Experimental study on seismic performance of steel reinforced high-strength concrete composite columns

Yong Yang¹, Chen Wang¹*, Hao Chang¹ and Yicong Xue¹

¹ Xi’an University of Architecture and Technology, Xi’an, Shaanxi, 710055, China
Corresponding author’s e-mail address: wangchen@xauat.edu.cn

Abstract. In order to combine the advantages of steel reinforced concrete column, high-strength concrete and precast structures, a novel steel reinforced high-strength concrete composite column is presented in this paper. With the aim to explore the seismic performance of this composite column, three column specimens were designed and tested under cyclic loading. The cyclic behavior of test specimens was evaluated through the failure patterns, hysteresis loops, skeleton curves, energy dissipation, stiffness degradation and displacement ductility. The test results indicated that the shear failure could be found in the specimens subjected to low aspect ratio, and the rest specimens all failed in flexural-shear failure. The initial stiffness and bearing capacity decreased with the increasing of aspect ratio, and the energy dissipation capacity and displacement ductility increased with the increasing of aspect ratio.

1. Introduction

The steel reinforced concrete (SRC) structure has been widely used in high-rise and heavy-load structures due to its higher bearing capacity, better seismic performance and durability [1-3]. But steel reinforced concrete structure of the site construction at the same time involved in steel structure and steel concrete structure construction process, so the construction process of cast-in-place steel reinforced concrete structure is more complicated. At the same time, precast concrete structures are highly recommended due to their simple on-site construction procedures and better quality control of structural components. The section layout is shown in Fig.1. The composite column is composed of high strength concrete precast part and ordinary concrete cast-in-place part, in which the precast part is composed of cross section steel, longitudinal bars, continuous stirrups and high strength concrete. The cast-in-place part is composed of ordinary concrete. In the construction site, it is only need to assemble the high strength prefabricated shell and pour the internal ordinary concrete to form a complete steel high strength concrete composite column. This not only effectively simplifies the construction process of the traditional SRC column, but also improves the integrity of the structure and reduces the amount of high-strength concrete to save the cost.

In order to study the seismic behavior of the composite steel column with high strength concrete, the low-cycle repeated loading test results of three composite columns are recorded in this paper. The failure pattern, hysteretic curve, skeleton curve, energy dissipation capacity, deformation capacity, bearing capacity and stiffness degradation characteristics of specimens were studied, as well as the influence of shear span ratio on their seismic performance, so as to provide reference for engineering design.
2. Description of tests

2.1 Specimen design

Three composite columns were designed. The cross section size of the specimen is 300mm×300mm, and the column height is divided into three sizes according to the different shear span ratio, which are 1050mm (λ=3.0), 750mm (λ=2.2) and 600mm (λ=1.7) respectively. The middle section steel of each specimen is a cross section, which is welded by two grade Q235 rolled section steel of HN175×90×5×8, and the steel ratio is 5.0%. All specimens were reinforced with 12C18 longitudinal bars, and the reinforcement ratio was 3.4%. Stirrup A8@65, volume stirrup ratio is 1.3%. The main design parameters of each specimen are shown in Table 1, and the section diagram of each specimen is shown in Figure 1.

Fig. 1 Specimen design
Table 1 Specimen design

| Specimen number | $\lambda$ | $a$ (mm) | $N$ (kN) | $f_{c,\text{out}}$ (MPa) | $f_{c,\text{in}}$ (MPa) | Stirrup ($\rho_s$) | Longitudinal reinforcement ($\rho_{ss}$) | Section steel |
|-----------------|-----------|----------|----------|------------------|------------------|----------------|---------------------------------|--------------|
| SRHCC-1         | 3.17      | 950      | 2000     | 24.3             | 96.8             | A8@65 (1.26%)  | 12B18 (3.4%)                    | 2(HN175×90×5×8) | 5.0% |
| SRHCC-2         | 2.17      | 650      | 2000     | 24.3             | 96.8             | A8@65 (1.26%)  | 12B18 (3.4%)                    | 2(HN175×90×5×8) | 5.0% |
| SRHCC-3         | 1.67      | 500      | 2000     | 24.3             | 96.8             | A8@65 (1.26%)  | 12B18 (3.4%)                    | 2(HN175×90×5×8) | 5.0% |

2.2 Mechanical properties
The precast high strength concrete is prepared according to C100 grade, and the measured axial compressive strength of concrete is 96.8MPa. The internal cast-in-place concrete is prepared according to grade C30, and the measured axial compressive strength of concrete is 24.3MPa. The mechanical properties of the steel used in the test are shown in Table 2.

Table 2 Mechanical properties of steel reinforcements

| Steel          | Size       | Steel level | Yield strength (MPa) | Tensile strength (MPa) |
|----------------|------------|-------------|----------------------|------------------------|
| Stirrup        | A8         | HPB300      | 393.2                | 562.3                  |
| Longitudinal   | C18        | HRB400      | 443.5                | 598.0                  |
| reinforcement  |            |             |                      |                        |
| Section steel  | Web        | Q235        | 272.5                | 520.0                  |
|                | Flange     | Q235        | 311.7                | 438.3                  |

2.3 Loading system and measurement scheme
As shown in FIG. 2, the test loading mode is cantilever type, and the axial load is applied to the top of the column through a horizontal sliding 5000kN hydraulic jack on the rigid girder. The horizontal load is applied to the top of the column by a 1000kN electro-hydraulic servo actuator fixed on the reaction wall. During formal loading, the target axial pressure is first applied on the top of the column through vertical jacks, which remains unchanged during the loading process, and then the low-cycle reciprocating horizontal load is applied through the actuator. The horizontal load is loaded with full displacement control. The target lateral movement of the first six stages is 0.1%, 0.2%, 0.3%, 0.6%, 0.8% and 1.0% respectively, and the lateral movement cycle is once for each stage. After that, the increment of lateral shift of each stage is 0.5%, each stage is cycled three times, and the loading stops when the horizontal load drops to 75% of the maximum load. During the test, the loading point and the lateral movement of the ground beam, as well as the strain of section steel, stirrup and longitudinal bars are mainly monitored. The arrangement of measuring points of displacement meter and strain gauge is shown in Figure 3.
3. Test results and analysis

3.1 Failure patterns
The failure mode of the specimen is shown in Fig. 4, and the main test results are shown in Table 3. It can be seen from Fig. 4 (a) and Fig. 4 (b) that both specimens SRHCC-1 and SRHCC-2 have bending-shear failure, in which the development degree of oblique crack increases with the decrease of shear-span ratio.
3.2 Hysteresis loops and skeleton curves

The hysteretic curves of all specimens are shown in Fig. 5. The specimens with a larger shear span ratio show better hysteretic performance and are more full. The skeleton curves of each specimen are shown in Fig. 6. It can be seen from Fig. 6 that the peak bearing capacity of the specimen SRHCC-3 is 44.5% and 8.8% higher than that of the specimens SRHCC-1 and SRHCC-2, respectively, indicating that the peak bearing capacity of the specimen decreases with the increase of the shear span ratio. After the peak bearing capacity, the skeleton curve of SRHCC-3 is steepest, indicating that the brittleness of shear failure is higher than that of bending shear failure.
3.3 Stiffness degradation

The stiffness degradation curves of the specimens were obtained by connecting the stiffness \( K \) values of the specimens at each stage of displacement. See Fig. 7 for the stiffness degradation curves of the specimens. In general, the stiffness degradation of specimens can be divided into two stages. In the first stage, from the beginning of loading to the yield of specimens, the stiffness degrades rapidly due to the development of cracks and cracks in specimens. After the specimen yield, the rigid degeneration trend becomes slow. It can be seen from Fig. 7 that the initial stiffness of the specimen increases with the decrease of the shear span ratio.

3.4 Displacement ductility and energy dissipation

The displacement ductility of each specimen was defined as the ratio of the ultimate displacement and yield displacement, in which the ultimate displacement was the lateral displacement when the specimen load was reduced to 75% of the peak load, and the yield displacement was determined by the "universal yield moment method" [6]. As shown in Table 3, the displacement ductility of each specimen decreases with the decrease of the shear span ratio. The cumulative energy dissipation curves of each specimen are shown in Figure 8. The cumulative energy dissipation curves of SRHCC-1 at the time of failure are 20.6% and 76.5% higher than those of SRHCC-2 and SRHCC-3, indicating that the energy dissipation capacity of the specimen decreases with the decrease of the shear span ratio.
4. Conclusion

Through the low-cycle reciprocating quasi-static tests on three new steel high-strength concrete composite columns, the following conclusions can be drawn:

(1) According to the different shear-span ratios, the failure modes of specimens can be divided into bending shear failure and shear failure. The specimen with the smallest shear-span ratio ($\lambda=1.7$) has shear failure, while the other specimens have bending shear failure.

(2) The specimen with a larger shear span ratio showed better hysteretic performance, and the hysteretic curves were more full. The hysteretic curves of all specimens were arched without obvious pinching effect. The peak bearing capacity of each specimen decreases with the increase of shear span ratio, and the brittleness of shear failure is higher than that of bending shear failure.

(3) The initial stiffness of the specimen increases with the decrease of the shear span ratio.

(4) The displacement ductility and energy dissipation capacity of each specimen decrease with the decrease of the shear span ratio.

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