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SHEAR STRENGTHENING OF REINFORCED CONCRETE BEAMS WITH HIGH STRENGTH STRAIN-HARDENING CEMENTITIOUS COMPOSITES (HS-SHCC)

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Abstract: Strain-hardening cementitious composites (SHCC) have been considered as a potential material for strengthening of reinforced concrete (RC) structures. Its superior properties include high tensile strength, high ductility with multiple cracking behaviour and excellent durability. In this study, reinforced concrete beams with different shear span-to-depth ratio (1.5:1 and 2.5:1) were cast. Thin layers of high strength SHCC were patched on both sides of the RC beams as a strengthening system. The results show that the shear capacity of strengthened group is significantly increased compared to the control group. Upon ultimate failure, the formation of stable multiple cracking on the strengthening layer restrained surface concrete from spalling. This study concludes that high strength SHCC is efficient in shear strengthening of reinforced concrete structures.

1 INTRODUCTION

Modern day concrete as a structural material has a prolonged history since the 1900s. Around 1940s, Steel reinforced concrete was established as a feasible alternative to steel as a major construction material. Due to degradation of materials over time and increase in design load, some existing structures may no longer comply with current standards or even become functionally obsolete. It is obvious that total replacement of all such structures would be infeasible in terms of both time and cost. Strengthening and retrofitting of reinforced concrete structures are often the most practical solution [1].

Strain-Hardening Cementitious Composites (SHCC), also known as Engineered Cementitious Composites (ECC) or Pseudo-Ductile Cementitious Composites (PDCC), proposed by Li and Leung (1992), was developed and optimized with micromechanics theory. Its superior properties include high tensile strength, high ductility by strain hardening (can be up to several percent strain) and multiple cracking (with crack opening below 100µm) behavior. The desirable properties of SHCC can be achieved with merely 2% of short, random fibers [2-6]. Investigations and experiments [1,14] confirmed that SHCC is a promising repair and strengthening material for reinforced concrete structures. In addition, as a cement-based bonding system, the bond between SHCC and reinforced concrete is expected to be strong due to their compatibility in both mechanical and physical properties [1, 7-9].

The compressive and tensile strength of SHCC in the early works are normally 20-70MPa and 4-6MPa, respectively [10]. With reduction of water/binder ratio, addition of silica fume and use of high strength polyethylene (PE) fiber, SHCC with higher tensile strength of over 10MPa was developed [11-13]. In previous research, the use of high strength SHCC for the flexural repair of RC beams with corroded steel reinforcement has been successfully demonstrated [14].

It is well recognized that shear failure of reinforced concrete structures is brittle and catastrophic. Although steel reinforcement can be applied to design against shear failure, for systems subject to significant shear force such as transfer structures or structures located in seismic regions, rebar congestion and depletion of structural ductility are common problems. Also, cracks induced by shear load can open quite widely, which causes harm to structural durability. Moreover, due to the increase in loading requirement over time, some old reinforced concrete needed to be strengthened in both flexure and shear. Extensive research has been done on the shear properties of SHCC, indicating that SHCC is superior compared to ordinary concrete and Fiber Reinforced Concrete (FRC) in terms of shear response because of its high tensile strength and strain capacity, and closely spaced multiple cracks [15-20].

In this paper, reinforced concrete beams at a span-to-depth ratio of 1.5:1 and 2.5:1 were patched on the sides with thin layers of high strength SHCC and tested under four-point bending. The longitudinal reinforcement was designed such that shear failure would occur ahead of flexural failure, in order to obtain the ultimate shear strength of beams. The observed failure mode and measured ultimate load capacity were compared with the reference group.

2 EXPERIMENTAL PROGRAMME

2.1 Materials

The design of high strength SHCC usually includes lowering the water/binder ratio and adding proper amount of silica fume. To maintain workability, a polycarboxylate-based superplasticizer was added to the mix. Polyethylene (PE) fiber (12mm long and 24μm in diameter) was chosen due to its excellent tensile strength and high modulus (Table 1). Very fine sand with particle size of 0.125mm-0.18mm served as fine aggregates in the mix.

The high strength SHCC in this study was composed of cement, silica fume, sand and water in the mass ratio of 0.8:0.2:0.3:0.2, with 2% by volume of PE fiber. The 28-day tensile and compressive strength of SHCC were 10MPa (tested with dumbbell specimen with a cross-section area of 30mm×13mm at the neck, shown in Fig.1) and 120MPa (tested with 40mm cube), respectively. The stress-strain response of the SHCC is shown in Fig.2. The tensile strain capacity was no less than 3% and elastic modulus was 35GPa.

Table 1: Properties of PE fiber

Diameter (μm)	24
Length (mm)	12
Tensile strength (GPa)	3
Young's Modulus (GPa)	120
Specific Gravity	0.97

Figure 1: Direct tension test set-up for SHCC

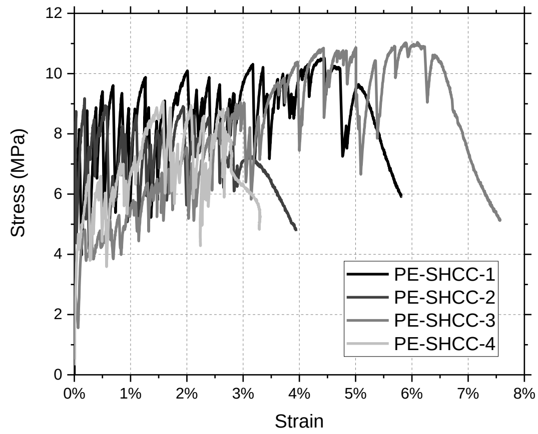


Figure 2: Stress-strain curve of HS-SHCC 28-day direct tension test

Table 2: Properties of steel reinforcement

	High-yield Ribbed Steel	Plain Round Steel
Yield Stress (MPa)	585	335
Tensile Strength (MPa)	610	530
Young's Modulus (GPa)	200*	200*

*As per local code of practice

Reinforced concrete beams were cast with ready-mix concrete from a local plant. The 28-day compressive strength was 36MPa (tested with 100mm cube) and elastic modulus was 26GPa. The properties of steel reinforcement used in the RC beams are listed in Table 2.

2.2 Specimen Preparation

Eight reinforced concrete beams were cast and divided into two groups according to the span-to-depth ratio (S/D), which were selected as 1.5:1 (total length L=1500mm) and 2.5:1 (L=2100mm) to promote the occurrence of shear failure. The four beams in each group were identical, two of them were set to be reference beams and the other two beams were to be shear strengthened with SHCC in a later stage. All RC beams had a sectional area of 180mm width and 350mm depth. Five Ø25mm and two Ø25mm high-yield ribbed steel bars were used as tensile and compressive reinforcement, respectively. The strengthening system with SHCC was only applied to one shear span of the RC beams. The shear reinforcement on the test span was plain round bars of 6mm diameter at 200mm center-to-center (c/c) spacing. The non-test span was heavily reinforced with high-yield ribbed bars of 10mm diameter at 100mm c/c spacing, which would ensure that ultimate failure would not happen on this side in both control and strengthened groups. The reinforcement details of RC beams are shown in Fig.4. For curing, all RC beams were kept wet by spraying water and covering with plastic sheets for 28 days. Afterwards, the concrete on the vertical faces of test span was roughened with a needle gun to expose sound aggregates for the beams to be strengthened with SHCC (Fig.3).

Figure 3: Roughened surface of RC beams

SHCC was prepared in the laboratory with a Hobart^{TM} HL400 mortar mixer. Raw dry materials including cement, sand and silica fume were mixed for a minute before water and superplasticizer were added. The mixing continued until the combination was fully transferred into consistent mortar. PE fibers were then added for another few minutes of mixing until they were well dispersed. The fresh mixtures were cast directly on roughened concrete surface in saturated-surface-dry (SSD) condition. The thickness of strengthening layer was 10mm on both faces of RC beams. The newly cast SHCC patches were cured by spraying water and covering with plastic sheets for 28 days before testing. The strengthening configuration of SHCC on RC beams is shown in Fig.5.

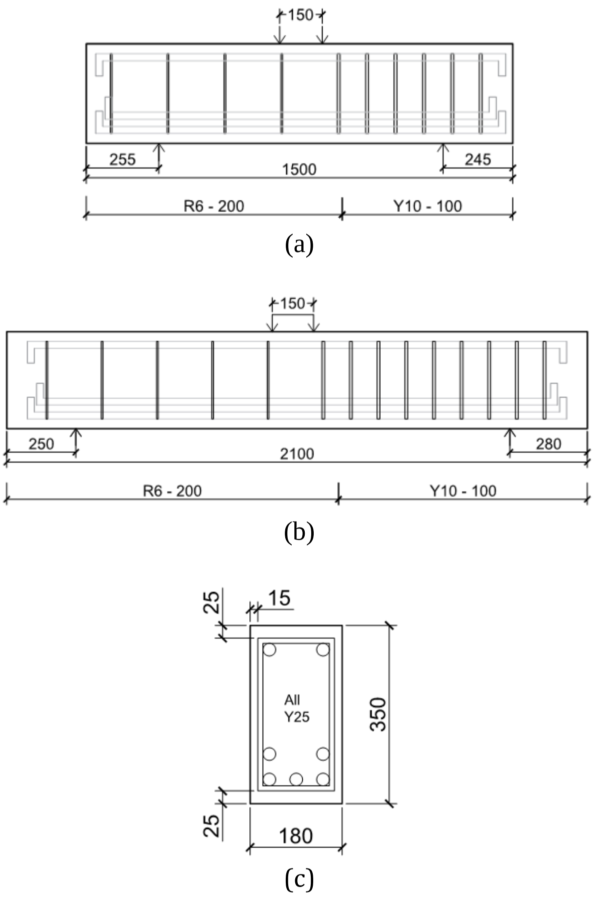


Figure 4: RC beam details (Unit: mm): (a) Group A, S/D=1.5:1, (b) Group B, S/D=2.5:1, (c) Section view

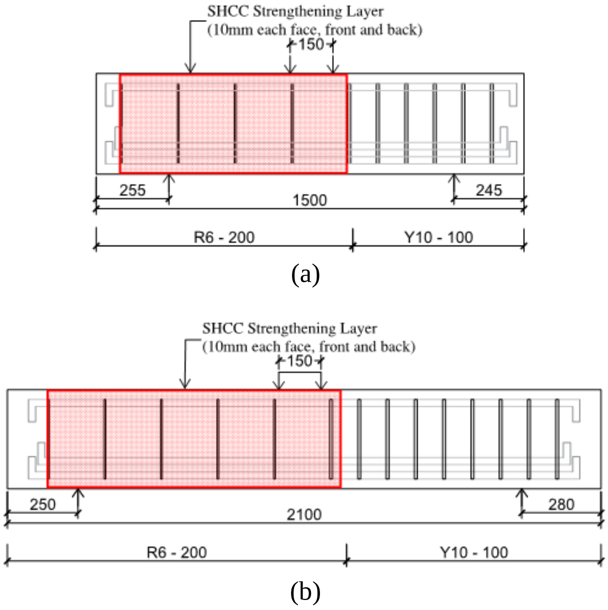


Figure 5: Strengthening configuration of RC beams: (a) Group A, S/D=1.5:1, (b) Group B, S/D=2.5:1

2.3 Testing Procedures

To demonstrate the effectiveness of SHCC in increasing shear capacity of RC beams, all specimens were tested under four-point bending configuration with a DARTEC testing machine (Fig.6). With the current RC details, the effective depth of RC beams was 284mm. Therefore, the shear spans were 425mm for group A (S/D=1.5:1) and 710mm for group B (S/D=2.5:1) with 150mm constant moment zone for both groups. The specimens were placed on two supports with a span of 1000mm for group A and 1570mm for group B. Three Linear Variable Displacement Transducer (LVDT) were placed at the mid-span and two supports to measure the deflection. The maximum beam deflection was calculated as the reading on the mid-span LVDT minus the average of the other two LVDTs. All beams were tested at a loading rate of 0.01mm/s. The test was terminated when the load dropped stably to about 80% of the ultimate load.

Figure 6: Four-point bending test set-up (S/D=2.5:1)

Figure 8: Crushing and spalling of surface concrete

3 RESULTS AND DISCUSSIONS

3.1 Failure modes

All reference beams in group A and group B exhibited shear failure with large diagonal cracks present at ultimate load (Fig.7). Minor flexural cracks at beam soffit near mid-span were present but they did not develop into major cracks affecting the failure. As the beam was over-reinforced with tensile and compressive bars, it did not collapse instantly after failure, but showed a certain level of ductility. Concrete crushing and spalling were observed by further increasing the deformation beyond ultimate capacity (Fig.8).

Figure 7: Shear failure of reference beams

For beams strengthened with SHCC layers, closely spaced multiple cracks were observed as the testing load increased (Fig.9). As the load was about to approach the ultimate load capacity, minor detachment was found between the SHCC and RC near the load points at the mid-span, where the deflection was the largest. At final failure, large shear cracks were found on RC part but no spalling or falling of debris were observed as these were prevented by the SHCC layers. The very fine cracks on SHCC did not fully expand and the system was able to maintain integrity. The debonding developed gradually, but the SHCC did not fall off from the concrete substrate (Fig.10).

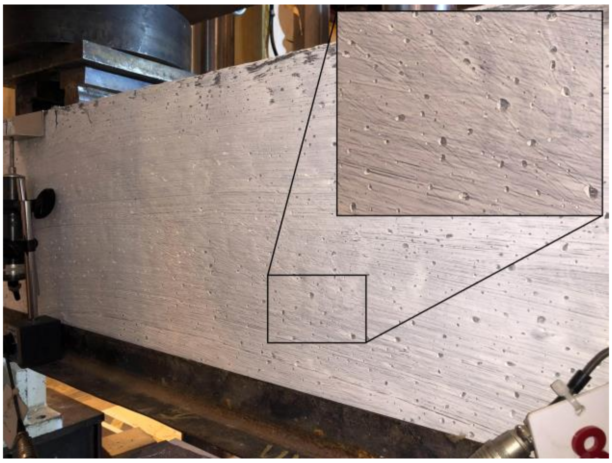


Figure 9: Closely spaced fine cracks on SHCC layer

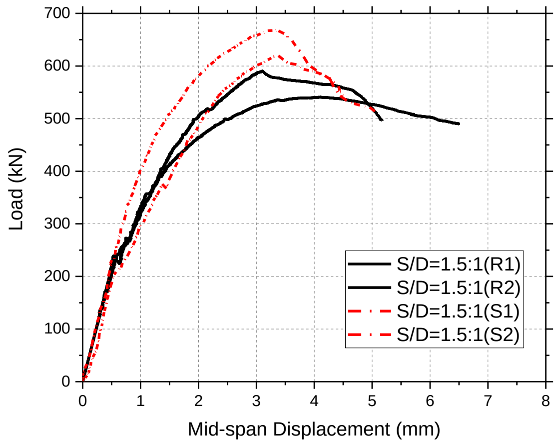
Figure 10: Debonding of SHCC at beam mid-span

3.2 Load-deflection curves

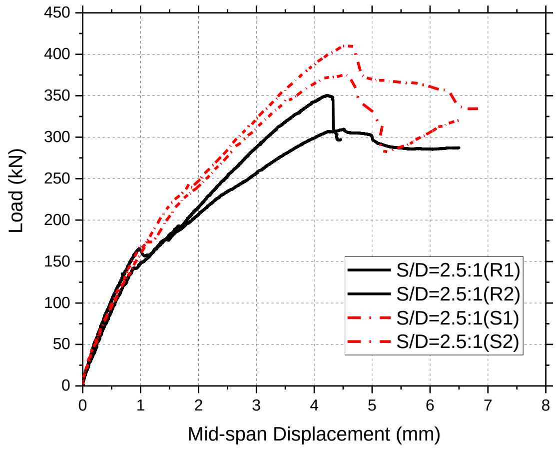
The load-deflection responses of all test beams are shown in Fig.11. In both group A (S/D=1.5:1) and group B (S/D=2.5:1), notable increase in ultimate load capacity was observed. For group A, the increase in ultimate load capacity after strengthening was 78.3kN, which is 13.84% enhancement compared to reference beams. For group B, the increase was 62.2kN, equivalent to an 18.82% enhancement. Considering that the additional shear load sustained by the test span was provided by the SHCC strengthening layer, and ignoring its shearing effect along diagonal cracks, the tensile stress provided by SHCC along the shear crack can be calculated by the following formula:

$$\sigma_t = \frac{V_{add}}{2t \times d \times \cot\theta}$$

where θ is the inclined angle of shear cracks which is assumed to be 45° for simplicity. The results of four-point bending tests and the calculated SHCC tensile stress are presented in Table 3.



(a)



(b)

Figure 11: Load-deflection curves for testing beams: (a) Group A (S/D=1.5:1), (b) Group B (S/D=2.5:1)

Table 3: Results of four-point bending test

Group No.	A	B
S/D Ratio	1.5:1	2.5:1
$P_{Reference}$ (kN)	565.6	330.4
$P_{Strengthened}$ (kN)	643.9	392.6
$P_{add}=P_S-P_R$ (kN)	78.3	62.19
Increase in P_{add}	13.8%	18.8%
$V_{add}=P_{add}/2$ (kN)	39.2	31.1
Tensile Stress by SHCC (MPa)	6.9	5.5

The tensile stress provided by SHCC in four-point bending test was slightly lower than that obtained from direct tensile test for the following reasons. First, the failure of SHCC strengthened RC beams was governed by the bond strength between SHCC and RC. As the load increased, the concrete cracked and lost its stiffness rapidly. However, as significant tensile stress can be carried by the fibers bridging the cracks, the stiffness reduction in SHCC was much less significant. Due to the increasing mismatch in stiffness, RC and SHCC responded differently under loading and gradually detached, especially at mid-span, where the deformation was the largest. At ultimate load capacity, the specimen failed because debonding occurred at certain locations, and SHCC could no longer work with RC to sustain additional loads. The actual capacity of SHCC was therefore not reached. Secondly, the shear stress transferred across a crack due to crack shear sliding mainly carried by the fiber bridging action may lead to increased fiber rupture and reduction of tensile stresses normal to the crack surface based on previous study with micromechanical analysis [21].

4 CONCLUSIONS

In this study, RC beams strengthened with high strength SHCC were tested against un-strengthened counterparts. At span-to-depth ratios of 1.5:1 and 2.5:1 and heavily reinforced in flexure, the specimens are ensured to fail in shear, and ultimate shear capacity was obtained. By comparing the results on reference beams and strengthened beams, the following conclusions can be drawn.

1) The shear capacity of strengthened beams is improved compared to the un-strengthened reference beams. Percentage-wise, the improvement of RC beams with larger S/D ratio (2.5:1) is more remarkable than beams with smaller S/D ratio (1.5:1). However, considering the tensile stress provided by SHCC, the results are comparable.

2) The cement-based bonding system between RC and SHCC is efficient. Debonding only occurred at mid-span between two materials under ultimate loading condition. Notable increase in load capacity was achieved even without additional anchoring system. In actual practice of shear strengthening, SHCC should be patched along the full span of RC beams. The debonding at mid-span should be better restrained by the beam ends. Alternatively, shear keys may be applied to ensure better bonding and more significant improvement on ultimate load capacity.

3) The failure mode of strengthened RC beams dominated by shear capacity is improved. Shear failure is usually brittle with large cracks, accompanied by collapse of crushed concrete. With SHCC patched on the beam sides, cracks on the strengthening layers are restricted to fine width and no spalling of surface concrete will occur.

The results in this paper demonstrated the feasibility and effectiveness of using high strength SHCC as strengthening method for reinforced concrete beams prone to shear failure. Such simple yet effective means should reduce significant time and labor force while enhancing the quality and safety of concrete structures. Further research should focus on the application of this approach in other structure members subject to high shear load, such as beam-column joints, corbels, and structures in seismic regions.

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