FLORIDA INTERNATIONAL UNIVERSITY

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Ferpecle Concrete Bridge in Switzerland Rehabilitation Utilizing UHPFRC

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Switzerland

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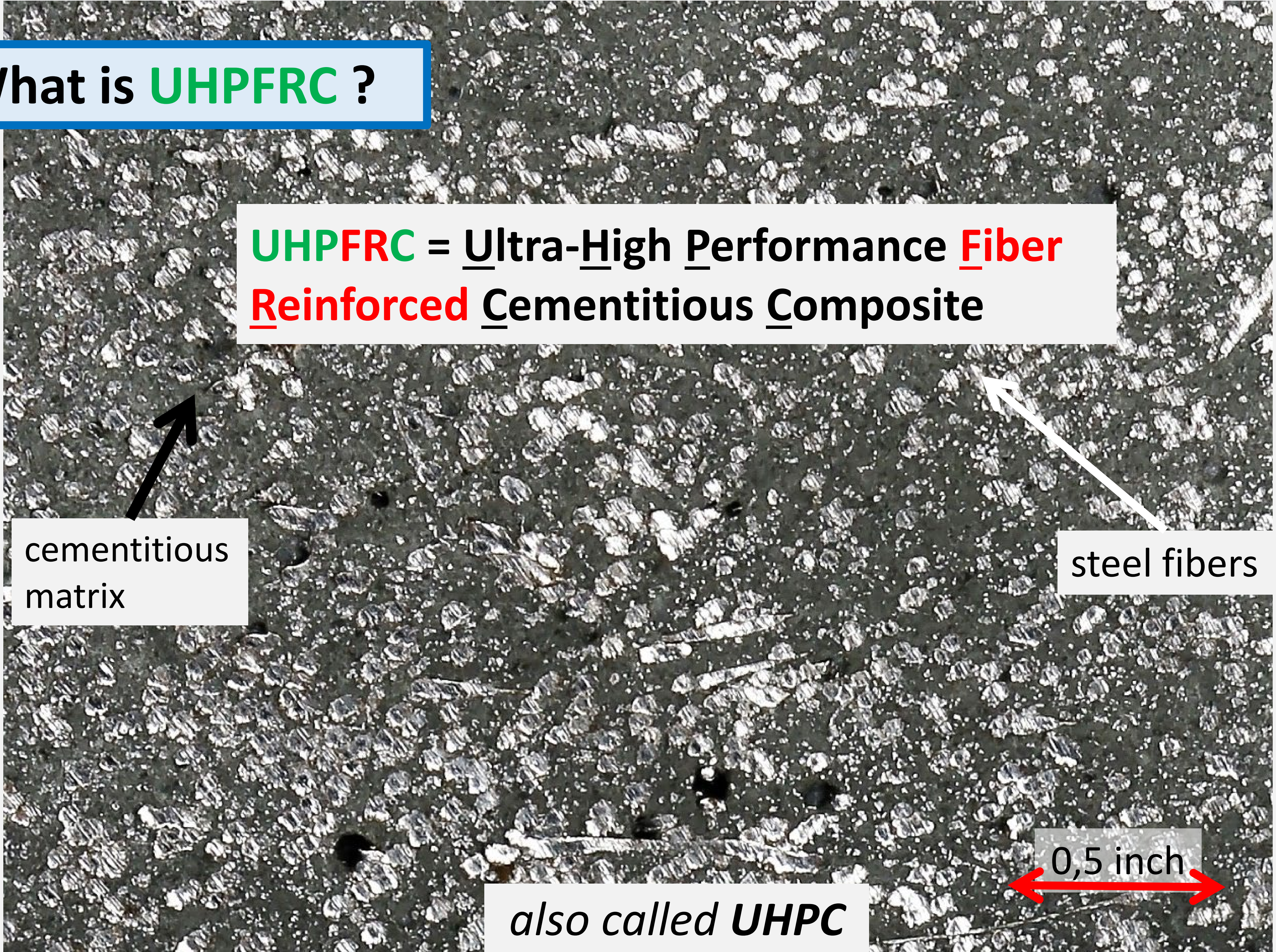
Ferpecle Concrete Bridge in Switzerland Rehabilitation Utilizing UHPFRC

1. What is UHPFRC ?

UHPFRC = Ultra-High Performance Fiber Reinforced Cementitious Composite

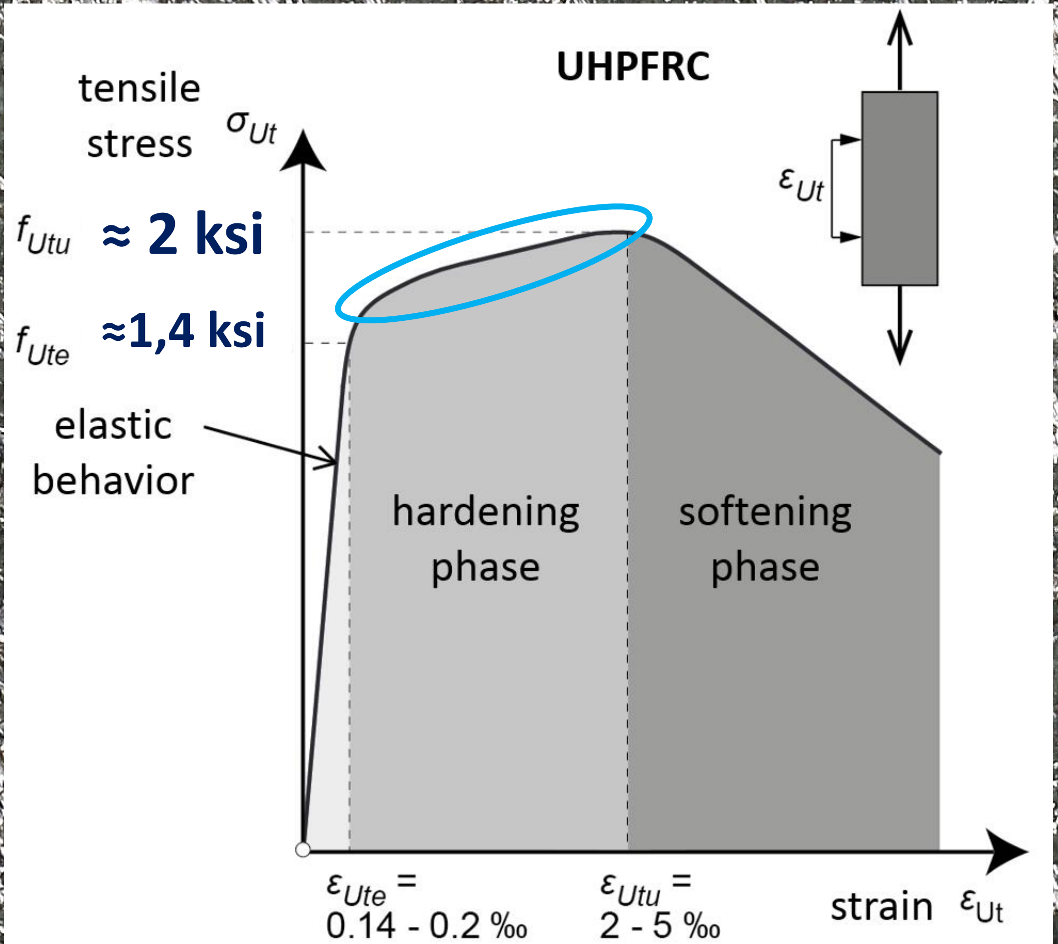


*also called **UHPC***

Performance of tensile strain hardening UHPFRC

compressive strength: **≈ 25 ksi**

modulus of elasticity: **7’000 ksi**



impermeable ➔ compact matrix: powders and particles (<1mm)

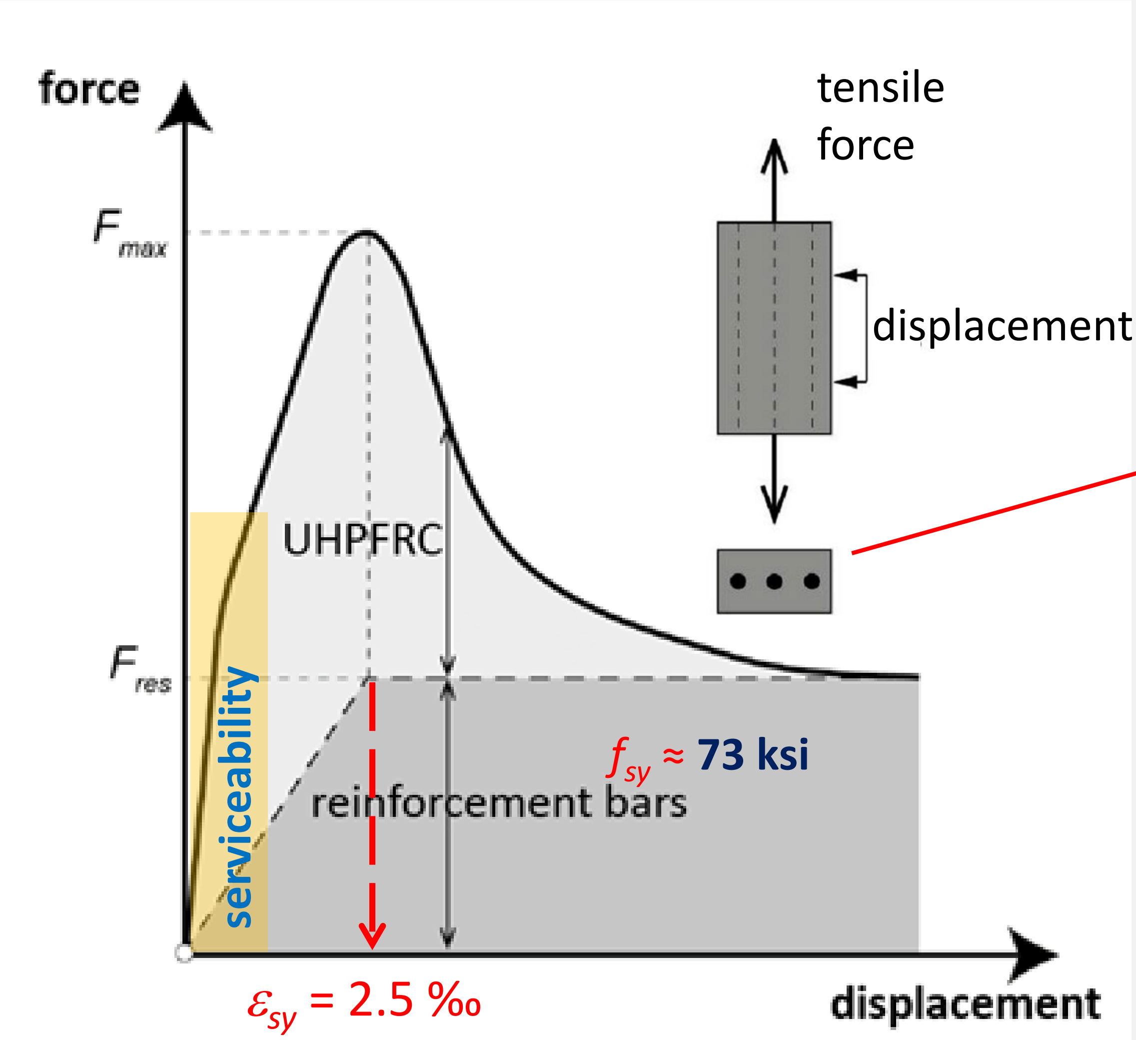
fiber reinforced with steel fibers
l = **0,5’’** *l/d*>65; > 3 vol.%

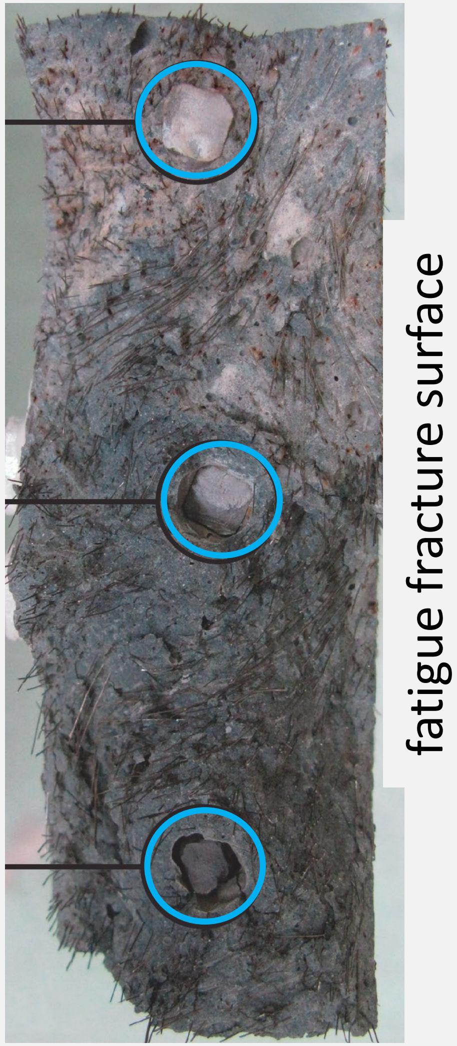
➔ strain hardening (in tension)

watertight and crack-free under service conditions

Swiss Standard SIA 2052 UHPFRC: Classification due to tensile properties of UHPFRC

Structural response of R-UHPFRC using strain hardening UHPFRC

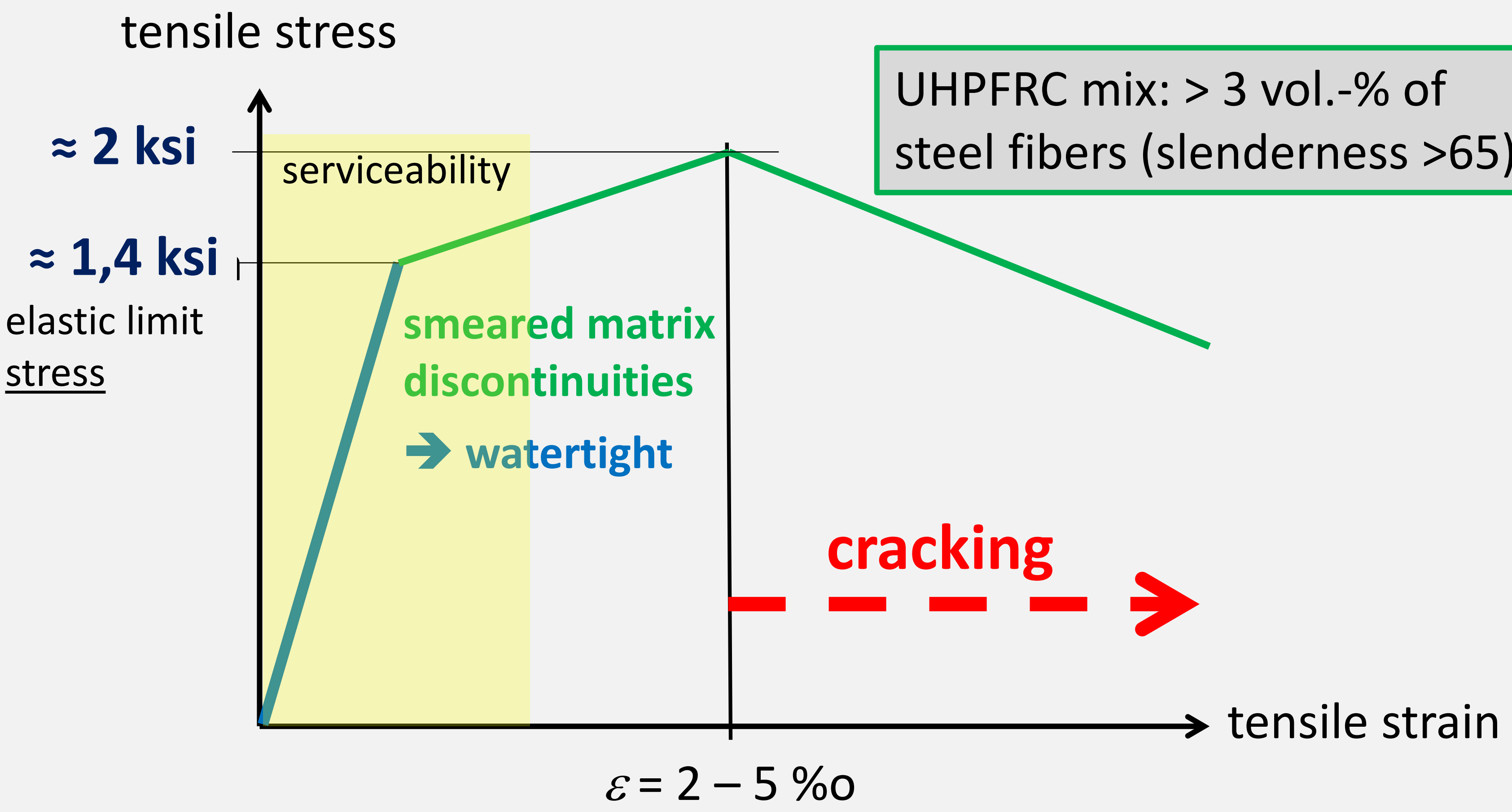




➔ superposition of UHPFRC and rebar responses

UHPFRC with tensile strain hardening

UHPFRC mix: > 3 vol.-% of steel fibers (slenderness >65)

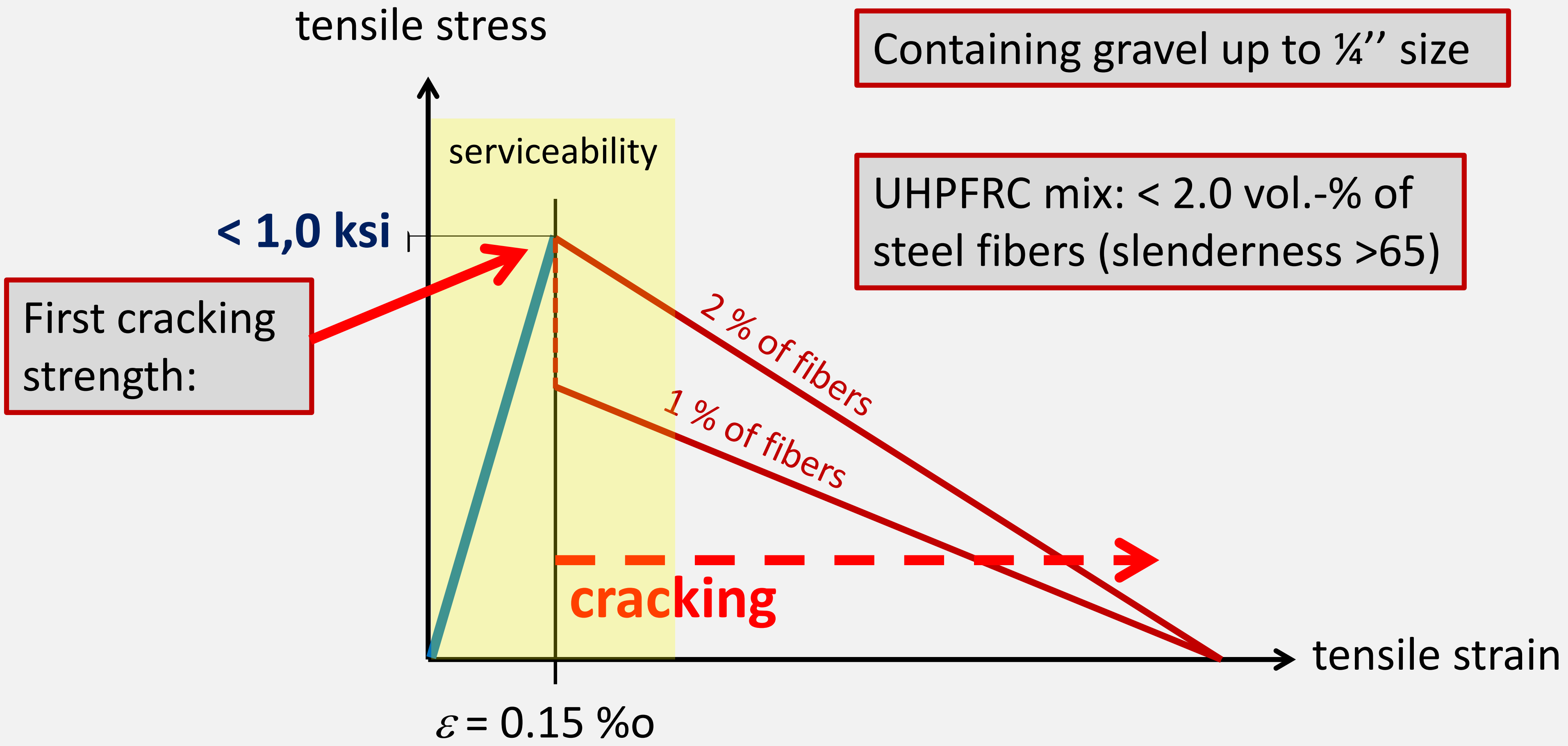


cracking in the softening domain **at large deformation** : $\varepsilon > \varepsilon_{service}$(1 %o)

➔ no durability issue due to cracking

➔ limited stiffness reduction

UHPC without tensile strain hardening



Containing gravel up to ¼'' size

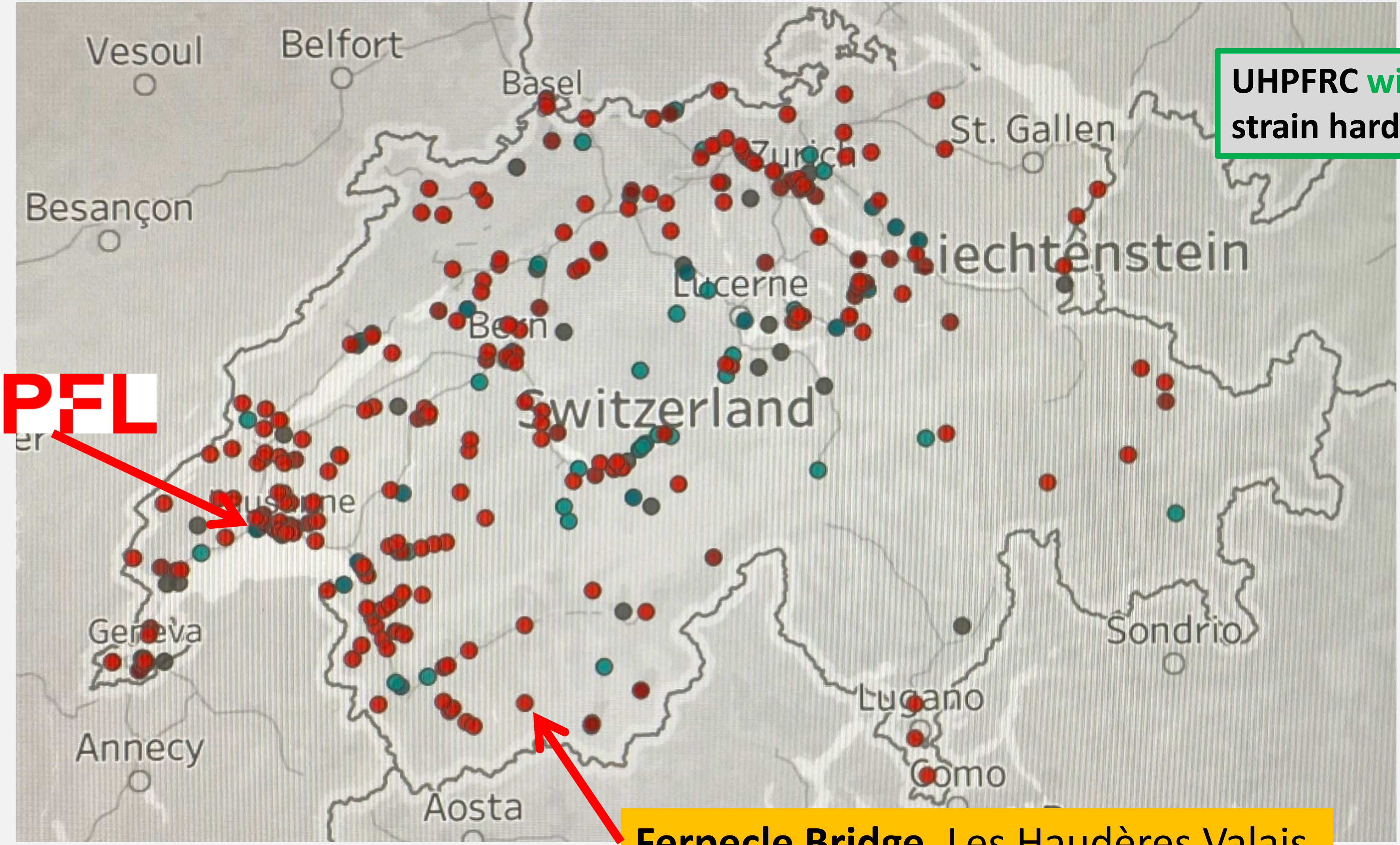
UHPFRC mix: < 2.0 vol.-% of steel fibers (slenderness >65)

cracking in the softening domain at **small deformation**:

➔ ingress of water and chloride ions (due to capillary suction)

➔ significant reduction in stiffness (similar to reinforced concrete)

≈400 realized UHPFRC projects in Switzerland since 2004



EPFL

UHPFRC **with** tensile strain hardening

Ferpecle Bridge, Les Haudères Valais

2. The Ferpecle Bridge project

Owner: Canton of Valais

Concept, project, consultant: E.Brühwiler, N.Bertola EPFL

Execution: Favre Engineers

Contractor: Prader Losinger

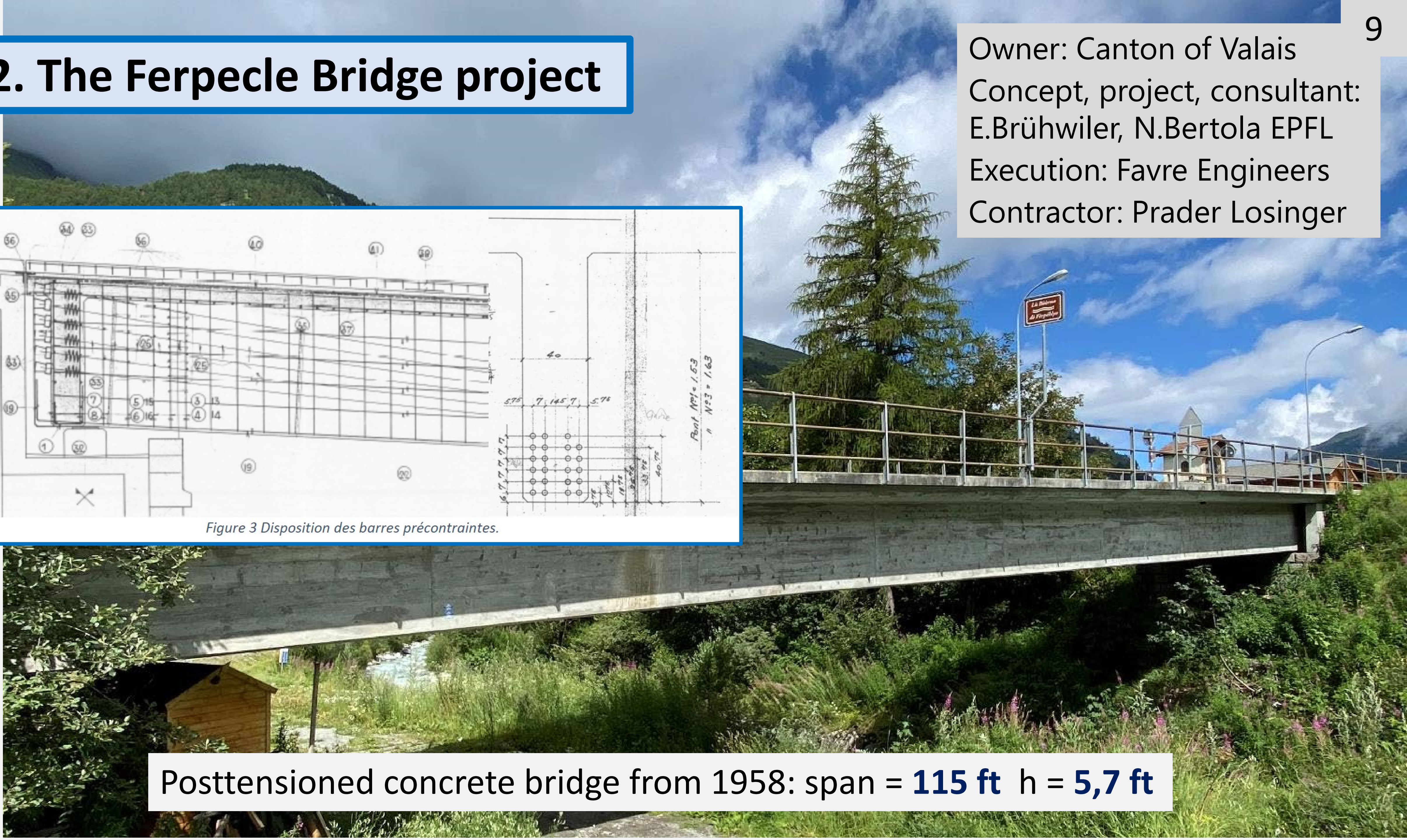


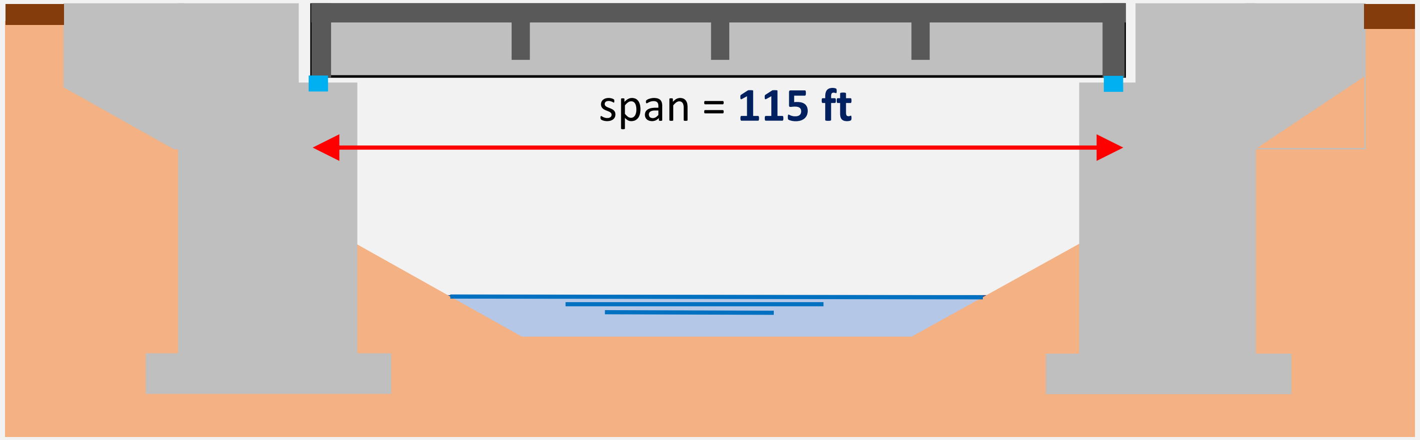
Figure 3 Disposition des barres précontraintes.

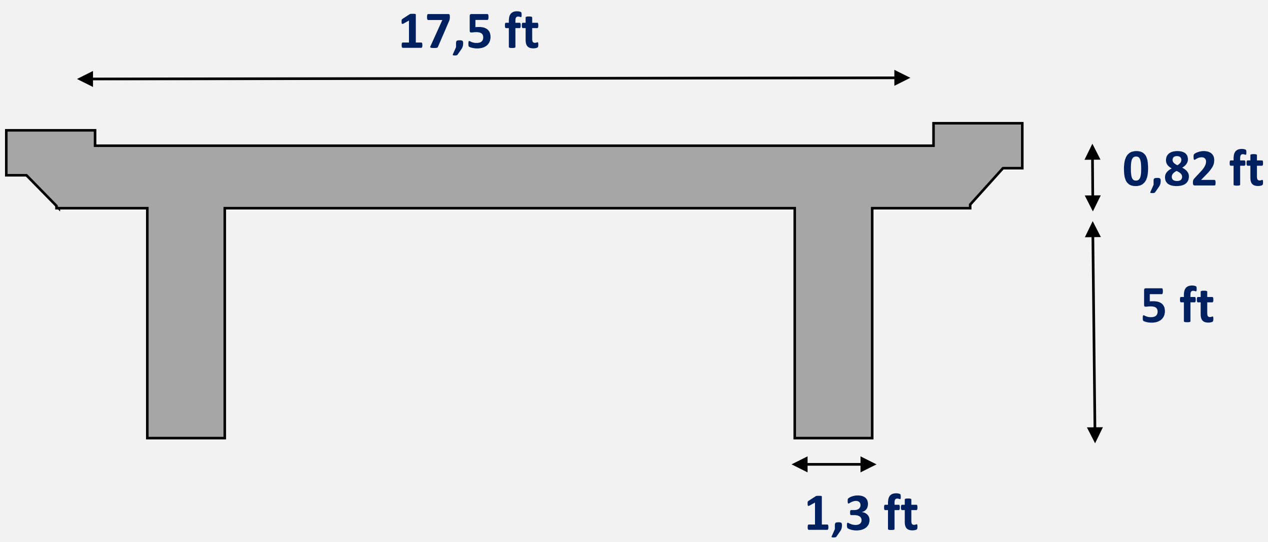
Posttensioned concrete bridge from 1958: span = **115 ft** h = **5,7 ft**

UHPFRC Intervention on an existing post-tensioned concrete road bridge

Requirements for the intervention using UHPFRC only:

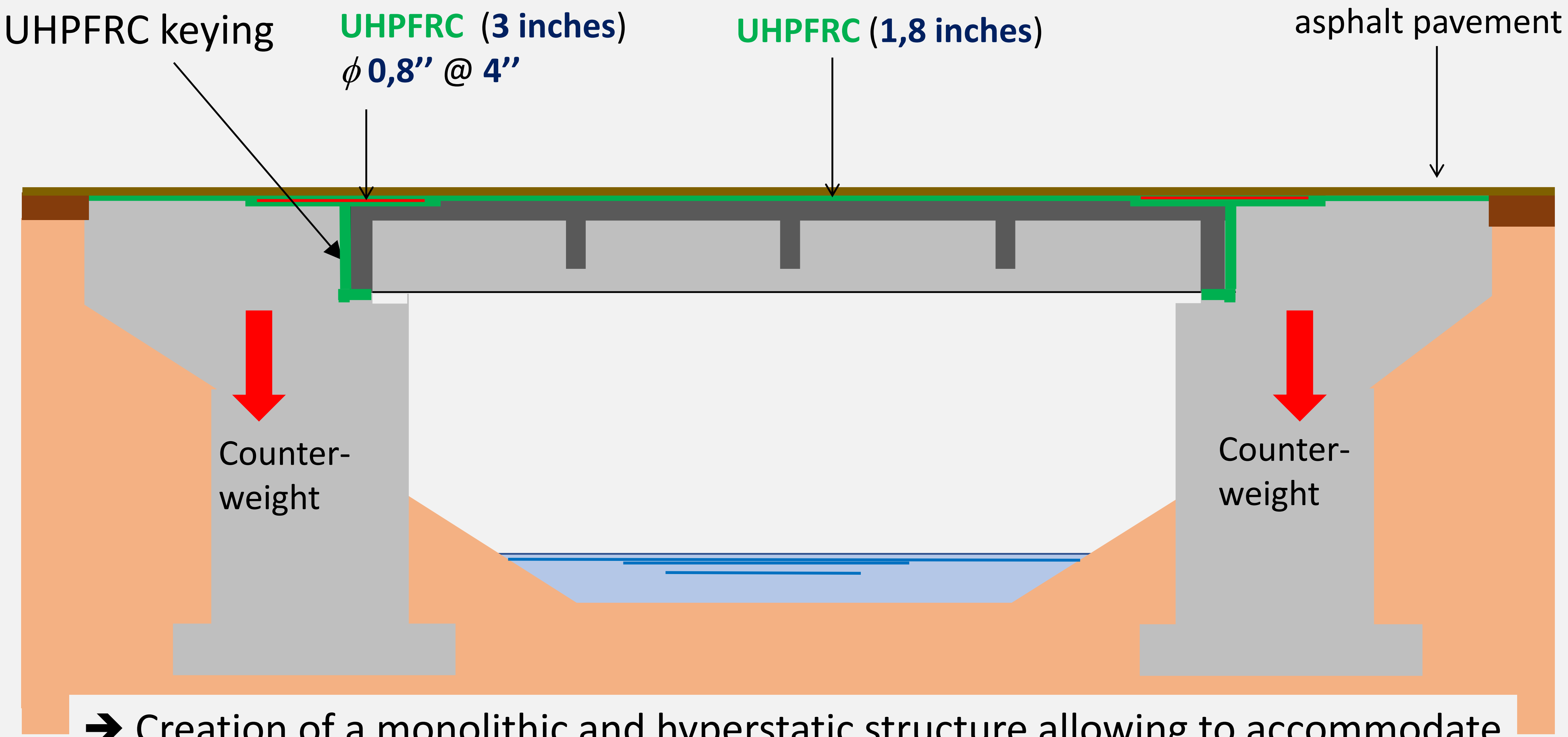
1) restore durability
2) widen the useful deck width from **17,5 ft** to **26 ft** (+ 50%)
3) One road lane (**10 ft** width) has to stay in use during works.
4) strengthen the structure given that:
   - bending moment at mid-span: $M_{Rd}/\ M_d \approx 0.72$
   - shear near abutment: $V_{Rd}/\ V_d \approx 0.78$





Current concrete compressive strength f_{ck} = **6,5 ksi** (characteristic value, without resistance coefficient)

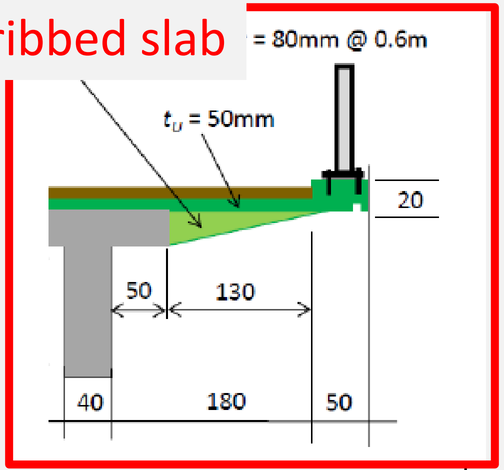
Conceptual design of the intervention

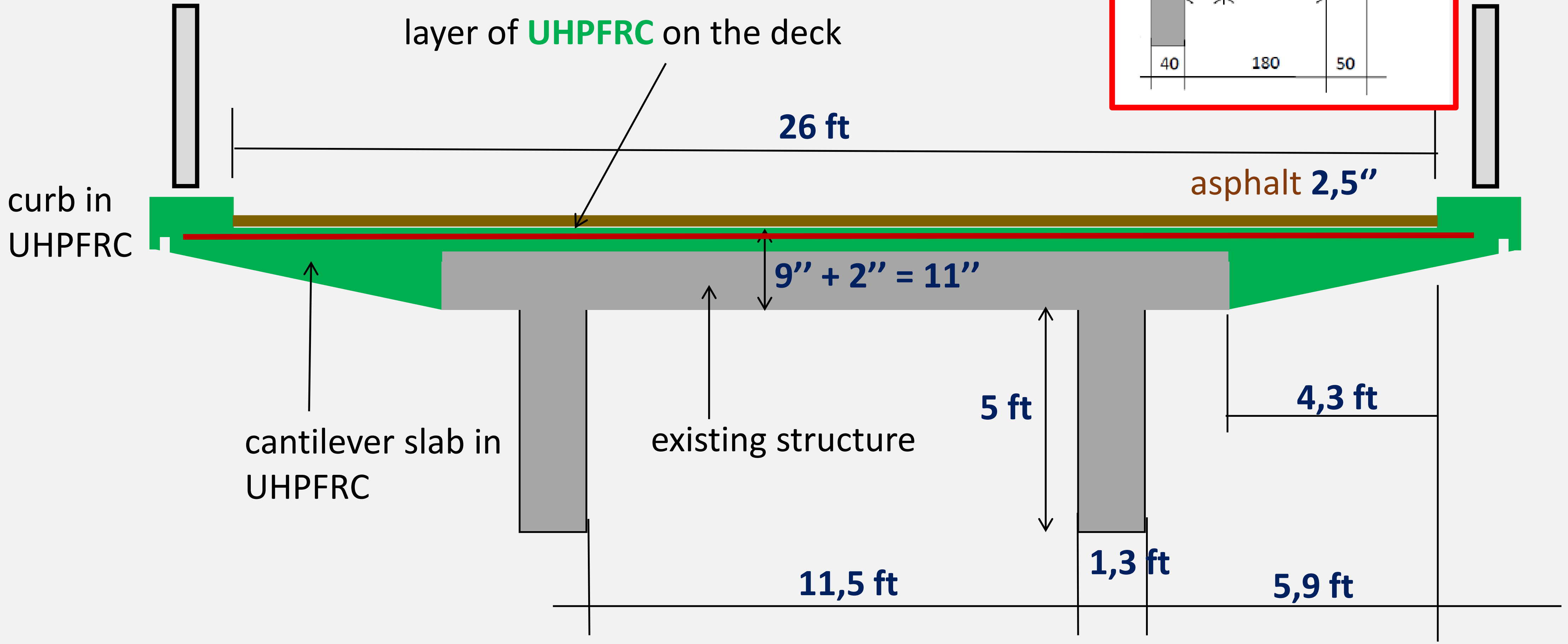


➔ Creation of a monolithic and hyperstatic structure allowing to accommodate for higher loads due to the widening and future traffic loads

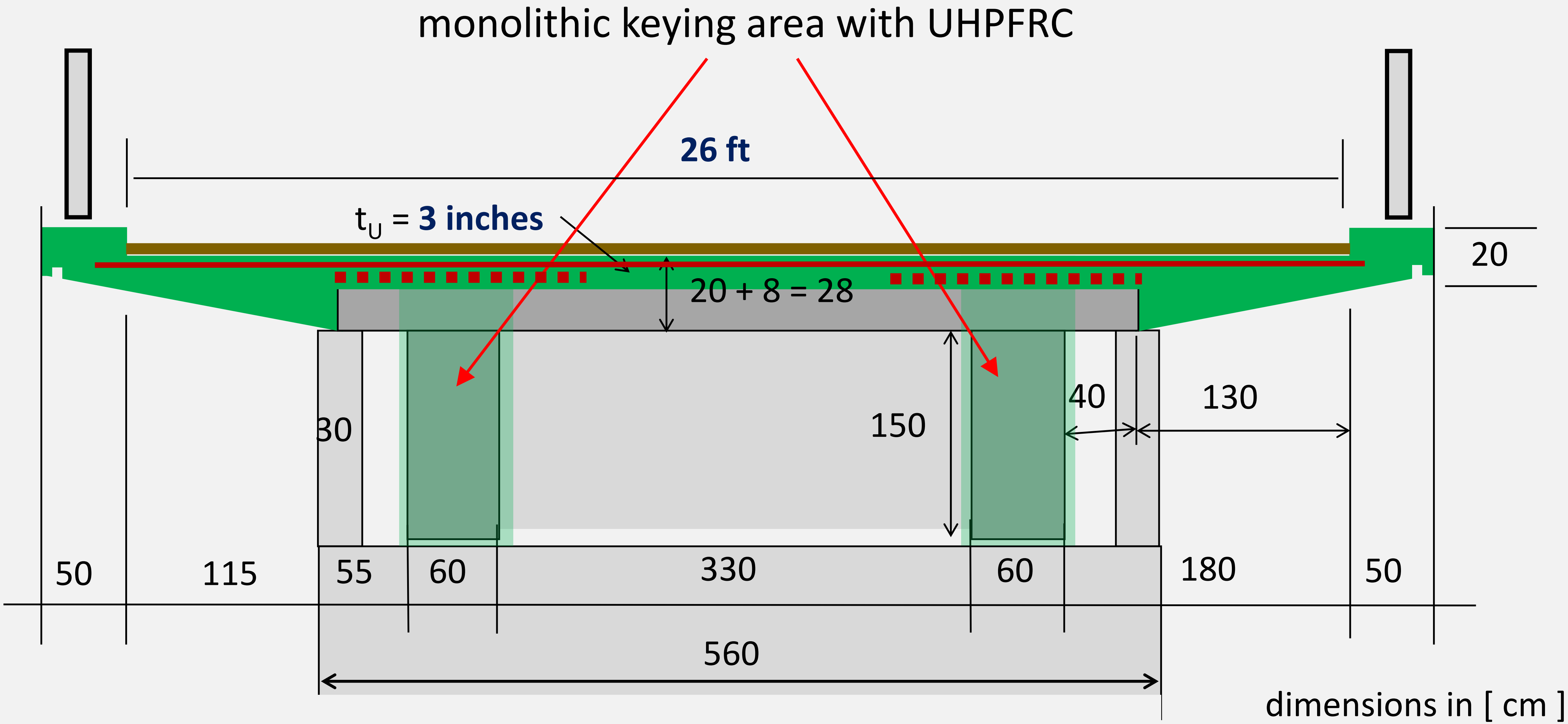
Cross-section at mid-span

alternative: ribbed slab



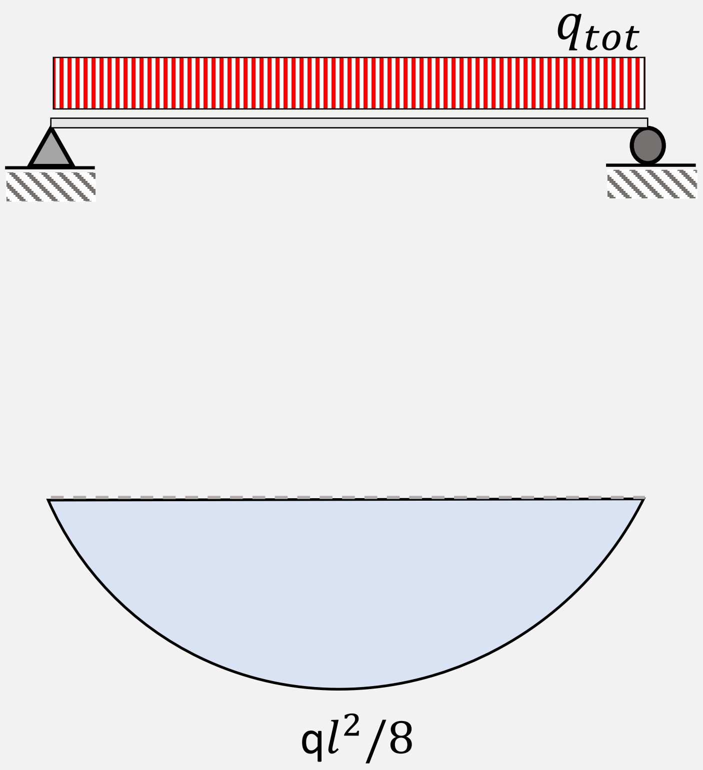


Cross-section on abutments

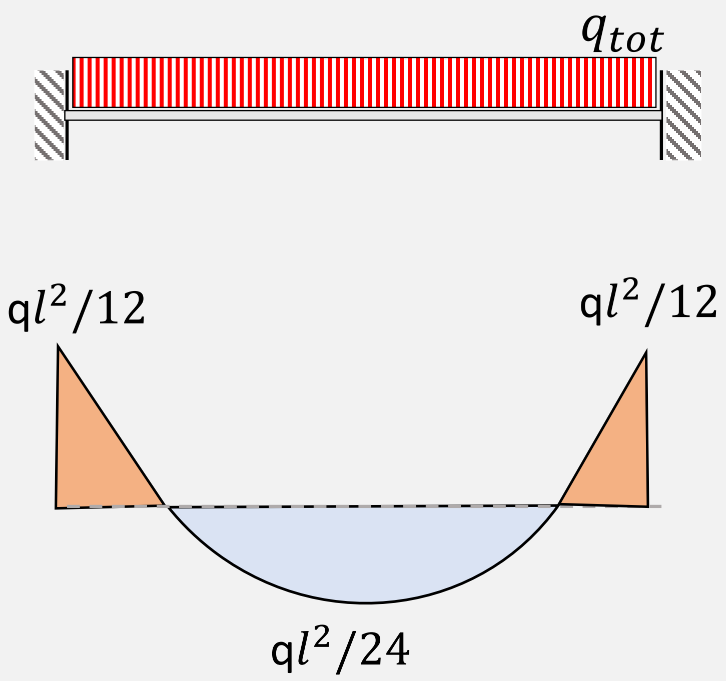


Modification of the static system

Initial static system

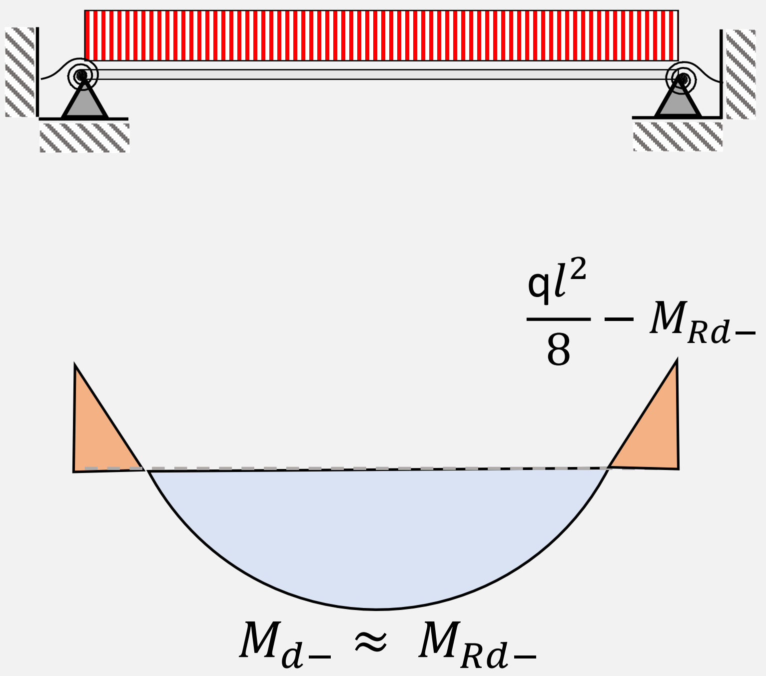


SLS static system



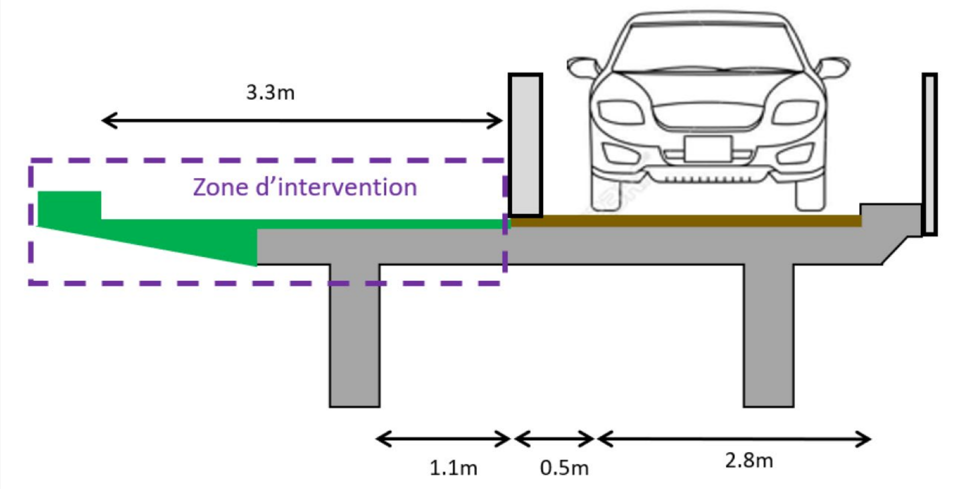
Serviceability: elastic behavior and fully fixity at the abutments

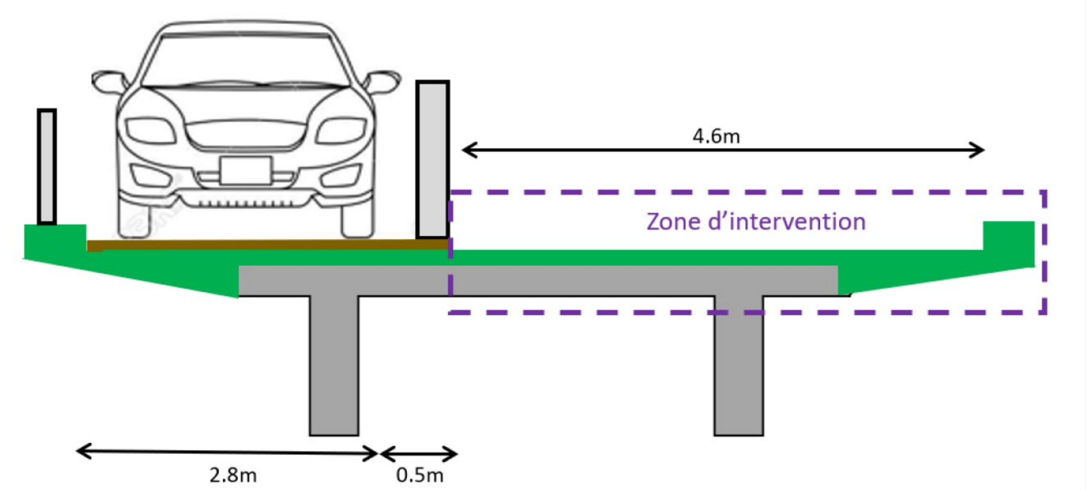
ULS static system



Ultimate limit state: plastification and partial fixity at the abutments

Construction procedure in 2 main phases





One road lane needs to remain in service over the entire duration of works !

Design (by hand calculation) in the longitudinal direction of the widened and strengthened bridge structure

A. Action effects

The permanent actions (self-weight of the structure and pavement) increase by 17% to obtain:

$g_{k,int}$ = 47 kN/m' (per beam or bridge half)

A1. Design bending moment (per bridge half):

- due to traffic loads:

$$M_{qd} = \gamma_Q \cdot [2 * \eta_1 * (Q_{k,1,act} + Q_{k,2,act}) \cdot (\frac{l}{2} - 0.6m) + (q_{k,1,act} \cdot 3 + q_{k,2,act} \cdot (\frac{7.9}{2} - 3)) \cdot \frac{l^2}{8}] = 9087 \ kNm$$

- due to permanent actions: $M_{gd} = \gamma_g * g_{k,int} * \frac{l^2}{8} = 8696 \, kNm$

➔ total design moment: $M_{d,+} = M_{gd} + M_{qd} = 17.8 \, MNm$

Demand in hogging bending resistance :
ΔM_{Rd} = 5'300 kN*m = **3'909'073 lbf*ft**

actual resistance at mid-span: $M_{Rd,+} = 12.5 \, MNm$

distribution of moments due to plastification of the hyperstatic structure:

design hogging moment over abutments: $M_{Ed,-} = M_{d,+} - M_{Rd,+} = \mathbf{5.3 \, MNm}$

A2. Design shear force (per bridge half):

- due to traffic loads:

$$V_{qd} = \gamma_Q * \left[2 * \eta_1 * (Q_{k,1,act} + Q_{k,2,act}) * \left(\frac{l-2.1m}{l}\right) + (q_{k,1,act} \cdot 3 + q_{k,2,act} \cdot (\frac{7.9}{2} - 3) * \frac{l}{2}\right] = 1161\ kN$$

- due to permanent action: $V_{gd} = \gamma_g * g_{k,int} * \frac{l}{2} * 0.5 = 994\ kN$

➔ total design shear force: $V_d = V_{gd} + V_{qd} = \mathbf{1847\ kN}$

= 415 kips

B. Design of the R-UHPFRC layer over the abutments with respect to flexural resistance

Assume: R-UHPFRC layer thickness $d_{U,app} = 80\ mm$

integrating 2 beds of steel rebars of diameter ϕ20mm, spacing of 150 mm, with a yield strength of 500 MPa, leading to a rebar section $A_s = 4189\ mm^2/m'$,

The resistance participating (effective) width is:

$$b_{part} = b_w + 2 * \left(0.1 * \frac{0.15}{2} * l_0 + 2 * b_i\right) = 0.6 + 2 * (0.0075 * 35 + 2 * 1.65) = 1.65\ m$$

Thus, the total tensile force F_{td} in the R-UHPFRC layer is:

$$F_{td} = A_s * f_{sd} + f_{utud} * b_{part} * d_{U,app} = 3920\ kN$$

= 881 kips

This tensile force must be in equilibrium with the resultant compressive force acting on the bottom web part of the RC beam. A stress bloc is assumed with a height of 30 cm and a width of 60 cm, leading to the following compressive stress in the concrete:

$$\sigma_{cd} = \frac{F_{cd}}{A_c} = \frac{3.92MN}{0.18m^2} = 21{,}8\ MPa < f_{cd,act} = 30MPa \text{ o.k.}$$

The distance between the resultant internal tensile and compression forces in the cross section is :

$$z = 1.78 - 0.04 - 0.125 = 1.615\ m$$

= 5.3 ft

Consequently, the ultimate hogging moment resistance is :

$$M^-_{Rud} = y \cdot F_{td} = 1.615m \cdot 3920kN = \mathbf{6283\ kNm}$$

= 4’634’096 lbf*ft

The resistance of the composite R-UHPFRC – RC cross section is thus higher than the acting design moment, since the degree of compliance is:

$$\boldsymbol{n_M^- = \frac{M_{Rd}^-}{M_{Ed}^-} = \frac{6283}{5386} = 1.17 > 1.0}$$

Finally: verification that the ductility of the strengthened cross section is sufficient to allow for the assumed plastic redistribution of moments, since :

$\frac{x_c}{d} = \frac{0.28}{1.55} = 0.18 < 0.25$ o.k.

C. Verification of sufficient ultimate shear resistance

The ultimate shear resistance of the original RC beam is: $V_{Rd0} = \mathbf{1466\ kN} \cong 1.5MN$ which is due to the vertical steel reinforcement.

Assuming that the simplified resistance model for ultimate shear resistance (see Lecture 2 on shear strengthening) is valid in the present case of the R-UHPFRC – RC composite beam, the following types of ultimate resistance contribute to the total ultimate shear resistance:

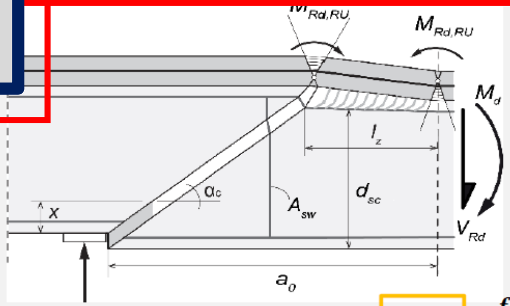
- contribution of compressed concrete zone over the height *x*, with:
  - angle of inclination of the critical crack: α_c = 30°
  - estimated height of compressed zone x = 0,4 m (can be precisely determined considering the area and ultimate resistance of steel reinforcements as well as the area and ultimate resistance of UHPFRC (in tension) and concrete in compression according to :

$$x = 0{,}9 \cdot \frac{d_{pc}A_{pc}f_{pd} + d_U A_U f_{Utud} + d_{sU}A_{sU}f_{sUd}}{A_c f_{cd}} = 0.4\ m$$

➔ ultimate resistance contribution of the compressed concrete is:

$$V_{Rd,c} = \frac{f_{cd} \cdot b_w}{2}\left[\frac{x}{sin\alpha_c} \cdot (1 - cos\alpha_c)\right] = \mathbf{836\ kN}$$

= 188 kips



$$V_{Rd} = V_{Rc} + V_{Rs} + V_{RU}$$

concrete

shear reinforcement

R-UHPFRC

Contribution of concrete $V_{Rc} = \frac{f_{ck}b}{2}\left[\frac{x}{sin\ \alpha_c}(1 - cos\ \alpha_c)\right]$

Without considering the contribution of the R-UHPFRC layer showing a double-hinge mechanism, the ultimate shear resistance is already sufficient, since:

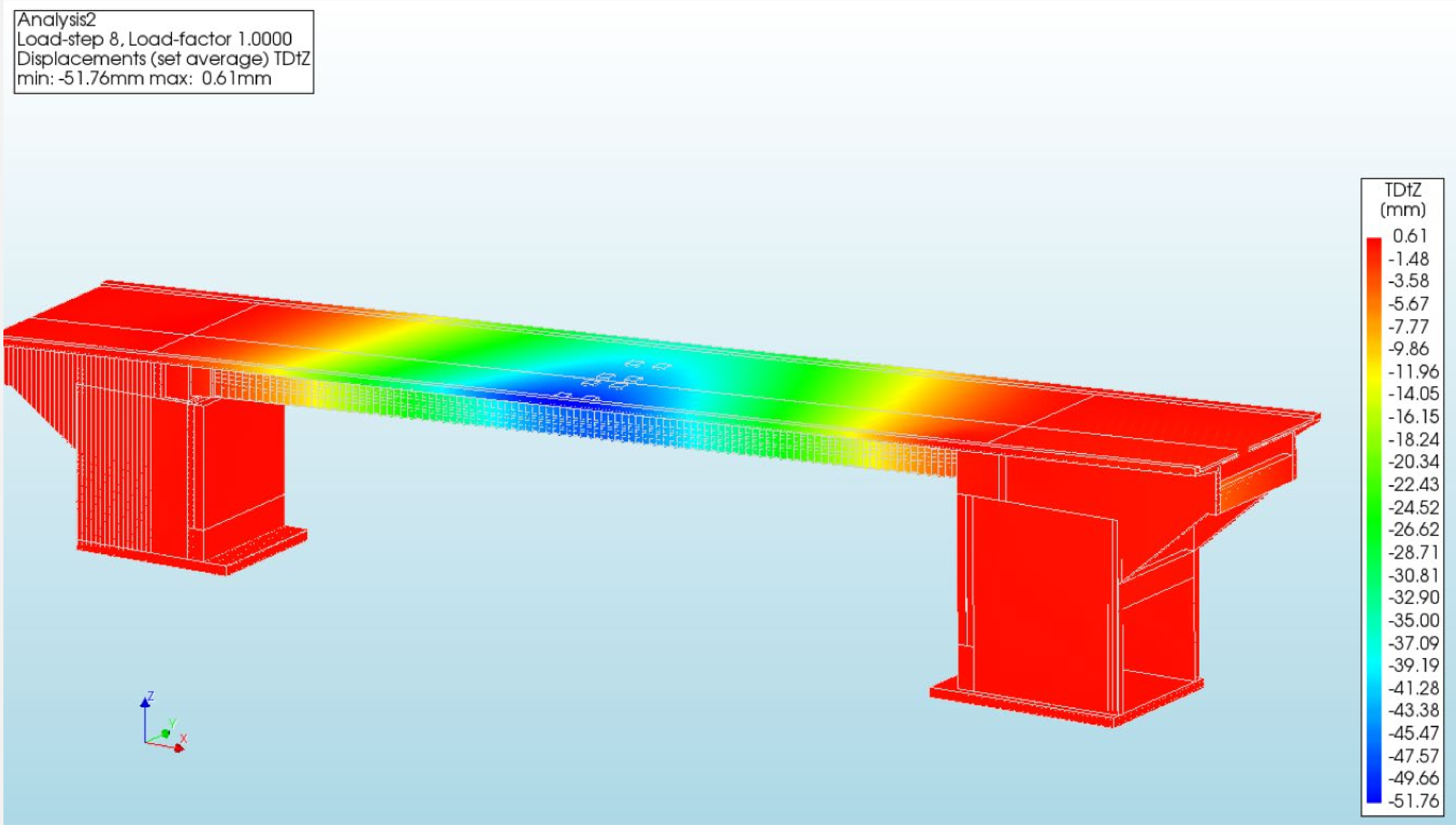
$$V_{Rd} \geq V_{Rd0} + V_{Rd,c} = 2302\ kN$$

and the degree of compliance:

$$n_V = \frac{V_{Rd}}{V_{Ed}} = \frac{2302}{1847} = 1.24 > 1.0 \text{ o.k.}$$

Remark : The R-UHPFRC layer produces a confinement of the beam subjected to shear, that is sufficient to activate the compressed concrete zone to contribute to the ultimate shear resistance. This is already enough to resist the acting design shear force.

Detailed structural analysis using a FE model: structural behavior at ultimate resistance



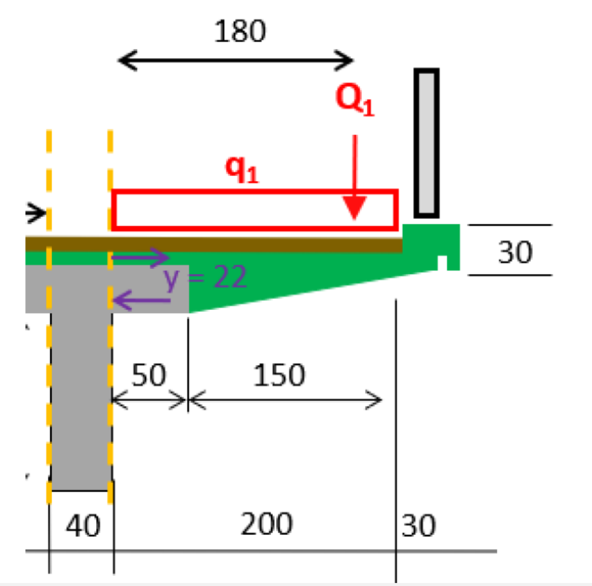
Further verifications:

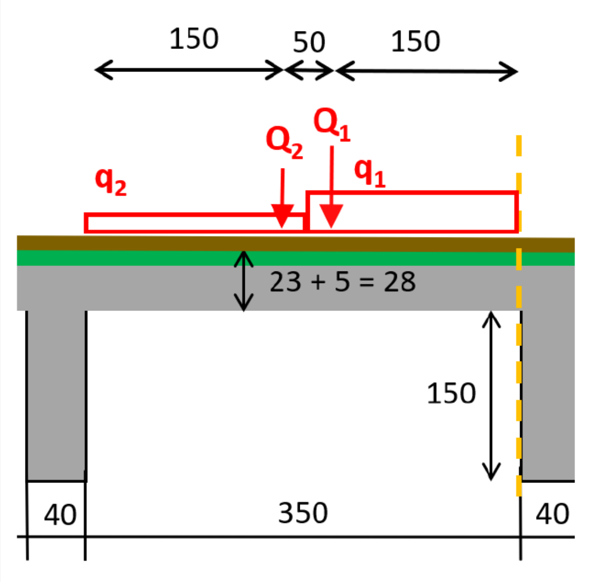
Serviceability limit state:

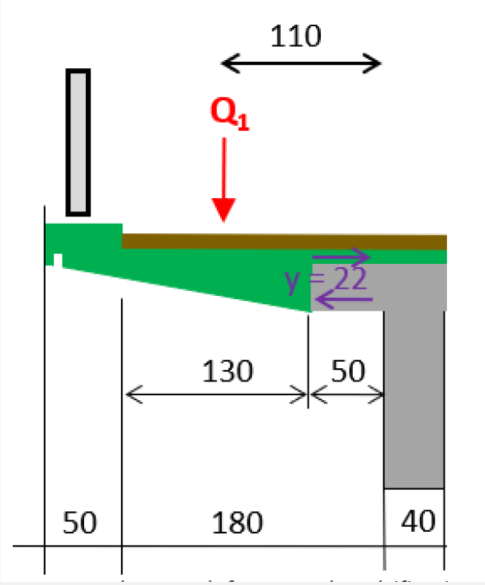
- show that tensile strain < 1 ‰ to assure water tightness of the UHPFRC protection layer

Transverse direction:

- ultimate bending and shear resistance of cantilever slab and slab between the two beams
- fatigue resistance of cantilever and deck slab

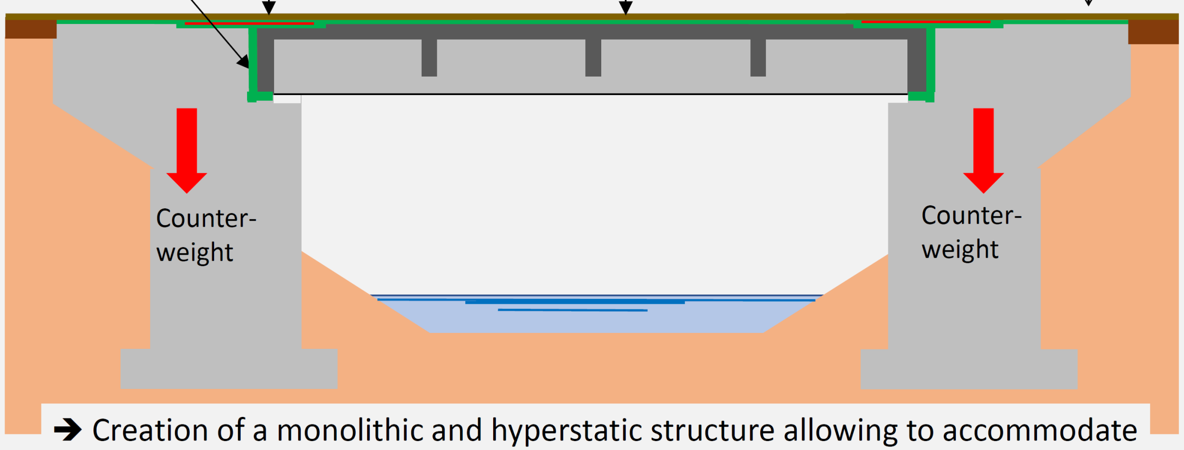






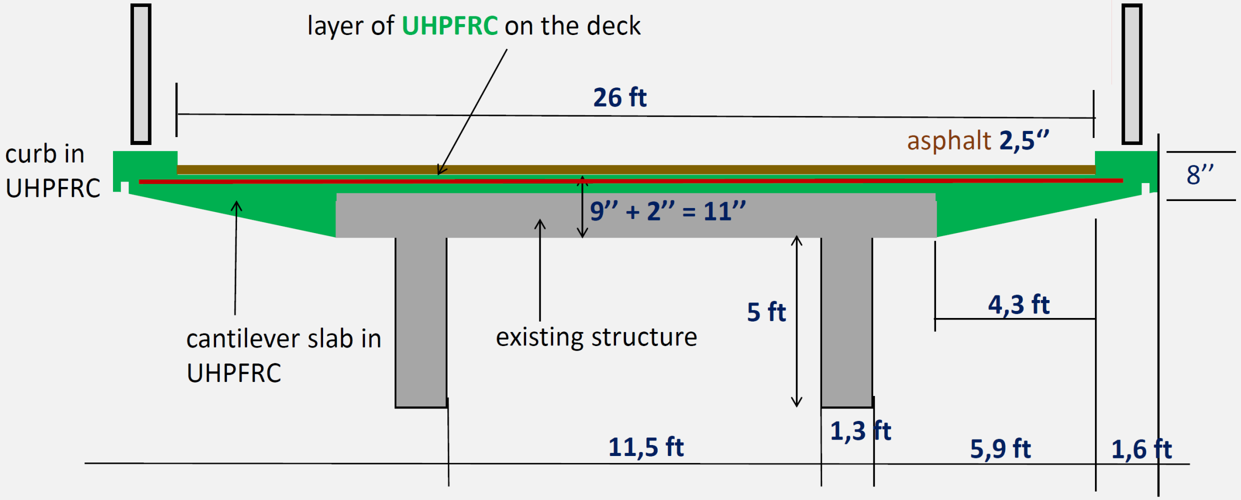
Ferpècle Road Bridge: Widening of the deck and strengthening of the structure

Concept: from single span to half-frame structure



➔ Creation of a monolithic and hyperstatic structure allowing to accommodate for higher loads due to the widening and future traffic loads

Execution: photo 3 May 2023

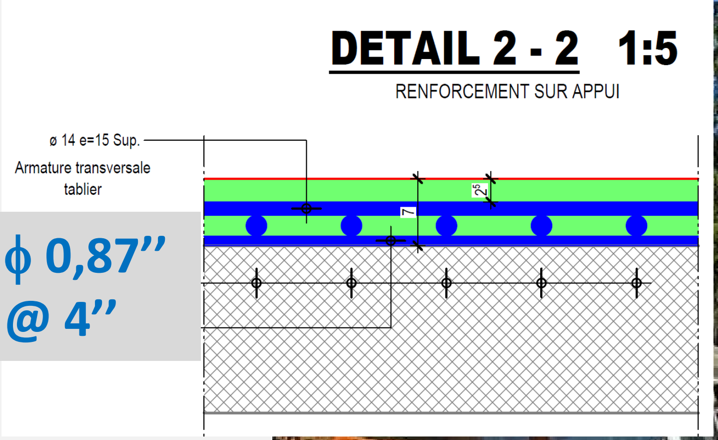


2 June 2023

2 June 2023

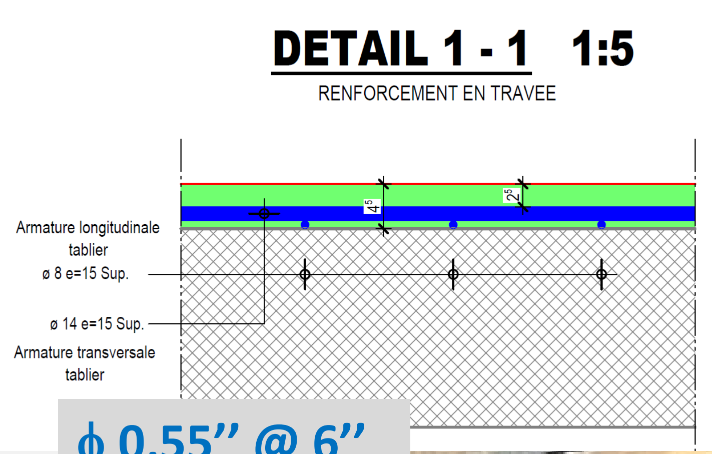
29 June 2023

Hogging moments, shear:



ϕ 0,87'' @ 4''

Sagging moments:



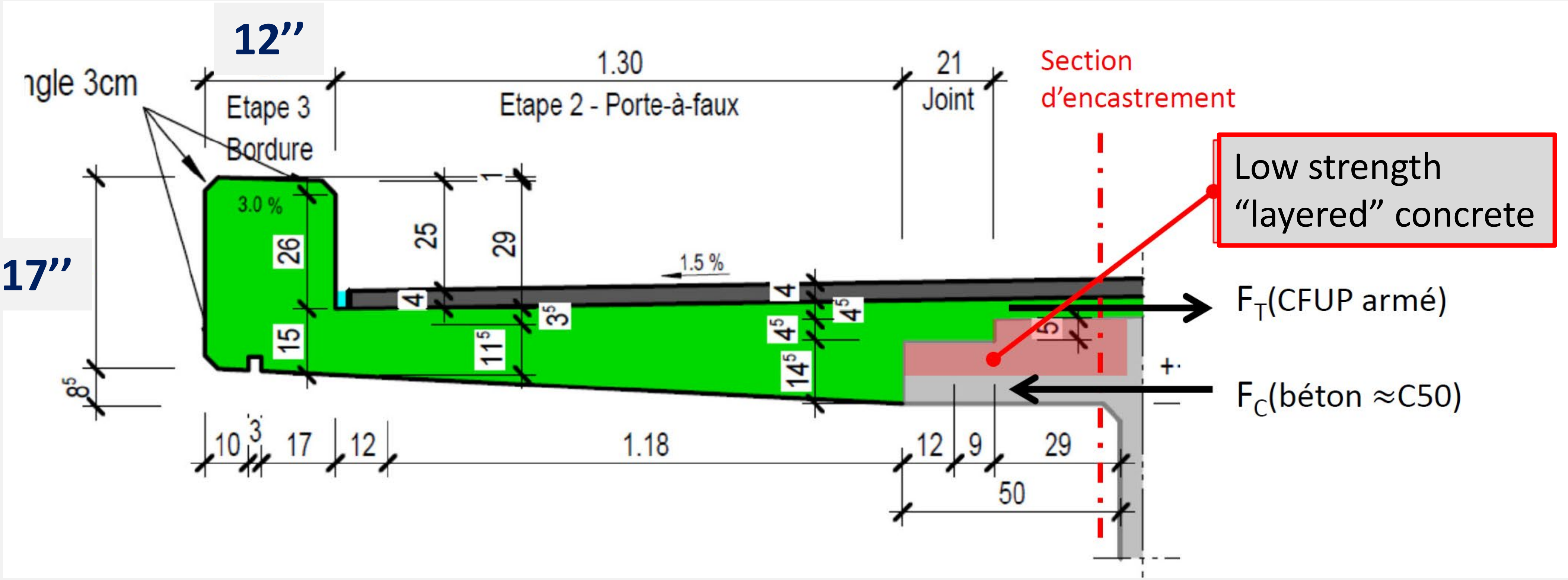
ϕ 0,55'' @ 6''

29 June 2023

Vibrating needle to facilitate the flow of the thixotropic fresh **UHPFRC**

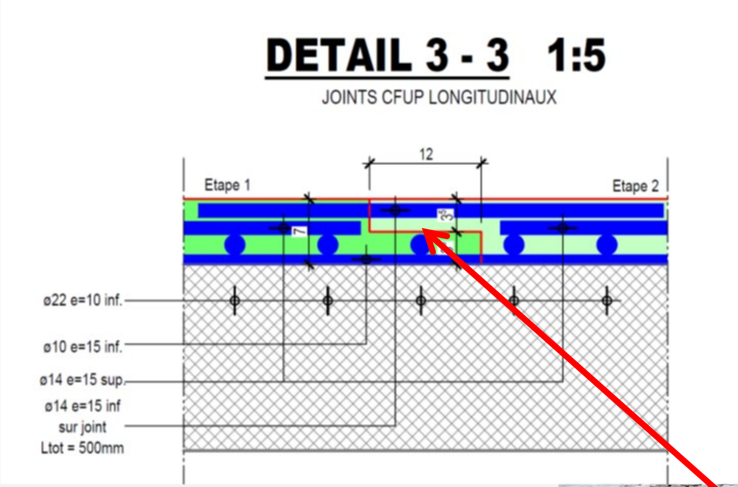
7 August 2023


7 August 2023
UHPFRC
Concrete (1958)
optical fiber for monitoring

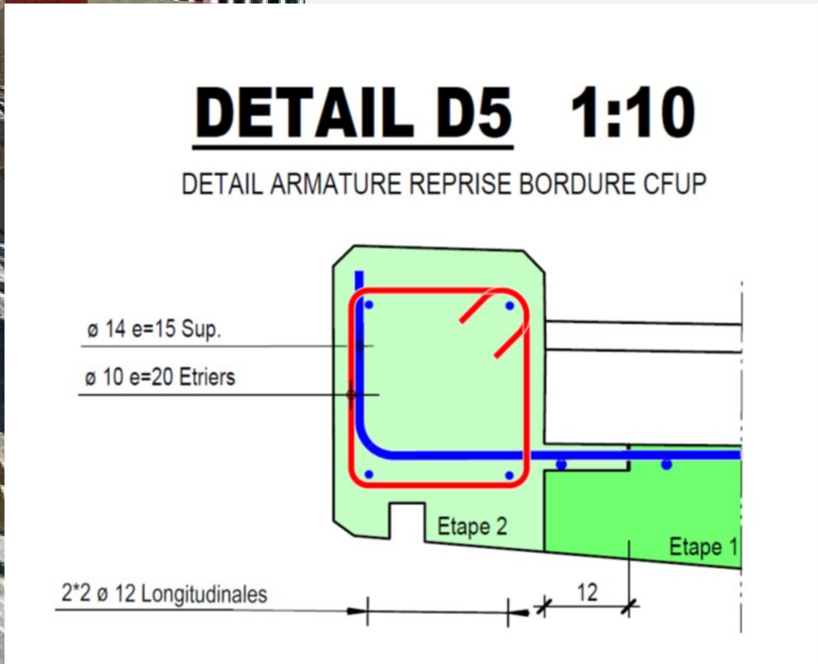

12’’
17’’
ngle 3cm
1.30
21
Etape 3
Bordure
Etape 2 - Porte-à-faux
Joint
Section
d’encastrement
Low strength
“layered” concrete
3.0 %
1.5 %
26
25
29
15
4
4
F_T(CFUP armé)
F_C(béton ≈C50)
10
3
17
12
1.18
12
9
29
50

7 August 2023

Longitudinal construction joint



26 September 2023



26 September 2023

26 September 2023

some «bubbles»
No cracks

4 October 2023


4 October 2023
Installation of optical fiber sensor

Works are being finalized currently.

Works finished : 27 October 2023

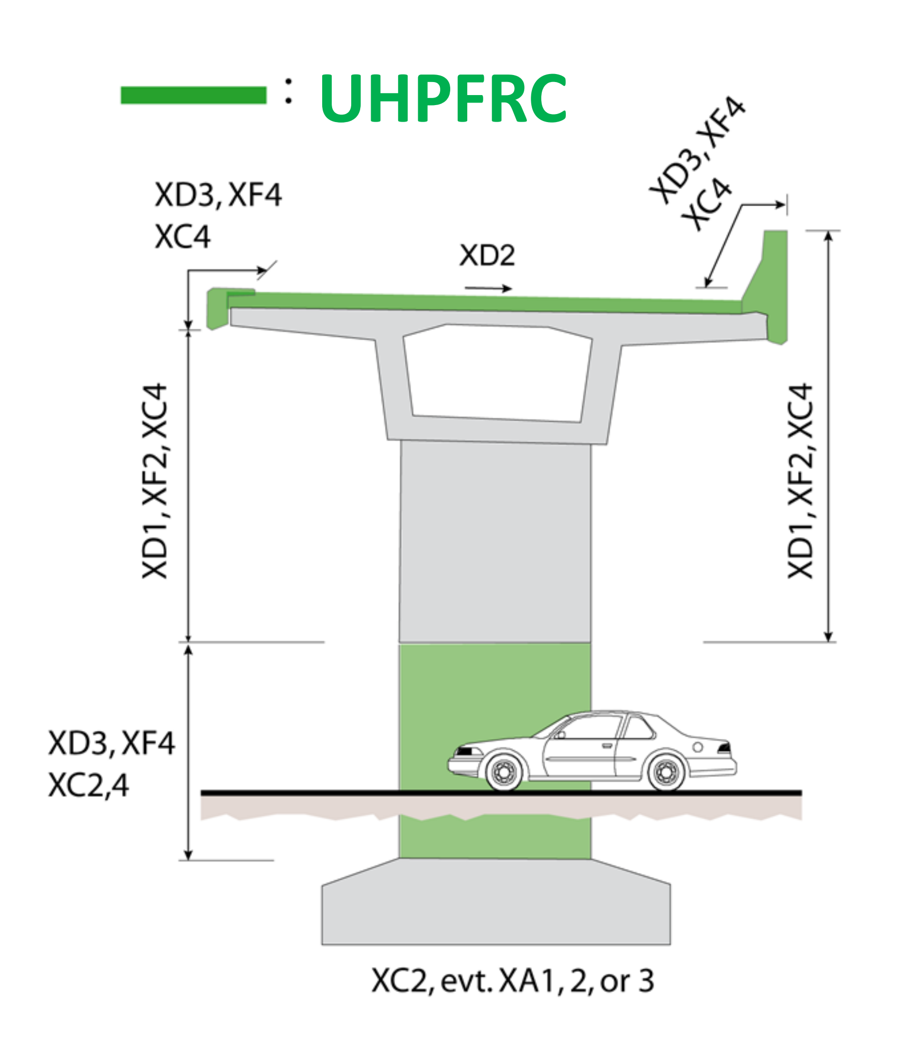
6 October 2023

Lessons learnt:

- clear structural concept
- simple «hand» design complemented by FEA
- clear tendering documents with strict quality control: requirements and correction measures
- suitability test before execution allows to finetune execution.

➔ ***No notable issues regarding UHPFRC execution quality and costs***

3. UHPFRC application concepts *and lessons learnt !*



Objectives of UHPFRC layers:

➔ increase structural capacity

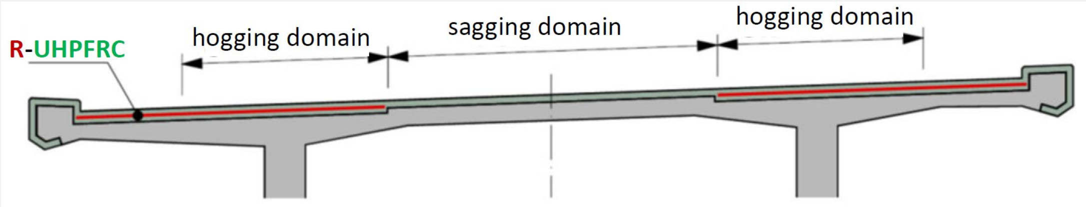
➔ protective watertight layer

Sustainability is preservation of existing structures by using little amount of **UHPFRC** !

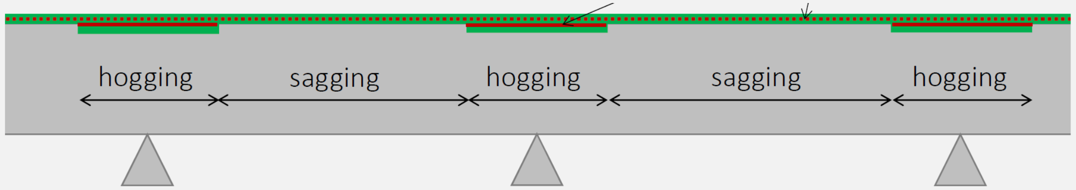
UHPFRC can do much more than only «overlays» !

Application concepts:

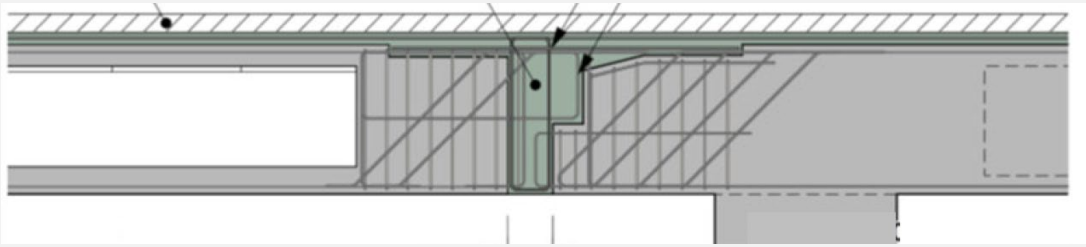
U1: Rehabilitation and increase of resistance of reinforced concrete **slabs**



U2: Rehabilitation and increase of resistance of reinforced concrete **girders**

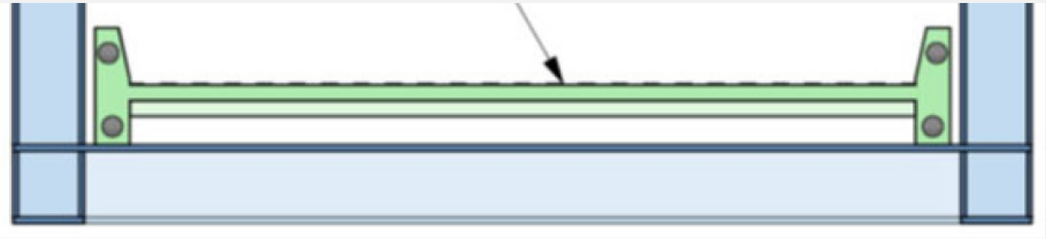


U3: **Joint closure** to obtain continuous and monolithic (hyperstatic) structural systems

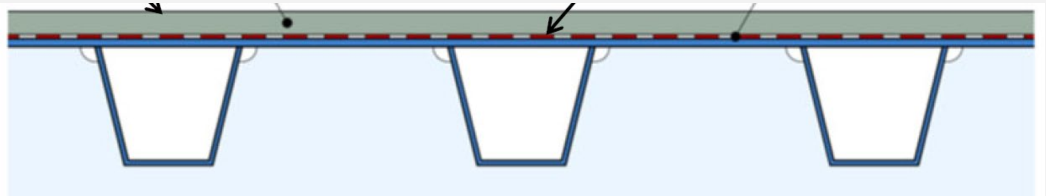


Application concepts:

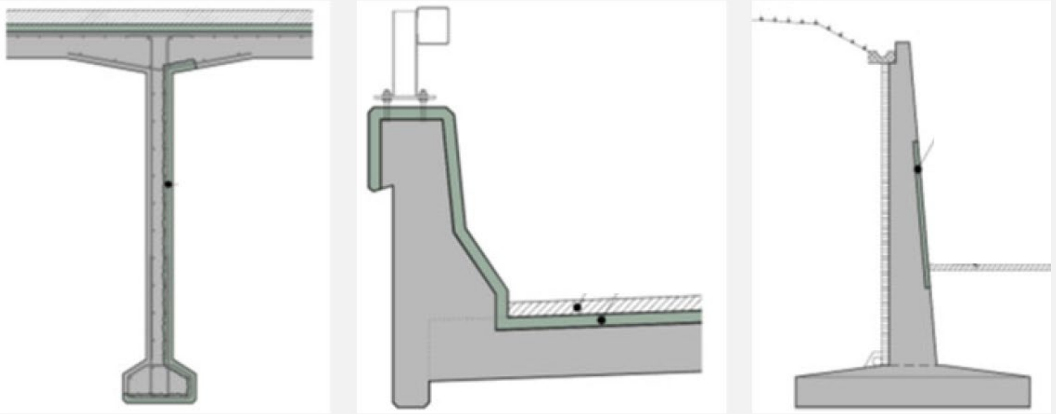
U4: Increase in load carrying capacity by replacing RC slab by **lightweight** UHPFRC slab



U5: Increase in **deck stiffness of OSD** by adding a bonded UHPFRC layer



U6: **Rehabilitation** of (rebar corrosion) damaged reinforced concrete using UHPFRC



R-UHPFRC to improve RC bridges: *Milestones… in Switzerland*

First application in 2004

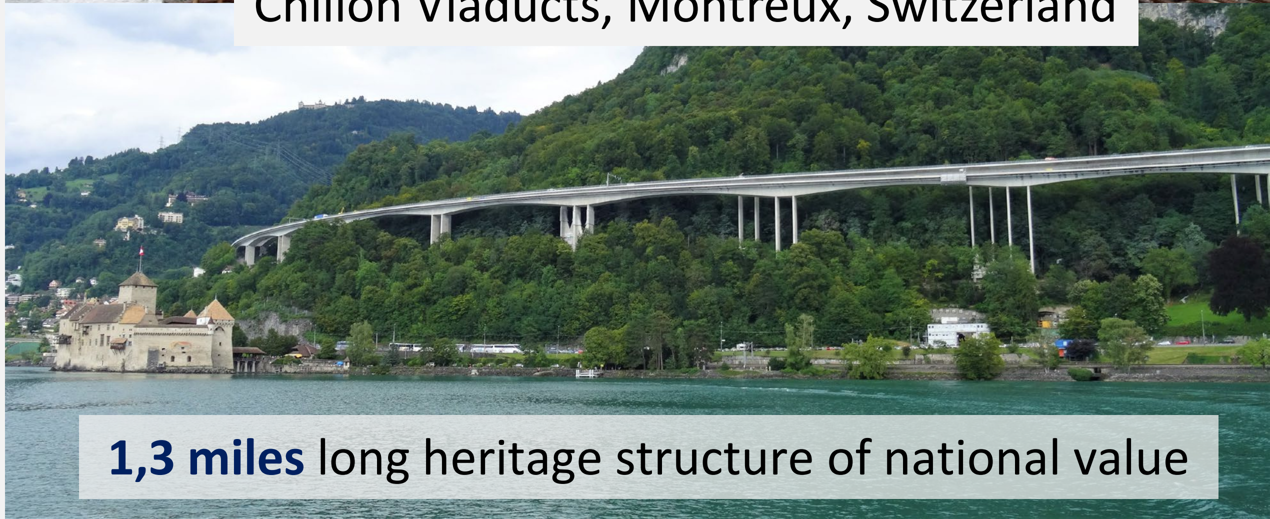
Pont sur la Morge
Sion, Switzerland

3,1 yd³ of **UHPFRC**

Break through in 2014/15

3’150 yd³ of **UHPFRC**

Chillon Viaducts, Montreux, Switzerland



1,3 miles long heritage structure of national value

By today: more than 350 known applications in Switzerland

more than 350 applications in Switzerland since 2004: why ?

UHPFRC Technology is cost-effective !

1: UHPFRC material cost (0.4 US $ / pound) in Switzerland

2: Construction cost : several requirements are fulfilled with one UHPFRC casting/layer → ***determinant !***

3: Intervention cost = construction cost + indirect (user) costs
→ ***added value for the owner and society***

4: ~~Life cycle~~ **Service** cost : reduction of maintenance and environmental impact → ***added value for owner and society***

Controlling of costs is an important project quality control !

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

FEDRO – Federal Roads Office

DOCUMENTATION

UHPFRC FOR THE MAINTE-NANCE AND CONSTRUCTION OF ART STRUCTURES OF THE ROAD INFRASTRUCTURE

Edition 2023 V1.00
FEDRO 82022

EPFL

Swiss Federal Institute of Technology (EPFL)
Laboratory of Maintenance, Construction and
Safety of existing structures – MCS
EPFL – ENAC – IIC – MCS, Station 18
CH-1015 Lausanne, Switzerland
http://mcs.epfl.ch

Prof. Dr. Eugen Brühwiler, struct. eng. dipl. ETH/SIA

Swiss UHPFRC Model Standard:

Ultra-High Performance Fibre Reinforced Cementitious composite (UHPFRC) – Materials, dimensioning and execution

The Ferpecle Bridge UHPFRC project will be presented at the 4th Swiss UHPFRC Day on 26 October 2023 and at the IABSE Symposium in Manchester, England, on 10-12 April2024

Conclusion: *Bringing UHPFRC research from the lab to the field:*

➔ ***this requires a focused state of mind !***

➔ ***it needs an exclusive commitment !***

➔ ***it's convincing others... to change their mindset !***

… and in case projected costs are high ?

⇒ inefficient project (concept)

⇒ unnecessary regulations, complicated project validation procedure

⇒ UHPFRC market is not functioning.

Taverne Road Bridge (2020): first R-UHPFRC road bridge in Switzerland

Thank you !