Engineering Structures 171 (2018) 247–259

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental study on seismic performance of steel fiber reinforced high strength concrete composite shear walls with different steel fiber volume fractions

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ARTICLE INFO

Keywords:
Ductility
Curvature
Hysteretic behavior
Seismic performance
Shear wall
Steel fiber

ABSTRACT

The concrete at the bottom corner of the reinforced concrete shear walls is easily crushed to failure under vertical and horizontal loads owing to its low tensile strength. Casting steel fiber reinforced high strength concrete (SFRHSC) in the plastic critical zone at the bottom of the shear walls is expected to improve the seismic performance of these walls for steel fibers can raise the toughness of high strength concrete (HSC). Based on the previously determined mechanical properties of SFRHSC, a type of SFRHSC composite shear wall was developed in this work. SFRHSC and HSC were cast in the lower and upper halves, respectively, and a steel profile was placed in each boundary member of the walls. Nevertheless, the influence of the steel fiber facture volume on seismic performance of the SFRHSC composite shear walls remains unclear. This paper aims to investigate the effect of the steel fiber volume fraction on the non-linear behavior of a SFRHSC composite shear wall. Four SFRHSC composite shear walls with 1/2 scale and shear span ratio of 2.25 were subjected to low cyclical quasi-static testing. Each specimen was tested under cyclically increasing lateral loads and a constant relatively high vertical load until failure. The impact of steel fiber on the seismic performance of composite elements with fiber volume fraction of 0%, 1.0%, 1.5% and 2.0% was evaluated. The results revealed the coordinated working performance of the SFRHSC composite shear wall. The deformation capacity of the SFRHSC composite specimen was higher than that of the HSC composite shear wall and the flexural deformation improved gradually, as the steel fiber prevented cracking of the cement matrix. Crack and damage process were postponed, and damage degree was reduced with increasing steel fiber volume fraction. Furthermore, the energy dissipation ability improved significantly, when a fiber volume fraction of 2.0% was employed.

1. Introduction

Reinforced concrete (RC) shear wall is widely used as structural members, owing to its excellent lateral and vertical load bearing capacity. However, for traditional RC shear walls, boundary members at the bottom of a wall subjected to high vertical load and lateral earthquake forces are easily damaged [1,2]. With an increase in the height of buildings, the thickness of the shear walls at the bottom of structures has increased significantly, which has severely limited the normal use of buildings. Using HSC (high strength concrete) can yield significant improvements in the load bearing capacity of RC members (including columns, shear walls), and reduce the cross-sections of members under fixed load [3]. Therefore, HSC constitutes a promising material for use in high-rise buildings. However, the toughness of HSC is (in general) lower than that of common concrete. The toughness and the ratio of the tensile or shear strength to the compressive strength decreases with increasing compressive strength of HSC.

To prevent undesirable brittleness of HSC, researchers developed high performance fiber reinforced concrete by mixing steel fibers or polyethylene fibers with HSC. Bhargava [4], Ramadoss [5], and Liao [6] investigated the stress-strain behavior of steel fiber reinforced concrete in compression. A positive correlation was obtained for the dependence of the compressive toughness on the fiber volume fraction (for fractions ranging from 0 to 3.0%). Kang [7], Yang [8], and Han [9] verified, via experiments, the fiber-induced improvement in the tensile toughness. The results indicated that the steepness of the descending branch of the stress-strain curve decreases with increasing steel fiber volume fraction.

Fibers are effective in increasing the toughness of HSC by preventing crack extension and damage accumulation, thereby improving

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https://doi.org/10.1016/j.engstruct.2018.05.068
Received 22 September 2017; Received in revised form 15 April 2018; Accepted 17 May 2018

the ductility and energy dissipation capacity of shear walls. Static and shaking table tests were implemented on fiber reinforced concrete shear walls and other elements to evaluate the seismic performance by many researchers. Quang [10] performed tests on six high performance fiber reinforced cementitious composite (HPFRCC) column specimens and found that HPFRCC could improve the ductility of columns. Parra-Montesinos [11,12] conducted HPFRCC shear wall tests, with a shear span ratio of 3.45 and 3.7, to determine the effect of fibers on the nonlinear behavior of shear walls. The results revealed that, for walls with a fiber volume fraction of 2.0%, the constituent concrete was only slightly damaged prior to fracture of the longitudinal bars in the boundary element. Dazio [13] investigated both experimentally and numerically the hysteretic behavior of three hybrid fiber concrete structural walls. The results revealed that the hybrid fiber concrete structural system provides large inelastic deformation capacity and, compared with conventional reinforced concrete, ensures superior post-earthquake functionality. Athanasopoulou [14] tested nine HPFRCC low-rise shear walls with a shear span ratio of 1.2 and 1.5. Although stirrups were absent from the boundary members, the test units with a fiber volume fraction of 1.5% and 2.0% had stable hysteretic properties. Through shaking table tests of six concrete walls, Carrillo [15] evaluated the (i) contribution of steel fibers to the shear strength and displacement capacities of concrete walls and (ii) possibility of replacing the conventional web shear reinforcement of walls with steel fibers. Zhao [16] determined the effect of the steel fiber volume fraction on the seismic performance of RC shear walls with fiber volume fraction of 1.0%, 1.5%, and 2.0%. Furthermore, the ductility and energy dissipation capacity increased gradually with increasing steel fiber volume fraction.

According to previous studies, the boundary elements at the bottom of shear walls are more likely to fail than other elements as they will be subjected to significant compression or tension [1,2]. Steel is often used to strengthen the boundary element of the RC shear walls, and has achieved excellent results [17,18]. Based on the above, a type of steel fiber reinforced high strength concrete (SFRHSC) composite shear wall has been proposed. In this wall, SFRHSC and HSC are cast in the lower and upper halves, respectively, and a steel profile is placed in each boundary member of the wall. Steel fibers are added to the vulnerable region to postpone cracking and retard the crushing of wall corner and, hence, improve the ductility and energy dissipation.

Compared with other fiber reinforced concrete, the compounding and construction technology of SFRHSC is mature and stable. The design strength of SFRHSC is also flexible (i.e., varies with the mixing proportion) and can therefore be tailored to fit an extensive range of applications. As previously mentioned, the study on steel fiber reinforced concrete with a maximum compressive strength of 60 MPa and an axial load ratio (calculated from the normalized axial force) of ∼0.1 has been conducted. The influence of the steel fiber volume fraction on the seismic performance of HSC shear walls under a high axial ratio has yet to be experimentally verified. Clarifying the coordinated working performance between components, such as the steel fibers and the cement matrix, the boundary steel profile and SFRHSC, the interface between SFRHSC and HSC, is extremely challenging. Furthermore, the optimal volume fraction of steel fiber required for engineering applications remains unclear.

Based on the previously determined mechanical properties of SFRHSC [19], four SFRHSC composite shear walls with SFRHSC and HSC in the lower and upper halves, respectively, are investigated, and each boundary member in these walls consists of a steel profile (see Fig. 1). The walls are subjected to cyclically increasing lateral loads and a constant vertical load until failure. The aim of the experiment is to determine the influence of the steel fibers on the seismic behavior for this new type of SFRHSC shear wall.

2. Experimental program

2.1. Design of experimental specimens

To investigate the coordinated working performance and seismic performance of the composite shear walls described above, four SFRHSC composite shear walls are designed and tested under a cyclic load. Based on the test conditions, these specimens are designed as 1/2 scaled shear walls with an aspect ratio of 2.25. The original specimens are designed in accordance with special provisions, such as Chinese seismic code GB50011–2010 [20], Chinese concrete structure code GB50010–2010 [21], and Chinese composite structure code JGJ138–2016 [22]. A shear span ratio > 2 means that the walls are approximately ductile for common RC shear walls [1,21]. In addition, the design incorporates a vertical force of 3100 kN. This force is equivalent to the upper limits of the axial load ratio for RC shear walls in Grade I structures with seismic intensity of 7 or 8 (as stipulated by the Chinese seismic design code [20]).

The height, width, and thickness of the specimen walls are 2400 mm, 1200 mm, and 150 mm, respectively, corresponding to a width to thickness ratio of 8.0. SFRHSC is only cast in the potential plastic region of shear walls with heights lower than 1200 mm, while HSC of the same strength as SFRHSC is cast in the upper parts of the walls. The parametric variables of the specimens are summarized in Table 1. The reinforcement details of all four composite shear walls are the same (see Fig. 1). A 10th hot-rolled I-shaped steel profile is included in each boundary member (cross-sectional area: 1430 mm^2). The difference of the walls is the steel volume fraction.

The specimens consist of SFRHSC, I-shaped steel profile, and reinforcing bars. The experimentally determined properties of the SFRHSC, HSC, and steel are listed in Tables 2 and 3. The middle of the wall consists of a joint, as two types of concrete are used to cast each part of the specimens. In addition, the reinforcement assembling, form work supporting, and HSC casting of the upper half of the wall are conducted after the SFRHSC of the lower half cast. Fig. 2(a) shows the reinforcement assembling process of the upper part after the lower part is completed. Fig. 2(b) shows the specimens after form-board removal.

2.2. SFRHSC properties

The following components are used to produce SFRHSC: Ordinary Portland Cement (P.O52.5R), crushed coarse aggregate (size: 5–16 mm), spherical quartz sand (fineness modulus: 2.6), water, condensed silica fume (920U, SiO_2 content: 92%), superplasticizer (water reducing rate: 25–40%), and hooked-end steel fibers. The tensile strength of these fibers, with an average length, equivalent diameter, and aspect ratio of 25 mm, 0.4 mm, and 62.5, respectively, is > 1100 MPa. Table 3 shows the mixture of SFRHSC design for 1 m^3 of the concrete batch used in the experimental program. Steel fibers and SFRHSC used in the construction are shown in Fig. 3. Table 4 shows the main material properties of the tested SFRHSC.

The uniaxial stress-strain response of SFRHSC under monotonic compressive loading or tensile loading is experimentally evaluated prior to the current experiment. Prisms (150 mm × 150 mm × 300 mm) are employed for the compressive stress-strain curve tests. The tensile stress-strain curve tests include dumbbells (length: 360 mm), with an end cross section (80 mm × 150 mm), and a middle cross section (80 mm × 80 mm). The resulting experimental stress-strain curves are shown in Fig. 4. Specimens of plain concrete are rapidly crushed or fractured after the peak load and, hence, the solid curves corresponding to HSC are similar to the theoretical curves presented in GB50010-2010. As Fig. 4 shows, the fibers have negligible influence on the compressive and tensile strength. However, the compressive deformation performance is enhanced, whereas the tensile deformation property improves initially and then deteriorates, with increasing steel fiber volume fraction of 0–2.0%. The