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EFFECT OF INTERFACE TREATMENT ON THE CRACKING BEHAVIOUR OF HYBRID SHCC (STRAIN HARDENING CEMENTITIOUS COMPOSITE) CONCRETE BEAMS

Shozab MUSTAFA[1], Shantanu SINGH[2], Mladena LUKOVIĆ[3]

1. PhD Student, Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
2. MSc Student, Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
3. Assistant Professor, Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

Corresponding author email: s.mustafa-2@tudelft.nl

Abstract

Strain Hardening Cementitious Composite (SHCC) is applied on the tension side of a flexural member in order to improve crack-width control of reinforced concrete and its effectiveness is investigated for varying treatment of the interface between SHCC and concrete. A four-point bending test configuration is used and the interface is varied locally within the constant bending moment region as smooth, partially debonded, completely debonded and profiled surface. The aim is to investigate the influence of interface on the cracking behaviour and the development of maximum crack-width in the hybrid SHCC beams with varying interface profile. Therefore, all the beams are designed to have a similar load carrying capacity by providing mechanical anchorage through the interface outside the constant bending moment region using stirrups. The cracking behaviour is analysed by measuring the maximum crack-width in SHCC layer using Digital Image Corelation (DIC), Linear Variable Differential Transformers (LVDTs) and visual inspection with a microscope. The effectiveness of the interface treatment is then judged by comparing the load at which the maximum crack-width in SHCC layer exceeds 0.3 mm, corresponding to the maximum allowable crack-width for most structural applications. It is observed that the relatively stronger interfaces (smooth and profiled) show better crack-width control when compared to partially debonded and completely debonded (weak) interfaces, probably because with weaker interface the hybrid action of the beam is reduced resulting in higher stresses and early crack localization in SHCC.

Keywords: *Hybrid Reinforced Concrete Beams, Interface, SHCC*

1. Introduction

Strain Hardening Cementitious Composite (SHCC) belongs to the family of fibre reinforced concrete and is distinguished by its hardening behaviour in tension due to the specially tailored fibre bridging effect (Li, Wang, and Wu 2001). SHCC has got a lot of attention due to its better mechanical and durability properties compared to regular concrete making it a suitable material for repair of concrete structures (Lim and Li 1997) and (Wagner, Slowik, and Waldenburger 2008). In order to enable structural applications of innovative materials like SHCC, efforts are also made to develop smart design approaches where SHCC is only placed at the critical locations in structural members – like the tension side of a beam as this is promising to enable better crack-width control of reinforced concrete structures.

Eurocode (1992-1-1 2011) specifies two criteria for design of concrete structures. The Ultimate Limit State (ULS) concerning the load carrying capacity and the Serviceability Limit State (SLS) concerning the deformation and crack-width control for durability of concrete structures. Generally, the SLS criterion is stricter and leads to higher amount of reinforcement for crack-width control than what is required to sustain the design loads. Applying SHCC with embedded reinforcement on the tension side of a flexural member results in an improved crack-width control (Luković et al. 2019). Such application results in composite structures where two different types of concretes are connected to each other through an interface which will govern the composite behaviour. The effectiveness of adding different thicknesses of SHCC layer on the tension side of hybrid reinforced concrete beams to achieve better crack-width control was investigated in an earlier study (Luković et al. 2019). It was shown that using 70 mm thick SHCC layer on the tension side of a 200 mm beam eliminates SLS as the governing design criterion, saving on the additional reinforcement required for crack-width control. However, in the aforementioned study, the influence of interface treatment on the hybrid behaviour or crack-width development was not studied.

The treatment of the substrate surface before application of overlay has been found to significantly influence the strength and ductility of the interface (Randl 2013; Júlio, Branco, and Silva 2004; Luković et al. 2013). In (Luković 2016), SHCC is used as an overlay material and it is shown that the substrate surface treatment also significantly influences the development of cracks under mechanical and environmental loads. It is also concluded that while the stronger interfaces are better to limit the damage due to imposed deformations (shrinkage caused by hygral gradient), the weaker interfaces show better crack-width control under mechanical loading when concrete structures are repaired using SHCC. This is because the weaker interfaces allow for larger delamination of the interface leading to better utilization of the micro-cracking behaviour of SHCC. On the other hand, the stronger interfaces resist this delamination and result in an early localization of crack in SHCC following the reflective cracking principle (Zhang and Li 2002). Developing on this conclusion, it is hypothesized that introduction of artificial debond at the interface before application of overlay might further improve the crack-width control of the hybrid system even when the SHCC is not applied as a repair material but is incorporated in the design of the structural member.

This research (performed as a part of MSc. study of Shantanu Singh (Singh 2017)) aims to investigate if a better crack-width control can be obtained in hybrid SHCC-Concrete beams by varying the substrate surface treatment before application of the overlay material. Therefore, different roughness profiles and artificially debonded areas are introduced at the interface in the region of interest. The development of cracks is monitored throughout the loading of the specimens and comparison is made based on the maximum crack-width exceeding the allowable limit (0.3 mm) for most structural applications in the Eurocode (1992-1-1 2011). As the scope of the study is limited to the SLS criterion, the beams are designed such that they have similar load carrying capacity by providing reinforcement crossing the interface outside the region of interest. This also avoids the brittle failure of interface during loading.

2. Materials and Methods

2.1. Experimental Design

In the previous study (Luković et al. 2019), it is concluded that the use of 70 mm thick SHCC layer on the tension side of 200 mm beam improves the cracking behaviour of hybrid SHCC-Concrete members. Therefore, the same dimensions and material composition of concrete and SHCC are adopted in this study. To investigate the effect of interface treatment on the local cracking behaviour, four different types of interfaces are studied as shown in Figure 1 (Smooth) and Figure 2 (Profiled (left), Partial Debond (middle) and Complete Debond (right)). The height of the grooved profile is 18 mm with a centre-to-centre distance of 70 mm between the grooves. All the beams have the same cross-sectional dimensions and reinforcement configuration as shown in Figure 1. The surface treatment is done locally in the constant moment region (Figure 2) as only the cracking behaviour in this region is of interest.

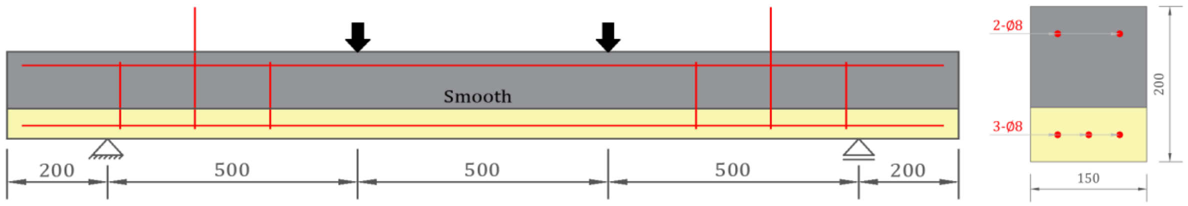

Figure 1. Longitudinal (left) and cross-sectional (right) view of the beam with smooth interface. Concrete (Grey), SHCC (Yellow) and Rebar (Red). Dimension in mm.

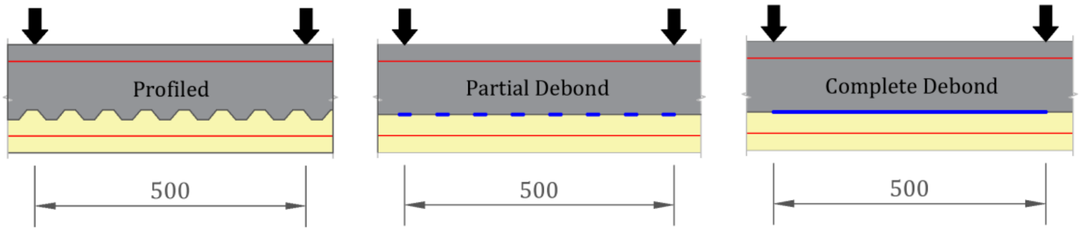

Figure 2. Constant moment region of beams showing variation of interfacial treatment. Concrete (Grey), SHCC (Yellow), Rebar (Red) and Debond (Blue). Dimensions in mm.

All the specimens are tested under a four-point bending set-up as shown in Figure 1. To allow for the development of large flexural cracks, the percentage of longitudinal reinforcement is kept close to minimum (0.54%). To avoid the failure of the beams in shear, three stirrups (Figure 1) of 8 mm diameter with a spacing of 150 mm are placed outside the constant moment region on each side. The central stirrups on each side are elongated so that a part of it is sticking outside the beam to help in handling of the specimen during testing. A reference beam with only reinforced concrete is also made as a control with the same cross-sectional dimensions and reinforcement layout following the previous study (Luković et al. 2019).

2.2. Specimen Preparation and Casting

The material composition of SHCC and regular concrete is shown in Table 1. The casting of composite beams is done in 2 phases using plywood moulds. First the 70 mm thick SHCC layer is cast along with the reinforcement cage. SHCC spacers are used at the bottom to ensure the placement of the cage is as per the design. After placing SHCC, a vibrating table is used for compaction following which the surface is smoothened using a trowel. For the profiled interface, the surface preparation is also done immediately following the laying of SHCC where a grooved plastic profile is pressed onto the SHCC surface and held in place using small weights.

The specimens are then allowed to cure under sealed conditions for 14 days. For the partially and completely debonded samples, the surface preparation is done after hardening of SHCC by placing duct tape in patches (20 mm with 70 mm centre-to-centre distance) and completely in the constant moment region respectively. The spacing of the duct tape for partially debonded specimen corresponds to crack spacing in the concrete part as observed in the previous study (Luković et al. 2019) and expected in the beam with smooth interface. The surface treatment is also depicted in Figure 2 for partial debond (middle) and for complete debond (right). The surface preparation of all the beams before laying the concrete is also shown in Figure 3.

Prior to casting the regular concrete, the top surface of all the specimens is cleaned using air jet, wire brush and ethanol to ensure that there is no dust at the interface. After pouring the regular concrete, the specimens are again covered with plastic sheets and allowed to cure for further 38 days at normal laboratory temperature before testing. The control (reinforced concrete beam) is also cast along with this second phase of casting.

Table 1. SHCC and concrete mixture composition

Material (amount in kg/m^3)	SHCC	Concrete
CEM IIIB	790	-
CEM I 52.5 R	-	260
Limestone Powder	790	-
Sand (0.125-4 mm)	-	847
Gravel (4-16 mm)	-	1123
PVA Fibres	26	-
Water	411	156
Superplasticizer	2.13	0.26

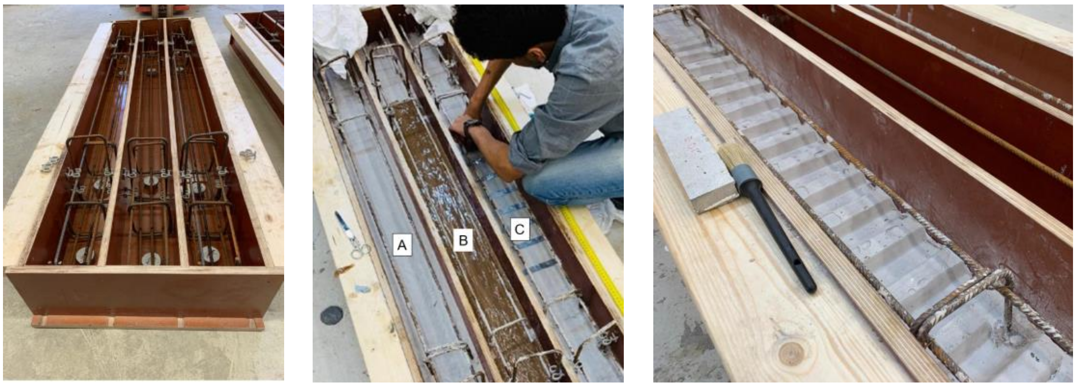

Figure 3. Plywood moulds with reinforcement cage and SHCC spacers (left). Smooth (A), completely delaminated (B) and partially delaminated (C) surfaces (middle). Profiled surface (right).

2.3. *Testing*

The four-point bending test is performed on all the specimens with a displacement-controlled jack at a loading rate of 0.01 mm/sec. The deformations of the beams are followed using Linear Variable Differential Transformers (LVDTs) on one side and Digital Image Correlation (DIC) on the other. The facet pattern for the DIC is made by painting the surface white followed by creating black speckles using roller brush. During the experiment, the pictures of the DIC side are captured after every 5 kN increment in the load using a single camera. The surface contour for displacement and strain fields can then be obtained by correlating these images with a reference image i.e. image captured just before the start of the test (Shih and Sung 2013).

3. Results and Discussion

For post-processing of DIC results, the free version of GOM Correlate ("GOM Correlate" 2017) is used and a 2-dimensional analysis is performed. It has already been shown (Luković et al. 2019) that the results of DIC are reliable but a verification is still performed to check the reliability of the followed experimental procedures. The vertical deformation is compared at the centre of the beam (labelled 1 in Figure 4) while the horizontal deformation is compared at the ends of a horizontal LVDT closest to the interface (labelled 2 and 3 in Figure 4). The results shown in Figure 4 are for the beam with smooth interface and it can be seen that the deformations obtained by LVDTs and DIC are in reasonably good comparison with each other.

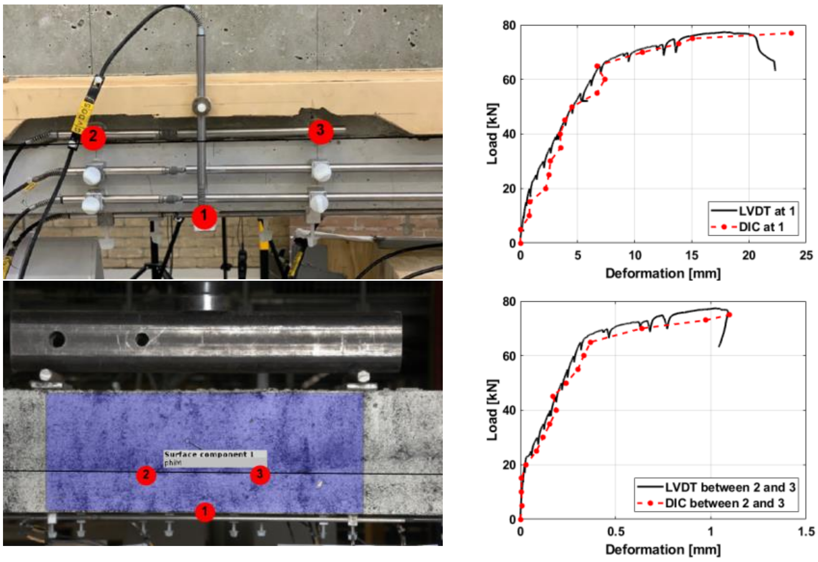

Figure 4. Comparison of DIC and LVDT results for vertical deformation at the centre of the beam (1) and horizontal deformation at the ends of the LVDT placed near the interface (2 and 3)

The SHCC used in these experiments has quite significant shrinkage due to the absence of coarse and fine aggregates therefore some shrinkage cracks were also observed in the specimens before application of the mechanical loading. As the focus is only the effect of surface treatment on crack-width control under mechanical loading, these cracks were just labelled prior to the experiments and their increasing widths were captured during the test.

It is reported that for DIC, the use of equivalent von Mises strain allows to study the crack-widths with good precision (Shih and Sung 2013), therefore the use of this option is made to visualize cracking. The resulting crack pattern at the final load step for all the specimens is shown in Figure 5 for a qualitative comparison. The surface contours shown are only of the region marked with blue colour in Figure 4 (constant bending moment region). The crack-width values obtained with DIC are also verified by processing pictures using another software (ImageJ). Both the techniques determine the crack-widths to be within a marginal error of each other (Singh 2017; Luković et al. 2019), further verifying the results of DIC.

It can be seen from Figure 5 that SHCC is able to develop micro-cracking behaviour in all the specimens but the crack pattern is quite different for different surface treatments. The smooth interface shows the greatest number of finely spaced cracks and the cracks do not directly travel from SHCC to concrete. They rather go through the delamination of the interface, as also reported in (Luković 2016). On the contrary, the profile interface shows merging of the cracks developed in SHCC as they reach the interface. This is expected of a profiled interface due to the mechanical interlock provided by the grooves. The completely debonded interface has the least number of cracks in concrete highlighting the lack of monolithic behaviour between the two types of concrete. The separation of concrete and SHCC is also observed with increasing load as both have different bending stiffness and deform independently. The cracking pattern in SHCC layer is also typical of a bending type load with wider cracks at the bottom that close towards the top due to the compressive zone, further showing the absence of bond between SHCC and concrete. The partially debonded interface shows a behaviour that is in between the smooth and completely debonded interface. In total, 7 cracks developed in the concrete layer following the placement of duct tape in the constant moment region and the number of cracks in SHCC is in between those observed for smooth and completely debonded interface.

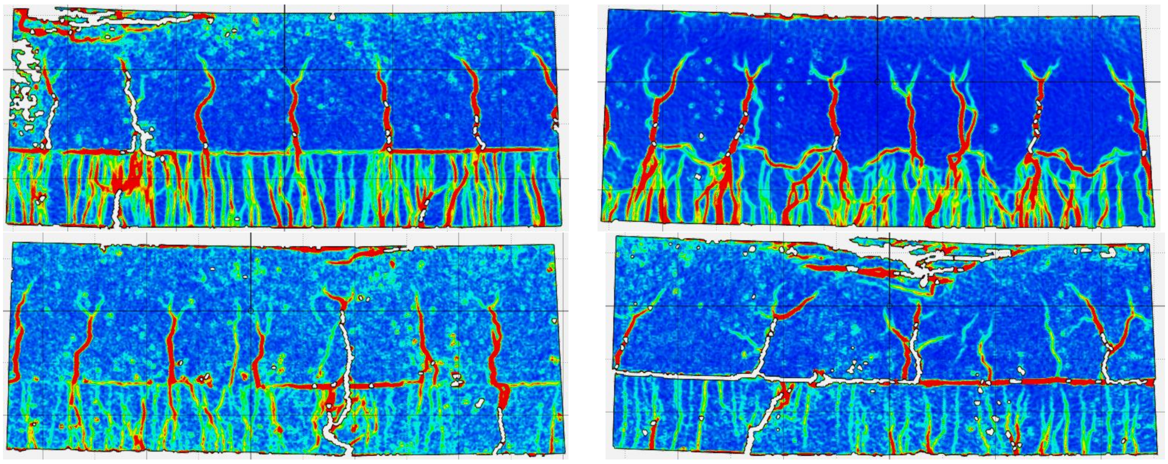

Figure 5. Qualitative comparison of cracking pattern in the constant moment region at ultimate load for smooth (top left), profiled (top right), partially debonded (bottom left) and completely debonded (bottom right) interface.

Figure 6 shows the load vs deformation vs crack-width response of all the beams along with the load level at which the maximum crack in SHCC exceeds the design criterion of 0.3 mm. The load carrying capacity of all the beams is comparable with a maximum difference of 6% due to the presence of stirrups crossing the interface outside the bending moment region. The completely debonded specimen shows the least initial stiffness as both SHCC and concrete act separately while the smooth interface has the highest initial stiffness signifying a good bond between SHCC and concrete.

In terms of crack-width control, it can be seen that both smooth and profiled interface show comparable behaviour with maximum crack-width in SHCC exceeding 0.3 mm at 71 kN and 69 kN respectively, reaching almost 90% of the ultimate capacity and occurring after the yielding of reinforcement. However, it must be noted that the smooth interface resulted in a very rapid increase in crack-width after exceeding the 0.3 mm criterion while the profiled interface limited the cracks to be smaller than 0.5 mm even at ultimate load level. The partially debonded interface again resulted in a behaviour that is in between completely delaminated and smooth interface. From the crack-width plot it can be seen that the partially debonded interface is able to limit crack-widths initially but soon loses the ability and results in crack-width exceeding 0.3 mm at a load of 54 kN compared to 44 kN of the completely debonded interface. The completely debonded interface shows localization at an earlier load level. This might be due to the fact that stresses in SHCC are much higher due to absence of the composite action (no bond at the interface). It is suspected that the limited area of the interface in the partially debonded specimen also delaminates and results in an early localization of cracks but further investigation is required to verify this.

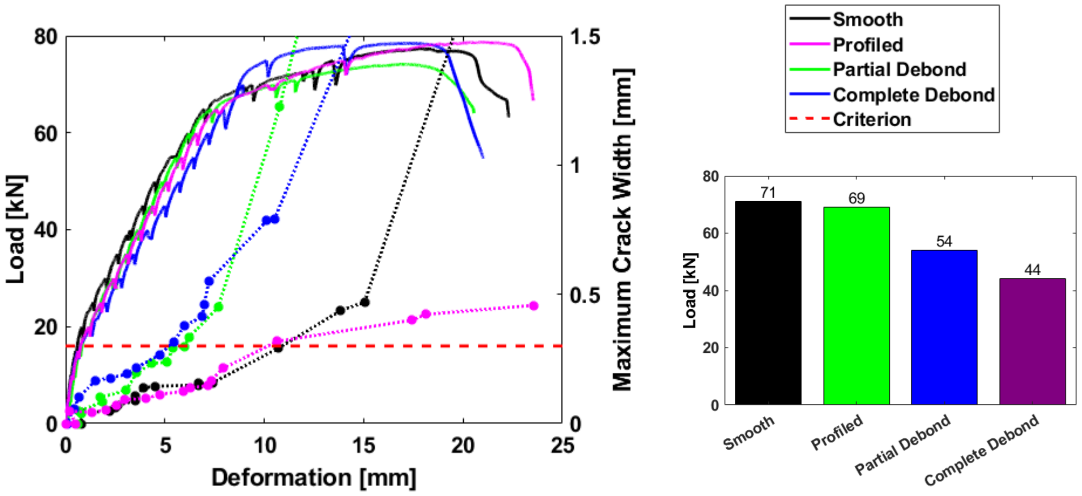

Figure 6. Load deformation and crack-width response of all the specimens (left). Loads at which the maximum crack-width exceeds 0.3 mm in SHCC (right).

The crack-width behaviour and load carrying capacity of the control beam and hybrid beam with smooth interface are also compared with the results of (Luković et al. 2019). For the hybrid beam, the ultimate load is within 5% while the load at which crack-width exceeds 0.3 mm is within 10%, ensuring the reproducibility of the tests. Similarly, the results for control beam are also found to be within 10% in both.

It is worth mentioning here that the effect of interfacial surface treatment on the effectiveness of SHCC in crack-width control might be significantly different when applied as a repair material over pre-cracked concrete and when incorporated in the design. This is because in the former, the cracks in concrete exist before application of SHCC. Therefore, cracking in SHCC is determined by the previously present cracks in concrete layer, while cracks in concrete are independent of the bond or SHCC behaviour. In the latter, cracks in concrete and SHCC are formed during composite action, when both SHCC and concrete are present and the number of cracks in concrete are governed by the bond characteristics as observed in this study.

4. Conclusions

The surface treatment of the interface is found to have a significant effect on the cracking response of hybrid SHCC-Concrete beams. However, the hypothesis that the introduction of artificial debonding might lead to better crack-width control is found to be invalid when the layer of SHCC is incorporated in the design of the beam. This is contradicting to the behaviour of SHCC in concrete repair applications where the existing cracks are able to beneficially use the debonding by activating a larger length of SHCC and delaying the localization of crack in the repair material. The specimen with smooth and profiled interface, where no artificial debonding is introduced, reached a maximum crack-width of 0.3

mm in SHCC at 71 kN and 69 kN respectively. Here, it might be concluded that beyond a certain strength of interface, the effect of roughness on crack-width control is limited. On the other hand, the specimens with partial and complete debonding of the interface exceed this criterion at a much lower load of 54 kN and 44 kN respectively. A possible reason for this early localization can be the higher tensile stresses in the SHCC layer as the monolithic behaviour of the hybrid beam is reduced/lost with the introduction of the artificial debond. Therefore, a certain strength of the interfacial bond is required to utilize the crack-width control ability of SHCC in hybrid beams.

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