Engineering of Existing Structures - CIVIL-511
Civil Engineering - Master 1 and 3
Teachers: Prof. Emmanuel Denarié, Prof. Alain Nussbaumer

Engineering of Existing Structures

Chapter 11
Intervention (III)

- Strengthening techniques
- External prestressing
- R-UHPFRC

Author: Prof. E. Denarié

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1. Introduction

Interventions – 4 chapters

Chapter 9: hybrid concrete members – new on old concretes

Chapter 10: interventions on cover concrete

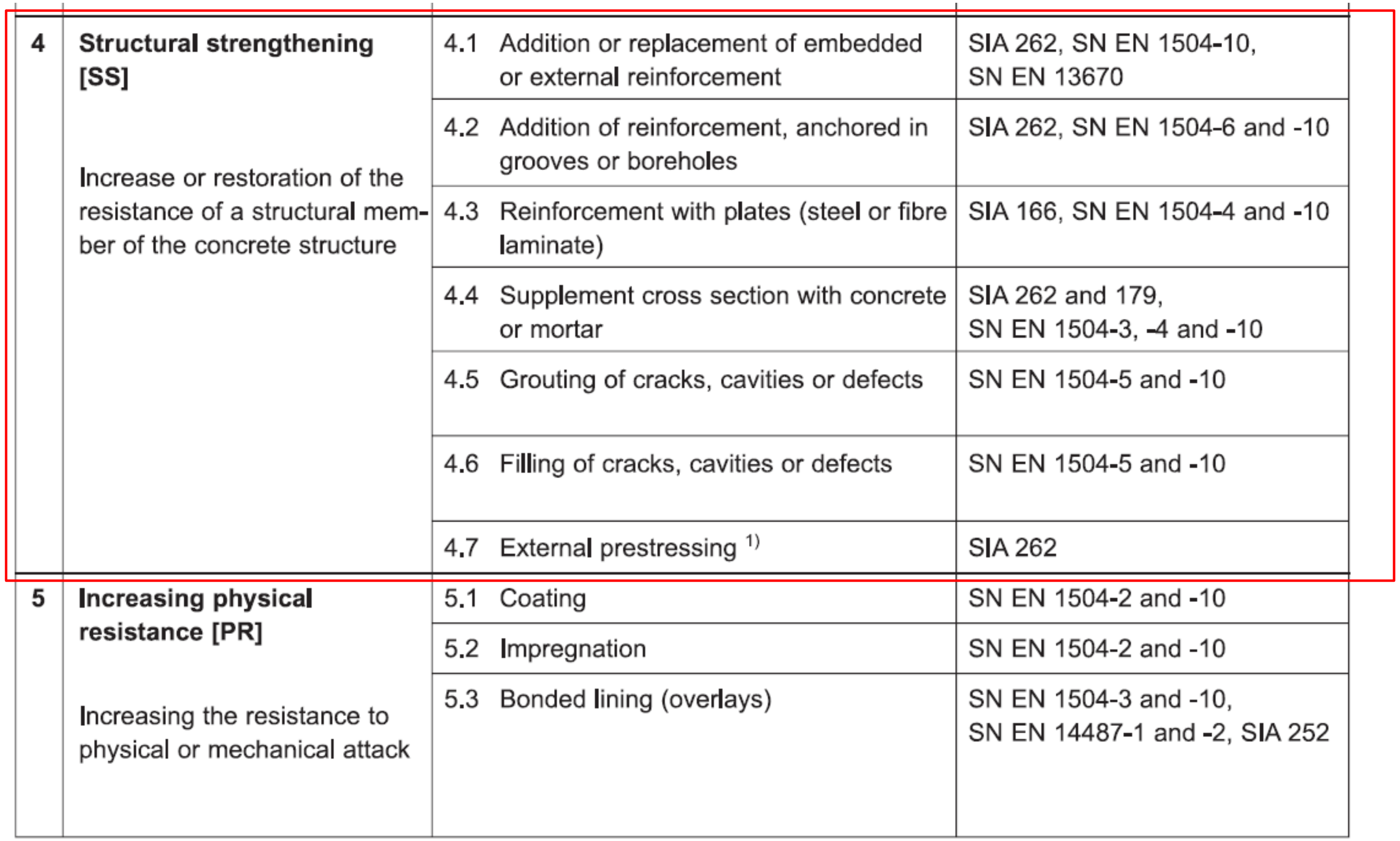
Chapter 11: strengthening (I): overview of methods & R-UHPFRC

Chapter 12: strengthening (II): glued CFRP lamellas

➔ Gives bases of possible intervention techniques to be proposed in intervention recommendations

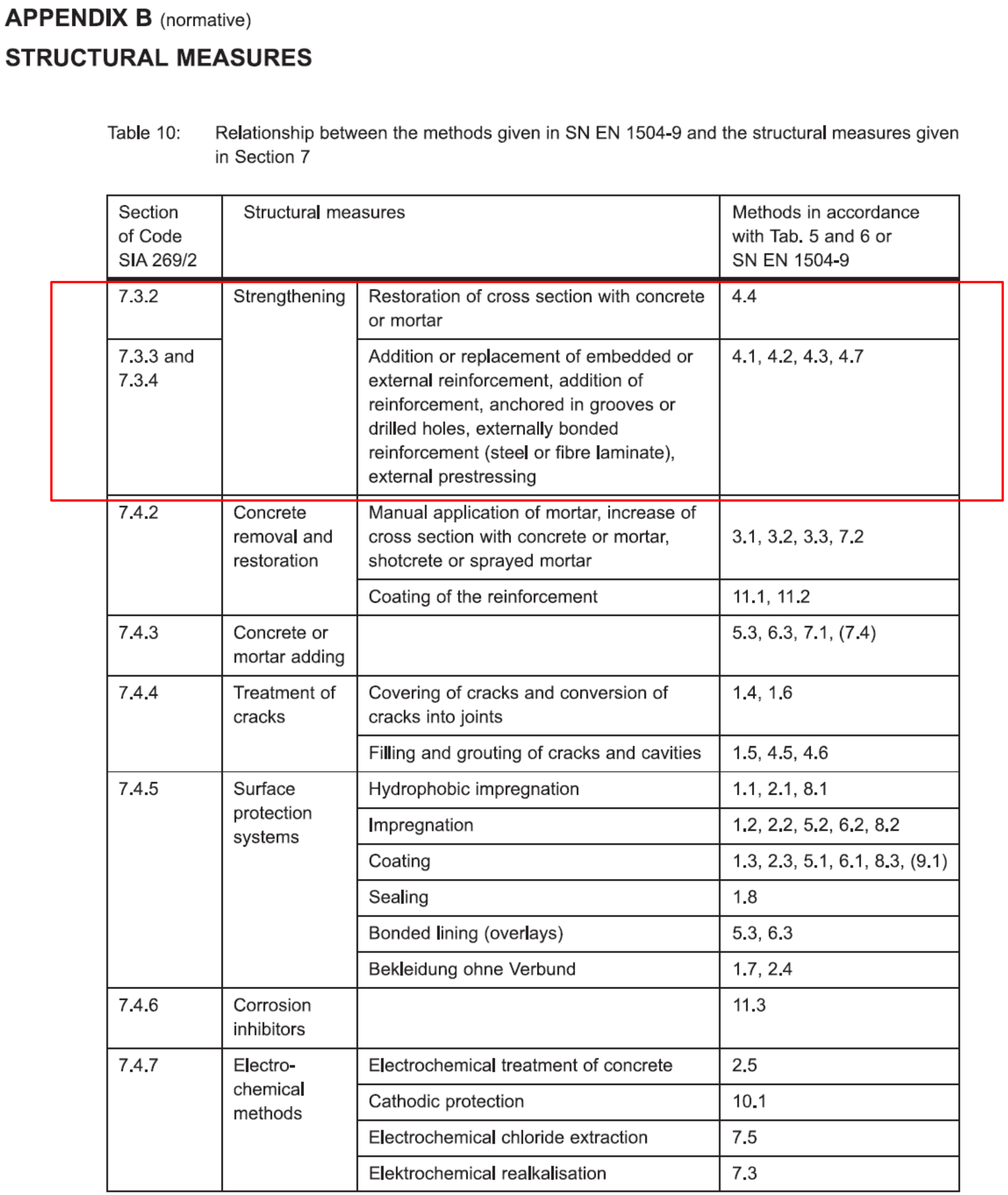
➔ Address causes of deterioration phenomena and lacks in structural safety and serviceability

- SIA 269/2 – List of principles of intervention



4	**Structural strengthening [SS]** Increase or restoration of the resistance of a structural member of the concrete structure	4.1 Addition or replacement of embedded or external reinforcement	SIA 262, SN EN 1504-10, SN EN 13670
		4.2 Addition of reinforcement, anchored in grooves or boreholes	SIA 262, SN EN 1504-6 and -10
		4.3 Reinforcement with plates (steel or fibre laminate)	SIA 166, SN EN 1504-4 and -10
		4.4 Supplement cross section with concrete or mortar	SIA 262 and 179, SN EN 1504-3, -4 and -10
		4.5 Grouting of cracks, cavities or defects	SN EN 1504-5 and -10
		4.6 Filling of cracks, cavities or defects	SN EN 1504-5 and -10
		4.7 External prestressing [1)]	SIA 262
5	**Increasing physical resistance [PR]** Increasing the resistance to physical or mechanical attack	5.1 Coating	SN EN 1504-2 and -10
		5.2 Impregnation	SN EN 1504-2 and -10
		5.3 Bonded lining (overlays)	SN EN 1504-3 and -10, SN EN 14487-1 and -2, SIA 252

- SIA 269/2



APPENDIX B (normative)

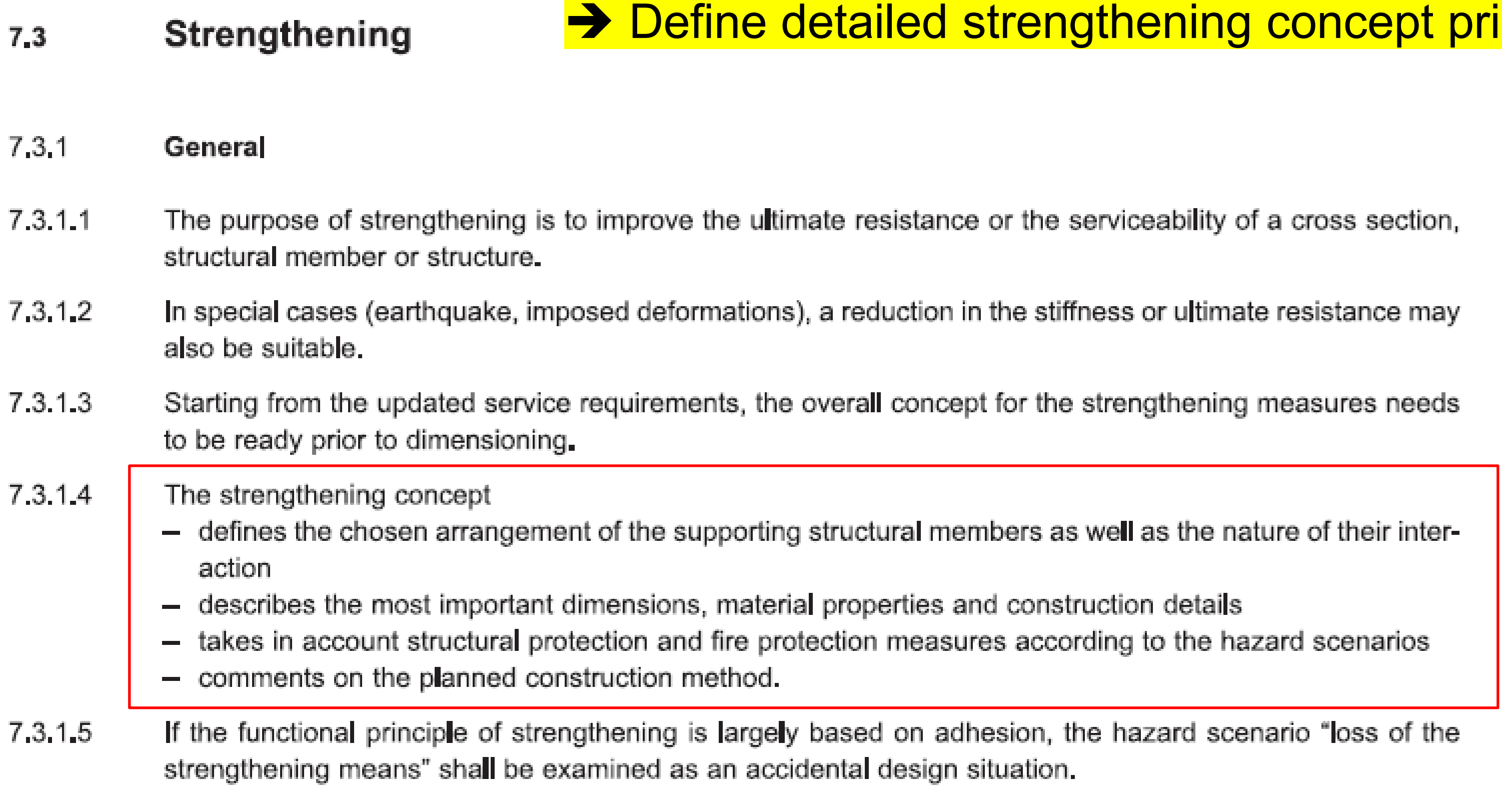
STRUCTURAL MEASURES

Table 10: Relationship between the methods given in SN EN 1504-9 and the structural measures given in Section 7

Section of Code SIA 269/2	Structural measures		Methods in accordance with Tab. 5 and 6 or SN EN 1504-9
7.3.2	Strengthening	Restoration of cross section with concrete or mortar	4.4
7.3.3 and 7.3.4		Addition or replacement of embedded or external reinforcement, addition of reinforcement, anchored in grooves or drilled holes, externally bonded reinforcement (steel or fibre laminate), external prestressing	4.1, 4.2, 4.3, 4.7
7.4.2	Concrete removal and restoration	Manual application of mortar, increase of cross section with concrete or mortar, shotcrete or sprayed mortar	3.1, 3.2, 3.3, 7.2
		Coating of the reinforcement	11.1, 11.2
7.4.3	Concrete or mortar adding		5.3, 6.3, 7.1, (7.4)
7.4.4	Treatment of cracks	Covering of cracks and conversion of cracks into joints	1.4, 1.6
		Filling and grouting of cracks and cavities	1.5, 4.5, 4.6
7.4.5	Surface protection systems	Hydrophobic impregnation	1.1, 2.1, 8.1
		Impregnation	1.2, 2.2, 5.2, 6.2, 8.2
		Coating	1.3, 2.3, 5.1, 6.1, 8.3, (9.1)
		Sealing	1.8
		Bonded lining (overlays)	5.3, 6.3
		Bekleidung ohne Verbund	1.7, 2.4
7.4.6	Corrosion inhibitors		11.3
7.4.7	Electro-chemical methods	Electrochemical treatment of concrete	2.5
		Cathodic protection	10.1
		Electrochemical chloride extraction	7.5
		Elektrochemical realkalisation	7.3

- SIA 269/2

➔ Define detailed strengthening concept prior to dimensioning



7.3 Strengthening

7.3.1 General

7.3.1.1 The purpose of strengthening is to improve the ultimate resistance or the serviceability of a cross section, structural member or structure.

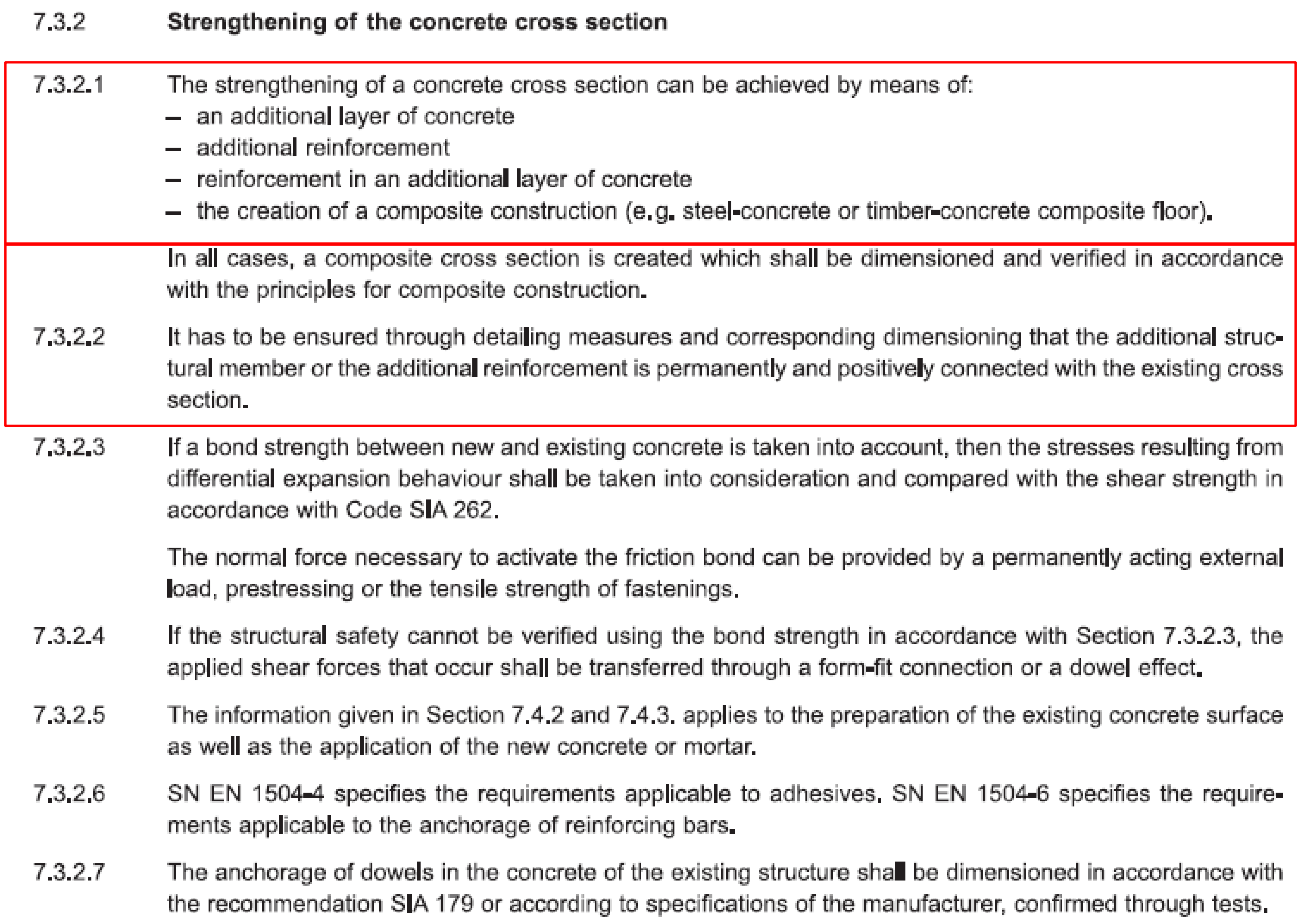
7.3.1.2 In special cases (earthquake, imposed deformations), a reduction in the stiffness or ultimate resistance may also be suitable.

7.3.1.3 Starting from the updated service requirements, the overall concept for the strengthening measures needs to be ready prior to dimensioning.

7.3.1.4 The strengthening concept
- defines the chosen arrangement of the supporting structural members as well as the nature of their interaction
- describes the most important dimensions, material properties and construction details
- takes in account structural protection and fire protection measures according to the hazard scenarios
- comments on the planned construction method.

7.3.1.5 If the functional principle of strengthening is largely based on adhesion, the hazard scenario "loss of the strengthening means" shall be examined as an accidental design situation.

- SIA 269/2



7.3.2 **Strengthening of the concrete cross section**

7.3.2.1 The strengthening of a concrete cross section can be achieved by means of:
- an additional layer of concrete
- additional reinforcement
- reinforcement in an additional layer of concrete
- the creation of a composite construction (e.g. steel-concrete or timber-concrete composite floor).

In all cases, a composite cross section is created which shall be dimensioned and verified in accordance with the principles for composite construction.

7.3.2.2 It has to be ensured through detailing measures and corresponding dimensioning that the additional structural member or the additional reinforcement is permanently and positively connected with the existing cross section.

7.3.2.3 If a bond strength between new and existing concrete is taken into account, then the stresses resulting from differential expansion behaviour shall be taken into consideration and compared with the shear strength in accordance with Code SIA 262.

The normal force necessary to activate the friction bond can be provided by a permanently acting external load, prestressing or the tensile strength of fastenings.

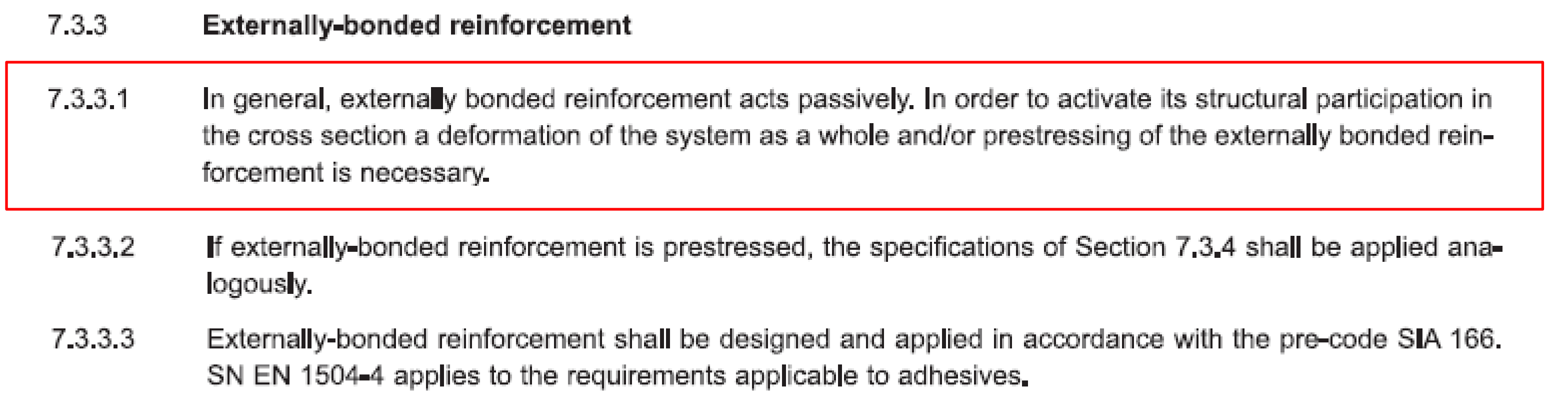
7.3.2.4 If the structural safety cannot be verified using the bond strength in accordance with Section 7.3.2.3, the applied shear forces that occur shall be transferred through a form-fit connection or a dowel effect.

7.3.2.5 The information given in Section 7.4.2 and 7.4.3. applies to the preparation of the existing concrete surface as well as the application of the new concrete or mortar.

7.3.2.6 SN EN 1504-4 specifies the requirements applicable to adhesives. SN EN 1504-6 specifies the requirements applicable to the anchorage of reinforcing bars.

7.3.2.7 The anchorage of dowels in the concrete of the existing structure shall be dimensioned in accordance with the recommendation SIA 179 or according to specifications of the manufacturer, confirmed through tests.

- SIA 269/2



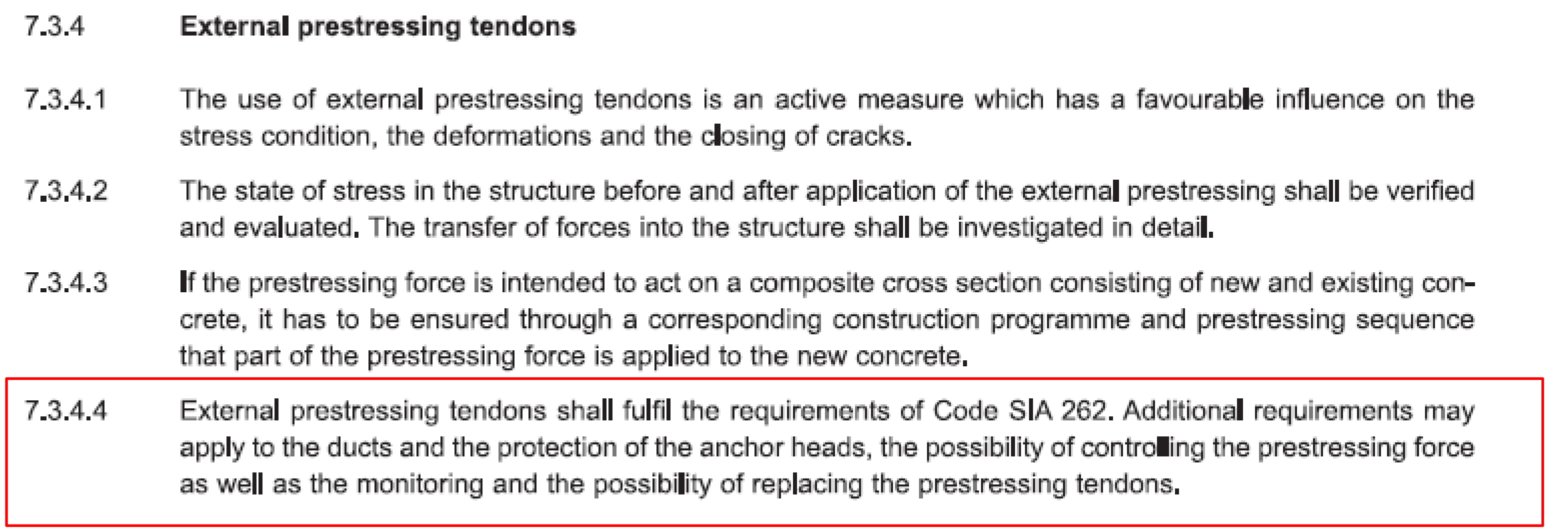
7.3.3 **Externally-bonded reinforcement**

7.3.3.1 In general, externally bonded reinforcement acts passively. In order to activate its structural participation in the cross section a deformation of the system as a whole and/or prestressing of the externally bonded reinforcement is necessary.

7.3.3.2 If externally-bonded reinforcement is prestressed, the specifications of Section 7.3.4 shall be applied analogously.

7.3.3.3 Externally-bonded reinforcement shall be designed and applied in accordance with the pre-code SIA 166. SN EN 1504-4 applies to the requirements applicable to adhesives.

➔ Upon method used, benefits of strengthening depend on "activation"



7.3.4 **External prestressing tendons**

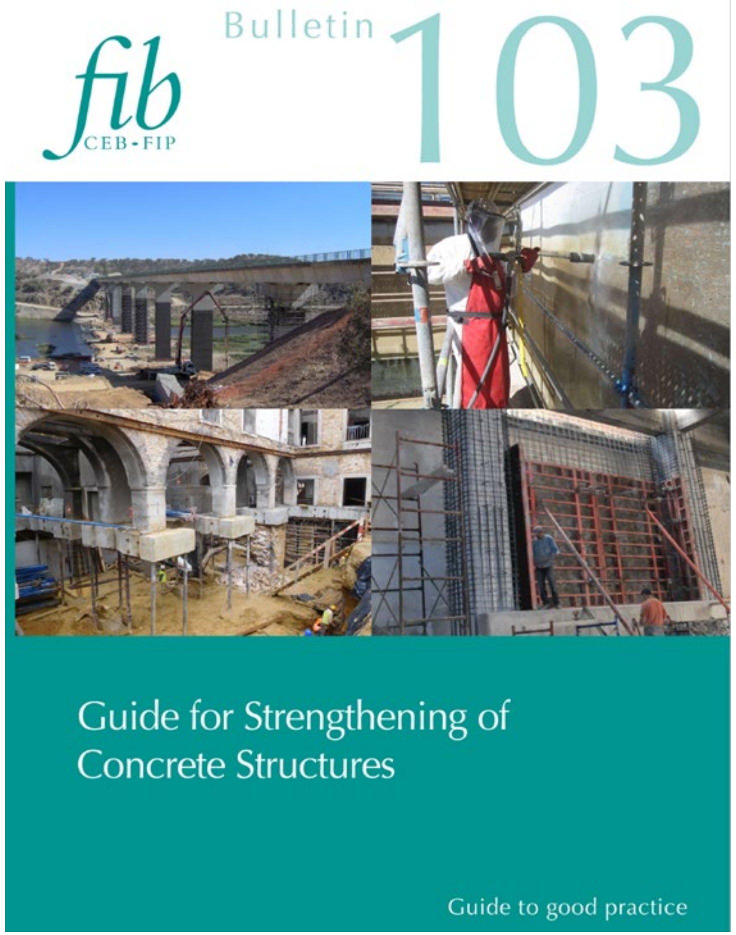
7.3.4.1 The use of external prestressing tendons is an active measure which has a favourable influence on the stress condition, the deformations and the closing of cracks.

7.3.4.2 The state of stress in the structure before and after application of the external prestressing shall be verified and evaluated. The transfer of forces into the structure shall be investigated in detail.

7.3.4.3 If the prestressing force is intended to act on a composite cross section consisting of new and existing concrete, it has to be ensured through a corresponding construction programme and prestressing sequence that part of the prestressing force is applied to the new concrete.

7.3.4.4 External prestressing tendons shall fulfil the requirements of Code SIA 262. Additional requirements may apply to the ducts and the protection of the anchor heads, the possibility of controlling the prestressing force as well as the monitoring and the possibility of replacing the prestressing tendons.

Detailed discussion of reinforcement techniques



Bulletin 103

fib CEB-FIP

Guide for Strengthening of Concrete Structures

Guide to good practice

[1]

Available in
"Complementary readings"
folder on Moodle
Chapter 11

➔ All techniques except use of R-UHPFRC (see below)

2. Overview of discussed methods

Methods for strengthening of structural members

- External prestressing / combinations with UHPFRC
- CFRP: Glued Carbon Fiber Reinforced Lamellas

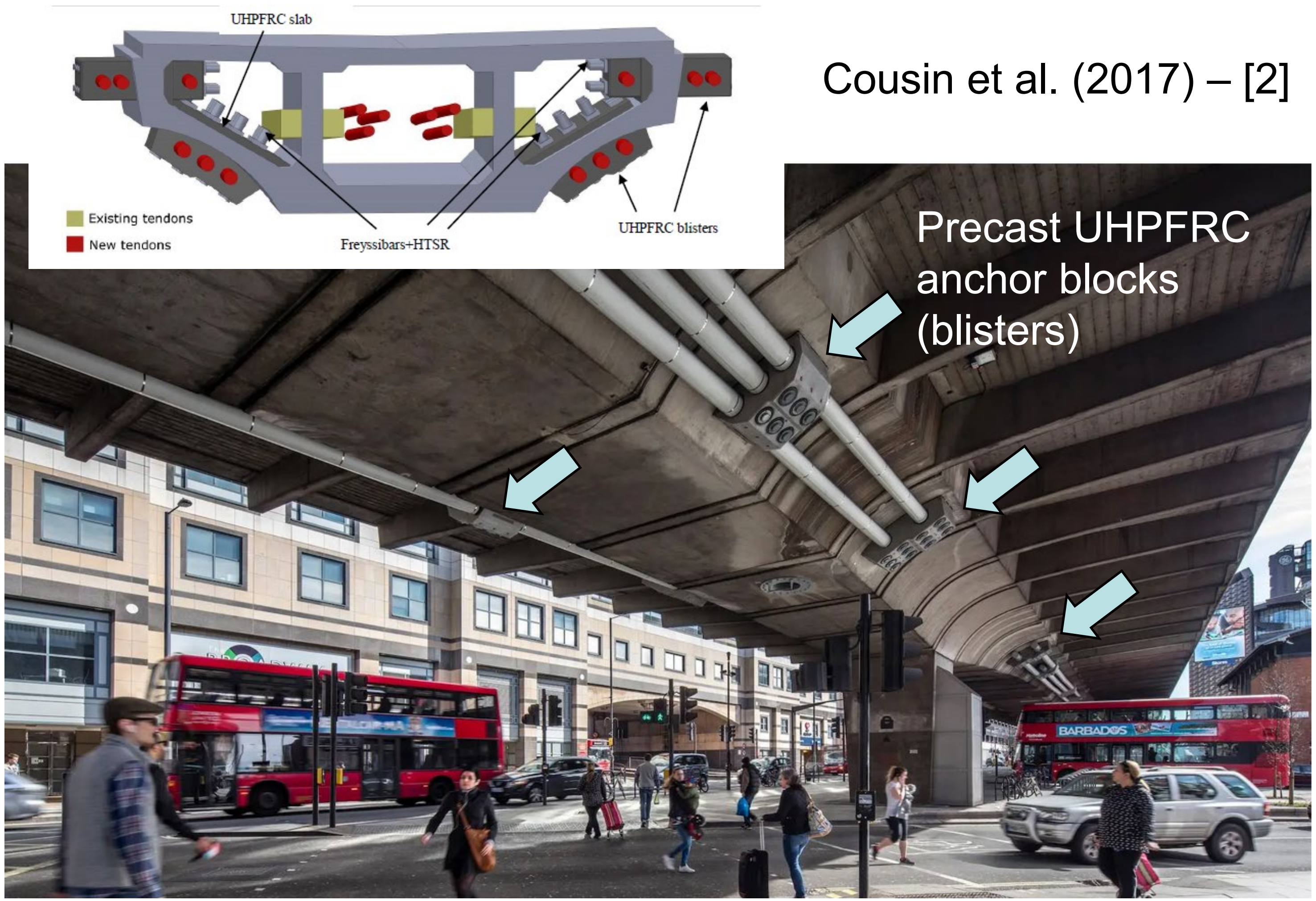
(see Chapter 12)

- Reinforced UHPFRC: R-UHPFRC

3. External prestressing

- Possible in longitudinal and transverse directions
- Challenge of deviation forces and anchorages
- Strong impact on structural response
- Ease of access for regular controls
- Challenge of durability in ducts

Hammersmith-flyover – London - 2015



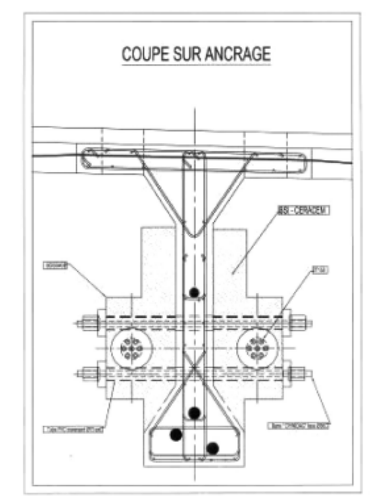
Cousin et al. (2017) – [2]

Precast UHPFRC anchor blocks (blisters)

https://www.ramboll.com/en-gb/projects/transport/hammersmith-flyover

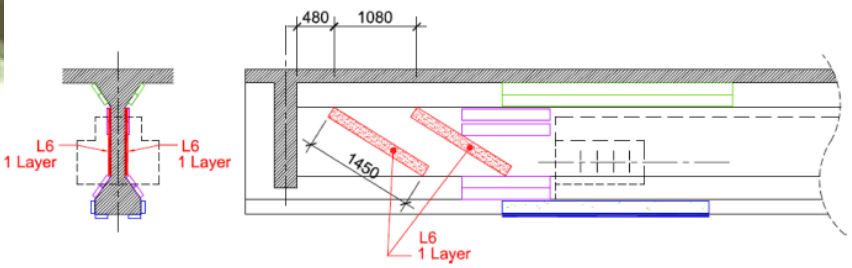
- Severely corroded existing post-tensionning system
- Combined use of external post-tensionning and UHPFRC to make the structure independent of the existing prestressing system

Bridge over l'Huisne – Le Mans, (F), 2006

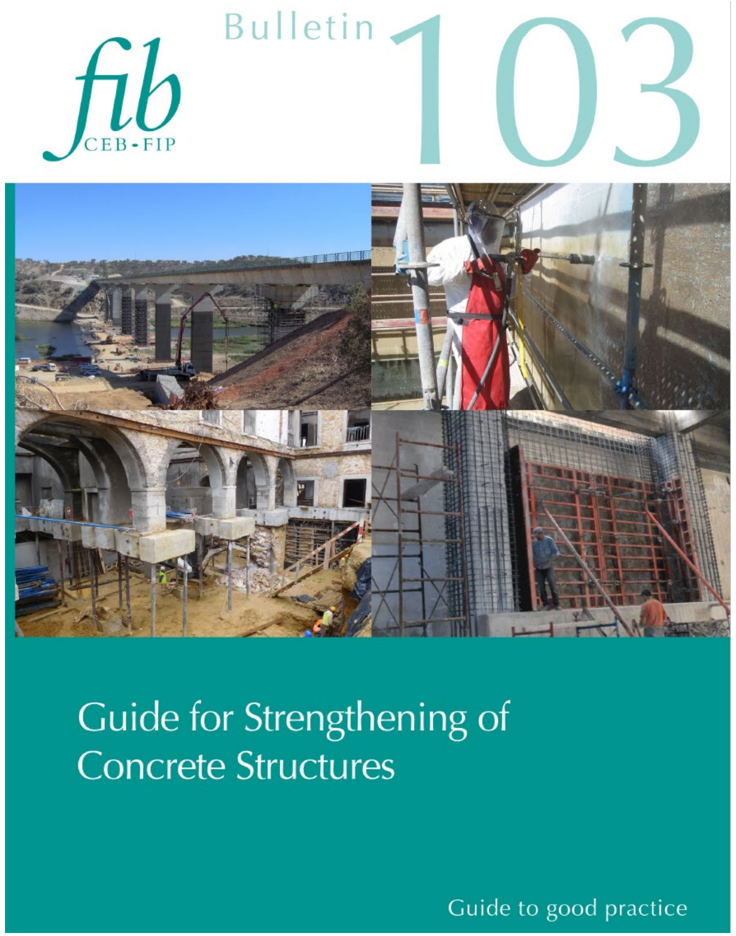


Thibaux (2008) – [3]

Glued CFRP strips



- Increase of traffic loads (lanes + tramway too)
- Increase of web thickness with cast-in place UHPFRC (BSI)
- High Emodulus of BSI (65 GPa) "drains" internal forces
- Additional external prestressing
- Glued CFRP strips to transfer shear loads where needed



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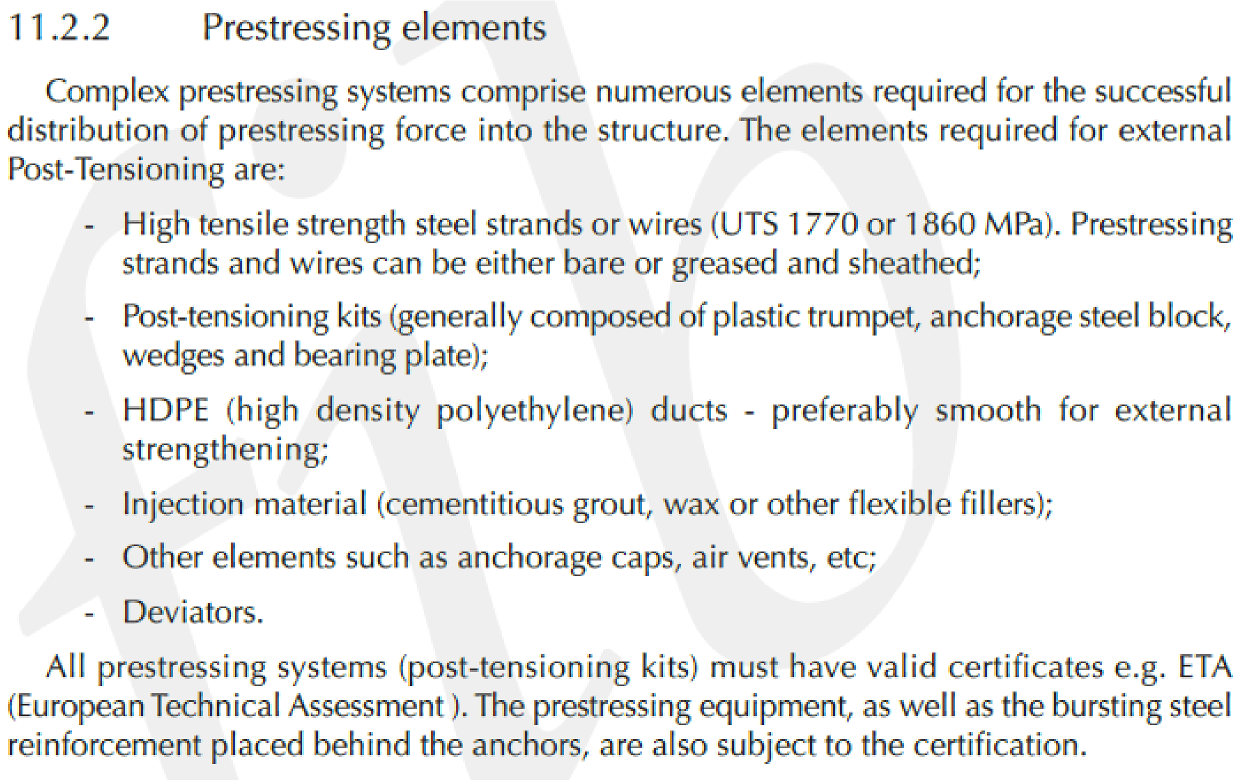
Bulletin 103

Guide for Strengthening of Concrete Structures

Guide to good practice

Chapter 11: "External post-tensionning"



11.2.2 Prestressing elements

Complex prestressing systems comprise numerous elements required for the successful distribution of prestressing force into the structure. The elements required for external Post-Tensioning are:

- High tensile strength steel strands or wires (UTS 1770 or 1860 MPa). Prestressing strands and wires can be either bare or greased and sheathed;
- Post-tensioning kits (generally composed of plastic trumpet, anchorage steel block, wedges and bearing plate);
- HDPE (high density polyethylene) ducts - preferably smooth for external strengthening;
- Injection material (cementitious grout, wax or other flexible fillers);
- Other elements such as anchorage caps, air vents, etc;
- Deviators.

All prestressing systems (post-tensioning kits) must have valid certificates e.g. ETA (European Technical Assessment). The prestressing equipment, as well as the bursting steel reinforcement placed behind the anchors, are also subject to the certification.

➔ For more details on external prestressing

4. Bases of R-UHPFRC materials

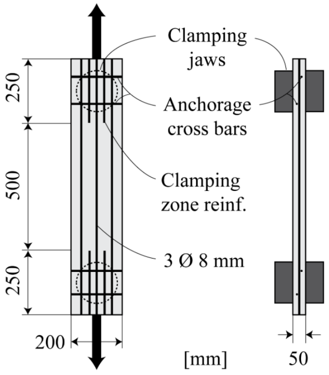
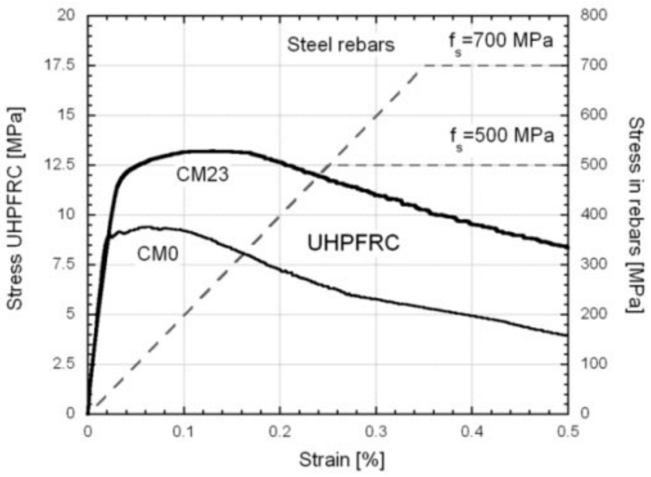


Figure 3.22.: R-UHPFRC tensile specimens and test set-up



Oesterlee (2010) – [4]

Combined response
rebar + UHPFRC assuming
superposition with perfect bond

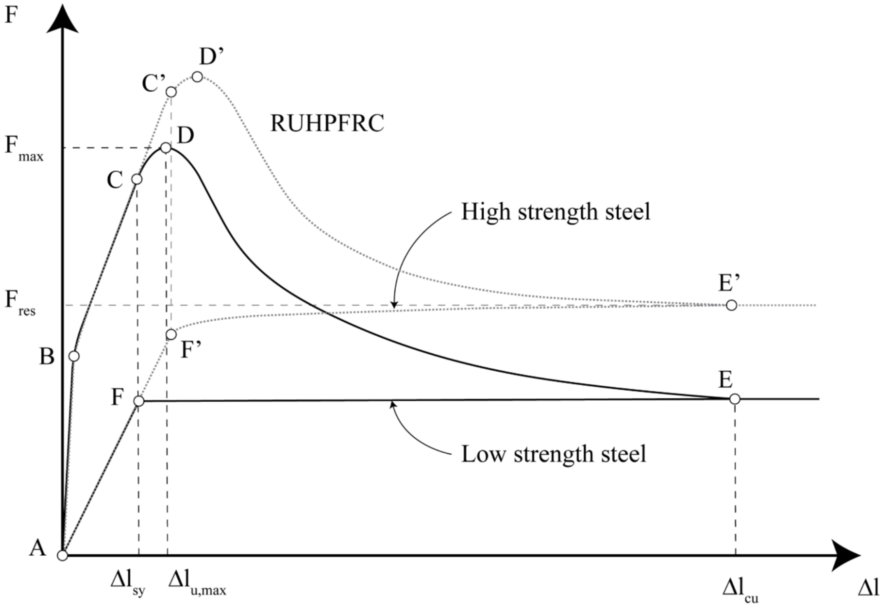


Figure 3.23.: Characteristic tensile behaviour of R-UHPFRC

PULL-OUT TESTS - OESTERLEE (2010)

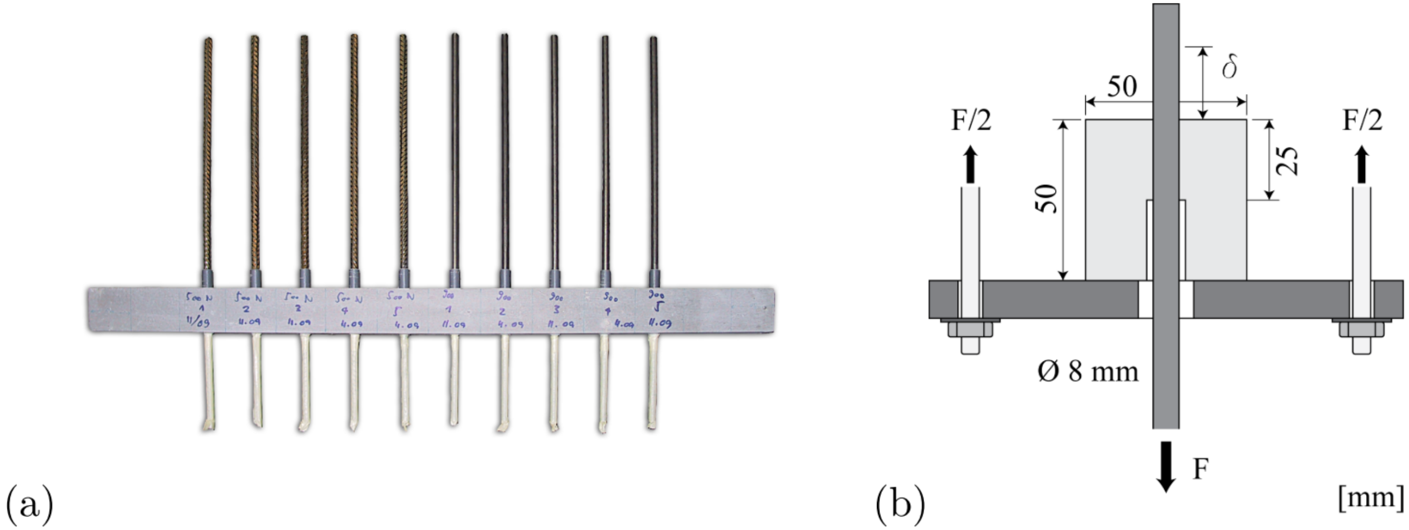
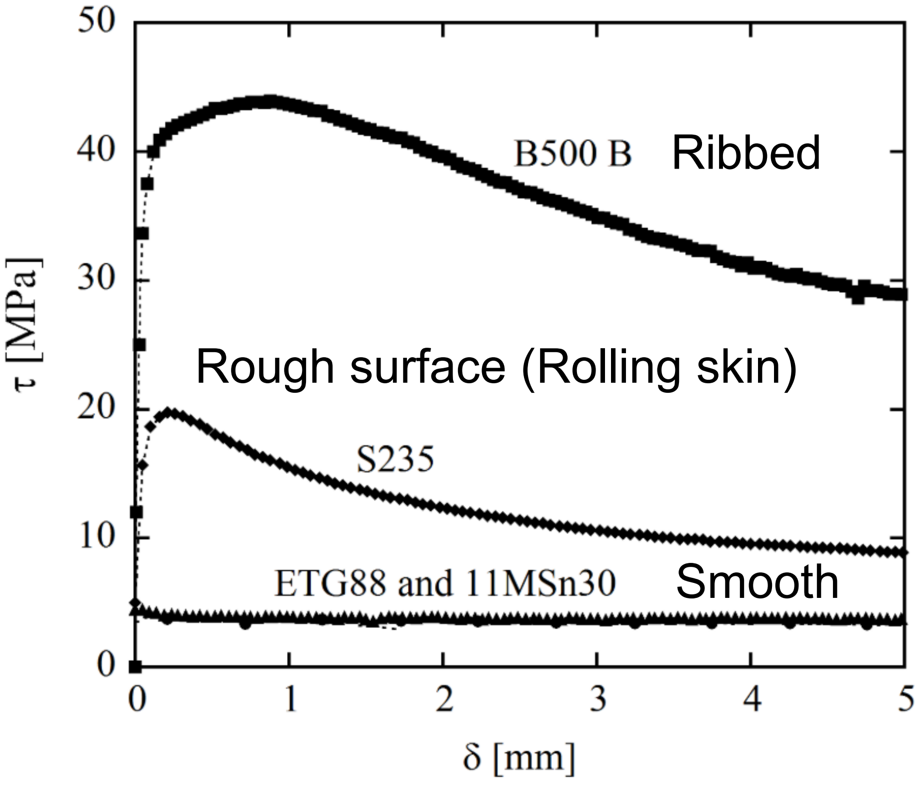


Figure 3.19.: (a) Pull-out specimens prior to cutting, (b) Test set-up for pull-out specimens

Oesterlee (2010)



(a)

➔ Very high bond strength of rebar in UHPFRC
➔ Anchoring length in tensile zones much smaller than in normal concretes (15 ϕ vs 40 ϕ) – CT 2052 SIA

➔ Bond strength B500B in NC: ~ 10 to 15 MPa upon concrete strength

Range of discontinuous fibers bond strength = 6 to 10 MPa

Figure 3.20.: Bond stress-slip response of reinforcing bars in UHPFRC, influence of (a) surface characteristics after 28 days with 3% fibres

R-UHPFRC vs UHPFRC tensile response

Back calculated elastic limit UHPFRC = 5.5 MPa
Scatter for 3 R-UHPFRC specimen: 3.5 to 8.5 MPa

Oesterlee (2010)

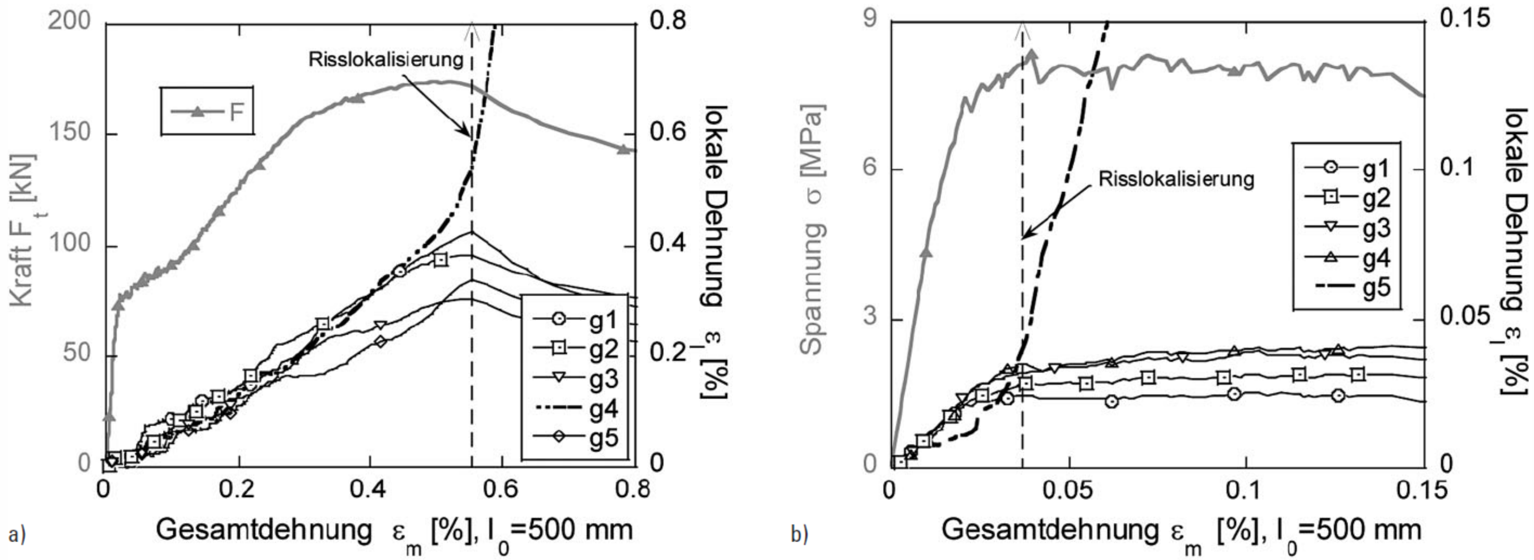


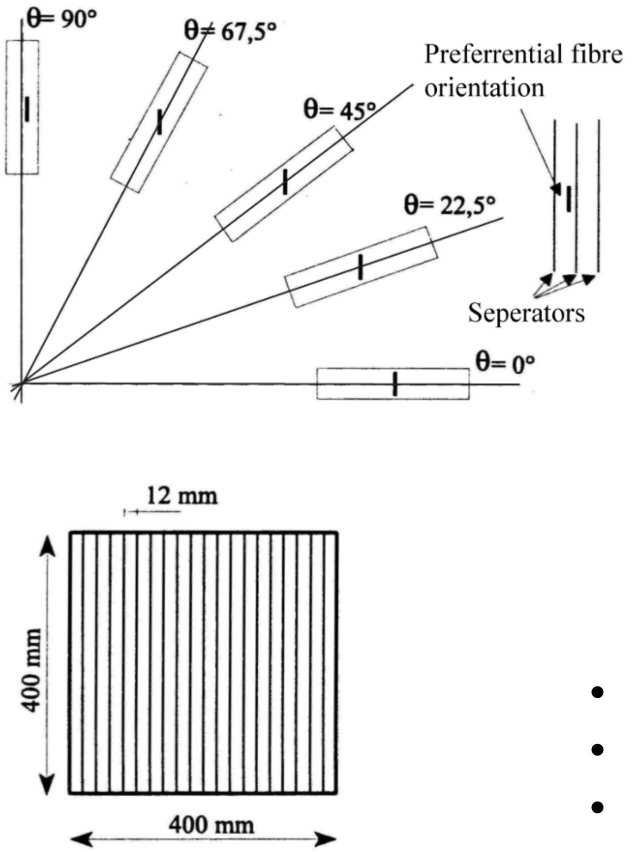
Bild 6. Lokale Dehnungsverteilung im Vergleich zur Gesamtdehnung einer a) mit B500 B bewehrten Zugprobe und einer b) ausschließlich faserbewehrten UHFB-Probe
Fig. 6. Local deformation versus mean deformation for a) B500 B reinforced tensile specimen and b) only fibre reinforced specimen

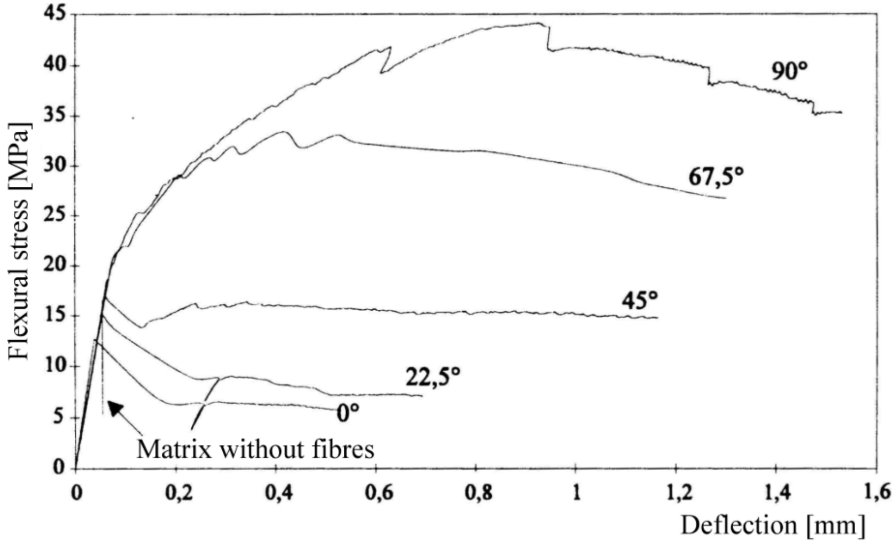
- Localization of fracture detected by multiple «local» gauges
- Assumed to represent end of hardening domain
- Elastic limit and deformability of UHPFRC affected

- Positive synergy between rebars and UHPFRC
- Apparent tensile strain hardening of UHPFRC deduced from global R-UHPFRC test results is significantly larger - factor of 2-3 x – than that for plain UHPFRC alone
- Apparent UHPFRC elastic limit reduced with rebars, but very large scatter observed
- Similar effects were observed by other authors
- Clear evidence of these effects still to be fully demonstrated and explained

➔ Possible influences of bond-slip response + pre-existing eigenstresses due to autogenous shrinkage

EFFECTS OF FIBRE ORIENTATION





- Thesis Behloul (1996)
- Deliberate forced orientation at casting
- Specimen cuts at different incidences

UHPFRC PANEL

Oesterlee (2010)

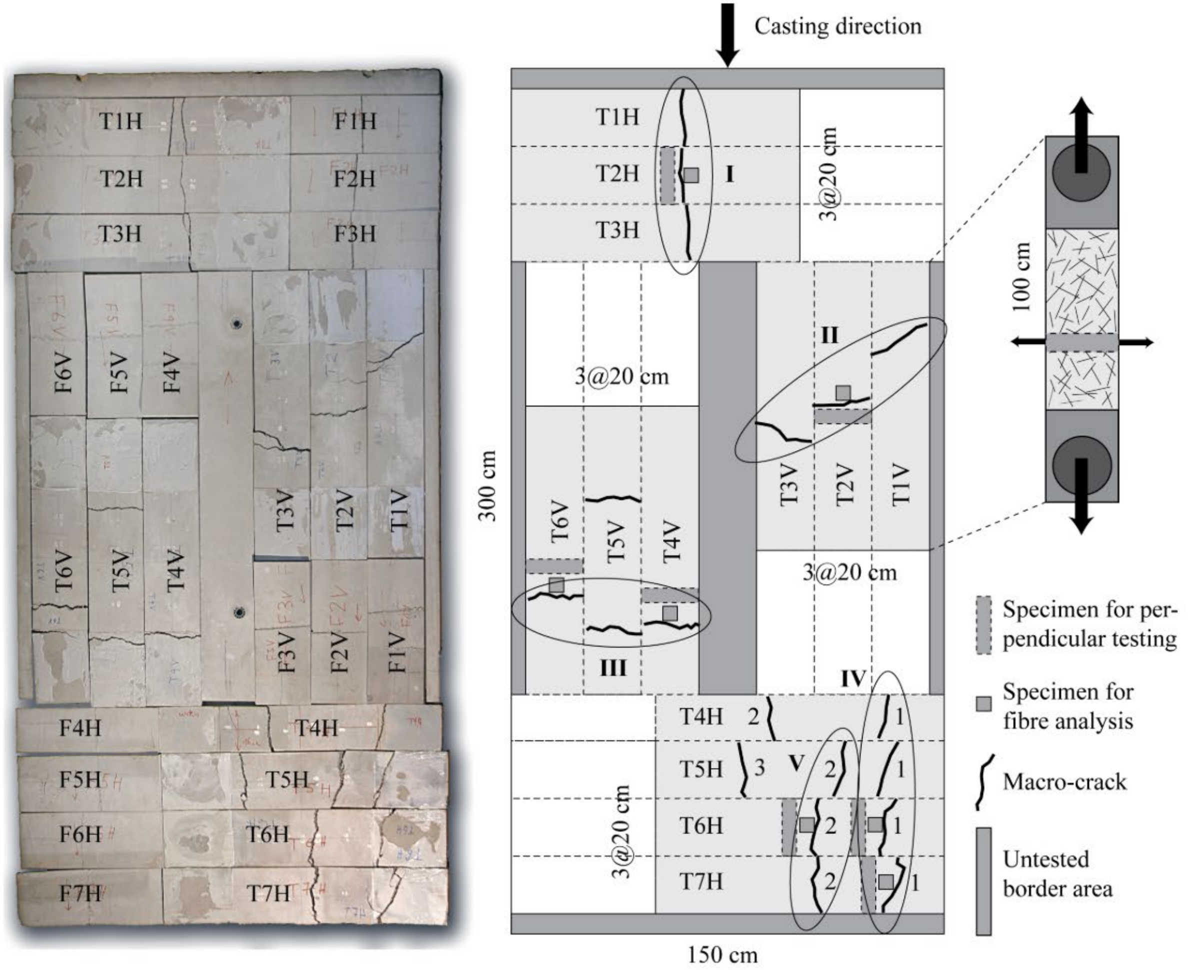
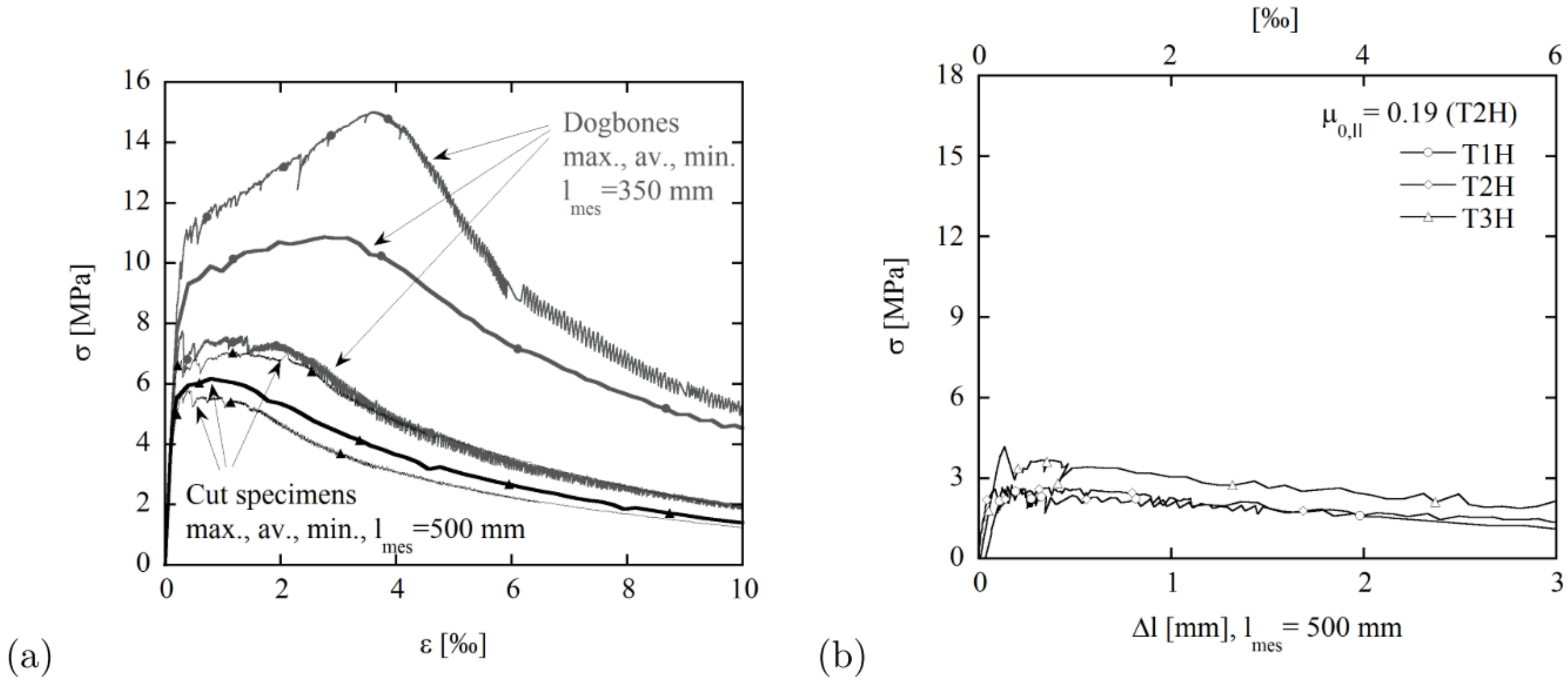


Figure 3.14.: Vertically cast UHPFRC panel, test series (3), with cutting plan for tensile specimens and specimens for perpendicular testing and fibre analysis, thickness 40 mm

TENSILE RESPONSE - UHPFRC HIFCOM$_{13S}$

Oesterlee (2010)

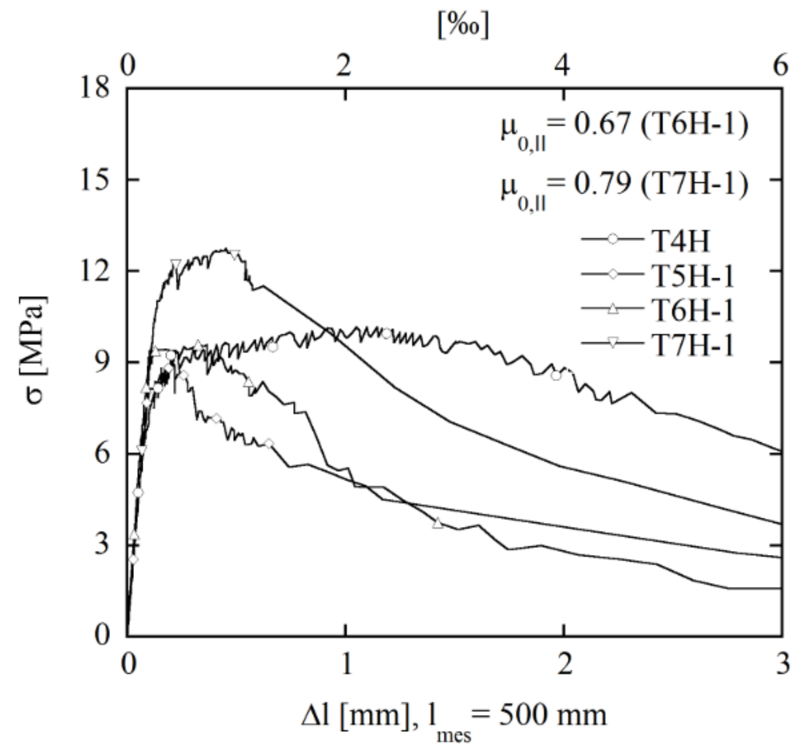


Dogbones and plates cast horizontally

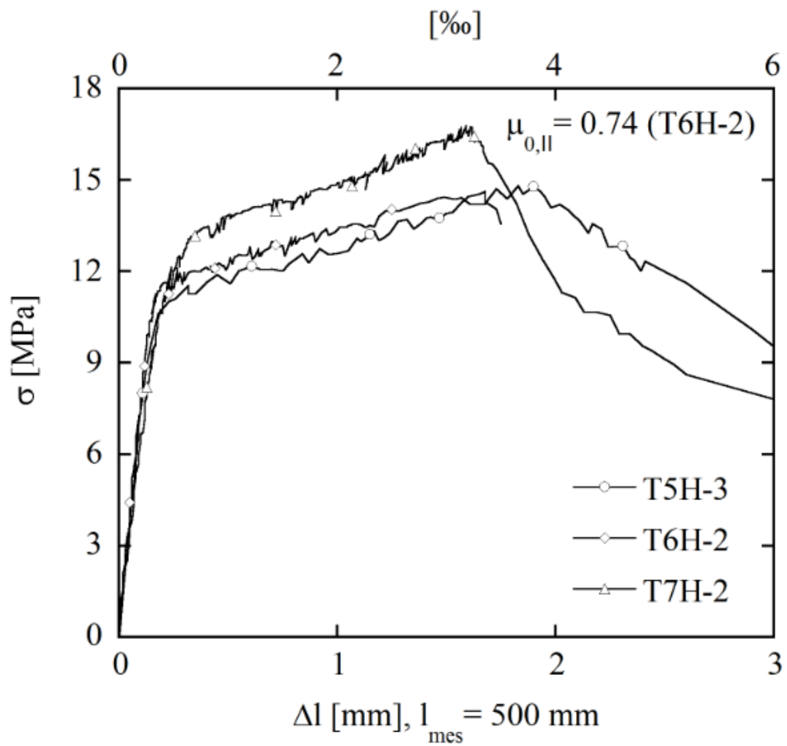
Cast upright and cut
Upper part of panel

LOWER PART OF PANEL

Oesterlee (2010)



(e)



(f)

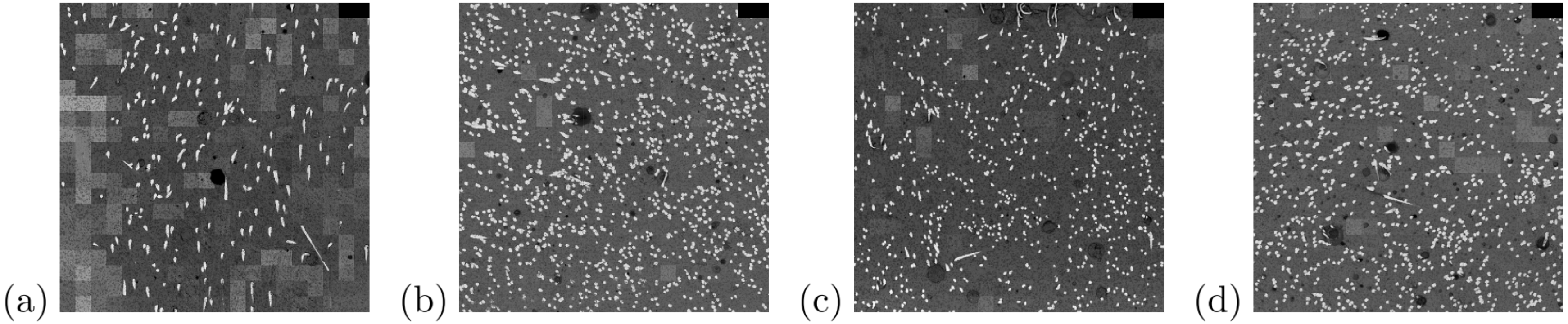
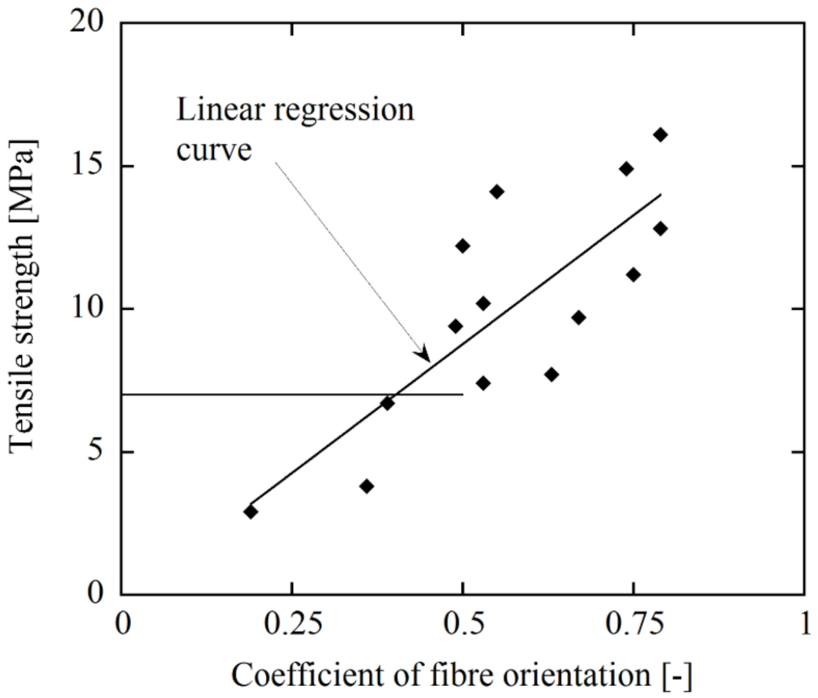


Figure 3.15.: Fibre analysis of UHPFRC specimens, (a) T2H perpendicular ($29\,fibres/cm^2$) , (b) T2H parallel ($123\,fibres/cm^2$), (c) T2V perpendicular ($83\,fibres/cm^2$), (d) T2V parallel ($100\,fibres/cm^2$) to the loading direction, surface $30 \cdot 30\,mm^2$

- Fibre counting by image analysis methodology after Wuest et al. (2009)

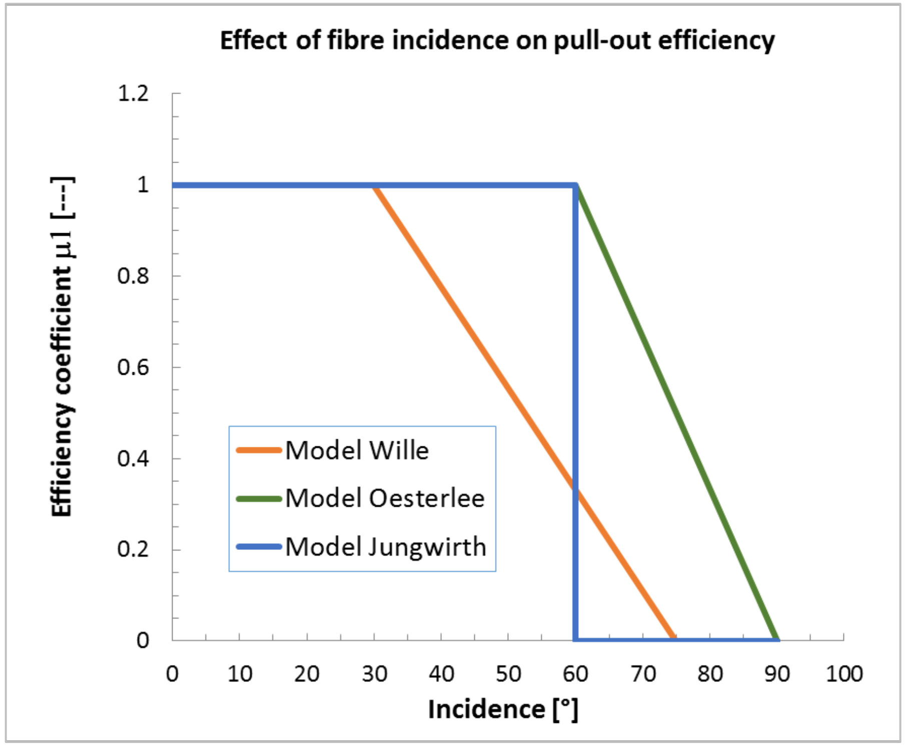


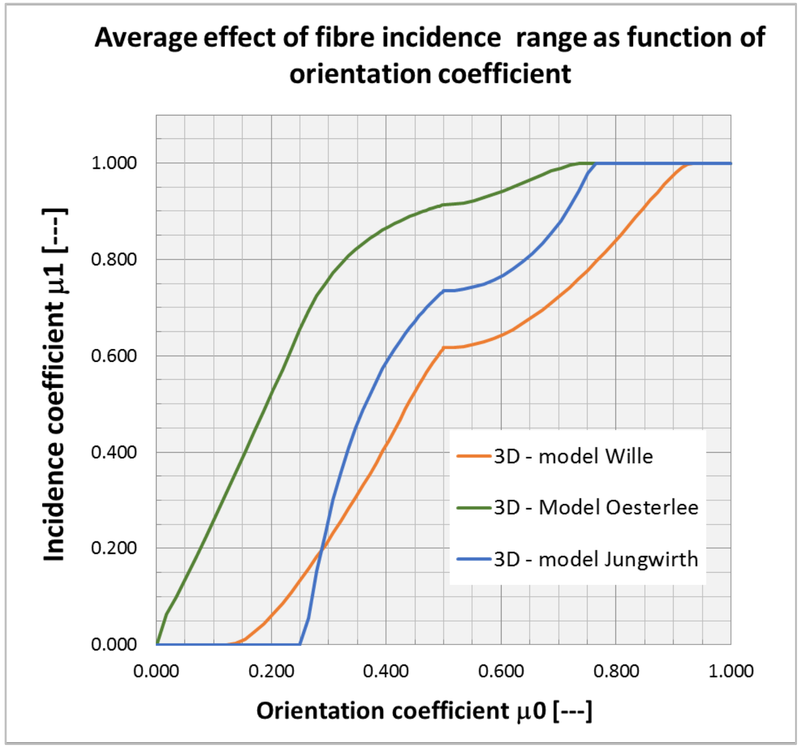
Oesterlee (2010)

Figure 3.13.: Tensile strength as function of the coefficient of fibre orientation μ_0

$$f_{t,pc} = \mu_0 \mu_1 \tau \frac{l_f}{d} V_f$$

EFFICIENCY COEFFICIENT μ_1





➔ Uniform distribution of fibers incidences within a given range of angles defines orientation coefficient μ_0 (stereology)

➔ Average value of μ_1 calculated by integration over a given range of angles

➔ Analytical resolution for «Oesterlee model»: Bastien-Masse (2015)

➔ Numerical integration for general model: Denarié (2015)

Thesis Oesterlee (2010)

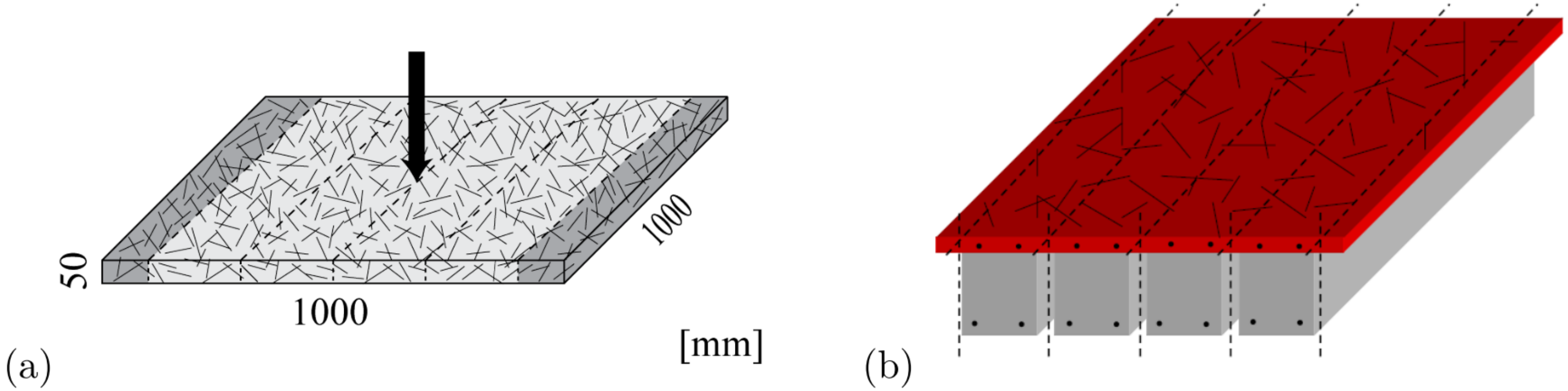
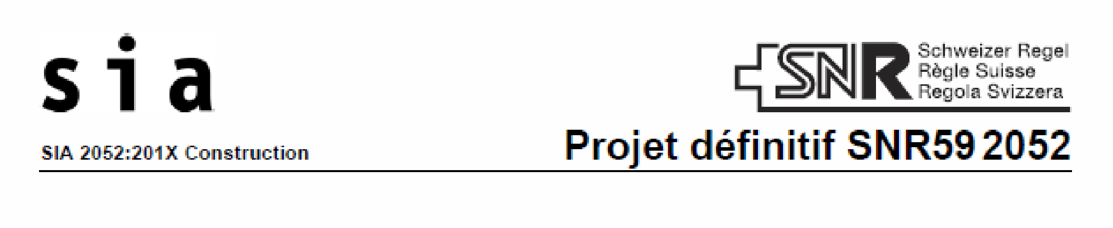


Figure 3.2.: Representative specimens, (a) tensile elements and (b) composite beams with continuous UHPFRC layer

- Method used for preparing "representative" tensile specimens and composite UHPFRC - RC members

SIA CT 2052 [5]
Edition 2016/2017



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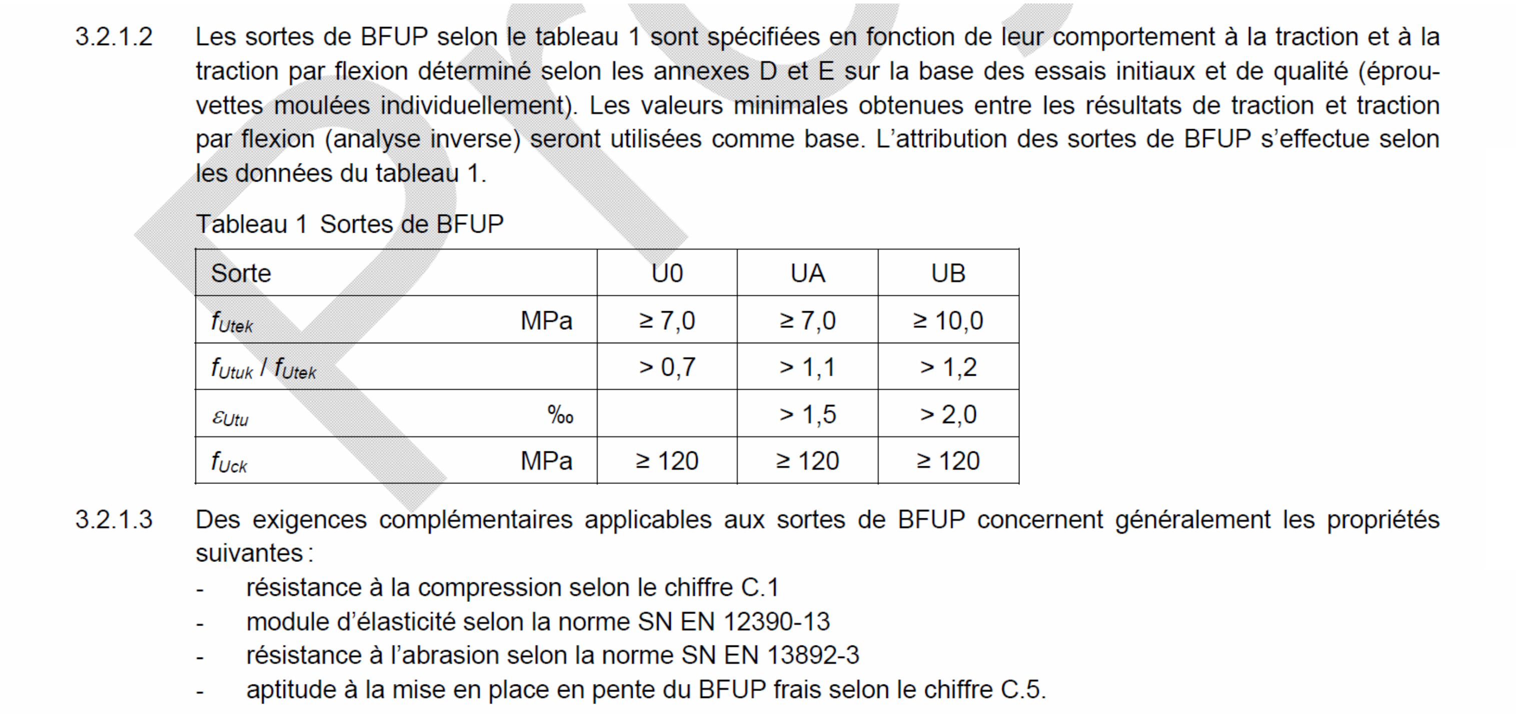
SIA 2052:201X Construction

SNR Schweizer Regel
Règle Suisse
Regola Svizzera

Projet définitif SNR59 2052



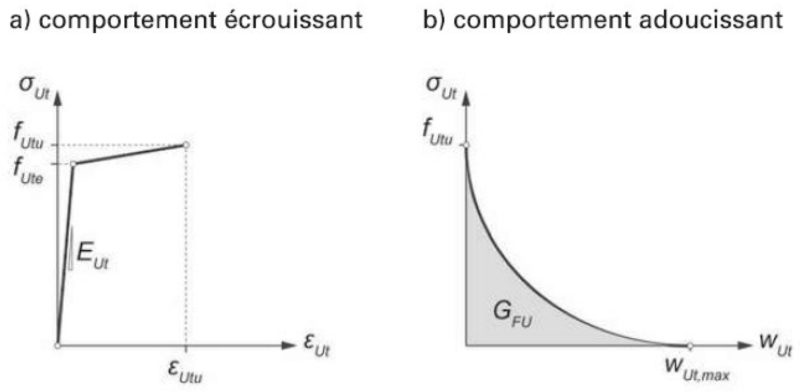
3.2.1.2 Les sortes de BFUP selon le tableau 1 sont spécifiées en fonction de leur comportement à la traction et à la traction par flexion déterminé selon les annexes D et E sur la base des essais initiaux et de qualité (éprouvettes moulées individuellement). Les valeurs minimales obtenues entre les résultats de traction et traction par flexion (analyse inverse) seront utilisées comme base. L'attribution des sortes de BFUP s'effectue selon les données du tableau 1.

Tableau 1 Sortes de BFUP

Sorte		U0	UA	UB
f_{Utek}	MPa	≥ 7,0	≥ 7,0	≥ 10,0
f_{Utuk} / f_{Utek}		> 0,7	> 1,1	> 1,2
ε_{Utu}	‰		> 1,5	> 2,0
f_{Uck}	MPa	≥ 120	≥ 120	≥ 120

3.2.1.3 Des exigences complémentaires applicables aux sortes de BFUP concernent généralement les propriétés suivantes:

- résistance à la compression selon le chiffre C.1
- module d'élasticité selon la norme SN EN 12390-13
- résistance à l'abrasion selon la norme SN EN 13892-3
- aptitude à la mise en place en pente du BFUP frais selon le chiffre C.5.



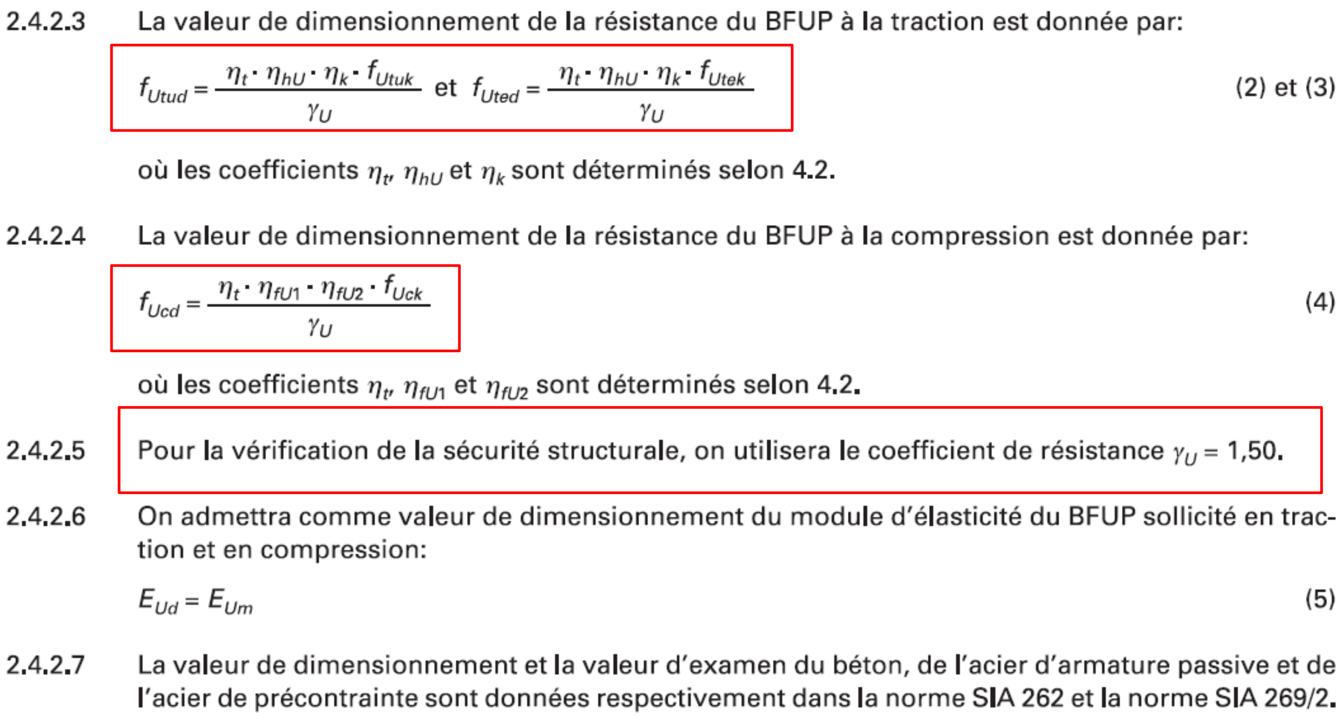
a) comportement écrouissant

b) comportement adoucissant

➔ Tension: characteristic values = average of test results or inverse analyses

➔ Compression: characteristic values = fractile 5 % of test results

SIA CT 2052



2.4.2.3 La valeur de dimensionnement de la résistance du BFUP à la traction est donnée par:

$$\boxed{f_{Utud} = \frac{\eta_t \cdot \eta_{hU} \cdot \eta_k \cdot f_{Utuk}}{\gamma_U} \quad \text{et} \quad f_{Uted} = \frac{\eta_t \cdot \eta_{hU} \cdot \eta_k \cdot f_{Utek}}{\gamma_U}} \qquad (2) \text{ et } (3)$$

où les coefficients η_t, η_{hU} et η_k sont déterminés selon 4.2.

2.4.2.4 La valeur de dimensionnement de la résistance du BFUP à la compression est donnée par:

$$\boxed{f_{Ucd} = \frac{\eta_t \cdot \eta_{fU1} \cdot \eta_{fU2} \cdot f_{Uck}}{\gamma_U}} \qquad (4)$$

où les coefficients η_t, η_{fU1} et η_{fU2} sont déterminés selon 4.2.

2.4.2.5 Pour la vérification de la sécurité structurale, on utilisera le coefficient de résistance $\gamma_U = 1,50$.

2.4.2.6 On admettra comme valeur de dimensionnement du module d'élasticité du BFUP sollicité en traction et en compression:

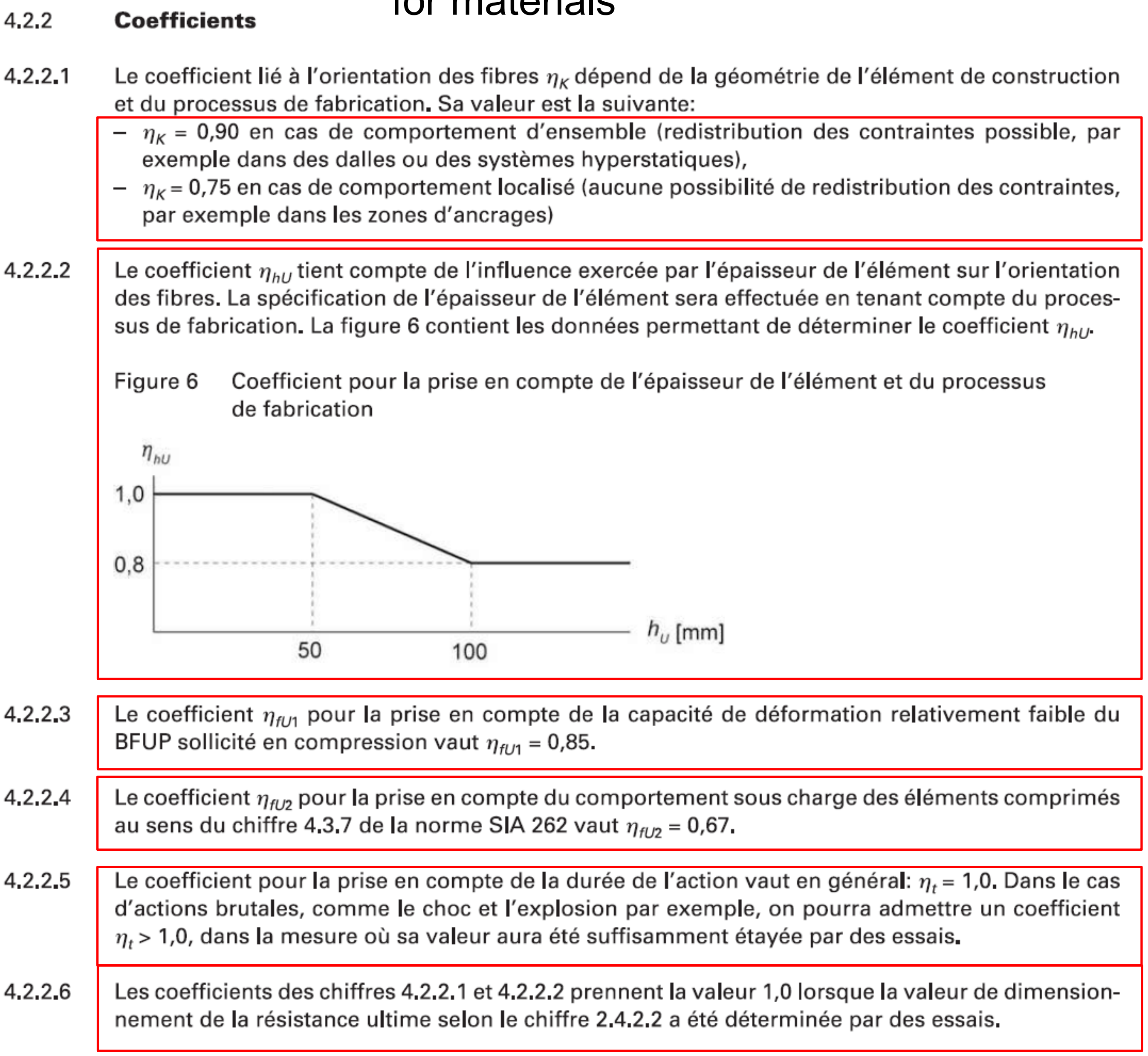
$$E_{Ud} = E_{Um} \qquad (5)$$

2.4.2.7 La valeur de dimensionnement et la valeur d'examen du béton, de l'acier d'armature passive et de l'acier de précontrainte sont données respectivement dans la norme SIA 262 et la norme SIA 269/2.

- Design values

SIA CT 2052

Partial safety coefficients for materials



4.2.2 **Coefficients**

Fiber orientation

4.2.2.1 Le coefficient lié à l'orientation des fibres η_K dépend de la géométrie de l'élément de construction et du processus de fabrication. Sa valeur est la suivante:

- η_K = 0,90 en cas de comportement d'ensemble (redistribution des contraintes possible, par exemple dans des dalles ou des systèmes hyperstatiques),
- η_K = 0,75 en cas de comportement localisé (aucune possibilité de redistribution des contraintes, par exemple dans les zones d'ancrages)

Member thickness

4.2.2.2 Le coefficient η_{hU} tient compte de l'influence exercée par l'épaisseur de l'élément sur l'orientation des fibres. La spécification de l'épaisseur de l'élément sera effectuée en tenant compte du processus de fabrication. La figure 6 contient les données permettant de déterminer le coefficient η_{hU}.

Figure 6 Coefficient pour la prise en compte de l'épaisseur de l'élément et du processus de fabrication

Compression response

4.2.2.3 Le coefficient η_{fU1} pour la prise en compte de la capacité de déformation relativement faible du BFUP sollicité en compression vaut η_{fU1} = 0,85.

! Only for 2nd order calc., else = 1 !

4.2.2.4 Le coefficient η_{fU2} pour la prise en compte du comportement sous charge des éléments comprimés au sens du chiffre 4.3.7 de la norme SIA 262 vaut η_{fU2} = 0,67.

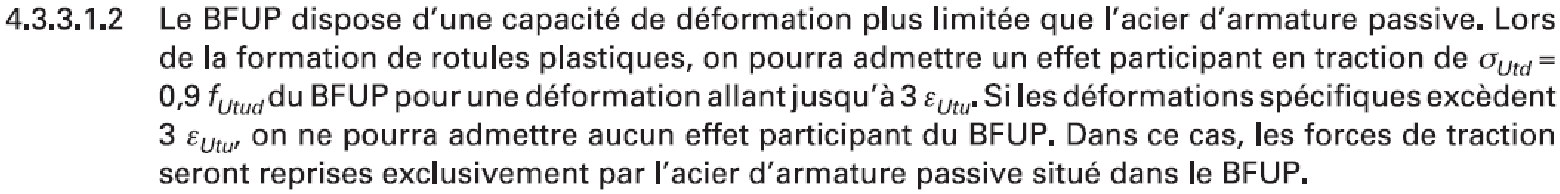
Duration of loading

4.2.2.5 Le coefficient pour la prise en compte de la durée de l'action vaut en général: η_t = 1,0. Dans le cas d'actions brutales, comme le choc et l'explosion par exemple, on pourra admettre un coefficient η_t > 1,0, dans la mesure où sa valeur aura été suffisamment étayée par des essais.

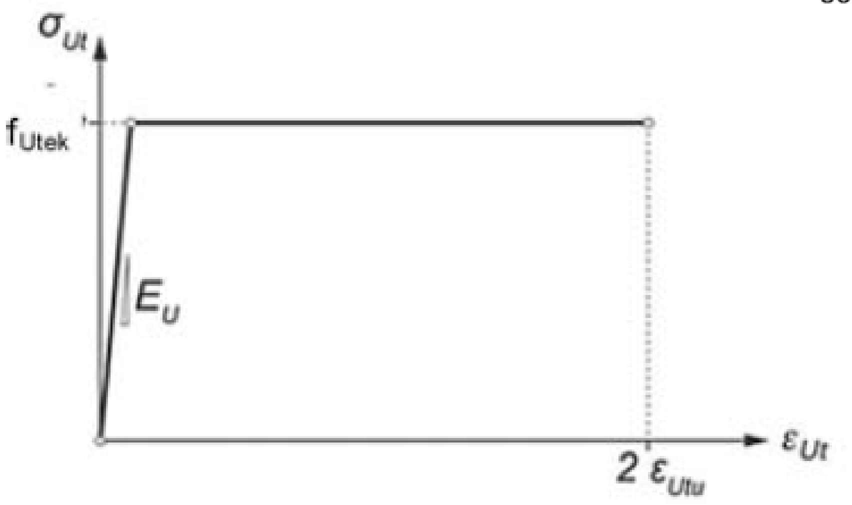
Fiber orientation known from full scale structural tests

4.2.2.6 Les coefficients des chiffres 4.2.2.1 et 4.2.2.2 prennent la valeur 1,0 lorsque la valeur de dimensionnement de la résistance ultime selon le chiffre 2.4.2.2 a été déterminée par des essais.

SIA CT 2052 – R-UHPFRC



4.3.3.1.2 Le BFUP dispose d'une capacité de déformation plus limitée que l'acier d'armature passive. Lors de la formation de rotules plastiques, on pourra admettre un effet participant en traction de $\sigma_{Utd} = 0{,}9\, f_{Utud}$ du BFUP pour une déformation allant jusqu'à 3 ε_{Utu}. Si les déformations spécifiques excèdent 3 ε_{Utu}, on ne pourra admettre aucun effet participant du BFUP. Dans ce cas, les forces de traction seront reprises exclusivement par l'acier d'armature passive situé dans le BFUP.



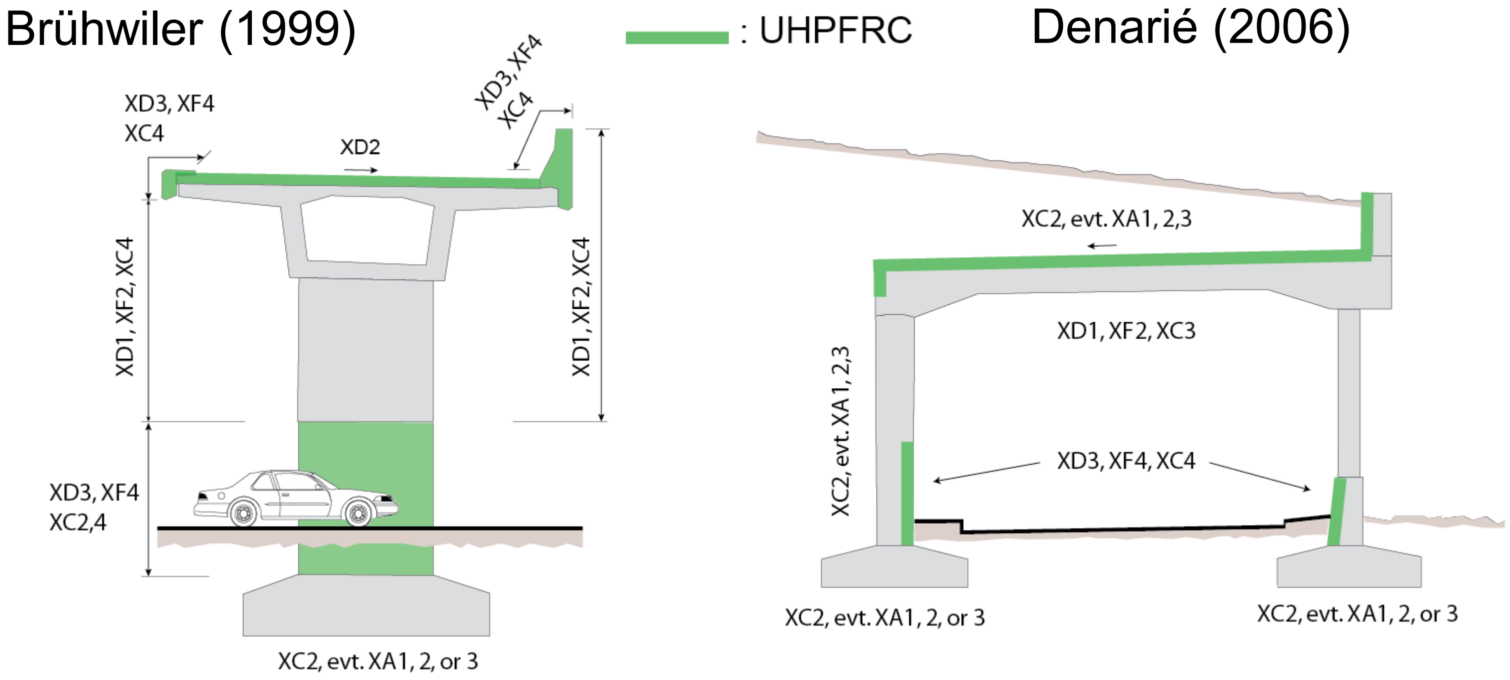
- ➔ Deformability of UHPFRC more limited than that of steel rebar
- ➔ In plastic hinges the following can be assumed:

Tensile stress in UHPFRC:

$\sigma_{utd} = 0.9\, f_{utud}$ up to $3\varepsilon_{utu}$
$\sigma_{utd} = 0$ after $3\varepsilon_{utu}$

Tensile response of UHPFRC, when combined with rebar

5. Reinforcement with R-UHPFRC



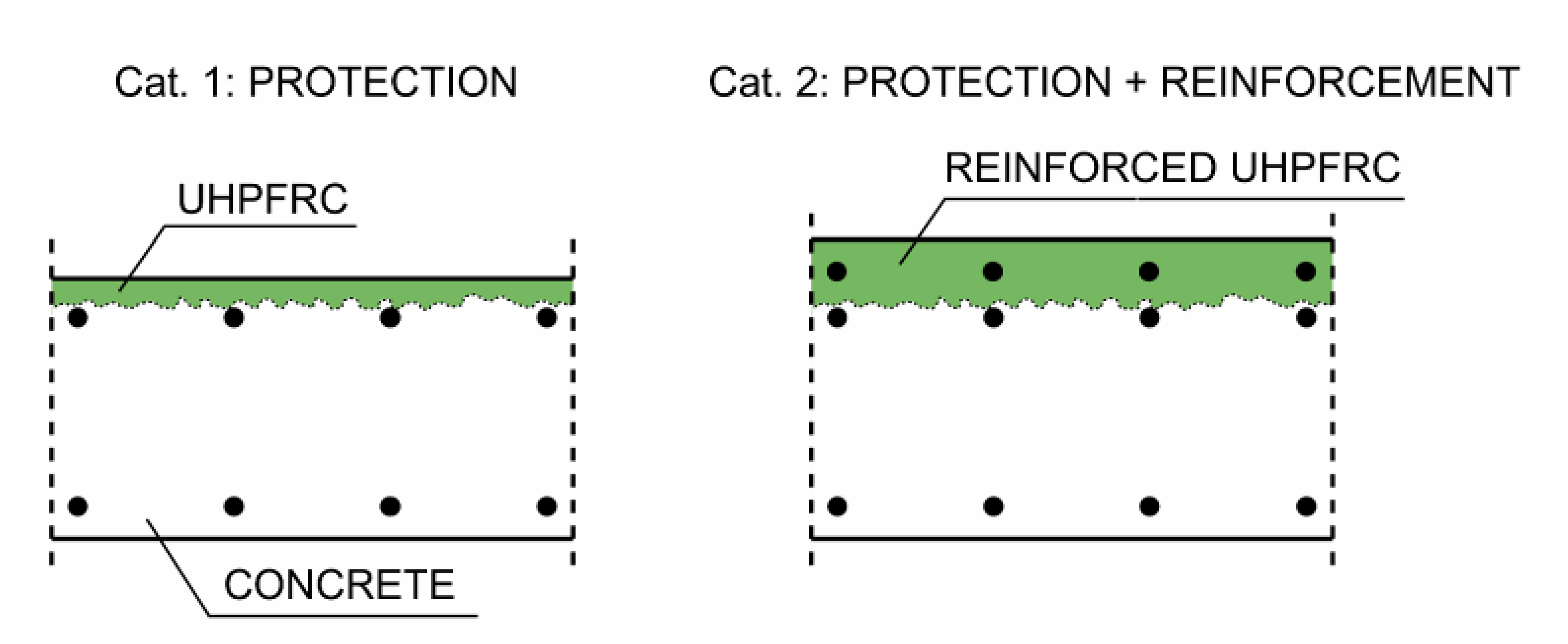
Brühwiler (1999)

🟩 : UHPFRC

Denarié (2006)

➔Long-lasting, targeted « hardening » of critical zones subjected to severe mechanical and environmental loads by means of a dense UHPFRC layer

Geometries of application



➔ Cat. 1: UHPFRC h_u= 20 to 30 mm = Protection

➔ Cat. 2: UHPFRC (h_u=40 to 50^+ mm) + additional rebars = Protection + Reinforcement ➔ **can double load carrying capacity !**

6. Bending response of R-UHPFRC/RC members

➔Optimize cross sections for stiffness vs/material volume
➔Take benefit of synergies with prestressing and rebar (narrow cover OK > 15 mm – 10 mm if precast)

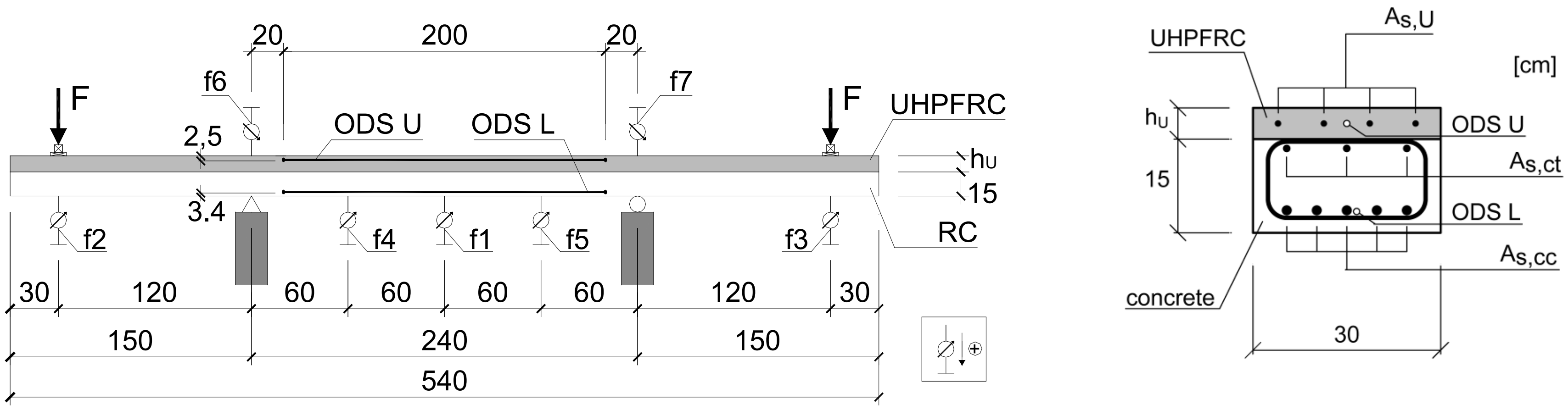
➔Optimize fibrous mix for best benefit of fibers

➔Optimize casting procedures for best benefit of fibers

➔Save significantly on material volume: at least 2 to 3 times less than a RC/PC solution

➔ Consider relevant tensile properties for design, according to casting mode and direction of loading

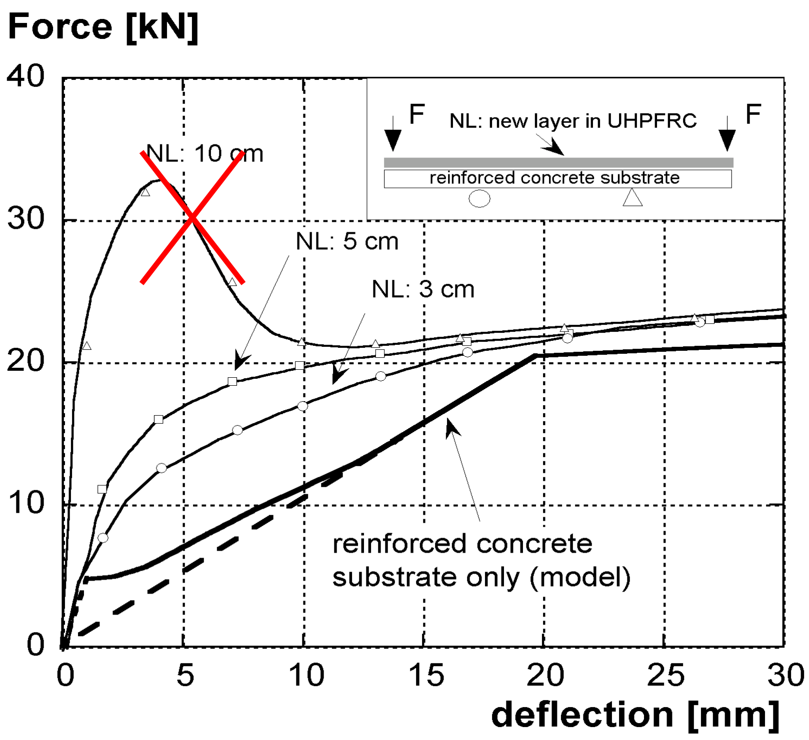
Structural response



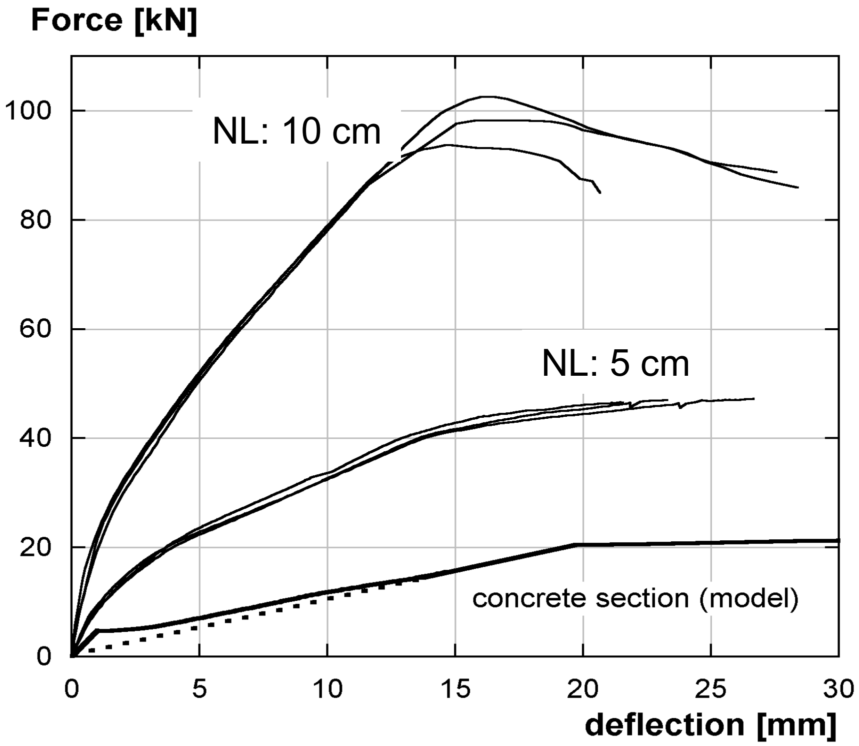
Flexural tests on composite beams with UHPFRC, Habel (2004) – [6]

➔ Effect of new UHPFRC layer thickness (h_u)
➔ Effect of combination of UHPFRC with rebars

Structural response



New layer: plain UHPFRC



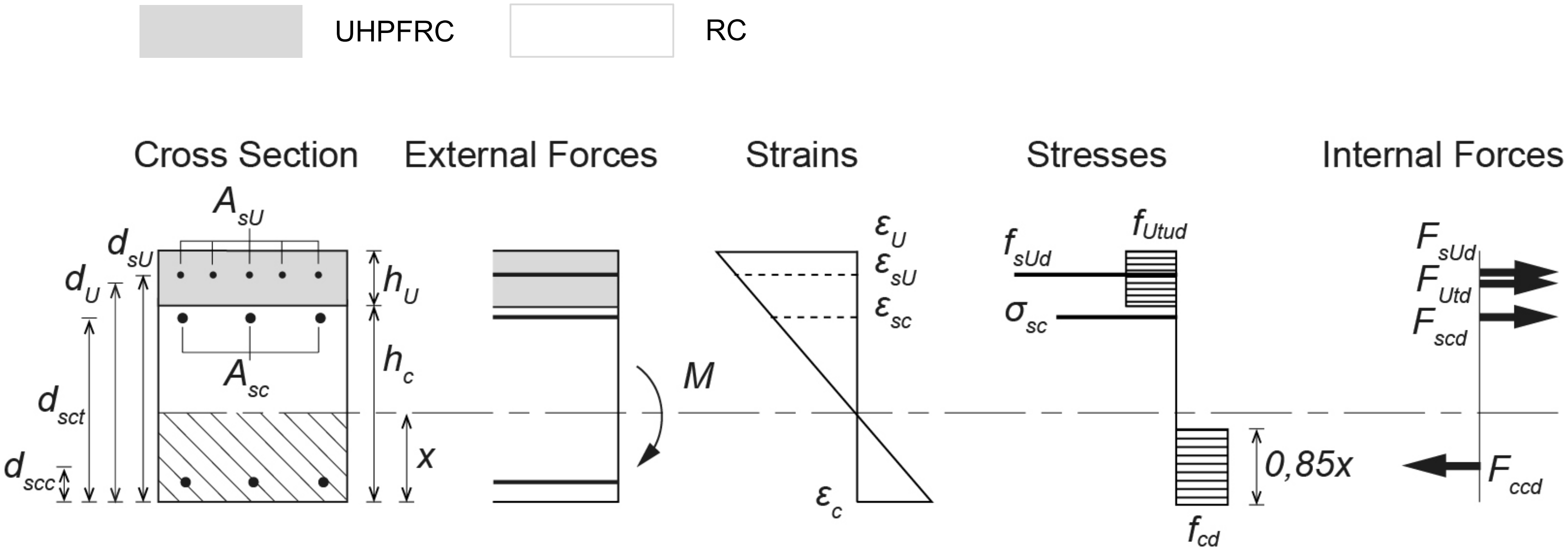
New layer: UHPFRC + rebars = R-UHPFRC

Flexural tests on composite beams with UHPFRC, Habel (2004)

➔ UHPFRC alone = significant stiffening

➔ UHPFRC + rebars = stiffening + increase of load carrying capacity

Cross sectional analysis – composite member



- "Bernouilly" + Materials laws + equilibrium

➔Position neutral axis ➔ Resisting Moment

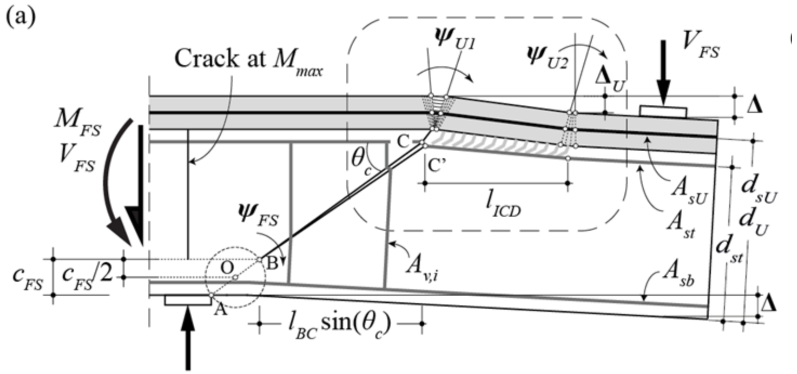
➔Solve for position of neutral axis

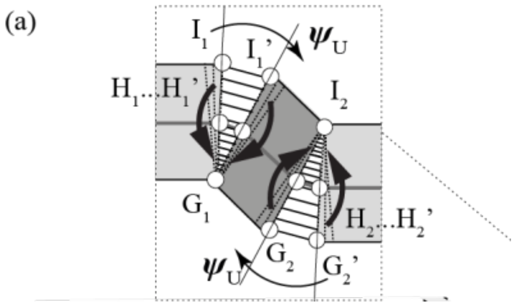
7. Shear response of R-UHPFRC/RC members

- Barely possible to "shear" UHPFRC (mode II fracture)
- Material "escapes" in mode I (tensile)

➔Plain UHPFRC webs = diagonal cracks with mode I fracture mechanism = "inclined" tensile response

➔ R-UHPFRC - RC composite members with UHPFRC overlays = membrane + flexural action (double hinge mechanisms = complex structural fracture mechanisms - see Noshiravani (2012)





Noshiravani (2012) – [7]

SIA CT 2052 - 2017

- The shear force resistance of UHPFRC-Concrete composite elements subjected to a point load at a distance a_o from the support zone will be determined by the superposition of the shear strengths of the reinforced concrete part and of the reinforced UHPFRC layer as shown in Fig. 10. The calculation principle is valid for $h_u/h_c > 0.1$. In case of discrepancies, further analysis is required.

- In the case of shear force loading, a 45° diffusion of the beam into the slab can be accepted for the participating width of the slab (figure 10b).

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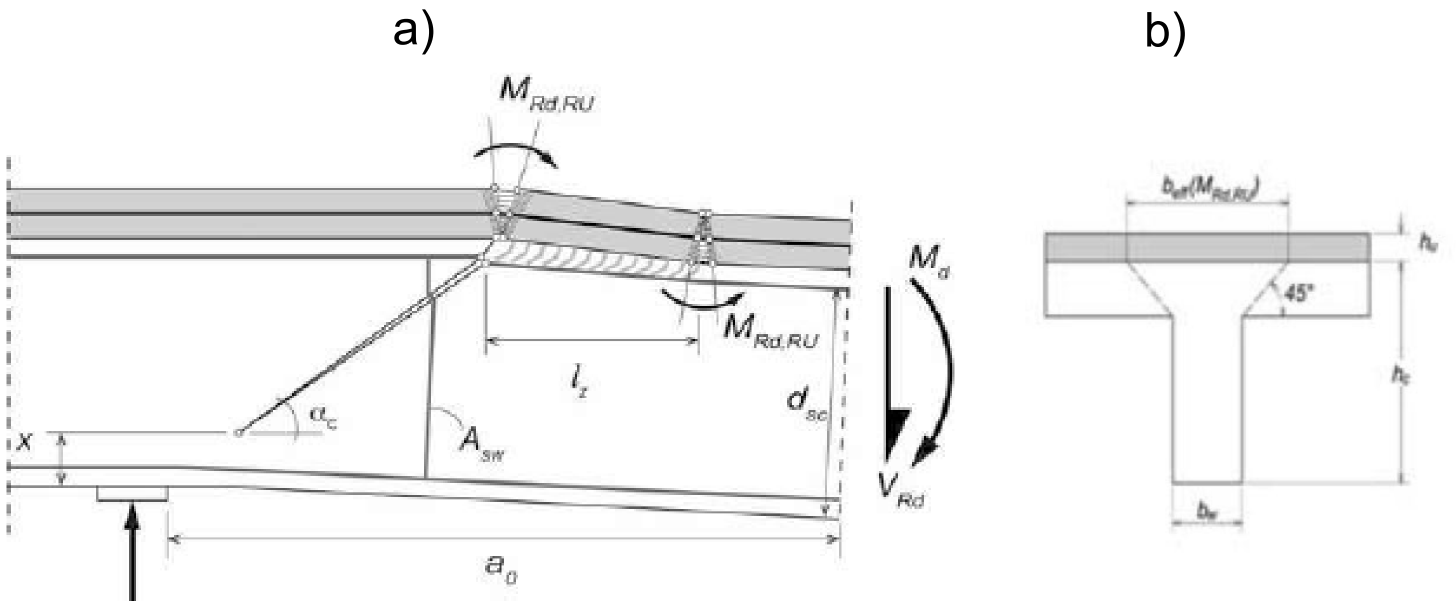


Fig. 10 Model for determining the upper limit of shear strength resistance (kinematic method)

For the inclination α_c of the diagonal bending shear crack in reinforced concrete, one can assume values from 20 to 60° . The inclination must be chosen so that the minimum value of shear resistance is found.

SIA CT 2052 - 2017

$$V_{Rd} = V_{Rd,c} + V_{Rd,s} + V_{Rd,U}$$

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

Concrete

$$x = 0{,}9 \cdot \omega_m \cdot d_{eq}$$ Compression zone

$$\omega_m = \frac{A_{sc}\, f_{sd} + A_U\, f_{Utud} + A_{sU}\, f_{sUd}}{A_c\, f_{cd}}$$

and

$$d_{eq} = \frac{d_{sc}\, A_{sc}\, f_{sd} + d_U\, A_U\, f_{Utud} + d_{sU}\, A_{sU}\, f_{sUd}}{A_{sc}\, f_{sd} + A_U\, f_{Utd} + A_{sU}\, f_{sUd}}$$

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot (d_{sc} - x) \cdot \cot\alpha_c \cdot f_{sd}$$

Design value for ultimate resistance of the vertical shear reinforcement bars

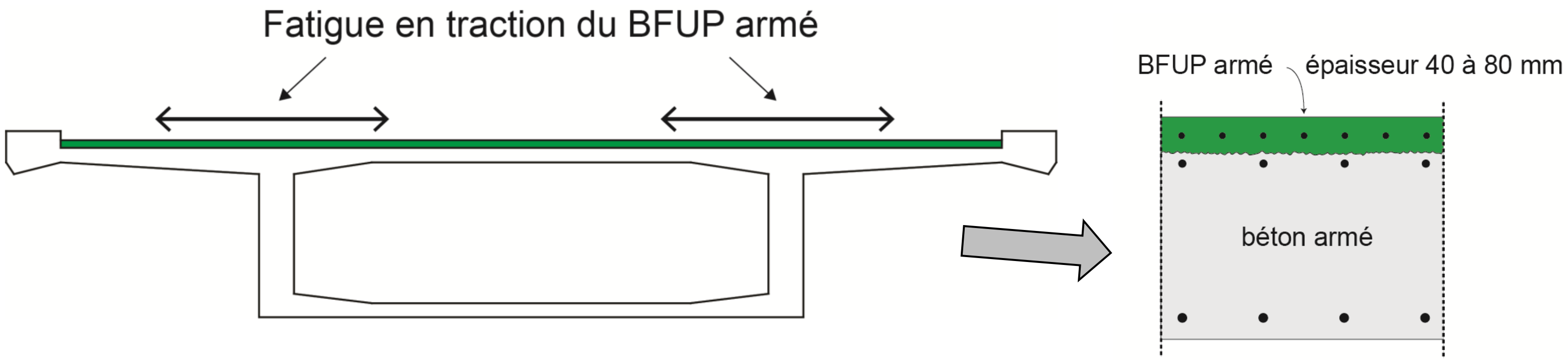
$$V_{Rd,U} = \frac{2 \cdot M_{Rd,RU}}{l_z}$$

$$l_z = a_0 - \frac{d_{sc}}{\tan \alpha_c}$$

R-UHPFRC

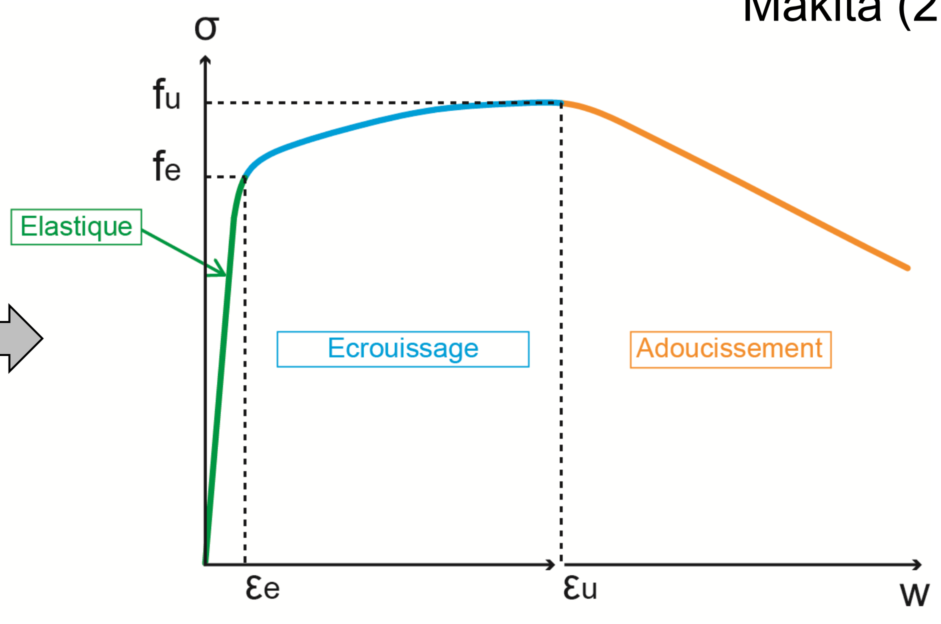
8. Fatigue of R-UHPFRC/RC members

- ➔ Challenge of material intrinsic scatter (fibre orientation effects) hides fatigue response
- ➔ Need for more effective methods of reinforcing bearing slabs against fatigue in tensile zones
- ➔ Reinforced UHPFRC layer, 40 to 80 mm, cast in place on top of wearing course slab



UHPFRC properties

- Compression ≥ 150 MPa
- Tensile strength ≥ 7 MPa
- Tension strain-hardening
- Extreme compactness = protection



Makita (2013) – [8]

➔ **Fatigue of UHPFRC, reinforced UHPFRC and reinforced UHPFRC/reinforced concrete composite elements = little studied**

➔ **Particularly under tensile stresses**

➔ **Need for calculation methods and criteria**

Fatigue testing program on UHPFRC

Makita (2013)

➔ **HIFCOM$_{13s}$ UHPFRC, CEM III/B, 3% steel fibres OL 13/0.16**

➔ **Constant force amplitude**

➔ **3 domains of application**
- **Elastic (S1)**
- **Hardening(S2)**
- **Softening (S3)**

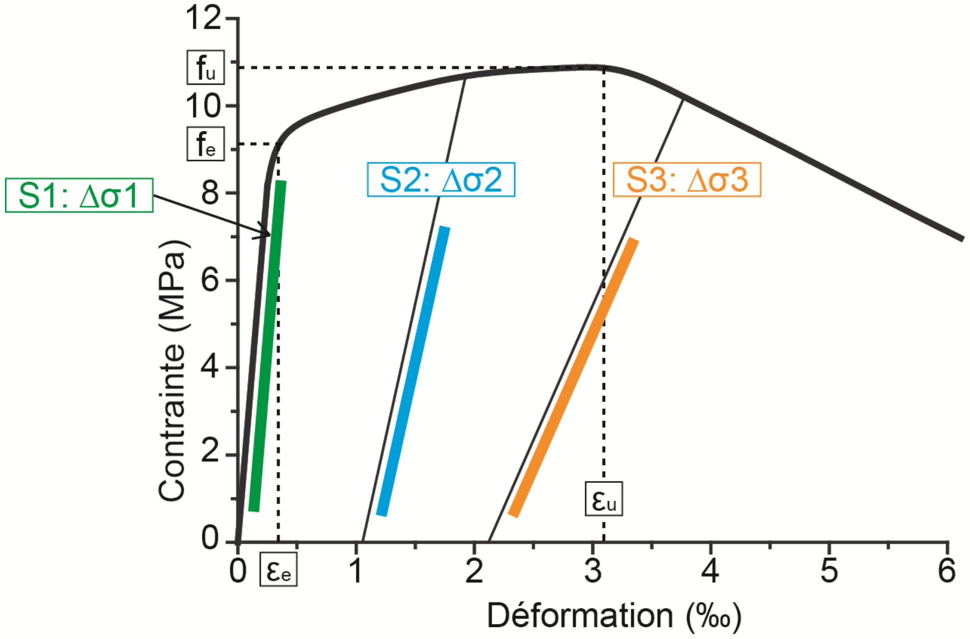
➔ **"Run-out": after 10 million cycles**

➔ **Endurance limit at 10 Million cycles determined from S-N diagram**

Fatigue cycle definition

Makita (2013)

- **S1 series = determination of endurance limit elastic range**
- **Series S2 and S3 = understanding the fatigue response of UHPFRC after yield point, in the damaged state**



S2 and S3:

1. **Preload in the form of imposed deformation when reaching the strain-hardening or softening range.**
2. **Unload-Reload**
3. **Cycles - fatigue**

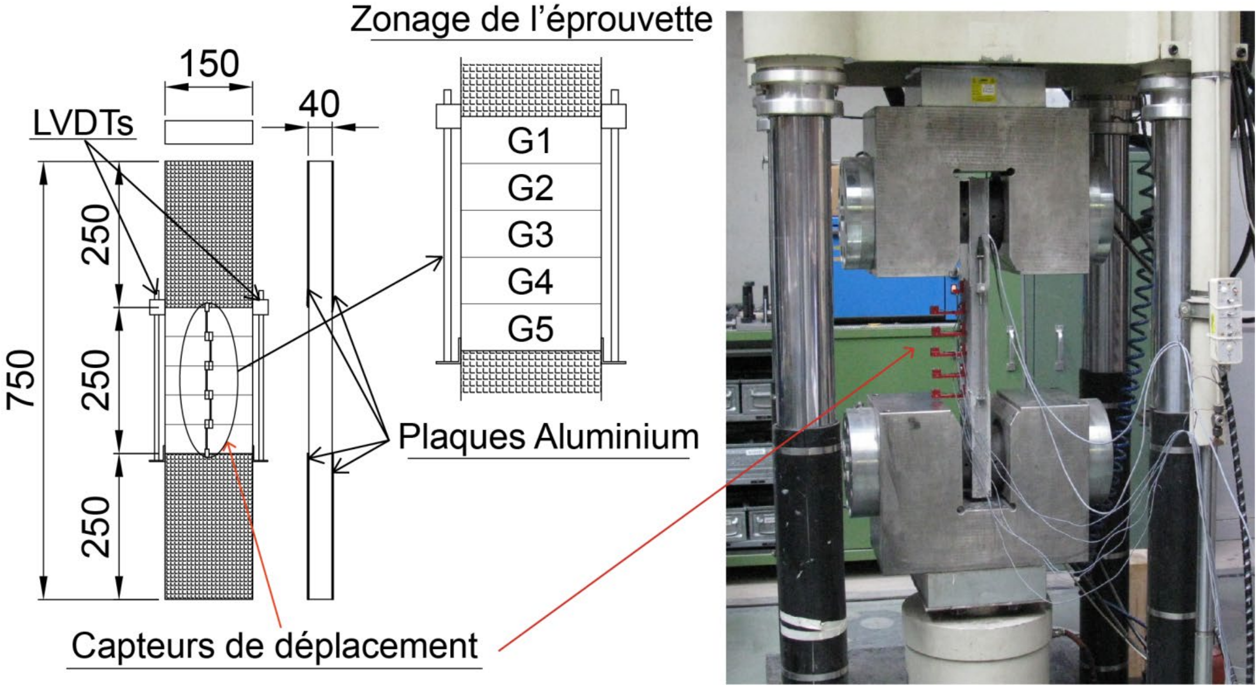
➔ Cast-in-place UHPFRC can reach the elastic limit under the action of eigenstresses induced by restrained shrinkage.

Tensile fatigue tests on UHPFRC

Makita (2013)

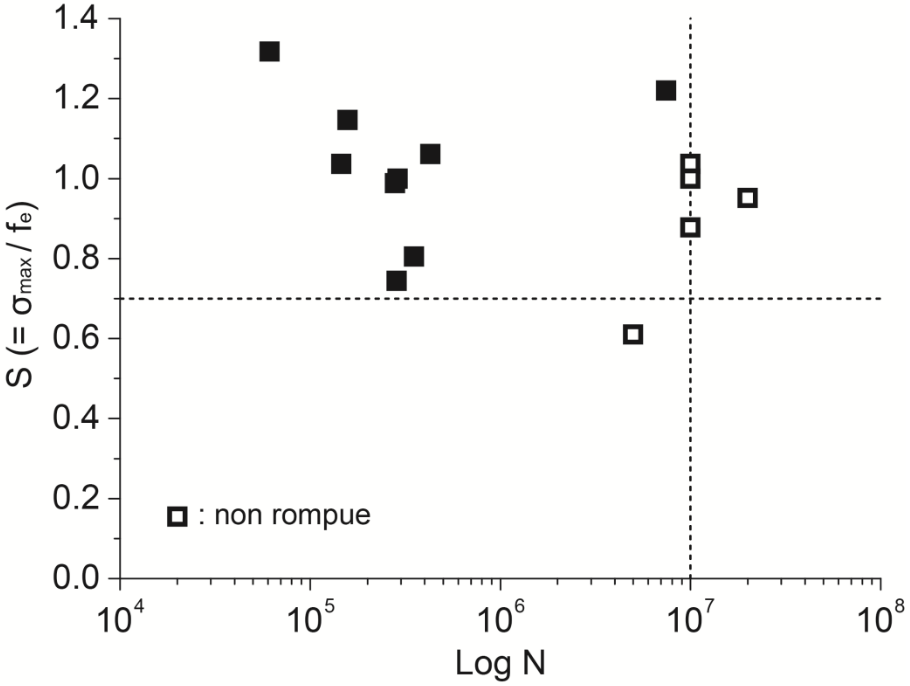
- **39 tests - frequency: 10 Hz**
- **3 different stress levels by varying maximum stress and strain**
- **Measurements: 2 inductive transducers (base 250 mm) + 5 local displacement transducers (G1 to G5)**

Units. [mm]



S-N diagram - S1 series

Makita (2013)



➔ **Calculation of S: average yield strength over 3 quasi-static tests, f_e =8.2 MPa**

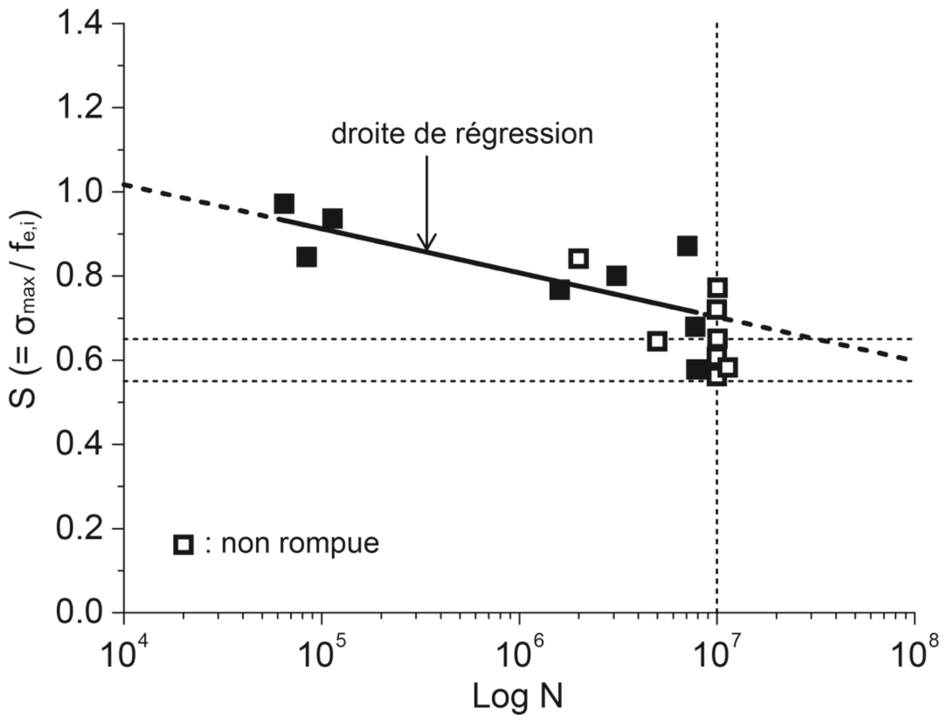
➔ **Differences with elastic limits of individual specimens**

σ_{max} : maximum applied fatigue stress (σ_{min} = 0.82 MPa)

➔ **Endurance limit at 10 million cycles: 70% of average f_e**

S-N diagram - S2 series

Makita (2013)



- ➔ **Calculation of S: yield strength of each specimen, $f_{e,I}$**
- ➔ **Deformation preset between 0.5 and 4.0 ‰**

σ_{max}: maximum fatigue stress applied ($\sigma_{min} = 0.1\sigma_{max}$)

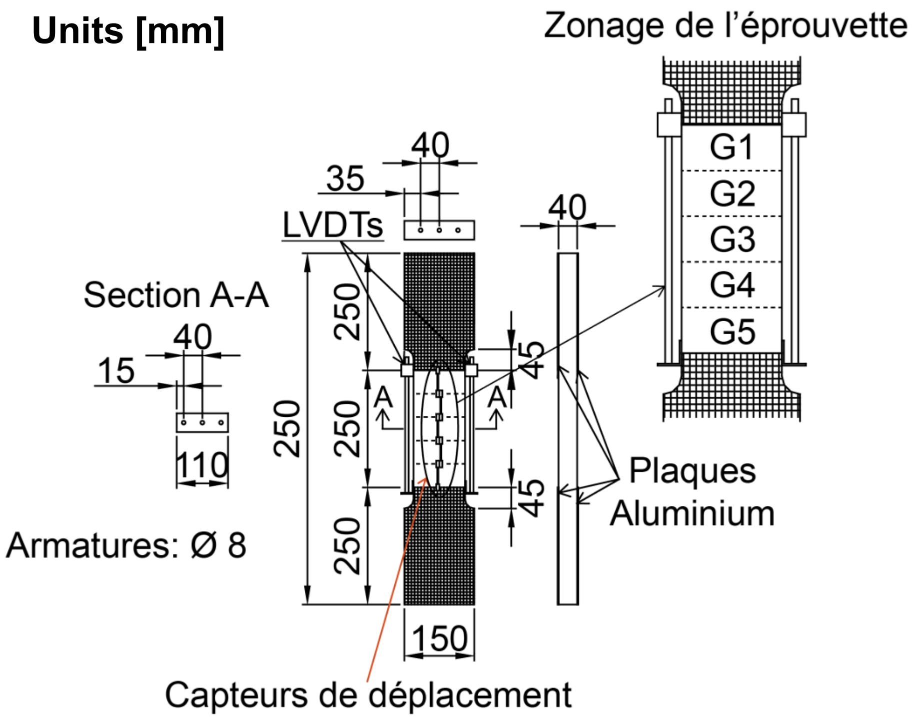
➔ **Endurance limit at 10 million cycles: 55 to 65% of $f_{e,i}$**

Tensile fatigue tests on reinforced UHPFRC

Makita (2013)

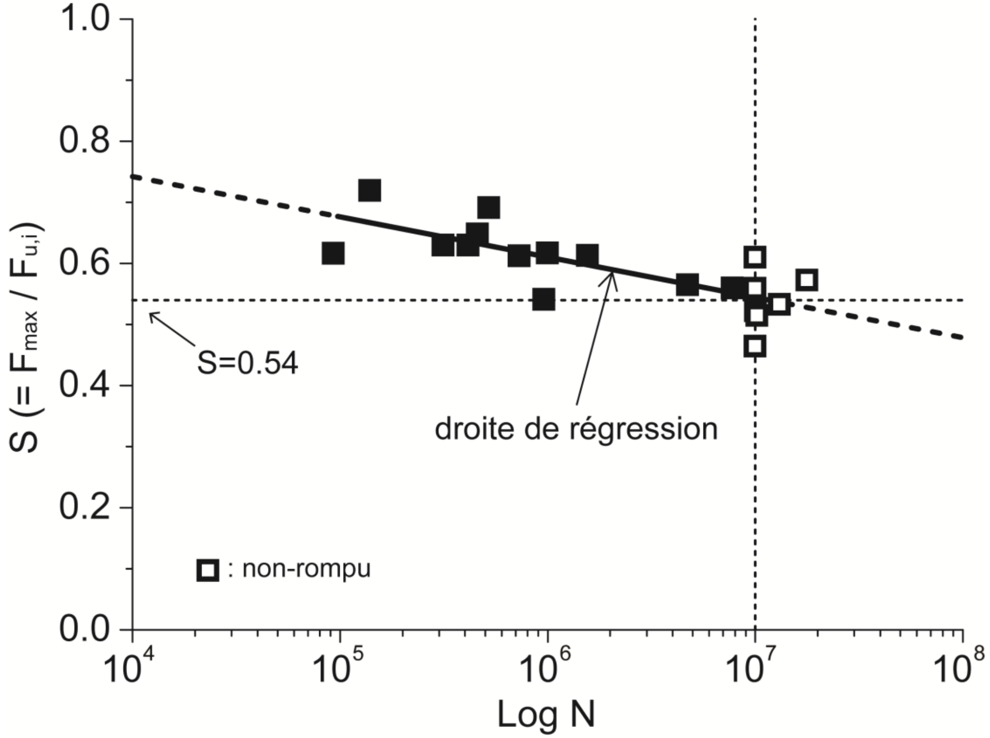
- **19 tests, frequency: 10 Hz, plates section 110x40 mm**
- **3 reinforcing bars Ø 8 mm, B500B**
- **Stress level in bars = 170 to 230 MPa**
- **Measurements: same as tests on UHPFRC alone**

Units [mm]



Makita (2013)

S-N Diagram - Reinforced UHPFRC



- ➔ $F_{u,i}$: estimated on the basis of the maximum strength of the quasi-static test
- ➔ Endurance limit similar to that of reinforced UHPFRC/RC beams
- ➔ Reinforcement bars reduce variability associated with UHPFRC fibrous mix

F_{max} : maximum fatigue force applied (F_{min} = 0.1F_{max})

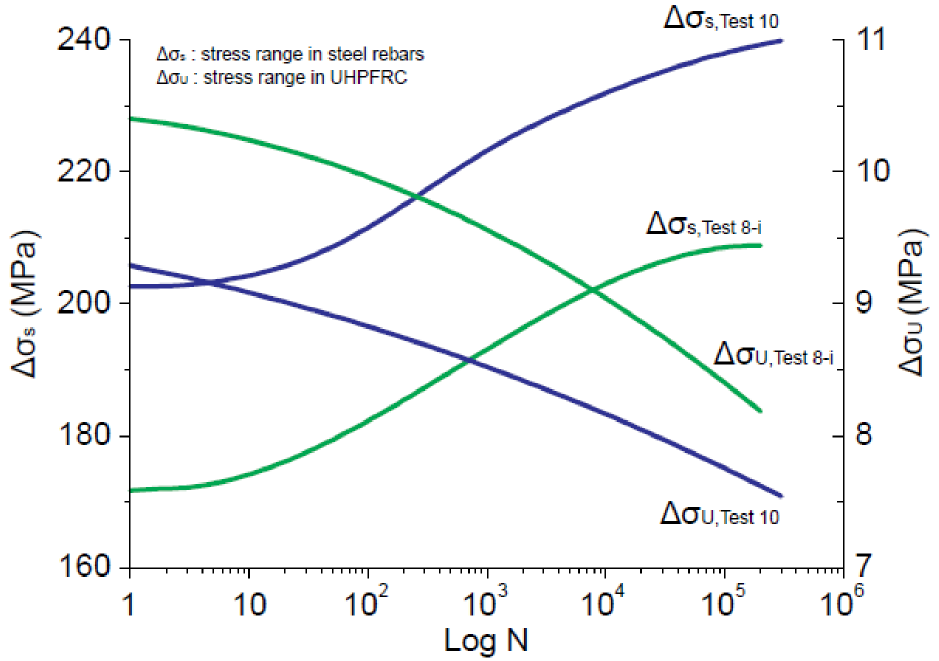
➔ Endurance limit at 10 million cycles: 54% of ultimate strength

Stress redistribution between UHPFRC and reinforcement

Makita (2013)

➔ Calculating stresses from strain measurements

➔ 2 tests with S>0.54, Test 8-i: 310,000 and Test 10: 520,000 cycles



$$\sigma_{s,i} = E_s \cdot \frac{\Delta \ell_{g,i}}{\ell_b} \qquad \sigma_{U,i} = \frac{F - A_s \cdot \sigma_{s,i}}{A_U}$$

$\sigma_{s,i}$: stress rebar - cycle i

$\sigma_{U,i}$: stress UHPFRC- cycle i

E_s : modulus of elasticity – steel

$\Delta\ell_{g,i}$: global displacement – cycle i

ℓ_b : measurement basis of LVDT

F : applied force

A_s : cross section of the 3 rebar

A_U : cross section of UHPFRC

- 1st phase: UHPFRC governs fatigue behavior

- 2nd phase = damage to the UHPFRC + transfer

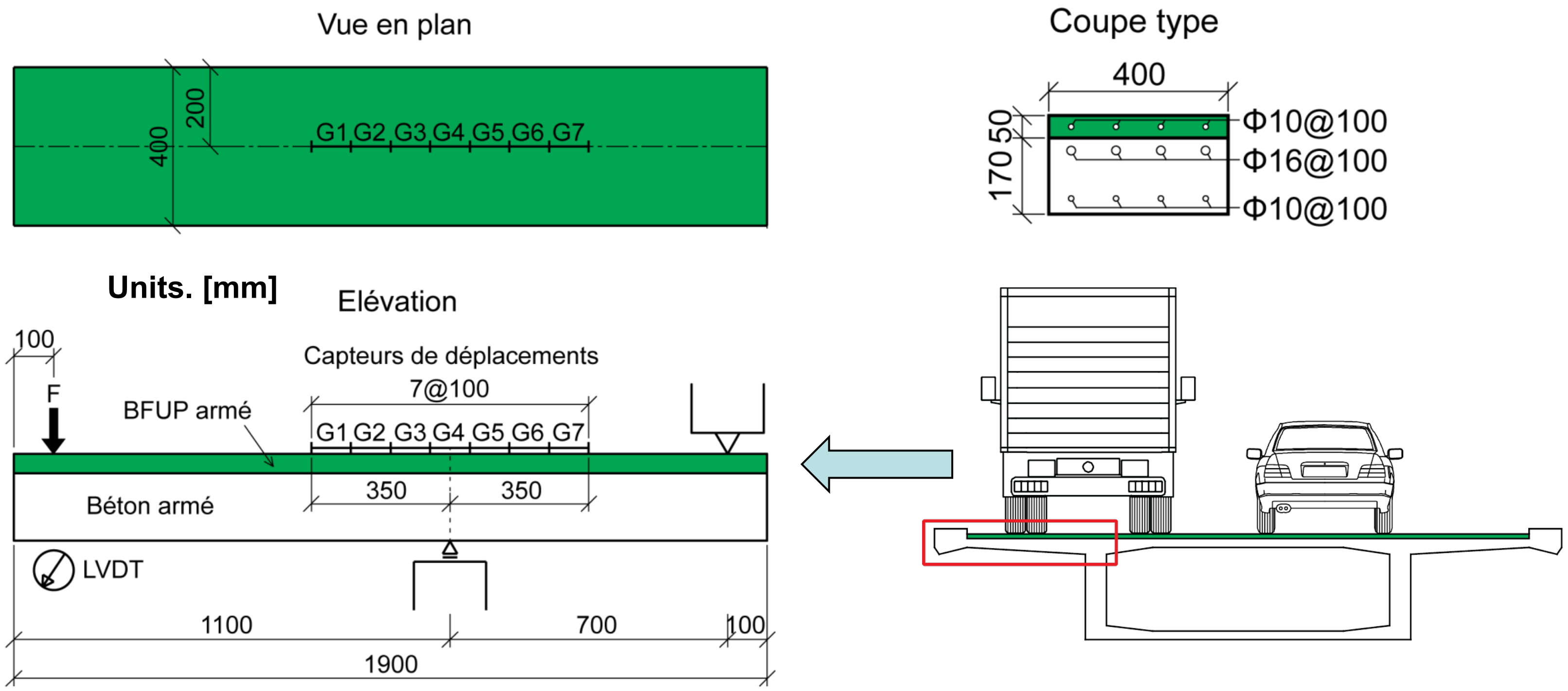
- 3rd phase: rebars govern

➔Fatigue fracture always due to fatigue failure of reinforcement bars

Fatigue composite element reinforced UHPFRC/reinforced concrete

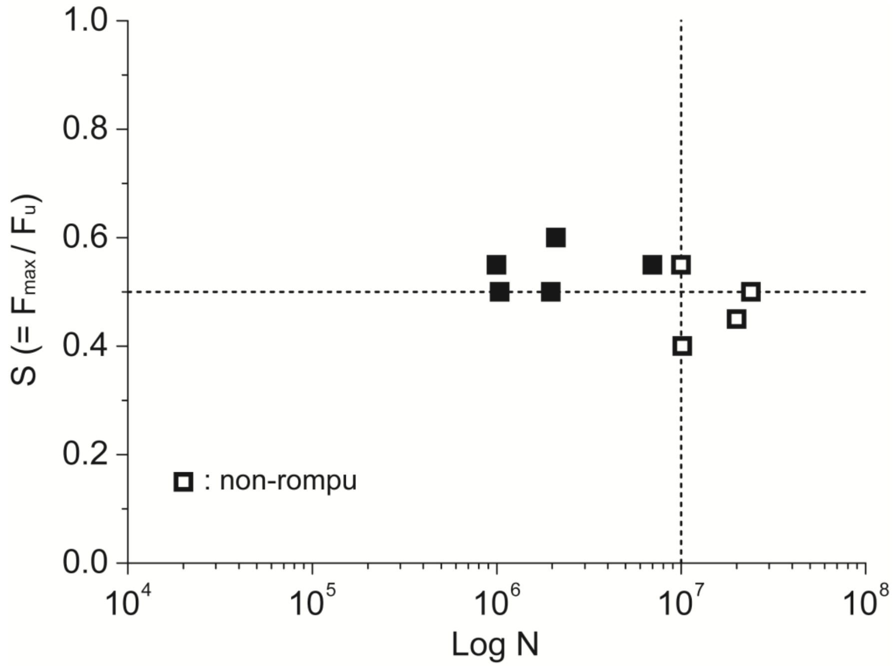
- 9 tests, frequency: 8 Hz, composite beams, width 400 mm
- Reinforcing bars B500B
- Concrete C30/37, D_{max} = 16 mm (f_{cc} = 64.5 MPa)
- Boom measurements + 7 local displacement transducers
- Fatigue - F_{max} = 40-60% of ultimate strength F_u (90 kN)

Makita (2013)



S-N diagram - UHPC beams Reinforced/ Reinforced concrete

Makita (2013)



- ➔ F_u : maximum quasi-static test resistance = 90 kN
- ➔ Endurance limit almost identical to that of reinforced UHPFRC ties
- ➔ Reinforcement bars reduce variability associated with UHPFRC fibrous mix

F_{max} : maximum fatigue force applied (F_{min} = 0.1F_{max})

- ➔ **Fatigue failure of reinforcement in reinforced UHPFRC**
- ➔ **Endurance limit at 10 million cycles: 50% (x F_u = 45 kN)**

Fatigue safety check

Makita (2013) – SIA CT 2052

- **Reinforced UHPFRC/reinforced concrete composite elements**
- **Base = fatigue endurance limit**
- **2 verification levels: structural elements and materials**

➔ Flexural strength of composite member

$$\boxed{n_{fat} = \frac{0,5 \cdot M_{Rd}}{M_{d,fat}} \geq 1,0}$$

n_{fat} : degree of fatigue compliance
M_{Rd} : examination value - composite element resistance
$M_{d,fat}$: examination value - fatigue loads

$$M_{R,D} = 0,5 \cdot M_{Rd}$$

Fatigue safety check

Makita (2013) – SIA CT 2052

➔ Rebar

$$\boxed{\Delta\sigma_{sd}(\Delta M_{df}) \leq \Delta\sigma_{sd,D}}$$

$\Delta\sigma_{sd}$: stress test value in the UHPFRC reinforcement under fatigue, calculated for moment variation ΔM_{df}

$\Delta\sigma_{sd,D}$: examination value for fatigue endurance limit of straight reinforcement (116 MPa for Ø ≤ 20 mm – B500B)

➔ UHPFRC

$$\boxed{\begin{array}{l} \sigma_{Ud,max}(\mathrm{M}_{df,max}) \leq \Delta\sigma_{Ud,D} \\ \Delta\sigma_{Ud,D} = 0.6(f_{Utek} + f_{Utuk})/2 = 0.3(f_{Utek} + f_{Utuk}) \end{array}}$$

$\sigma_{Ud,max}$ $(M_{df,max})$: maximum tensile stress in the UHPFRC due to maximum fatigue bending moment

$\Delta\sigma_{Ud,D}$: fatigue strength of UHPFRC subjected to tensile stresses

➔ Concrete

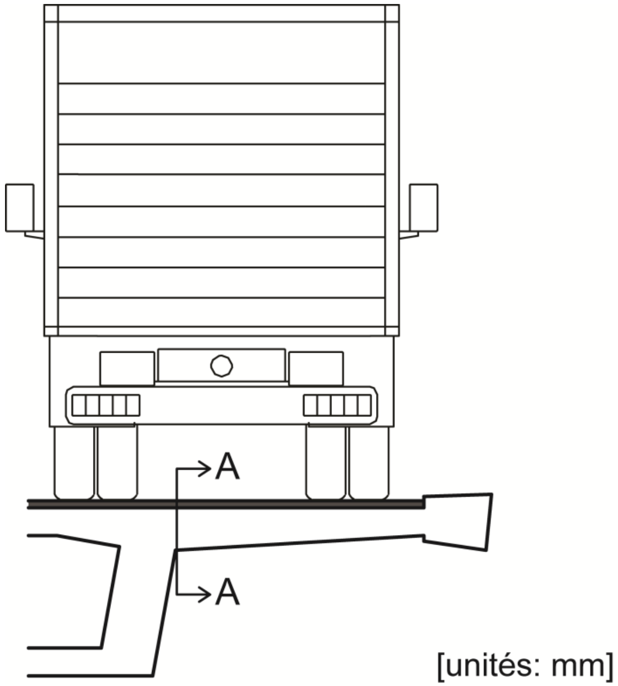
$$\boxed{\begin{array}{l} \sigma_{cd,max}(\mathrm{M}_{df,max}) \leq \Delta\sigma_{cd,D} \\ \Delta\sigma_{cd,D} = 0,5 f_{cd} \end{array}}$$

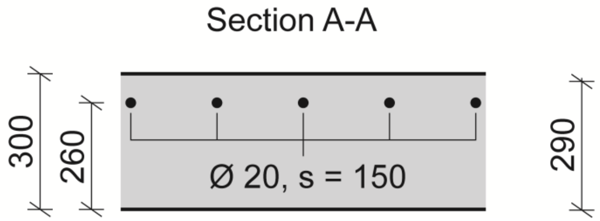
$\sigma_{cd,max}$ $(Mdf_{,max})$: maximum compressive stress in concrete due to maximum fatigue bending moment

$\Delta\sigma_{cd,D}$: fatigue strength of concrete subjected to compressive stresses

Example: bearing slab to be reinforced

Brühwiler et al. (2014) – [9]





Section A-A: $M_{df,max}$=*150* kNm/m, $M_{df,min}$= 20 kNm/m
$\Delta\sigma_{sd}$ (ΔM_{df}) = 263 MPa >>$\Delta\sigma_{sd,D}$ = 116 MPa KO!

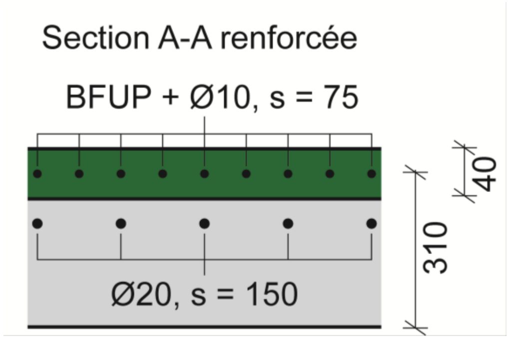
Reinforced section A-A: M_R = 394 kNm/m

$$M_{RfD,d} = \frac{0{,}5M_{Rk}}{\gamma_{Mf}} = \frac{0{,}5.394}{1.1} = 179\text{ kNm/m}$$

$$M_{df,max} = 150\text{ kNm/m} < M_{RfD,d} = 179\text{ kNm/m OK !}$$

Reinforcement: $\Delta\sigma_{sd} = 97$ MPa < $\Delta\sigma_{sd,D}$ =116 MPa OK!

UHPFRC: $\sigma_{Ud,max}$ = 5.6 MPa < $\sigma_{Ud,D}$ =0.3(10+12)=6.6 MPa OK!



✓Tests on UHPFRC, reinforced UHPFRC and reinforced UHPFRC/reinforced concrete composite elements helped determine the endurance limit under fatigue, tensile and compressive loads.

✓The addition of a 50 mm layer of reinforced UHPFRC increases the ultimate load-bearing capacity of reinforced concrete slabs by a factor of 2.

✓50% endurance limit for reinforced UHPFRC composite elements - Reinforced concrete.

✓Redistribution of efforts and highly favorable synergies between UHPFRC and reinforcement.

✓Fatigue amplitude in reinforcement is decisive for the fatigue strength of reinforced UHPFRC composite elements - Reinforced concrete.

✓Fatigue safety verification method with two levels: structural element and materials.

✓Reinforced UHPFRC provides effective fatigue reinforcement of reinforced concrete elements by reducing the amplitude of stresses, with little increase in dead weight, and with the benefit of UHPFRC's exceptional waterproofing properties.

➔ New developments based on recent research are ongoing and will be implemented in next generation of Swiss guidelines CT 2052 (publication expected in 2026) – see [10] Brühwiler et al. [2024], available in complementary readings.

9. Examples of application – construction details

Orthotropic bridge decks (steel)

De Jong (2006) – [11]

➔ UHPFRC topping to reduce fatigue stresses

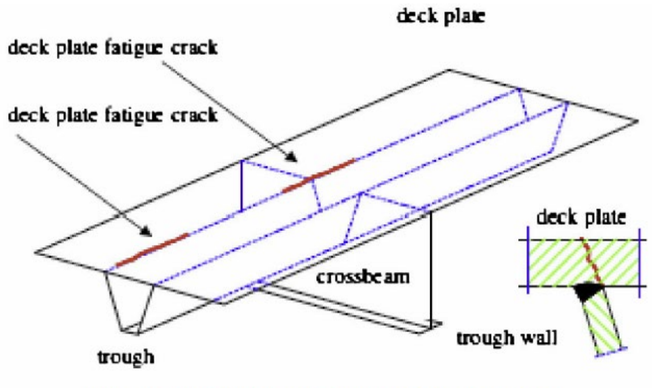
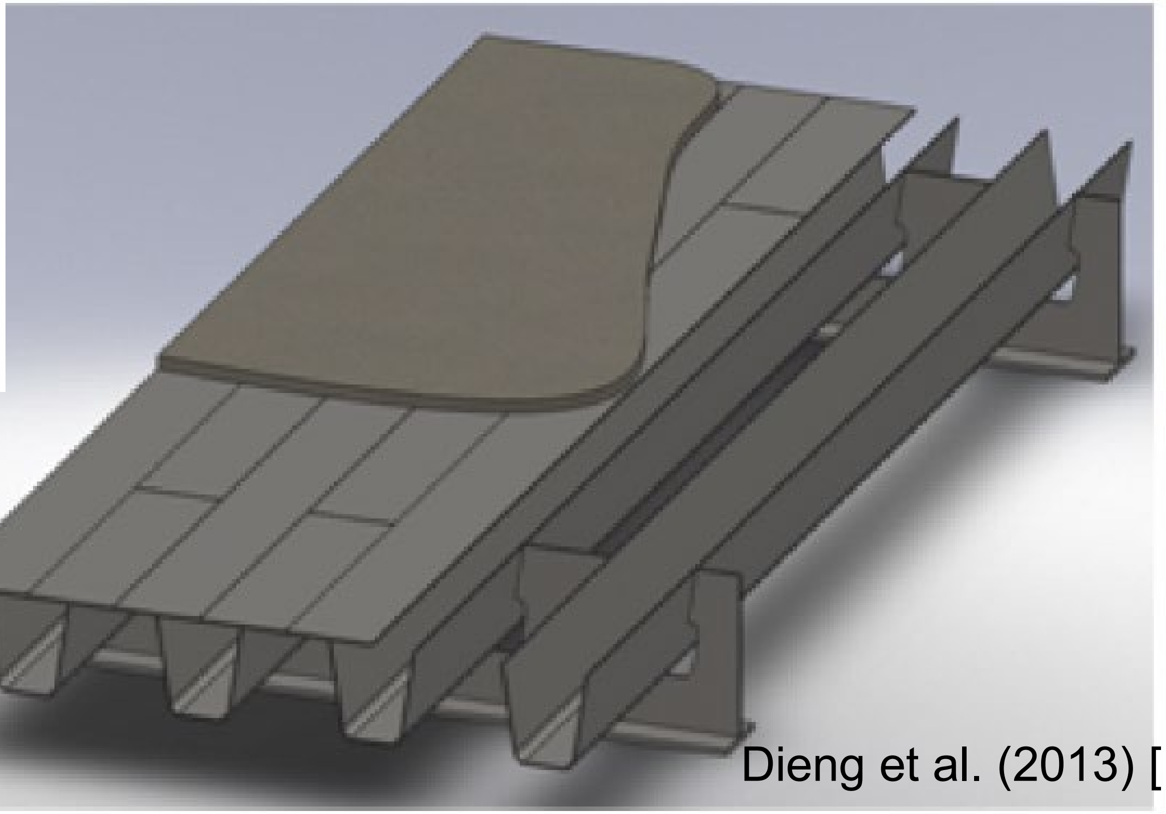


Fig. 2. Details of an orthotropic bridge deck fatigue cracks [1].



Dieng et al. (2013) [12]

Fig. 1. Orthotropic steel bridge deck geometry including topping layer.

Reinforcement of lighthouses

Denarié (2011)

Access = weather + tide permitting

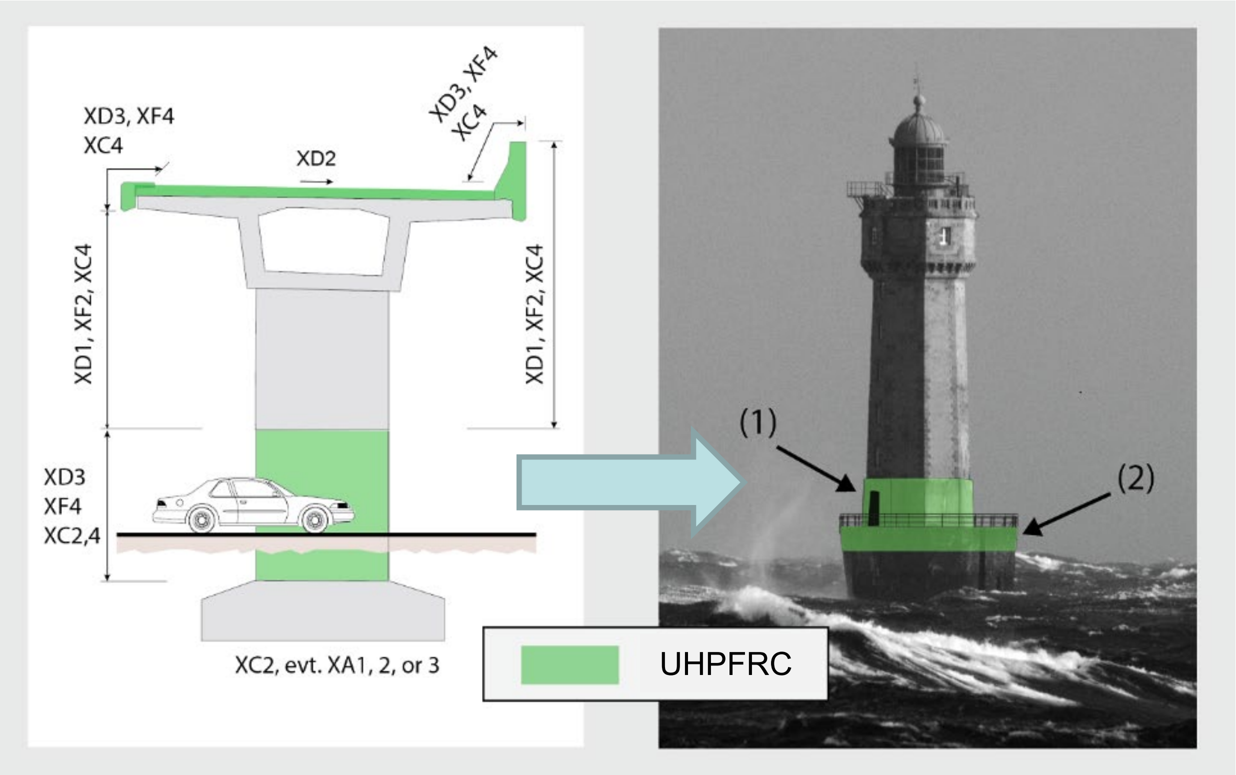
"La Jument" lighthouse
Ouessant /France 47 m high

Heritage structure – 104 years old
Construction = 7 years (1904-1911)
Masonry / Concrete core structure

Multiple reinforcements over time

- ➔ Severely limited access time + agressive environment
- ➔ Issues similar to conservation of existing bridges
- ➔ Apply UHPFRC to protect/reinforce

Concept of intervention

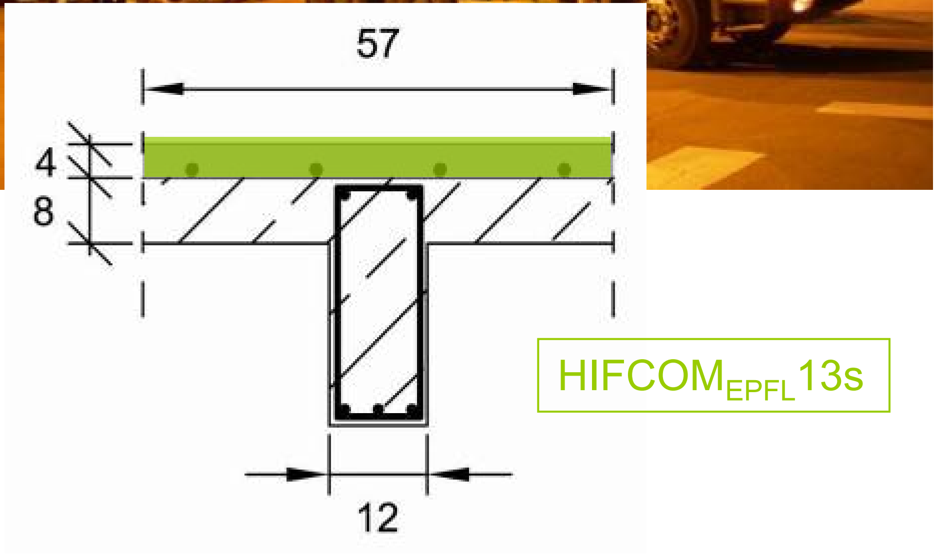


Brühwiler (1999) Denarié (2011)

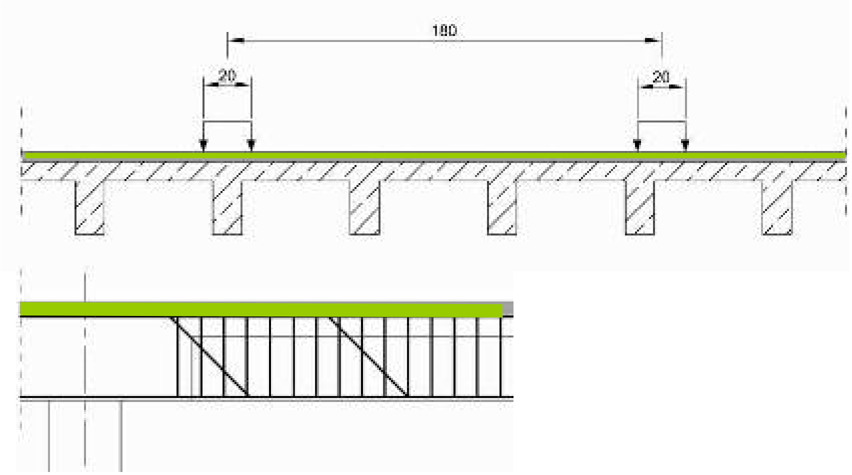
- ➔ Application of concept developped for bridges
- ➔ Cast in place UHPFRC, with rebar locally, (could be shotcreted)
- ➔ Reinforcement and protection of RC ring around tower base (1)
- ➔ Confinement and protection of upper part of foundation base (2)

Strengthening of a slab on an industrial floor

Autumn 2007
Firemen brigade
Geneva



HIFCOM$_{EPFL}$13s



Increase of traffic loads

Remplacement of non-load carrying mortar overlay by 40 mm UHPFRC with rebars

Load-bearing and protective functions

720 m^2 or 36 m^3 of UHPFRC

CIVIL-511, Prof. E. Denarié - Prof. A. Nussbaumer

Strengthening of Guillermaux bridge (CH)

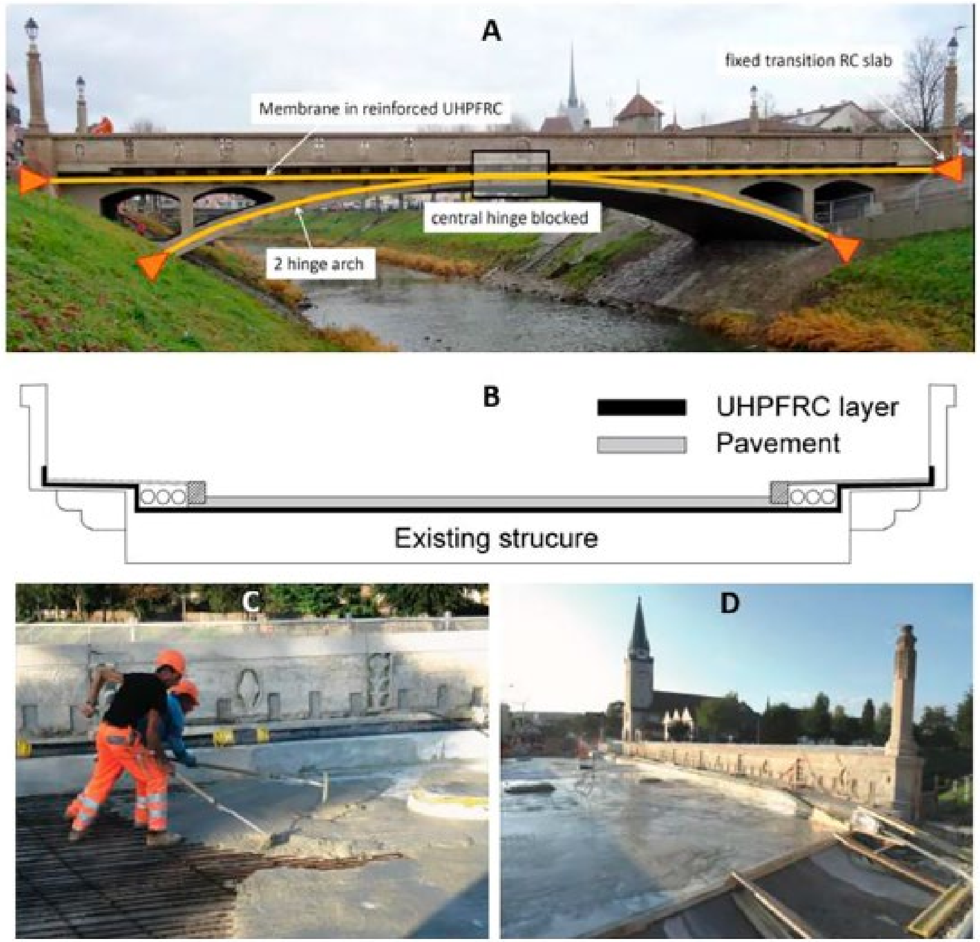


FIGURE 8 | Guillermaux Bridge. **(A),(B)** static system and intervention; **(C),(D)** Photographs of the pouring UHPFRC (Photograph A. Herzog).

Bertola et al. (2021) – [13]

2015

- Blocking of central arch hinge by UHPFRC
- Tensile membrane with R-UHPFRC (50 mm thick)
- Strengthening of deck slab by R-UHPFRC
- Transfer of tensile forces by fixed transition slabs in ground
- Preservation of cultural value

Concept of intervention: E. Brühwiler

Strengthening of Chillon Viaducts

2014 - 2015

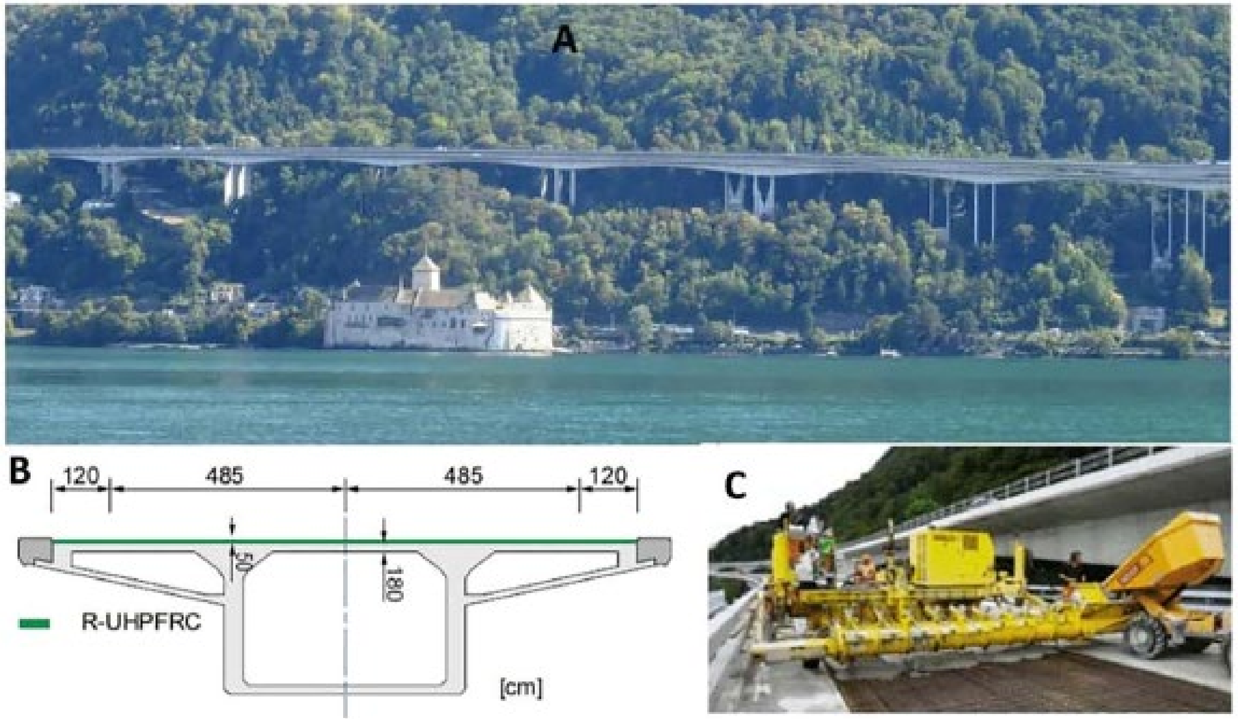


FIGURE 9 | Chillon Viaduct. **(A)** Overview of the viaduct above the Leman Lake and Chillon Castle; **(B)** cross-section of the bridge and the intervention; **(C)** UHPFRC casting (Photographs: E. Brühwiler).

- Twin viaducts 2120 m long
- Strengthening of upper deck slab for fatigue, bending and shear.
- Waterproofing
- Control of ongoing AAR
- 50 mm layer R-UHPFRC with rebar ϕ12 mm/s=125 mm (transverse)
- 2400 m^3 UHPFRC cast over 2 years
- Casting of up to 50 m^3 /day
- UHPFRC production plant on site

Bertola et al. (2021) – [13]

Concept of intervention: E. Brühwiler

UHPFRC
2024
October 21-23

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CAST ON-SITE UHPFRC FOR THE REHABILITATION OF EXISTING STRUCTURES – FEEDBACK OVER 20 YEARS OF EXPOSURE TO CHLORIDES

Emmanuel Denarié[1], Lionel Sofia[2], Jacques Rudaz[3]

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CONSTRUCT/IIC/ENAC/EPFL

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LMC/IMX/STI/EPFL

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et gestion des infrastructures (INFRA), DMTE - Valais

EPFL

CANTON DU VALAIS
KANTON WALLIS

Introduction

Bridge over river la Morge/VS/CH (2004) – single span 10 m

- Severe exposure to deicing salts (XF4, XD3, XD2)
- First cast-on site SH-UHPFRC application in Swit
- EU 5th FP project SAMARIS (2003-2006)
- Widening of the bridge
- Bridge deck + kerbs rehabilitated or replaced with CEMTEC$_{multiscale}$®
- Durability assessment after 9.5 and 19.5 years
- Chloride profiles on cores (UHPFRC and repair mortars) + sorptivity of UHPFRC
- Determination of chlorides diffusivities
- Visual survey

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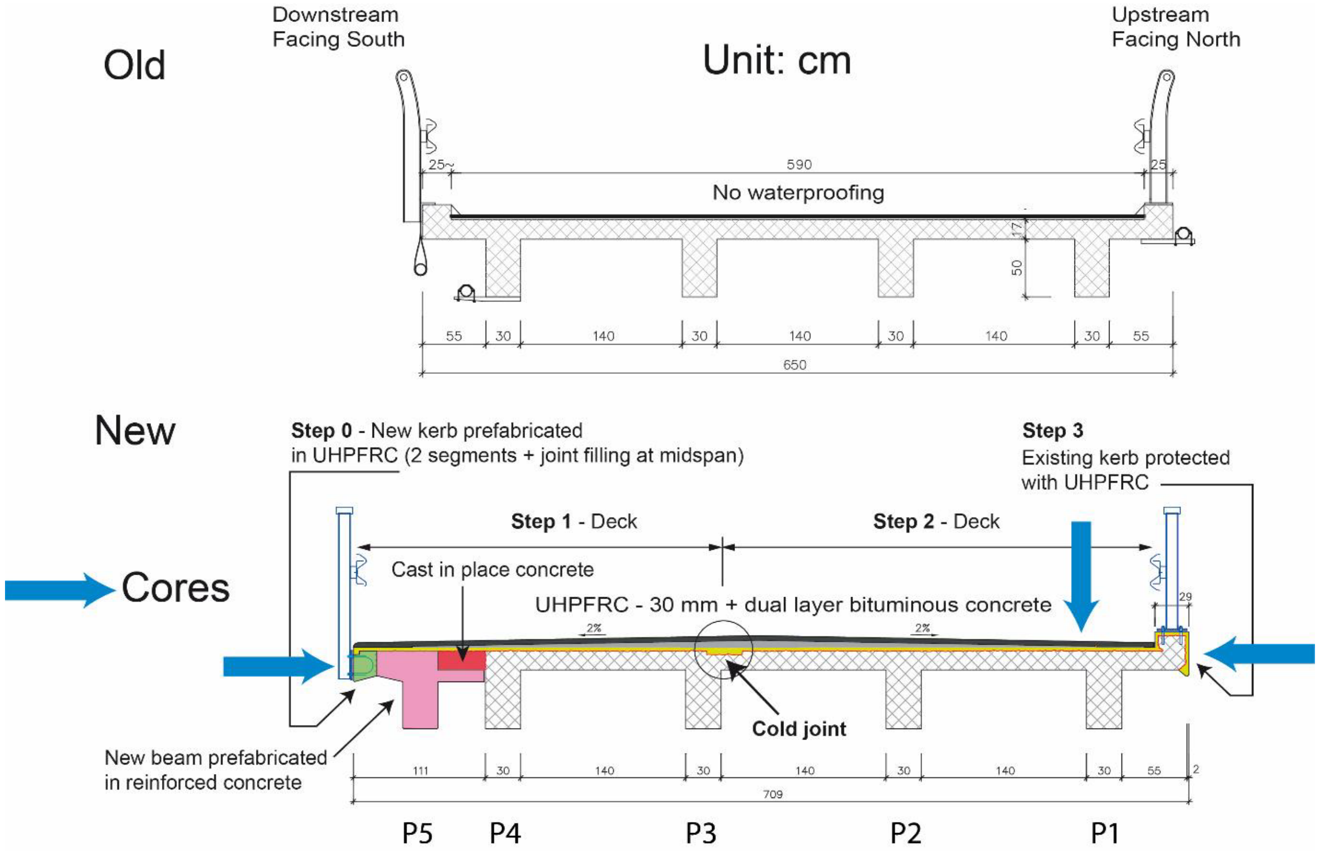
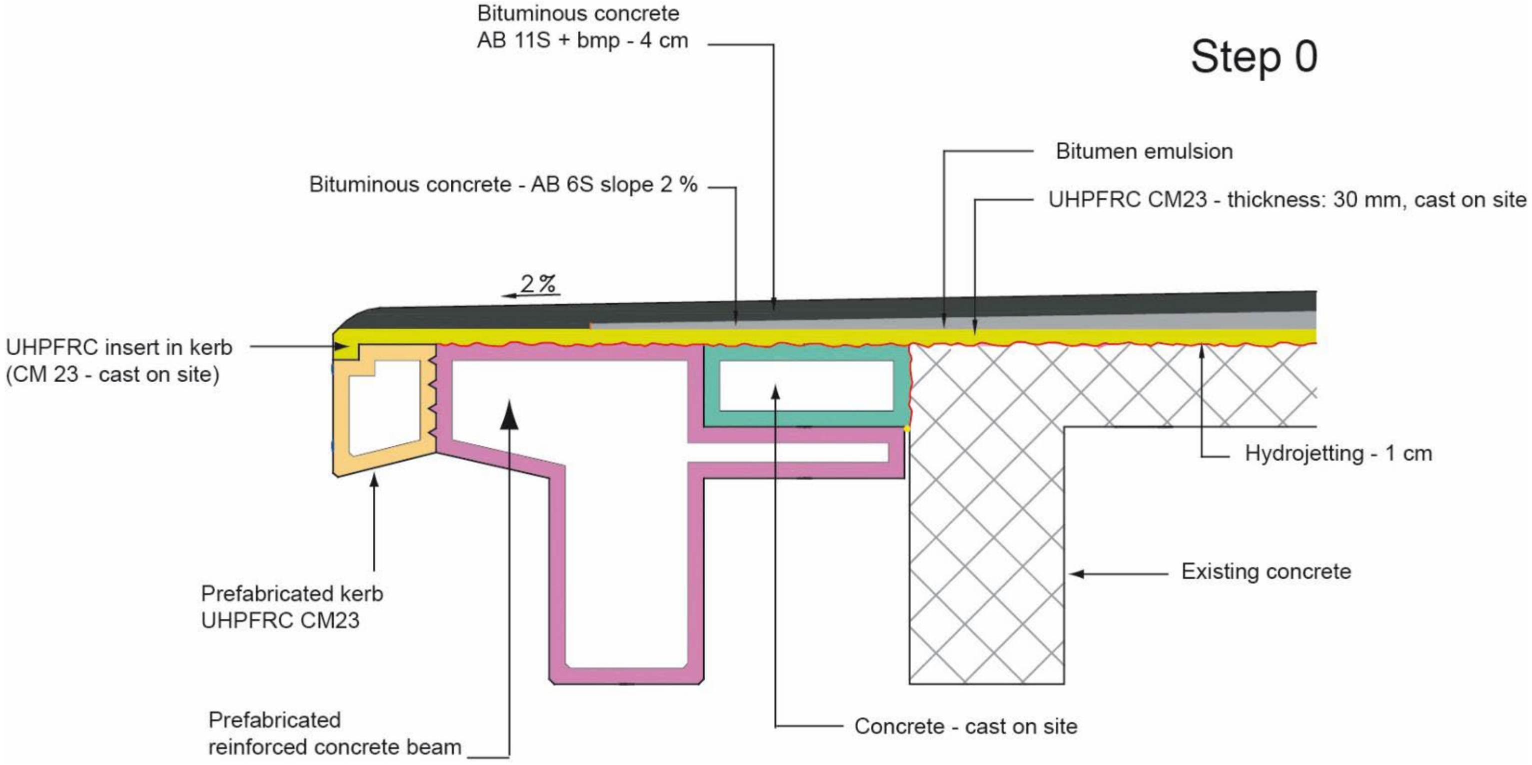
CAST ON-SITE

Concept of intervention and location of cores

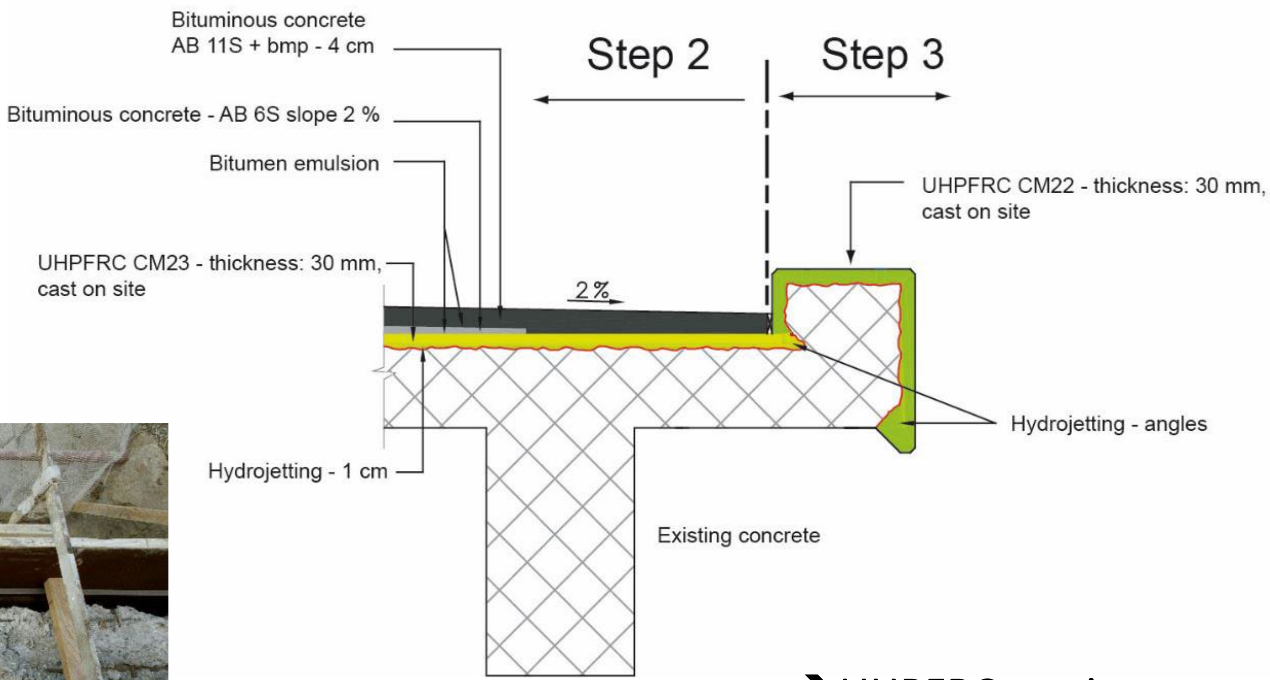


Downstream kerb





Upstream kerb



Existing kerb
after hydrojetting

➔UHPFRC casting
with low temperatures
(5° C)

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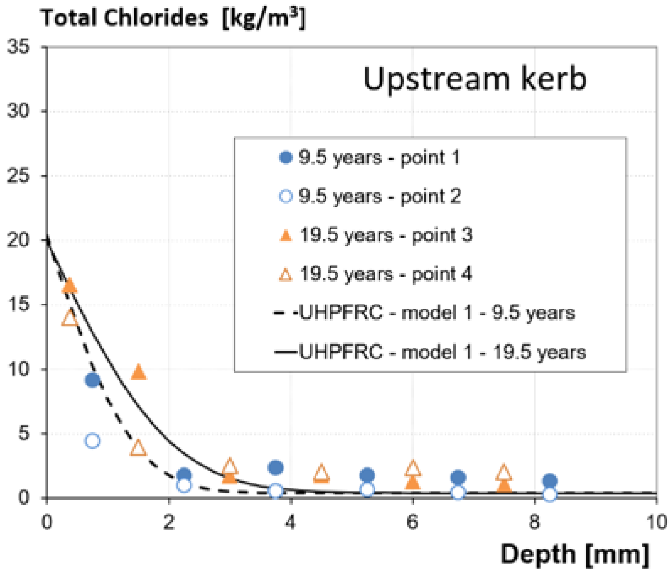
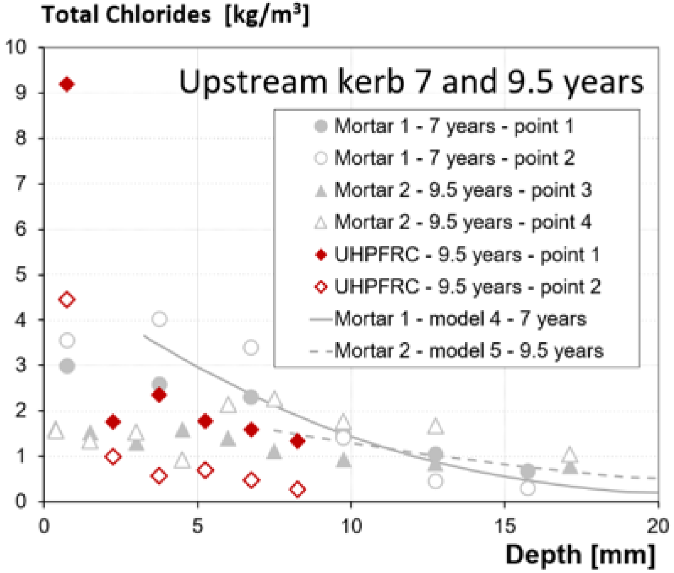
CAST ON-SITE

Chloride profiles and models (1)

Mortar 1 cast in 2007 and tested in 2014; mortar 2 cast in 2014 and tested in 2024





- For UHPFRC, similar boundary conditions can be used at 9.5 and 19.5 years
- Very small progress of chlorides penetration in UHPFRC until 2024
- In-depth penetration of chlorides in repair mortars after 7 and 10 years

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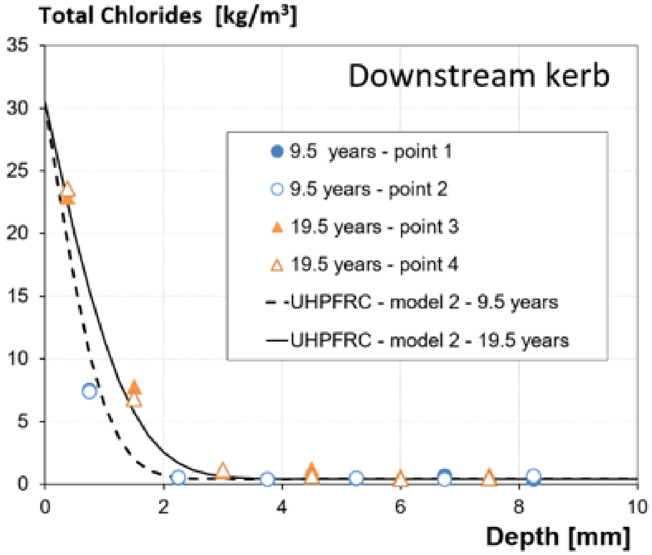
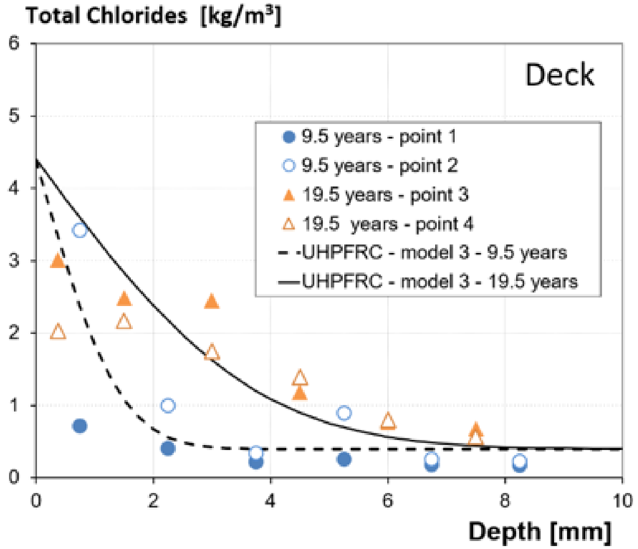
Chloride profiles and models (2)





- Similar boundary conditions can be used at 9.5 and 19.5 years
- Significant difference for deck between 2014 and 2024 campaigns
- Overall, very small progress of chlorides penetration in UHPFRC until 2024

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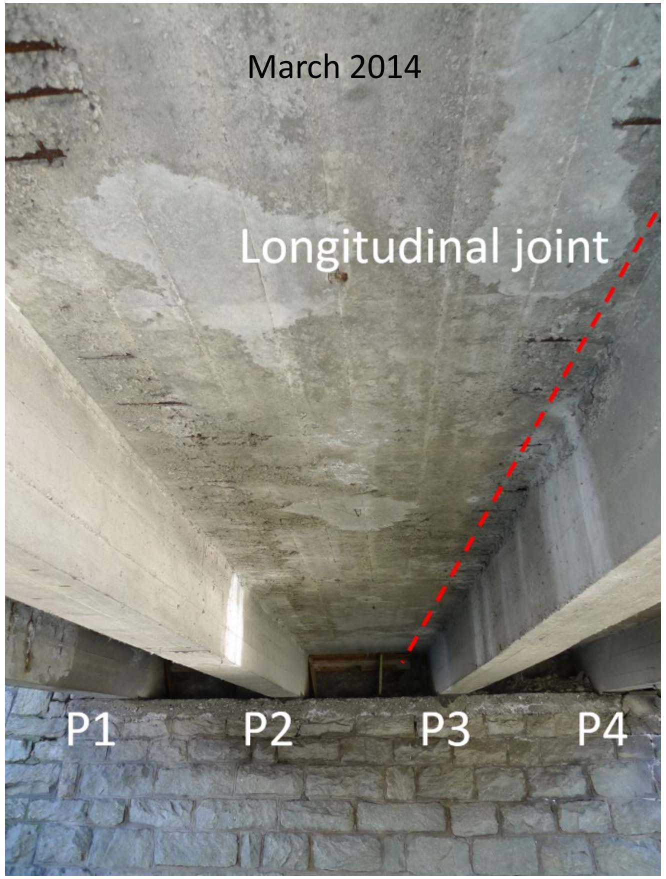
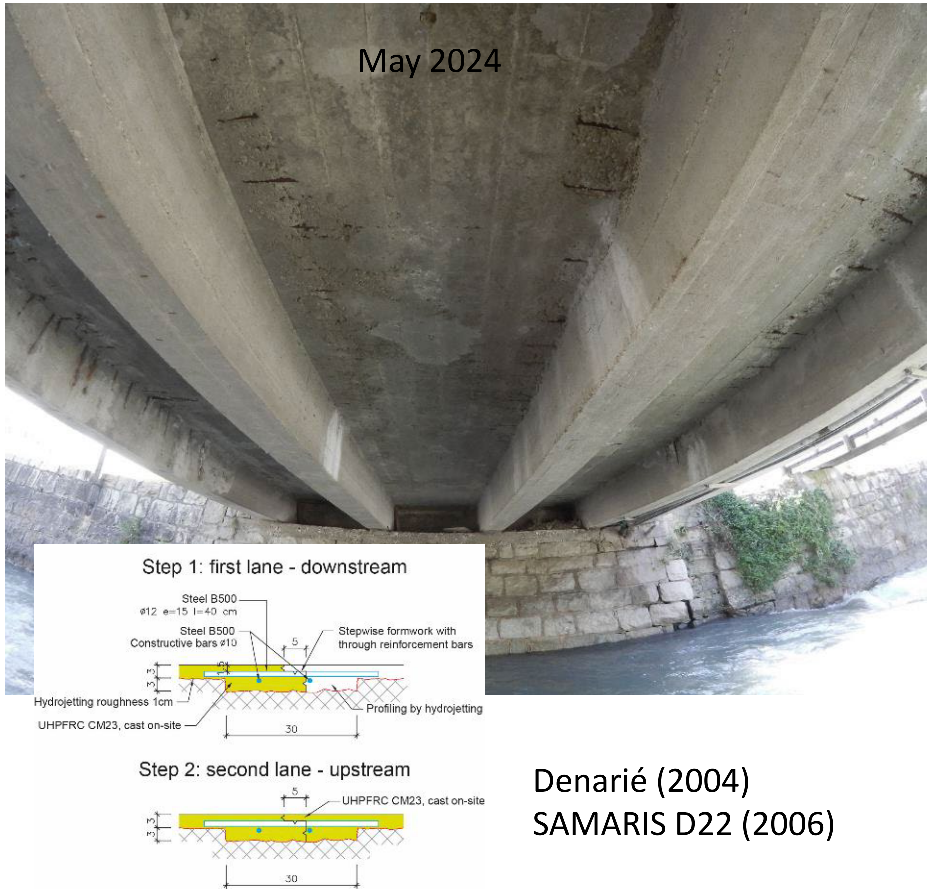
CAST ON-SITE

Longitudinal cold joint





Denarié (2004)
SAMARIS D22 (2006)

10. Synthesis

- Three main strengthening methods: external prestressing, glued CFRP lamellas, application of R-UHPFRC
- Specific features of R-UHPFRC: synergy UHPFRC-Reinforcement bars + effects of orientation of fibers
- Design of composite R-UHPFRC-RC members with support of analytical methods: non linear calculations + plasticity theory (shear)
- Fatigue verification of R-UHPFRC-RC members at materials and structural level

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