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Notched Beam Test for SHCC-Concrete Interface

Shozab Mustafa(✉), Othman Harras, and Mladena Luković

Delft University of Technology, Delft, The Netherlands
s.mustafa-2@tudelft.nl

Abstract. The number of hybrid concrete structures is increasing due to the need for repairing/strengthening existing structures and the development of new hybrid concrete systems. The structural response of these hybrid structures might be governed by the strength of the interface between the two concretes, making it essential to characterize the mechanical response of the interface. In this research, a notch beam tests is proposed to investigate the structural behavior of the interface. Hybrid beams consisting of Strain Hardening Cementitious Composites (SHCC) and conventional concrete are designed with a notch at mid-span and are tested under a four-point bending configuration. The effect of interface treatment (i.e. surface roughness) and the curing condition is tested using two sets of hybrid beams. The first set has three beams which are cured in sealed conditions until the day of testing and the interface is varied between smooth, profiled and roughened. The second set has two beams with smooth interface where one beam is seal cured and the other one is exposed to drying in the laboratory. The opening of the interface is visualized using Digital Image Correlation (DIC) and quantified using Linear Variable Differential Transformers (LVTDs) during testing of the hybrid beams. It is observed that increasing the roughness of the interface leads to higher load-bearing capacity and controlled opening of the interface. The beam exposed to drying showed somewhat reduced capacity, possibly due to the pre-damage caused by differential shrinkage of the two concretes.

Keywords: SHCC-Concrete Hybrid Beams · Interface · Notch-Beam Test · Composite Structures

1 Introduction

Hybrid concrete structures are formed when a fresh concrete (i.e. overlay) is cast over an existing/hardened concrete (i.e. substrate). The construction industry is experiencing a rapid increase in the number of hybrid concrete structures mainly due to two reasons: (i) the development of novel concretes which show superior mechanical behavior but are more costly than the conventional concrete encouraging the engineers to use them only at the critical locations in the structural elements [1, 2] and (ii) the increasing need to repair/strengthen the existing concrete infrastructure which is mostly achieved by placing a new layer of (novel) concrete over the existing concrete [3, 4]. In both these applications, the behavior of the hybrid structure might be governed by the performance

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of the interface formed between the two concretes which is often considered the weakest link [2, 5, 6]. This makes it essential to characterize the interfacial response for safe and appropriate design of hybrid concrete structures.

However, the mechanical response of this interface still presents a challenge to the construction industry due to its dependence on several parameters and lack of standardized testing procedures. Some of the main factors affecting the interface strength include the surface roughness [7, 8] and moisture condition [9] of the interface, and the time-dependent development of strength [10] and stresses due to differential shrinkage [11] of the two concretes forming the interface. Current design codes also provide very limited and conservative information for the design of interface due to lack of knowledge regarding the interfacial response under varying stress conditions and the effect of environmental effects (e.g. drying).

The mechanical response of the interface is usually obtained using small-scale bond tests [12, 13] in which the structural effects are not appropriately taken into account. Furthermore, these bond tests cause different stress-states at the interface, and rarely results in a failure entirely at the interface, leading to a large scatter in the measured interface strength [14]. An overview of the discussion on the suitability and comparability of different testing methods can be found in [12–15].

In [15, 16], an interface test on a notched hybrid beam is proposed which can be used to determine the strength of the interface including the effects of structural phenomena like the differential shrinkage between the two concretes. This is achieved by creating a notch at the mid-span of the substrate causing (i) maximum shrinkage stresses to localize around it and (ii) maximum stresses due to external mechanical load to also develop around the notch when beam is exposed to bending. This paper reports the experimental results of preliminary tests on SHCC-Concrete notched beams with different curing conditions and roughness of the interface profile.

2 Materials and Methods

2.1 Experimental Design

To investigate the effect of interface treatment, the interface is varied between smooth, profiled and rough while to study the effect of curing conditions hybrid beams with smooth interfaces are used where one beam is cured in sealed conditions and the other is exposed to drying. An overview of the tested hybrid beams with their names, interface treatments and curing conditions is given in Table 1.

All the beams have cross-sectional dimensions of 150 mm x 200 mm and a length of 1900 mm with a constant bending moment region of 700 mm (Fig. 1). Three ribbed steel bars with 8 mm diameter are used as the bottom longitudinal reinforcement in SHCC. Additionally, three steel bars with 8 mm diameter and 600 mm length are provided at the center of the concrete part of the beam to ensure the continuity of reinforcement and the transfer of stresses from concrete to SHCC. These bars are referred to as coupling reinforcement in the paper and have a clear concrete cover depth of 10 mm from the interface. Stirrups are provided in shear-spans of the beam to prevent the failure outside the constant bending moment region. Figure 1 shows a schematic representation of the beam geometries, reinforcement configuration and the roughness profiles.

Table 1. Overview of the beams with their interface roughness profile and curing condition.

	Beam Name	Interface Treatment	Curing Condition
Set-1 (Effect of roughness)	Smooth	As cast	Sealed
	Profiled	Profiled	
	Rough	Sand with epoxy	
Set-2 (Effect of curing)	Smooth-Sealed	Smooth	Sealed
	Smooth-Exposed		Exposed

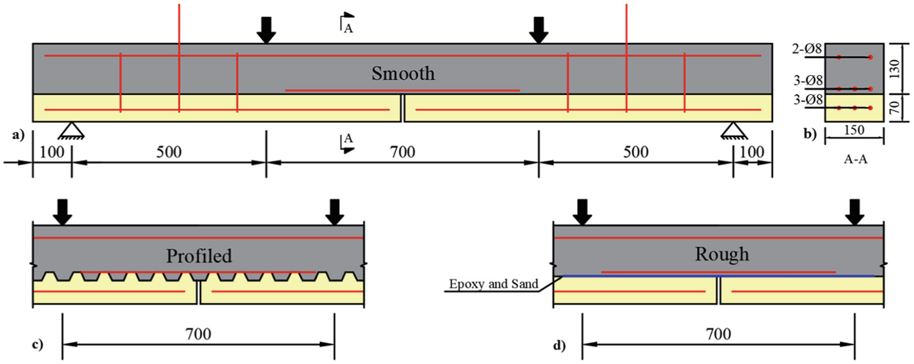


Fig. 1. Schematic representation of (a) longitudinal, (b) cross-section at A-A of the hybrid beam with smooth interface and the constant bending moment region of hybrid beams with (c) profiled and (d) rough interface. Concrete (Grey), SHCC (Yellow) and Reinforcement (Red). All dimensions are in mm.

2.2 Specimen Preparation and Casting

The hybrid beams for the first series are cast is two stages using wooden molds. The insides of the molds are oiled and a 4 mm thick plastic sheet is installed at mid-span to act as a notch (Fig. 2a). The reinforcement cages are installed with the help of spacers to ensure the designed cover depth of reinforcement and the bottom 70 mm thick SHCC layer is cast. For all the beams, the fresh surface of SHCC is first leveled using a trowel and then the surface is prepared according to the designed surface profile. The interface in Smooth is left as casted (Table 1, Fig. 2b) while for Profiled, a plastic sheet is pressed against the freshly cast SHCC. Since the commonly used mechanical roughening techniques (like sand blasting) are not suitable for SHCC due to absence of aggregates, the interface in Rough is prepared by adding a thin layer of epoxy on the hardened SHCC after 2 days of curing followed by the addition of sand with small size fractions (up to 2 mm). All surface profiles of SHCC are shown in Fig. 2b-2d. After 2 days of sealed curing of SHCC, all the interfaces are cleaned using pressurized air and ethanol, followed by placing of the coupling reinforcement and casting the concrete top layer. All of the three hybrid beams are left inside the wooden molds under sealed conditions until the testing day i.e. around 42 days after the casting of concrete layer.

The second series of beams, focusing on the effect of varying curing conditions, is cast using a similar approach with minor differences: (i) the notch is created using a 5 mm thick steel plate instead of the 4 mm thick plastic sheet (ii) the concrete is cast after fourteen days of sealed curing of SHCC instead of two days and (iii) the test is conducted after 28 days of casting concrete instead of 42 days. One beam is kept inside the mold under sealed conditions until the testing day while the other beam is taken out of the mold and exposed to a relative humidity of 58.8 ± 3.7% and a temperature of 22.1 ± 0.3 ℃ two days after casting of the concrete. The mix compositions of SHCC and the conventional concrete used for both the series are shown in Table 2.

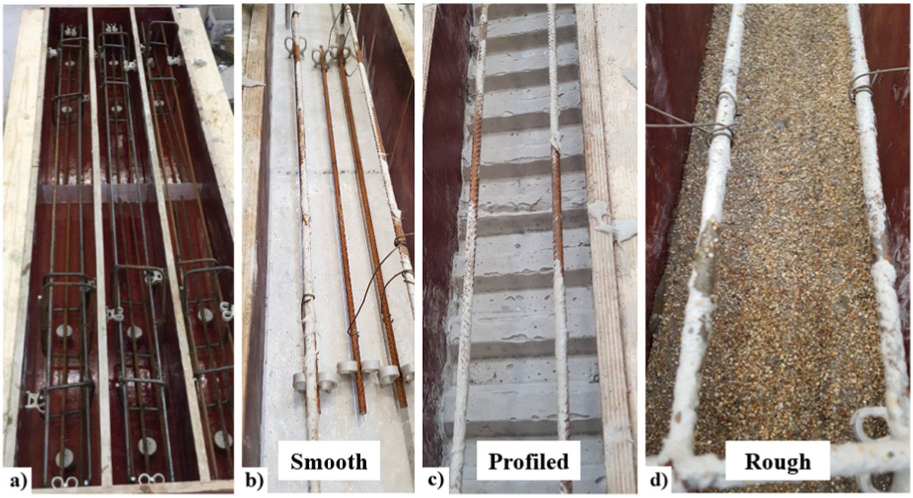


Fig. 2. Pictorial representation of (a) the wooden molds with reinforcement cages and plastic insertions to create notches at mid-span followed by the hardened (b) smooth interface with coupling reinforcement and the surface of (c) profiled and (d) rough interface.

Table 2. Mix composition of SHCC and conventional concrete.

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

2.3 Testing and Monitoring

All the beams are tested under a four-point bending configuration as schematically shown in Fig. 1a. A displacement-control test is performed with a loading rate of 0.002 mm/sec using a hydraulic jack and a 100 kN load cell to measure the load.

The monitoring systems used during testing are shown in Fig. 3. Seven Linear Variable Differential Transformers (LVDTs) are used to measure the opening of the interface at varying distances from the notch (v2-v5 and v6-v8) and two LVDTs are used to measure the opening of the joint at the bottom of the beam (v9-v10). The vertical deflection of the beam is measured using one LVDT close to the notch on one side (v1 in Fig. 3b). In this paper, only the results from v5-v6 for interface opening and v9-v10 for joint opening are discussed. In addition to the localized LVDT measurement, Digital Image Correlation (DIC) is performed on the other side of the beam during loading to capture the full-field deformations. Since significant out-of-plane motion is not expected during the loading of the beams, only one camera is used to capture the images and the field of vision is limited to the constant bending region of the beam as shown in Fig. 3c.

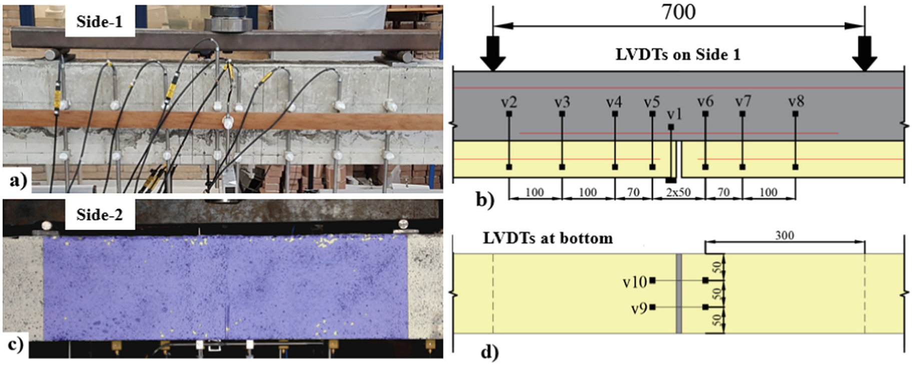


Fig. 3. (a) Pictorial and (b) schematic representation of LVDTs on one side of the beam. (c) DIC in the constant bending moment region on the other side and (d) LVDTs at the bottom of the beam.

3 Results and Discussion

GOM software [17] is used to post-process the images for DIC. The development of damage in beams with varying interface roughness profiles (Smooth, Profiled and Rough) is shown in Fig. 4 using the computed maximum principal strain. All the beams show very fine flexural cracks in concrete before the ultimate failure of the beam is reached. Comparing the principal strain contours of the beams at lower load levels (5 kN and 10 kN), it can be seen that Smooth already shows significant damage of interface on both sides of the notch while only minor cracks in concrete are visible in both Profiled and Rough. At failure load, Smooth developed a crack directly at the interface until the end of coupling reinforcement after which the crack propagated in concrete. However, both (Profiled and Rough) experienced only a partial failure at the interface after which the crack propagated along the coupling reinforcement in concrete. This type of failure can results from a combination of pulling out and the crack extending along the length of coupling reinforcement. However, the effect of pulling out is expected to be limited due to low stresses in coupling reinforcement. The partial failure at the interface signifies that for the given boundary conditions one of the governing mechanism is also the failure of concrete at the level of coupling reinforcement and not the interface between SHCC and concrete, thus these tests can only provide a lower bound estimate of the SHCC-Concrete interfacial strength.

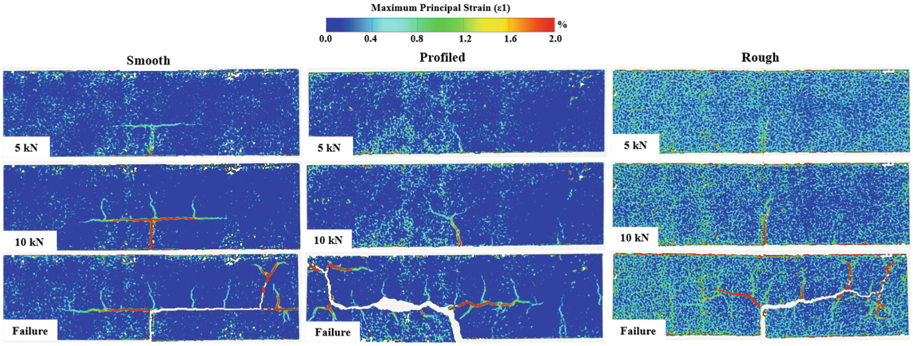
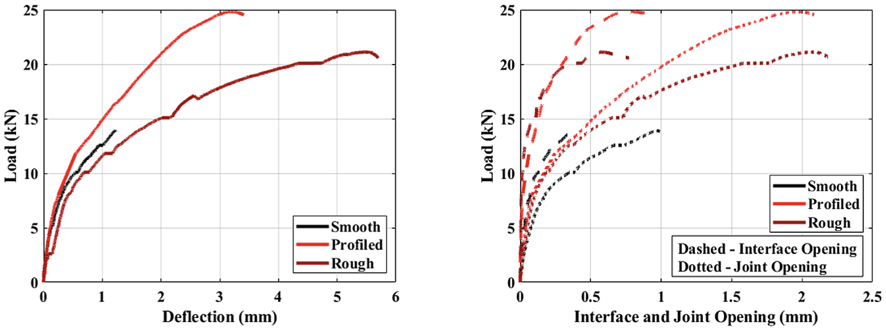


Fig. 4. Maximum principal strain contours showing the development of damage in Smooth, Profiled and Rough at 5 kN (top), 10 kN (middle) and failure (bottom).

The load deflection responses of Smooth, Profiled and Rough are shown in Fig. 5a while the load against maximum interface opening (maximum of v5 and v6 in Fig. 3b) and the maximum joint opening (maximum of v9 an v10 in Fig. 3d) are shown in Fig. 5b. It can be seen that Smooth shows the lowest load capacity of 13.9 kN while Profiled and Rough show a capacity of 24.8 kN and 21.1 kN, respectively. Possibly, the differences in ultimate capacities of Profiled and Rough can be explained by the relatively denser cracks and more crack branching around the profiled interface, leading to larger dissipation of energy before failure compared to Rough. From Fig. 5b, it can be seen that both Profiled and Rough were able to limit the opening of interface/joint better than Smooth when compared at the same load as also seen from DIC results (Fig. 4). This shows that the roughness increases the strength of the interface due to larger effective surface area of the bond [18]. Furthermore, both Profile and Rough, also shows larger interface and joint openings before failure of the beam showing that the stresses could be transferred until a larger crack opening at the interface.

The maximum principal strain contours with increasing load of the second series of the beams (Smooth-Sealed and Smooth-Exposed) are shown in Fig. 6. Similar to the previous series along with delamination, fine cracks in concrete part are observed in both the beams due to the activation of coupling reinforcement at the onset of the loading. Comparing the development of damage in the two beams, it can be seen that Smooth-Exposed exhibits delamination earlier, i.e. larger crack length at the interface than Smooth-Sealed at the same load levels presented before failure, probably due to the damage caused by the differential shrinkage between the two concretes. Furthermore,



(a) (b)

Fig. 5. (a) Load-deflection response of Smooth, Profiled and Rough along with (b) load against maximum interface and joint opening of the beams.

both the hybrid beams experience a failure directly at the interface until the end of coupling reinforcement allowing for a direct comparison for the effect of exposure conditions on the response of the beams.

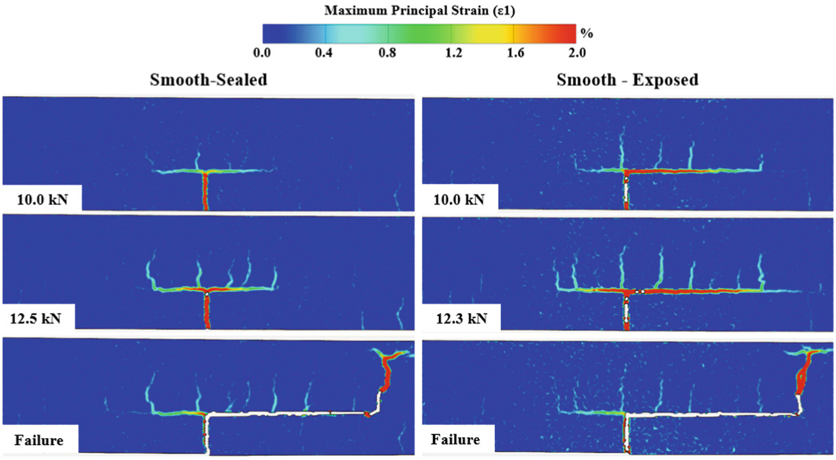
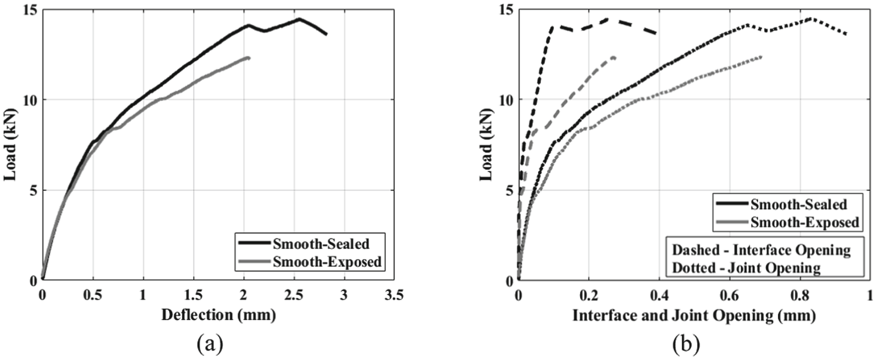


Fig. 6. Maximum principal strain contours showing the development of damage in Smooth-Sealed and Smooth-Exposed at 10 kN (top), 12.5 kN for sealed and 12.3 kN for exposed (middle) and failure (bottom).

The load-deflection response of Smooth-Sealed and Smooth-Exposed along with the load against interface and joint opening are shown in Fig. 7a and Fig. 7b, respectively. Although several cracks in SHCC were observed in Smooth-Exposed before the application of the mechanical load, the initial stiffness of the beam is comparable to the beam cured in sealed conditions. However, the effect of exposure condition is more obvious when comparing the behavior of the beam at a slightly higher load (from 5 kN) when Smooth-Exposed shows reduction in stiffness and increase in interface and joint opening compared to Smooth-Sealed. These observations complement the development of damage observed from DIC in Fig. 6. Furthermore, Smooth-Sealed failed at 14.5 kN while Smooth-Exposed failed at 12.3 kN – a reduction of 15%. The capacity of the smooth beams cured in sealed conditions from both the series (Smooth and Smooth-Sealed) is within 5% of each other. However, there are some differences in stiffness of the beams which are subjected to further study.



(a) (b)

Fig. 7. (a) Load-deflection response of Smooth-Sealed and Smooth-Exposed along with (b) load against maximum interface and joint opening of the beams.

From the progression of damage in DIC and the opening of joint/interface, it can be seen that the beam cured in sealed conditions was able to effectively limit the opening of the interface until a higher load level when compared to the beam exposed to drying. This shows that shrinkage can pre-damage the interface before the application of mechanical load and lead to premature debonding failure. Therefore, it is essential to appropriately quantify the damage caused by the differential shrinkage between the two concretes when measuring the strength of the interface.

The current results show that the suggested testing method is appropriate to study the effect of interface on the structural response of the beams and can capture the effect of differential shrinkage between the two concrete. However, due to only partial failure at the interface, limited influence of the roughness profile could be studied. Furthermore, due to a combination of failure (flexural cracking in concrete and damage at the interface) and complex boundary conditions of the test, these experimental observations need to be complemented with the numerical simulations which can allow to replicate the failure observed in experiments and calculate the strength of the interface using inverse analysis.

4 Conclusions

A hybrid beam with a notch at mid-span is proposed as a method to test the mechanical response of the interface between two concretes. The tests is designed such that the effects of environmental and mechanical loads are concentrated around the notch allowing to study the effect of differential shrinkage between the two concretes which is limitedly taken into account using small-scale bond tests. Two series of SHCC-Concrete notched hybrid beams are tested. In the first series, the interface roughness is varied between smooth, profiled and roughened. The results show that increasing the roughness of interface increases the load bearing capacity of hybrid beams by limiting the opening of the interface and allowing for larger interface openings to develop before the ultimate failure. For the second series, both the beams had smooth interface and one of the beams was kept in sealed conditions until the day of testing while the other was exposed to drying after two days of concrete casting. The beam exposed to drying showed 15% lower load-bearing capacity and poor control of interface opening when compared to the beam cured in sealed conditions. This signifies that the differential shrinkage between the two concrete can pre-damage the interface before the application of mechanical loads and that the testing procedure is suitable to capture this effect.

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