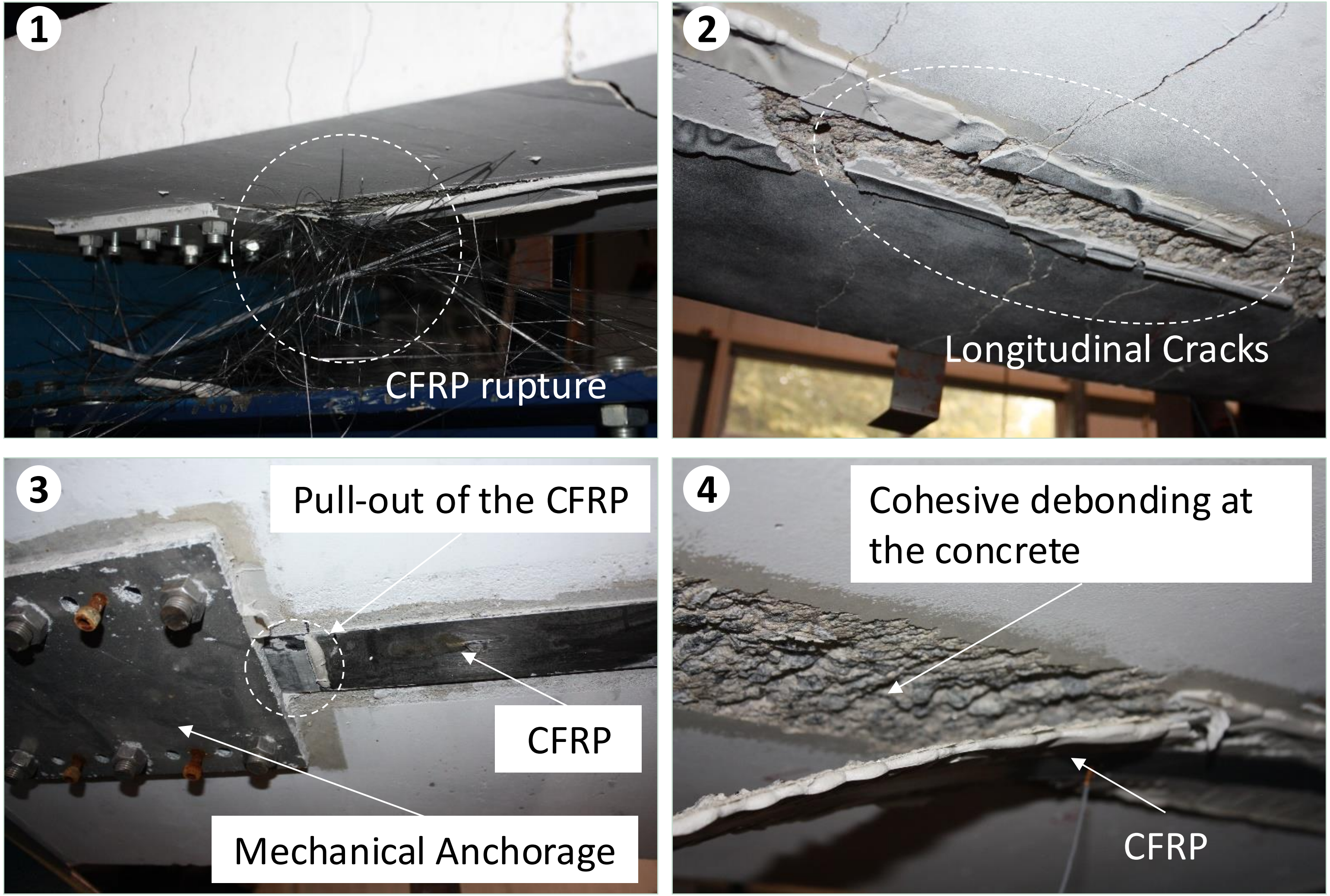
5. Advanced strengthening techniques with composite materials

❑ Mechanical Anchorage *vs*. Gradient Anchorage



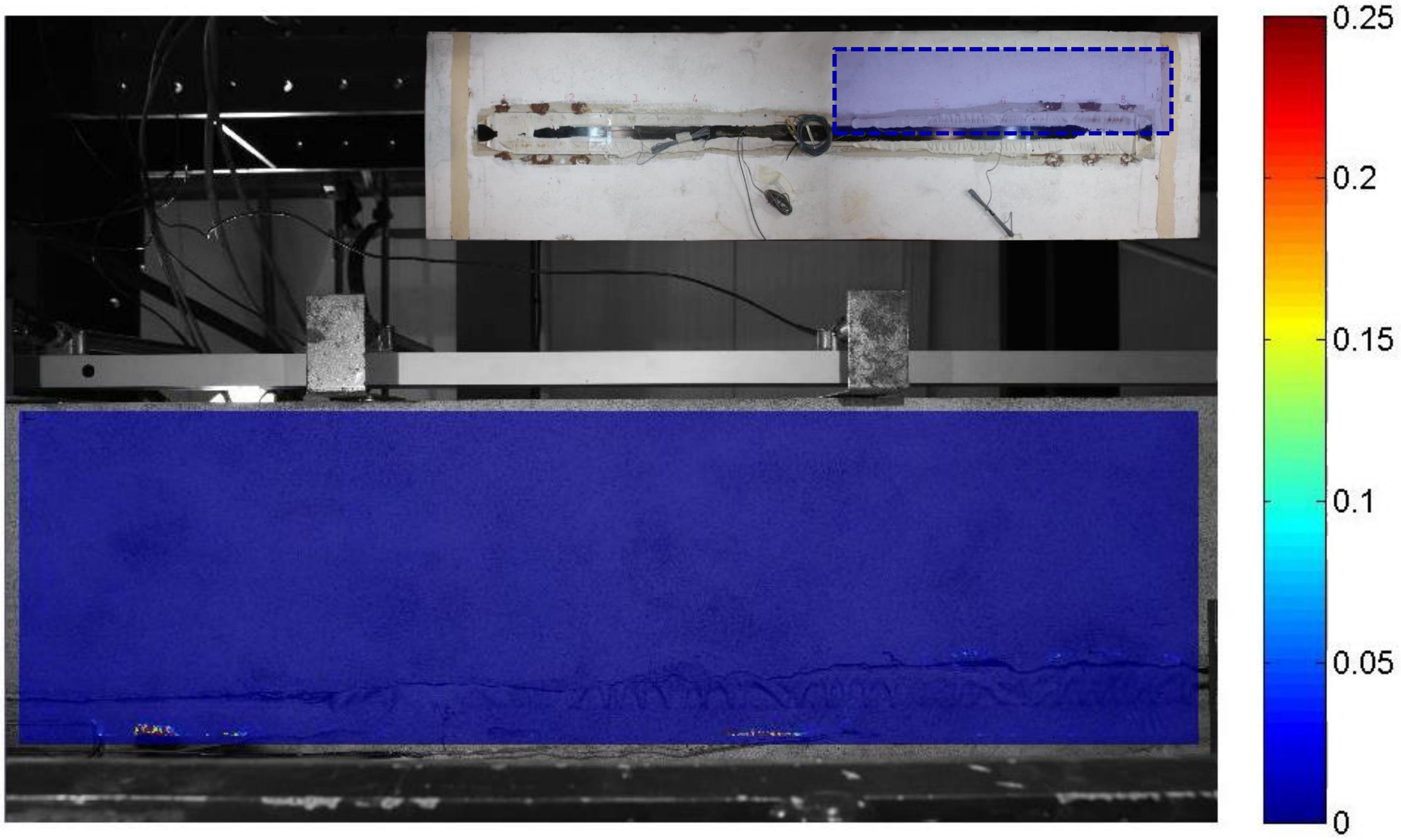
5. Advanced strengthening techniques with composite materials

❑ Mechanical Anchorage *vs*. Gradient Anchorage



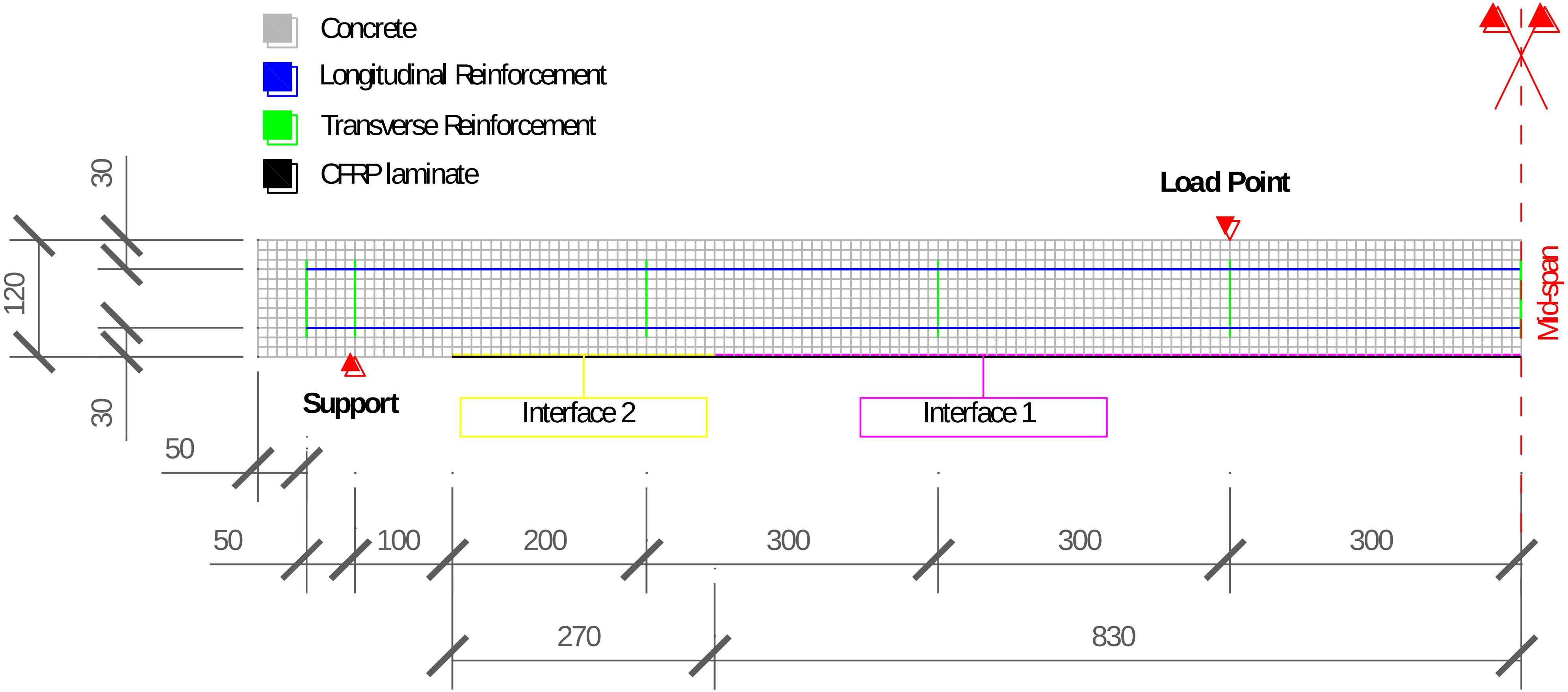
5. Advanced strengthening techniques with composite materials

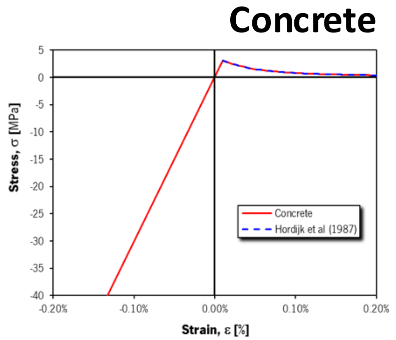
❑ Mechanical Anchorage *vs*. Gradient Anchorage

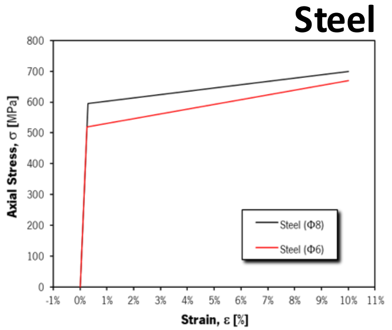


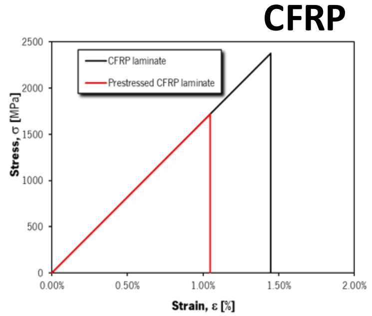
5. Advanced strengthening techniques with composite materials

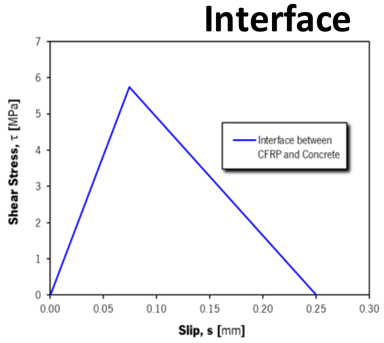
❑ Mechanical Anchorage *vs.* Gradient Anchorage





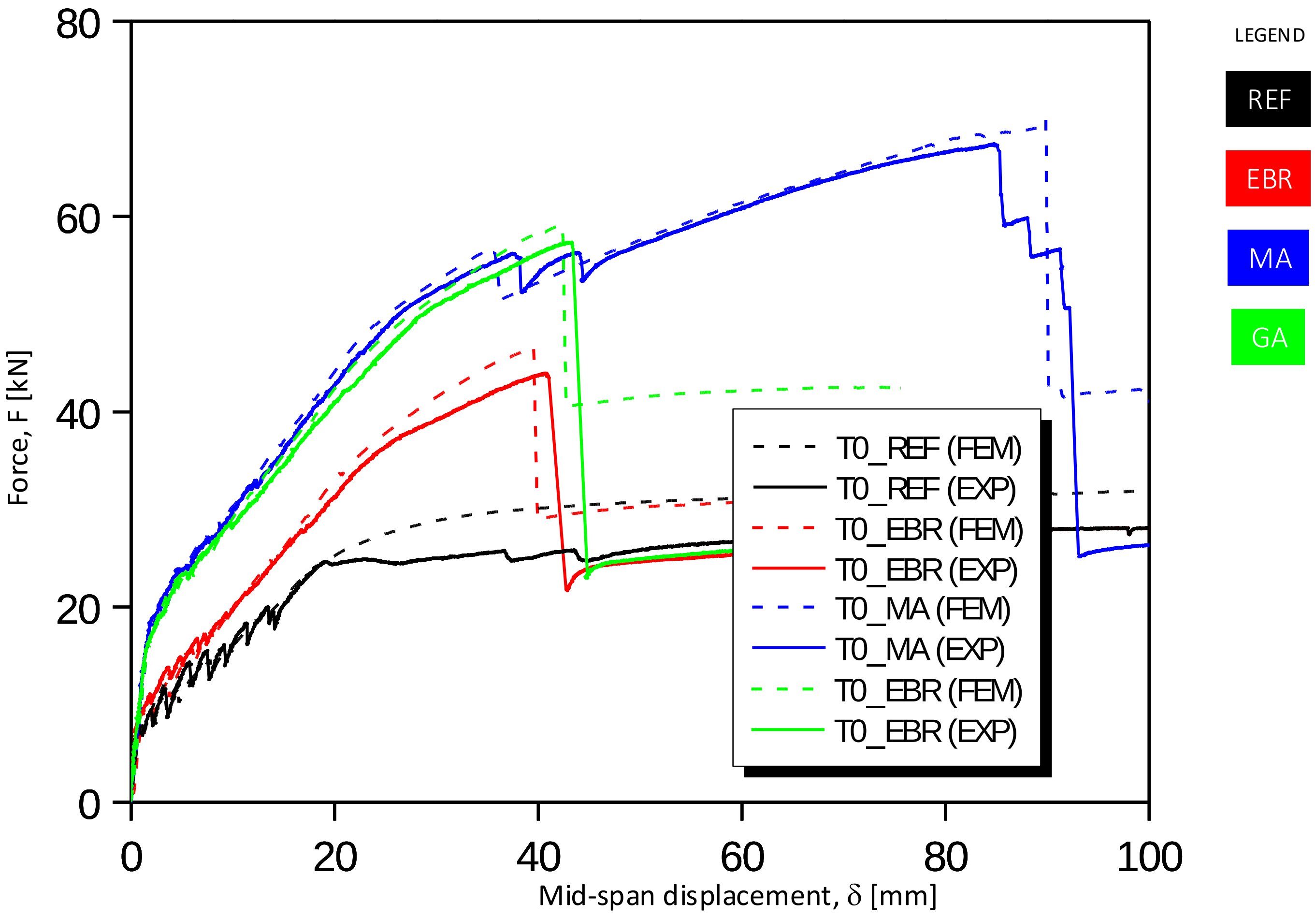






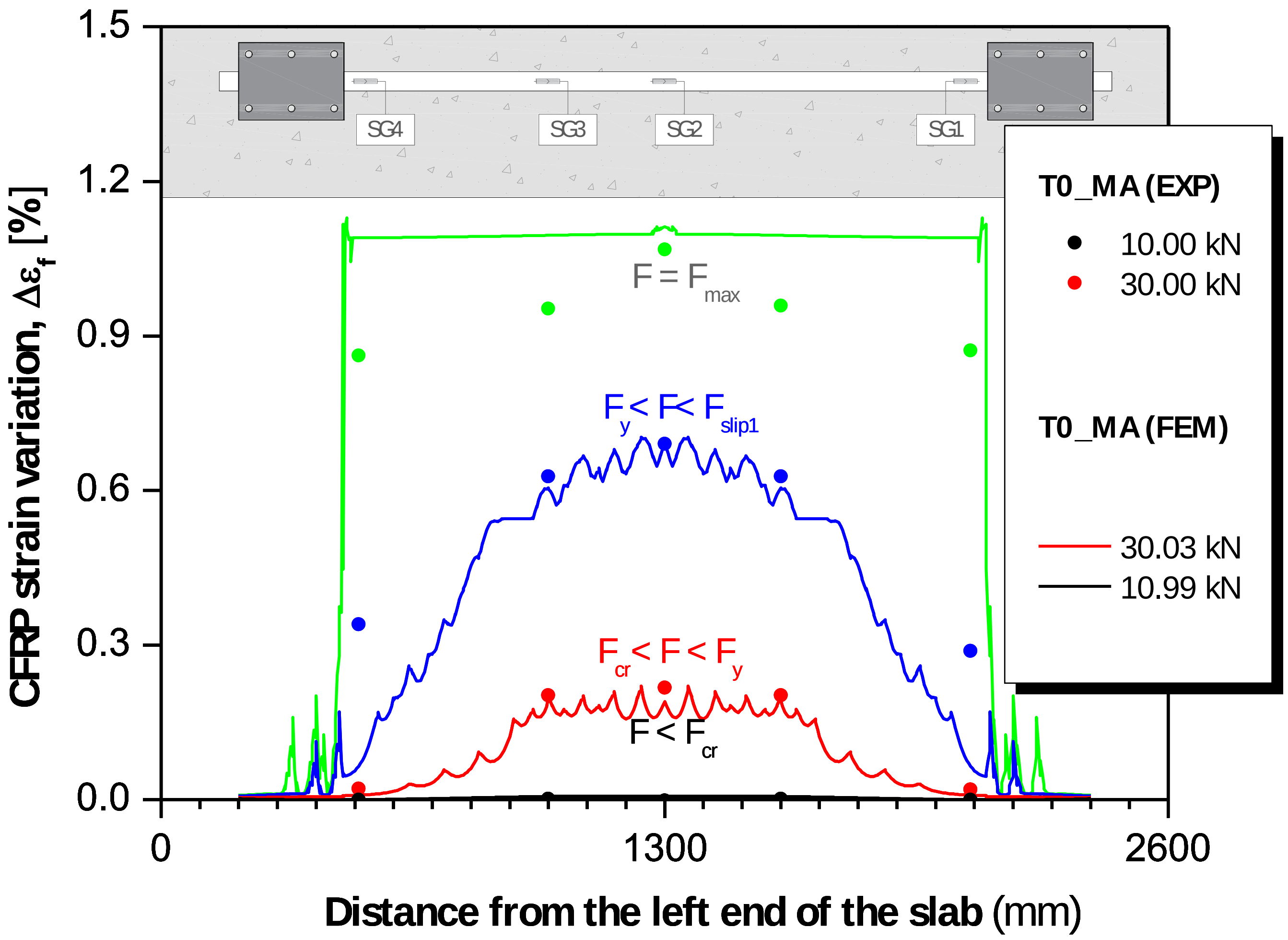
5. Advanced strengthening techniques with composite materials

❑ Mechanical Anchorage *vs*. Gradient Anchorage



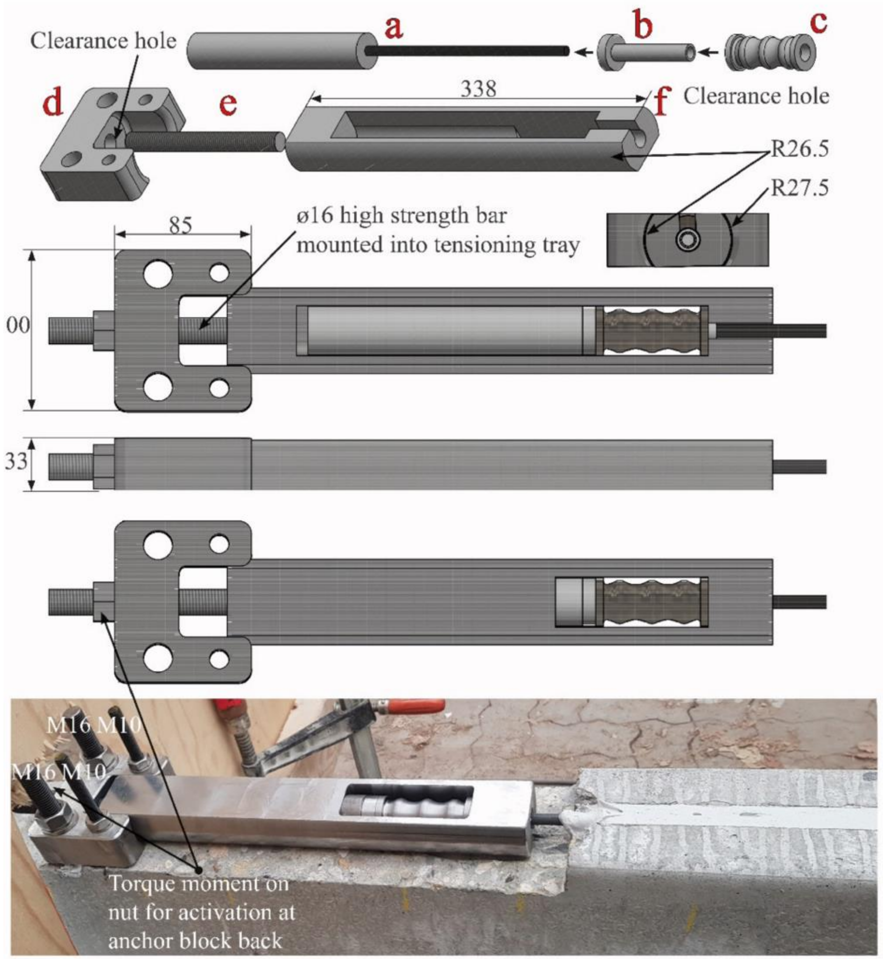
5. Advanced strengthening techniques with composite materials

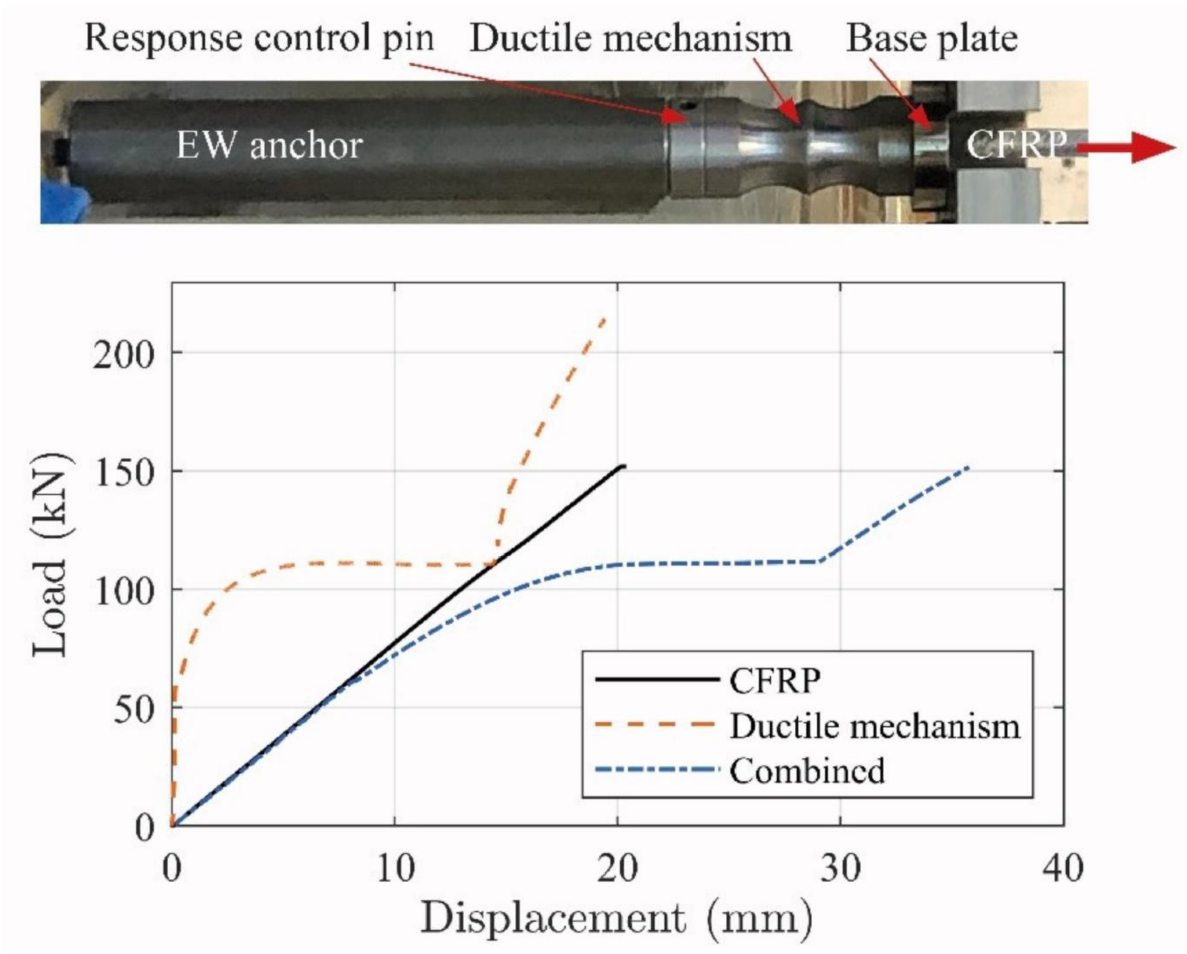
❑ Mechanical Anchorage *vs*. Gradient Anchorage



5. Advanced strengthening techniques with composite materials

❑ Activated Ductile CFRP NSMR Strengthening

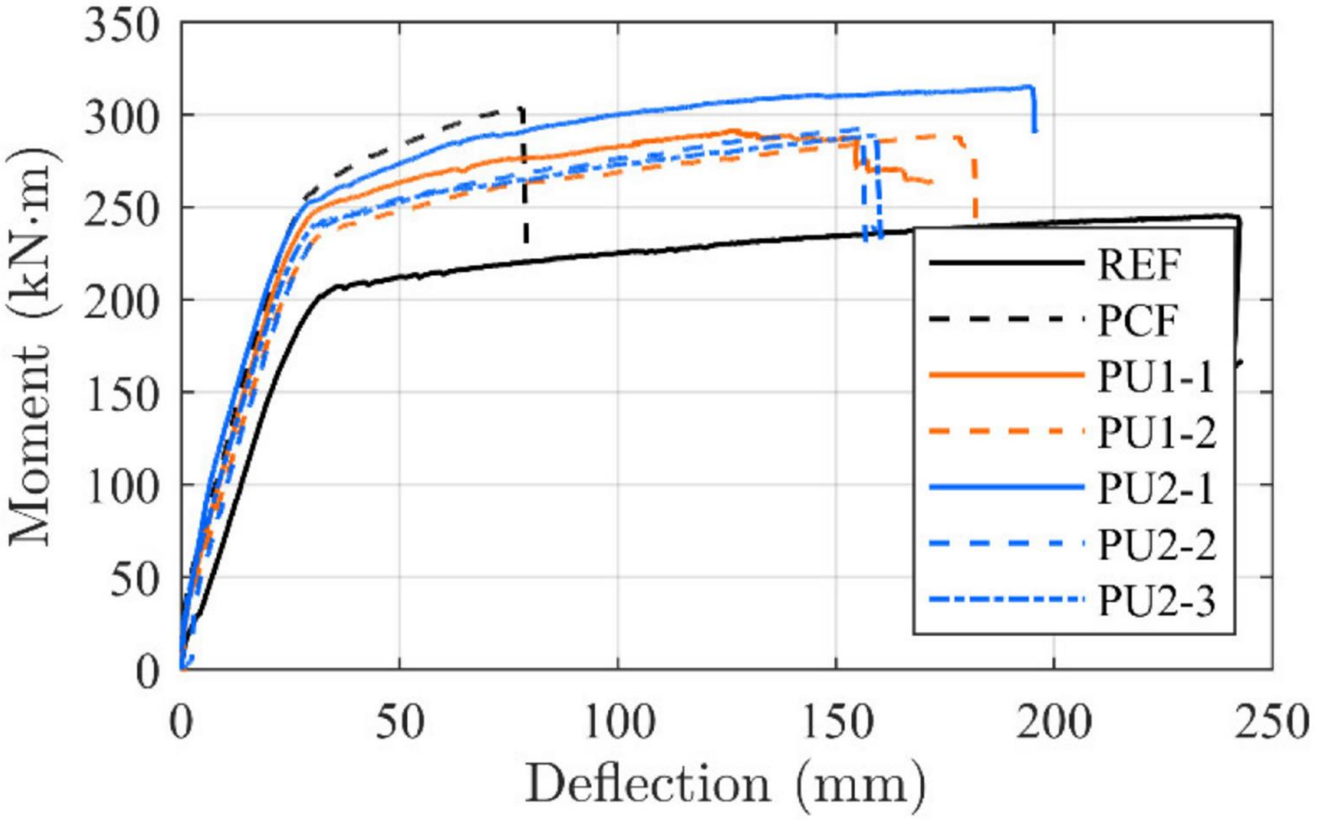


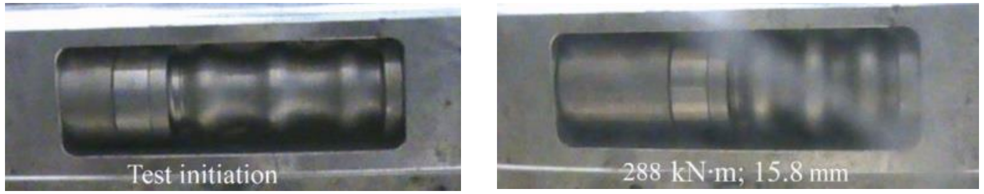


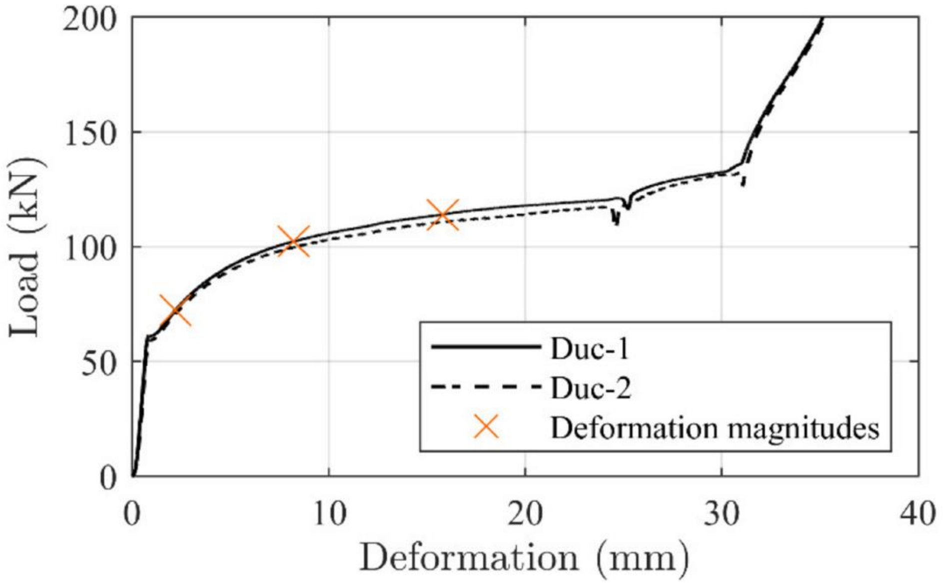
Source: Schmidt, J.W.; Christensen, C.O.; Goltermann, P.; Sena-Cruz, J. (2021). Activated Ductile CFRP NSMR Strengthening. *Materials*, 14: 2821, 21 pp. https://doi.org/10.3390/ma14112821

5. Advanced strengthening techniques with composite materials

❑ Activated Ductile CFRP NSMR Strengthening







Source: Schmidt, J.W.; Christensen, C.O.; Goltermann, P.; Sena-Cruz, J. (2021). Activated Ductile CFRP NSMR Strengthening. *Materials*, 14: 2821, 21 pp. https://doi.org/10.3390/ma14112821

5. Advanced strengthening techniques with composite materials

❑ Activated Ductile CFRP NSMR Strengthening

Thank you for your attention!