Composites: Part B 56 (2014) 512–519

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Flexural performance of reinforced concrete beams strengthened with strain-hardening cementitious composite and high strength reinforcing steel bar

Yun Yong Kim [a], Bang Yeon Lee [b], Jin-Wook Bang [a], Byung-Chan Han [c], Luciano Feo [d], Chang-Geun Cho [e,*]

[a] Department of Civil Engineering, Chungnam National University, 220 Gung-dong, Yuseong-gu, Daejeon 305-764, Republic of Korea
[b] School of Architecture, Chonnam National University, 300 Yongbong-dong, Buk-gu, Gwangju 500-757, Republic of Korea
[c] Department of Remolding Architecture, Woosong Information College, Daejeon 300-715, Republic of Korea
[d] Civil Engineering, University of Salerno, 84084 Fisciano, SA, Italy
[e] School of Architecture, Chosun University, Gwangju, Republic of Korea

ARTICLE INFO

Article history:
Received 15 March 2013
Received in revised form 12 July 2013
Accepted 19 August 2013
Available online 28 August 2013

Keywords:
A. Fibers
B. Strength
C. Analytical modeling
D. Mechanical testing
Strain-hardening cementitious composite (SHCC)

ABSTRACT

The cracking and strength improvement in beams are one of main issues in the area of architecture and civil engineering. This paper presents the experimental and numerically predictive studies on the flexural performance of reinforced concrete (RC) beams strengthened with a strain-hardening cementitious composite (SHCC) and high strength reinforcing steel bar (HSRS bar) as a new strengthening method for beams. In order to investigate the effects of SHCC and HSRS bar on the control of cracking and load bearing capacity, four types of beam specimens were manufactured and a series of flexural bending tests were performed. The test results showed that the crack width can be controlled by applying SHCC and the load-bearing capacity of beams improved by applying the SHCC and HSRS bar.

1. Introduction

Recently, improving aging and deteriorating structures has become an important issue in the area of architecture and civil engineering. According to the 2009 Report Card for America's Infrastructure at the National Press Club, the overall grade of American infrastructures was a "D" [1]. There is a need for technological advances that improve either the condition or performance of the members of existing structures.

The cracking of concrete is considered to be one of the main causes of the deterioration of reinforced concrete structures [2–4]. It is a well-known fact that cement-based materials are inherently brittle and susceptible to cracking under tension. Cracking increases permeability and allows water, air and aggressive agents, such as chloride, to reach the reinforcing steel under the concrete cover, leading to lower durability in reinforced concrete structures. One approach to addressing this problem is the incorporation of fibers, which enables the control of cracking and increases the fracture toughness of the brittle matrix through fiber bridging [5–10].

A high performance fiber reinforced cementitious composite (HPFRCC) is considered a promising construction material due to its high ductility and durability, which is due to its multiple fine cracks and pseudo strain-hardening characteristics under uniaxial tensile stress [9,11,12]. Despite the various advantageous potentials mentioned above of HPFRCC as a rehabilitation material, the strengthening effect is negligible because the HPFRCC has the same order of magnitude of strength. One possible approach to improving the load bearing capacity of existing members is to adopt a high strength rebar. However, careful attention must be paid when a high strength rebar is used in reinforced concrete members because the yielding strain of the high strength rebar is higher than that of the normal strength rebar, which can lead to concrete fracture before the yielding of the rebar.

The objective of this study was to evaluate the flexural performance of reinforced concrete (RC) beams strengthened with a strain-hardening cementitious composite (SHCC) and high strength reinforcing steel bar (HSRS bar) as one of the new strengthening methods for beams. This new strengthening approach has some advantages in terms of controlling the crack width and enhancing the durability and loading bearing capacity. The RC beam strengthened with the SHCC and HSRS bar was composed in such a way that the concrete was chipped for the rough

* Corresponding author. Tel.: +82 62 230 7023; fax: +82 62 230 7155.
E-mail address: chocg@chosun.ac.kr (C.-G. Cho).

1359-8368/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2013.08.069

surface leading composite action. Then, the HSRS bars were placed followed by the SHCC. The strengthened RC beams were evaluated from experimental and analytical viewpoints.

2. Experimental program

2.1. Materials

The materials and mix proportions of SHCC used in this study are listed in Table 1. Type I Ordinary Portland cement, ground granulated blast furnace slag (GGBS) and fly ash were used as binding materials. The Blaine fineness of GGBS used in this study was 4204 cm^2/g and the maximum and average diameter of GGBS were 30 μm and 9.9 μm, respectively. The specific gravity of GGBS was 2.93. The Blaine fineness of fly ash used in this study was 3589 cm^2/g and the maximum and average diameter of fly ash were 36 μm and 12 μm, respectively. The specific gravity of fly ash was 2.15. Large aggregates, which can lead to higher matrix toughness, were excluded from the mixture design. Fine silica sand with a sand-to-binder (cement + GGBS + fly ash) ratio by mass (S/B), of 0.83, which has an average particle size of 139 μm, was only used as an aggregate in order to maintain adequate stiffness and volume stability [6,8]. The optimized amounts of the high-range water-reducing admixture (HRWRA) and the viscosity modifying admixture (VMA) were used to achieve the proper rheology in order to ensure uniform fiber dispersion [13]. PVA fiber (2 vol.%) was used as a reinforcement. The properties of the PVA fiber used in this study are listed in Table 2. The typical tensile stress–strain curve of SHCC used in this study is shown in Fig. 1. Three specimens for the uniaxial tension test and three 50 mm cubes for the cube compression test were made and tested at 28 days. The average tensile strain capacity and ultimate tensile strength were 2.1% and 1.6 MPa. The compressive strength was 29.2 MPa.

The maximum aggregate size used in the mixture design of concrete was 25 mm. The slump of fresh concrete was 180 mm, and the measured compressive strength of the concrete in the cylinder test at 28 days was set to 26.1 MPa. The concrete mixture design and mechanical characteristics of the concrete are given in Tables 3 and 4.

The yield strength and elastic modulus of the indented high strength reinforcing steel bar of 6 mm in diameter used in this study were 1200 MPa and 186 GPa, respectively. Two types of reinforcing bars were used in the experiment. Reinforcing bars with a yield stress of 450 MPa and 300 MPa were used for the main reinforcing bar and stirrup, respectively. The mechanical properties of the reinforcing bars are listed in Table 5.

2.2. Beam details

In order to evaluate the flexural performance of reinforced concrete beams strengthened with SHCC and HSRS bars, a series of specimens were manufactured. As shown in Fig. 2, each specimen had a span length of 3400 mm and a cross-section of 500 mm × 300 mm. The experimental variable for each beam specimen is presented in Table 6. Specimen RC-P is a conventional RC beam. Four D19 steel bars terminating with a standard 90° hook and two D10 steel bars were used as the main reinforcing and compression bars, respectively. To avoid shear failure, U-shape stirrups (D10) with a spacing of 200 mm were used as shear reinforcement. Specimens SHCC-0, SHCC-3 and SHCC-5 are designed as a RC beam strengthened with the SHCC and HSRS bar, as shown in Fig. 3. Specimen SHCC-0 is strengthened with 60 mm-thickness of SHCC. Specimens SHCC-3 and SHCC-5 are strengthened with 60 mm-thickness of SHCC, as well as three HSRS bars and five HSRS bars, respectively.

Fig. 4 shows the manufacturing process of the beam specimens. The main reinforcing bars, compression bars and stirrups were located and the concrete was placed. In order to do the composite action between the SHCC and the concrete, the concrete was chipped for the rough surface at 7 days after concrete placement. Then, the HSRS bars were located, followed by SHCC placement. Finally, the specimens were cured under wet conditions until bending tests (age: 5 weeks).

Table 1
Mixture proportion of SHCC.

W/B	S/B	GGBS/B	FA/B	VMA/B	HRWRA/B	PVA fiber (vol.%)
45	83	20	20	0.22	0.14	2.0

W: water, B: binder (cement, GGBS and FA), S: silica sand, FA: fly ash.
Note: all numbers are mass ratios of binder weight except fiber contents.

2.3. Test setup and bending test

The four specimens were tested by four-point bending test under simply supported conditions, as shown in Fig. 5. The bending test was conducted using a universal testing machine with a capacity of 2500 kN. The pure bending span length between two loading points was 800 mm. A monotonic transverse load was applied in order to lead to the failure of each specimen by crushing the concrete in compression. Fig. 6 shows the installation of gauges and LVDTs. The deflection at the mid-span of each specimen was measured using linear variable differential transducers (LVDTs) installed in the vertical direction at mid-span. For the calculation of curvature, additional LVDTs were installed in a horizontal direction at the bottom, sides and top of the specimens. In addition, concrete gauges were bonded to the top surface of the beams in order to measure the compressive concrete strain and steel gauges were bonded to the main reinforcing bars at mid-span.

3. Test results and discussions

3.1. Cracking and failure mode

Fig. 7 shows the cracking patterns at mid-span for the four beam specimens. For Specimen RC-P, the initial crack took place near the mid-span of the concrete at a load of 54.0 kN. The cracks spread from the mid-span to the support with a crack spacing of 50–200 mm. After the load level of yielding, the width of the cracks greatly increased until failure of the specimen was reached. The final failure of the specimen was obtained by crushing the concrete at the top of the specimen and the cracks reaching the upper part of the beams, which is similar to a typical failure pattern of under-reinforced beams.

For Specimen SHCC-0, an initial crack was observed near the mid-span on the SHCC at a load of 65.6 kN. After reaching the yield load, the crack width did not increase. After reaching the mid-span deflection of 16.8 mm, multiple micro-cracks on the SHCC were found to spread near the mid-span and the specimen stably resisted with high-ductile bending behaviour to reach a mid-span deflection of 26.8 mm. The final failure was obtained by crushing the concrete at the top of the specimen, as with Specimen RC-P. Any delamination (or debonding) between the two materials was not observed during the bending test. This is attributed to the concrete chipping. The crack widths were in the range of 60–200 μm.

The cracking pattern and failure of Specimens SHCC-3 and SHCC-5 were very similar to those of Specimen SHCC-0. Specimens SHCC-3 and SHCC-5 showed multiple micro-cracks on the SHCC. The cracking load increased with an increase in the number of HSRS bars. On the other hand, the crack widths of Specimens