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Axial Compressive Behaviour of Recycled Aggregate Concrete Columns Externally Confined by Square Steel Tube

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Abstract: *By the axial compression tests on a total of 9 recycled aggregate concrete (RAC) columns confined by square steel tube, the effect of recycled coarse aggregate replacement percentage (RCARP) on the axial compressive strength was studied. Test results indicated that the failure modes of core concrete were diagonal shearing failure. With the increase of RCARP from 0% to 100%, the peak load of specimens decreased 14.5%. The simplified calculative method of bearing capacity was discussed by test data and theoretical analysis, which can provide a reference for engineering designers.*

Keywords: *Square steel tube, recycled concrete, axial compression test, recycled coarse aggregate replacement*

1. Introduction

Recycling waste concrete is the hot topic in the field of new green energy-saving building materials. Putting the recycled concrete into steel tube and forming steel tube confined concrete column is one of good engineering application directions. Recycled aggregate concrete filled square steel tubular (RACFSST) column is a new steel concrete composite structure forms, many structural engineers and researchers were interested in such specimens for their inherent advantages, including high load bearing capacity, saving natural coarse aggregate and having good seismic performance [1-7]. In contrast to the numerous available tests on axially loaded short RACFSST columns with steel tube bearing vertical load, only limited researchers have been conducted on the square stub columns while no axial load transfer through the tube. Xuhong Zhou conducted an static axial compression test to investigate the behaviour of 20 square tubed reinforced columns (STRC) with normal concrete [8]. The test results indicate that the height of separated tubes in a STRC column affects little on the axial load strength and ductility of STRC stub columns, the ductility of STRC columns decreases as the compressive strength of concrete and width-thickness ratio of the steel tube increases. There is no relevant specification application because of the differences of recycled coarse aggregate, so the further experimental study is necessary. The aim of this study was to investigate the effect of RCARP on the axial load-carrying capacity of RACFSST columns while no axial load transfer through the tube.

2. Experimental Description

2.1 Material properties

The recycled coarse aggregate (RCA) and natural coarse aggregate (NCA) were washed for several times and dried out naturally, the size of coarse aggregate was 5~35mm. Table 1 gave the basic properties of NCA and RCA. The square steel tubes used for specimens were cold rolled tubes, the material properties of the steel tubes were obtained through tensile coupons tests. The average yield strength was 215MPa, and the thickness of steel tube was 3mm.

Table 1: *Basic properties of natural coarse aggregates and recycled coarse aggregates*

Style	Apparent density (kg/m^3)	Bulk density (kg/m^3)	Water absorption (%)	Index of crushing (%)
NCA	2580	1560	0.67	6.9
RCA	2365	1245	5.5	13.7

2.2 RAC columns

For each group of RACFSST columns, two RAC columns were cast. The diameter of RAC columns was 155 mm. These columns were tested after 28 days. The 28-day compressive strength and the details of RAC columns were presented in Table 2. The failure modes of RAC columns were shown in Figure 1.

2.3 RACFSST columns

Axial compression tests were carried out on three groups of RACFSST columns (3 identical columns for each group) with different recycled coarse aggregate replacement percentages (i.e. 0%, 50%, and 100%). In order to make sure steel tube not to bear vertical load, there was a cutting gap with the width of 10mm at the top and bottom of specimens. The position of gap was shown in Figure 2.

2.4 Experimental setup

The test loading setup was shown in Figure 3. All columns were tested in a hydraulic testing machine with a capacity of 2000 kN. Both ends of the core concrete were placed on a steel plate in order to

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transmit force uniformly. The dimension of steel plates was 200mm×200mm×10mm .The arrangement of the strain gauges were shown in Figure 2.

Table 2: *Details of the tested RAC columns*

Group	Specimen	Height (mm)	Diameter (mm)	r (%)	Peak load (kN)	Concrete strength (MPa)
1	Y-0-1	450	155	0	578	30.6
	Y-0-2	450	155	0	584	30.9
2	Y-0.5-3	450	155	50	539	28.6
	Y -0.5-4	450	155	50	533	28.3
3	Y -1.0-5	450	155	100	471	25.0
	Y -1.0-6	450	155	100	484	25.6

Y-0-1 Y-0-2 Y-0.5-3 Y-0.5-4 Y-1.0-5 Y-1.0-6

Figure 1: *Failure modes of RAC columns*

3. Experimental results and analysis

The details of the tested RACFSST columns were presented in Table 3. According to the test results, the load capacity and the failure modes of all RACFSST columns were showed and discussed in the following sections.

3.1 Failure process and modes

The failure process of RACFSST columns was similar to those of concrete filled steel tube (CFST) columns. All RACFSST columns collapsed in a shear failure mode that was shown in Figure 3. The yellow lines in Figure 3 were concrete shear slip plane. The crushed regions were mainly located at one end or the mid-height of stub columns.

Table 3: *Details of the tested RACFSST columns*

Group	Specimen	RARP (%)	Peak load (kN)	LMV (kN)
1	FG-0-1	0	715	716
	FG-0-2	0	687	
	FG-0-3	0	747	
2	FG-0.5-4	50	675	667
	FG-0.5-5	50	640	
	FG-0.5-6	50	685	
3	FG-1.0-7	100	620	612
	FG-1.0-8	100	611	
	FG-1.0-9	100	605	

Note: LMV is the mean value of peak load in each group.

3.2 Effect of RARP on peak load

The peak load in the test was summarized in Table 3. These parts focus our discussion on the effect of recycled coarse aggregate replacement percentage. The test results in Figure 4 showed the influence of the recycled coarse aggregate replacement percentage on the peak load of RACFSST columns. With the increasing inclusion level of RCA, the maximum compressive load of specimens decreased modestly. With the increase of recycled coarse aggregate replacement percentage (RCARP) from 0% to 100%, the peak load of RACFSST columns decreased 14.5%.

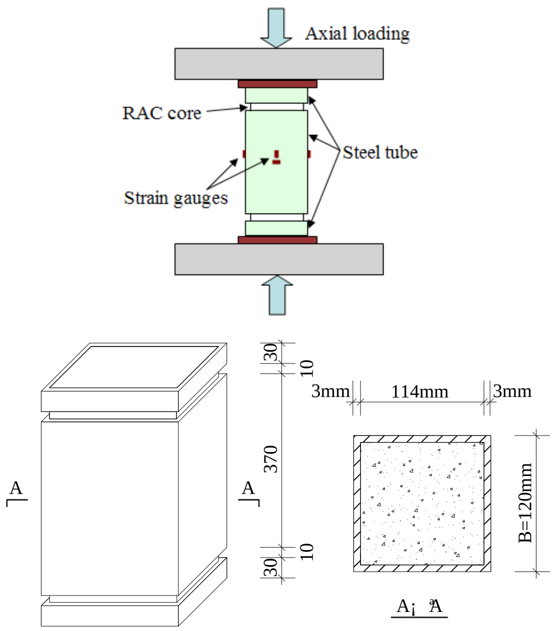
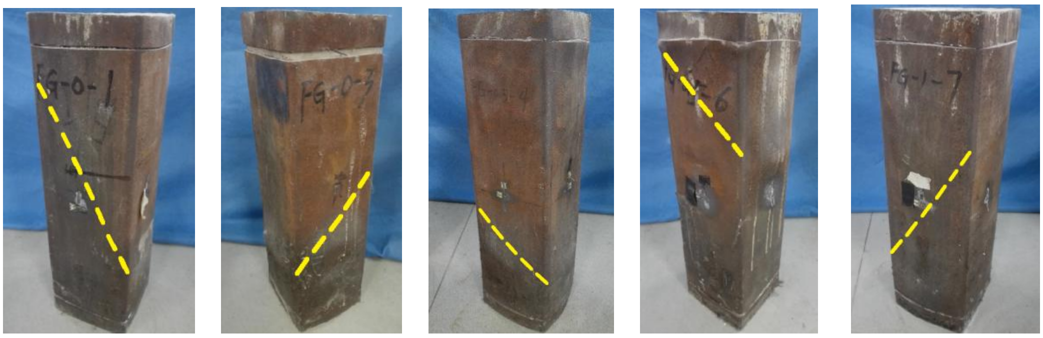


Figure 2: *Layout of test setup and cross-section of RACFSST columns*

The reasons for the decreasing of peak load were largely due to: the recycled coarse aggregate surfaces had been wrapped with screed in different degrees, and the recycled coarse aggregate crushing internally also determined the existence of a certain amount of micro cracks.



FG-0-1 FG-0-3 FG-0-4 FG-0.5-6 FG-1.0-7

Figure 3: *Failure modes of representative RACFSST specimens*

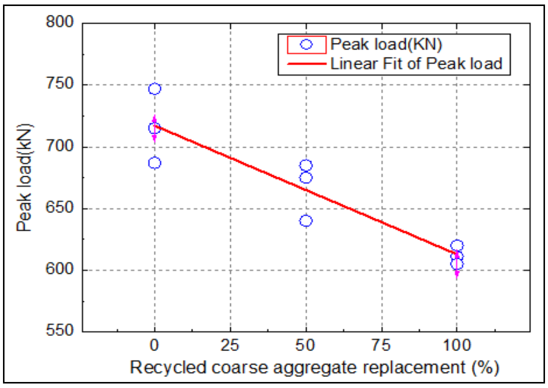


Figure 4: *Effect of RCARP*

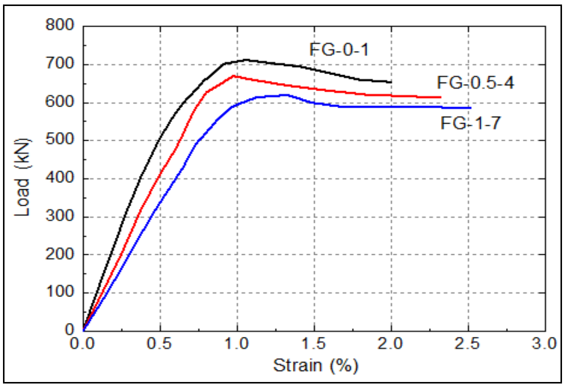


Figure 5: *Load-axial compression strain of stub columns*

3.3 Axial load–strain behaviour

Figure 5 was the relational graph between the load and axial compression strain of stub columns, the axial compression strain was refers to the ratio of axial compression deformation and specimen length. When the load reached 70 percent of peak load, the specimens began to exhibit nonlinear behaviour. At the point of peak load, no local buckling was observed for steel tubes. The peak load point was not corresponding to the yield point of steel tube. After the peak load point, the steel yielded and the shear failure of core concrete led to the rapid lateral expansion of concrete.

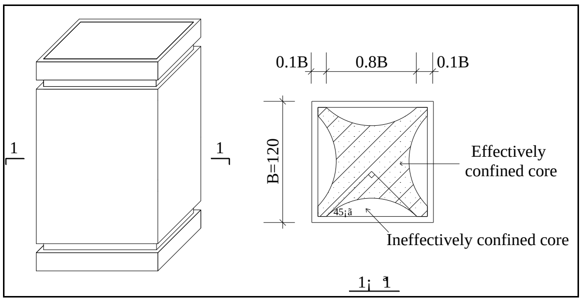


Figure 6: *Effectively Confined Core for RACFSST columns*

4. Peak load calculation

Many calculation models of axial compression capacity for CFST columns cannot be adopted for RACFSST columns, because steel tube could not bear vertical load. Based on the limit equilibrium theory and Mander calculation model [9], the effectively confined core for RACFSST columns was showed in Figure 6. According to Mander Calculation Model, the peak load formula of RACFSST columns under axial compression N_u was given by Eq. (1).

$$N_u = 0.9(f'_{cc}A_{cor} + f_s A_s) \quad (1)$$

Where f'_{cc} represents the confined compressive strength, A_{cor} represents the area of core section enclosed by steel stub, f_s is the design strength of steel bar, A_s is the area of steel bar.

The confined compressive strength could be predicted with Eq. (2).

$$f'_{cc} = f'_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}\right) \quad (2)$$

Where, f'_{co} is the unconfined concrete compressive strength.

The effective lateral confining pressure $f_l^{/}$ was given by Eq. (3).

$$f_l^{/} = f_l k_e = 0.5 k_e \rho_s \sigma_{hp} \tag{3}$$

According to ZHOU Xuhong Model [8], σ_{hp} was the lateral effective stress of steel tube, which could be predicted with Eq. (4).

$$\sigma_{hp} = 0.1(B/t)^{0.5} f_{215} \tag{4}$$

Where, f_{215} is the steel design strength of Q235, f_l is the lateral pressure from the transverse reinforcement, t is the thickness of steel tube.

As shown in Figure 6, k_e is the confinement effectiveness coefficient, which can be calculated by Eq. (5).

$$k_e = \frac{A_e}{A_{cor}} = 0.635 \tag{5}$$

Where, A_e is the area of effectively confined core concrete (ω is the steel tube chamfering radius, $\omega = 0.1B$), ρ_s is the ratio of the volume of transverse confining steel to the volume of confined core concrete, $\rho_s = \dfrac{2t_s(b+h)}{A_{cor}}$.

A comparison of experimental data and the calculated values was shown in Table 4. The calculated value of RACFSST columns was less than the tested one. The deviation was small within 10.2%, the predictions by Eq. (1) compared with the test results were conservative. Hence, Eq. (1) can be used for predicting the peak load of RACFSST columns under axial compression conditions. Due to the discrete type of recycled concrete materials and in order to get a more accurate theoretical model for RACFSST columns, more experimental work should be undertaken in the future.

5. Conclusions

The failure process of RACFSST columns was similar to those of concrete filled steel tube (CFST) columns. All RACFSST columns collapsed with shear failure mode.

With the increase of recycled aggregate replacement percentage (RARP) from 0% to 100%, the peak load of RACFSST columns decreased 14.5%.

Based on the experimental data, approximate formulas for the peak load of RACFSST columns had been presented, which accuracy should be further verified by more experimental data in the future.

Table 4: *Comparisons between calculative and experimental peak load*

Specimen	FG-0-1	FG-0-2	FG-0-3	FG-0.5-4	FG-0.5-5	FG-0.5-6	FG-1.0-7	FG-1.0-8	FG-1.0-9
Tested (kN)	715	687	747	675	640	685	620	611	605
Calculated (kN)	671	671	671	637	637	637	590	590	590
Deviation	6.2%	2.3%	10.2%	5.6%	0.5%	7.0%	4.8%	3.4%	2.5%

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