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Strain Hardening Cementitious Composite in Reinforced Concrete Cover Zone for Crack Width Control

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Abstract. In the current study, experiments were carried out to investigate the cracking behaviour of reinforced concrete beams consisting of 1-cm-thick layer of Strain Hardening Cementitious Composite (SHCC) in the concrete cover zone. The hybrid SHCC/concrete beams with different types of interfaces were tested and compared with control reinforced concrete beams without a SHCC layer. A new SHCC/concrete interface that features a weakened chemical adhesion but an enhanced mechanical bonding was also developed to facilitate the activation of SHCC. The beams were tested in four-point bending configuration, while Digital Image Correlation (DIC) was used to evaluate crack pattern development and crack widths. Results show that hybrid beams possessed similar load bearing capacity but exhibited an improved cracking behaviour as compared to the control beam. The maximum crack width of the best performing hybrid beams exceeded 0.3 mm at approximately 53.3 kN load, whereas in the control beam it exceeded 0.3 mm at only 32.5 kN load. It is thus expected that the hybrid beams developed in the current study will possess an improved durability and enhanced self-healing potential as a result of having smaller cracks, leading to an extended service life at the expense of minimal additional cost.

Keywords: Crack width control · DIC · SHCC · interface

1 Introduction

Design of concrete structures are required to meet criteria in both ultimate limit states (ULS) and serviceability limit states (SLS). The ULS addresses structural safety and stability, while the SLS are essential for appropriate function and durability of concrete structures. Within the SLS design, the attention is paid especially to the analysis and control of crack width. The criteria for crack width control by SLS usually demand concrete structures to have additional reinforcement than what is required by ULS. Therefore, a relatively large amount of reinforcement is usually added only to meet the SLS crack width criterion, making the design uneconomical.

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The employment of Fibre Reinforced Concrete (FRC) is becoming more and more prominent as numerous research have demonstrated that FRC significantly improves the behaviour of structural elements at SLS, with respect to crack and deflection control [1]. Among all fibre-reinforced cementitious composites (FRCCs), the Strain Hardening Cementitious Composite (SHCC) or Engineered Cementitious Composite (ECC), initially developed in the 1990s based on the micro-mechanics theory [2], possesses the most desirable crack control ability as it can exhibit multiple microcracking behaviour (i.e., average crack width of 60–80 μm) with strain hardening response even at a tensile strain over 3% [3]. The ability to strain-hardening and to self-controlling the crack width makes SHCC a promising candidate for improving the resilience and durability of structural members. However, due to the high material cost of current SHCCs, complete replacement of reinforced concrete (RC) with SHCC is not economically feasible for most of construction projects. Applying SHCC material only locally may be a potential solution.

To investigate the possibility of combining SHCC and conventional concrete, several research have designed SHCC/RC hybrid systems for different structural member, including shear strengthening by placing SHCC on lateral surface of a beam [4] and flexural strengthening by placing SHCC at the tension side [5]. In a recent study, the crack width control ability of hybrid SHCC concrete beams with different interface is investigated [6]. The study adopted a 70-mm-thick layer of SHCC in the tensile zone of a 200-mm-high beam and confirmed that, when the interface is sufficiently strong, the SHCC layer is effective in providing appropriate crack width control such that the SLS criterion is no longer governing for reinforcement design. However, the amount of SHCC used in this hybrid system is still relatively large, comprising 35% of the whole beam by volume. Given that the material cost of SHCC is roughly 3 times of the cost of concrete [7], a 35% concrete replacement rate by SHCC will incur a significant amount of additional cost. It is therefore desirable to investigate the effectiveness of a SHCC/RC hybrid system with much reduced thickness of SHCC layer.

Therefore, in the current study, experiments were carried out to investigate the cracking behaviour of reinforced concrete beams consisting of a very thin layer (*i.e.*, 1 cm in thickness) of SHCC in the concrete cover zone. The hybrid SHCC/concrete beams with different types of interfaces were tested and compared with control reinforced concrete beams without a SHCC layer. A new interface type which allows a controlled extent of partial delamination between the two layers is also presented.

2 Material and Methods

2.1 Experimental Design

The test program consists of 4 beams, including 1 conventional reinforced concrete beam as a reference specimen and 3 hybrid beams consisting of a 1-cm-thick SHCC layer in the tensile zone. The geometry and reinforcement details of the beams are given in Fig. 1. The 1st hybrid has a smooth interface between the SHCC layer and the reinforced concrete, while the 2nd hybrid beam has a profiled interface which is made of a pattern of protruding keys from the SHCC layer and the 3rd hybrid beam has a Vaseline treated profiled interface. This treatment is to reduce the chemical adhesion between SHCC and concrete and to promote the activation of SHCC. The profile pattern consists of equally sized and evenly spaced circular keys which have a diameter of 2.5 cm and a height of 1 cm. The spacing between the keys is 2.5 cm, which is designed such that the largest aggregate in the concrete can fill into the gap between 2 adjacent keys. The pattern is produced by using silicone rubber as shown in Fig. 2. The shear keys are designed to provide sufficient mechanical interlocking between the 2 layers to ensure their deformational compatibility and to fully utilize the tensile strain capacity of the SHCC. The reference beam is referred as Ref and the hybrid beams with smooth interface, profiled interface and Vaseline treated profiled interface are referred as Smooth, Profile and Vaseline, respectively.

The reason why the hybrid beams in the current study only have the SHCC layer in the bottom cover is for easy examination of the different crack patterns in SHCC and in concrete. Cracks on the front and back sides of the beams are not considered to govern the durability, for that eventually the SHCC layer will be applied in the 4-side cover zone of the entire beam for an all-around protection.

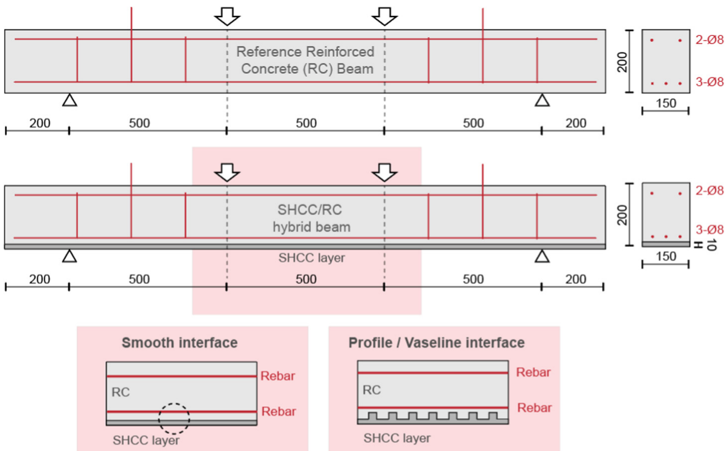

Fig. 1. Design details of the beams [unit in mm].

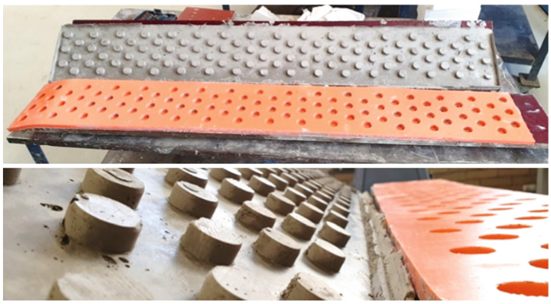

Fig. 2. Shearkeys in profied SHCC laminates.

2.2 Materials and Sample Preparation

Table 1 shows the mixture compositions of SHCC used in the current study. The mix design of the control SHCC was tailored based on a SHCC mix developed in the group previously [8, 9]. The modified SHCC matrix has a water-to-binder ratio of 0.4 and a filler-to-binder ratio of 0.5. Blast furnace slag (BFS) cement CEM III/B 42.5 N from ENCI (the Netherlands), consisting of 20–34% clinker and 66–80% BFS, was used as binder and finely grinded limestone powder Calcitec® from Carmeuse (Belgium) was used as filler. A polycarboxylate-based superplasticizer MasterGlenium 51 produced from BASF (Germany) with 35.0% solid content by mass was used to reach desired workability. The fibre used in this study is PVA fibre from Kuraray (Japan) with 1.2% by weight oiling coating, the mechanical and physical properties of which are presented in Table 2.

All the hybrid beams in the current study were casted in 2 steps. In the 1st step, SHCC laminates were prepared and cured for 14 days in a climate room before casting of concrete. In the second step, SHCC laminates were first taken out from the climate room and then placed into plywood mould. On top of the SHCC laminates, reinforcement cages were placed with appropriate spacers. After the preparation, the concrete casting was then performed and compacted using a vibration needle. The hybrid beams were then cured for 28 days in sealed conditions before testing. Reinforced Concrete (reference beam) was cast along with this second phase.

Table 1. Mixture compositions of SHCCs [unit in kg/m3].

Material	SHCC	Concrete
CEM I 52.5 R	–	260
CEM III/B 42.5 N	1060	–
Limestone powder	530	–
Sand (0.125–4 mm)	–	847
Gravel (4–16 mm)	–	1123
PVA fibre	26	–
Water	424	156
Superplasticizer	2	0.26

Table 2. Physical and mechanical properties of PVA fibres.

Length (mm)	Diameter (μm)	Density (kg/m3)	Nominal tensile strength (MPa)	Young’s modulus (GPa)
8	39	1300	1640	41.1

2.3 Testing

All the beams were tested in a four-point bending test setup (Fig. 3) under displacement control at a rate of 0.01 mm/s. The deformation of the beams was measured within the constant bending moment region using Digital Image Correlation (DIC) on both sides of the beam. The surface of the beam for DIC was first painted in white and sprayed with a black speckle pattern by using an air gun. Images for DIC were captured throughout the loading for each 5 s. The resolution of the images is 0.08 mm/pixel. Post-processing of DIC results was carried out with a free version of GOM Correlate.

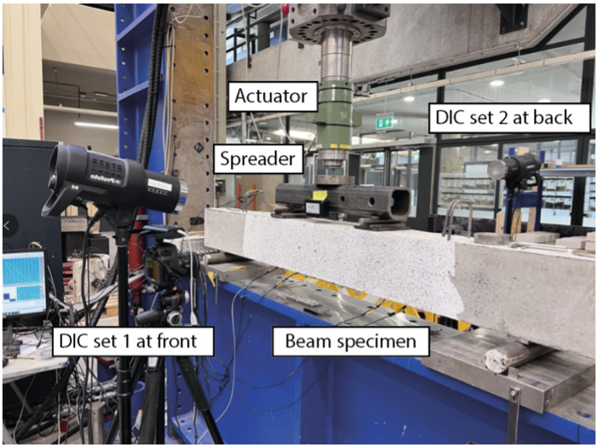

Fig. 3. Experimental setup of the four-point bending test

3 Results and Discussion

Figures 4 and 5 show the evolution of crack pattern in the constant bending moment region at 30 kN, 50 kN and ultimate load for all tested beams. As can be seen, all the beams failed in flexural tension as designed, which is characterized by the formation of flexural cracks at the tension side and the crushing of concrete at the compression side. By comparing Figs. 4a and 4b, it can be found that the SHCC layer has very little influence on the cracking behaviour of the beam when a smooth interface is adopted. Branching of crack from concrete to SHCC was observed only to a very limited extend. This indicates that the adhesion between SHCC and concrete at smooth interface is so strong that the debonding is thoroughly resisted, causing only a small portion of SHCC to be activated and an early localization of cracks in SHCC.

Figures 5a and 5b show the crack pattern of the hybrid beams with profiled interface (*i.e.*, Profile and Vaseline beams). Unlike the crack pattern of the Smooth beam, the thin SHCC layer with a distinct cracking behaviour from that of concrete can be easily noticed at the bottom of the beam. The cracks from concrete were also found to be largely arrested in both the Profile and Vaseline beams and that the branching of cracks were much more obvious than that of the Smooth beam. The reason for the better crack performance of the SHCC with a profiled interface is probably because that the presence of shear-keys can lead to a non-uniform load transfer between the concrete and the SHCC layer. In such a case, stresses may have concentrated around the shear-keys even at a low load level and thus led to a relatively early local delamination near shear-keys as shown by the crack patterns at 30 kN, which then facilitated the activation of SHCC and the formation of microcracks.

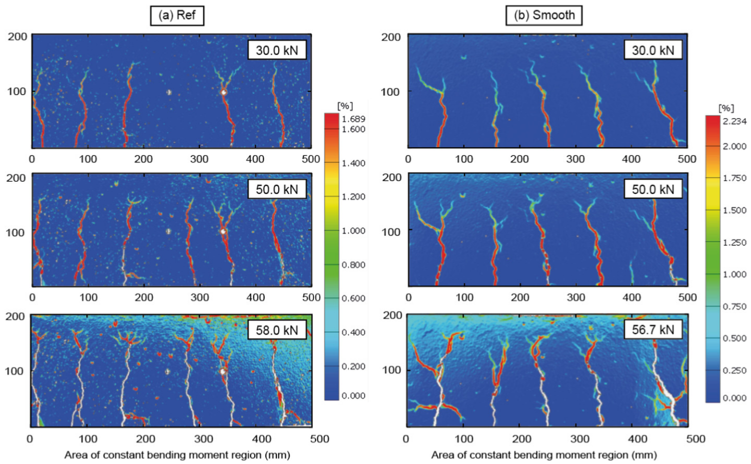

Fig. 4. Crack pattern development at 30 kN, 50 kN and ultimate load for (a) Ref beam and (b) Smooth beam.

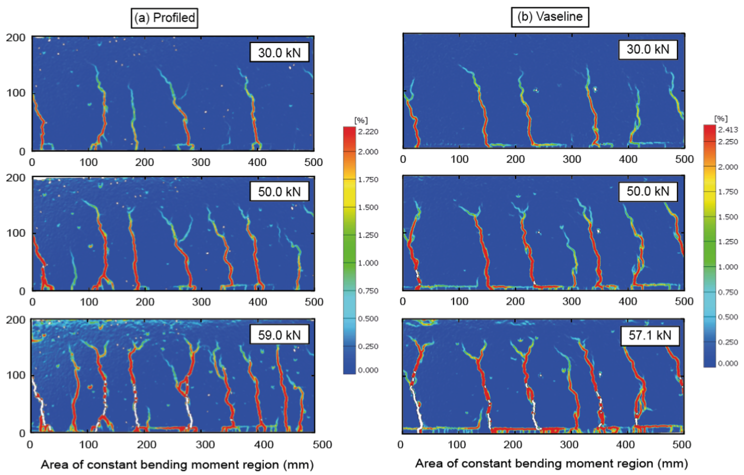

Fig. 5. Crack pattern development at 30 kN, 50 kN and ultimate load for (a) Profile beam and (b) Vaseline beam.

By comparing the crack patterns between the Profile and the Vaseline beam, it can also be found that a higher portion of the SHCC was activated in the Vaseline beam than the Profile beam. It can be found that delamination between SHCC and concrete was more pronounced in the Vaseline beam than in the Profile beam, which facilitates the activation of a wider range of SHCC and the formation of more cracks.

Figure 6 shows the comparison of Load-Deformation response and crack development between the beams. As can be seen from the curves, Load-Deflection relation of the hybrid beams are similar to the that of reference reinforced concrete beams. For all beams, the first-cracking loads were close and the curves behaved linearly before cracking. After cracking, the stiffness of the beams was weakened, resulting in a turning point in the curve. The next turning point is when the load ceased to increase with increasing deflection, which marks the starting point of reinforcement yielding. The last stage is when the load started to decrease, which indicates the failure stage of the beams. In terms of load bearing capacity, all the hybrid beams have similar load carrying capacity (around 60 kN) as compared to that of the reference reinforced concrete beam. This is as expected because all the beams have the same reinforcement and that the contribution to tension from the 1-cm-thick SHCC layer is expected to be very little.

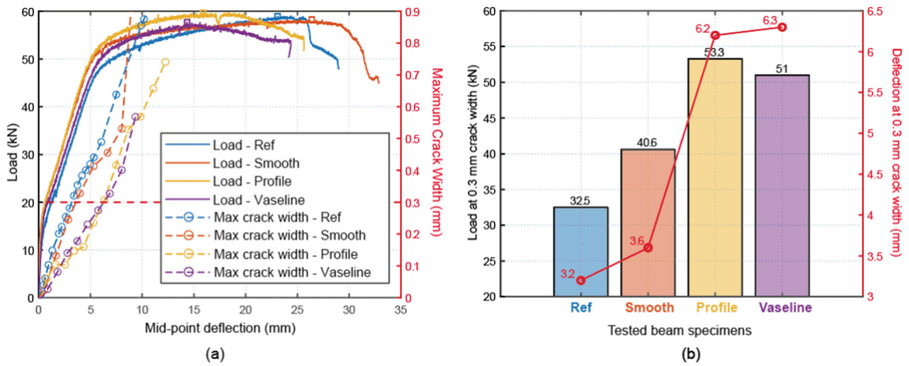

Fig. 6. (a) Load-deflection-crack width response of all tested beams and (b) summary of load and deflection values when the maximum crack width exceeds 0.3 mm for each beam.

More importantly for the aim of this study, it can be seen from the dashed lines in Fig. 6a that all hybrid beams show improved crack width control ability. The dashed lines in Fig. 6a show the development of the maximum crack widths along the bottom edge of the beams with increasing deflection as calculated from the DIC results. The maximum values were taken from the side of beam with larger crack widths. As can be seen, the maximum crack widths exceeded 0.3 mm in reference beam at the load of 32.5 kN, while the hybrid beams with smooth, profiled, and Vaseline applied profiled interfaces limited the crack widths until the loads of 40.6 kN, 51.0 kN and 54 kN, respectively. For this paper, a maximum crack width of 0.3 mm at the surface was taken as the limit for that this value is recommended for reinforced concrete under quasi-permanent load for all exposure classes except for X0 and XC1 in Eurocode 2. For the best performing hybrid beam (*i.e.*, the Profile beam), its load at 0.3 mm crack width reaches 89.3%

of its ultimate capacity. Figure 6b summarizes the loads and deflections for the tested beams where the maximum crack widths reached 0.3 mm. Though the hybrid beams all exhibited a deferred opening of cracks in SHCC, it is obvious that the hybrid beams with a profiled interface (*i.e.*, the Profile and Vaseline beams) have a superior crack width control ability. Not only the loads at 0.3 mm crack width of the Profile and Vaseline beams were much higher than the Smooth beam, a 0.3-mm-wide crack also happened at a much larger deflections for the Profile and Vaseline beams (*i.e.*, at 6.2 mm and 6.3 mm respectively) as compared to the Smooth beam which reached the 0.3 crack width at only 3.6 mm. This deflection value is only slightly higher than that of the Ref beam, showing that the crack width control ability of the SHCC material was only marginally activated in the Smooth beam.

It is thus concluded a 1-cm-thick SHCC layer can provide proper crack width control without harming its load-bearing capacity. Unlike previous research which usually apply a large quantity of SHCC in hybrid systems, the hybrid beams developed in the current study with only a thin layer of SHCC can possess an extended service life at the expense of minimal additional cost.

4 Conclusions

An experimental study was performed aiming to investigate the cracking behaviour of hybrid reinforced concrete beams enhanced with a very thin layer of SHCC in the cover zone of beams. Structural behaviour, crack pattern and crack width development during loading were compared to the control reinforced concrete beams. Results show that hybrid beams possessed similar load bearing capacity but exhibited an improved cracking behaviour as compared to the control beam. With a 1-cm-thick layer of SHCC, the maximum crack width of the Profile and Vaseline beams exceeded 0.3 mm at 53.3 kN and 51.0 kN load, whereas in the control beam it exceeded 0.3 mm at only 32.5 kN load. The effect of interface on the crack width control ability is found to be vital. The proposed new interface which allows partial delamination can indeed facilitate the formation of more cracks in SHCC. But in terms of the ability of controlling the maximum crack width, the effect of forming more cracks is not obvious.

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