Strain Hardening Cementitious Composite (SHCC) for crack width control in reinforced concrete beams

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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 beam 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 thicker the SHCC layer, the higher the load capacity is. More importantly for the aim of this study, composite beams with a 70 mm SHCC layer showed a better crack width control compared to the reference beams. 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 hybrid beams with a 30 mm SHCC layer, the benefits were much lower, as expected.

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.

Key words: Strain hardening cementitious composite (SHCC), crack width control, reinforced concrete beam, digital image correlation (DIC)

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 component to ensure the structural safety, crack width is an important parameter for a reinforced concrete structure in SLS to ensure its functionality and durability. If the calculated crack width of a reinforced concrete 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 the structural capacity (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 fibre reinforced material is designed to exhibit multiple microcracking with limited crack widths under tensile stresses [1], resulting in strain hardening behaviour with an ultimate tensile strain of at least 0.5% before crack localization and subsequent strain softening. With cracks smaller than 100 microns, the strain capacity of SHCC is usually around 500 times that of conventional concrete. In order to reach this, only fine particles (e.g. mostly only fine sand fractions up to 300 μm size, and sometimes coarse sand fractions up to 3 mm size) are used for making SHCC [2]. Whereas multiple cracks are associated with high energy dissipation, for which SHCC usually has been exploited (e.g. enhancing the earthquake resistance of buildings), a major benefit of this class of material may lie in the improved durability of reinforced concrete structures due to crack width control.

The main idea of this research (performed within the MSc study of Zhekang Huang [3]) was to apply SHCC in the beam tension zone, which may help to control the crack widths, without the need to add the extra reinforcing 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. As the price of SHCC is more than double that of regular concrete worldwide [4-6], such application is both cost-effective and optimal for the performance of the system.

The idea of applying a layer of SHCC in composite reinforced concrete structures is not new. For example, studies have been performed aiming to investigate if a ultra-high performance SHCC strengthened beam has higher capacity and better crack control behaviour compared to a conventional reinforced concrete beam [7, 8]. Similarly, the performance of composite SHCC - reinforced concrete slabs [9] and reinforced concrete beams strengthened by SHCC, additionally reinforced with Basalt Fibre Reinforced Polymer grid [10], were studied. Still, in most of these investigations, the primary focus is on the load capacity, whereas cracks were inspected either at failure or when they by far exceeded the maximum allowable crack width. At that point cracks were already too large to be relevant for applications in practice.

The main aim of the current research was to investigate if a layer of SHCC around the reinforcement can make that a localized, discrete crack in the conventional concrete changes in distributed cracks with limited crack widths in SHCC around the reinforcing bar. Although SHCC is a material with large ductility and controlled cracking behaviour when tested in direct tension tests, the question is if this behaviour can also be found under other boundary conditions. In a hybrid SHCC/concrete structure, local discrete cracks in the concrete will cause that the SHCC is loaded very locally. Then, the question is whether the crack from the adjacent concrete can go over in distributed cracks with smaller crack widths over a larger area in the SHCC or that it directly continues as a discrete crack in the SHCC layer. Similarly, as reported for concrete repairs [11, 4], local conditions around the crack in the adjacent concrete, the interface properties and the thickness of SHCC might determine the deformational capacity and crack control ability of SHCC.

The applied strategy in this research was to continuously monitor the crack development and crack opening in hybrid and reference reinforced concrete beams during loading, and to focus on cracks being in the range commonly defined as limiting. As a result, it could be estimated whether the addition of an 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. 31 mm cover is chosen to represent the concrete cover depth commonly applied in practice, whereas 11 mm cover is close to the minimum concrete cover with regard to the bond requirement.

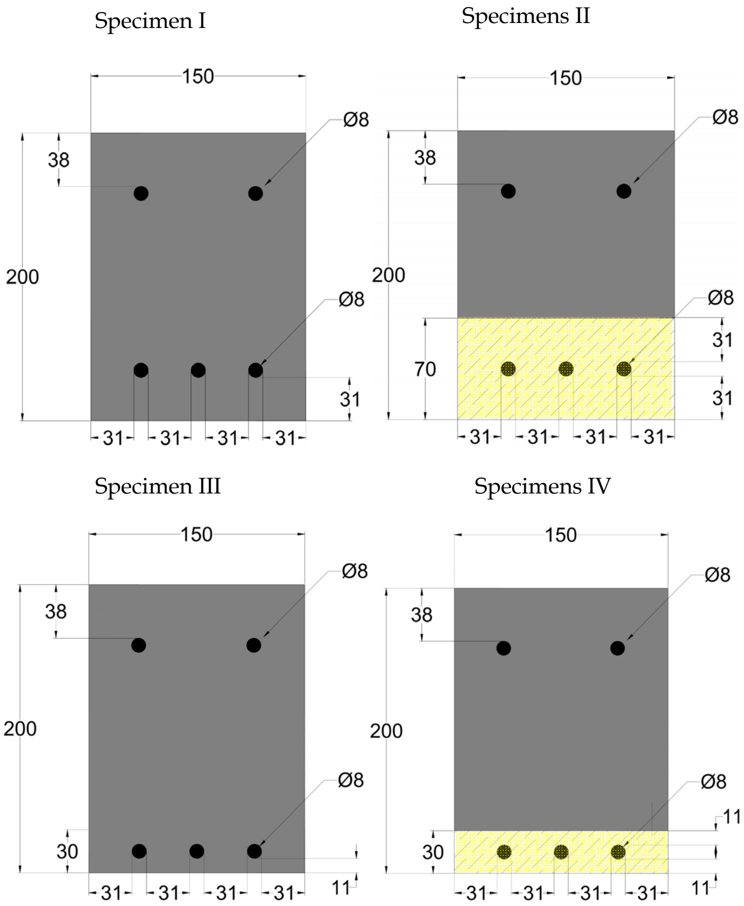

Figure 1: Cross sections of beams; concrete = grey, SHCC = yellow (units in [mm])

Specimens named II and IV were 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 is not dealt with. Furthermore, since it appeared that self-healing agent did not affect the compressive strength of SHCC, as shown later, 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 flexural failure occurs. Therefore, to prevent shear failure, stirrups were placed outside the constant moment region. The intention was to get relatively large cracks in the reference reinforced concrete beams and therefore the percentage of longitudinal reinforcement was kept relatively low (0.54% in Specimen III and 0.61% in Specimen I).

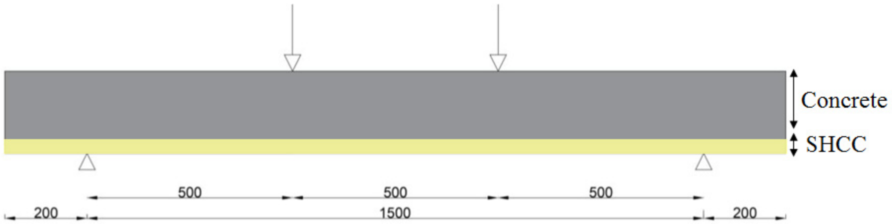

Figure 2 Experimental setup of the four-point bending test (units in [mm])

2.2 ***Specimen preparation and casting***

First, the SHCC layers with the thicknesses of 30 mm and 70 mm and reinforcement embedded in it, were cast. A huge variety of SHCC mixtures, with different raw materials, are being developed in laboratories all over the world. A "green" mixture of SHCC, originally developed by Zhou et al. at [12], consisting of blast furnace slag cement CEM III/B commonly used in the Netherlands and limestone powder, was used in this research. The SHCC mix composition is given in Table 1. As it can be seen from Figure 3a, unlike regular concrete, SHCC consists only of fine particles. Material properties of this mixture are given in Table 2.

In order to control the 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, 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. Although being a different type of application, a similar procedure as used for concrete repair was followed in order to enable good bond between prefabricated SHCC and concrete. After 33 days of sealed curing, (composite) beams were taken out of the mould (Figure 4d) and prepared for mechanical tests.

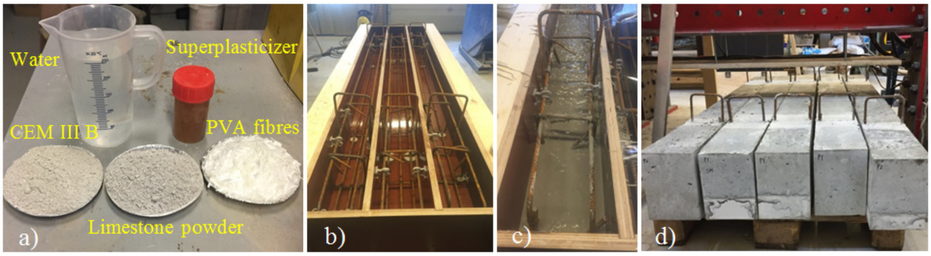

Figure 3 a) SHCC mix constituents b) mould before and c) after casting of SHCC and d) whole beams

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

Material (amounts in [kg/m³])	SHCC	SHCC+SH	Concrete
CEM III B	790	790	-
CEM I 52.5 R	-	-	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

Table 2: Material properties of applied SHCC mixture [12]

Density [kg/m³]	E modulus [GPa]	First cracking strength [MPa]	Tensile strength [MPa]	Strain capacity [%]	Shrinkage [µm/m]
2025	18.5	3	3.5	3.1	2460

In addition to beams, standard cubes (150 x 150 x 150 m^3) were cast to determine the compressive strength of the components. The average compressive strength of concrete at the age of 33 days was 46 MPa. The average compressive strengths of SHCC with and without the self-healing agent were 64 MPa and 63 MPa, respectively. All values are based on three tested specimens.

2.3 *Testing*

During the tests, Digital Image Correlation (DIC) was used to evaluate the crack pattern development and crack widths [13]. 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 [14, 15].

During loading, a series of photos was taken at different time intervals. The image resolution was 0.15 mm per pixel. By comparing these photos with the reference photo (photo taken at the unloaded state), the displacements, strain field and crack development in the specimen at a certain load level 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 cover the total displacement field and not only displacement between certain points. Still, DIC is a relatively new method and its accuracy cannot always be ensured. 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 but at the opposite

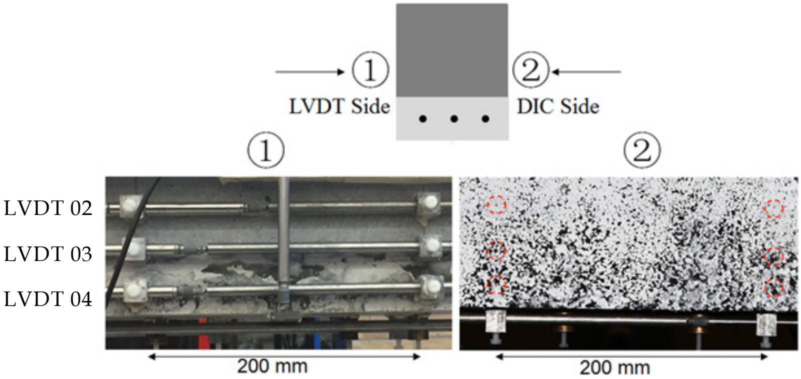

Figure 4a: 200 mm LVDTs for verification of DIC

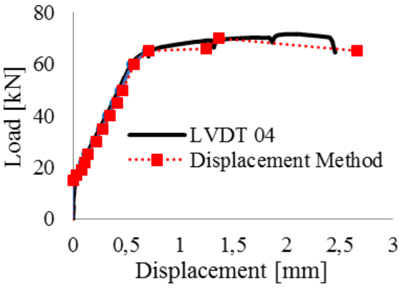

Figure 4b: Comparison DIC and LVDT results

face of the beam (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 5).

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 for the bottom LVDT are presented. It can be concluded that the DIC is accurate for measuring displacement over a length of 200 mm.

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

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

where X1 and Y1, and X2 and Y2 are coordinates of 2 chosen pixels from both sides of the crack (Figure 5). The displacement of these pixels was used to measure the crack opening at a certain loading step.

The result of the DIC analysis was compared to measurements from images taken by a camera placed underneath the sample during the different loading steps (Figures 5 and 6).

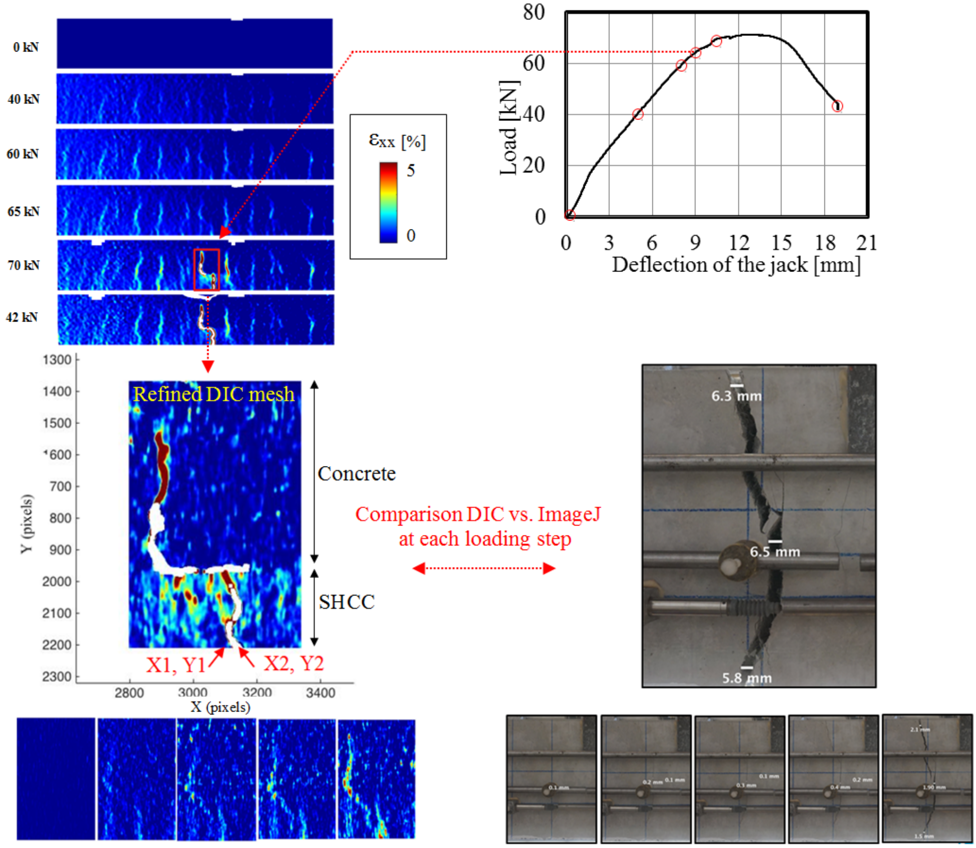

Figure 5: DIC measurement with ImageJ measurements, Specimen II-2 (the crack opening by DIC at each loading step was obtained by equation (1) and it was measured at the side of the beam, whereas the same crack is measured from the bottom of the sample by ImageJ)

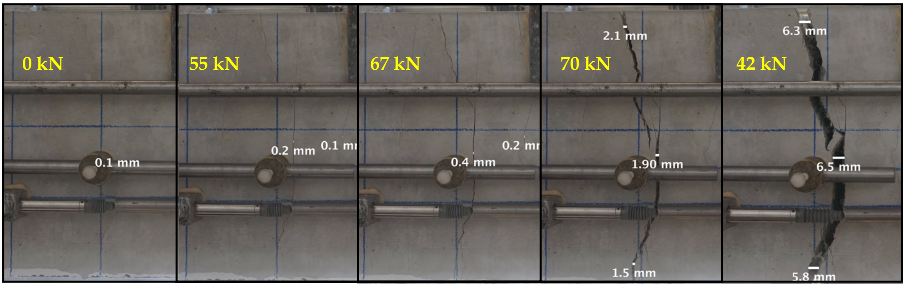

Figure 6: Crack widths at different loading steps obtained by ImageJ

These images had a resolution of 0.1 mm/pixel and were analysed by ImageJ software. Note that images taken from the bottom of the sample were not taken exactly at the same instant as those from the side of the beam. The crack width measured by the two methods is shown in Figure 7. It can be seen that the difference between the DIC and ImageJ is

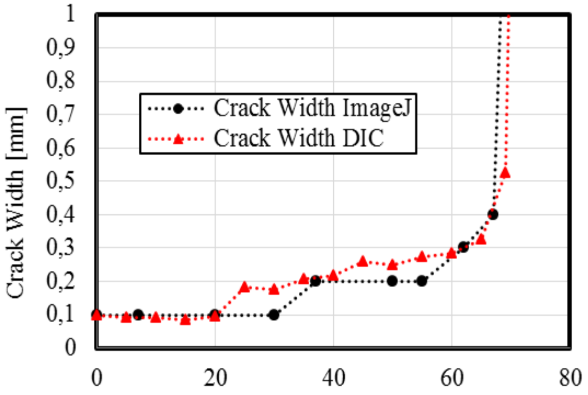

Figure 7: Crack width – load relations for DIC and ImageJ

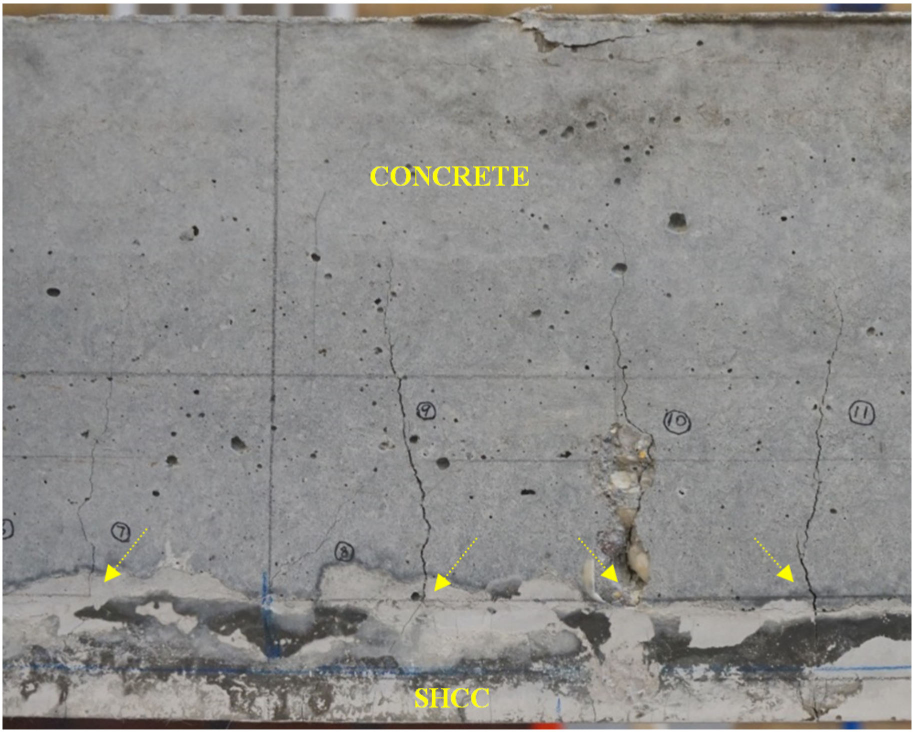

Figure 8: Discrete cracks from the concrete part are transferred into many distributed cracks in SHCC layer of 30 mm thickness

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 and reference concrete specimens.

3.2 *Experimental results*

In hybrid SHCC/concrete beams, most of the cracks from the adjacent concrete part dispersed into many finely spaced microcracks in the SHCC layer with significantly smaller crack widths compared to those in the concrete part (see example in Figure 8).

The crack pattern at failure and crack width of the hybrid-SHCC beams with SHCC layer of 70 mm and 30 mm are given in Figure 9 and Figure 10 respectively. These cracks were

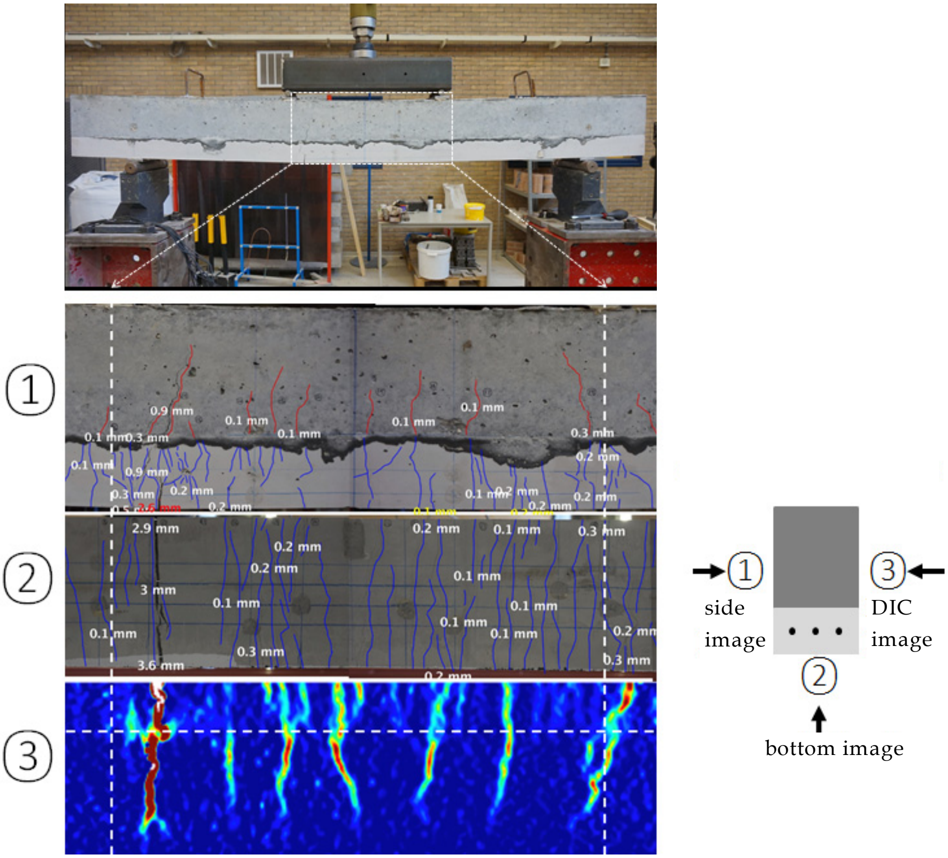

Figure 9: Damage at the failure in the Specimen II-1 beam

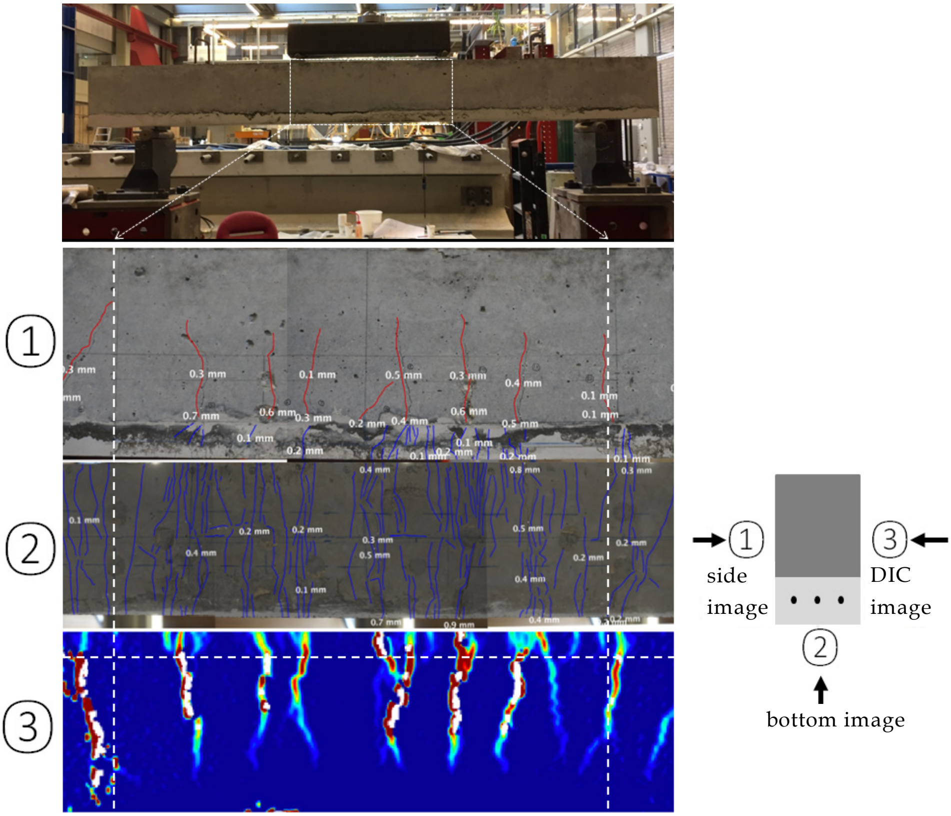

Figure 10: Damage at the failure in the Specimen IV-2 beam

generally smaller and more closely spaced compared to the crack widths and spacing at failure observed in reference beams (Figure 11). In addition, at similar load levels, more cracks with smaller crack widths were observed in hybrid beams compared to the reference beams, as shown later.

Even though SHCC has a high strain capacity in commonly applied direct tension tests (up to 3% before crack localization), localized cracking is observed at failure in all hybrid concrete beams. For example, there are locations both in Specimen II-1 and Specimen IV-2 at the failure (Figures 9 and 10, respectively) where cracks in SHCC reached cracks with crack width (far) above the limited. This is because boundary conditions in these tests differ significantly from those in direct tension tests where tensile load is applied on a specimen with a relatively large length. Here, the SHCC is loaded very locally, in the vicinity of the crack in the neighbouring concrete. Therefore, its response is determined by the local boundary conditions around this crack. Similar behaviour was observed for non-reinforced SHCC layer applied as repair [4, 11].

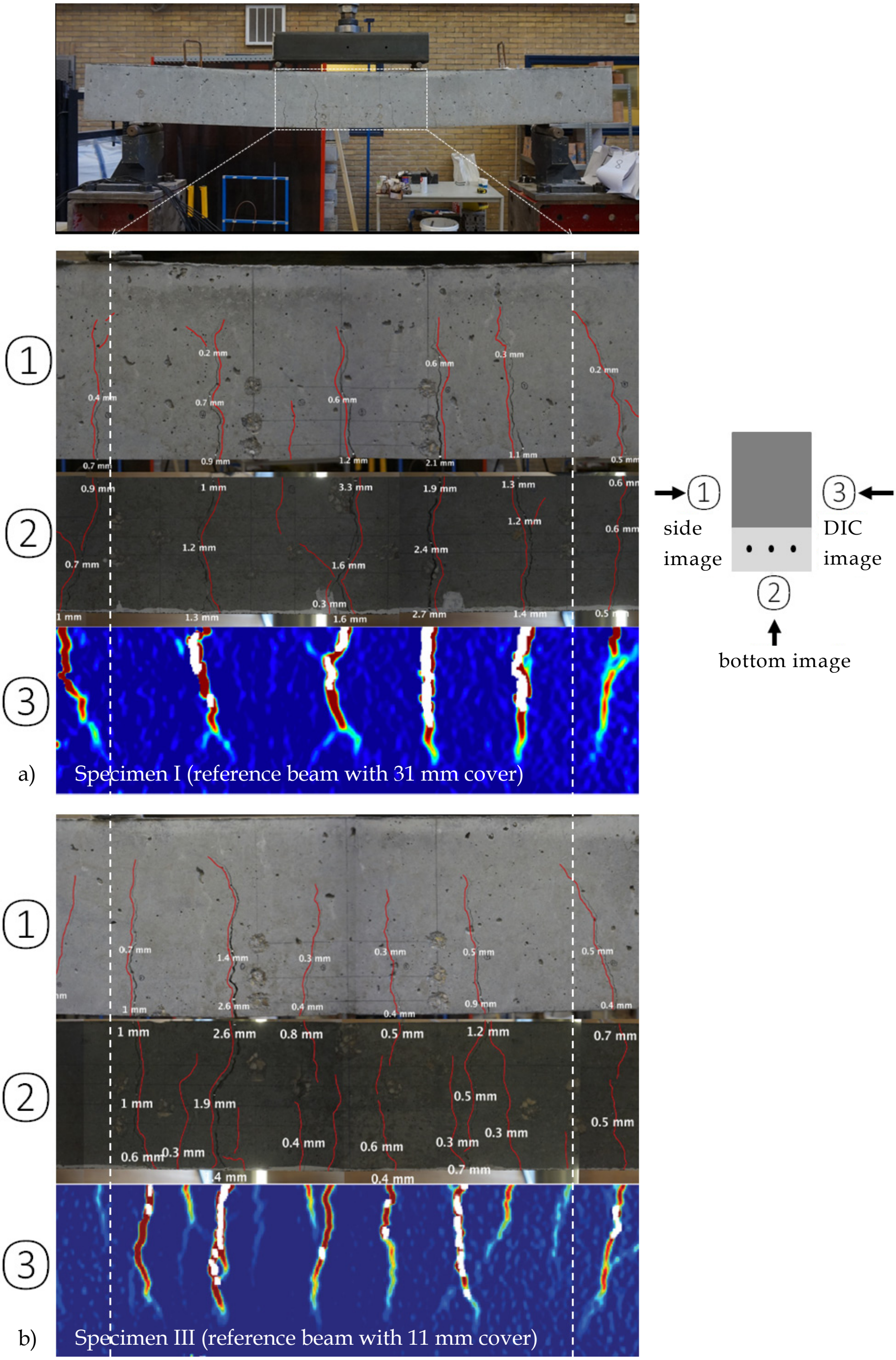

Figure 11: Damage at the failure in Specimens I (a) and III (b)

In order to study crack localization, in each specimen, the maximum crack was defined and it was observed how this crack grows in time, with increased loading (similarly as done in Figure 7). Subsequently the behaviour of specimens with and without the SHCC layer were compared.

In Figure 12a and 12b the load-deflection relation combined with the load-maximum crack width in the beam with a cover depth of 31 mm (i.e. SHCC layer of 70 mm) and 11 mm (i.e. SHCC layer of 30 mm), respectively are given. Note that in reference beams with 11 mm cover, due to the reinforcement being closer to the surface, the crack spacing and crack widths are already smaller than those in beams with 31 mm cover, and therefore, the effect of applying a SHCC layer will be lower.

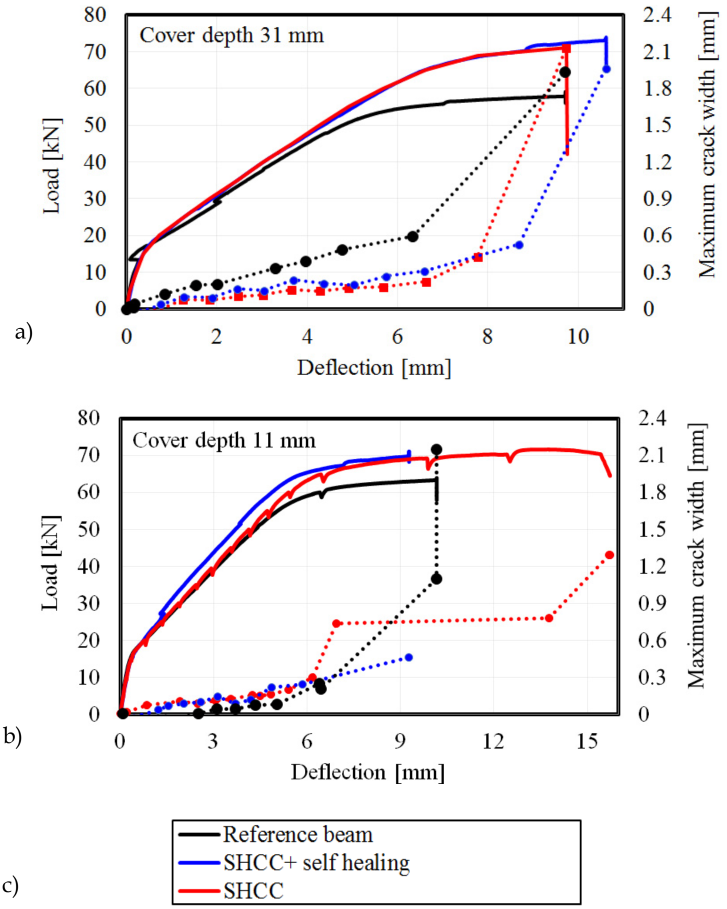

Figure 12: Load-deflection relation and load-maximum crack width relation in beams with a cover depth of a) 31 mm and b) 11 mm, with a legend given in c)

The load-bearing capacities of the hybrid beams with 70 mm thick SHCC layer were 72 kN and 74 kN and that of the reference reinforced concrete beam was 58 kN. Therefore, the SHCC beams had a higher load-bearing capacity. This is due to the SHCC capacity to withstand load in tension, due to strain-hardening. However, it is also realized that the beams in practice will generally have a higher cross-section, while the thickness of the SHCC will be more or less the same (covering the reinforcement), so that one should be careful when drawing conclusions for the effect of the SHCC layer on the capacity of beams.

A critical value for crack width was defined. Requirements related to the maximum crack width are usually related to susceptibility of reinforced concrete structures to corrosion of the embedded steel. A more hazardous environment requires 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 [16] 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 30 mm (Figure 12b), the capacities of SHCC beams were also higher compared to the reference reinforced concrete beam. Crack widths of SHCC beams reached 0.3 mm at around 66 kN, whereas the maximum crack width of the reinforced concrete beam reached 0.3 mm at 61 kN. For these beams the SHCC layer did not result in a better crack width control compared to the conventional reinforced concrete beam. However, due to the very small cover (only 11 mm), this group is not really representative for structural applications in practice. In addition, and as already indicated, with the small cover, reinforcement itself is able to control the cracks at the load level close to ULS load.

4 Perspective for future study

An important parameter determining the performance of hybrid concrete systems is also the interface between the two concrete types. In the presented study the influence of this parameter was not investigated. Varying the interface properties and allowing local debonding, as long as it does not lead to complete delamination, could possibly allow for higher strain capacity of SHCC to be achieved before crack localization, thereby hypothetically further postponing the crack localization and improving the performance of the hybrid system even more. Similar behaviour was reported for SHCC patch repair systems [10] and SHCC strengthened masonry structures [17]. Furthermore, for the sake of further applications of hybrid systems, it is important to investigate if the experimentally obtained results could be predicted by numerical models. A study on modelling the behaviour of reinforced UHPFRC hybrid systems with a DIANA model showed that, whereas the structural capacity of the beams could be reliably predicted, modelling of the cracking pattern and crack openings seems to be a challenge [18]. Provided that a reliable model is made, studying the influence of governing parameters (i.e. influence of bond strength, reinforcement crossing the interface, SHCC material properties, etc.) would allow for further system optimization of the hybrid system which will be the aim of further study.

5 Conclusions

An experimental study was performed aiming to investigate the cracking behaviour of hybrid reinforced concrete beams enhanced with SHCC layers in the beam tension zone. Structural behaviour, crack pattern and crack width development during loading was compared to the control reinforced concrete beams.

Hybrid beams showed better cracking behaviour compared to control beams, whereas also a higher bending moment capacity was found. This is due to the capacity of SHCC to transfer tensile load under large deformations. Quantitatively, this effect will depend on the ratio between the thickness of SHCC and that of conventional concrete. More importantly for the aim of this study, composite beams with a 70 mm SHCC layer showed 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 thin (30 mm) SHCC layer, the benefits were lower. This 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.

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