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STRAIN HARDENING CEMENTITIOUS COMPOSITE (SHCC) LAYER FOR THE CRACK WIDTH CONTROL IN REINFORCED CONCRETE BEAM

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Abstract

Strain Hardening Cementitious Composite (SHCC) is an innovative material which, due to the special material composition and the addition of fibres, exhibits a controlled microcracking behaviour under tensile stresses. As such it might be a promising material for improvement of durability of concrete structures.

An experimental study was performed aiming to investigate the cracking behaviour of reinforced concrete beams enhanced with SHCC layers in the tension zone (hybrid SHCC-concrete beams). Specimens with SHCC layers of different thickness were tested. The hybrid SHCC/concrete beams were compared to regular reinforced concrete (control) beams with the same dimensions and rebar position. Specimens were tested in four-point bending while Digital Image Correlation (DIC) and an image analysis software package (ImageJ) were used to evaluate crack pattern development and crack widths.

In the experiments, hybrid beams showed better cracking behaviour compared to control beams, whereas also a higher bending moment capacity was found. The study indicates that by using a combination of conventional concrete and advanced concrete (SHCC in this case), possibly optimal design of reinforced concrete structures could be achieved by eliminating the crack width as governing design parameter and thus saving on reinforcement needed for crack width control.

1. INTRODUCTION

In structural design, two governing criteria should be satisfied: Ultimate Limit State (ULS) and Serviceability Limit State (SLS). Whereas ULS focuses on the strength of the structural components to ensure the structural safety, for reinforced concrete structures in SLS an important parameter is the crack width to ensure its functionality and durability. If the calculated crack width of a reinforced structure exceeds the maximum allowable crack width, additional reinforcement needs to be added to control the cracks. This reinforcement is not needed and is redundant for capacity criterions (ULS). Therefore, other possibilities to control crack width in reinforced concrete structures are desirable. May recently developed innovative cement-based materials offer a solution?

Strain Hardening Cementitious Composite (SHCC) is a relatively new material, known for its ductility and crack control ability. This material exhibits multiple microcracking behaviour under tensile stresses. With cracks smaller than 100 microns, it has a ductility around 500 times higher than that of conventional concrete. This makes it a promising material for improvement of durability of concrete structures. The main idea of this research (performed within the MSc study of Zhekang Huang [1]) was to apply SHCC in the beam tension zone, which may help to control the crack widths, without the need to add the extra steel. In this way, SHCC was used only where necessary and where most effective: in the cover of a highly loaded tension zone, whereas regular concrete was used on remaining, low demanding locations i.e. resisting compressive stresses.

The idea of applying an SHCC layer in the composite reinforced concrete structures is not new. For example, studies have been performed aiming to investigate if the ultra-high performance SHCC strengthened beam has higher capacity and better crack control behaviour compared to conventional reinforced concrete beam [2]. Similarly, the performances of composite SHCC - reinforced concrete slabs [3] and reinforced concrete beams strengthened by SHCC additionally reinforced with Basalt Fibre Reinforced Polymer grid [4] were studied. Still, in most of these investigations, the primary focus is on the load capacity, whereas cracks were inspected either at failure or at the moment when they by far exceeded the maximum allowable crack widths. At that point cracks were already too large to be studied and compared in samples with and without SHCC. The main aim of the current research was to monitor continuously crack development and crack opening during the loading, and to focus on cracks being in the range commonly defined as limiting. As a result, it can be estimated whether the addition of SHCC layer shifts the moment of reaching the critical crack width to higher load levels and therefore allows for more optimal design.

2. MATERIALS AND METHODS

2.1 Experimental design

Four types of reinforced concrete cross-sections were designed (Figure 1). The control groups, Specimens I and III, were conventional concrete beams with concrete covers of 31 mm and 11 mm, respectively. Specimens named II and IV are SHCC-concrete composite specimens where SHCC was applied in the tension zone. Specimens II and IV each consisted of 2 beams, one with a pure SHCC layer (labelled 1) and the other one with a SHCC layer containing self-healing agents (labelled 2). In this paper, the self-healing property of SHCC was not dealt with. Furthermore, since it appeared that self-healing agent did not affect the mechanical properties of SHCC, for the structural behaviour of the SHCC hybrid system, specimens II-1 and II-2, and IV-1 and IV-2 can be considered as duplicate samples.

Specimens were tested in four-point bending according to the setup given in Figure 2. The beams were designed such that the flexural failure occurs. Therefore, to prevent shear failure, stirrups were placed outside the constant moment region. In order to have large crack widths, the percentage of longitudinal reinforcement was close to the minimum.

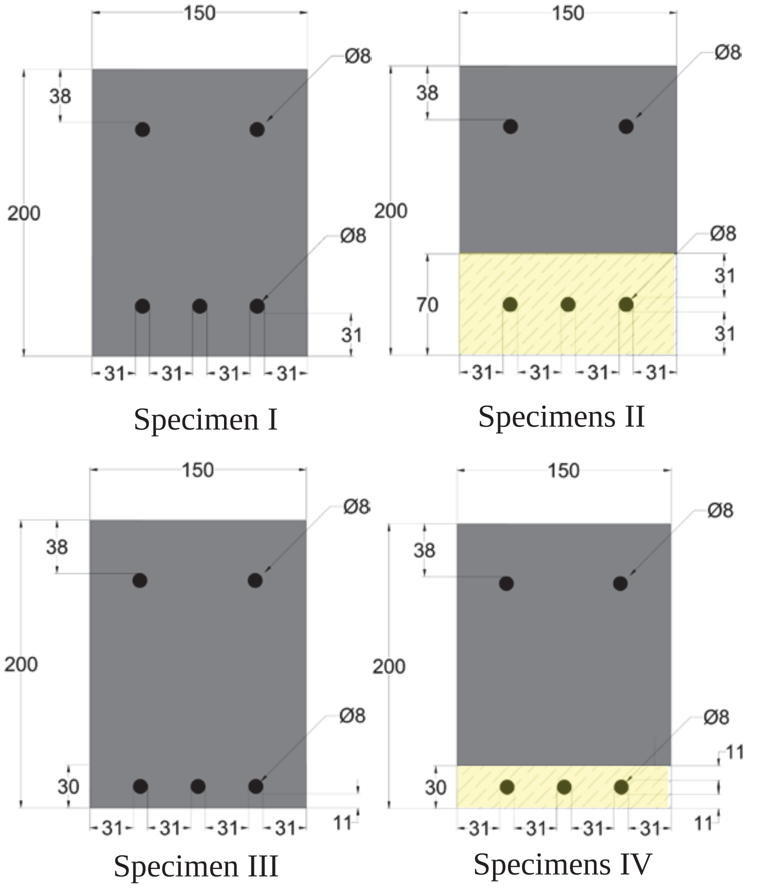


Figure 1: Cross sections of beams; concrete = grey, SHCC = yellow (units in [mm])

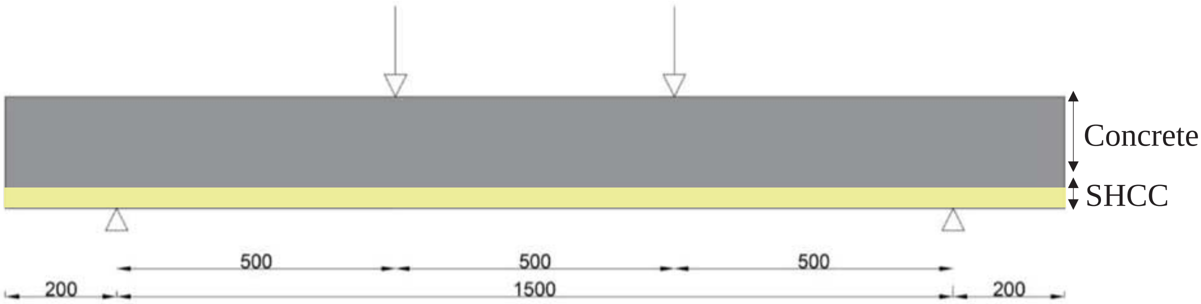


Figure 1 Experimental setup of the four-point bending test (units in [mm])

2.2 Specimen preparation and casting

First, the SHCC layers with the thicknesses of 31 mm and 70 mm and reinforcement embedded in it, were cast. The SHCC mix composition is given in table 1. As it can be seen from Figure 3a, unlike regular concrete, it consists only of fine particles. In order to have controlled cover thickness, reinforcement was placed on SHCC spacers with the thicknesses of 11 mm and 31 mm (Figure 3b). Since the thickness of the SHCC layer was small and the mixture is almost self-compacting, it was not necessary to use the vibration needle or any other way of compacting (Figure 3c).

After 14 days of sealed curing, the ordinary concrete was cast on top of the precast SHCC layers. The concrete mix composition is given in Table 1. Prior to concrete casting, the interface, i.e. the top surface of SHCC, was cleaned with air jet, subsequently wiped by a steel brush, and finally cleaned with ethanol. After 33 days of sealed curing, (composite) beams were taken out of the mould (Figure 4d) and prepared for the mechanical tests. The average compressive strength of concrete at the age of 33 days was 46 MPa. The average compressive strength of SHCC with and without the self-healing agent was 64 MPa and 63 MPa, respectively.

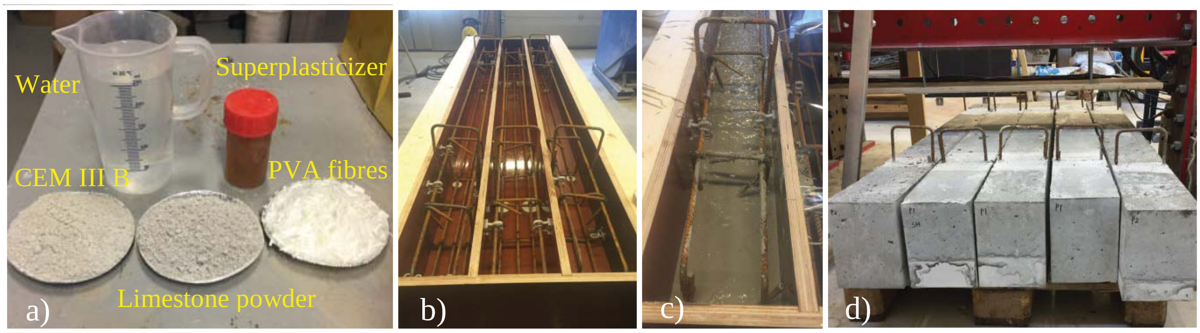


Figure 2 a) SHCC mix constituents b) before and c) after casting of SHCC d) whole beams

Table 1: SHCC and concrete mixture composition, SH stands for the self-healing agent

Material (amounts in [kg/m^3])	SHCC	SHCC+SH	Concrete
CEM III B	790	790	-
CEM I B	-	-	260
Limestone powder	790	790	-
Sand (0.125-4 mm)	-	-	847
Gravel (4-16 mm)	-	-	1123
PVA fibers	26	26	-
Self-healing powder	-	10	-
Water	410	410	156
Superplasticizer	2.13	2.13	0.26

2.3 Testing

During the tests, Digital Image Correlation (DIC) was used to evaluate the crack pattern development and crack widths. DIC is a non-contact optical method that employs tracking and image registration techniques for accurate 2D measurements of changes in images. This allows calculating deformation, displacement and strain on the observed surface. The technique is becoming to be widely used in concrete research [5, 6].

During loading, a series of photos was taken at different time intervals. By comparing these photos with each other, the displacement, strain field and crack development in the specimen were tracked. In order to make this more feasible, prior to testing the surface of the specimen was painted white, and a black speckle was applied. Compared to linear variable differential transformers (LVDTs), DIC can analyse the entire area of an element and achieve the total displacement field and not only displacement between certain points. Still, DIC is a relatively new method and its accuracy is not known. In order to verify it and be able to reliably track all the crack openings in the beam, results from DIC were compared to the measurements obtained by three LVDTs placed in the middle of the beam, over the beam height (Figure 4a). Furthermore, an image analysis software package (ImageJ) was used to evaluate crack pattern development and crack widths at different loading steps in the beam and to further verify the DIC measurements (Figure 4a).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Verifying DIC measurements

First, the DIC measurements were verified with the LVDT measurements over the length of 200 mm. In Figure 4b a comparison between the two methods is presented. It can be concluded that the DIC is accurate for measuring displacement over a certain length.

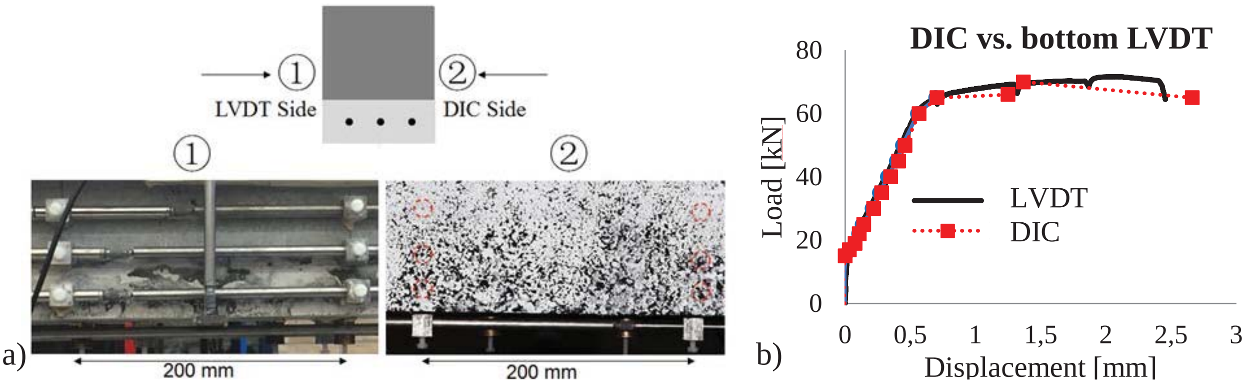


Figure 3 a) Verification of DIC over the length of 200 mm measured by LVDT b) Results

The next step was to evaluate its accuracy over a shorter length, for example, to capture the crack opening. So, first the whole sample was analysed and the location of maximum crack was determined (Figure 5). Successively, the mesh for DIC was refined and the analysis was repeated only for a specific crack. The crack opening at each loading step was obtained by following equation:

$$\text{Crack Width (Load)} = U_{horizontal}\,(\text{Load}, X1, Y1) - U_{horizontal}\,(\text{Load}, X2, Y2) \qquad (1)$$

The result of analysis with DIC was compared to measurements from images taken by a camera placed underneath the sample during the different loading steps (Figure 5). These images were analysed by ImageJ software. A comparison between the two methods is shown in Figure 6. It can be seen that the difference between the DIC and ImageJ is always smaller than 0.1 mm and therefore, DIC measurements are considered to be reliable. Note that the crack width was never measured exactly at the same location (in DIC it was captured from the side while with ImageJ from the bottom of the sample).

Once verified, DIC was used to assess the development of cracks during the loading in hybrid SHCC-concrete specimens a

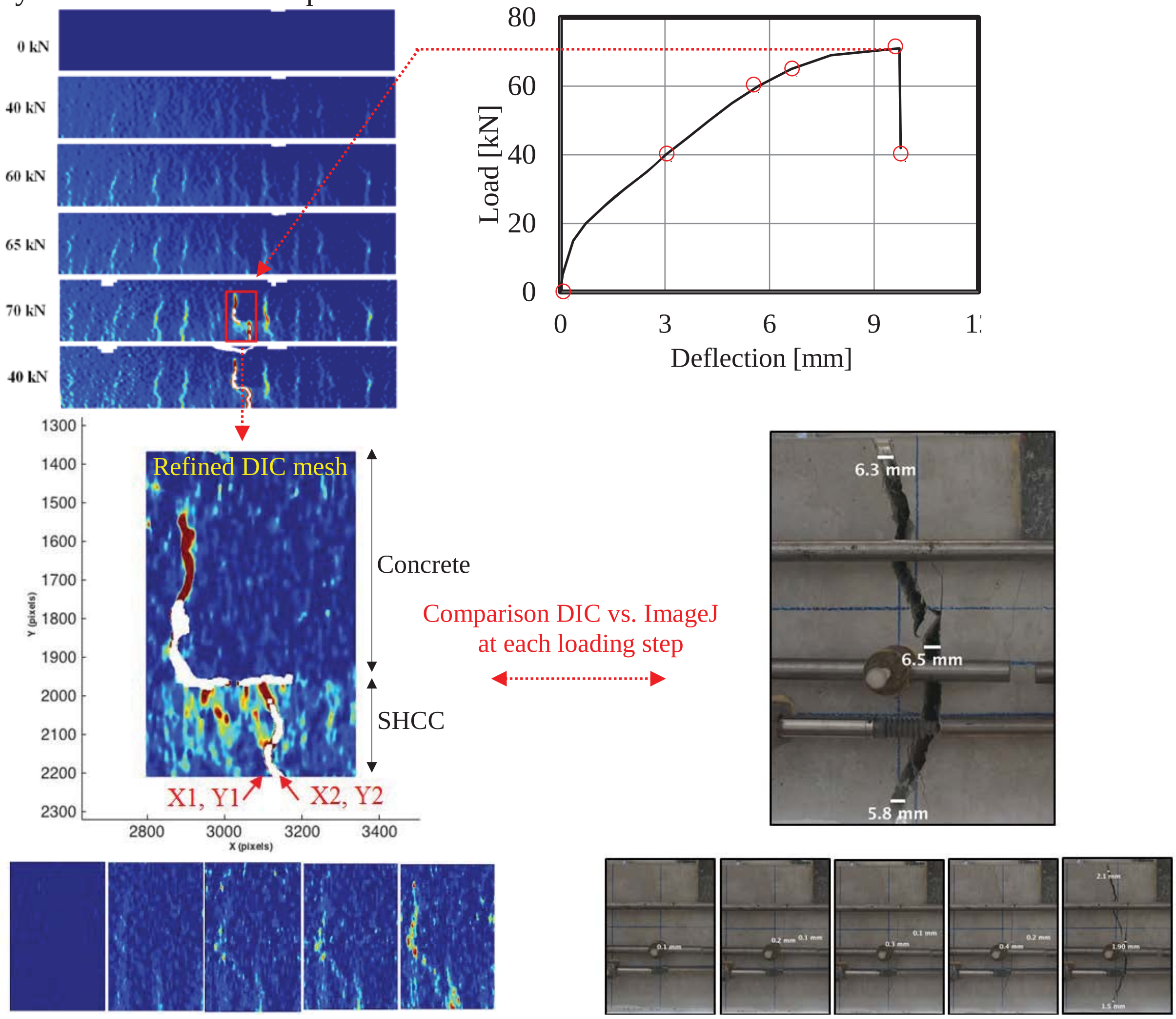


Figure 5: Verification of DIC measurement with ImageJ measurements (the crack opening at each loading step was obtained by equation (1) from DIC)

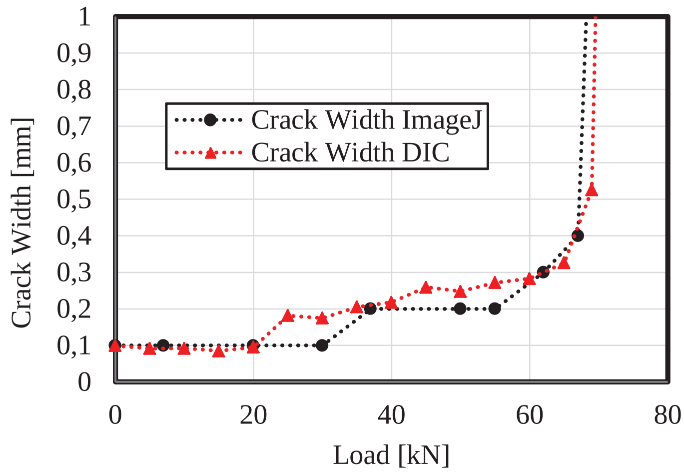


Figure 6: Verification of DIC for capturing crack opening, comparison with ImageJ analysis

3.2 Experimental results

The final crack pattern and crack width of the hybrid-SHCC beam (Specimen II-2) is given in Figure 7. Most of the cracks from the reinforced concrete part dispersed into many finely spaced microcracks in the SHCC layer with significantly smaller crack widths. Still, at one location, cracks in SHCC reached 3 mm width, which is far above the limited crack width. Therefore, in each specimen, the maximum crack was defined and it was observed how this crack grows in time, with increased loading (Figure 6). Subsequently the specimens with and without the SHCC layer were compared.

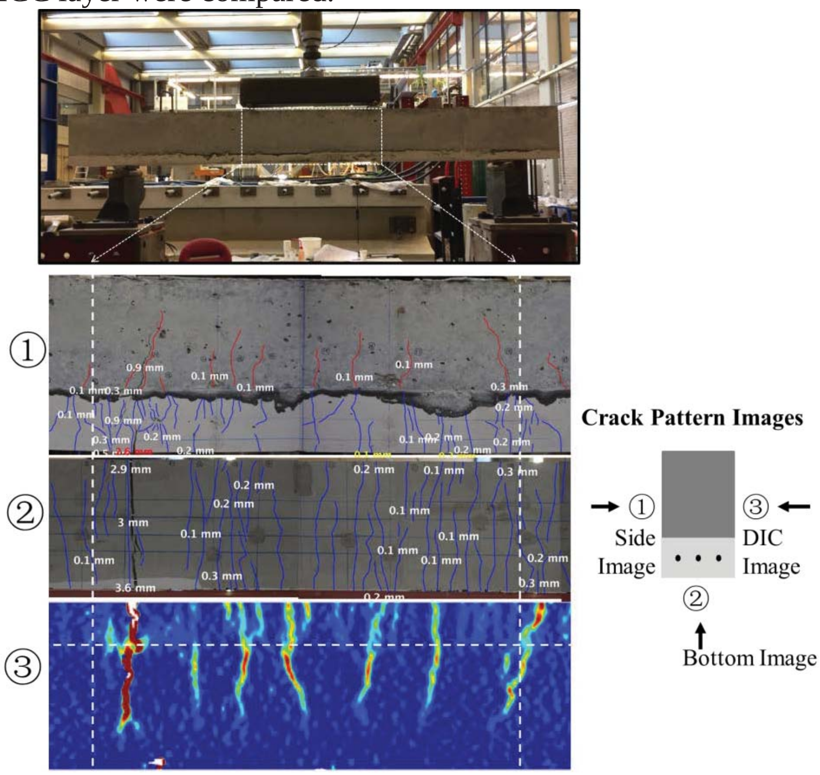
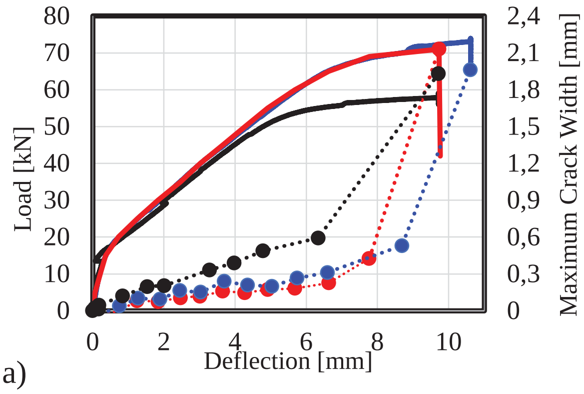


Figure 7: Damage at the failure in the Specimen 2-II beam

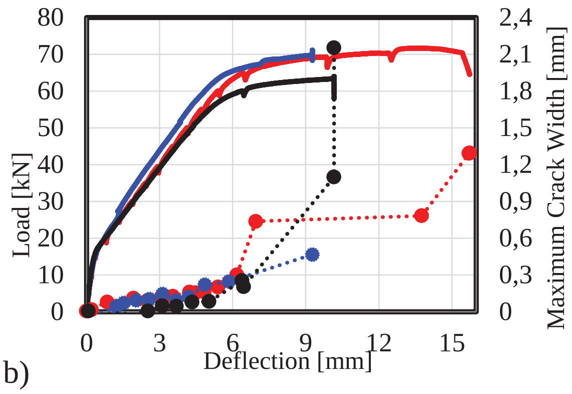
In Figure 8a the load-deflection relation combined with the load-maximum crack width in the beam with SHCC layer of 70 mm thickness is given. The capacities of the SHCC beams were 72 kN and 74 kN and that of the conventional reinforced concrete beam was 58kN. Therefore, the SHCC beams had higher capacity. This is due to the SHCC capacity to withstand load in tension, due to strain-hardening. However, increased capacity was not the main aim of this study, as in reality, the beams would have a higher cross-section, and the contribution of a thin SHCC layer on their structural capacity would be lower.

A critical value for crack width first needed to be defined. Requirements related to the maximum crack width are usually related to susceptibility of reinforced concrete structures for the corrosion of the embedded steel. The more hazardous environment requires a more strict crack width control. In this research, a maximum crack width of 0.3 mm was taken as limiting, as recommended by Eurocode 2 for reinforced concrete under quasi-permanent load for all exposure classes except for X0 and XC1. The beams with 70 mm SHCC layer had a better crack control behaviour: the maximum crack width exceeded 0.3 mm at 66 kN and 62 kN, whereas the maximum crack width of the control beam reached 0.3 mm at only 35 kN.

For the beams with the SHCC layer of 31 mm, the capacities of SHCC beams were higher, but the difference was smaller compared to the previous group due to the smaller layer thickness. Crack widths of SHCC beams reached 0.3 mm at 66 kN and 67 kN, whereas the maximum crack width of the reinforced concrete beam reached 0.3 mm at 61 kN. For these beams crack width control ability of an SHCC hybrid beam compared to the conventional reinforced concrete beam was not very significant. However, due to the small cover (only 11 mm), this group might not be representative. In addition with the small cover, reinforcement itself is able to control the cracks at the load level close to ULS load (figure 8b).



a)



b)

Figure 8: Load-deflection relation and load-maximum crack width relation in beams with a SHCC layer of a) 70 mm and b) 31 mm (black = reference beam, red = pure SHCC layer and blue = SHCC + self-healing)

4. CONCLUSIONS

In the experiments, hybrid beams showed better cracking behaviour compared to control beams, whereas also a higher bending moment capacity was found. The thicker the SHCC layer, the higher the load capacity was. More importantly for the aim of this study, composite beams with a 70 mm SHCC layer showed a better crack control. The maximum crack width exceeded 0.3 mm at approximately 64 kN load, whereas in the control beam it exceeded 0.3 mm at 35 kN load. In the hybrid beams with a 30 mm SHCC layer, the benefits were lower.

The study indicates that by using a combination of conventional concrete and SHCC, possibly optimal design of reinforced concrete structures could be achieved by eliminating the crack width as governing design parameter and thus saving on reinforcement.

REFERENCES

[1] Huang, Z., Flexural behaviour of reinforced concrete beams with a layer of SHCC in the tension zone: Experimental Study. MSc thesis, TU Delft. 2017.

[2] Khalil, A.E.-H. et al., Behavior of RC beams strengthened with strain hardening cementitious composites (SHCC) subjected to monotonic and repeated loads. Engineering Structures, 2017. 140: p. 151-163.

[3] Cho, C.-G. et al. Experiments and failure analysis of SHCC and reinforced concrete composite slabs. Engineering failure analysis, 2015. 56: p. 320-331.

[4] Zheng, Y.-Z., et al., Flexural behaviour of reinforced concrete beams strengthened with a composite reinforcement layer: BFRP grid and ECC. Construction and Building Materials, 2016. 115: p. 424-437.

[5] Luković, M., et al., Tailoring strain-hardening cementitious composite repair systems through numerical experimentation. Cement and Concrete Composites, 2014.

[6] Yang, Y., et al., Calibration of the shear stop criteria based on crack kinematics of reinforced concrete beams without shear reinforcement, to be published at *fib* Congress 2018, Melbourne, Australia.