Experimental study on seismic behavior of recycled steel tubular columns

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Abstract: In order to study the seismic performance of recycled steel tubular columns, four round steel tube recycled concrete columns were designed and fabricated, and low-cycle reciprocating tests were carried out. Considering the two parameters of regenerative coarse aggregate replacement rate and axial compression ratio, the whole process and failure mode of the specimen were observed, and the hysteresis curve, skeleton curve and stiffness degradation of the specimen were analyzed. The experimental results show that the failure process and failure modes of the recycled steel tubular columns are similar to those of ordinary circular steel tubular columns. The main performance is the drum bending of the steel pipe at the root of the test piece; the hysteresis curve of the test piece is full, and the replacement ratio of coarse aggregate is contrary. The hysteresis curve of the specimen has little effect, and the axial compression ratio has a great influence on the shape of the hysteresis curve, the skeleton curve, and the stiffness degradation. The recycled steel tubular column has good seismic performance.

1. Introduction
In recent years, the research and application of recycled concrete technology [1] has increased the effective utilization of construction waste resources. Recycled aggregate concrete (RAC) refers to recycled concrete aggregates that have been crushed from waste concrete and partially or completely replaced with natural aggregates. However, since a large part of the raw materials in the RAC are derived from the existing buildings with lower strength grades of the removed concrete, and the recycled aggregates are in the process of crushing, a large number of micro cracks or cracks appear inside the aggregates, correspondingly from the regenerated bones. The concrete prepared by the material has low compressive strength and low elastic modulus, so that RAC is generally applied to non-load-bearing or load-bearing structures such as roadbed backfilling. Therefore, the application of RAC to the load-bearing structure will be an important issue for researchers [2].

Concrete-filled steel tubular structures are widely used in single- and multi-layer industrial buildings, high-rise and super-tall buildings, as well as equipment structures and supports, due to their high bearing capacity and good seismic performance [3]. The structure of the recycled concrete filled steel tube (RACFST) [4] is a new combined structure formed by pouring RAC into the inside of the steel pipe. At present, domestic and foreign scholars have studied the steel pipe recycled concrete structure [5-6] mainly in the static compression performance. In terms of seismic performance, the literature [7] used the beam loading method to test the seismic performance of 15 square steel tube recycled concrete columns, and studied the effects of the parameters such as the replacement ratio of the coarse aggregate and the axial compression ratio on the seismic performance of the test piece. The results show that the seismic performance of the square steel tube recycled concrete column is similar to that of ordinary steel tube concrete, and the square steel tube regenerative concrete column exhibits high ductility and...
horizontal bearing capacity.

In order to better understand the failure mode and seismic behavior of recycled steel tubular columns under cyclic loading, this study studied four recycled steel tubes by changing the replacement ratio of coarse aggregate and the axial compression ratio. The column was subject to horizontal low-cycle repeated load test to analyze the influence of various parameters on the seismic performance of the test piece.

2. Test overview

2.1 Test material

The test steel pipe material is seamless round steel pipe, 42.5R ordinary Portland cement, ordinary natural river sand, 5-14mm continuous grade natural gravel, recycled coarse aggregate and high-efficiency water reducing agent. The mix ratio is shown in Table 1. The concrete compressive strength is measured by a 150X150X150mm cube standard test block which is molded and cured under the same conditions as the test piece. The test method is based on the "Test Method for Mechanical Properties of Ordinary Concrete" (GB50081-2002, 2003), and finally takes the average value of the measured strength of each of the three test blocks. The average compressive strength of concrete measured at 28 days was 41.2 MPa when the substitution rate was 70%, and 37.7 MPa when the substitution rate was 100%. The measured yield strength of the round steel pipe used in the test is 326 MPa, and the measured outer diameter of the steel pipe is 168 mm, and the wall thickness is 5.0 mm.

Table 1. Recycled concrete test piece mix ratio

| Number | Replacement rate (%) | Water (kg/m³) | Cement (kg/m³) | Sand (kg/m³) | natural Coarse aggregate (kg/m³) | Recycled coarse aggregate (kg/m³) | Nickel iron slag (kg/m³) | Silica fume (kg/m³) | Water reducing agent (kg/m³) |
|--------|----------------------|----------------|----------------|--------------|--------------------------------|---------------------------------|------------------------|-----------------|---------------------------|
| 24,25,26 | 70                   | 188.77         | 382.2          | 604.44       | 322.4                         | 752.2                           | 109.2                  | 54.6            | 6.55                       |
| 22     | 100                  | 194.66         | 382.2          | 604.44       | 0                             | 1074.56                         | 109.2                  | 54.6            | 6.55                       |

2.2 Component design and production

The test piece has a circular cross section with a column height of 1008 mm. When the test piece is made, the steel pipe of 1008mm length is cut as required. The two ends of the steel pipe are welded with a thickness of 30mm and 300mmX300mm steel plate with bolt holes. The top steel plate also has a hollow hole with a diameter of 80mm which is convenient for concrete to be poured into the steel pipe. The concrete inside the steel pipe is poured into two layers and is compacted by vibrating bar. The actual age of the concrete is 480 days.

Table 2 Test piece basic parameters

| Number | L/mm | t/mm | D/mm | fcu/MPa | fy/MPa | R/% | n | N/kN |
|--------|------|------|------|---------|--------|-----|---|-----|
| 22     | 1008 | 5    | 168  | 37.7    | 326    | 100 | 0.3| 553 |
| 24     | 1008 | 5    | 168  | 41.2    | 326    | 70  | 0.1| 184 |
| 25     | 1008 | 5    | 168  | 41.2    | 326    | 70  | 0.3| 553 |
| 26     | 1008 | 5    | 168  | 41.2    | 326    | 70  | 0.5| 921 |

Design and manufacture 4 components, numbered 22, 24, 25, 26 respectively. The detailed parameters of each test piece are shown in Table 2. In the table, L is the length of the component, and D is the outer diameter of the steel pipe, and t is the wall thickness of the steel pipe, and fcu is the cubic concrete compressive strength measured by the core concrete, and fy is the yield strength of the steel pipe, and R is the coarse aggregate replacement rate (mass fraction), and n is the axial compression ratio of the test piece, and N is the applied vertical axial pressure.
2.3 Test loading scheme

During the test, the test piece is preloaded and unloaded to eliminate the influence of the gap between the support and the loading surface, to eliminate the unevenness inside the test piece and to check whether the test device and the response of each measuring instrument are normal. According to ACT-24 (1992), the loading procedure adopts the load-displacement double control method, that is, the load control is applied before the yielding of the test piece and the grading load is applied. After the yielding, the deformation control is adopted, and the deformation value is taken as the yield displacement of the test piece, and the displacement is taken. The multiple of the value is controlled for the level difference until the test piece is broken. The specimens were loaded according to 0.25Puc, 0.5Puc, and 0.7Puc before yielding, and Puc was the calculated ultimate bearing capacity. After the specimen is yielded, it is loaded according to the deformation control, using 1△y, 1.5△y, 2.0△y, 3.0△y, 5.0△y, 7.0△y and 8.0△y. △y is the yield displacement of the test piece from 0.7Puc determines: Δy = Puc / Ksec, Ksec is the secant stiffness of the load-deformation curve when the load reaches 0.7Puc. The number of turns of each stage of the load cycle is also different. When the load is controlled according to the load, each stage of the load is cycled 2 times. When the deformation is controlled, the first 3 stages of load (1△y, 1.5△y, 2.0△y) are cycled 3 times. The rest are looped 2 times. The test loading device is shown in Figure 1. The test is terminated when the horizontal load of the test drops to 15% of the peak load, or if the steel tube breaks, or the vertical force cannot be stabilized.

3. Test results and analysis

3.1 Test phenomenon

Observing the whole process of the test, the failure phenomenon of the recycled steel tube of the circular steel tube is similar to that of the ordinary round steel tube concrete column. At the beginning of the test, no other phenomena were observed except for the bending deformation of the column; until the test piece approached the damage, local buckling occurred at the pressure side of the stiffener at the bottom of the column about 30 mm, as shown in Fig. 2(a); Or the steel pipe on the pressure side is broken as shown in Fig.2 (b); all the test pieces are stopped when the horizontal load drops to 85% of the peak load, or when the steel pipe on the pressure side is broken.
3.2 Hysteresis curve
The load of each test piece measured in the test-displacement hysteresis curve is shown in Fig. 3. When the displacement is small, the hysteresis loop formed by the forward and reverse loading and unloading of all the test pieces is not prominent, and almost coincides with a diagonal line. After the unloading, the residual deformation of the test piece is small and can be ignored. When the displacement is gradually increased, the load value of the peak point reached by the hysteresis loop formed by all the test pieces gradually increases. After reaching the peak value, the displacement is inversely proportional to the tangent slope of the hysteresis curve, and the bearing capacity of the specimen shows a downward trend. When the load is equal to 0, the test piece appears obvious residual deformation. As the axial compression ratio increases, the shape of the hysteresis loop changes significantly from "/" to "\", and the axial compression has a significant effect on the seismic performance.

3.3 Skeleton curve
The horizontal load of the specimen under different axial compression ratios - the displacement skeleton comparison curve is shown in Fig. 4 (a). It is shown in Fig. 4(a) that the skeleton curves of all the specimens in different axial compression ratios have a "Z" shape, and the skeleton curves of the specimens almost coincided during the initial ascent phase; the curve with the smallest axial compression ratio among the three curves was the outermost. As the axial compression ratio gradually increased, the curve contracted inward, the stiffness gradually decreased, and the load decreased rapidly.
The horizontal load of the specimen under the replacement rate of different recycled coarse aggregates - the displacement skeleton comparison curve is shown in Fig. 4 (b). In the case where the axial compression ratio is constant at 0.3, the replacement curve is almost completely coincident with the skeleton curve of the test piece at 70% and 100% which indicating that the replacement ratio of the recycled aggregate has little influence on the skeleton curve of the test piece.

3.4 Stiffness degradation

The stiffness degradation indicates the cumulative damage of the structure under repeated loading, usually expressed by secant stiffness. The measured secant stiffness of the specimen under different axial compression ratios is plotted as shown in Fig. 5(a). With the increase of the axial pressure ratio, the stiffness degradation of the specimen becomes more obvious, and the curve is more steep on the graph. But as the axial pressure ratio decreases, the curve becomes smoother. The measured secant stiffness of the test piece under different recycling conditions of different recycled coarse aggregates is plotted as shown in Fig. 5(b). When the substitution rate is 70% and 100%, the stiffness degradation curves of the two test pieces almost completely coincided which indicate that the substitution rate has little effect on the stiffness degradation of the test piece.
4. Conclusion
Through the seismic performance test of four round steel tube recycled concrete columns, the following conclusions were obtained:

(1) The failure process and failure modes of the specimens are similar to those of ordinary CFRC columns. The main performance is the drum deformation at the bottom of the steel tube. A relatively obvious drum wave is formed at the front and rear sides of the specimen at a distance of 30 mm from the stiffener at the bottom of the column.

(2) The hysteresis curve of all the test pieces is full. With the increase of the axial compression ratio, the shape of the hysteresis curve develops from the "/" shape to the "\" shape. The hysteresis curve of the test piece is not significant and shows good stability.

(3) The replacement rate of recycled aggregates slightly reduced the initial stiffness of the recycled steel tubular columns, and had little effect on the later stiffness degradation. As the axial compression ratio increases, the stiffness degradation of the test piece becomes more apparent. The steeper the curve, the smaller the axial compression ratio, and the smoother the stiffness degradation curve.

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