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Experimental investigation of seismic behavior of ultra-high performance steel fiber reinforced concrete columns

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ABSTRACT

This paper presents an experimental study on seismic behavior of ultra-high performance steel fiber reinforced concrete (UHPSFRC) columns. Based on a series of cyclic loading tests on 14 UHPSFRC specimens subjected to combined static axial loading and cyclic lateral loading, the investigation and analysis have been carried out on crack status, failure modes, hysteretic loops, skeleton curves, strength and stiffness degradation, energy dissipation capacity and ductility of UHPSFRC columns. The influence of stirrup spacing, type of stirrup, axial compression ratio and shear span ratio on the seismic performance of UHPSFRC columns was also investigated in details. The experiment results show that three typical failure modes are observed, i.e., flexural, flexural-shear and shear failure mode. The existence of steel fiber could prevent the cracked concrete from spalling efficiently and delay the bulking of longitudinal reinforcement further. It noteworthy that the limit plastic drift ratio of all columns changes from 0.036 to 0.061, indicating that the UHPSFRC columns represent a good ductility which is obviously different from the conventional high strength concrete columns that exhibit much more brittleness with the increase of strength.

1. Introduction

In recent years, a lot of post-earthquake investigations [1,2] have confirmed that most of conventional high strength reinforced concrete columns, which were in areas strongly stricken by earthquakes, were seriously damaged in shear failure so that these columns could not resist seismic loading by utilizing their large deformation and corresponding energy dissipation efficiently. Gu [3] and Barrera [4] have figured out that the phenomenon described above is mainly attributed to the poor toughness and remarkable brittle nature of conventional high strength concrete. Obviously, it is a very effective method to set closely spaced transverse stirrups, which could provide a stronger confinement on core concrete, for improving the properties of conventional high strength reinforced concrete columns. However, too dense stirrups would not only raise cost in both steel reinforcement material and fabrication expense, but also result in much more difficulties in constructions. Ultra-high performance steel fiber reinforced concrete (UHPSFRC) presents extraordinary properties, i.e. superior compressive and tensile strength, excellent toughness and energy dissipation capacity [5–8]. Therefore, UHPSFRC is an attractive alternative option for reinforcement solution because of its extraordinary properties.

Although a lot of researches have been carried out on properties of UHPSFRC [9–12], study on seismic behaviors of UHPSFRC columns is limited. Huang [13] reported a series of seismic performance of hybrid fiber reinforced concrete columns including 24 specimens subjected to combined constant axial load and cyclic lateral force. Karen [14] presented an experimental research on behavior of steel fiber reinforced high-strength concrete slender columns subjected to combined constant compression and cyclic lateral loads. To evaluate the steel fiber reinforcing effect on shear strength and seismic behavior of the reinforced concrete columns, Lee [15] carried out a series of experimental research including eight specimens under seismic loading. Hung [16] conducted a series of experimental investigations on cyclic flexural performance of UHPFRC cantilever beams reinforced with high-strength steel. The results show that UHPFRC beams reinforced with high-strength steel are able to show satisfactory cyclic flexural performance prior to failure. Besides, other researchers also studied the mechanical properties of UHPFRC columns or beams [17–19]. In summary, just

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Table 1
Properties of silica fume.

Properties	Description
Component	SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO
Average particle size (μm)	0.1–0.3
Specific surface area ($m^2\,g^{-1}$)	20–28

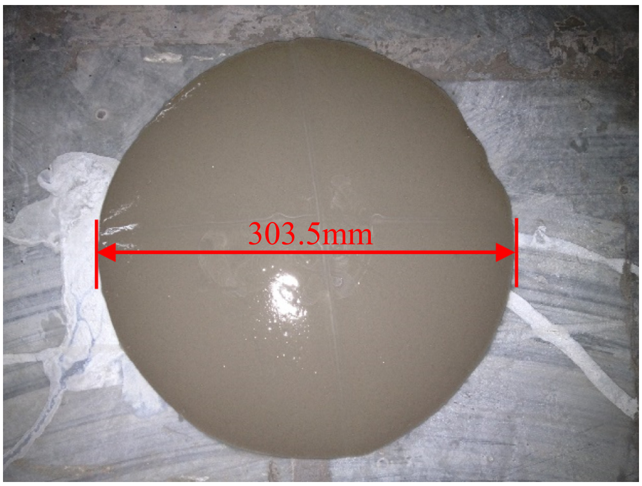

Fig. 1. Slump of UHPSFRC.

few investigations on the seismic behavior of UHPSFRC columns are reported.

In this study, 14 UHPSFRC columns were fabricated including 12 columns with shear span ratio of $\lambda = 3.3$ and another 2 columns with shear span ratio of $\lambda = 5.3$. Low cyclic loading tests were conducted in order to investigate the seismic behavior of UHPSFRC columns. The crack status, failure modes, hysteretic loops, skeleton curves, strength and stiffness degradation, energy dissipation capacity and ductility of UHPSFRC columns were extensively presented. The influence of design parameters (i.e., stirrup spacing, type of stirrup, shearing span and axial compression ratio) on the seismic behavior of UHPSFRC columns were analyzed in detail.

2. Experimental program and setup

2.1. Materials

The UHPSFRC used in this study is a kind of reactive power concrete (RPC) and the minimum strength grade specified in the standard GB/T31387-2015 is RPC100 [20]. The main mechanical properties of the RPC100 are as follows: the compressive strength $\geqslant$100 MPa, the flexural strength $\geqslant$12 MPa, and the elastic modulus $\geqslant$40 GPa. In addition, the super high mechanical properties of UHPC is mainly reflected in its super high tensile strength (flexural strength can be up to 60 MPa) and excellent toughness i.e., fracture energy is more than 1500 J/m^2 [21]. According to these mechanical property indexes, the mixture of UHPSFRC used in this study is designed as follows.

Typical ordinary Portland cement (C) with a 28-day nominal compressive strength of 52.5 MPa was used as a binder material in this research. Silica fume was chosen as a supplementary cementitious material to improve microstructure of hardened cement paste since it has excellent pozzolanic activity effect and micro-aggregate effect. Table 1 lists the properties of silica fume. River sand made up of naturally graded with a maximum aggregate size of 2.5 mm (0.8–2.5 mm) was used as fine aggregates, and the average particle size of quartz powder is 500 mesh

Fig. 2. Dimension of steel fibers.

Table 2
Properties of steel fiber.

Diameter (mm)	Length (mm)	Tensile strength (MPa)
0.12	8	>4000

(25 μm). Polycarboxylic type superplasticizer (SP) with a specific gravity of 1080 kg/m^3 was added to the concrete mixture to achieve the required concrete workability with an average slump of 303.5 mm (Fig. 1). 2% volume ratio of smooth steel fiber with 8 mm length and 0.12 mm diameter (Fig. 2) was added to the concrete mixture in order to improve the toughness effectively (see Table 2). Table 3 lists the mix proportion design of UHPSFRC (m^3).

In order to further illustrate the properties of UHPSFRC used in this study, especially for the toughness, Fig. 3 shows two typical curves, i.e. compressive stress-strain curve (Fig. 3(a)) and flexural force-deflection curve (Fig. 3(b)). It indicates that the strain energy density is more than 2 MJ m^{-3} and the fracture energy is more than 50,000 J m^{-2}. Therefore, the UHPSFRC used in this study represents an excellent toughness.

Bache [22] and Spasojevic [23] figured out that the flexural behaviors of high-strength steel reinforced UHPC beam are similar to steel beams. Based on the researches, all columns were made with high strength reinforcements as longitudinal rebar (PHB 1080). HPB300 was chosen as stirrups, which can provide confinement to core UHPSFRC effectively. Table 4 summarizes the mechanical properties of rebar used in this research, where f_y is the yield strength and f_u is the ultimate strength.

2.2. Specimens design and fabrication

As illustrated in Fig. 4, every specimen consisted of a column with a rectangle cross-section of 300 mm × 300 mm and a stub with dimension of 500 mm × 500 mm × 1100 mm. All the 14 columns were casted by utilizing the same mix proportion of UHPSFRC listed in Table 3.

The variables in this test matrix are types of stirrup (tied stirrup and rectangle stirrups), stirrup spacing (50 mm and 80 mm), axial compression ratio (0.20, 0.27 and 0.36) and shear span ratio (3.3 and 5.3). Table 5 lists the properties of these specimens. In this table, ρ is the reinforcement ratio; f_{cu} is the compressive strength of UHPSFRC; f_f is the flexural strength of UHPSFRC; λ is the shear span ratio calculated as $\lambda = H/h$, where H is the height of loading and h is the section width; N_t is the axial compression ratio