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Experimental analysis of crack development of an UHPC wall element under shear loading

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Abstract. UHPC (Ultra High-Performance Concrete) is an innovative material that enables design of lightweight and structurally optimized, long-lasting structures. In this paper is presented experimental analysis of precast webs of "butterfly web" box-girder bridge on scaled-down specimens. Pretensioned beam specimens were analysed in 2 variants – with continuous web and with lightened web. Based on the experimental results are both variants compared and are presented numerical and material models suitable for UHPC modelling in software SCIA Engineer. In SCIA Engineer is implemented modified Mazarz material damage model which is applicable for material with residual strength typical for FRC and UHPFRC.

1. Introduction

This paper describes experimental analysis of initiation and propagation of cracks in webs of bridge with box cross-section. The web is composed of thin UHPC precast walls rigidly connected to bottom and top slab of the bridge cross-section. The shape of these UHPC wall element was optimized in order to achieve the most favourable stress distribution. The optimal shape was determined from optimisation based on principal tensile and compressive stress distribution with distinctive shape of tensile and compressive diagonal, which are caused by shear force transfer between top and bottom slab. The web of the box cross-section is lightened and viable for prefabrication so these elements may be used on bridges over 100 m span (concept shown on Figure 1). The design of lightened web elements is based on concepts of so called "butterfly web" bridges [1].

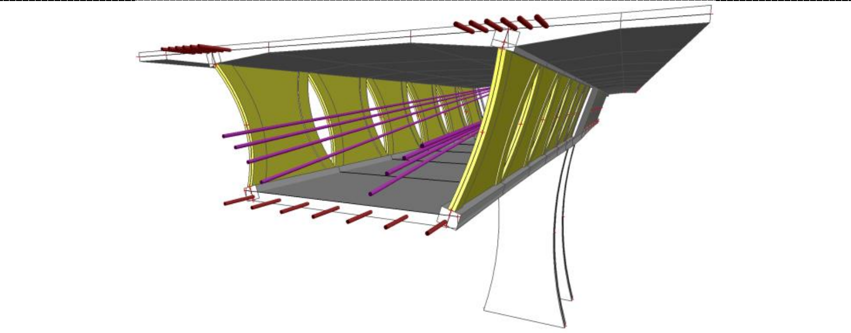


Figure 1. "Butterfly web bridge" concept visualisation.

Precast panels connected with top and bottom slab by composite action do not transfer shear force as continuous web would and their behaviour is well differentiated with tensile and compressive diagonals and is closer to Warren truss system [2]. Based on research in this paper, the viable description of the behaviour is the analogy of Vierendeel beam, where discrete web elements act as vertical members with rigid connection to top and bottom slab (flange) in the longitudinal direction. Vierendeel frame are more fitting to describe the behaviour with UHPC webs, due to different UHPC properties in plain tensile strength and bending tensile strength.

2. Analysis methods implemented in SCIA Engineer for UHPFRC analysis

Physical non-linear analysis represents a very powerful tool for analysing any kind of structure in civil engineering created not only from UHPFRC but also from other materials. Generally, there could be significant differences of results compared to a linear analysis, especially in case of hyper-static structures. In case of linear analysis, only the E-modulus of the material is considered for the preparation of the stiffness matrix. There is no stress distribution based on increasing the strain in the component. On the other side the non-linear analysis provides a stress distribution and increase of the bearing capacity after reaching the ultimate strain until the collapse mechanism. This mechanism is based on different values of stress and strain, dependent on a predefined nonlinear stress-strain relationship in the material diagram.

Generally, two approaches are usually used for considering fibres in nonlinear analysis. The first one uses the fibre and concrete matrix independently. The second and more common one considers the steel fibre directly in the behaviour of the concrete material. The second, more exact option was selected in this paper.

A typical shape of the stress-strain diagram is best described with a parabolic behaviour in compression in the same way as for standard concrete. The tensile behaviour displays a narrow peak expressed by the mean tensile strength. From the point of strain, this peak works very well as a crack localizator. After the crack formation, the toughness of steel reinforced fibre concrete allows to keep a certain level of tensile stress with increasing of the strain up to failure.

2.1. Modified Mazarz material damage model

The nonlinear calculation uses a very efficient damage material model called the Mazars model [3]. This material model is very well applicable for a material diagram with peaks and descending stress-strain diagrams typical for steel fibre concrete. The combination of elasticity and damage behaviour is combined in this material model. Moreover, the damage description was initially considered as isotropic and directly affecting the stiffness matrix. The modified Mazars model [4] is modified to very simples anisotropic damage model to better respect different behaviour of the fibre concrete in tension and compression. This leads to decomposition of stress tensor ($\boldsymbol{\sigma}$) to tension ($\boldsymbol{\sigma^t}$) and compression ($\boldsymbol{\sigma^c}$) part.

$$\boldsymbol{\sigma} = \boldsymbol{\sigma^t} + \boldsymbol{\sigma^c} \tag{1}$$

The resultant stress tensor is based on so called “effective damage parameter” in tension (d^t) and in compression (d^c) which determines changes of the stiffness depending on the elastic estimation of stress ($\boldsymbol{\sigma^{trial}}$) from the loading.

$$\boldsymbol{\sigma} = (1-d^t)\cdot\boldsymbol{\sigma^t} + (1-d^c)\cdot\boldsymbol{\sigma^c} = [(1-d^t)\cdot\boldsymbol{P^t} + (1-d^c)\cdot\boldsymbol{P^c}]\colon\boldsymbol{\sigma^{trial}} \tag{2}$$

This elastic estimation of stress can be expressed using constitutive tensor ($\boldsymbol{C}$) as follows:

$$\boldsymbol{\sigma^{trial}} = \boldsymbol{C}\colon\boldsymbol{\varepsilon} \tag{3}$$

The damage parameters are calculated based on equivalent Mazars strains (ε_t; ε_c) which help for determining of actual values of stress from stress-strain diagram of material.

$$d^t = 1 - \frac{\sigma(\varepsilon_t)}{\sigma^{trial}(\varepsilon_t)};\ d^c = 1 - \frac{\sigma(\varepsilon_c)}{\sigma^{trial}(\varepsilon_c)} \tag{4}$$

As the stress-strain diagrams of UHPC has typically descending branch of stress-strain in tension, it is not possible to use tangential constitutive tensor ($\boldsymbol{C}$) but it is recommended to use secant one ($\boldsymbol{C^s}$) to fulfil its positive definition which is finally calculated as below.

$$\boldsymbol{C^s} = [(1 - d^t) \cdot \boldsymbol{P^t} + (1 - d^c) \cdot \boldsymbol{P^c}] : \boldsymbol{C} \quad (5)$$

Additionally, the effect of cracks must be considered during application. Here an analogy with the thermodynamic variable is applied for the two main damage states which are cracking of concrete in tension and crushing in compression. In case of plotting the surface failure of the steel fibre reinforced concrete the very well-known curve described by Kupfer [5] for biaxial loading is obtained which is also typical for regular reinforced concrete. The standard Newton-Raphson method is used for solving of this physical nonlinear problem.

3. Experimental analysis of UHPC web elements

3.1. Description of tested UHPC specimens

For experimental analysis of slender structural members of UHPC under shear loading were designed 2 types of beam specimens – one with full, continuous web and one with longitudinally lightened web. These beams have I cross-section with sufficiently designed flanges with longitudinal pretensioned tendons in order to mitigate effects of bending. The topology of these beams is apparent on figure 2 below. The aim of this experimental setup is to verify behaviour of lightened specimens and viability of application of similar larger scale precast and pretensioned web elements in greater magnitude and on bridges of span over 100 m.

The dimensions of the beams were chosen with respect to prefabrication, manipulation and transportation possibilities. Beams were 2.3 m long and 0.39 m high. Bottom flange was prestressed with 2 straight tendons with initial prestressing stress 900 MPa.

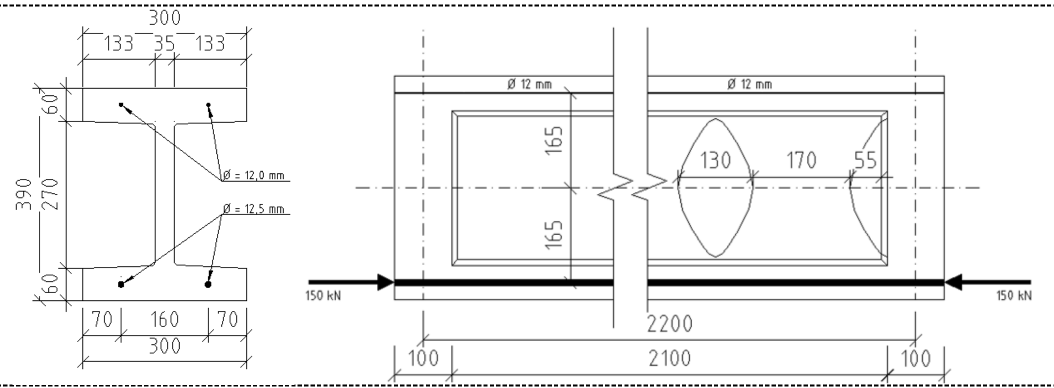


Figure 2. Shape of UHPC specimens.

In the structural analysis software SCIA Engineer was the specimen with loading mechanism modelled as half (from support to midspan) with corresponding boundary conditions for reduction of analysis time. Furthermore, FEM mesh was refined in areas where cracks were expected to develop.

3.2. UHPC beam specimens and UHPC mixture characteristics

In total, 6 beam specimens were casted and loaded in 4-point bending test, 3 specimens with continuous web labelled P1, P2, P3 and 3 beams with lightened web labelled V1, V2, V3. First beam from each set (P1, V1) was loaded till failure. On other 2 specimens in each set was first applied cyclical loading and after that the specimens were loaded till failure. Compressive strength of the UHPC mixture was measured on cubes 100x100x100 mm and average compressive strength was 157.1 MPa. Tensile strength in bending was measured on prismatic specimens of 40x40x160 mm and was in average

28.0 MPa. Modulus of elasticity was measured on cylindrical specimens 300 mm high with diameter 150 mm and the average modulus of elasticity was 51.6 GPa.

4. Results and experiment evaluation

In this section are presented results of the experiment for bothy types of beam specimens. Results are presented in form of force – deflection diagrams and are approximated by numerical model in SCIA Engineer 18 where was used nonlinear material model with damage. Basic characteristics of the material model were set according to experimental results on cubes (strength in compression), prisms (tensile strength in bending) and cylinders (modulus of elasticity). These specimens had the same age in the time of testing as the bigger beam specimens. For both beam specimens was in the numerical model counted with the effects of longitudinal prestressing with estimated short-term and long-term losses of 15%. The age of the specimens at the time of testing was in average 90 days.

4.1. Results on beam with full web

Beams with continuous web were tested in 4-point bending in 2 separate scenarios. In the first scenario was the first beam (P1) loaded by continuous increase of displacement till failure. In the second scenario were 2nd and 3rd beams (P2 and P3) loaded with cyclic loading pattern. Five loading cycles of approximately 0 – 100 kN were applied and the beams were loaded till failure. Force – displacement diagram of this experiment is presented on figure 3 below.

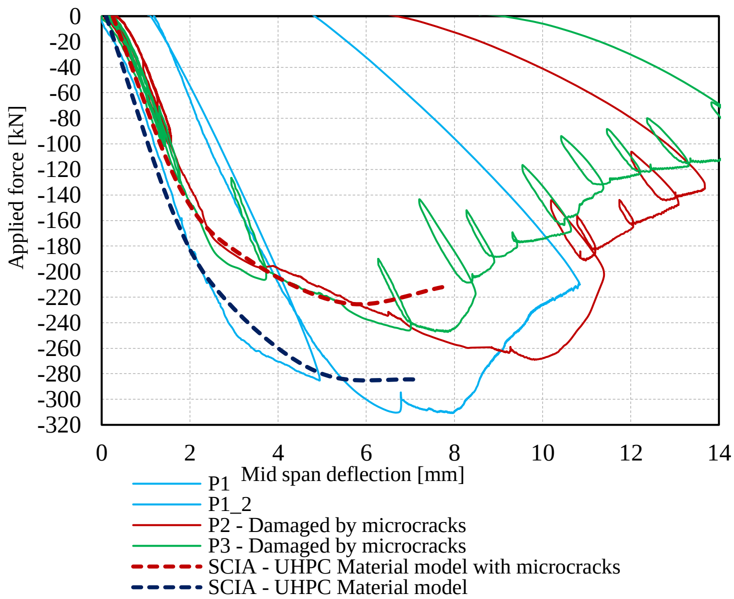


Figure 3. Force – displacement diagram: beams with continuous webs.

From the force – displacement diagram it is apparent softening of the beams with applied cyclical loading to magnitude of applied load of approximately 150 kN when compared to the beam which was loaded without the cyclic scenario. Furthermore, specimens with applied cyclical loading appeared fist visible cracks at much lower magnitude of acting force. Cause of this behaviour is initiation of microcracks when cyclical loading was applied. From the figure 3 is apparent, that this effect has a significant effect on both mean and residual tensile strength of the UHPC.

For numerical model of beams with continuous webs were used material models of UHPC with characteristics shown below in figure 4. Magnitudes of mean and residual stresses were obtained iteratively in order to achieve behaviour consistent with measured force – displacement diagram in figure 3. Magnitudes of residual strain in the material model are dependant on FEM mesh size. In this case the size of mesh in areas of crack initiation was set to 10 mm and crack width was limited to 5 mm.

This corresponds to upper limit of residual strain for the mesh elements to be 50% (for better readability of values in figure 4 is displayed only section below 3% strain).

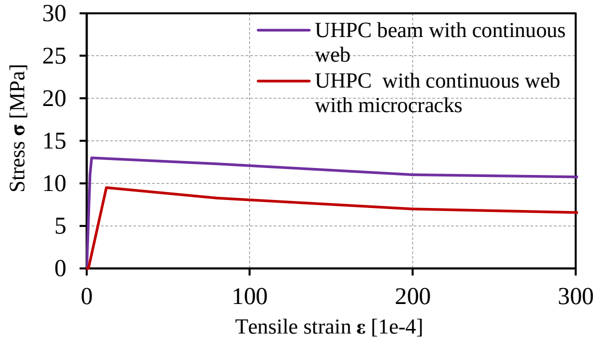


Figure 4. Stress – strain diagrams of UHPC – tension.

Type of failure and shape of the developed cracks is apparent on figure 5 below. Photography taken during the experiment is compared to shape of developed crack in program SCIA Engineer 18, where on figure 5 (b) and (c) are shown possible modes of shear failure obtained by numerical analysis. These modes are consistent to shape on tested specimen.

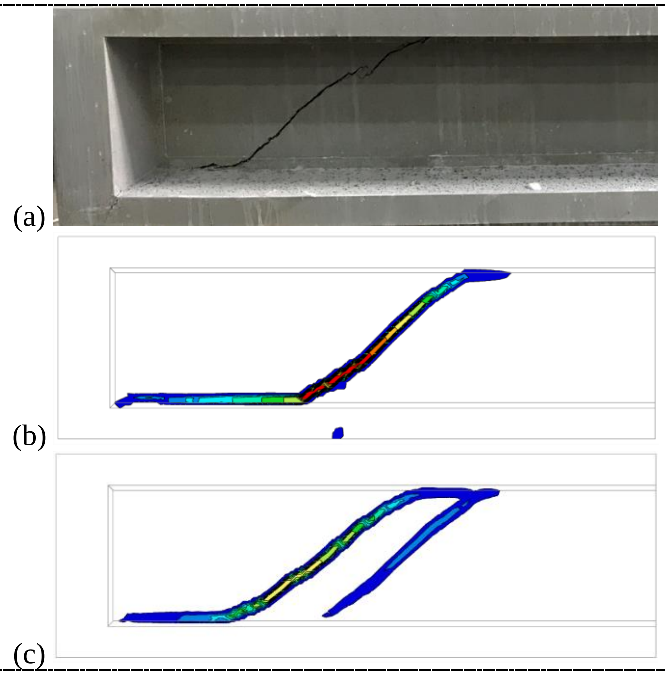


Figure 5. Analysis of crack shape: photo (a); development of one (b), or 2 (c) macrocracks in the numerical model.

4.2. Results on beam with lightened web

Beams with lightened web were tested in 4-point bending in 2 separate scenarios the same way as beams with continuous web. In the second scenario was applied cyclic loading pattern on specimens V2 and V3. Five loading cycles of approximately 0 – 40 kN were applied and the beams were loaded till failure. Force – displacement diagram of this experiment is presented on figure 6 below.

From the force – displacement diagram is apparent softening of the beams with applied cyclical loading to magnitude of applied load of approximately 50 kN when compared to the beam which was loaded without the cyclic scenario. Furthermore, specimens with applied cyclical loading appeared fist visible cracks at significantly lower magnitude of acting force.

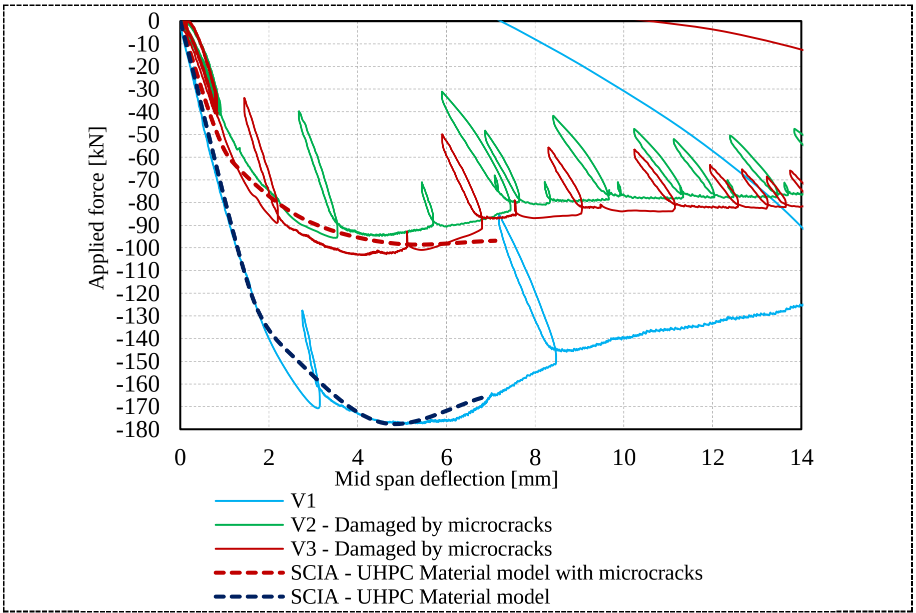


Figure 6. Force – displacement diagram: beams with lightened webs.

For the specimen which was not cyclically loaded is apparent much better performance in comparison with the beam that was subjected to cyclical loading. The increase of the load bearing capacity between the scenarios is much greater than in the case of specimens with continuous web. This effect is very important and is influenced by the fact, that tensile strength of UHPC in tension is few times greater when subjected to bending rather than plain tension. Tension strength in bending was experimentally verified on prismatic specimens 40x40x160 mm, which represents cross-section with comparable dimensions as thickness of the web of beam specimens to mitigate the size effect. For numerical model of beams with lightened webs were used material models of UHPC with characteristics shown below in figure 7.

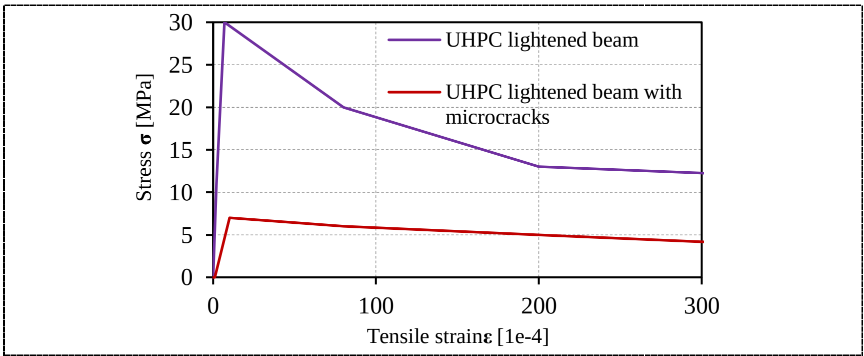


Figure 7. Stress – strain diagrams of UHPC – tension.

Type of failure and shape of the developed cracks is apparent on figure 8 below and again shows good correlation between observed crack distribution and numerical model.

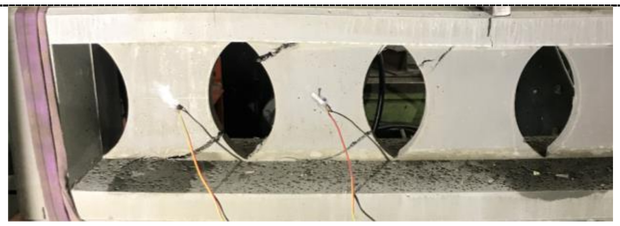
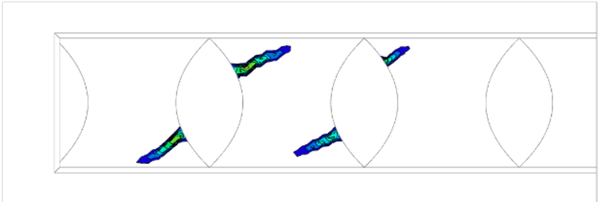
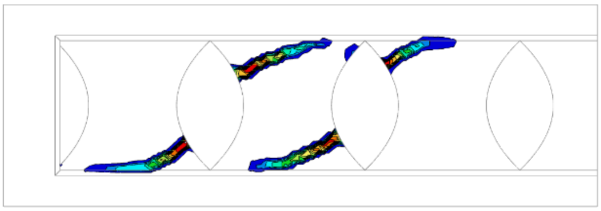
(a)

(b)

(c)


Figure 8. Analysis of crack shape: photo (a); initialization (b) and development (c) of macrocracks in the numerical model.

4.3. Comparison of solid and lightened web beams

For an objective comparison of beams with continuous and lightened webs which were loaded till failure (loading scenario 1) it is prudent to determine values of maximal applied loading on such lightened specimens, that would require identical amount of UHPC as the specimen with continuous web. Such modified specimen would have lightened web with thickness 48.4 mm increased by 38%. On figure 9 below is shown the comparison of magnitude of applied forces on level of macrocrack initiation and with maximal applied load.

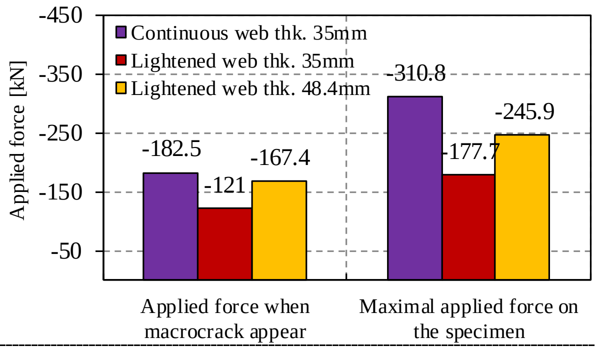


Figure 9. Comparison of specimen behaviour.

The recorded effect of reduction of both mean and residual strength of UHPC beam specimens loaded with cyclical loading when compared to beam loaded straight till failure without cyclical loading is more severe in the case of the lightened specimen. This effect is caused by higher magnitude of tensile stresses in the specimens when the cyclical loading is applied. In localised areas of the lightened web specimen rise the magnitudes of tensile stresses to 16.5 MPa when compared to tensile stresses in specimen with continuous beam 9.0 MPa. Localised tensile areas in lightened beam with greater magnitude lead to higher initiation of microcracks and more severe damage of the specimens, before any visible macrocracks are visible. On figure 10 below are shown distributions of principal tensile stresses from combination of self-weight, prestressing and amplitude of applied cyclical load.

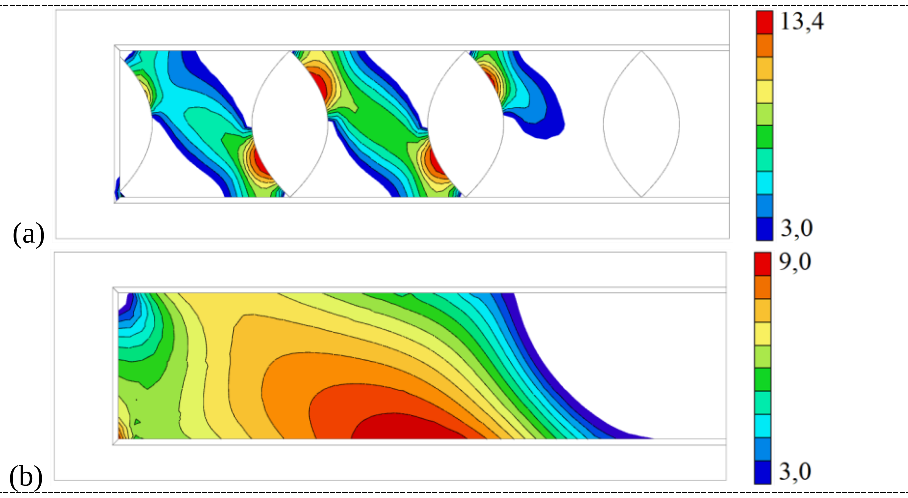


Figure 10. Maximal tensile stresses in web of (a) lightened beam and (b) beam with continuous web during cycled loading.

Furthermore, it can be concluded, that due to initiation of microcracks in the UHPC structure and consecutive development of macrocrack, the UHPC loses its high tensile strength caused by the bending characteristic of lightened web element failure. Tensile strength reduction of UHPC damaged by fatigue cyclical loading have significant effect on the performance of the beam specimens. For web segments used on structures with realistic proportions, it is however possible to add pretensioned tendons in the web segments in the direction of the tensile diagonal in order to eliminate tensile stresses in serviceability combinations.

5. Discussion

The comparison of beam with lightened and continuous web is made on specimens with the same amount of material required. Beam with continuous web with web thickness 35mm (as real specimen) and lightened beam with recalculated web thickness 48,4 mm. First macrocracks appear in the case of beam with lightened web on load level 15% lower and maximal loading 22% lower than the beam with continuous web. Despite the magnitudes are lower, there are following important aspects:

- Lightened beam shape may be yet further optimized (increase thickness on edges of the wall segments, where macrocracks first appear).
- Possibility of prefabrication of separate web segments to ensure superior quality.
- Due to clear and consistent shear force transfer by the web segments, these segments may be provided with prestressing tendons in the direction of the tensile diagonal to mitigate tensile stresses.
- Contradictory to analysis performed prior the experiments and based on available studies of butterfly-web bridges [1],[2] where web segment behaviour was described as an approximation with tensile and compressive diagonal, more suitable seems analogy with Vierendeel beam. Wall segments are thus approximated as frame members and their action is bending in longitudinal direction. Given the excellent UHPC properties in tensile strength in bending, this behaviour is most convenient.

6. Conclusions

In this paper were presented results of an experimental analysis of UHPC beams with lightened webs and numerical verification in program SCIA Engineer. These specimens demonstrate in smaller scale behaviour of precast web segments of a bridge with box cross-section, which are connected to top and bottom monolithic slabs of the cross-section by composite action. Discrete behaviour of the web segments was compared to continuous behaviour of beam with solid web with constant thickness. Conclusion of the analysis is viability of application of UHPC precast webs especially due to the excellent properties of the UHPC in tension under bending action. When these web segments are provided with efficient prestressing to eliminate tensile stresses on their edges, the precast web segments prove superior performance to beams with continuous web.

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