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October 2-4
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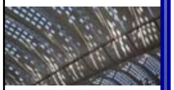

CHARACTERIZATION OF THE TENSILE RESPONSE OF STRAIN HARDENING UHPFRC - CHILLON VIADUCTS

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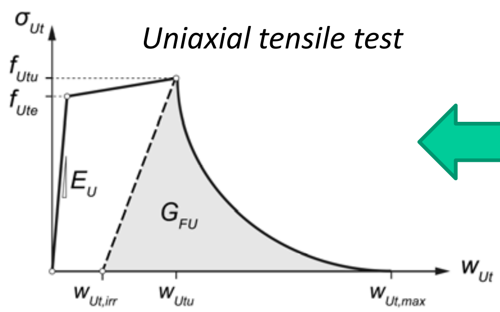
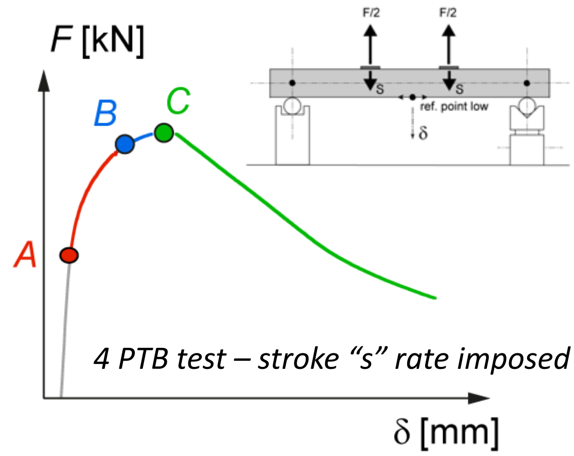
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Motivation

- Normative approach (works for Swiss document SIA CT 2052)
- Focus on elastic-hardening domain
- Avoid range of action of tensile softening on flexural response
- Improve detection of elastic limit with objective criterion
- Propose simple inverse analysis method
- Compare with results of Non Linear FEM calculations
- Apply to the case of Chillon viaducts site (CH 2014-2015)

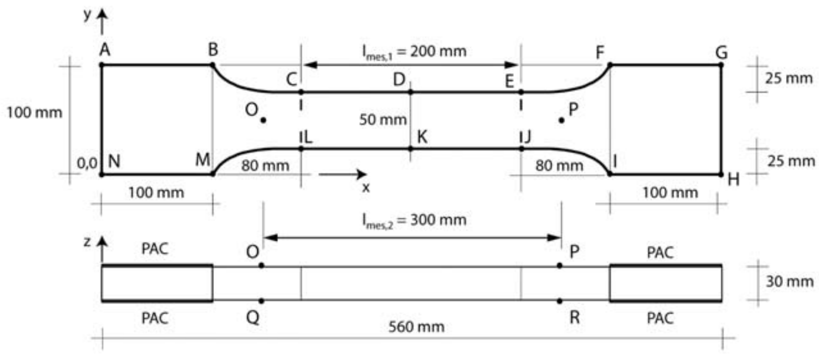
Challenges





- ➔ Point A = elastic limit
- ➔ From points A to B, tensile hardening active (if any)
- ➔ Pre-peak, after point B, effect of tensile softening on flexural response
- ➔ Multiple cracks with tensile softening zones likely between B and C
- ➔ Deflection hardening = increase of resistive moment !
- ➔ Remain between points A and B for simplified inverse analysis
- ➔ Detect point B

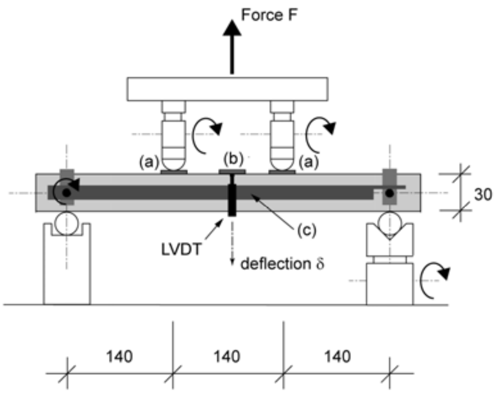
Uniaxial tensile test



PAC: glued aluminium plates

- ➔ Supports: fixed ends
- ➔ 2 pairs LVDT in two perpendicular planes
- ➔ Constant stroke rate
- ➔ Cast in molds or cut out of larger cast plates (suitability tests)
- ➔ Thickness: 30 mm
- ➔ Data acquisition at 5 Hz

4 PT bending test on strips



➔500 mm long specimen, height h_m=30 mm, width b_m=100 mm, span l_m= 420 mm; upper casting face, surfaced, under tension

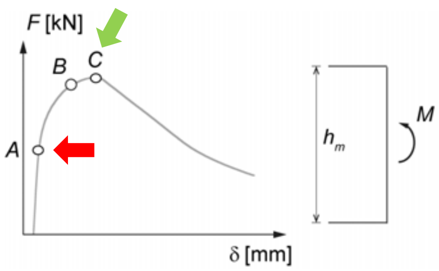
➔Cast in molds or cut out of larger cast plates

➔LVDT attached to measurement frame, fixed to middle axis of specimen

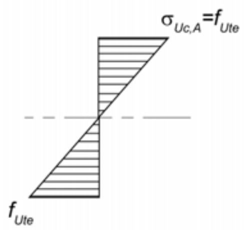
➔Constant loading rate imposed: stroke at points (a)

➔Data acquisition at 5 Hz

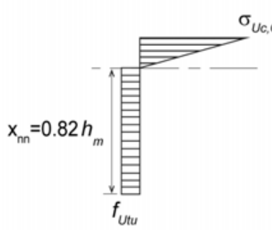
Interpretation



$$f_{Ute} = \frac{F_A \cdot l_m}{b_m \cdot h_m^{\ 2}}$$



$$f_{Utu} = 0.383 \cdot \frac{F_C \cdot l_m}{b_m \cdot h_m^{\ 2}}$$



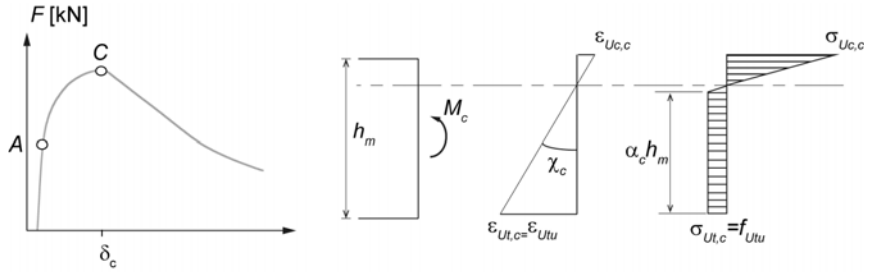
➔ f_{Ute} and E_{Ut} (point A) defined by irreversible variation of more than 1 % of the moving average of the secant elastic modulus

➔ f_{Utu} (point C) defined at peak force by stress block assumption validated by large FEM calculation database for the specimen geometry

$f_{Utu} > f_{Ute}$: strain hardening UHPFRC
➔ *ε_{Utu} (point B) determined by simplified inverse analysis*

$f_{Utu} < f_{Ute}$: Strain softening UHPFRC
➔ *No inverse analysis*

Inverse analysis – Simplified method after AFGC (2013)



$$\chi = \frac{216}{23} \cdot \frac{\delta}{l_m^{\ 2}}$$

$$M = \frac{F \cdot l_m}{6}$$

$$2\alpha^3 - 3\alpha^2 + 1 - \frac{M}{\chi \cdot E_U \cdot I} = 0 \qquad \sigma_{Ut} = 0.5(1-\alpha)^2 h_m \chi E_U \qquad \varepsilon_{Ut} = \frac{\sigma_{Ut}}{E_U} + \chi \alpha h_m$$

AFGC UHPFRC guidelines (2013) , Annex 4, §3.2: “Simplified back analysis”

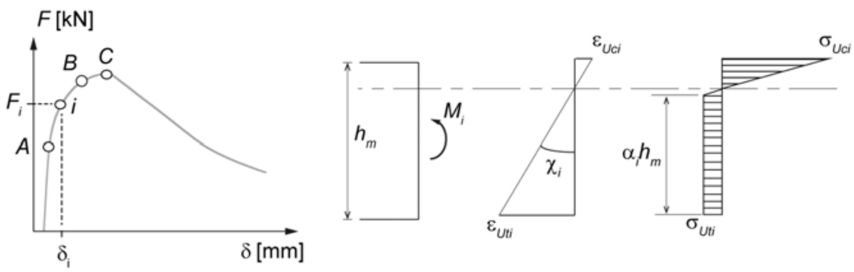
➔ *Assumes elastic expression of curvature in constant moment zone (explicitly mentioned as simplification, strictly valid only in elastic domain)*

➔ *Calculation only for peak force F_c and associated deflection*

➔ *Assumes «f_{Utu} and ε_{Utu} are calculated from the stress and strain obtained under the maximum moment” i.e.: maximum force = point C*

➔ *Simple method but effect of tensile softening already significant at peak*

Inverse analysis – proposed method



$$\chi_i = \frac{216}{23} \cdot \frac{\delta_i}{l_m^{\ 2}}$$

$$M_i = \frac{F_i \cdot l_m}{6}$$

$$2\alpha_i^3 - 3\alpha_i^2 + 1 - \frac{M_i}{\chi_i \cdot E_U \cdot I} = 0 \quad \text{with} \quad \lambda_i = \frac{M_i}{\chi_i \cdot E_U \cdot I} = 12\frac{M_i}{b_m \cdot h_m^3 \cdot \chi_i \cdot E_U} \quad \text{yields} \quad 2\alpha_i^3 - 3\alpha_i^2 + 1 - \lambda_i = 0$$

$$\sigma_{Ut_i} = 0.5(1-\alpha_i)^2 h_m \chi_i E_U \qquad \varepsilon_{Ut_i} = \frac{\sigma_{Ut,i}}{E_U} + \chi_i \alpha_i h_m$$

➔ Same basis as AFGC (2013)

➔ Generalization + “stop” after point B to avoid effect of tensile softening

➔ *Calculation for a series of points «i» regularly spaced between points A and C. First point «B» for which calculated stress at lower face is higher than tensile strength f_{Utu} defines end of strain hardening domain : $\varepsilon_{Utu=}\varepsilon_{Ut,B}$*

Chillon viaducts site (CH 2014/2015)

➔ 2 x 2.1 km long – special casting machine

➔ Deck reinforcement with 40 mm R-UHPFRC

➔ Rebar in transverse direction + longitudinally only over piles

➔ 2400 m^3 thixotropic Ductal® NaG3 Tx cast on site with up to 7 % slopes

➔ Quality control with representative samples cut out of square plates cast under machine

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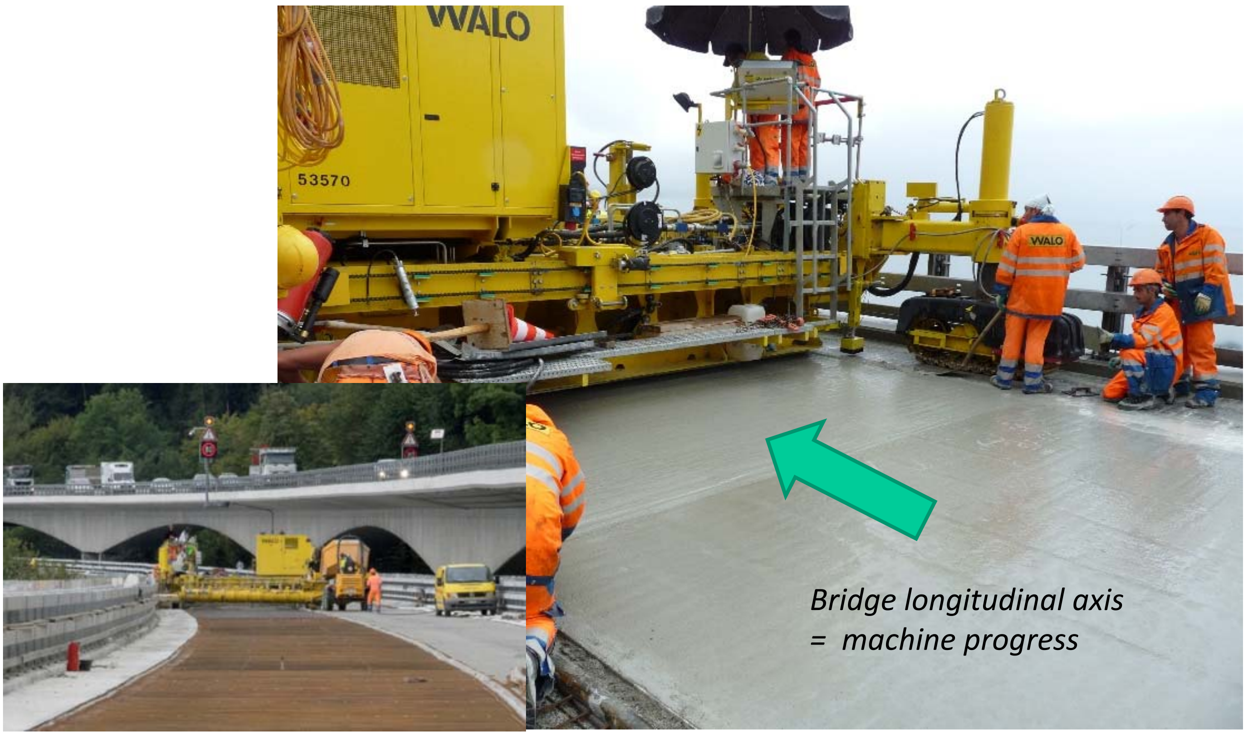
Characterization tensile response…

Chillon viaducts site (CH 2014/2015)



Quality control 2015

Number of specimen

Laboratory	Series 1 - Parallel to laying direction		Series 2 - Perpendicular to laying direction	
	Tensile test	4 PTB test	Tensile test	4 PTB test
Lab. 1	6 x	6 x	6 x	6 x
Lab. 2		6 x		6 x

- ➔Two different Swiss laboratories involved
- ➔Tensile and 4 PT bending tests
- ➔Two directions tested vs casting direction
- ➔All tests at 28 days, 20°C curing
- ➔Inverse analysis of 4 PTB via FEM + simplified method

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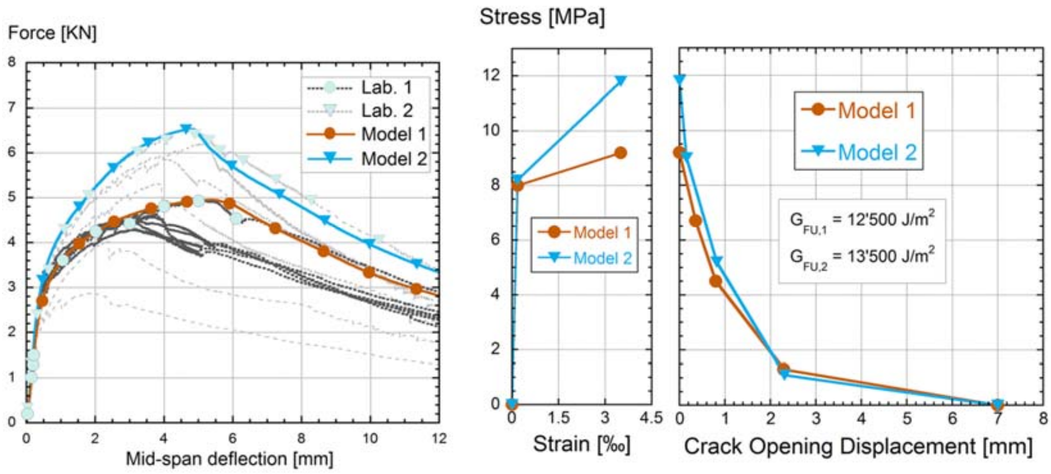
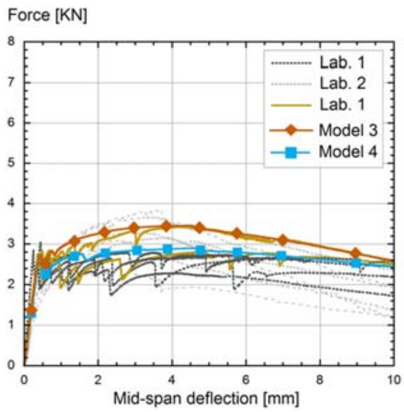
4 PTB test series 1 + FEM models

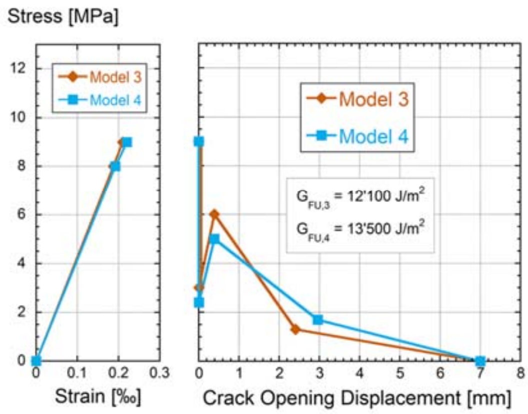


Loading parallel to casting direction

- ➔ Good correspondence between test results of two labs on average. More scatter for specimens of lab.2
- ➔ Material exhibits significant strain hardening response

4 PTB test series 2 + FEM models



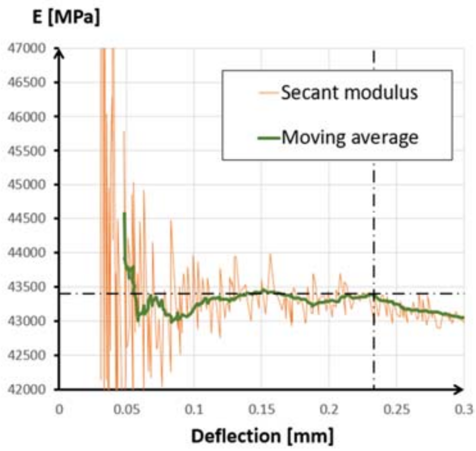


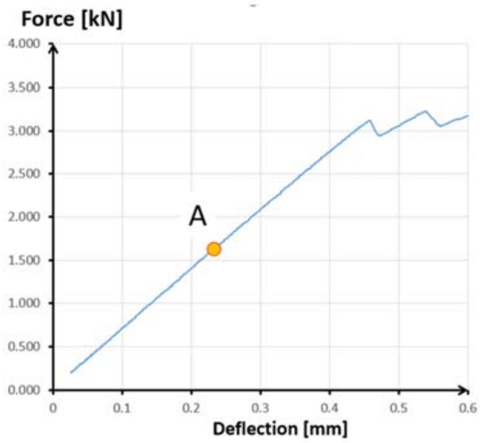
Loading perpendicular to casting direction

→ Good correspondence between test results of the two labs.

→ Material exhibits tensile softening response

Determination of elastic limit - example

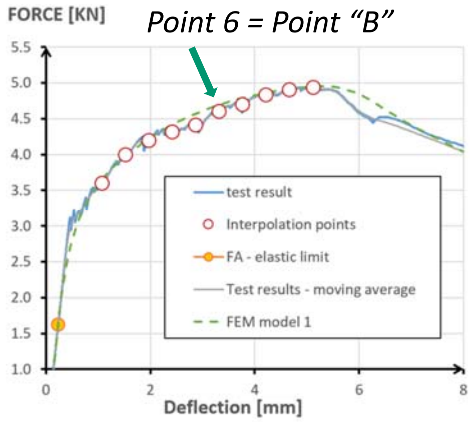


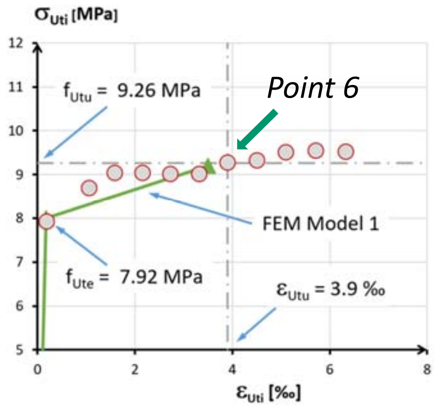


Loading parallel to casting direction 4 PTB series 1 sample

→Point A, elastic limit (irreversible decrease of secant modulus > 1 %) for a deflection of 0.223 mm, f_{Ute}=7.92 MPa, elastic modulus 43,400 MPa

Simplified Inverse Analysis - example



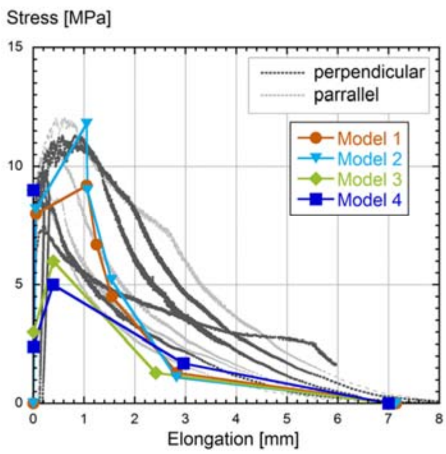


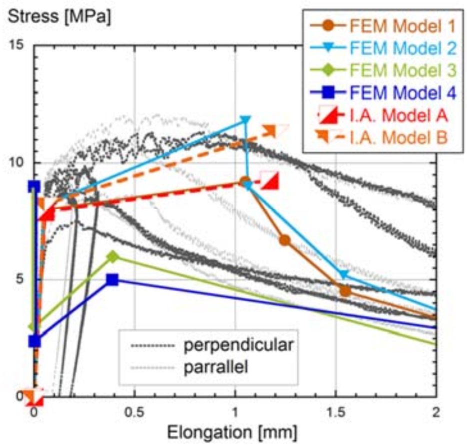
4 PTB series 1 sample *Simplified inverse analysis*

➔Excellent agreement between results of inverse analyses with simplified method and FEM

➔ Tensile softening activated after point 6 of inverse analysis. largely prior to peak force

Synthesis of results





Tensile test results vs inverse analyses predictions

➔ No significant effect of direction of loading vs casting for tensile test results

➔ Results of tensile test and inverse analyses correspond well

Conclusions

- Two tests methods + inverse analysis method proposed and validated to characterize tensile response of SH-UHPFRC
- Original method for accurate determination of elastic limit
- Original method for inverse analysis of bending test results
- Excellent correspondence with predictions of FEM inverse analyses and tensile test results
- Successfully applied for practical applications in Switzerland since 2015 such as Chillon viaducts reinforcement

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Thank you for your attention !