ACI-*fib*-RILEM FRC-UHPFRC Workshop 2026
Fiber Reinforced Concrete – from Design to Structural Applications
28-30 September 2026 – Budapest, Hungary

HPFRC for the Strengthening of Aging Structures with Flexural and Shear Deficiencies

Full-scale evidence, interface mechanics and failure-mode control

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INTRODUCTION

Material degradation

Load increment

Corrosion

→

Out of service Deflections

Cracking

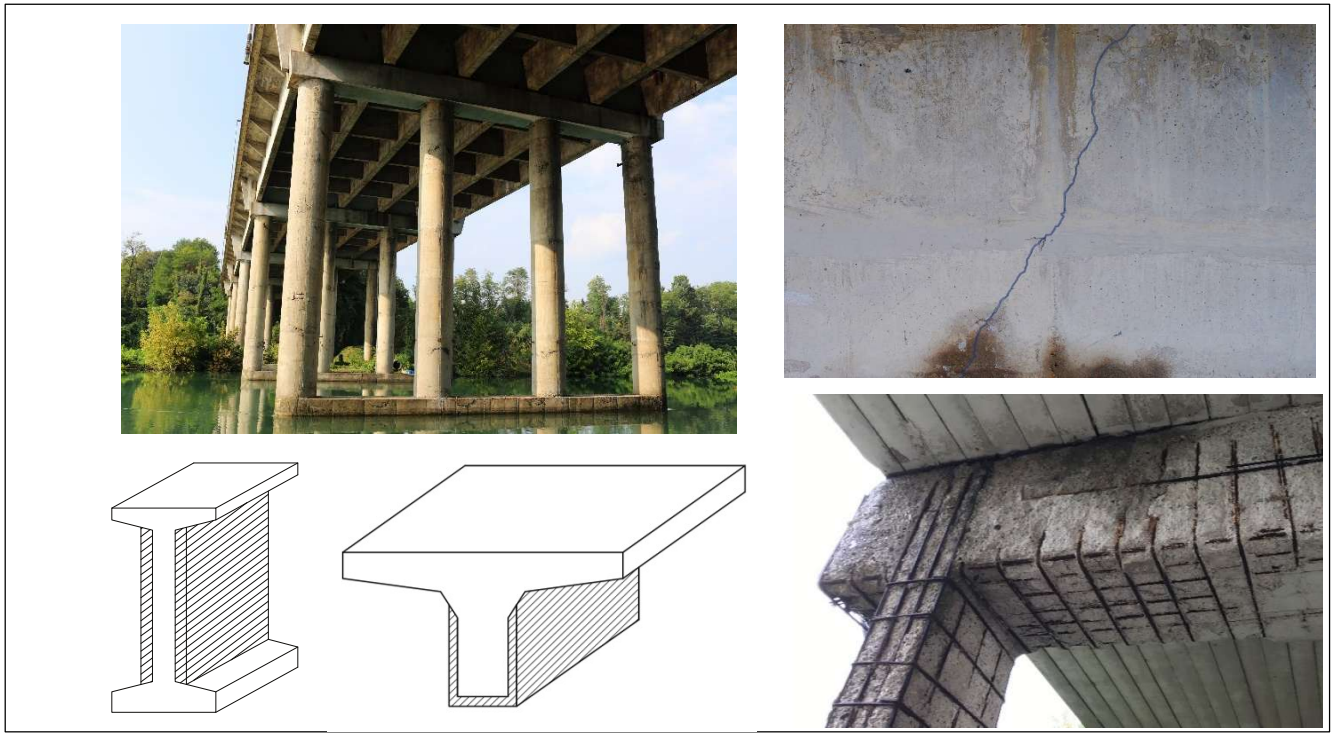
Prestress Loss

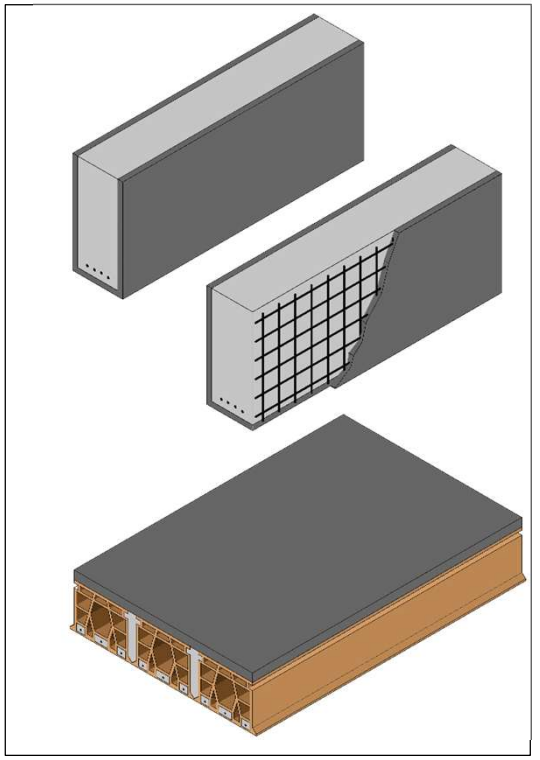
Strength decay

→

Need of **strengthening of existing structures.**

Focus on SHEAR AND FLEXURE





THE STRUCTURAL SYSTEM BEHIND A THIN HPFRC LAYER

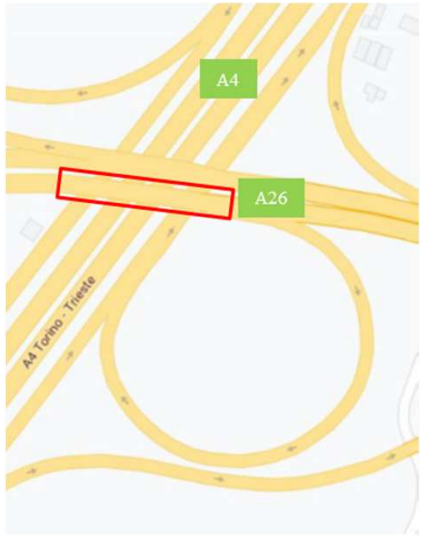
Reliable strengthening depends on the response of the existing member, the new layer and their interface.

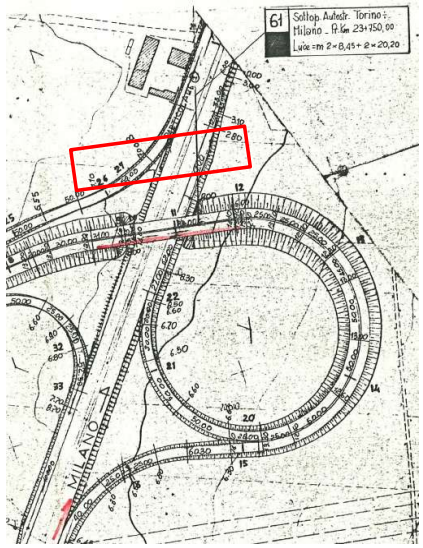
01	**Existing member**	Assessment of geometry, materials and deterioration degree (corrosion, prestress loss…)
02	**Strengthening layer**	Force transfer, crack control and added-extra resistance
03	**Interface**	Compatibility and bond under structural demand
04	**Failure mode**	Control of the governing mechanism after strengthening avoding as far as possible those undesirable and brittle

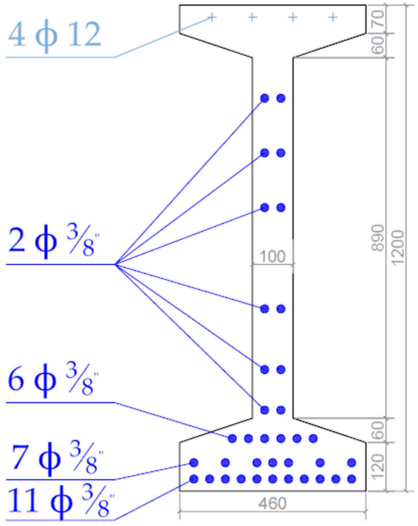


SHEAR STRENGTHENING OF 60-YEAR-OLD PRESTRESSED GIRDERS

STARTING POINT



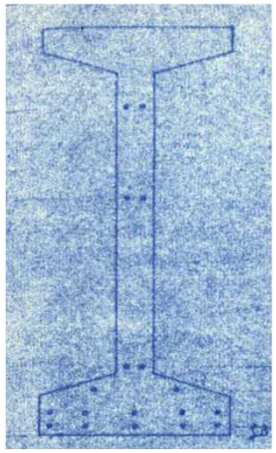


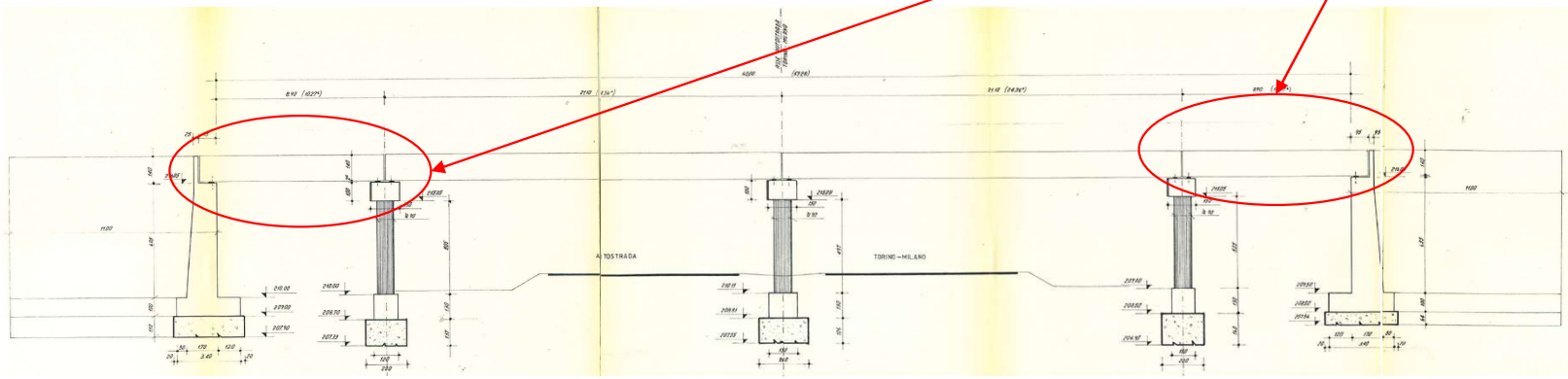


- Age: **1967-1969**
- Location: **Highway Ivrea-Santhià** – overpass on Torino-Milano highway
- Static Scheme: Simply Supported Pre-tesioned Beams

  4 span bridge: 2 central spans 24 m long and

  2 end spans 11 m long





DEGRADATION CONDITIONS AND SECTIONS RECONSTRUCTION

1. **Sealing of Existing cracks**
2. **Hydro demolition** with water high pressure
3. **Reconstruction of the damaged (during dismantling) flanges** (concrete similar to the existing one – only repairing no strengthening)





Beam 1



Beam 2



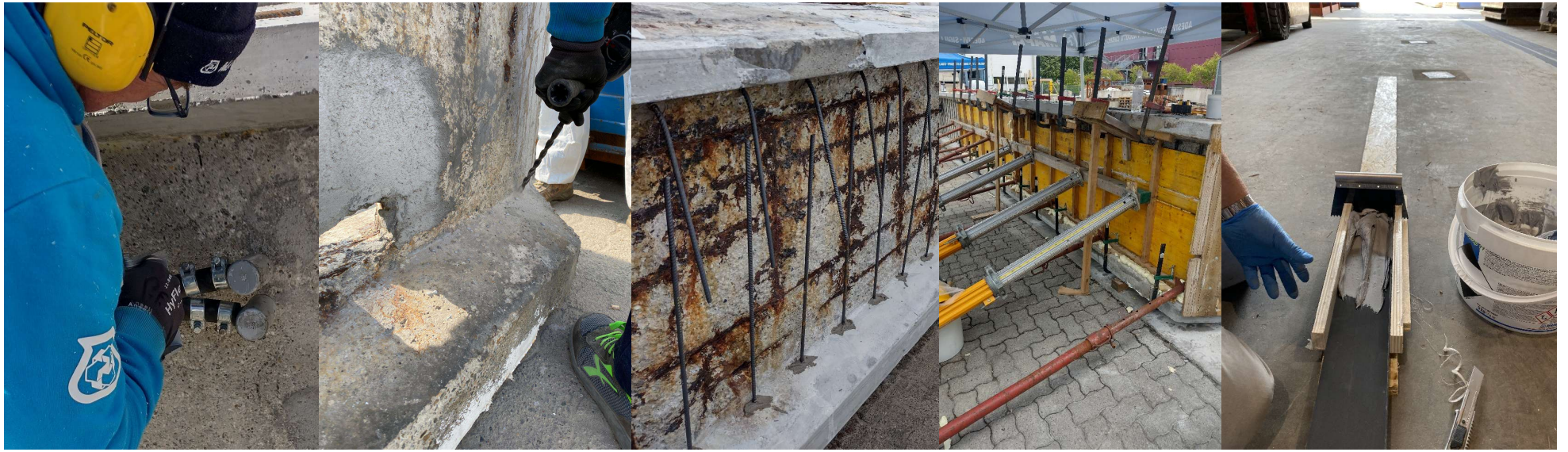
Beam 3



STRENGTHENING TECHNIQUE

1. **(Machine) Roughening** of the surface ±*3mm*
2. Implementation of inclined holes for the anchorage shear **additional reinforcement** and position of the reinforcement
3. **Wooden formworks** except for the last 15 cm on the top for pouring HPFRC
4. **Cast** of the 50 mm **FRC overlay,** last 15 cm on the top completed with tixotropic mortar (compatible with HPC floor 46)
5. Position of **FRP:** 4 side by side CFRP plates, 14 mm thick, to give flexural over-resistance





STRENGTHENING TECHNIQUE

50 mm HPFRC overlay – CLASS 8C

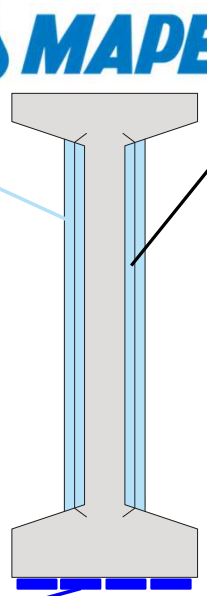


Cementitious Matrix:

Bulk Density (kg/m^3):	1400
Maximum Size of Aggregate (mm):	6
Compressive Strength (MPa):	125

Fibers:

Shape:	Hooked
Material:	Steel
Length (mm):	30
Diameter (mm):	0,38
Elongation at Failure (10^{-3}):	min. 7,0

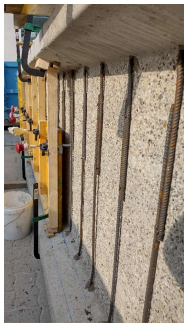


Additional Shear Reinforcement

Stirrups or Dowels
B450C Ø10/200 mm

Specimen	Stirrups	Dowels
1S EXP		X
2S EXP	X	
3S EXP	X	

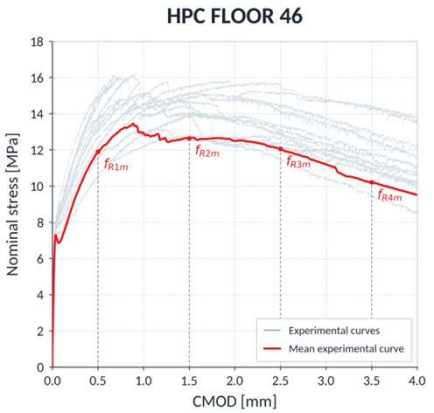






4 side by side **FRP plate** (14 mm thick)

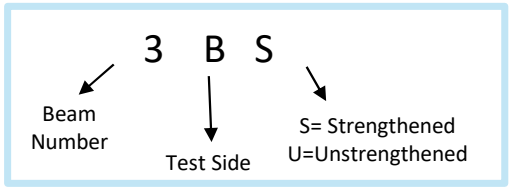
System Class FRP:	C150/2300
Thickness (mm):	1,4
Width (mm):	100
Modulus of Elasticity (GPa):	160
Tensile Strength (MPa):	2.700
Elongation at failure (10^{-3}):	16





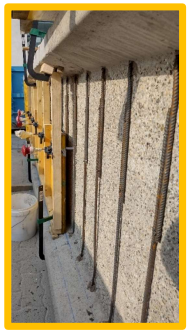
EXPERIMENTAL PROGRAM

10 TESTS ON 3 BEAMS



SPECIMEN	STRENGTHENED / UNSTRENGTHENED	SIDE	TEST
BEAM1	UNSTRENGTHENED	SIDE A	1AU EXP
	STRENGTHENED	SIDE A	1AS EXP
		SIDE B	1BS EXP
BEAM2	UNSTRENGTHENED	SIDE A	2AU EXP
	STRENGTHENED	SIDE A	2AS EXP
		SIDE B	2BS EXP
BEAM3	UNSTRENGTHENED	SIDE A	3AU EXP
		SIDE B	3BU EXP
	STRENGTHENED	SIDE A	3AS EXP
		SIDE B	3BSEXP





	SIDE	UNSTRENGTHENED SHEAR PRE-CRACK TARGET [mm]
BEAM1	A	0,17
BEAM2	A	0,39
BEAM3	A	0,60
	B	0,57

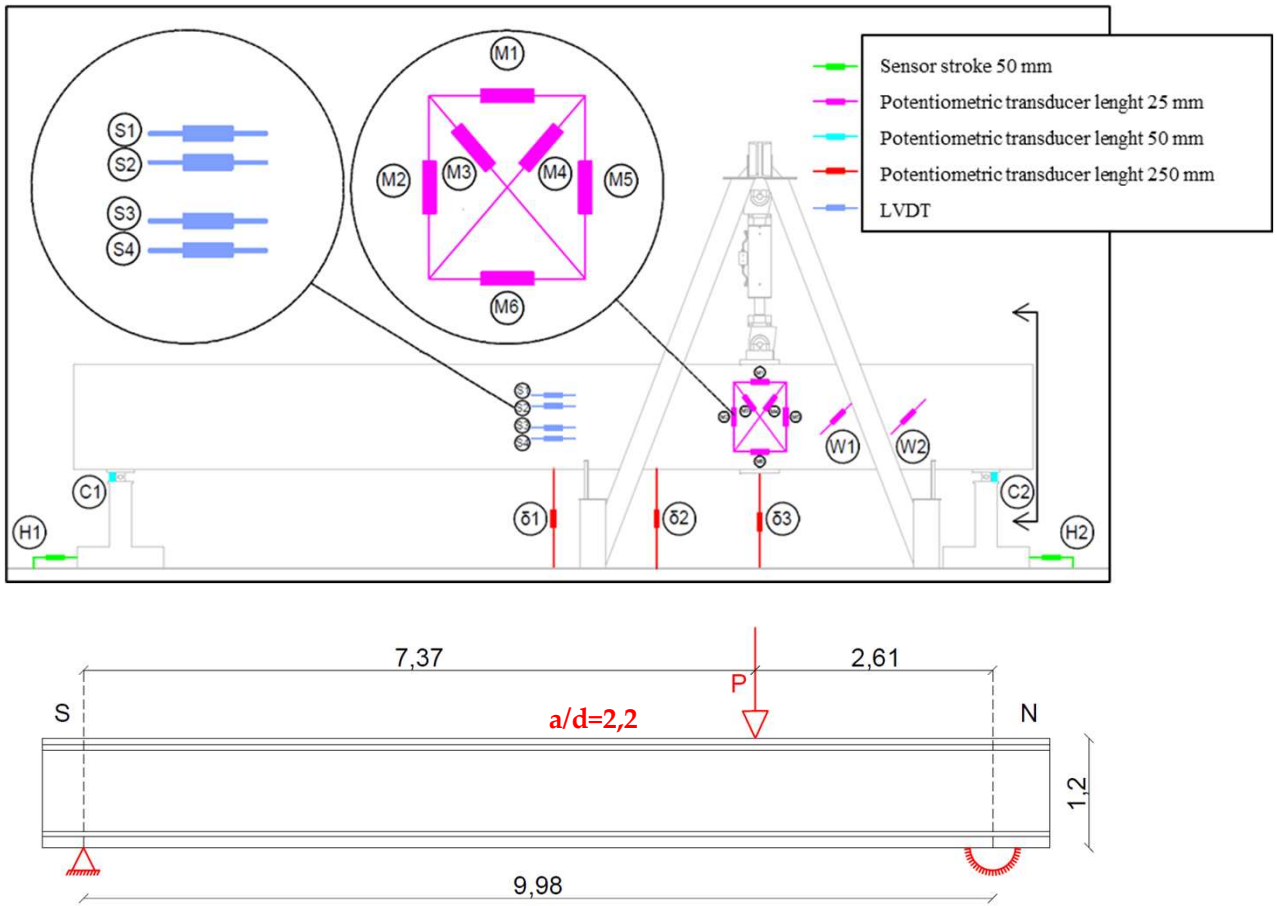
4 Unstrengthened Tests – Precrack Target



6 Strengthened Tests



TEST SETUP AND INSTRUMENTATION



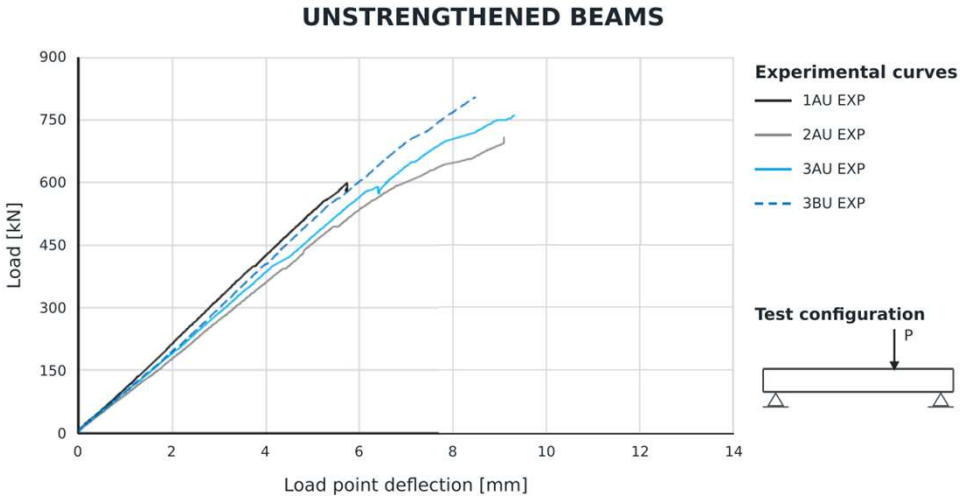
3 Points Loading in displacement control with Max Load of 1400 kN (jack limit)

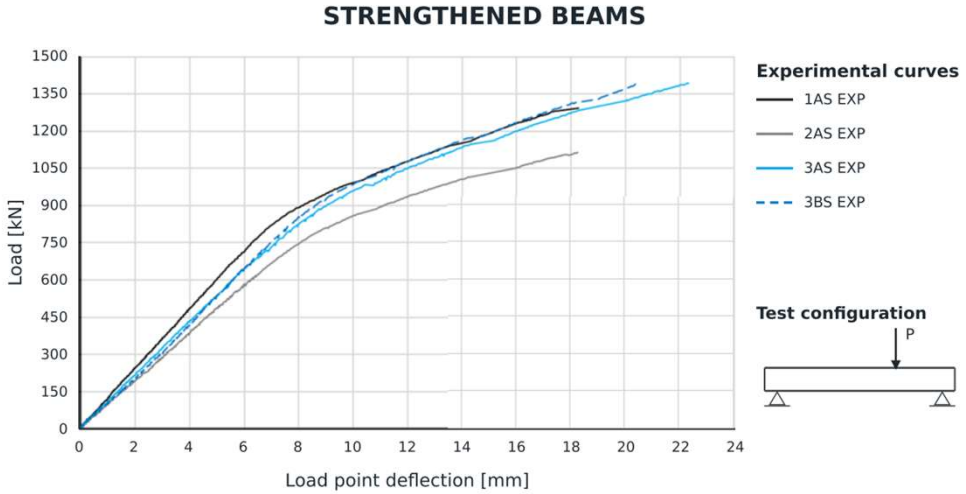
Max Strength at precracking: 800 kN



THE HPFRC LAYER INCREASED THE AVAILABLE LOAD RANGE

Load Point Deflection Curve – UNSTRENGTHENED vs STRENGTHENED – SIDE A



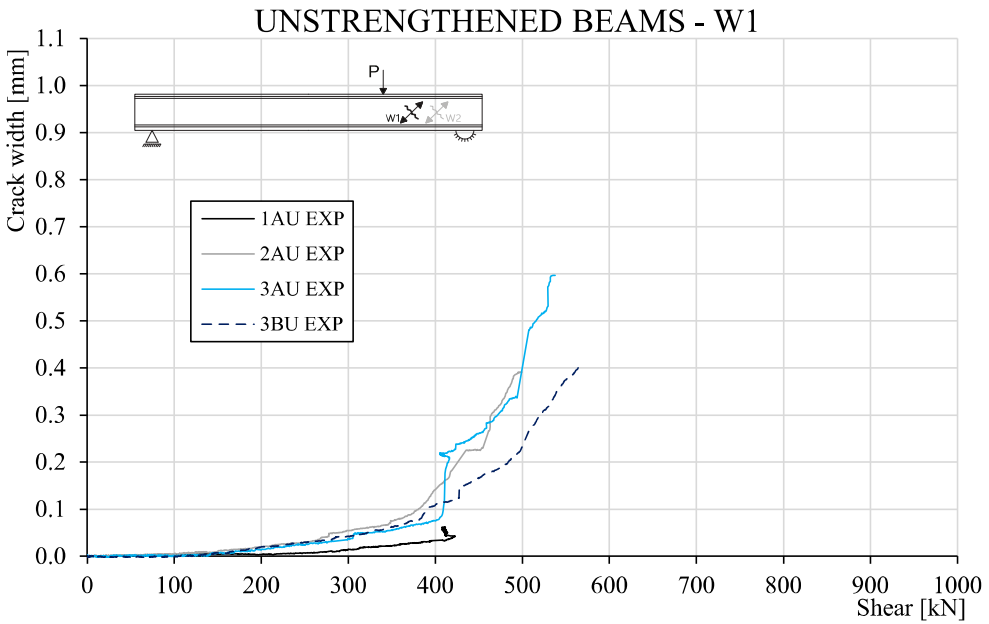


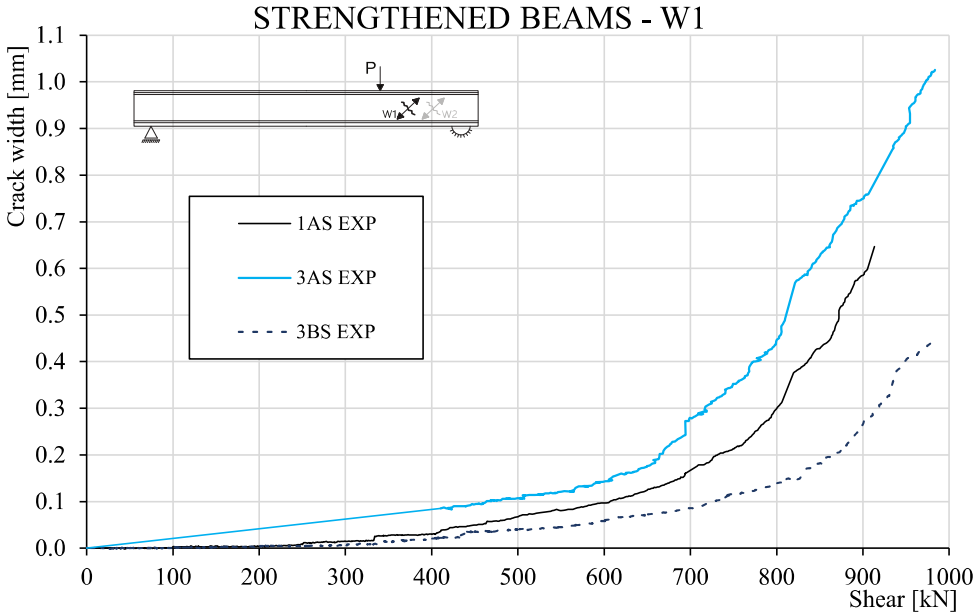
- Experimental curves confirm that **Beam 2** was the **most damaged (corroded)**
- Max load of test A was chosen to allow tests also on Side B

	SIDE	UNSTRENGTHENED			STRENGTHENED	
		PRE-CRACK TARGET [mm]	MAX LOAD [kN]	MAX DEFLECTION [mm]	MAX LOAD [kN]	MAX DEFLECTION [mm]
BEAM1	A	0,17	599	5,7	1294	18,3
BEAM2	A	0,39	708	9,1	1116	18,4
BEAM3	A	0,60	761	9,3	1394	22,4
	B	0,57	805	8,4	1388	20,4

STRENGTHENING STABILIZED SHEAR-CRACK OPENING

Crack Width near Load Point – UNSTRENGTHENED vs STRENGTHENED – SIDE A

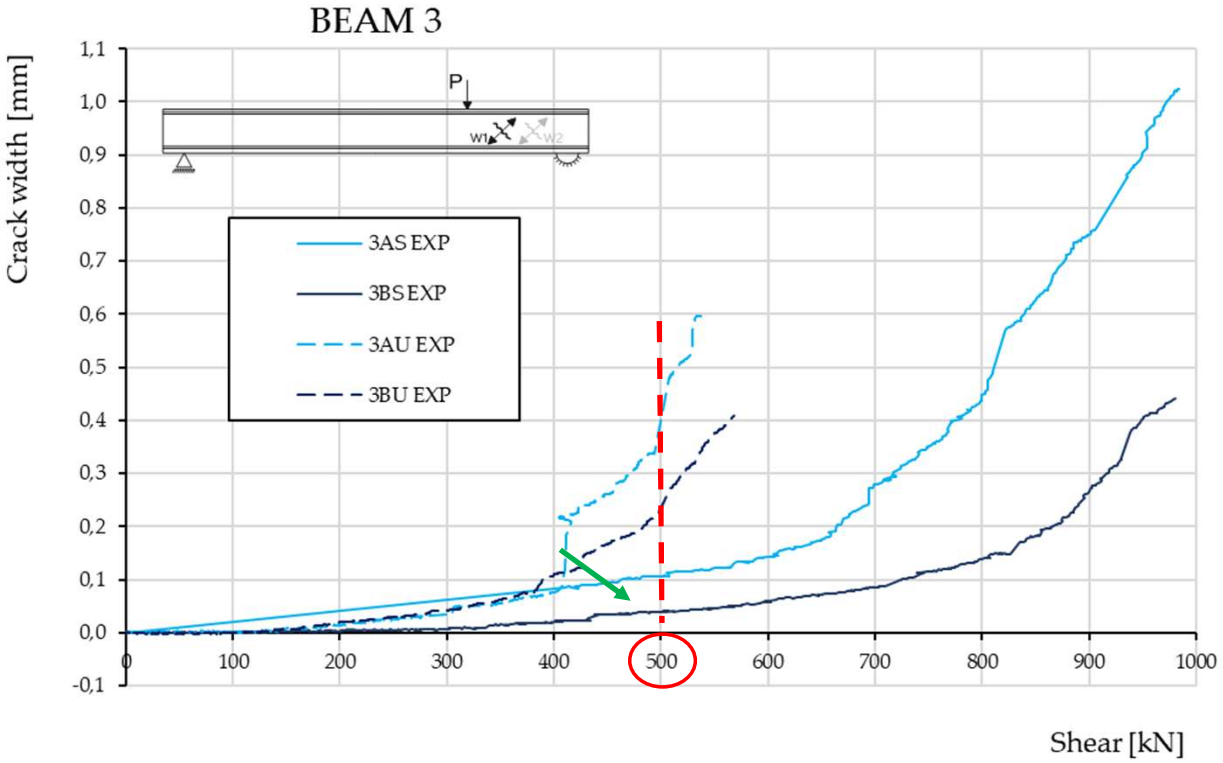




Stabilization of crack initiation and development

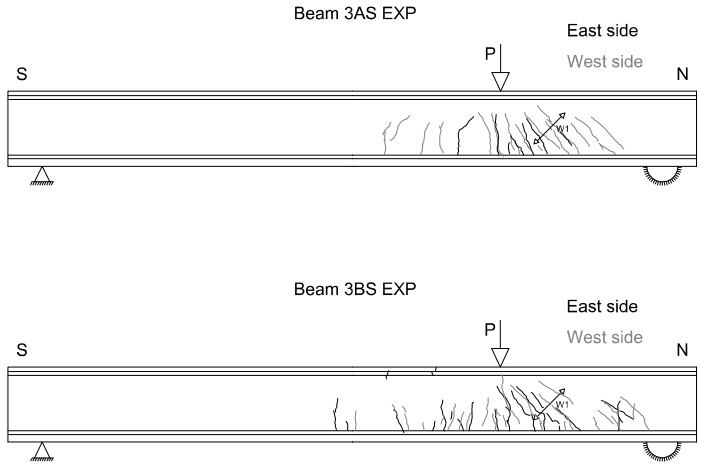
Beam	δ at 500 kN Load [mm]		w at 400 kN Shear [mm]		Crack Width Reduction [%]	w at 500 kN Shear [mm]		Crack Width Reduction [%]
	U	S	U	S		U	S	
1A	4.7	4.1	0.0325	0.0297	8.6%	-	0.0674	-
1B	4.7	4.3	0.0325	0.0312	4%	-	0.0483	-
2A	5.6	5.1	0.0142	0.0061	57%	0.3917	0.0084	98%
2B	5.6	5.6	0.0142	0.0223	-57%	0.3917	0.0464	88%
3A	5.3	4.6	0.0747	0.0731	2%	0.3362	0.107	68%
3B	4.9	4.7	0.108	0.0204	81%	0.2232	0.0392	82%

EXPERIMENTAL RESULTS



Crack width reduction at the same load level

The strengthening provides stabilization of crack width, avoiding sudden openings

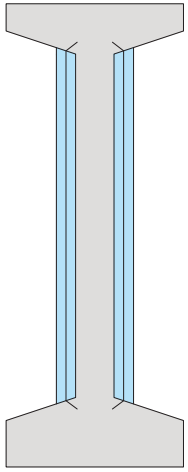


At a shear force of 500 kN, the UBs show a crack width of about 0.25-0.40 mm, whereas the SBs only of 0.05-0.1 mm

FULL-SCALE SHEAR STRENGTHENING: MAIN EVIDENCE

50 mm

HPFRC overlay



- The study demonstrated the **feasibility of a demanding full-scale structural application of HPFRC, from both structural and technological perspectives**.
- The proposed strengthening technique provided a **substantial reduction in shear-crack width** compared with the unstrengthened girders.
- The interface exhibited **excellent bond performance**, with no measurable slip or premature debonding between the existing concrete substrate and the overlay.
- **Stirrups and dowels** used as shear connectors produced no significant differences in the global response. This result suggests **scope for optimizing connector detailing, particularly the anchorage length**.
- Further research should investigate the **interface shear–slip response between HPFRC and normal to medium strength concrete substrates**.

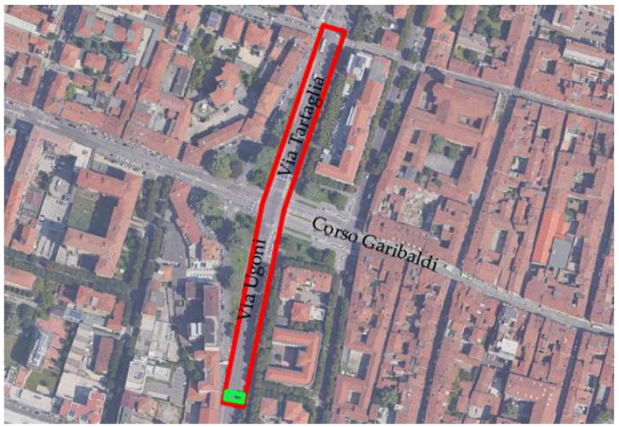
The intervention changed the structural response, not only the local material resistance.

FLEXURAL STRENGTHENING OF A HISTORIC RC GIRDER



COMUNE DI BRESCIA

STARTING POINT

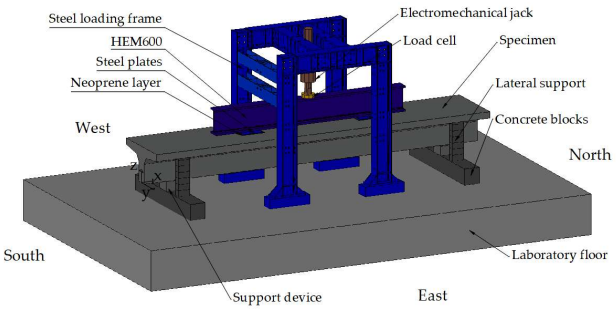


1927



- **94 years** of service life
- Weight **12,5 ton**
- Length **9 m**
- Height **90 cm**

a/d = 2.5
a ≈ l/4





2021



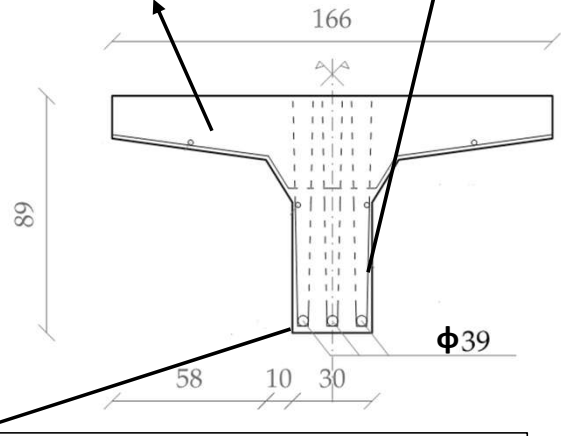


EXISTING GIRDER: ASSESSMENT

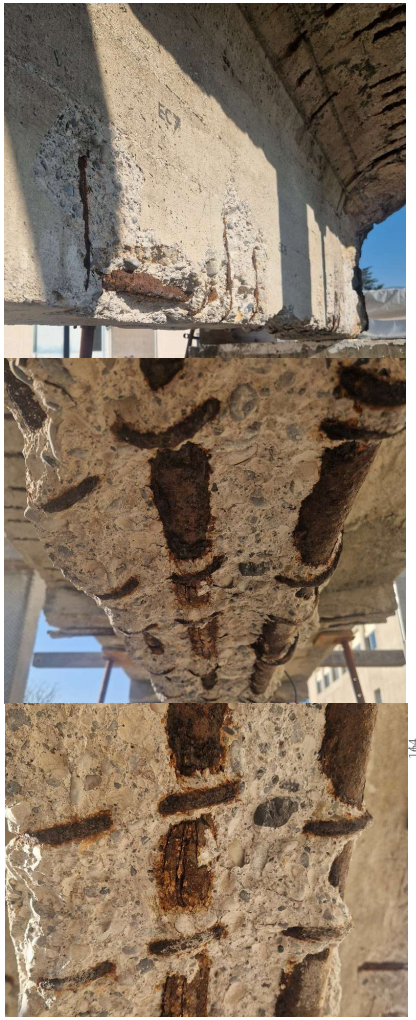
Geometry, Materials, Degradation conditions

Existing Stirrups
6 arms ϕ10/20cm
m_{corr}= 31.6%
f_{ym}= 268 MPa

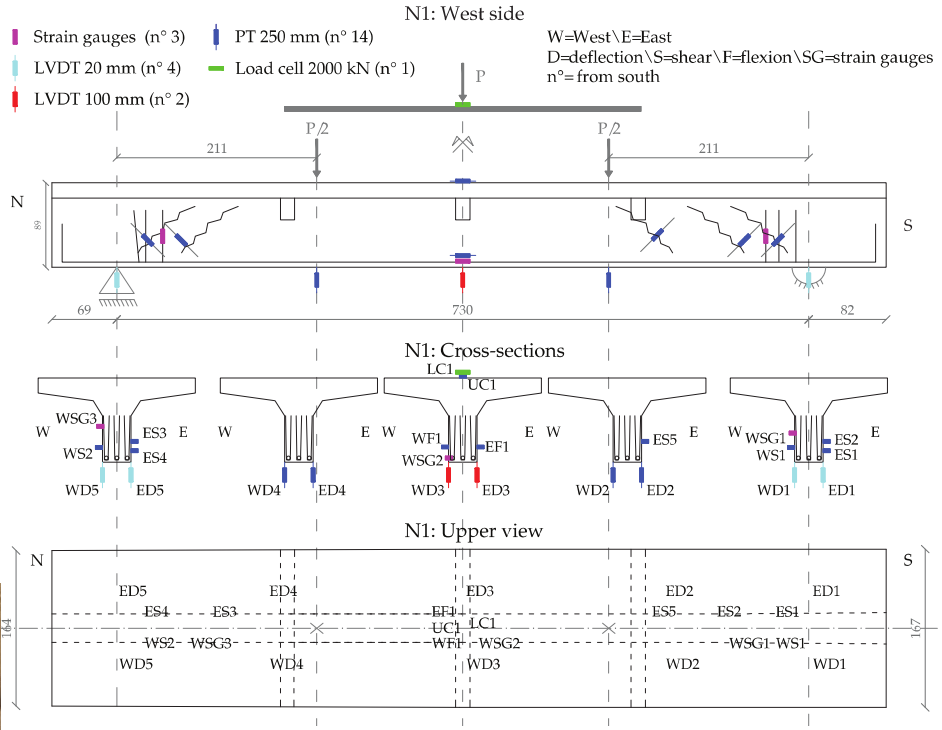
Existing Concrete
f_{cm}= 44 MPa



Existing Long. Bars (smooth) ϕ39
m_{corr}= 3.8%
f_{ym}= 287 MPa
f_{um}= 412 MPa
E_{sm}= 203000 MPa



25 measuring devices



STRUCTURAL AND OPERATIONAL REASONS FOR STRENGTHENING

Exposure Conditions and Degradation

- Exposure to water, humidity and aggressive agents



- Corrosion, concrete cover loss and compromised durability



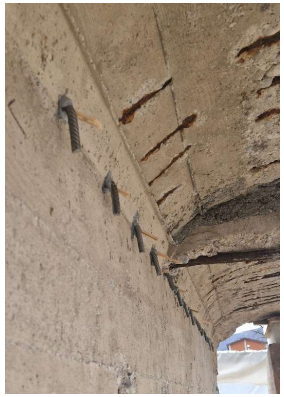
Traffic Interruption



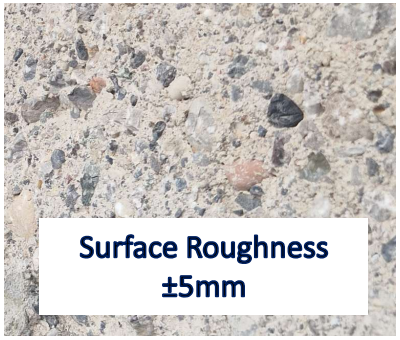
Via Ugoni is a **key urban traffic corridor** in Brescia. Bridge replacement would require prolonged traffic interruption, resulting in **significant user delays** and **socio-economic costs**.

Strengthening often represents a more sustainable and less disruptive intervention strategy

STRENGTHENING CONCEPT

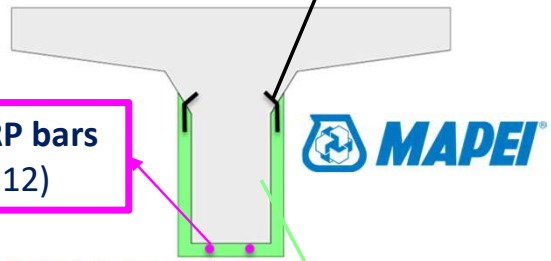


Dowels (B450C Ø10/200 mm)



Surface Roughness ±5mm





2 CFRP bars (Ø12)



50 mm overlay
FRM–PP (EN14651 3e)

- **Sprayed thixotropic Mortar** (no formworks)
- **Non-metallic materials** (durability)







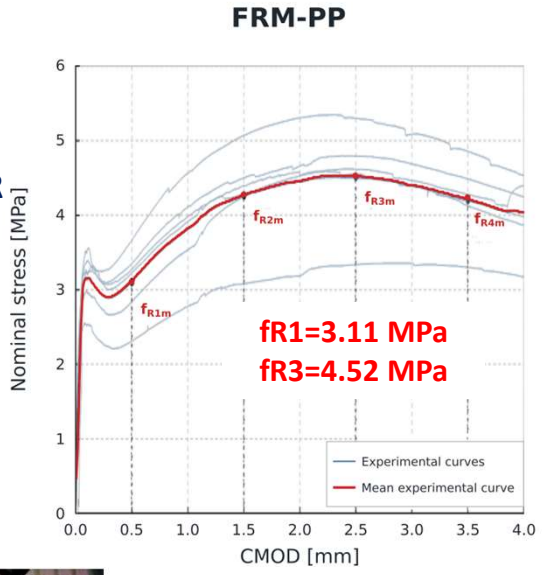


MATERIALS PROPERTIES



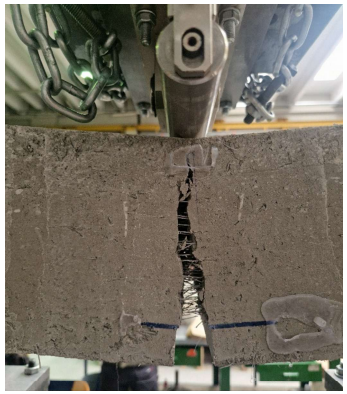


SPRAYED FIBRE-REINFORCED MORTAR AND CFRP BARS





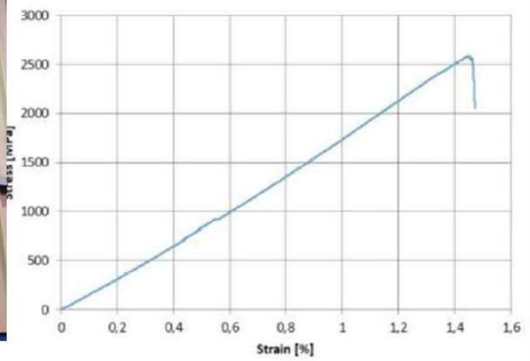
- **10 cubes**
  (dimensions 150 × 150 × 150 mm)
- **6 notched beams**
  (dimensions 150 × 150 × 600 mm)
- **12 prismsmatic specimens**
  (dimensions 40 × 40 × 160 mm)
- **8 cylinders**
  (dimensions 100 mm diameter × 200 mm height)



FRM-PP	
f_c [MPa]	41.2
E_c [GPa]	28
Fibers' shape	straight
V_f [%]	0.44
Fibers' length [mm]	24
Class [UNI EN 14651]	3e



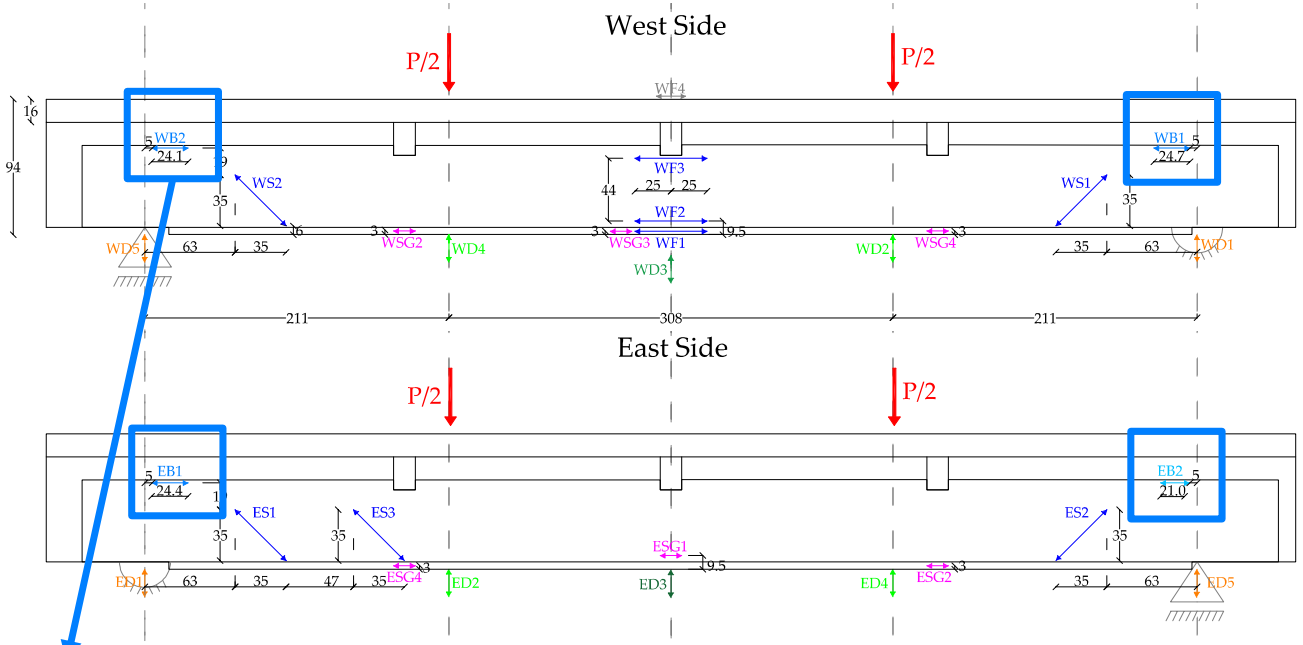
Strengthening CFRP Bars



CFRP bars	
Ø [mm]	12
f_u [MPa]	2540
E [GPa]	168
Ultimate strain [%]	1.5%

TEST SETUP AND INSTRUMENTATION





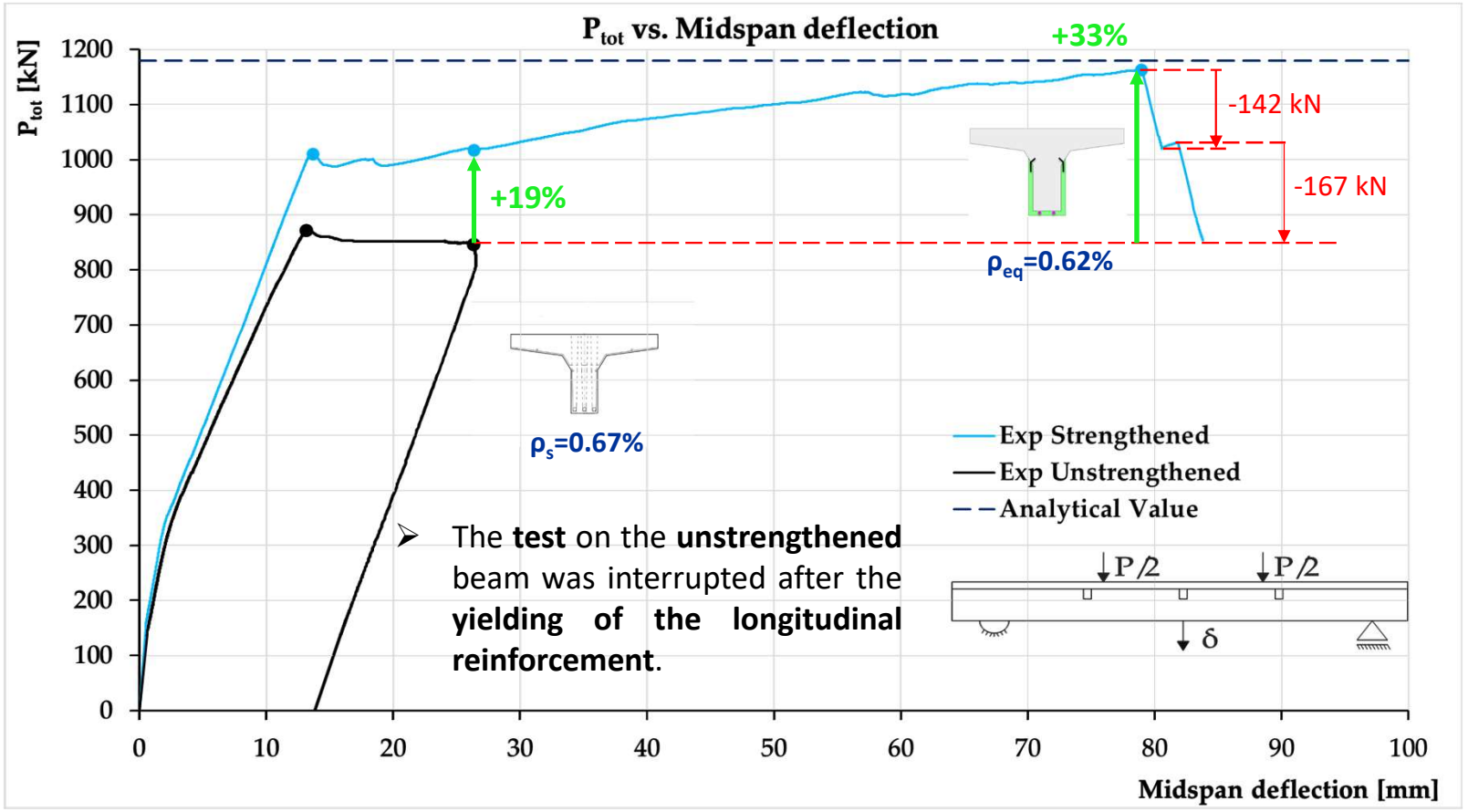
	Gauge Length [mm]	Δmax [mm]	εmax
WB1	247	0,00075	3,0E-06
EB1	241	0,01031	4,3E-05
WB2	244	0,00823	3,4E-05
EB2	210	0,00611	2,9E-05



Legend

- LVDT (10 mm) - Support displacement
- LVDT (100 mm) - Midspan deflections
- PT (250 mm) - Load Points Deflections
- PT (250 mm) - Shear and Flexural cracks width
- PT (50 mm / 25 mm) - slip between existing section and overlay
- SG on existing bars (ESG1) and on the CFRP bars
- PT (50) - Concrete compressive strain

EXPERIMENTAL RESULTS: 33% HIGHER CAPACITY

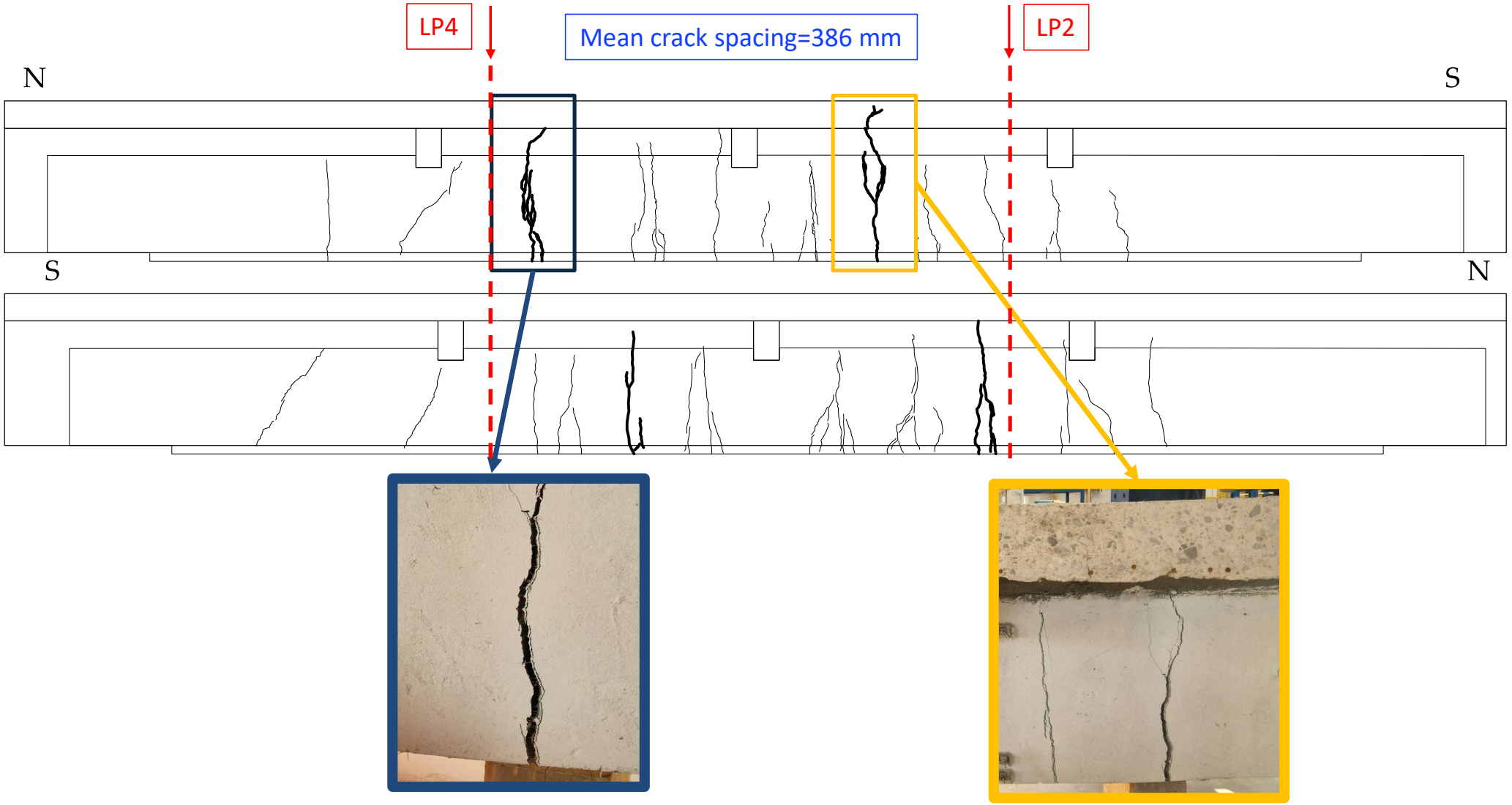


- The **strengthened** specimen exhibited a **33% increase** in **maximum load**, consistent with the analytical prediction of the ultimate capacity.
- **Failure** occurs due to **rupture of the CFRP bars** (the curve drops back to the load level of the unstrengthened test).

Ductility μ_s=6

	P_s [kN]	δ [mm]	P_u [kN]
Yielding	1011	13,6	873
Unloading	1018	26,3	846
Max Load	1163	78,9	873

CRACK PATTERN



SECTION ANALYSIS AND CONSTITUTIVE ASSUMPTIONS: ANALYTICAL M-χ

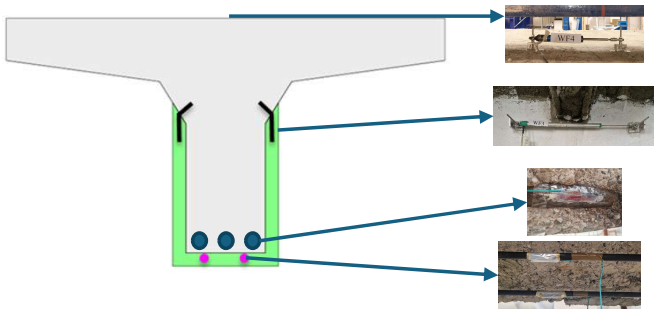
For a given curvature χ:

1. Assume the neutral axis → 2. Calculate strain distribution → 3. Calculate internal forces → 4. Check equilibrium

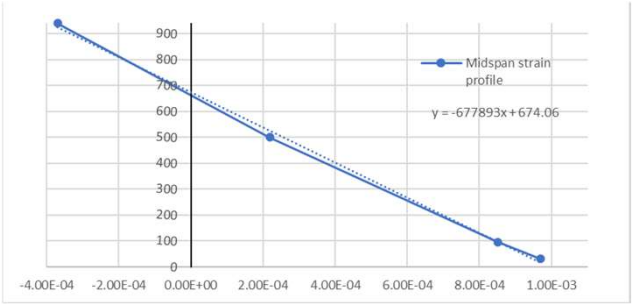
Verified

Update neutral axis

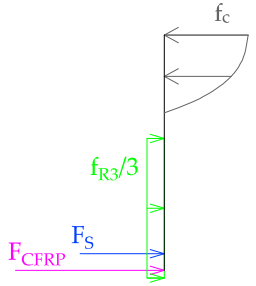
Experimental Measurement



Strain Distribution

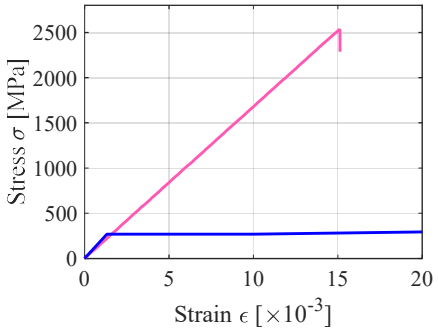


Stresses Distribution

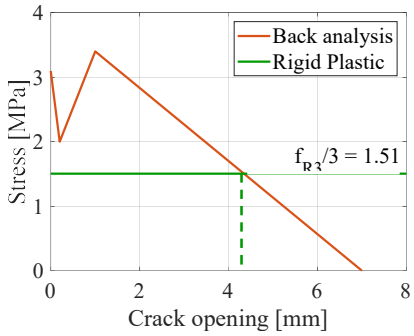


Constitutive Laws in the Analytical Calculation

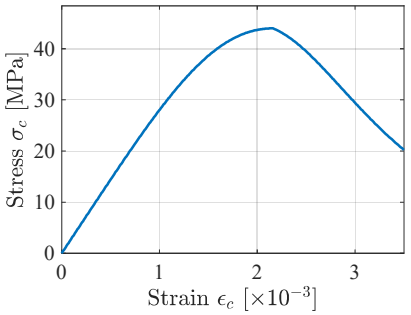
CFRP + Existing Steel



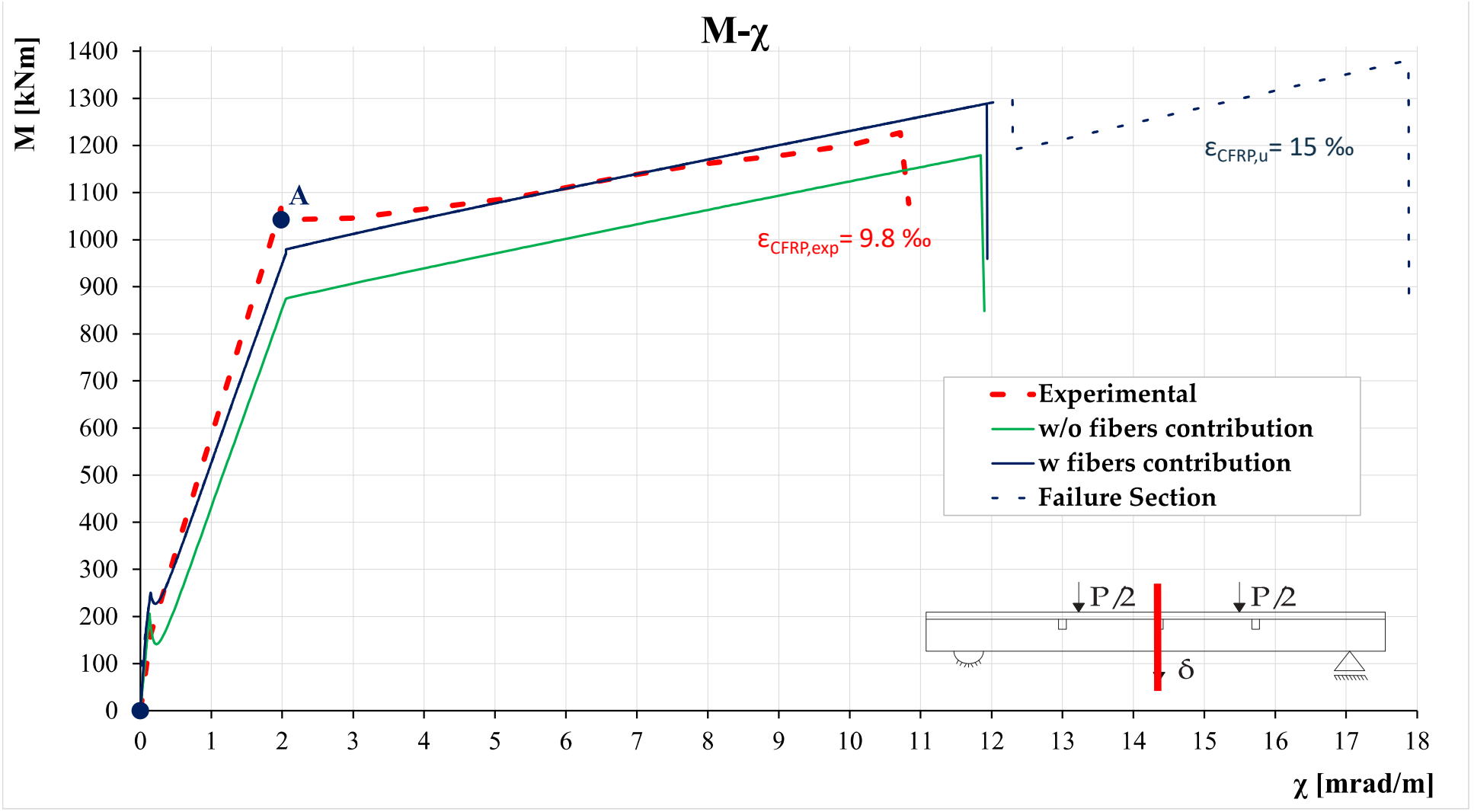
PP Fibers (Rigid plastic behaviour)



Existing Concrete



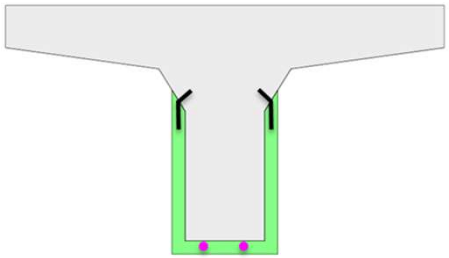
MOMENT–CURVATURE RESPONSE AND FAILURE STRAIN



FULL-SCALE STRENGTHENING: MAIN EVIDENCE

50 mm

HPFRC overlay



- **ULTIMATE CAPACITY**: The strengthening system increased the maximum load by 33%, meeting the targeted flexural performance.
- **DISPLACEMENT DUCTILITY**: The strengthened girder achieved a displacement ductility of approximately 6, owing to the combined response of the existing steel reinforcement, CFRP bars and fibre-reinforced mortar.
- **CONTROLLED FAILURE MODE**: Failure was governed by CFRP bar rupture, with no premature debonding or interface failure.
- **DURABILITY**: The use of CFRP bars and fibre-reinforced mortar reduces the vulnerability of the strengthening system to future corrosion-related deterioration.

Mechanics-based assessment and targeted strengthening can restore structural capacity and support the service-life extension of deteriorated existing girders



INTERFACE MECHANICS

LOCAL BOND TEST

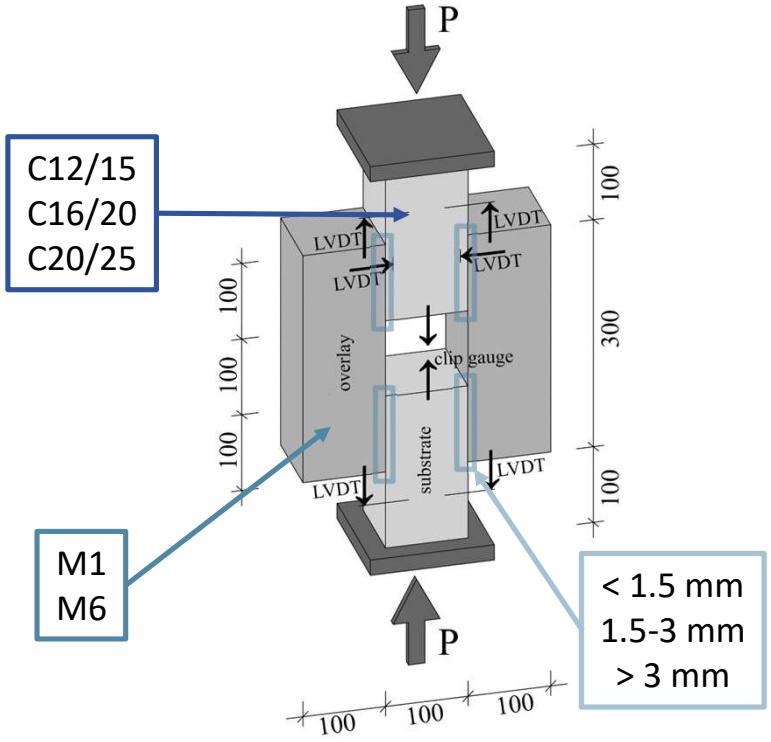
Strengthening: M1, M6 (x2) – Class 8c

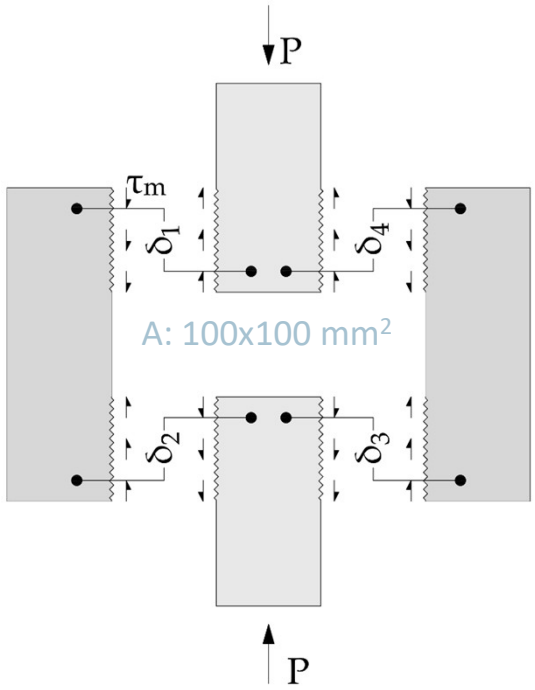
Roughness: < 1.5 mm, 1.5-3 mm, > 3 mm (x3)

Substrate: C12/15, C16/20, C20/25 (x3)

(x4)
n_p=72

$$\tau_m = \frac{P}{2A}$$



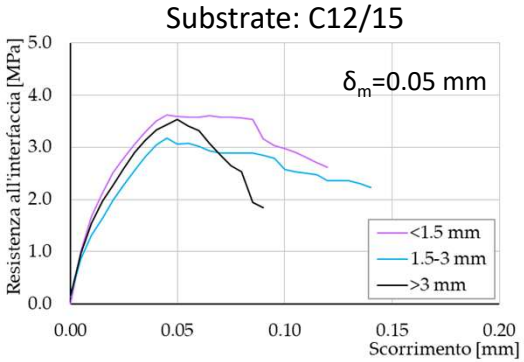


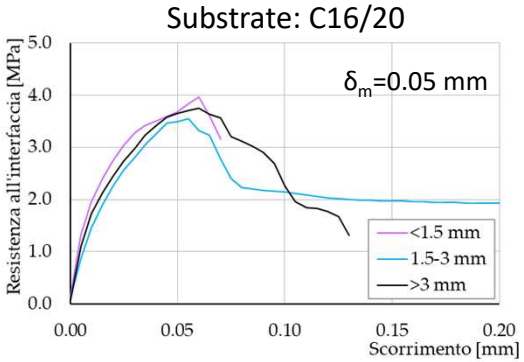


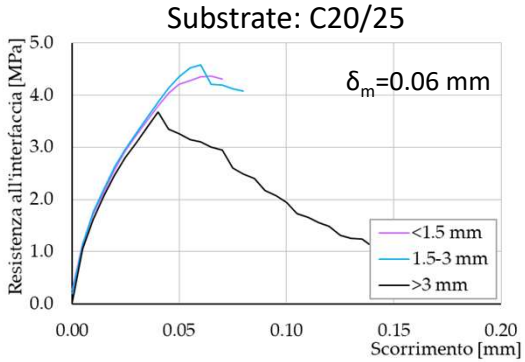
LOCAL BOND TEST

Influence of concrete substrate surface roughness: **shear stress vs slip curves**

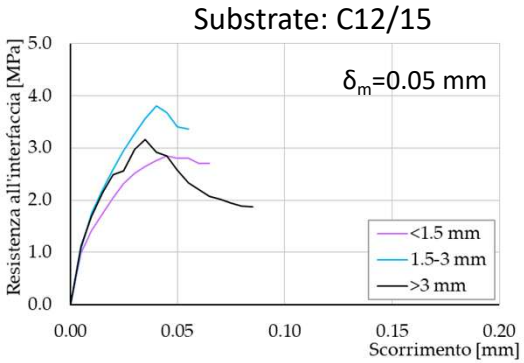
Strengthening: M1 **1**

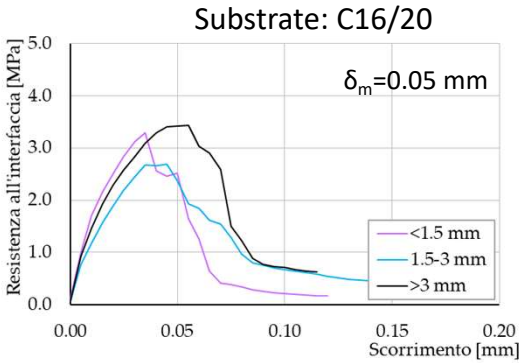


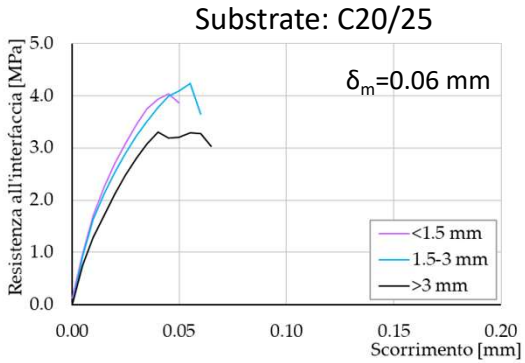




Strengthening: M6 **6**



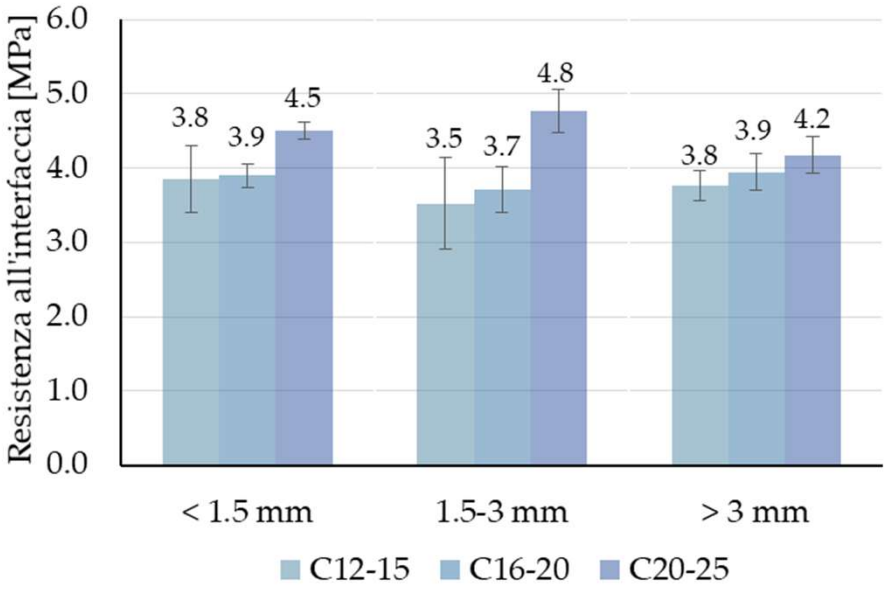




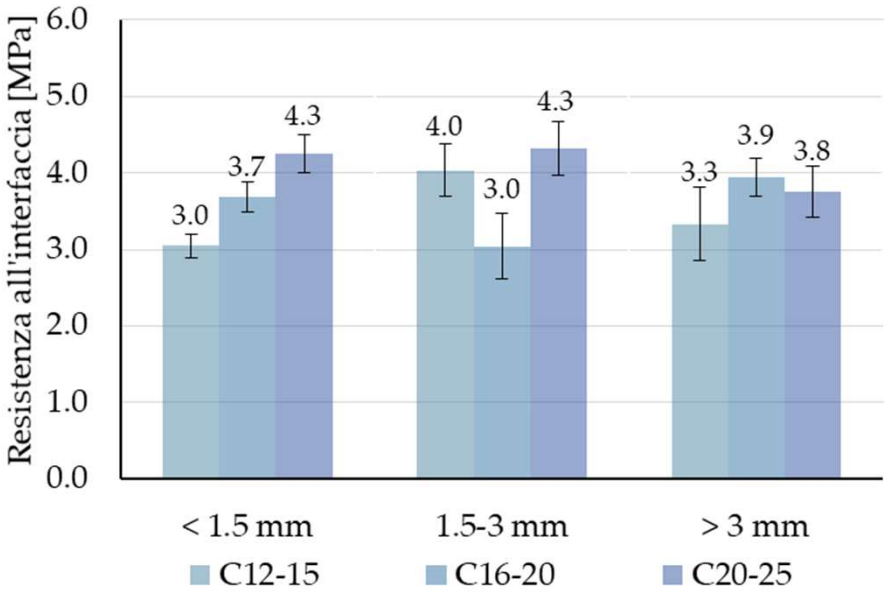
SUBSTRATE STRENGTH CONTROLS THE BOND RESPONSE

Influence of the concrete substrate strength class

Strengthening: M1 1

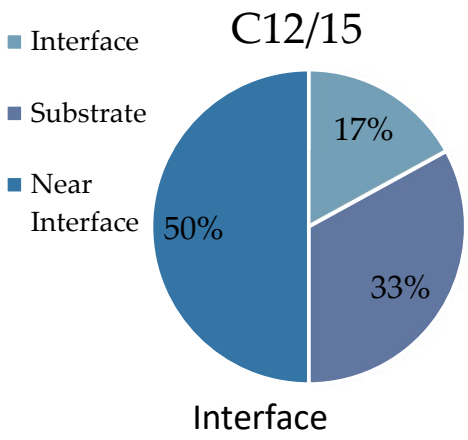


Strengthening: M6 6



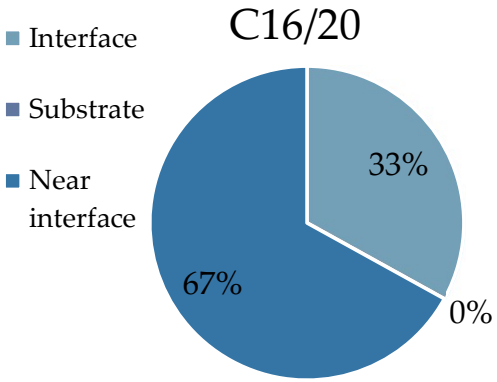
FAILURE MODE

Failure mode M6 6



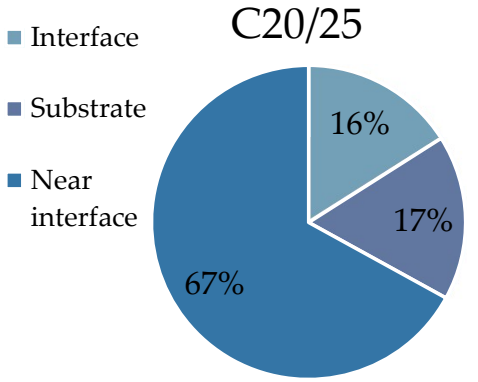
Interface





Near interface





Substrate

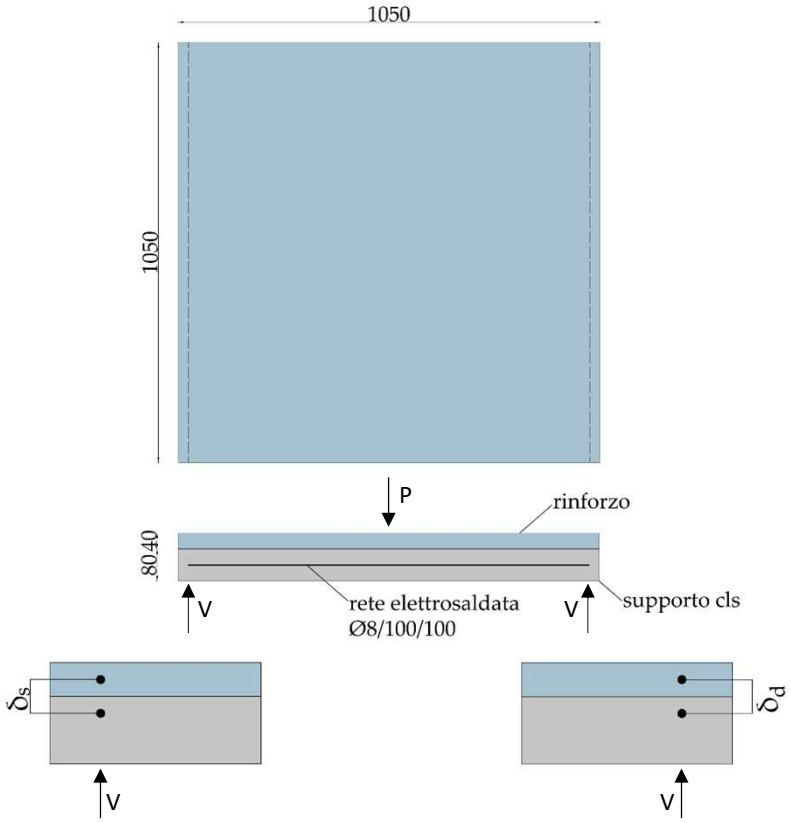


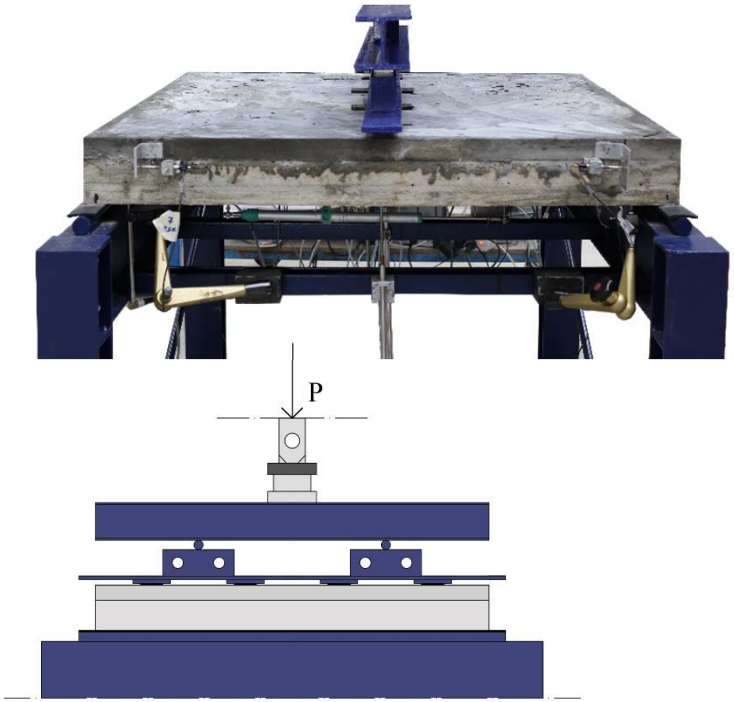
INTERFACE BOND IN SLABS

Strengthening: M1, M6

Roughness: < 1.5 mm, 1.5-3 mm, > 3 mm

Substrate: C16/20





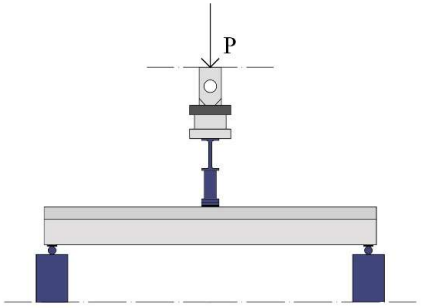


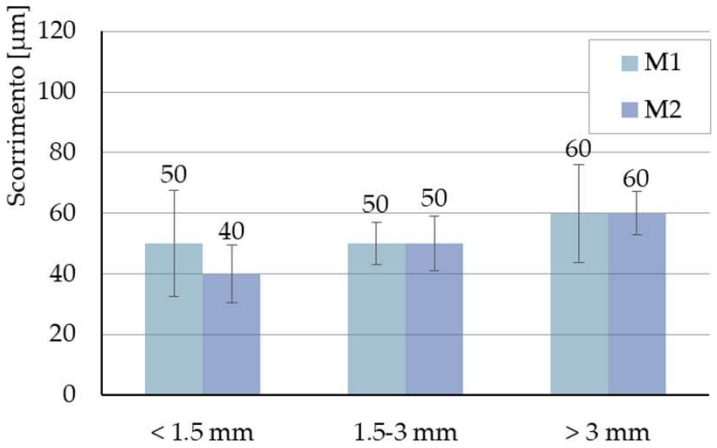
plate supported on two sides
line load at midspan

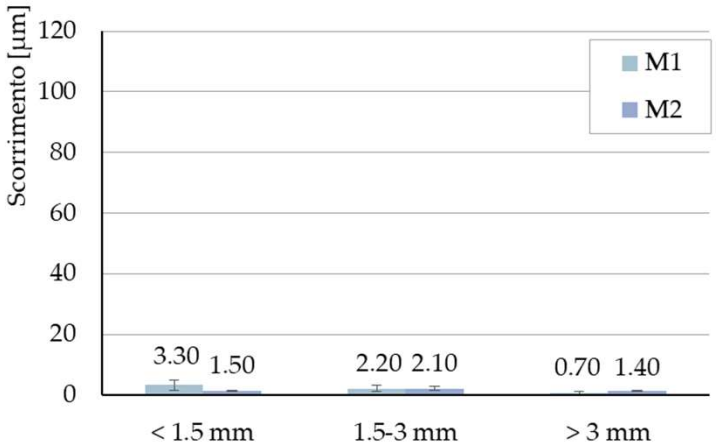
INTERFACE BOND IN SLABS

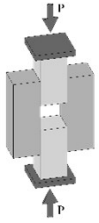
Strengthening: 1 M1

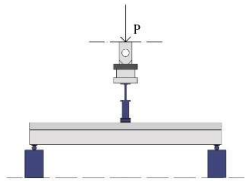
6 **M6**

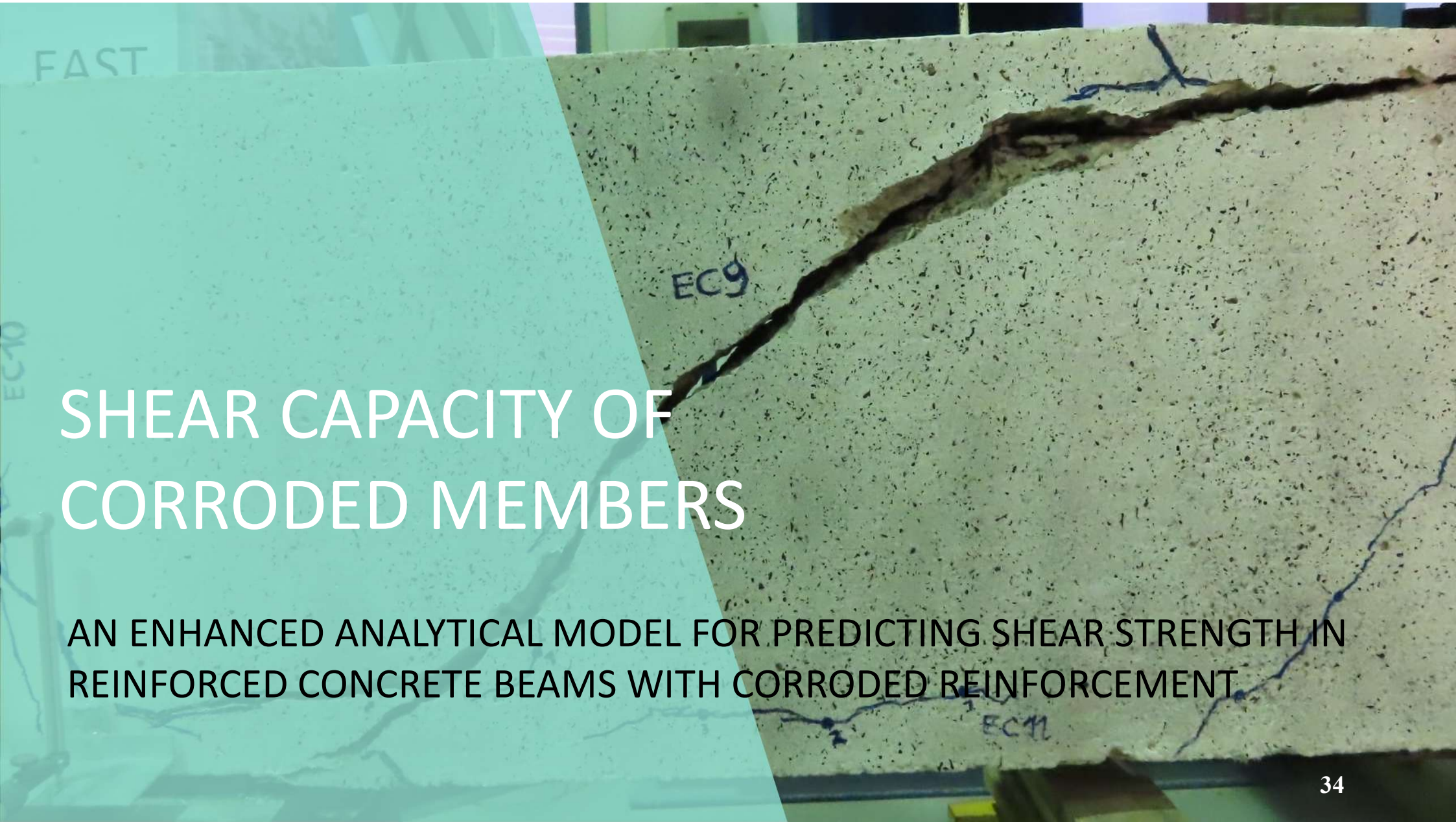
Substrate: C16/20











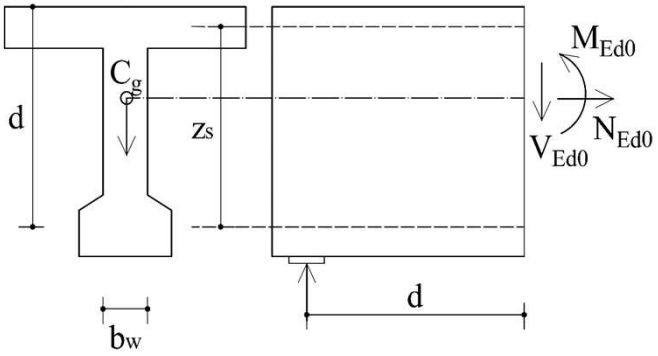
SHEAR CAPACITY OF CORRODED MEMBERS

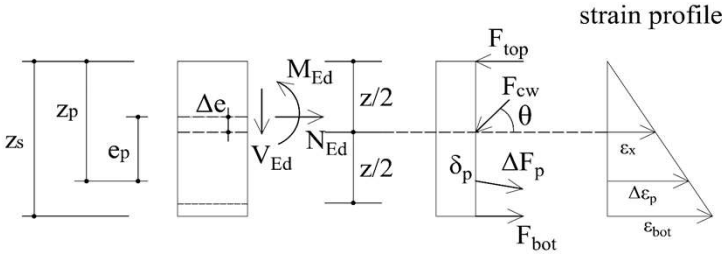
AN ENHANCED ANALYTICAL MODEL FOR PREDICTING SHEAR STRENGTH IN REINFORCED CONCRETE BEAMS WITH CORRODED REINFORCEMENT

AN ENHANCED ANALYTICAL MODEL FOR PREDICTING SHEAR STRENGTH IN REINFORCED CONCRETE BEAMS WITH CORRODED REINFORCEMENT

STRUCTURAL CONCRETE, ACCEPTED 29/12/2025

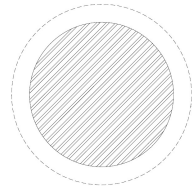
Based on the Model Code 2020
Members with shear reinforcement, **IIb approach**







Uniform Corrosion



$$V_{AN} = V_C + V_S$$

$$V_C = k_v \sqrt{f_c} B_{corr} z_v$$

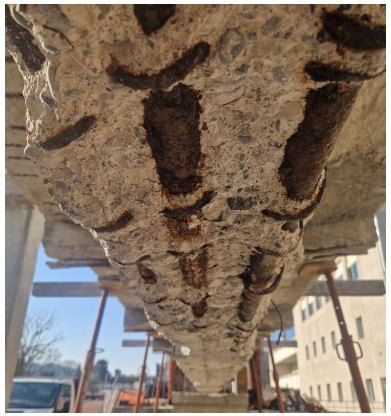
Concrete contribution

$$V_S = \frac{A_w}{s_w} z_v f_{yw,corr} \cot\theta$$

Stirrup's contribution

CORROSION PARAMETERS

Longitudinal Reinforcement



$m_{corr,L}$ *average mass loss ratio related to the longitudinal rebars*

$$A_{L,corr} = n_L \frac{\Phi_L^2}{4}\pi(1 - m_{corr,L})$$

reduced cross section of longitudinal rebars

$$\varepsilon_x = \frac{1}{2E_S A_{L,corr}}\left(\frac{M_E}{z_v} + V_E\right)$$

average state of strain at the mid–depth of the effective shear depth

$$k_v = \frac{0.4}{1 + 1500\varepsilon_x}$$

coefficient for the calculation of V_c

$$\theta = 29 + 7000\,\varepsilon_x$$

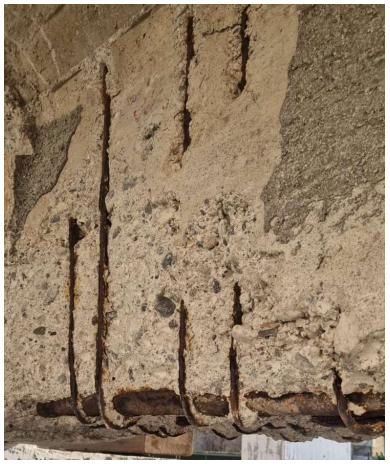
inclination of the compressive stress field with respect to the longitudinal axis of the beam

$$V_C = k_v\sqrt{f_c}\,b_{corr}z_v$$

$$V_S = \frac{A_w}{s_w} z_v f_{yw,corr}\cot\theta$$

CORROSION PARAMETERS

Stirrups



Corrosion parameters

- Longitudinal Rebars
- Concrete
- Stirrups

$m_{corr,w}$

average mass loss ratio related to the stirrups

α_w

empirical coefficient as a function of the diameter of the stirrups (Imperatore et al., 2017)

Φ_w [mm]	α_w
6	0.01642
8	0.01642
10-14	0.01435

$$f_{yw,corr} = f_{yw}(1 - \alpha_w m_{corr,w} * 100)$$

yield stress of the corroded stirrups

$$V_C = k_v \sqrt{f_c} b_{corr} z_v$$

$$V_S = \frac{A_w}{s_w} z_v f_{yw,corr} \cot \theta$$

CORROSION PARAMETERS

Concrete

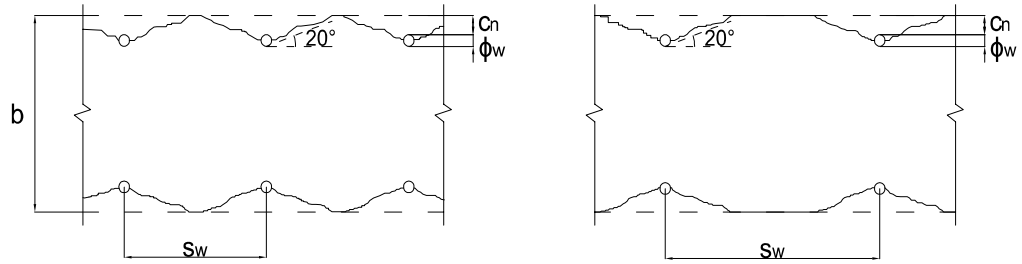


Corrosion parameters

- Longitudinal Rebars
- Concrete
- Stirrups

Higgins et al., 2010

$s_w \leq 5.5c_n$ $\qquad$ $s_w > 5.5c_n$

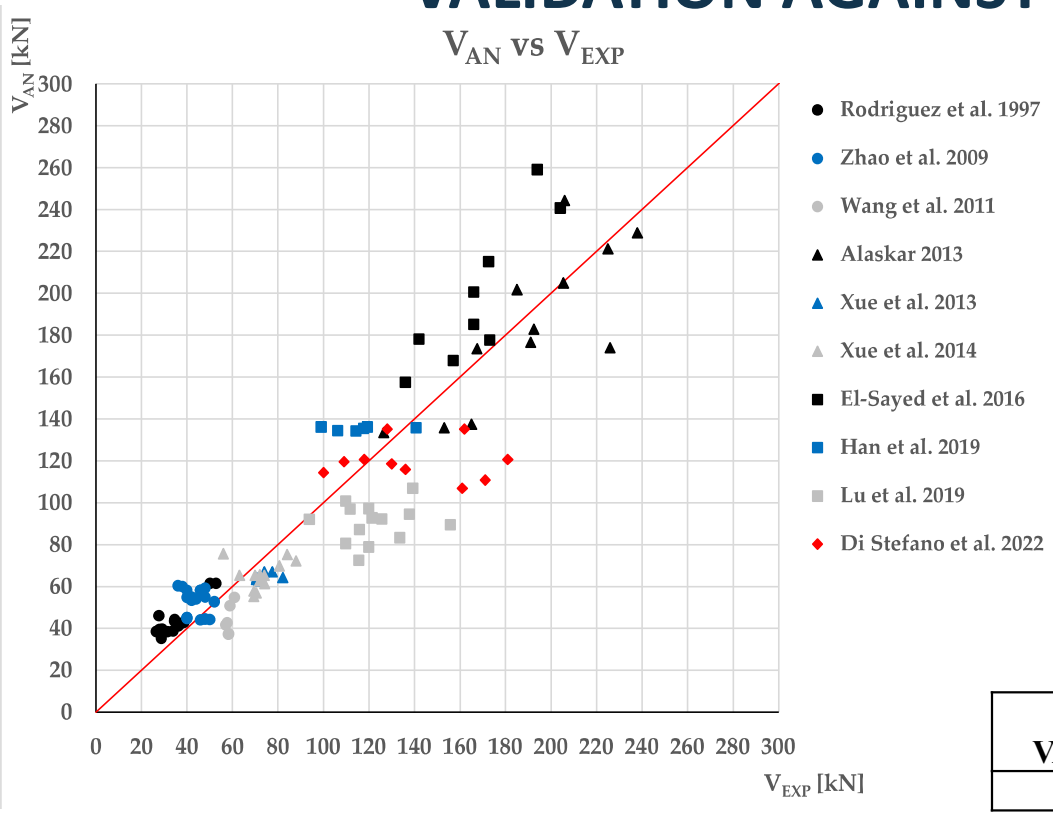


(a) $\qquad$ (b)

$$b_{corr} = b - 2(c_n + \phi_w) + \frac{s_w}{5.5} \qquad b_{corr} = b - \frac{5.5}{s_w}(c_n + \phi_w)^2$$

$$V_C = k_v \sqrt{f_c} b_{corr} z_v \qquad V_S = \frac{A_w}{s_w} z_v f_{yw,corr} \cot\theta$$

VALIDATION AGAINST 108 SHEAR TESTS



	Mean	CoV
Rodriguez et al. 1997	1,27	12%
Zhao et al. 2009	1,23	17%
Wang et al. 2011	0,73	17%
Alaskar 2013	0,98	12%
Xue et al. 2013	0,87	5%
Xue et al. 2014	0,91	16%
Han et al. 2019	1,18	12%
El-Sayed et al. 2016	1,19	8%
Lu et al. 2019	0,77	16%
Di Stefano et al. 2022	0,89	21%

	Control Sp.	Corroded Sp.	All Sp.
Mean VAN/VEXP	1,09	1,00	1,02
CoV	19%	25%	23%

- **The relatively high CoV is expected, given the inherent uncertainties in both corrosion development and shear failure. It is also worth noting that the control specimens (without corrosion) exhibited a CoV of 19%, a value that can reasonably be expected to increase when corrosion effects are introduced;**

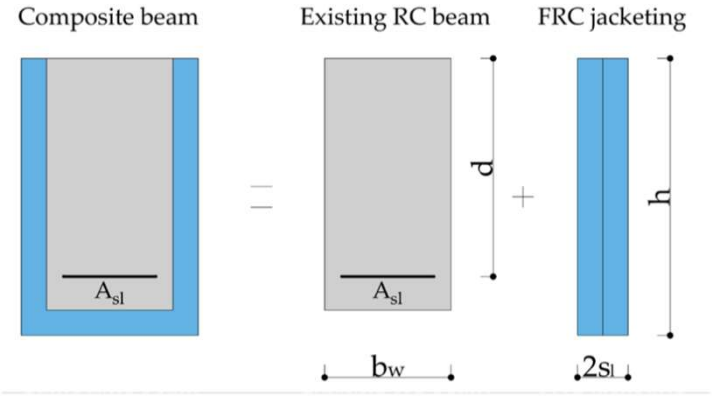
- **The proposed model, based on the SMCFT, represents a rigorous extension of the *fib* MC2020 framework and exhibits strong predictive accuracy across a wide range of test scenarios.**

FINAL GOAL

Unified Analytical Framework for Corroded and Strengthened RC Beams

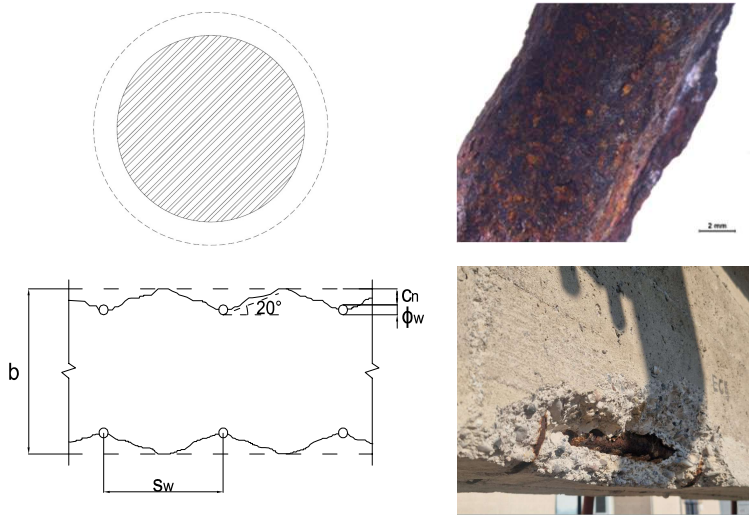
Existing Model

for shear strength of **composite beams**
(Iavarone, 2022)



Proposed Model

for shear strength of **corroded beams**
(Bontempi et al., 2025)



Future Combined Model

for shear strength of corroded and strengthened beams

MAIN CONCLUSIONS: CONDITIONS FOR EFFECTIVE HPFRC STRENGTHENING

1	**Assessment**	The existing member defines the starting capacity and the reliable design assumptions.
2	**Structural effect**	A thin layer can increase strength, delay crack formation, stabilize crack development, provide greater durability, extend service life.
3	**Interface**	Bond and substrate strength may govern before the HPFRC capacity is mobilized. Further research should be done.
4	**Design objective**	The intervention should target a controlled failure mode of the composite member. SUITABLE STRUCTURAL CONCEPTUAL DESIGN is needed
5	**Analytical Models**	Structural engineers need suitable, reliable and easy-to-apply analytical tools for designing structural retrofitting

Thin strengthening layers can produce major structural effects when the whole composite system is properly designed.

Acknowledgements



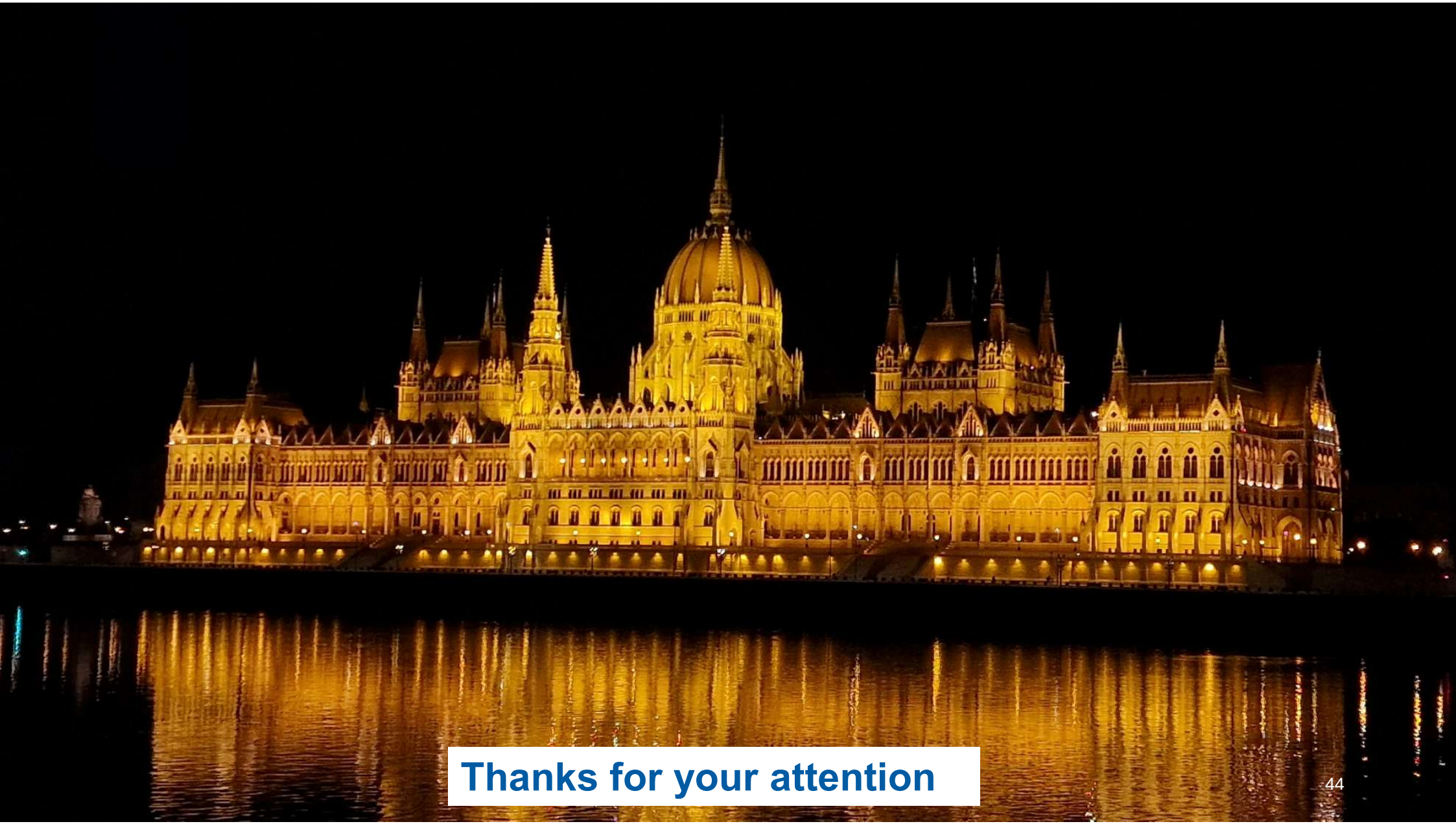
Anna Bontempi, Nico Di Srefano, Fabiola Iavarone, Giovanni Plizzari

I would also like to acknowledge **the students who contributed** to the experimental and analytical work presented today.

Università di Brescia

SPIN-OFF IC&BERG Infrastructure Civil & Bridge Engineering Rehabilitation Group


Thanks for your attention
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Thanks for your attention