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Experimental Design and Material Properties Research of the Reinforced UHPC Columns

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Abstract: Medium shear span ratio reinforced columns are prone to complex failure under seismic action. This paper compares the seismic performance of normal concrete columns and UHPC columns by introducing ultra-high-performance concrete (UHPC). The shear span ratio (2.4-4.4) and axial compression ratio (0.10, 0.36) were used as variables, and the bearing capacity, ductility and failure mode were analyzed through low-cycle reciprocating loading studys. The results showed that UHPC significantly improved the bearing capacity, stiffness and energy dissipation capacity of the column, and suppressed the crushing and spalling of concrete. When the shear span ratio is 2.4 and the axial compression ratio is 0.36, the failure mode of UHPC columns was changed from shear failure to flexural shear failure. Thus this study can become a reference for the seismic design of UHPC columns.

Keywords: Medium shear span ratio; UHPC; Low-cycle reciprocating study; Shear failure; Axial compression ratio

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1. Introduction

The failure modes of medium shear span ratio reinforced UHPC columns under seismic action are complex and lack theoretical prediction methods [1]. UHPC has both high strength (compressive and tensile) and ductility[2], but its seismic performances are yet to be verified. Hence in this paper, one normal concrete column and five UHPC columns were designed with concrete type, axial compression ratio (0.10, 0.36) and shear-span ratio (2.4-4.4) as variables. Low-cycle reciprocating studys were conducted to analyze the horizontal bearing capacity, ductility and failure law, supplemented by concrete and steel bar material property study to provide a theoretical basis for the seismic design of UHPC columns.

1.1. Specimen design and fabrication

Six square short column specimens with a side length of 250 mm were designed, including one ordinary concrete column and five UHPC columns. The variables were concrete type, axial compression ratio (0.10, 0.36), and shear span ratio (2.4, 3.6, 4.4)[3]. The specimens were composed of the column body and end connection blocks, with a protective layer thickness of 30 mm. The longitudinal bars were eight 16 mm HRB400 bars (with a reinforcement ratio of 2.6%), and the stirrups were 8 mm HRB400. The end was set with a stirrup densification zone (densification of 50 mm for specimen 2.4 with a shear span ratio, densification of 100 mm for the rest, with a spacing of 50 mm) to control local stress failure.

1.2. Study setup

The low-cycle reciprocating study setup for the column consists of a reaction beam, a reaction wall, a horizontal actuator and a vertical jack. The specific loading process is as follows: First, a vertical load was applied to the specimen through the vertical jack, and after the vertical load stabilizes, a horizontal reciprocating load was then applied to the specimen through the horizontal actuator. In this study, pushing from left to right was indicated as positive while pulling from right to left was indicated as negative.

1.3. Study point arrangement

The contents measured in the study include the horizontal displacement of the column head, the rotation angles of each column section, the strain of the longitudinal bars and stirrups in the plastic hinge area, the shear deformation of the column, and the distribution of cracks in the column body.

1.3.1. Arrangement of the displacement gauge

Displacement gauge 1 was located at the top column head of the specimen for measuring its horizontal displacement; Displacement gauge 2 was located above the main body of the column and was used to measure the horizontal displacement of each column at different column heights; Displacement gauge 3 was located at the position of the column piers below the specimen and was used to measure its horizontal displacement; Displacement gauge 4 and displacement gauge 5 are fixed on both sides of the column to measure the shear deformation of the specimen, and the vertical displacement gauge were used to measure the bending deformation of the column.

1.3.2. Arrangement of the strain gauge

The strain gauge was attached to the surface of the longitudinal bars and stirrups in the potential plastic hinge area of the specimen. Then, the strain was measured at the corresponding position. The reinforcement strain gauges were evenly arranged along the cross-section.

1.4. Loading regime

The low-cycle reciprocating loading system was designed in accordance with the Code for Seismic Studying of Buildings[4]. The force-displacement hybrid control mode was adopted: the target loads were $0.5F_y$ and $0.75F_y$ before yield, with two cycles at each level; After yield, the target displacement was multiplied $_y$ by Δ, with three cycles per stage. The load was terminated either decreased to 85% of its peak or when the longitudinal bars broke.

2. Concrete material property tests

2.1. Concrete mix ratio

The main components of the ultra-high performance concrete material used in this study include: masterbatch, steel fibers, and water. The masterbatch was mainly composed of sand, cement, silica fume, high-efficiency water reducing agent, ultrafine active powder, quartz powder and additives. The steel fibers were straight steel fibers[6] with a length of 14 mm and a volume content of 2%[7] .

The UHPC mix ratio (by mass) used in this study included: masterbatch: steel fiber: water = 1:0.1:0.115. The main raw materials of Normal concrete (NC) used in this study and their mix ratios (by mass) were as follows: 42.5 grade cement: river sand: crushed stone (coarse aggregate): water: polycarboxylic acid type high performance water reducer = 1:0.7:2.2:0.21:0.1

2.2. Slump and fluidity

UHPC and ordinary concrete were used in the study to measure the slump and fluidity difference in accordance to the Standard study methods for properties of ordinary concrete mixtures (GB/T 50080-2021)[8]. The expansion and slump of the UHPC mixture were continued until it stop expanding or expanding for a duration of 90 seconds. The study measured the expansion of UHPC at 760 mm and the slump at 275 mm. Using the same measurement methods and tools, the slump and fluidity of ordinary concrete were measured, with a fluidity of 470 mm and a slump of 240 mm[9].

2.3. Compressive strength

2.3.1. Cube compressive strength

Concrete compressive strength study were conducted on a 500 t pressure studying machine using the method specified in Standard Study methods for Physical and mechanical properties of concrete (GB/T 50081-2022)[10] , UHPC using 100 × 100 × 100 mm cubic study blocks. For ordinary concrete, 150 × 150 × 150 mm cubic study blocks were used. The loading rate of the studying machine was 1.2 MPa/s - 1.4 MPa/s, and the average value of the material specimens with an average deviation of less than 10% is taken as the measured value of the cubic compressive strength of the material.

Based on **Table 2**, due to the bridging effect of steel fibers, the UHPC cube specimens were remained relatively intact after compression failure, while the ordinary concrete cube specimens were crushed and peeled off at the time of failure, showing a distinct brittle failure pattern.

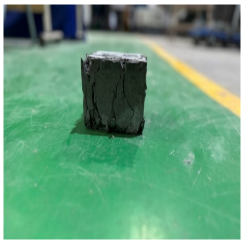
The cube compressive strength of UHPC was measured to be 103.2 MPa, while that of ordinary concrete was 41.2 MPa.

2.3.2. Axial compressive strength

The axial compressive strength of UHPC and ordinary concrete was measured using cylindrical study blocks with diameters of φ100 × 200 mm. The studys were conducted on a 500 t pressure studying machine and loaded using the method specified in GB/ T50081-2022[10]. The compression failure modes of UHPC and ordinary concrete were shown in **Table 1**. The study loading rate was 1.2 MPa/s-1.4MPa/s, and the average value of the material specimens with a deviation of less than 10% has been taken as the measured axial compressive strength of the material.

Due to the use of non-standard specimens, the study results were multiplied by the size conversion factor 0.95 according to the conversion method in Appendix C of GB/ T50081-2022[10] , and the axial compressive strength of UHPC was measured to be 98.0 MPa, and that of ordinary concrete to be 38.4 MPa.

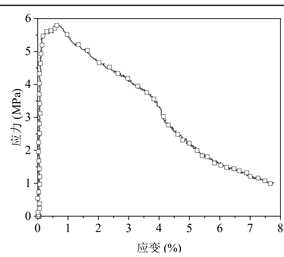
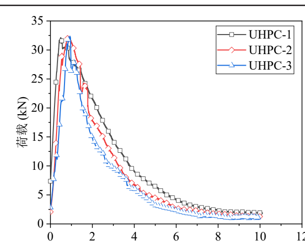
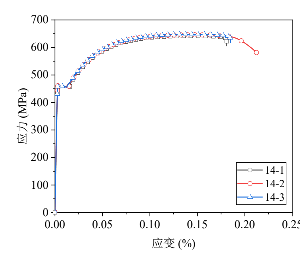
Table 1. Measuring instruments for compressive strength and the final failure mode of specimens

a: UHPC cube failure	b: Ordinary concrete	c: Axial compression failure of UHPC	d: Axial compression failure of ordinary concrete
			

2.4. Tensile strength

Uniaxial tensile tests of UHPC were conducted using “dog bone” shaped specimens (50 mm thick) as stipulated in “Basic Properties and Study Methods[11] of Ultra-High Performance Concrete”. Fiber cloth was pasted in the contraction zone of the middle section of the specimen to ensure the concentration of the failure location, and 50 t universal studying machine was used for loading. Pre-pull (15%-20% of the failure load) and monitor the strain gauge data before the study, and realign when the eccentricity is greater than 15%. The formal loading rate is 0.2 mm/min, and strain gauges (pre-crack strain) and displacement gauges (post-crack displacement) are arranged on the specimen surface. The termination condition of the study is: tensile stress < 30% tensile strength, tensile strain $\geq 1 \times 10^{-2}$ or specimen breakage.

Table 2. Stress-strain curves at the final failure of the specimen under tensile and flexural conditions

a: Typical stress-strain curve under axial tension of UHPC	b: Load-displacement curve of the UHPC four-point bending study for flexural strength	c: Stress-strain curve of reinforcing bars with yield platforms
		

The study shows that the specimen was initially in the elastic phase, then crack sign was appeared rapidly and expanded at their weak points, and the steel fibers was gradually pulled out or break after the concrete breaks. Observation of the fracture section of the “dog bone” specimen shows that all the steel fibers are pulled out or broken, indicating the characteristic of ductility failure.

Taking the typical stress-strain curves obtained from the axial tensile study of UHPC as shown in **Table 2**, it was found that the stress-strain relationship was linear in the early stage of axial tensile of UHPC. After the specimen cracked, the tensile strength of UHPC increased due to the effect of steel fibers. With the complete pull-out and breakage of steel fibers, the specimen eventually failed. The axial tensile strength of UHPC was taken as 5.5 MPa, which is the average of the three specimens.

2.5. Flexural strength

The flexural strength of UHPC was measured using 100 × 100 × 400 mm prismatic study blocks. The study was conducted on the SANS microcomputer-controlled electro-hydraulic servo universal studying machine and loaded using the method specified in GB/T 50081-2022[10]. Before the study, the loading points and support positions were marked on the surface of the specimen. The specimen was located at left and right as well as front and back centered on the support, and the position of the upper loading frame was adjusted before loading. The specimen was loaded continuously and evenly. After the initial crack, the load was loaded 30% lower from the maximum load to fulfill our objective.

The phenomenon of the UHPC flexural study was similar to that of the axial tensile study. In the later stage of the elastic section of the force-displacement curve, cracks in the middle of the concrete was developed rapidly resulting to fracture; Then the steel fibers were gradually pulled out or broke, accompanied by a "sizzling" sound and debris falling. The load-displacement curves were measured for the UHPC specimens, where result was shown in **Table 2**. It was observed that in the early stage of loading, the force on the specimen and its displacement presented a linear relationship. After the concrete cracked, the loading force on the specimen decreased rapidly. Then, due to the effect of the steel fibers at the crack, several ascending sections with unequal peaks appeared on the load-displacement curve, resulting the "jagged" curve. Finally, all the steel fibers at the concrete crack were pulled out and disconnected. The specimen was completely destroyed.

2.6. Elastic Modulus

The elastic modulus of UHPC was measured using prismatic study blocks of 100 × 100 × 300 mm. Vertical strain gauges were attached to the left and right sides of the specimen and displacement gauges were installed to measure the compressive deformation of the specimen before and after the study. The study was conducted on a 500 t testing machine, and the loading[12] was carried out using the method based on GB/ T50081-2019[4]. The specimens were neutralized and preloaded twice before formal loading to minimize the impact of asymmetry and non-uniformity on the specimens. The loading rate was 1.2 MPa/s-1.4 MPa/s. The elastic modulus of UHPC was measured at 43.0 GPa.

2.7. Poisson's ratio

The Poisson's ratio of UHPC was measured using prismatic blocks of 100 × 100 × 300 mm. To measuring the horizontal and vertical strength, both strain was attached to the left and right sides of the specimen, respectively. After the specimen was positioned centered, it is initially loaded to 0.5 F_0 and held for 60 seconds, then loaded to one-third of the ultimate load F_a and held for 60 seconds. The operations was repeated twice as preloading. Then, reduce to F_0 and hold for 60 seconds and record the strain gauge data. Then, load to F_a again and hold for 60 seconds and record the strain gauge data. The average Poisson's ratio test results of UHPC were 0.2.

3. Results

All of the reinforcing bars used in this study was HRB400 bars, which were further classified into four types according to their diameters: 8 mm (used as column stirrups), 14 mm (used as column piers stirrups), 16 mm (used as column longitudinal bars), and 20 mm (used as column piers longitudinal bars) [13].

To determine the material properties of the bars, three 400 mm specimens of each type of bar were cut and fixed on a 30 t universal studying machine, in accordance with "Metallic materials-Tensile Studying-Part 1:

Uniaxial tensile mechanical tests were carried out, and the deformation of the reinforcing bars was determined by placing an extensometer with a clamping length of 50 mm in the middle of the reinforcing bar specimens [14,15].

The stress strain curves of various bars were observed, and it was found that except for the 8 mm diameter bar which had no obvious yield plateau, the stress-strain curves of the other bars included the elastic stage, the yield stage, the strengthening stage and the necking stage (see **Table 2**).

4. Conclusion

This paper compared the low-cycle reciprocating loading study of ordinary concrete columns and reinforced UHPC columns, the improvement effect of UHPC on the seismic performance of columns with medium shear span ratio was systematically studied and reported. The results showed that the application of UHPC significantly enhances the bearing capacity, stiffness and energy dissipation capacity of the column, and effectively suppresses the crushing and spalling of concrete in the compression zone; When the shear span ratio was 2.4 and the axial compression ratio was 0.36, the failure mode of the UHPC column changed from shear failure to flexural failure, confirming its potential in improving complex failure modes. In addition, the increase in the axial compression ratio reduced the ductility of the column, while the increase in the shear span ratio intensifies the stiffness degradation, further revealing the law of the influence of parameters on the seismic performance of the column.

This study provides an important experimental basis for the seismic design of UHPC columns, especially with engineering reference value for optimizing failure modes and improving structural toughness within the medium shear span ratio range. However, the high cost of UHPC and its compatibility with construction techniques still need to be further explored in combination with actual engineering requirements to promote its wider application.

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Disclosure statement

The authors declare no conflict of interest.

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