Fatigue behaviour of UHPFRC, R-UHPFRC and RU-RC composite members

Eugen Brühwiler

Swiss Federal Institute of Technology Lausanne (EPFL)
Lausanne, Switzerland

FUZHOU UNIVERSITY

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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PhD Thesis (2014) by Tohru Makita

Introduction
- Context
- Objectives

Tensile fatigue behaviour of UHPFRC | **Tensile fatigue behaviour of R-UHPFRC** | **Fatigue behaviour of RU-RC members**
- Fatigue endurance limit
- Characteristics of the fatigue behaviour

Fatigue damage modelling of UHPFRC and R-UHPFRC
- Damage evolution model of UHPFRC
- Empirical fatigue relationship for R-UHPFRC

Modelling of fatigue behaviour of RU-RC members
- Evolution of stress and deformation
- Function of R-UHPFRC in fatigue strengthening

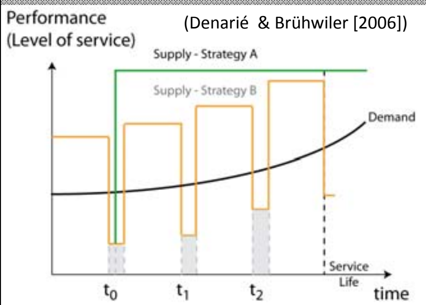
Conclusion

Functionally Obsolete Bridges

- ✓ Construction of most existing bridges during the middle to end of 20th century based on former design codes
- ✓ No consideration of the performance necessarys for today's bridges in terms of ultimate, serviceability and fatigue limit states
- ✓ Necessary to update such existing bridge to satisfy the current requirements through interventions

Massive RC slab bridge built in 1963 with insufficient load bearing capacity and no waterproofing → ***Need improvement!***

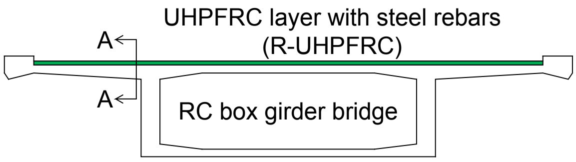
Strengthening of Bridge Deck Slab with UHPFRC



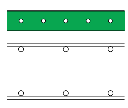
- ✓ Need to manage a large number of bridges with limited budget
- ✓ More efficient and effective methods to strengthen bridge deck slabs for the increase of traffic load

Strategy A is preferable.

Conceptual idea:
Overlay UHPFRC or UHPFRC with steel rebars (R-UHPFRC) on top of bridge deck slab

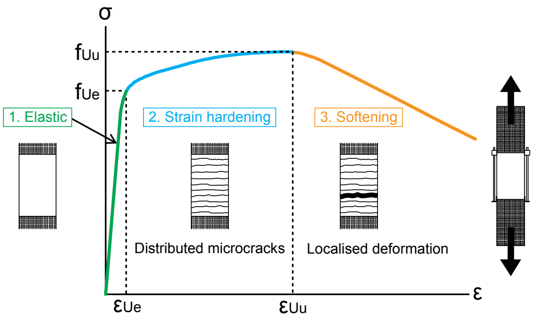


Cross section A - A



UHPFRC as a Strengthening Material

Ultra-**H**igh **P**erformance **F**ibre **R**einforced **C**oncrete



UHPFRC material properties

Compressive strength ≥ 150 MPa
Tensile strength ≥ 7 MPa
Tensile strain hardening behaviour
High packing density

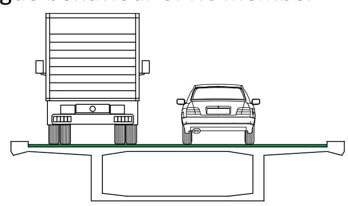
UHPFRC to "harden" the specific zone of structural members subjected to severe mechanical and environmental actions

- ✓ Investigation of UHPFRC as a cast-in-place strengthening material
- ✓ Limited studies on the fatigue behaviour of UHPFRC, R-UHPFRC and RU-RC members

Objectives

For more focused application of UHPFRC to fatigue vulnerable parts of structures like bridge deck slab, the following objectives were determined.

- ✓ Determine the fatigue endurance limit of UHPFRC, R-UHPFRC and RU-RC members
- ✓ Understand the characteristics of the fatigue behaviours of UHPFRC, R-UHPFRC and RU-RC members
- ✓ Study the influence of steel rebars on the fatigue behaviour of UHPFRC when steel rebars are arranged in UHPFRC
- ✓ Analyse and model the fatigue damage mechanism of UHPFRC
- ✓ Investigate the contribution of R-UHPFRC layer as a fatigue strengthening element to the fatigue behaviour of RC member



In-House Developed UHPFRC Mix "HIFCOM 13"

Characterised by

- 3.0 vol. % content of 13 mm long steel fibres with a diameter of 0.16 mm
- CEM III/B type cement containing 66 to 80 % of blast furnace slag

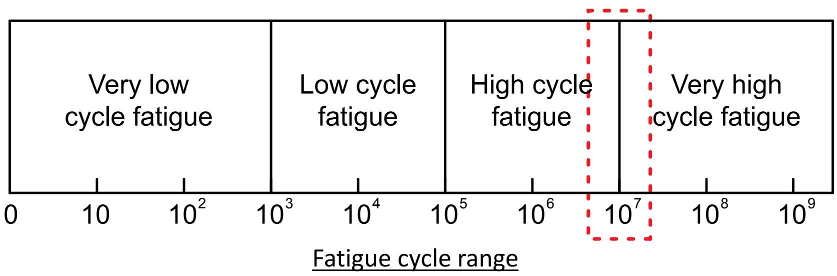
Component	Type	Mass [kg/m³]	Remarks
Cement	CEM III/B	1277.4	
Silica fume	Elkem Microsilica 971 U	95.8	7.5 % of cement mass
Sand	Quartz sand MN 30	664.6	d_{max} < 0.5 mm
Steel fibres	Bekaert OL 13/0.16 mm	235.5	3.0 vol.-%, brass coating
Superplasticiser	Sikament P5	42.3	3.3 % of cement mass
Water		198.0	W/C = 0.155

Fatigue Test

- ✓ Application of constant amplitude fatigue force in force-controlled mode
- ✓ "Run-out" : when a specimen sustained 10 million cycles
- ✓ Fatigue endurance limit at 10 million cycles determined from *S-N* diagram

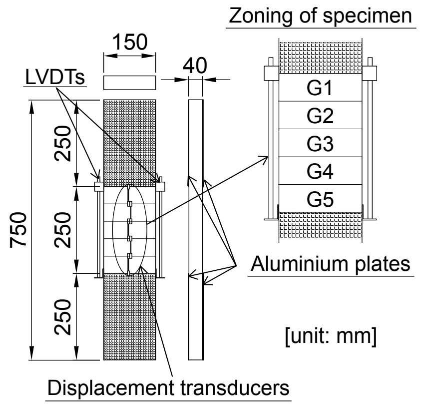
10 million extreme cycles

 # Realistic number of axle loading in heavily trafficked bridges
 # Lower bound of the very high cycle fatigue domain.



Tensile Fatigue Test of UHPFRC

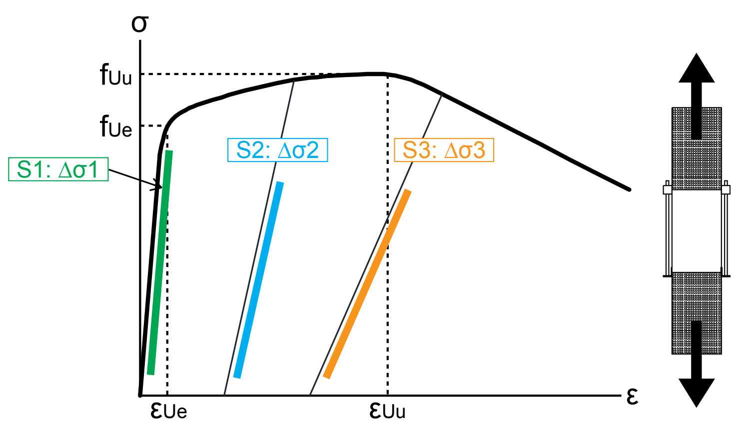
- ✓ 39 uniaxial tensile fatigue tests on UHPFRC plate specimens with force applying frequency of 10 Hz
- ✓ Three different fatigue stress levels as characterised by varying maximum stress and pre-applied deformation
- ✓ Measuring instruments: two LVDTs and five displacement transducers



Definition of Tensile Fatigue Stress

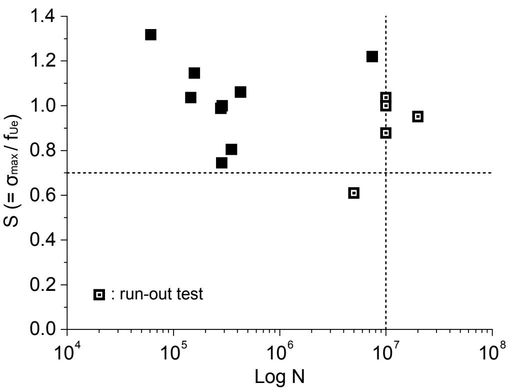
- ✓ **S1** series to determine fatigue endurance limit within the elastic domain
- ✓ **S2** and **S3** series to understand tensile fatigue behaviour of UHPFRC after it is damaged beyond the elastic limit

→ *UHPFRC cast on existing concrete elements may be deformed into the strain-hardening domain due to eigenstresses.*



S-N Diagram Obtained from S1 Series

Fatigue endurance limit at 10 million cycles:
70 % of elastic limit strength

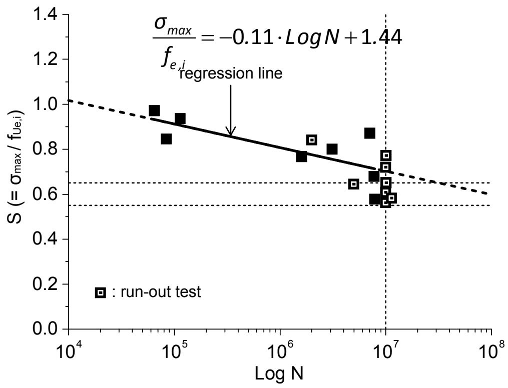


- ✓ Average elastic limit strength of three quasi-static test specimens to calculate *S*
- ✓ Difference between elastic limit strength of each fatigue test specimen and average elastic limit strength

σ_{max} : maximum fatigue stress (σ_{min} = 0.82 MPa)
f_{Ue} : average elastic limit strength determined from three quasi-static tensile tests (= 8.2 MPa)

S-N Diagram Obtained from S2 Series

Fatigue endurance limit at 10 million cycles:
55 to 65 % of elastic limit strength

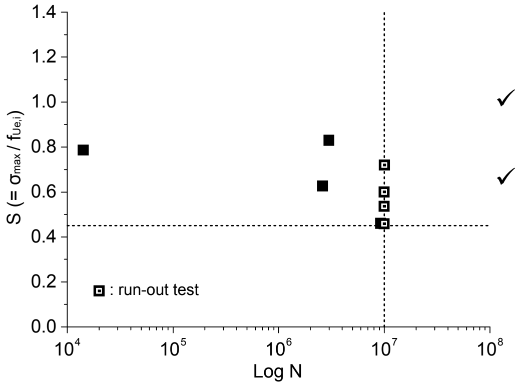


- ✓ Pre-applied deformation entering into the strain-hardening domain, ranging from 0.5 to 4.0 ‰ strains
- ✓ Elastic limit strength of each specimen to calculate *S*
- ✓ Elimination of variations in material composition, specimen size and testing set-up
- ✓ A linear regression line for fatigue strength with a correlation coefficient of -0.69

σ_{max} : maximum fatigue stress ($\sigma_{min} = 0.1 \cdot \sigma_{max}$)
$f_{Ue,i}$: elastic limit strength of each specimen

S-N Diagram Obtained from S3 Series

Fatigue endurance limit at 10 million cycles:
45 % of elastic limit strength

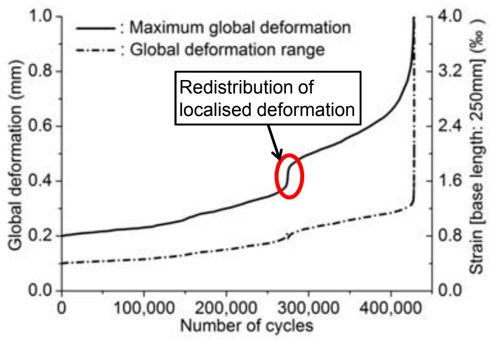


- ✓ Pre-applied deformation entering into the softening domain, ranging from 3.0 to 6.0 ‰ strains
- ✓ Elastic limit strength of each specimen to calculate *S*
- ✓ Influence of pre-applied deformation level on the fatigue behaviour

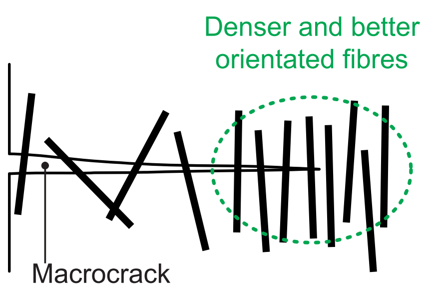
σ_{max} : maximum fatigue stress (σ_{min} = 0.1· σ_{max})
$f_{Ue,i}$: elastic limit strength of each specimen

Redistribution of Localised Deformation

- ✓ Carrying tensile fatigue stress even after localisation of deformation resulting in macrocrack opening of about 0.1 mm
- ✓ Arresting further macrocrack growth with denser and better orientated fibres



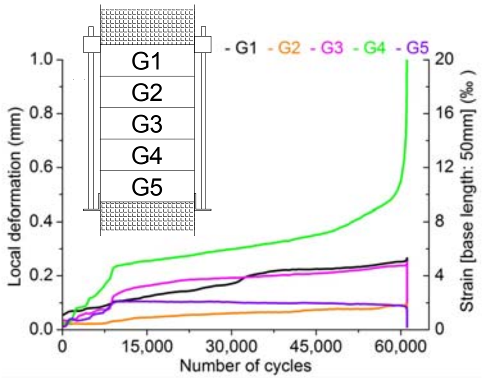
Evolution of global deformation (S1-3_ii test)



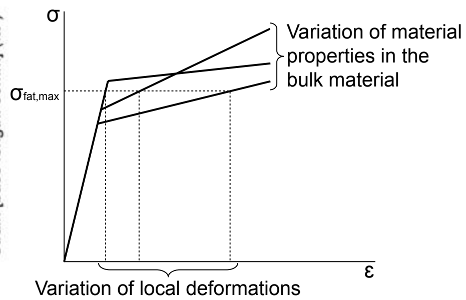
Arresting of macrocrack growth

Variations in Local Deformation

- ✓ Variations in local deformation despite equal nominal tensile fatigue stress in UHPFRC specimen
- ✓ Local variations in material properties, in particular elastic limit strength and strain-hardening behaviour
  → ***Significant stress and deformation redistribution capacity of UHPFRC***



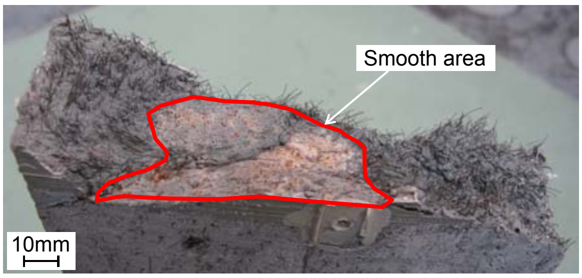
Evolution of local deformation (S1-5_ii test)



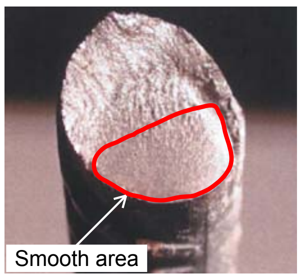
Variations of material properties

Smooth Area on the Fatigue Fracture Surface of UHPFRC

- ✓ Distinct smooth area on fatigue fracture surface of UHPFRC
- ✓ Two processes for the formation of smooth area: UHPFRC fabrication process and tribocorrosion fracture of fibres
- ✓ Similar fatigue fracture mechanism between UHPFRC and steel, while fatigue crack propagation mechanism is different.



(a)



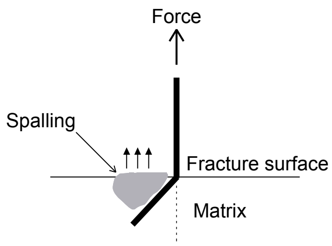
(b)

Fatigue fracture surface of (a) UHPFRC and (b) steel rebar

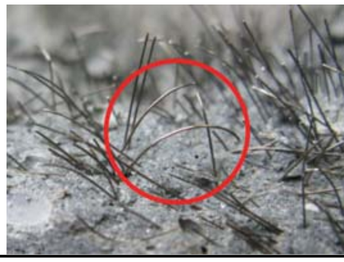
Spalling and Pulverisation of Matrix

- ✓ Spalling of matrix might occur when fibres were partially or fully pulled out of the matrix in a direction other than fibre axis (snubbing).
- ✓ Pulverisation of matrix may be due to abrasion of spalled matrix, while the irregular faces of the rough fracture surface were subjected to fretting and grinding under fatigue force.

Snubbing (after Li et al. [1990])

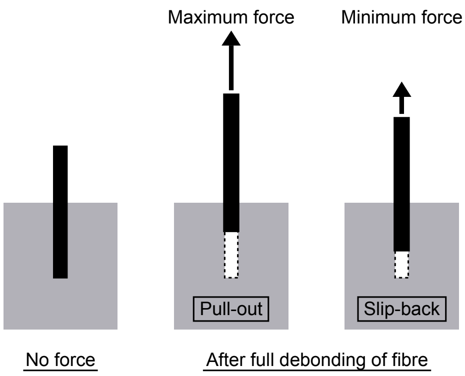


Bent fibres due to snubbing



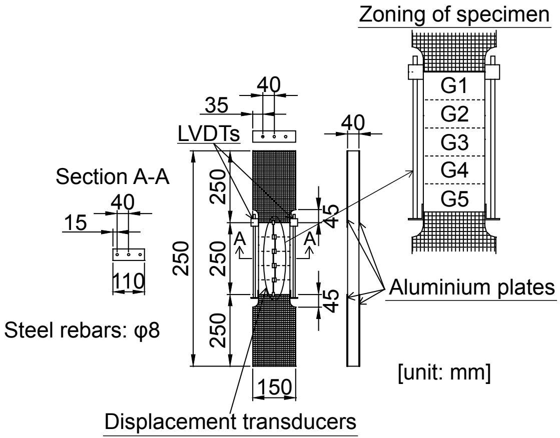
Rust-Coloured Powdery Products on Fracture Surface

- ✓ Smooth fracture surface areas were covered with rust-coloured powdery products which were identified to be corrosion products from fibres by EDS and SEM analysis.
- ✓ Tribocorrosion due to friction of fibre on matrix was considered to cause corrosion of the fibres subjected to pull-out – slip-back movement.



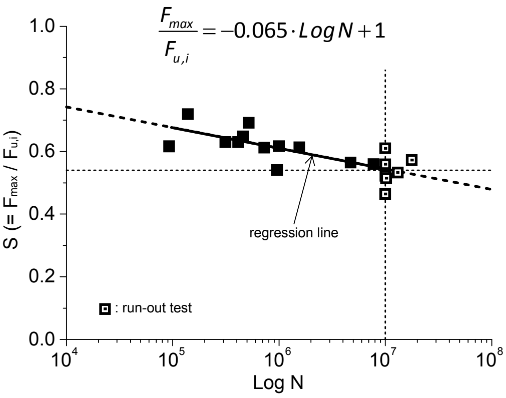
Tensile Fatigue Test of R-UHPFRC

- ✓ 19 uniaxial tensile fatigue tests on R-UHPFRC plate specimens with force applying frequency of 10 Hz
- ✓ Maximum fatigue force to cause stress range of 170 to 230 MPa in steel rebars
- ✓ The same test set-up and instrumentation as tensile fatigue test of UHPFRC



S-N Diagram of R-UHPFRC

Fatigue endurance limit at 10 million cycles:
54 % of ultimate strength



F_{max} : maximum fatigue force (F_{min} = 0.1· F_{max})
$F_{u,i}$: estimated ultimate strength of each specimen

- ✓ Estimation of ultimate strength of each specimen based on the single quasi-static tensile test result.
- ✓ A linear regression line with a correlation coefficient of -0.66.
- ✓ Similar fatigue endurance limit to RU-RC beams

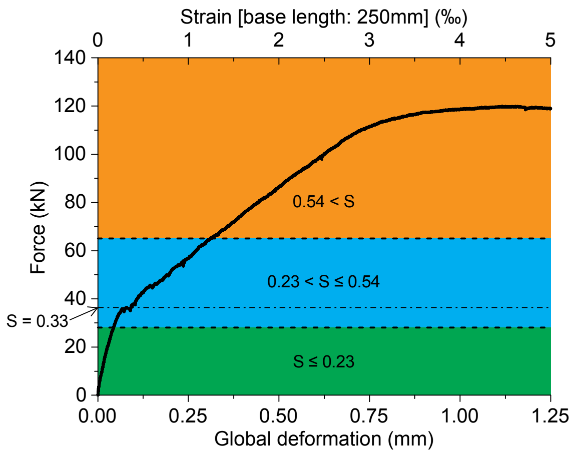
Fatigue Resistance of R-UHPFRC

$S \leq 0.23$: UHPFRC contributes more significantly than steel rebars.

$0.23 < S \leq 0.54$: Similar contribution of UHPFRC and steel rebars

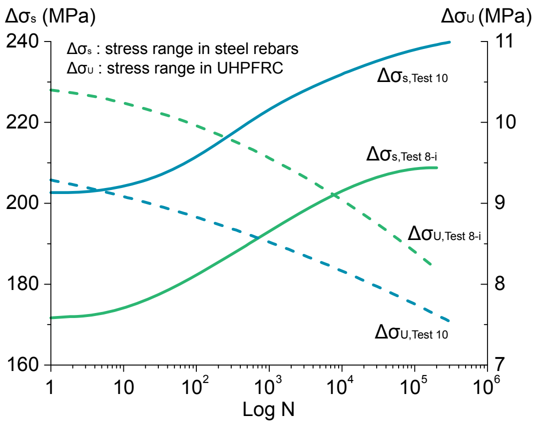
$0.54 < S$: Steel rebars primarily determine the fatigue resistance. UHPFRC functions as a stress reducing element for steel rebars.

$$S = \frac{F_{max}}{F_{u,i}},\ F_{min} = 0.1 \cdot F_{max}$$



Stress Transfer from UHPFRC to Steel Rebars

✓ Calculating stress in UHPFRC and steel rebars using specimen global deformation measurements



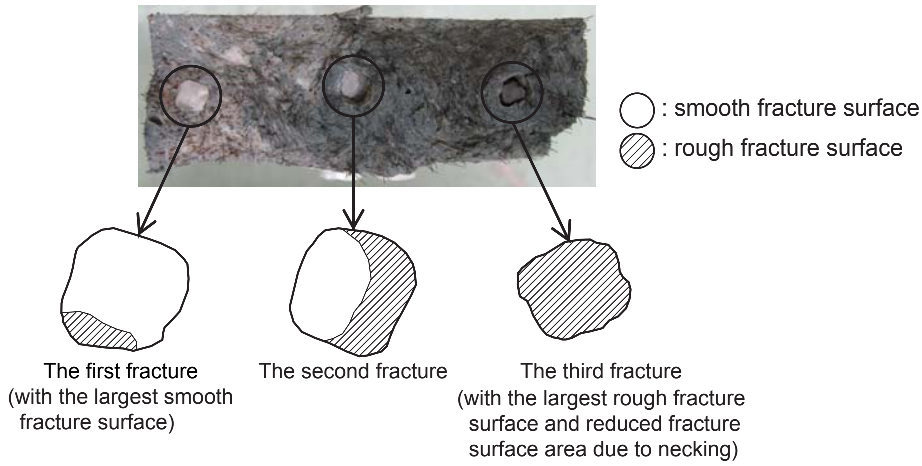
Stress range evolution in UHPFRC and steel rebars

($S > 0.54$ in both tests)

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

$\sigma_{s,i}$: stress in steel rebar at *i*-th cycle
$\sigma_{U,i}$: stress in UHPFRC at *i*-th cycle
E_s : modulus of elasticity of steel
$\Delta \ell_{g,i}$: global deformation at *i*-th cycle
ℓ_b : base length of LVDTs
F : applied force
A_s : sectional area of three steel rebars
A_U : sectional area of UHPFRC

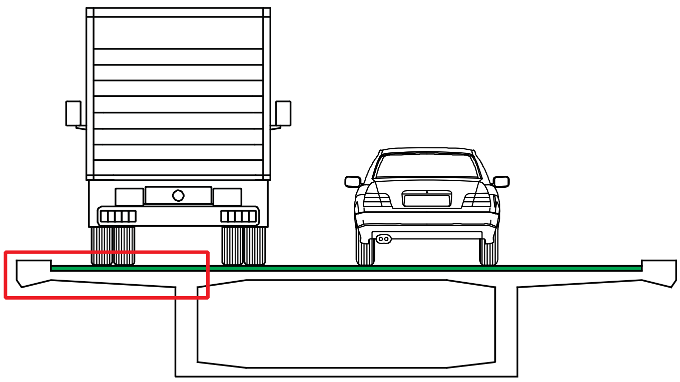
Fatigue Fracture Mechanism of R-UHPFRC



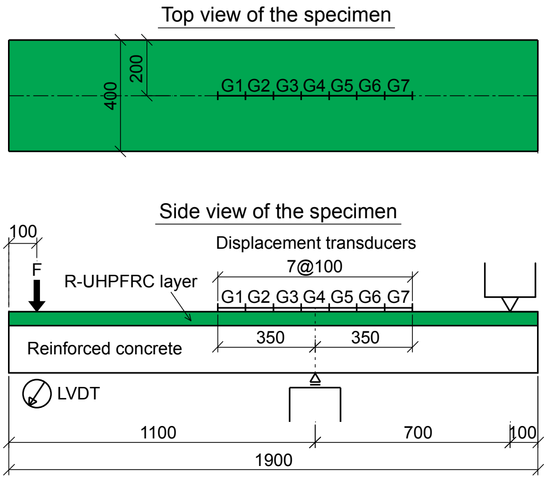
- ✓ Two distinct types of fracture surfaces of steel rebar: smooth and rough surfaces
- ✓ Extrapolation of chronological order of fracture of the three steel rebars based on the characteristics of the fracture surface

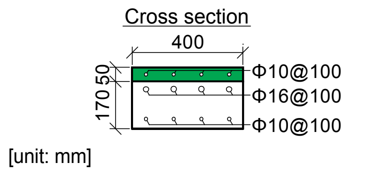
Bending Fatigue Test of RU-RC beams

- ✓ 9 bending fatigue tests on RU-RC beam specimens with force applying frequency of 8 Hz
- ✓ Cantilever static system representing a strip of RC bridge deck cantilever strengthened with R-UHPFRC layer
- ✓ Maximum fatigue force between 40 to 60 % of the ultimate static strength of the specimen (F_u = 90 kN)



Specimens, Test Set-Up and Instrumentation



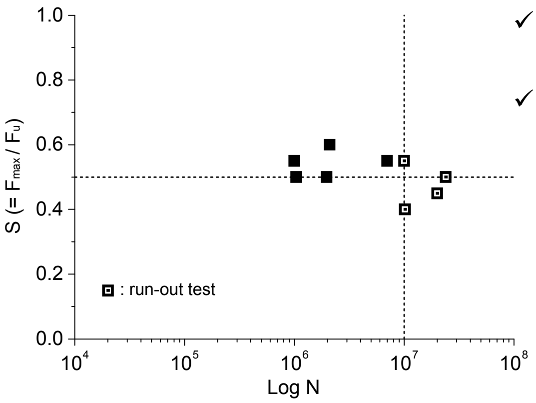


- Concrete: Grade C30/37 with d_{max} of 16 mm (f_{cc} = 64.5 MPa)
- Steel rebar: Grade B500B (f_{sk} = 500 MPa)
- LVDT to measure the specimen deflection
- Seven displacement transducers to measure the R-UHPFRC deformation

S-N diagram of RU-RC beams

Fatigue endurance limit at 10 million cycles:

50 % of the ultimate static strength

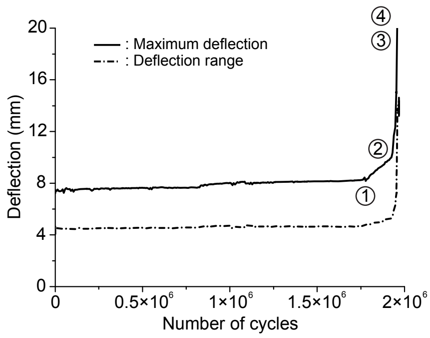


F_{max} : maximum fatigue force (F_{min} = 0.1· F_{max})
F_u : ultimate static strength (= 90 kN)

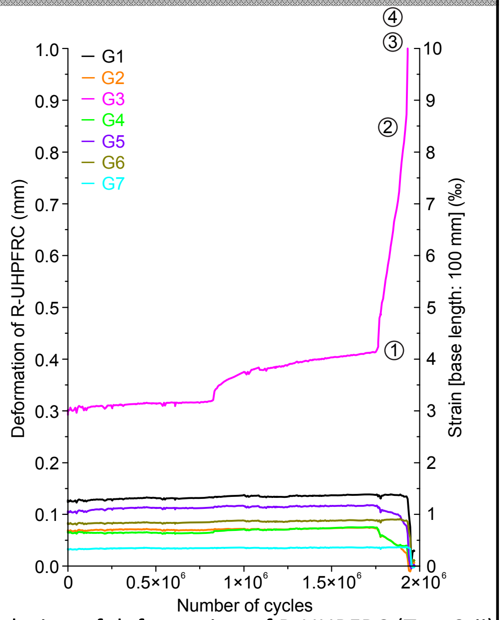
- ✓ Variations in ultimate static strength and age of specimens.
- ✓ Influence of variations of UHPFRC material properties on the ultimate static strength

Fatigue Failure Process of RU-RC Beam

- ✓ Four steel rebars in the R-UHPFRC layer fractured one by one.
- ✓ The fracture of a steel rebar was understood from the change of the specimen behaviour.



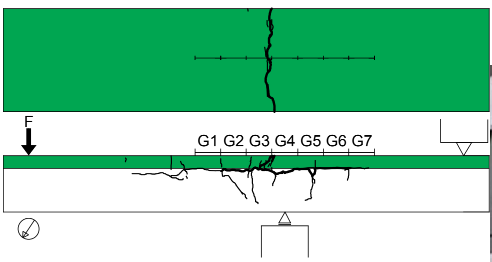
Evolution of deflection (Test 2-ii)



Evolution of deformation of R-UHPFRC (Test 2-ii)

Fatigue Failure of RU-RC Beam

Final crack pattern of a specimen



All the four rebars in the R-UHPFRC layer fractured almost at the same cross section, causing one fracture plane in the R-UHPFRC layer.

The R-UHPFRC layer, in particular steel rebars in the R-UHPFRC layer determine the fatigue behaviour of the RU-RC beam.

Fatigue Design Rules for RU-RC member

- ✓ Design rules for RU-RC members for the fatigue safety verification with respect to the fatigue endurance limit
- ✓ The fatigue safety verification: macro- and meso-level check

Macro-level check : moment resistance of RU-RC member

$$n_{fat} = \frac{0.5 \cdot M_{Rd}}{M_{d,fat}} \geq 1.0$$

n_{fat} : fatigue safety index
M_{Rd} : examination value of moment resistance of the RU-RC member
$M_{d,fat}$: examination value of maximum acting moment due to fatigue loading

Meso-level check : stress range in steel rebar in the R-UHPFRC layer

$$\Delta\sigma_{sd}(Q_{fat}) \leq \Delta\sigma_{sd,D}$$

$\Delta\sigma_{sd}$: examination value of stress range in steel rebars due to fatigue
Q_{fat} : characteristic value of fatigue loading
$\Delta\sigma_{sd,D}$: examination value for fatigue endurance limit of straight steel rebars
(= 115 MPa for straight steel rebars ϕ ≤ 20 mm)

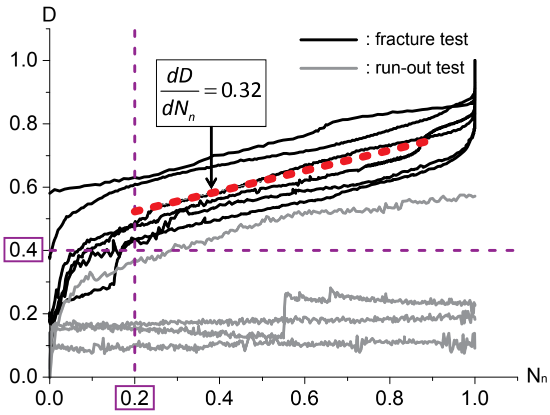
Damage Analysis of UHPFRC Tensile Fatigue Behaviour

- ✓ Constant damage evolution in fatigue fracture test
  → the capacity of UHPFRC to redistribute local deformation increases due to damage concentration
- ✓ Significant damage in UHPFRC at the early stage of the fatigue life when UHPFRC fractures due to tensile fatigue

Damage variable

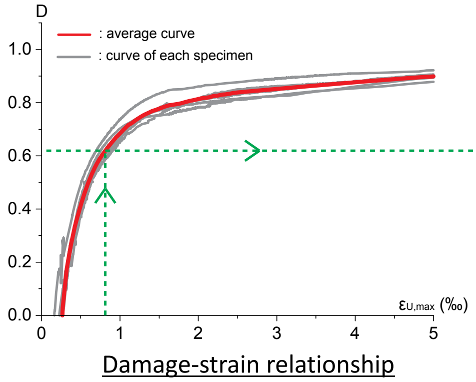
$$D = 1 - \frac{E_{U,fat,i}}{E_{U,fat,0}}$$

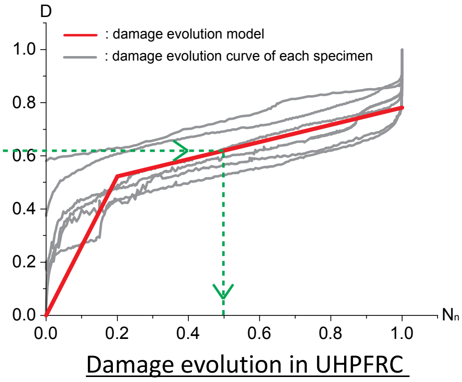
$E_{U,fat,i}$: modulus of deformation at *i*-th cycle
$E_{U,fat,0}$: initial modulus of deformation



Damage Evolution Model of UHPFRC

- ✓ Determination of remaining fatigue life of UHPFRC from maximum fatigue strain
- ✓ Model for existing structures





Fatigue life: $Log\,N = -9.55 \cdot \frac{\sigma_{max}}{f_{Ue}} + 13.72$

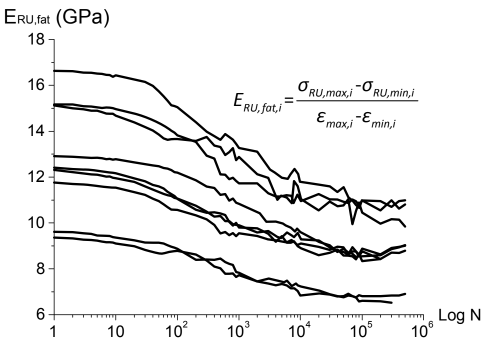
σ_{max} : imposed maximum fatigue stress

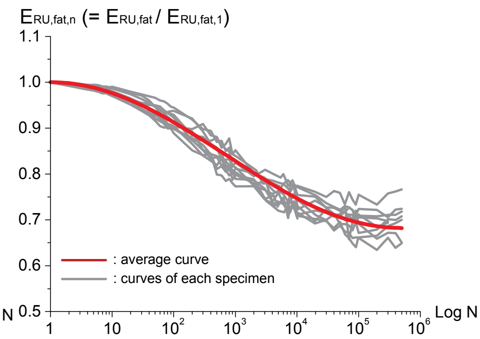
f_e : elastic limit strength of UHPFRC

Empirical Fatigue Relationship for R-UHPFRC

- ✓ Stress transfer from UHPFRC to steel rebars due to fatigue damaging of UHPFRC part of R-UHPFRC element
- ✓ Similar behaviour among all decreasing curves of deformation modulus of UHPFRC part $E_{RU,fat}$.

$$E_{RU,fat,n} = 0.68 + 0.32 \cdot \sin^2\left(\frac{LogN + 5.7}{11.4}\pi\right) \quad \text{for} \quad N \leq 500{,}000$$



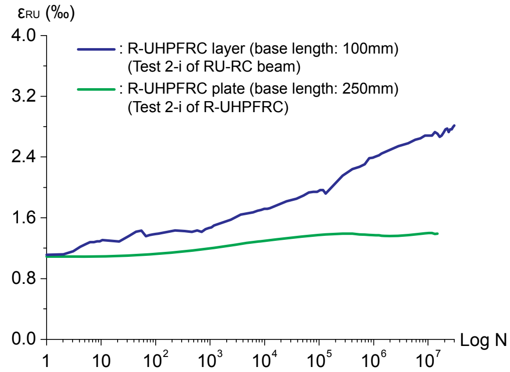


Modelling of the Fatigue Behaviour of RU-RC Beams

The fatigue behaviour of the RU-RC beam is determined by the R-UHPFRC layer.

→ Modelled by considering fatigue damaging of the R-UHPFRC layer

- ✓ Need to modify the fatigue relationship for R-UHPFRC element
- ✓ Different damaging behaviour between the R-UHPFRC plate and the R-UHPFRC layer

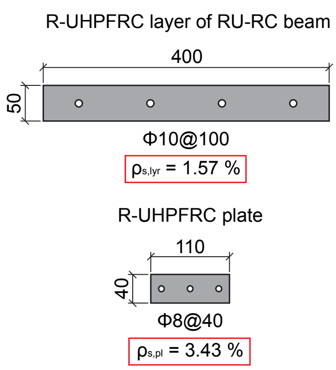


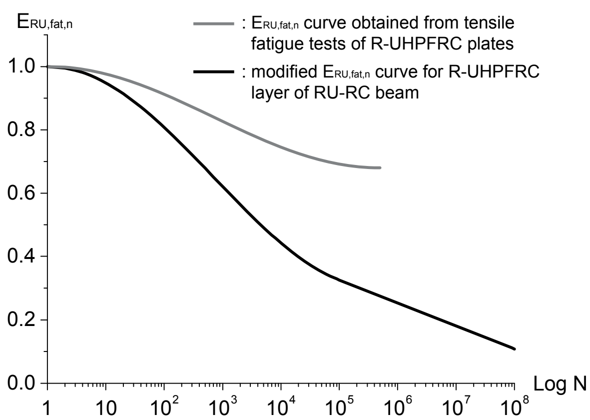
Strain growth of R-UHPFRC

Modification of Fatigue Relationship for R-UHPFRC

- ✓ Assumption for modification: damaging degree of R-UHPFRC element is inversely proportional to the steel rebar ratio
- ✓ Extension of fatigue relationship to describe continuing deformation growth of R-UHPFRC layer

Comparison of cross section

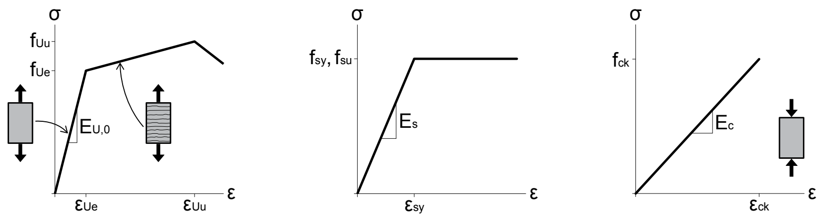




Assumptions and Conditions

- ✓ Calculation of stress and deformation based on Euler-Bernoulli beam theory and equilibrium of force

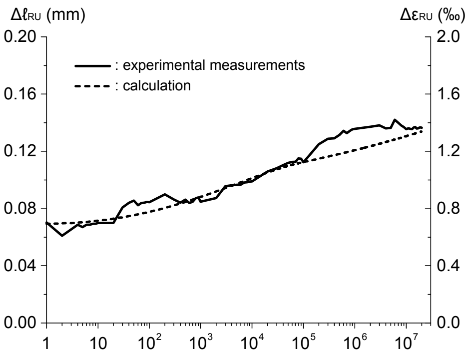
Constitutive laws of the three components of the RU-RC beam



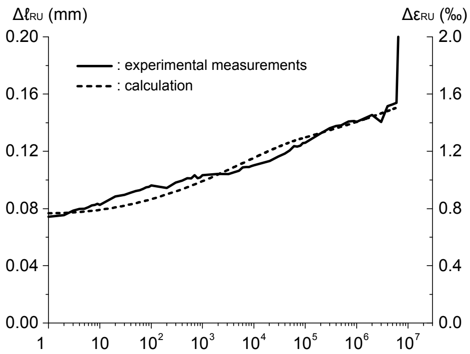
UHPFRC	Steel rebar	Concrete
$E_{U,0}$: variable	E_s = 205 GPa,	E_s = 33 GPa
$f_{Ue} = \varepsilon_{Ue} / E_U$	$f_{sy} = f_{su}$ = 500 MPa	f_{ck} = 30 MPa
ε_{Ue} = 0.17 ‰	ε_{Uu} = 2.44 ‰	
$f_{Uu} = 1.225 \cdot f_{Ue}$		
ε_{Uu} = 2.44 ‰		

Model Validation: Comparison of Deformation Range

- ✓ Deformation of the R-UHPFRC layer at a local zone whose measured deformation was the largest
- ✓ Calculation until the number of cycles at which the first fracture of the four steel rebars occurred for fatigue fracture test



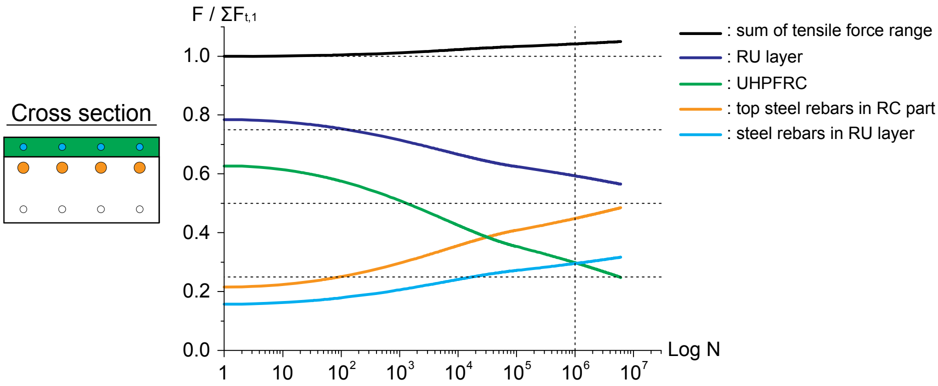
Run-out test (Test 2-i)



Fatigue fracture test (Test 4)

Fatigue Behaviour of RU-RC Member

- ✓ Contribution degree of each component to fatigue resistance of the RU-RC member changes due to fatigue damaging of UHPFRC.
- ✓ The R-UHPFRC layer reduces fatigue stress range in the top steel rebars in the RC part.



Evolution of tensile force range (Test 4)

Conclusions

- ✓ Fatigue endurance limit is determined for UHPFRC and R-UHPFRC under tensile fatigue and RU-RC beam under bending fatigue.
- ✓ UHPFRC sustains fatigue stress carrying capacity even after statically subjected to deformation beyond the elastic limit.
- ✓ Significant stress and deformation redistribution capacity is given to the UHPFRC bulk material by local variations in material properties.
- ✓ Stress distribution and transfer between UHPFRC and steel rebars in R-UHPFRC element enhance the fatigue stress carrying capacity of both material components.
- ✓ Fatigue stress amplitude in steel rebars in the R-UHPFRC layer is determinant for the fatigue strength of the RU-RC beam.
- ✓ R-UHPFRC effectively strengthens RC member for fatigue by reducing stress range in the steel rebars in the RC members.

Future works

- ✓ The behaviour of UHPFRC, R-UHPFRC and RU-RC members under variable amplitude and fully reversed fatigue action
- ✓ Influence of the tensile strain-hardening property on the tensile fatigue behaviour of UHPFRC
- ✓ Fatigue tests of RU-RC slabs using moving wheel-type force and the fatigue behaviour of RU-RC members in a practical situation
- ✓ Micromechanics based analysis and modelling of the tensile fatigue behaviour of UHPFRC
- ✓ Investigation of the tensile fatigue behaviour of UHPFRC by changing its moisture condition

Thank you for your attention.