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FATIGUE BEHAVIOR OF UHPFRC AND ITS IMPLEMENTATION FOR DESIGN

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Abstract

The fatigue behavior of UHPFRC in the range of high number of fatigue cycles is relevant for fatigue-prone elements of structures like bridges. Experimental and analytical research, conducted over the last 15 years by the authors and their team, on the fatigue behavior of UHPFRC, R-UHPFRC and composite elements consisting of R-UHPFRC and reinforced concrete are summarized in view of implementation for fatigue design. The existence of a fatigue endurance limit was evident at stress levels due to maximum fatigue loading corresponding to 40 to 60 % of the ultimate resistance. Subseqeunetly, fatigue design provisions are deduced and proposed for the fatigue strengthening of reinforced concrete bridge deck slabs by means of a layer of R-UHPFRC as well as for the fatigue dimensioning of R-UHPFRC structural elements. The application of these fatigue design provisions is illustrated by means of two realized UHPFRC bridge projects.

Résumé

Le comportement à la fatigue des composites cimentaires fibrés ultra-performants (communément appelé BFUP) dans le domaine d'un nombre élevé de cycles de fatigue est pertinent pour les éléments de structures sujets à la fatigue comme les ponts. Les recherches expérimentales et analytiques, menées au cours des 15 dernières années par les auteurs et leur équipe, sur le comportement à la fatigue du composite cimentaire fibré, également combiné avec des barres d'armatures en acier et des éléments mixte avec du béton armé sont résumées en vue de leur implémentation pour le dimensionnement à la fatigue. L'existence d'une limite d'endurance en fatigue était évidente aux niveaux de contrainte maximale due aux charges de fatigue correspondant à 40 à 60 % de la résistance ultime. Par la suite, des méthodes de calcul à la fatigue sont déduites et proposées pour le renforcement en fatigue des dalles de pont en béton armé au moyen d'une couche de composite cimentaire fibré ainsi que pour le dimensionnement en fatigue des éléments de structure. L'application de ces règles de dimensionnement en fatigue est illustrée à travers deux projets de ponts réalisés.

1. INTRODUCTION

UHPFRC has established itself in Switzerland as an effective material for the rehabilitation and strengthening of existing structures and the construction of new structures such as bridges and structural members under high stress.

Higher and more frequent axle loads on the transportation networks has increased the demand for higher resistance of fatigue-prone elements of existing reinforced concrete bridges such as deck slabs as well as short span girders and frames. The higher loads can cause fatigue damage in these structural elements which subsequently need to be strengthened.

Traditional strengthening methods often add considerable self-weight to the existing structure, which in turn increases the need for strengthening of the entire bridge structure and its foundations. Consequently, traditional strengthening is often found to be uneconomic, and invasive and costly demolition-replacement projects are realized.

The basic idea consisting in adding a high performance material in minimal thickness, is often technically and economically effective. The concept is to add a relatively thin layer (typically 40 to 50mm in thickness) of UHPFRC (Ultra-High Performance Fiber Reinforced Cementitious Composite) on top of the existing RC deck slab in order to increase both the structural and fatigue resistance of the deck slab, without increasing notably the self-weight of the slab (Figure 1).

a) b)

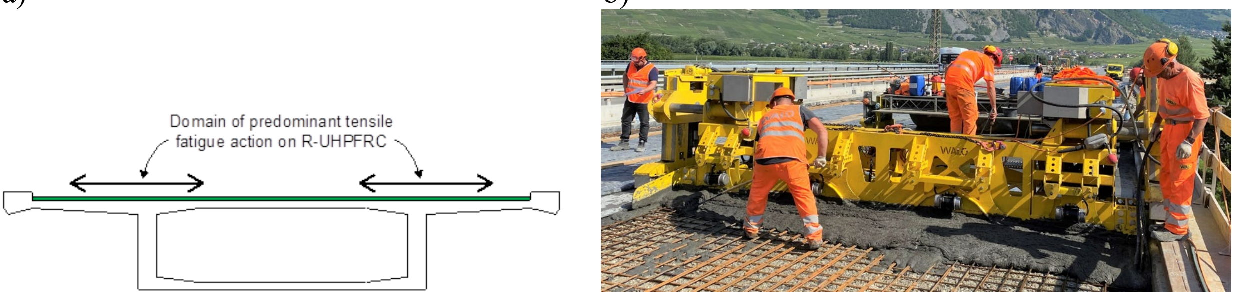

Figure 1: (a) cross section of a box girder and fatigue-prone domains, (b) casting of R-UHPFRC on top of the slab of the box girder of a road bridge.

In the domain of new construction of R-UHPFRC bridges, the fatigue design is important and sometimes critical (f.ex. for railway bridges) because R-UHPFRC structures are lightweight structures, i.e. the ratio of traffic load to self-weight is high.

Because of the long-lasting durability of UHPFRC, a very long service duration of UHPFRC structures and RC structures strengthened with a layer of UHPFRC is expected. Consequently, the fatigue behavior of UHPFRC in the domain of high number of fatigue cycles, which is the relevant domain for structures like bridges, must be well understood, which emphasizes the importance of fatigue research on UHPFRC.

This paper first summarizes the experimental and analytical research, conducted over the last 15 years by the MCS-team at EPFL Lausanne, on the fatigue behavior of UHPFRC, R-UHPFRC (UHPFRC combined with steel reinforcement bars) and composite elements consisting of R-UHPFRC and reinforced concrete (RC), in the following also indicated RU-RC elements.

In the second part of the paper, fatigue design provisions for the fatigue strengthening of reinforced concrete bridge deck slabs by means of a layer of R-UHPFRC as well as for the dimensioning of R-UHPFRC girders are deduced from the research results. Finally, the application of these fatigue design provisions is illustrated by means of two realized UHPFRC bridge projects: 1) fatigue strengthening of the deck slab of a RC road bridge; and, 2) the design and construction of a new short span railway bridge.

2. FATIGUE BEHAVIOUR OF UHPFRC AND R-UHPFRC

2.1 Characterization of fatigue resistance

The fatigue resistance of UHPFRC as determined by fatigue testing is, like for other materials and constructive details, presented using a S-N diagram similar to Figure 2. The fatigue stress is presented as S-value which is the ratio between the maximum fatigue stress (imposed during fatigue testing) and the specimen's ultimate resistance. N is the number of fatigue cycles N until specimen failure.

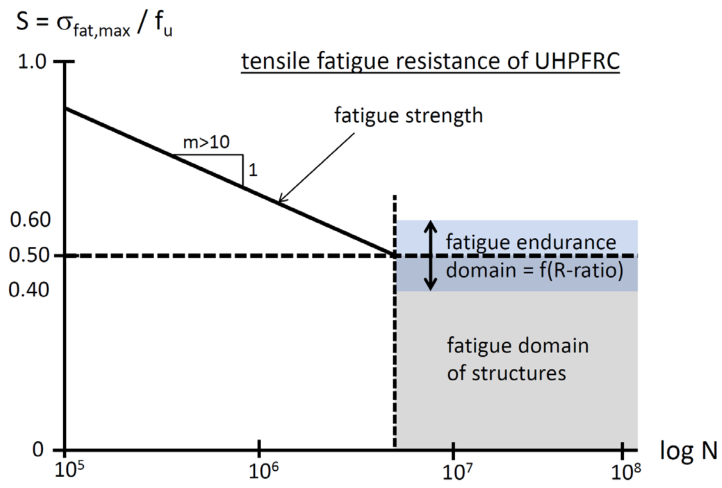

Figure 2: Schematic presentation of the fatigue resistance of UHPFRC in a S-N diagram.

Two domains are distinguished: 1) *fatigue strength* characterized by an inclined line, and 2) fatigue endurance characterized by a *fatigue endurance limit*. In reality, the transition from 1) to 2) is continuous.

In research practice, most tests are performed at relatively high stress resulting in small number of cycles, i.e. in the fatigue strength domain, while on real bridge structures the number of relevant fatigue cycles is relatively high, typically exceeding 10 million cycles over the service duration, i.e. in the fatigue endurance domain. Since theoretical models extrapolating from the (experimentally investigated) fatigue strength domain to the fatigue endurance domain are unreliable, it is necessary to perform fatigue tests at low stress level leading to high number of fatigue cycles of at least 10 million.

2.2 Fatigue of UHPFRC [1-5]

Fatigue tests were performed on UHPFRC uniaxial tensile and slab specimens. Fatigue stress cycles with mostly constant stress amplitudes and going up to a maximum number of 10 million cycles (and in exceptional cases 20 million cycles) were applied to the specimens, and fatigue behavior was characterized in terms of deformation, using four measurement techniques (LVDT, DIC, acoustic emission, magnetic probe to determine fiber volume and orientation).

The existence of a fatigue endurance limit was evident. The fatigue endurance limit was found to be at a stress level corresponding to 40 % to 60 % of the uniaxial tensile strength of the tested UHPFRC for specimens tested in the elastic and strain hardening behaviour domains. No fatigue damage (i.e. no increase in deformation) was identified at fatigue stresses below this fatigue endurance limit.

When subjected to fatigue stress higher than the fatigue limit, UHPFRC showed an important capacity for deformation (and thus stress) redistribution in the material volume. The number of stress cycles until fatigue failure of UHPFRC test specimens varied significantly, which suggests local influences of the fibre orientation on the fatigue behaviour:

- During fatigue testing, damage in terms of deformation increase, concentrates in the specimen zones with low fiber orientation.
- One fictitious crack always develops in the zone of lowest fiber orientation (as determined prior to testing using a magnetic probe). Additional fictitious cracks may develop, competing with the one fictitious crack leading to fatigue fracture.
- The evolution of deformation exhibits three stages of fatigue behavior for UHPFRC preloaded into the hardening domain, i.e. 1: rapid initial increase to stabilization; 2: moderate and constant increase; and 3: rapid increase to fracture.
- Similar to steel, the fatigue fracture surface of UHPFRC shows smooth surface areas that indicated fatigue crack growth, and a rough surface typical of the residual fracture.

This is likely the underlying fatigue damage mechanism including for the inherent deformation redistribution behavior of UHPFRC.

The fatigue behaviour of UHPFRC under uniaxial compressive loading [5] is characterised by a fatigue endurance limit at about 60% of the compressive strength of the test specimens. At fatigue stresses below this value, neither a fatigue fracture nor any significant fatigue damage occured even after 10 million stress cycles.

2.3 Fatigue of R-UHPFRC [1,6,7]

The tensile fatigue behavior of R-UHPFRC uniaxial tensile specimens and bending beams under both a fatigue stress ratio (R-ratio) of 0,1 and 0,3 was investigated and observed using four measurement techniques. The tensile fatigue endurance limit of R-UHPFRC depends on the R-ratio and is at S=0,50 for R=0,1 and at S=0,40 for R=0,3. Other parameters such as the stress concentration at the rib detail of the ribbed rebars may also have an influence. The fiber orientation of UHPFRC has only minor influence which explains the relatively low scatter in test results.

The fatigue behavior of R-UHPFRC was characterized by tensile stress transfer from the UHPFRC to the steel rebars with fatigue fracture always appearing in the rebars:

- The deformation increase mainly occurs in zones with low fiber orientation values in UHPFRC, where matrix discontinuities of large extension form and propagate. The strain along steel rebars also has higher value and increase rate in these zones of low fiber orientation.
- Cracks in UHPFRC always localize in the zones with lowest fiber orientation values, where in turn the steel rebars show significant increase of local strain and stress (because of the high bond between rebar and UHPFRC).

- This localization with high local stress leads to rapid fatigue damage accumulation in the steel rebars, finally resulting in fatigue fracture of the rebars and thus of the R-UHPFRC elements.
- The fatigue fracture surface of UHPFRC showed both smooth surfaces which pointed to fatigue crack growth, and rough surfaces indicating final fracture with little deformation.

The lowest fiber orientation in UHPFRC determines the locus of critical crack and fatigue fracture but the fatigue resistance of the R-UHPFRC element depends on the fatigue resistance of the steel reinforcement bar.

2.4 Fatigue of RU-RC composite elements [8]

The fatigue behavior of R-UHPFRC (RU) – reinforced concrete (RC) composite elements was investigated using slab-like bending beams. The fatigue endurance limit was again defined as the resistance up to 10 million fatigue cycles without failure. The results showed that this fatigue endurance limit is at about 50% of the ultimate bending resistance of the tested element. The "run-out" tests showed no notable deformation and deflection increase during the fatigue test, which led to the assumption that the specimen had no fatigue damage after the 10 million fatigue cycles.

Similar to the R-UHPFRC, the fatigue failure of the RU-RC composite beams was characterised by the fatigue fracture of the steel reinforcement bars in the R-UHPFRC layer. Thus, the stress level in the reinforcing bars determines the fatigue resistance of the RU-RC composite element.

These experimental results implicitly include Eigenstresses due to restrained (thermal and autogenous) shrinkage deformation of UHPFRC at early age when the UHPFRC layer is cast on the reinforced concrete support:

- Numerical analyses and analytical approximations show that maximum restrained shrinkage deformations of UHPFRC at early age are close to the elastic limit strain of UHPFRC.
- Consequently, when adding stresses due to externally imposed fatigue loading to the tensile Eigenstresses, UHPFRC is in the hardening domain where it utilizes its hardening capacity, while the tensile stress increase at this stage will be small.
- The tests on the RU-RC composite elements also showed that, during the fatigue test, these Eigenstresses are released because of the tensile stress transfer from UHPFRC to steel rebars.
- In this way, the strain hardening behaviour represents a significant stress release potential which is essential for the structural response of the R-UHPFRC layer.

Consequently, for the fatigue design of reinforced UHPFRC – reinforced concrete composite members, these Eigenstresses due to early age effects in the RU-RC composite system do not need to be considered explicitly.

3. FATIGUE DESIGN RULES AND THEIR APPLICAITON

3.1 Basic principles

The most fatigue sensitive structural elements in bridges made of UHPFRC and concrete are deck slabs and associtated parts (like cross beams) as well as short-span beams and frame structures. For these structural elements of short spans, it can be assumed that each wheel load causes a load cycle in the bulk material and the steel reinforcement. Assuming a 150 year service life of a busy highway bridge, the number of stress cycles often adds up to more than 100 million cycles of significant stress amplitudes.

For practical applications, this means that the fatigue safety verification for these elements has to be *verified with respect to the fatigue endurance limit* only. Any verification with respect to the fatigue strength would not be relevant (Figure 2).

Regarding the tensile fatigue resistance of the UHPFRC bulk material, the influence of R-ratio on the fatigue strength has shown to be notable and has to be considered. However, the fatigue stress range is the determinant parameter for the fatigue strength of steel reinforcement, and related fatigue design provisions as defined in standards for reinforced concrete do apply. However, these standards suggest a fatigue endurance limit for straight steel reinforcement bars which appears to be very conservative. Very high cycle fatigue test results indicate that the fatigue endurance limit of steel rebars higher than 200 MPa [9], already implemented in the French standard NF P 18-710.

3.2 Fatigue verification of structural elements

The fatigue verification of structural elements in RU-RC and R-UHPFRC, as suggested in the Swiss UHPFRC standard [10], is carried out for both the structural element and the building materials:

- The fatigue verification of the *structural elements* is carried out for bending moments as a function of the ratio of minimum to maximum fatigue loading:

  $$\Delta M_{fat} = (M_{max} - M_{min}) \leq M_{R,D} = 0{,}5 \cdot M_{Rd} \cdot (1 - 0.7\frac{M_{min}}{M_{max}})$$

  where M_{min} is the bending moment due to the characteristic value of the permanent actions, and M_{max} is the bending moment due to the characteristic value of the permanent actions and the fatigue action. $M_{R,D}$ is the fatigue endurance limit of the structural member, and M_{Rd} is the ultimate bending resistance of the structural member at ULS (Ultimate Limit State).

- Verification of the *building materials* (steel reinforcement and UHPFRC):
  - For R-UHPFRC under tensile loading, the fatigue strength of the steel reinforcement is critical. The stress difference in reinforcing steel due to fatigue action is verified according to the rules for reinforced concrete as given in the related standards.
  - The fatigue safety check of the UHPFRC without reinforcement under tensile fatigue stress is carried out with respect to the fatigue endurance limit:

    $$\sigma_{Ufat,max} \leq \sigma_{U,D} = 0{,}55 f_{Utuk}$$

    where the maximum tensile stress $\sigma_{Ufat,max}$ due to fatigue loading is determined as a function of the characteristic value of the permanent actions and the fatigue action in the UHPFRC for elastic behaviour.
    Thereby, stress in the UHPFRC undergoing strain hardening behaviour, is calculated assuming a modulus of elasticity of 0,20 E_U. The associated stress analysis in the cross section thus requires iteration.
  - Fatigue of UHPFRC under compressive stress only occurs if fatigue stresses are higher than 60% of the compressive strength. Such high compressive stress values are unlikely to occur in structures that are correctly designed with respect to ultimate resistance (at ULS). Therefore, a fatigue safety check is often not necessary as it is not critical.

- Fatigue of UHPFRC subjected to high shear stress is also not critical since the shear resistance of UHPFRC is relatively high compared to the tensile resistance which means that bending fatigue resistance of structural elements is determinant. For beam webs, it is suggested to verify the principal tensile stress acting in the web. Often, it is indicated (also for reasons of rebar detailing) to add single steel rebars in the web.

These fatigue verifications implicitly mean that fatigue of R-UHPFRC does not become critical if the structural element is not subjected to more than about 50 % of its ultimate resistance by the fatigue loading. This is usually the case, because the fracture safety verification at ULS implies a global safety margin that corresponds to approximately half of the ultimate resistance of the structural element.

3.3 Example 1: Cantilever slab of a RC bridge deck slab strengthened with UHPFRC

The fatigue safety verification of the cantilever slab of a RC bridge deck slab in reinforced concrete according to Figure 3a/b gives the following results:

The acting maximum and minimum bending moments at the determinant cross section A-A due to fatigue loading are $M_{df,max}$ = 150 kNm/m and $M_{df,min}$ = 20 kNm/m respectively. The resulting stress range in the top steel rebars is calculated: $\Delta\sigma_{sc}(Q_{fat})$ = 263 MPa ≥ $\Delta\sigma_{sd,D}$ = 116 MPa which is a very conservative value, however imposed by current standards in Europe for the design of reinforced concrete structures. Since this stress range is significantly higher than the fatigue endurance limit, the slab is strengthened by means of a layer of R-UHPFRC which has to be dimensioned.

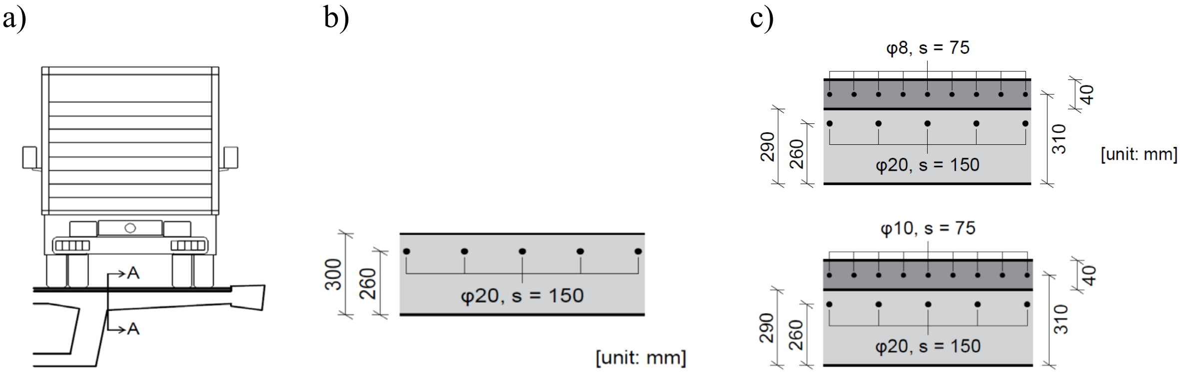

Figure 3: (a) Box girder bridge with cantilever slab, (b) original RC cantilever slab cross section at A-A section, and (c) RC slab strengthened with R-UHPFRC (two rebar contents).

R-UHPFRC layer with minimum thickness of 40 mm is cast on top of the RC deck slab after 10mm deep concrete removal due to hydrodemolition of the RC top surface leading to the RU-RC cross section shown in Figure 3c:

- The tensile fatigue endurance limit of UHPFRC to be cast is assumed to be: $\sigma_{U,D} = 0{,}55 f_{Utuk} = 0{,}55 \cdot 12MPa = 6{,}6MPa.$
- Steel reinforcement consisting of straight 8 mm thick rebars spaced by 75 mm with a fatigue endurance limit $\Delta\sigma_{sd,D}$ = 116 MPa is assumed.

The fatigue safety of the resulting RU-RC slab at A-A cross section is verified, applying the fatigue design provisions given in section 3.2 as follows:

- The ultimate resistance of the RU-RC cross section is calculated to be M_{Rd} = 368 kNm/m, and thus, the fatigue endurance limit is calculated as:
  $$M_{R,D} = 0.5 \cdot M_{Rd} = 0.5 \cdot 368 = 184 kNm/m'$$
  The fatigue safety verification *at the element level* is fulfilled since:
  $$M_{dfat,\max} = 150 kNm/m' \leq M_{R,D} = 184 kNm/m'$$
- The fatigue verification *at the material level* consists in controlling the stresses:
  - The calculated maximum stress range in the rebars of the R-UHPFRC layer at the first fatigue cycle (assuming fully linear elastic deformation in the cross section) is $\Delta\sigma_{s,ct}(Q_{fat})$ = 75 MPa which is much smaller than the fatigue endurance limit $\Delta\sigma_{sd,D}$ = 116 MPa for rebars according to standards.
  - However, this sectional analysis yields corresponding maximum UHPFRC strains due to maximum fatigue bending moment of $\varepsilon_{U,fat,max}$ = 0,42 ‰ which means that UHPFRC is subjected to strain in the hardening domain. As a consequence, the stiffness of UHPFRC will decrease due to fatigue and thus, a significantly lower modulus of elasticity of 0,20 E_U is assumed anticipating the situation beyond 10 million fatigue cycles where stresses in rebars will have increase correspondingly. Based on experimental findings, a reduced modulus of elasticity of 10 GPa (instead of the initial value of 50 GPa) is assumed for UHPFRC in the strain hardening domain.
  - Note that Eigenstresses due to early age shrinkage deformation of UHPFRC do not need to be considered explicitly (see section 2.4).
  - The resulting stress range in the rebars is now 145 MPa which is higher than the fatigue limit imposed by standards.

Thus, the rebar diameter needs to be increased from 8 to 10 mm (Figure 3c) leading to the following results:

- With M_{Rd} = 394 kNm/m', the fatigue endurance limit of the structural element is calculated as:
  $$M_{R,D} = 0.5 \cdot M_{Rd} = 0.5 \cdot 394 = 197 kNm/m'$$
  Obviously, the fatigue safety verification *at the member level* is again fulfilled since:
  $$M_{dfat,\max} = 150 kNm/m' \leq M_{R,D} = 197 kNm/m'$$
- The fatigue verification *at the material level* leads to calculated stress range in the rebars of the R-UHPFRC layer at the first fatigue cycle of $\Delta\sigma_{s,ct}(Q_{fat})$ = 66 MPa; the corresponding maximum UHPFRC strains of $\varepsilon_{U,fat,max}$ = 0,36 ‰ indicate strain-hardening behaviour.
- Reduced modulus of elasticity of UHPFRC of 10 GPa results in stress range in the rebars of 90 MPa and maximum tensile strain of UHPFRC is 0,42 ‰.
- The steel reinforcement now respects the fatigue limit criterion since:
  $$\Delta\sigma_{sd}(\Delta M_{df}) = 90 MPa < \Delta\sigma_{sd,D} = 116 MPa$$

The fatigue safety verification is fulfilled. A 40mm thick UHPFRC with a tensile strength of 12 MPa has been cast on the deck slab of this continuous box girder road bridge (Figure 1).

3.4 Example 2: Fatigue dimensioning of a short span, ribbed slab UHPFRC railway bridge
On November 11th 2017, a short span railway bridge built in reinforced UHPFRC was put in service on a main railway line lane in Switzerland (Figure 4). Important geometric constraints

related to both clearance of the underpassing road and the railway track imposed a limited construction height, which led to the R-UHPFRC ribbed slab of one single span of 6m, built as precast element.

Figure 4: Short span, ribbed slab UHPFRC railway bridge

In the design phase, the following material properties were assumed:

– tensile fatigue endurance limit of UHPFRC: $\sigma_{U,D} = 0{,}55 f_{Utuk} = 0{,}55 \cdot 12MPa = 6{,}6MPa$
– straight steel reinforcement bars with a diameter larger than 20mm: $\Delta\sigma_{sd,D}$ = 96MPa which is a very conservative value, however imposed by current standards in Europe for the design of reinforced concrete structures.

The fatigue safety verification of one representative rib gives the following results:

– The acting maximum bending moment at mid-span due to the fatigue load model imposed by the standards in Switzerland and Europe is: $M_{dfat,max} = 107kNm/m'$
– The ultimate resistance of the R-UHPFRC cross section is calculated to be M_{Rd} = 254 kNm/m', and thus, the fatigue endurance limit is calculated as:
  $M_{R,D} = 0.5 \cdot M_{Rd} = 0.5 \cdot 254 = 127kNm/m'$
  The fatigue safety verification *at the element level* is fulfilled since:
  $M_{dfat,max} = 107kNm/m' \leq M_{R,D} = 127kNm/m'$
– The fatigue verification *at the material level* consists in controlling strain and stress values due to maximum fatigue loading in the cross section of the rib (Figure 5):

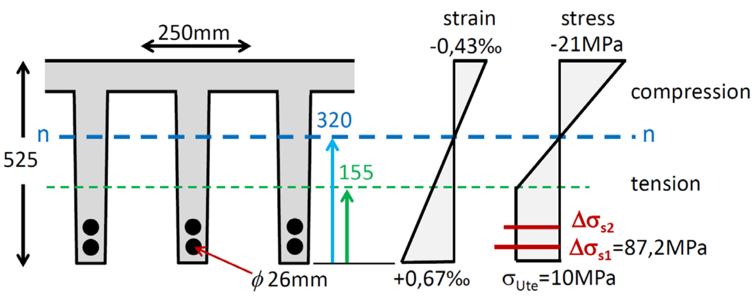

Figure 5: Strain and stress values due to maximum fatigue loading in the cross section of the rib

- Obviously, in order to activate the rebars, the UHPFRC surrounding the rebars is subjected to strain in the tensile strain hardening domain (i.e. strain higher than the strain at the elastic limit ($\varepsilon_{Ute}=\sigma_{Ute}/E_U$=10MPa/50GPa=0,2‰)).
- For the present cross section, UHPFRC is in the hardening domain over a rib height of 155mm, assuming a reduced E-modulus of 0,20 E_U = 10 GPa over this rib height when calculating the stiffness of the cross section.
- By sectional analysis, the maximum fatigue stress range in the determinant lower rebar was found to be: $\Delta\sigma_{s1}(Q_{fat})$ = 87,2MPa.
- The fatigue safety is verified since: $\Delta\sigma_{s1}(Q_{fat})$ = 87,2 MPa < $\Delta\sigma_{sd,D}$ = 96 MPa.
- The linear strain distribution over the static height of the rib yields maximum tensile strain values of $\varepsilon_{Ut,fat,max}$ = 0,67‰ (obviously in the strain hardening domain). The maximum compressive strain values of $\varepsilon_{Uc,fat,max}$ = -0,42‰ which corresponds to an elastic compressive stress of 21MPa which is only about 7% of the compressive strength of the UHPFRC. At such low compressive stress, there is no fatigue issue.

Consequently, the fatigue safety verification is fulfilled.

A monitoring system was installed with the construction of this R-UHPFRC railway structure. The measured values confirm the expected deformation values which were, as anticipated, about 2,5 times smaller than the calculated values. This very high discrepancy is due to the unrealistic, over-conservative railway load model in European standards in particular for structural bridge elements of short spans (which represent in practice about 90% of all spans).

4. CONCLUSIONS

The two examples of realized projects reveal the basic character of fatigue safety verification in structural engineering of UHPFRC strengthening of existing RC elements and the dimensioning of R-UHPFRC structures, i.e. deformation and stress due to fatigue loading must be below the fatigue endurance limit.

High-cycle fatigue behaviour and thus the exploration of the fatigue endurance limit of UHPFRC, R-UHPFRC and in particular also of steel reinforcement bars is of first importance and thus a significant research need.

The verifications are conducted at Fatigue Limit State (FLS) with respect to two levels:

- the structural level, implying the determination of the ultimate resistance of the structural element subjected to fatigue. Obviously, the ultimate resistance is a property that also needs to be determined to verify structural safety at ULS.
- the material level, consisting in fatigue stress verification assuming quasi-elastic cross sectional behaviour, i.e. considering a significantly reduced elastic modulus for the UHPFRC behaving in the tensile strain hardening domain, showing that the structural element has sufficient stiffness. This analysis of quasi-elastic behaviour also is required when verifying the Serviceability Limit State (SLS).

This fatigue verification approach is rational and coherent as it interrelates with the also required verification at ULS and SLS.

A stepwise procedure is recommended consisting in (1) basic analytical calculations as shown in sections 3.3 and 3.4 for the predesign and (2) detailed finite element analysis to confirm, validate and optimise the dimensioning for the construction project.

Finally, although known for many years through monitoring of structural behaviour, the fatigue load models in Swiss and European standards for bridge design are over-conservative and lead to significant overdesign and over-consumption of material ressources.

REFERENCES

[1] Zhan, J., Influence of Fiber Orientation on the Tensile Behavior of UHPFRC and Reinforced UHPFRC under Static and Fatigue Loadings, Doctoral thesis no 10789, EPFL Lausanne, Switzerland, 2024.

[2] Zhan, J., Nussbaumer, A., Brühwiler, E., Influence of fiber orientation on the high cycle tensile fatigue resistance of UHPFRC, *International Journal of Fatigue*, Volume 180, March 2024. https://doi.org/10.1016/j.ijfatigue.2023.108103

[3] Shen, X., Brühwiler, E., Biaxial flexural fatigue behavior of strain-hardening UHPFRC thin slab elements, *International Journal of Fatigue*, Volume 138, 2020. https://doi.org/10.1016/j.ijfatigue.2020.105727

[4] Makita, T., Brühwiler, E., Tensile fatigue behaviour of Ultra-High Performance Fibre Reinforced Concrete, Materials and Structures, Vol. 47, 2014, pp. 475–491.

[5] Loraux, C.T., Long-term monitoring of existing wind turbine towers and fatigue performance of UHPFRC under compressive stresses, Doctoral thesis No 8404, EPFL Lausanne, Switzerland, 2018.

[6] Sawicki, B., Brühwiler, E., Fatigue resistance of reinforced UHPFRC beams, *International Journal of Fatigue*, Volume 148, 2021. https://doi.org/10.1016/j.ijfatigue.2021.106216

[7] Makita T, Brühwiler E. Tensile fatigue behaviour of Ultra-High Performance Fibre Reinforced Concrete combined with steel rebars (R-UHPFRC), *International Journal of Fatigue*, Vol. 59, 2014.

[8] Makita, T., Brühwiler, E., Fatigue behaviour of composite R-UHPFRC – RC structural members, UHPFRC-2013: October 1-3, 2013, Marseille, France.

[9] Rocha, M., Michel, S., Brühwiler, E., Nussbaumer, A., Very high cycle fatigue tests with quenched and self-tempered reinforcement steel bars, Materials and Structures, Vol. 49, 2016.

[10] Brühwiler, E., Swiss UHPFRC Model Standard: Ultra-High Performance Fibre Reinforced Cementitious composite (UHPFRC) – Materials, dimensioning and execution (adapted and translated version of the Technical Leaflet SIA 2052), 20 March 2024.