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Study of seismic behavior of recycled aggregate concrete-filled steel tubular columns

Yun-Chao Tang, Li-Juan Li *, Wen-Xian Feng, Feng Liu, Ming Zhu

School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou, China

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ABSTRACT

This paper discusses the effects of recycled aggregate concrete strength, axial compression ratio, slenderness ratio and steel tube thickness on the seismic performance of recycled aggregate concrete-filled steel tubular columns. The failure process, hysteresis behavior, skeleton curve, stiffness degeneration, ductility coefficient, and energy consumption function were investigated by conducting low cyclic loading test on six recycled aggregate concrete-filled steel tubular columns and two normal concrete-filled steel tubular columns. The finite element method was applied to investigate the effects of slenderness ratio, steel tube thickness, and axial compression ratio on the seismic behavior. A restoring force model for the recycled aggregate concrete-filled steel tubular columns was constructed accordingly and used to compare the experimental and simulated results. The recycled aggregate concrete-filled steel tubular columns showed excellent seismic performance and deformability compared to the normal concrete-filled steel tubular columns, suggesting that they may feasibly and effectively be applied to load-bearing structures in seismic regions.

1. Introduction

Rampant urbanization in developing countries produces large amounts of untreated construction waste which may be transported to suburban areas for open disposal or simple landfill. China, which has a comprehensive utilization rate <5%, produced up to 3.5 billion tons of construction waste in 2016; this represents a serious threat to the natural ecological environment. Recycled aggregate concrete made from waste concrete has a higher void ratio, water absorption rate, and shrinkage rate but poorer strength and durability compared to normal concrete [1,2]. The high discreteness and low strength of recycled aggregate concrete unfortunately render this material a poor substitute for ordinary concrete in regards to structural use. These drawbacks limit its applicability to some extent [3], despite its well-recognized societal and economic benefits; it can not only save substantial land resources but also reduce the environmental pollution arising from waste concrete [4]. The recycled aggregate concrete-filled steel tubular columns (RACSTC) has been proposed as an approach to compensate for the performance defects of recycled aggregate concrete [5]. Steel tubes significantly improve the strength and durability of recycled aggregate concrete by means of restriction and inclusion; recycled aggregate concrete strengthens the anti-buckling performance of the tubes by internally supporting them [6,7]. This novel type of composite component has excellent mechanical and seismic performance, lending it substantial scientific significance as well as attractive market prospects.

Many previous researchers have analyzed the mechanical behavior of RACSTCs [8–10]. The material's structural seismic performance has attracted a great deal of attention in particular, especially in countries where earthquakes are a frequent occurrence. It seems possible that these novel composite components can be applied in bearing structures in regions where seismic fortification is necessary. Yang [11], for example, investigated the seismic performance of RACSTC under low cyclic loading to find that similar to normal columns, recycled columns can be designed with high ductility and energy dissipation. Xiao [12] found that the binding-slippage has only a slight effect on seismic indexes per a series of pseudo static test and finite element simulation results. The seismic performance of RACSTCs is superior to that of recycled aggregate concrete columns confined with glass fiber reinforced polymer (GFRP), but the performance degrades as axial compression ratio increases. Tang [13] examined the effect of axial compression ratio, steel tube strength, and steel tube thickness on the seismic performance of RACSTCs. RACSTCs have also been shown to have lower energy dissipation and higher ductility than normal concrete-filled steel tubular columns (OCSTC).

Despite numerous valuable contributions to the literature with respect to seismic tests, there has been no fully comprehensive research to date on the seismic performance of RACSTCs. The failure mechanism and restoring force model are necessary to provide a workable reference for elastic-plastic time-history analysis and further development of seismic theories related to RACSTCs.

* Corresponding author.
E-mail address: lilj@gdut.edu.cn (L.-J. Li).

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Table 1
Mixed proportions of recycled aggregate concrete (kg/m^3).

Type	Water	Cement	Sand	RCA	NCA	w/c (%)
C40	189	357	653	625	625	53
C50	189	439	558	632	632	43

Table 2
Main parameters of test specimens.

Specimen	$f_{cu,\,k}$ (MPa)	f_c (MPa)	θ	N_u (kN)	n	N (kN)
D-1	40.7	27.2	2.15	2241.9	0.2	448.4
D-2	40.7	27.2	2.15	2241.9	0.4	896.8
D-3	40.7	27.2	2.15	2241.9	0.6	1345.2
G-1	53.4	35.7	1.64	2498.1	0.2	499.6
G-2	53.4	35.7	1.64	2498.1	0.4	999.2
G-3	53.4	35.7	1.64	2498.1	0.6	1498.8
X	45.8	30.6	1.91	2345.9	0.4	938.3
Y	59.6	39.9	1.47	2618.7	0.4	1047.6

This paper discusses the effects of different axial compression ratios and recycled aggregate concrete strengths on such seismic indexes as hysteresis behavior, energy dissipation, stiffness degeneration, and ductility coefficient per a series of low cyclic loading tests on six RACSTCs and two OCSTCs. The effects of slenderness ratio, steel tube thickness, and axial compression ratio on RACSTC structural seismic performance were also explored by FEM to establish an accurate tri-linear simplified formulation for restoring force model, as discussed below.

2. Test overview

2.1. Material properties

We used 42.5R normal Portland cement and normal river sand with a maximum grain size of 5 mm to create continuously graded concrete samples. A natural coarse aggregate was used with a grain size of 5–20 mm; recycled aggregate with a grain size of 5–20 mm was also used. The mixed proportions of the recycled aggregate concrete are shown in Table 1. The stress-strain curves of recycled aggregate concrete and normal concrete are shown in Fig. 1. The replacement rate of the recycled aggregate concrete was 50%, the outer diameter of the steel tubes was 203 mm, the wall thickness was 8 mm, and the effective computation height was 1000 mm. The type of steel was Q235 with yield strength f_y of 328 MPa, ultimate strength f_u of 401 MPa, and elasticity modulus E_S of 2.15×10^5.

2.2. Specimen parameters

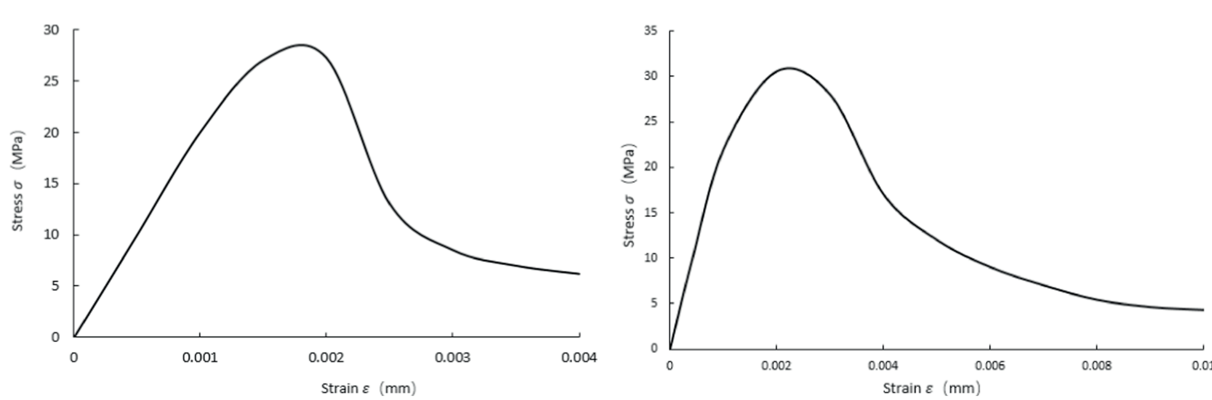
Table 2 describes the design of the specimens. D and G indicate the strength grade C40 and C50 of the recycled aggregate concrete, respectively; 1, 2, and 3 correspond to the axial compression ratio of the steel tubes, 0.2, 0.4, and 0.6, respectively. X and Y represent the OCSTC with C40, C50, respectively. According to previously published calculation methods [13,14], f_c is the designed value of the compressive strength of recycled aggregate concrete, f_c=0.88*0.76*$f_{cu,k}\cdot f_{cu,k}$ is the measured value of the compressive strength of the cylinder of the recycled aggregate concrete. θ is the confinement index of the RACSTC, $\theta = \frac{A_a f_a}{A_c f_c}$, where A_a and A_c are the cross-sectional area of the steel tubes and the core recycled concrete, respectively. The yield strength of the steel tubes f_a is 328 MPa. N is the axial force applied during testing. $N = \text{n}N_u$, where n is the axial compression ratio and N_u is the designed value of the axial compressive-bearing capacity of the RACSTC.

2.3. Test device

As shown in Fig. 2, the loading device used is comprised of a FlexTest GT controller (MTS Systems Corporation) with a rated loading capacity of 500 kN, a hydraulic jack with a measuring range of 5000 kN, and a fully automatic digitally-controlled oil pump. Two displacement meters were placed on the horizontal load of the upper part of the specimen and in the middle part of the specimen to measure changes in the horizontal displacement of the specimen during the loading process. The base was an adjustable solid all-steel bearing platform. A displacement meter was arranged on the base to measure slippage during the loading process. Strain gauges were arranged on the steel tube surface at distances of 50 mm, 150 mm, and 300 mm from the column bottom. Three vertical strain gauges and three circumferential strain gauges were arranged symmetrically on the front and back sides of the column, in addition to three vertical strain gauges arranged symmetrically on the two sides. The specifications of the strain gauges is BX120-5AA. Data for the displacement meters and strain gauges were collected in TDS-530 Data Logger (Tokyo Sokki Kenkyujo Co., Ltd).

2.4. Loading procedure

The force-displacement mixed control method was adopted in the low cyclic loading test [15]. Vertical axial force pre-loading was performed before the official test. Fifty percent of the axial pressure was used for pre-loading followed by unloading; this process was repeated twice. The loading then continued until full load was achieved. The variation range was controlled within 5% throughout the test. The horizontal reversed load was introduced stepwise, and loading was controlled by force before the steel tube yielded in 20 kN increments. The load at



(a) Stress-strain curve for RAC **(b)** Stress-strain curve for Concrete

Fig. 1. Stress-strain curves for the RAC and concrete.