

# Use of High Strength SHCC for the Repair of Concrete Structures with Significant Steel Reinforcement Corrosion

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**Abstract.** Steel corrosion is a major cause of deterioration of concrete structures, which can lead to significant loss of steel area that affects structural safety. The most common repair approach is to splice a new piece of steel to the corroded reinforcement, which is time and cost consuming, as a large volume of sound concrete on both sides of the corroded steel has to be removed to provide sufficient lap length for stress transfer. The present study focuses on a new repair methodology based on the use of high strength Strain-Hardening Cementitious Composite (SHCC). With the SHCC providing tensile load carrying capacity to compensate for the steel loss, splicing of additional steel reinforcement is no longer necessary. The amount of concrete removed to provide the bond length is then significantly reduced. In this paper, the design of high strength SHCC is first discussed. Then, reinforcements with reduced area over part of their length are embedded inside SHCC blocks with cross-sectional area representative of typical concrete patches and having different bond lengths on both sides. Direct tension test is then performed to investigate the feasibility of the SHCC to recover the load carrying capacity. The results demonstrate the potential of a new repair technique which is more efficient and less costly.

## 1 Introduction

The durability and safety of concrete structures are greatly affected by the corrosion of the steel reinforcements, which can induce cracking and spalling of the concrete cover. Once the steel reinforcement is exposed to the external environment, corrosion occurs at a higher rate, leading to rapid loss of the steel area. To recover the original safety factor, structural repairs must be performed. For a concrete member with a significant loss of steel area, the most common repair method is to splice an additional piece of steel reinforcement to the corroded rebar to compensate the area reduction. The repair operation involves the removal of sound concrete on the two sides of the corroded rebar, up to at least 40 times the diameter of the new reinforcement, to provide sufficient lap length for stress transfer. This is a very time consuming and costly process.

Strain-hardening cementitious composites (SHCCs) with tensile hardening behavior up to several percent strain and excellent crack control ability may be an attractive alternative for the repair of concrete structures with significant steel reinforcement corrosion, as SHCC can still carry significant tensile stress after the rebar starts to yield

at the reduced cross section. Strong bonding between steel reinforcements and SHCC has been reported by Fischer and Li (2002), implying that relatively short bond length will suffice. Based on a rough calculation, SHCC that can carry tensile stress of 8–10 MPa should be sufficient for the repair application. Early work on SHCC has focused on the achievement of high ductility and the tensile strength is normally 4–6 MPa. Recently, several research groups have developed SHCC with high strength, through the reduction of the water/binder ratio, incorporation of silica fume and the use of polyethylene (PE) fiber with very high strength of 2.5–3 GPa. In Kamal et al. (2008), with 1.5% in volume of PE fiber added to a high strength matrix, SHCC with 10 MPa tensile strength and ductility of 2.8% was made. In Ranade et al. (2013a, b), SHCC with tensile strength between 11.8–14.5 MPa and ductility of 2.5–3.5% was made with 2% of PE fibers. In Curosu and Mechtcherine (2016), high strength SHCC was tested under impact loading, and the performance was found to be superior to that of normal strength SHCC.

In this study, a high strength SHCC with PE fibers was designed through increasing the sand content and reducing the water/binder ratio. Then, reinforcements with reduced area over part of their lengths were prepared to simulate the corroded steel, and SHCC blocks with cross sectional area representative of typical concrete patch were placed over the region of reduced area, with different bond lengths on the two sides. Direct tension test was then performed on the specimens to investigate the feasibility of SHCC to recover the load carrying capacity.

## 2 Design of High Strength SHCC

### 2.1 Materials

To design the high strength SHCC, it is desirable to maintain a low water/binder ratio (w/b ratio) and replace some of the ordinary Portland cement with silica fume (SF). Several mixes investigated in this study are listed in Table 1. In all mixes, 20% of the cement was replaced by silica fume, and the w/b ratio was no higher than 0.18. Three kinds of silica sands with different particle sizes (595–1410, 297–595 and 177–297  $\mu\text{m}$ ) were used as fine aggregates. Super-plasticizer (SP) provided by Grace<sup>TM</sup> was added to ensure good workability of the mortar with very low w/b ratio. A kind of domestic PE fiber, with properties given in Table 2, was employed for its high strength

**Table 1.** Mix proportions of the high strength SHCC.

Mixture	Cement	Silica fume	Sand*	Water	SP	Fiber
M1	0.8	0.2	0.5	0.180	2.0%	2%
M2	0.8	0.2	0.8	0.180	1.7%	2%
M3	0.8	0.2	0.3	0.160	2.0%	2%
M4	0.8	0.2	0.3	0.155	2.5%	2%
M5	0.8	0.2	0.3	0.145	2.5%	2%

\*Sand content: 15% of 595–1410  $\mu\text{m}$ , 35% of 297–595  $\mu\text{m}$ , 50% of 177–297  $\mu\text{m}$ .

**Table 2.** Nominal geometry and mechanical properties of PE fiber.

Fiber properties	Diameter, $\mu\text{m}$	Length, mm	Strength, GPa	Young's modulus, GPa	Specific gravity
PE fiber	24	12	3	120	0.97

and modulus. The SHCC mixes can be grouped into two series for studying different approaches to achieve high strength. One series (M1 and M2) focuses on the effect of sand content under fixed w/b ratio of 0.18, while the other series (M3–M5) studies the effect with different w/b ratios under fixed sand/binder ratio of 0.3.

## 2.2 Specimen Preparation and Testing Procedures

Cement, silica fume and sand were first dry mixed in a Hobart<sup>TM</sup> HL400 mortar mixer. Then, water and SP were added and the mixture was mixed until it appeared flowable. This procedure took much longer time than that of normal SHCC because of the extremely low w/b ratio and fine particle sizes of cement and silica fume. PE fibers were subsequently added into the mortar and mixed until they were sufficiently well dispersed. The fresh mixture was very viscous, which was necessary for a repair material. Since the dosage of SP was high, it took longer time for the specimens to set, and they were demolded after 48 h. After demolding, the specimens were cured at a temperature of  $23 \pm 2$  °C and relative humidity of  $95 \pm 5\%$  until 14 days after casting.

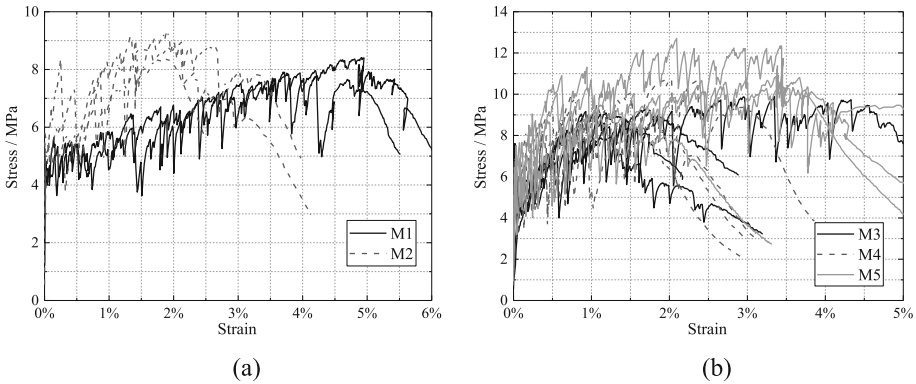
At least three cube specimens measuring  $40 \text{ mm} \times 40 \text{ mm} \times 40 \text{ mm}$  were prepared for uniaxial compression test. The loading rate was set as 1 kN/s. For the tension test specimens, at least four dumbbell specimens were prepared according to JSCE's recommendation (JSCE 2008), with a cross-sectional area of  $30 \text{ mm} \times 13 \text{ mm}$  in the middle. They were tested in a 25 kN servo-hydraulic machine, with the gripped ends strengthened by aluminum plates. A linear variable displacement transducer (LVDT) was attached to the specimen to measure the elongation of the middle part of the specimen. The loading was displacement controlled at a rate of 0.5 mm/min, as recommended by JSCE.

## 2.3 Test Results and Discussion

The test results are summarized in Table 3, and the stress–strain curves for direct tension specimens are shown in Fig. 1. From the test results, all mixes present very high compressive strength (over 130 MPa), and it is obvious that both increasing the sand content (at the same w/b ratio) and decreasing the w/b ratio (at a relatively low sand content) can improve the tensile strength. Strain capacity is not the major focus of the work, but the SHCC should be able to carry significant stress (and hence compensate for steel loss) under a relatively small deformation (e.g., at around 0.5% strain). In the mixing process, M2 exhibited poor fiber dispersion even after very long mixing time. As the flowability of M2 was comparable to other mixes, it should be the high sand content that kept the fiber from good dispersion. Higher sand content was

**Table 3.** Summary of test results for M1-M5 at 14-day age.

Mixture	Compressive strength (MPa)	Tensile strength (MPa)	Strain capacity (%)
M1	148	8.4	4.6
M2	154	9.0	1.8
M3	147	9.1	1.8
M4	138	9.5	1.2
M5	150	10.8	2.4

**Fig. 1.** Tensile stress-strain curves of (a) M1 and M2, (b) M3 to M5.

therefore not tried. On the other hand, by keeping the sand content at a low level while decreasing the w/b ratio (and with more SP added to maintain enough workability), a high strength could be achieved.

### 3 Direct Tension Tests for SHCC Patch

#### 3.1 Specimen Preparation

To investigate whether the proposed high strength SHCC could recover the loss of load capacity of the reinforcements, direct tension tests were performed on steel reinforced SHCC blocks with dimensions shown in Fig. 2(a). Also shown in the figure is the shape of a typical repair patch, with additional concrete removed above the corroded reinforcement to ensure sufficient bonding. The reason for choosing a smaller rectangular section (with an area of  $6000 \text{ mm}^2$ ) in the test rather than the patching shape ( $7500 \text{ mm}^2$ ) was to eliminate eccentricity without overestimating the performance. Mixture M5 was adopted as the SHCC material. The reinforcement was a high yield strength (510 MPa) bar with 20 mm diameter. The middle part of the rebar with a length of 50 mm was ground to a diameter of 17.3 mm to simulate 25% area loss due to corrosion. In total 6 specimens with three different bond lengths (4.0D, 5.5D and 7.0D, D is the full diameter of rebar) on both sides were studied. Steel rebars with

reduced sections were also tested for comparison. In a real member, the patch is bonded to the concrete substrate along which stress transfer can also take place. The test is therefore conservative in terms of the required bond length and the ability of the SHCC to recover the load carrying capacity.

### 3.2 Test Setup

The test setup is shown in Fig. 2(b). A 500 kN servo-hydraulic machine with fixed grips was used, with a loading rate of 0.5 mm/min before and 1.0 mm/min after steel yielding. Two linear variable differential transformers (LVDT) were attached to the specimens to measure the elongation over a range of 100 mm in the middle, where most of the cracks were formed. During the test, the load and displacement of the machine were also recorded.

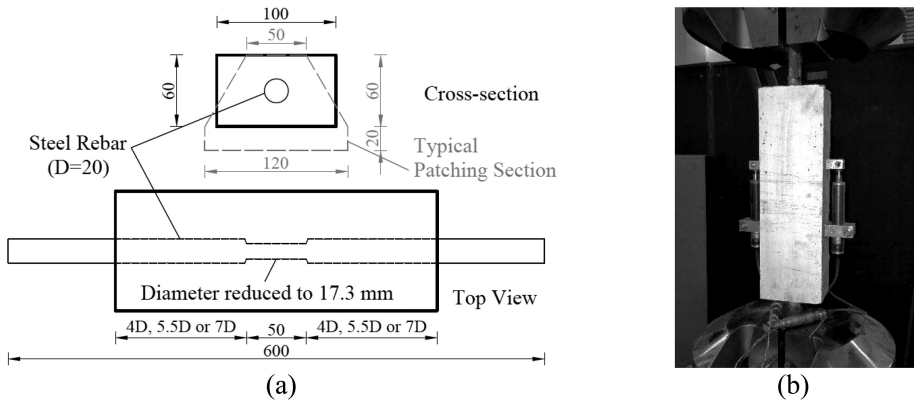


Fig. 2. (a) Dimensions of a typical concrete patch (b) Direct tension test setup.

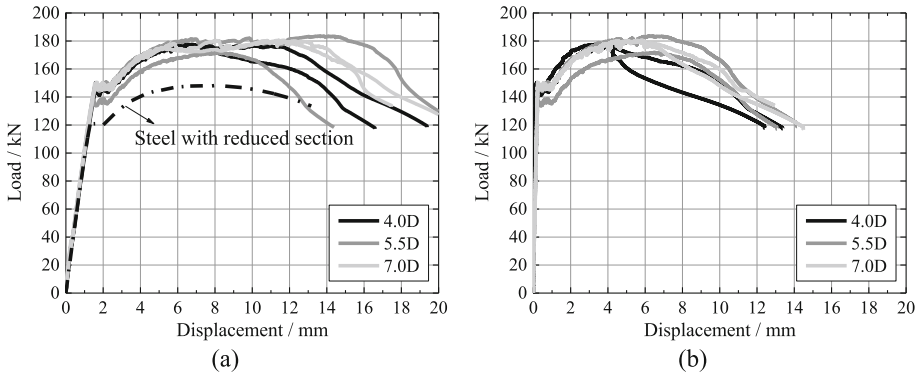


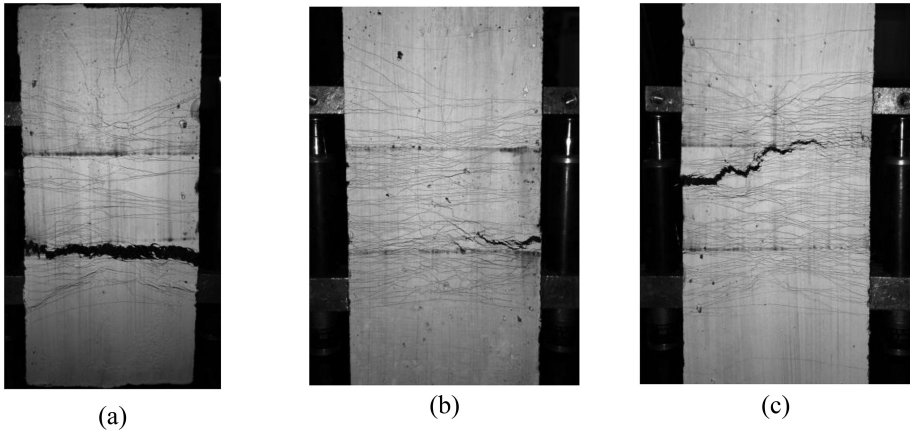
Fig. 3. (a) Load-machine displacement (b) Load-averaged LVDT reading.

### 3.3 Results and Discussion

The relations between the load and the displacements recorded from both LVDTs and the testing machine for specimens with different bond lengths are shown in Fig. 3. Failure patterns of some specimens are shown in Fig. 4.

For each specimen, the two kinds of curves show similar trend initially but different magnitudes in displacement due to different gauge lengths. The load first increases linearly with the displacement before it reaches 30–40 kN, reflecting elastic behavior, followed by a sudden decrease in load and stiffness caused by the first crack in the SHCC. The curves afterwards are still almost straight. A few transverse cracks were found over the whole specimens, and short splitting cracks appeared at the two ends. Most curves show a plateau at around 150 kN, indicating that the steel with reduced section has yielded. At this stage, multiple fine cracks occurred over the gauge length of the LVDTs, as the load transferred from the steel to the SHCC in that region was sufficient to cause multiple cracking. After the plateau, there is a further load increase, contributed by the hardening of both the steel and the SHCC. During the hardening, cracks within the gauge length became denser and the distribution was uniform. In the meantime, more splitting cracks appeared at the ends, but were effectively bridged by fibers. The splitting cracks almost reached the region of reduced steel section for specimens with 4.0D bond length, but bond failure did not occur. Beyond hardening, one specimen with 4.0D and one with 5.5D bond length showed gradual decrease in load, caused by premature failure of the SHCC plausibly due to poor casting. For other specimens, when the load reached around 180 kN, the load–displacement curves recorded from the machine and LVDTs start to deviate. The former ones show significant displacement increase at this load level, while the latter do not exhibit such a trend. These results indicate the yielding of uncovered steel at the two ends. During the yielding, the SHCC actually underwent further cracking and pullout of the fibers, and finally localization occurred, resulting in failure accompanied by a subsequent descending trend of the curves. Upon further loading, a concave part in the curves implies that the stress in the SHCC gradually dropped to zero.

From the results, 4.0D bond length is already enough for transferring the load from steel rebar to the SHCC, and enabling the specimen to reach the yield load of the original steel rebar. In real practice, with additional bonding between SHCC and concrete substrate, it is sufficiently safe to use such short bond length. Compared to traditional repair method, the removal of sound concrete and the use of the repair material can be greatly reduced. In terms of the recovery of load capacity, comparing the curves for steel reinforced SHCC and the uncovered steel bar with reduced section (Fig. 3(a)), almost 27 kN could be compensated by the SHCC when the reduced section yielded, and the load capacity could be fully recovered during hardening stage, as long as no premature failure occurred in the SHCC. However, according to tensile test results, the strength of the SHCC could have reached at least 8 MPa at the first plateau of the curves (within 1% strain, estimated from Fig. 3(b)). With the SHCC area of about 5700 mm<sup>2</sup> in the specimens, the estimated load contribution should be over 45 kN. One explanation for this difference would be the fiber orientation: SHCC blocks provide another free dimension for fibers to orientate themselves, compared to the thin dumbbell specimens. Another reason would be the bending effect brought by



**Fig. 4.** Failure patterns of specimens with bond length (a) 4.0D (b) 5.5D (c) 7.0D.

inhomogeneous fiber dispersion, which was observed in the testing (Fig. 4), leading to a non-uniform stress distribution. Nevertheless, the results are still promising, as the sectional area of the patch is likely to be much larger in practice and severe corrosion may not occur at the location with maximum moment. Therefore, the potential of the proposed repair method is illustrated.

## 4 Conclusions

This study focuses on using high strength SHCC as a repair material to compensate the loss of load capacity in concrete structures due to severe corrosion of steel reinforcement. Based on the mix design study and direct tension tests on SHCC blocks containing rebar with reduced area, the following conclusions can be drawn:

- (1) With the addition of silica fume and a very low water/binder ratio in the SHCC, high tensile strength of over 8 MPa can be achieved. A larger sand content can increase the tensile strength, but may result in a poor fiber dispersion, whereas lowering the w/b ratio can effectively improve the tensile strength;
- (2) SHCC patch repair can fully recover load-carrying capacity during the hardening of the reduced steel, and 4.0D bond length is already enough for corresponding load transfer. Although the performance of the SHCC is not as high as expected, the test results still demonstrate the feasibility and potential of the SHCC for patching repair.

In ongoing work, structural elements with SHCC patching repair will be designed, prepared and tested to investigate the performance of the repair material in the structure. Verifying the effectiveness of this repair method should facilitate practical applications.

## References

- Curosu, I., Mechtcherine, V., Millon, O.: Effect of fiber properties and matrix composition on the tensile behavior of strain-hardening cement-based composites (SHCCs) subject to impact loading. *Cem. Concr. Res.* **82**, 23–35 (2016)
- Fischer, G., Li, V.C.: Influence of matrix ductility on tension-stiffening behavior of steel reinforced engineered cementitious composites (ECC). *Struct. J.* **99**(1), 104–111 (2002)
- JSCE: Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC). Concrete Engineering Series no. 82. JSCE, Tokyo (2008)
- Kamal, A., Kunieda, M., Ueda, N., Nakamura, H.: Evaluation of crack opening performance of a repair material with strain hardening behavior. *Cem. Concr. Compos.* **30**(10), 863–871 (2008)
- Ranade, R., Li, V.C., Stults, M.D., Rushing, T.S., Roth, J., Heard, W.F.: Micromechanics of high-strength, high-ductility concrete. *ACI Mater. J.* **110**(4), 375–384 (2013a)
- Ranade, R., Li, V.C., Stults, M.D., Heard, W.F., Rushing, T.S.: Composite properties of high-strength, high-ductility concrete. *ACI Mater. J.* **110**(4), 413–422 (2013b)