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Use of high strength Strain-Hardening Cementitious Composites for flexural repair of concrete structures with significant steel corrosion

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HIGHLIGHTS

- This study explores using SHCC to repair RC members with severely corroded rebars.
- 14-Day high-strength SHCC has tensile strength of 10 MPa and strain capacity over 2%.
- SHCC patch can fully recover the load-carrying capacity of the rebar with reduced area.
- The proposed repair method is more efficient and less costly than conventional approach.

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ABSTRACT

Steel corrosion is a major cause of deterioration for reinforced concrete structures, leading to significant area loss of rebars that affects structural safety. The most common repair approach is to splice additional reinforcements to the corroded rebars, which is time consuming and costly, as a large volume of sound concrete beyond the corroded part must be removed to provide sufficient lap lengths. The present study explores a new repair technique using high strength Strain-Hardening Cementitious Composites (SHCC) in the aforementioned situation. With SHCC compensating for the area loss of rebars, splicing additional reinforcements or removing a large amount of concrete is not necessary. In this paper, the design of high strength SHCC was first discussed. Then, rebars with reduced area were embedded inside SHCC blocks and tested under direct tension. Further, beams containing rebars with reduced area and patched with SHCC were tested under four-point bending. The test results at different scales verify the feasibility of the proposed repair technique which is more efficient and less costly. The findings of this study can support future repair applications using SHCC.

1. Introduction

The durability and safety of reinforced concrete structures are greatly affected by the corrosion of the rebars, which can induce cracking and spalling of the concrete cover. Once the rebars are exposed to external environment, the corrosion occurs at a higher rate, leading to rapid area loss of rebars. To recover the original safety factor, structural repairs must be performed. For a concrete member with significant corrosion, the most common repair method is to splice an additional piece of reinforcement to the corroded rebars to compensate for the area reduction. In Hong Kong practice, the conventional repair operation involves the removal of sound concrete on the two longitudinal sides of the corroded rebar, about 30 times the diameter of the new reinforcement, to provide sufficient lap lengths for stress transfer. This is a time consuming and costly process.

Strain-Hardening Cementitious Composites (SHCC), also known as Engineered Cementitious Composites (ECC), Pseudo-Ductile Cementitious Composites (PDCC) or Ultra-High Toughness Cementitious Composites (UHTCC), can be attractive materials for the above-mentioned repair applications. SHCC with tensile strain hardening behavior up to several percent strain, can be made by adding random short fibers to brittle cementitious matrix. The high ductility (or pseudo-ductility) results from the formation of closely spaced multiple cracks with opening about 100 μm until the ultimate tensile strength is reached at the end of the hardening regime [1–13]. The development of SHCC was not through trial and error, but was guided by the theory of micromechanics. The criteria to achieve pseudo-ductile behavior were first proposed by Li and Leung [14], and were further refined in Li [15], Leung [16] and Kanda and Li [17]. Based on these criteria, the properties of the

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matrix, fiber and fiber/matrix interface can be selected or tuned to achieve pseudo-ductile behavior with the addition of about 2% (volume fraction) of polyvinyl alcohol (PVA) or polyethylene (PE) fibers [15]. As pseudo-ductility of the material can translate into high deformation capacity, high energy absorption and excellent durability (by controlling the crack width to limit water/chemical penetration) of structural members, SHCC has been shown to have advantage over conventional concrete in various structural applications. Notable examples include the link slab for continuous bridges [18], coupling beams in concrete buildings [19,20], beam/-column joint [21], wall panels [22], members under high shear stress [23], the repair layer of concrete pavements [24], concrete dams [25] as well as regions of stress concentration such as in the vicinity of an anchor bolt [26] or the anchor for post-tensioning tendons [27]. Moreover, strong bonding between steel rebars and SHCC has been reported by Fischer and Li [28], which is an advantage for the repair application as a relatively short bond length suffices.

In the repair applications for corroded rebars in flexural concrete members, based on the experience in Hong Kong, it is reasonable to assume a SHCC patch with cross-sectional area at least 20 times that of the original steel rebar, and up to 30% area loss for steel rebar due to significant corrosion. With the strength of steel rebars being about 550 MPa (commonly used high-yield rebar), the required tensile strength of SHCC should be over 8 MPa. For the mechanical properties of SHCC, early work mainly focused on the achievement of high tensile strain capacity (which is favored by low matrix toughness), and the compressive and tensile strengths are normally 20–70 MPa and 4–6 MPa, respectively [29]. In the last decade, several research groups have developed SHCC with high tensile strength, through the reduction of the water/binder ratio, incorporation of silica fume and utilization of polyethylene (PE) fiber with high tensile strength (2.5–3 GPa). In Kamal et al. [3], by adding 1.5 vol% of PE fiber to a high strength matrix, SHCC with tensile strength of 10 MPa and ultimate tensile strain of 2.8% was made. Their material was developed as a repair mortar, but it was applied as a layer to the bottom of beam members rather than employed as load-bearing patching material to replace spalled concrete. In Ranade et al. [5,30], SHCC with tensile strength of 11.8–14.5 MPa and ultimate tensile strain of 2.5–3.5% were made with 2 vol% of PE fibers. However, their composites had to be subjected to high temperature curing at 90 °C for 8 days (5 days in water plus 3 days in air) after room temperature curing for 7 days, to obtain the high tensile strength. Such a curing condition is hard to implement in the field for a repair mortar. The properties of SHCC without thermal curing were not reported in Ranade et al. [5,30]. In Curosu et al. [9], four types of fibers including PE fiber were utilized to successfully achieve high tensile strength over 8 MPa and ultimate tensile strain about 4%. In He et al. [10], SHCC with tensile strength of about 13 MPa and ultimate tensile strain over 2% were developed by enhancing the fiber/matrix interfacial bond through coating carbon nanofibers on 1.5 vol% PE fiber. Recently, SHCC with tensile strength up to 18 MPa and ultimate tensile strain about 8% was achieved under conventional curing by Yu et al. [13] with 2 vol% PE fiber and a matrix with high toughness.

In the present study, a high strength SHCC with PE fibers was first designed through increasing the sand content and reducing the water/binder ratio. To investigate the potential of SHCC to recover the load-carrying capacity of corroded rebars, direct tension test was performed on rebars with reduced area and patched by SHCC. The SHCC patch was designed to have a cross-sectional area representative of typical concrete patch, and different bond lengths between SHCC patch and rebars were explored. Further, beam specimens using rebars with reduced section and patched with SHCC with different bond lengths were tested under four-point bending along with control specimens. The test results were then analyzed to assess the feasibility of the proposed repair method.

2. Design of high strength SHCC

2.1. Materials

To design high strength SHCC, it is desirable to maintain a low water/binder ratio (w/b ratio) and introduce a proper amount of silica fume. Several mixes investigated in this study are listed in Table 1. In all mixes, 20% of the cement was replaced by silica fume as in [3], and the w/b ratio was no higher than 0.18. Silica sands with particle size less than 1.4 mm were used as fine aggregates. A polycarboxylate-based super-plasticizer was added to ensure good workability of the mixes with very low w/b ratios. A kind of PE fiber shown in Fig. 1, with properties given in Table 2, was employed due to its high strength and modulus. The SHCC mixes in Table 1 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 another series (M3-M5) studies the effect of different w/b ratios with 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™ HL400 mortar mixer. Then, water and super-plasticizer were added and the mixture was mixed until it appeared flowable. This procedure took much longer time than 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 cementitious matrix and mixed until they were sufficiently well dispersed. The fresh mixture was very viscous, which was necessary for a repair material, thus the specimens were cast by pressing into cubic and dumbbell-shaped molds, with detailed geometry described in the next paragraph. Since the dosage of super-plasticizer was high, it took longer time for the specimens to set, thus they were demolded after 48 h. After demolding, the specimens were cured at a temperature of 23 ± 2 °C and relative humidity of 95 ± 5% until 14 days after casting.

At least three cube specimens of size 40 mm × 40 mm × 40 mm were prepared for uniaxial compression test. For uniaxial tension test specimens, at least four dumbbell specimens were prepared according to a recommendation from the Japan Society of Civil Engineers (JSCE) [31], with a cross-section area of 30 mm × 13 mm in the middle (Fig. 2). They were tested in a 25 kN servo-hydraulic machine. 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 [31]. The compressive and tensile test setups are shown in Fig. 3.

2.3. Test results and discussion

The test results, interpreted from the test data following JSCE's recommendation [31], are summarized in Table 3, and the stress-strain curves for uniaxial tension specimens are shown in Fig. 4. From the test results, all mixes show very high compressive strength (over 130 MPa), and it is obvious that increasing the sand content and/or decreasing the w/b ratio can improve the tensile strength. Tensile 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 0.3–0.5% strain, which is shortly after the yielding