Open Access Library Journal
2022, Volume 9, e8544
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Finite Element Study on Mechanical Properties of Recycled Concrete Filled Square Steel Tubular Short Columns

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How to cite this paper: Nie, Q.P. (2022) Finite Element Study on Mechanical Properties of Recycled Concrete Filled Square Steel Tubular Short Columns. *Open Access Library Journal*, **9**: e8544.
https://doi.org/10.4236/oalib.1108544

Received: March 1, 2021
Accepted: March 19, 2022
Published: March 22, 2022

Abstract

Using finite element software, the seven specimens are used respectively to set square cross section with circular cross section and seven sets of the combination of the steel tube recycled concrete short column and a solid section of recycled concrete filled steel tubular short column determine the strength of recycled concrete, eccentricity, the outer steel tube wall thickness and steel yield strength for variables; static load analysis of the finite element model is established. The effects of various parameters on the load-longitudinal displacement and ultimate bearing capacity of specimens were simulated and analyzed. The results show that the ultimate bearing capacity and deformation capacity of square hollow sandwich recycled concrete short columns increase with the increase of concrete strength, the decrease of eccentricity, the increase of outer steel tube wall thickness and steel strength. Among the three different section forms, the square section sample has the highest stiffness and ultimate bearing capacity.

Subject Areas

Civil Engineering

Keywords

Square Hollow Composite Steel Tube Recycled Concrete Short Column, Finite Element Analysis, Eccentric Compression, Ultimate Bearing Capacity

1. Introduction

With economic development, urbanization and the continuous advancement of new rural areas, the demolition of old buildings has led to an increasing amount of construction solid waste. In recent years, the output of construction waste is nearly huge, and the proportion of abandoned broken brick blocks can reach more than 50% [1]. If traditional treatment methods are followed, it will occupy a large amount of valuable land resources and cause serious pollution to the living environment of residents. Recycled concrete technology is to crush, sieve, and clean solid waste, so that it can replace natural aggregates in a certain proportion and mix into recycled concrete. Recycled concrete technology not only saves natural aggregates and relieves the pressure of wanton mining of sand and gravel, but also reduces the environmental pollution caused by construction waste disposal difficulties.

Recycled concrete still has many deficiencies in its performance because the aggregates come from demolished old buildings. There are more or less micro-cracks or cracks in the crushed recycled aggregate, so its initial damage is relatively large, and its durability and strength are poor compared with ordinary concrete mixed with natural aggregates, which limits its performance to a large extent in practical engineering [2]. The recycled concrete is combined with the steel pipe to form the recycled concrete component of the steel tube. The interaction between the steel tube and the recycled concrete is used. The constraint of the steel tube makes the core concrete in a three-way stress state, which improves the deformation capacity of the recycled concrete and makes it applicable in the project. The stability of the thin-walled steel pipe is also improved due to the support of recycled concrete. The combination of the two has the advantages of high ultimate strength, good economic benefits, strong deformation ability and easy construction. The synergy of the two can be widely used in prefabricated low-rise residential buildings.

Many scholars have done corresponding research on steel tube recycled concrete structure. The researchers Konno *et al.* [3] first conducted the mechanical performance test of the steel tube recycled concrete column. The analysis showed that the stiffness, strength and ductility of the steel tube recycled concrete column are inferior to ordinary concrete, but it can still meet the actual engineering needs. Mohanraj *et al.* [4] found that the EC4 specification underestimated the bearing capacity prediction by 26%, the American specification ACI318-95, the Australian specification AS3600 and AS4100 underestimated by 42%; the ACI and AS specifications had better calculation results for specimens with a slenderness ratio greater than 12. When the slenderness ratio is 4 - 12, the correction formula of the ultimate bearing capacity of ACI and AS codes is:

$$N_{\mathrm{ACI/AS}} = k\left[0.85A_c f_{cc} + A_s f_y\right],$$

A_c, A_s for concrete area and steel pipe area; f_y, f_{cc} are steel yield strength and concrete cube compressive strength; k is the correction coefficient. Moon [5] established the bending model of concrete-filled circular steel tubular columns based on the improved finite element method, analyzed the influence of parameters on the bending performance of the structure, and proposed a simplified calculation model that can predict the bending moment-rotation curve. Tao [6] proposed a fine finite element model to study the axial compression performance of concrete-filled steel tube columns. This three-stage model can well reflect the stress hardening/softening law of core concrete under the constraint of steel tube, and it is also applicable to high strength concrete or thin-walled steel tube. Zhong [7] made a comparison between recycled concrete filled steel tube column and ordinary concrete filled steel tube column, and verified that recycled concrete can be used as filling material in bearing structure. The axial compression performance of recycled concrete filled steel tube column is not significantly lower than that of ordinary concrete filled steel tube column. Through ABAQUS modeling, Zhang [8] analyzed the bending capacity of concrete-filled steel tube columns subjected to static load and impact load, respectively. The simulation results were in good agreement with the experimental results, and a mathematical model for predicting the bending of concrete-filled steel tube columns under different stress conditions was proposed. Wang *et al.* [9] found that the specimen occurred drum bending failure, shear slip line appeared at the end, and developed with the increase of load, the short column showed shear failure, and the long column showed bending failure. Sangeetha *et al.* [10] showed that the mechanical properties of recycled concrete filled steel tubular columns decreased with the increase of slenderness ratio. Cao and other studies [11] show that the ductility of recycled concrete filled steel tube members is better, and the bearing capacity is about twice the total bearing capacity of single steel tube and recycled concrete.

The purpose of this paper is to establish a reasonable material constitutive model and use the finite element analysis software to obtain the square steel tube recycled concrete short column with three different cross-section forms: square hollow sandwich, square hollow sandwich and square solid. The load-longitudinal displacement relationship curve of the specimen, calculate and analyze the influence of the eccentric distance, concrete strength, outer steel pipe wall thickness and steel strength and other parameters on the mechanical properties of the square steel tube recycled concrete short column, and make some benefits for the limited steel tube recycled concrete structural members. A discussion of meta-numerical analysis.

2. Material Constitutive Relationship

2.1. Constitutive Relation of Steel

The steel constitutive model adopts five-stage model. For low-carbon steel, the stress-strain strength ($\sigma_i - \varepsilon_i$) curve of steel is divided into five stages, as shown in **Figure 1**. These five stages are respectively elastic stage (oa), elastic-plastic stage (ab), plastic stage (bc), strengthening stage (cd) and secondary plastic flow stage (de). The dotted line in the figure is the actual $\sigma_i - \varepsilon_i$ relationship curve of steel, and the simplified $\sigma_i - \varepsilon_i$ relationship curve is represented by the solid line. At the same time, the strengthening section is simplified to a straight line after reaching the strength limit, which is convenient for calculation.

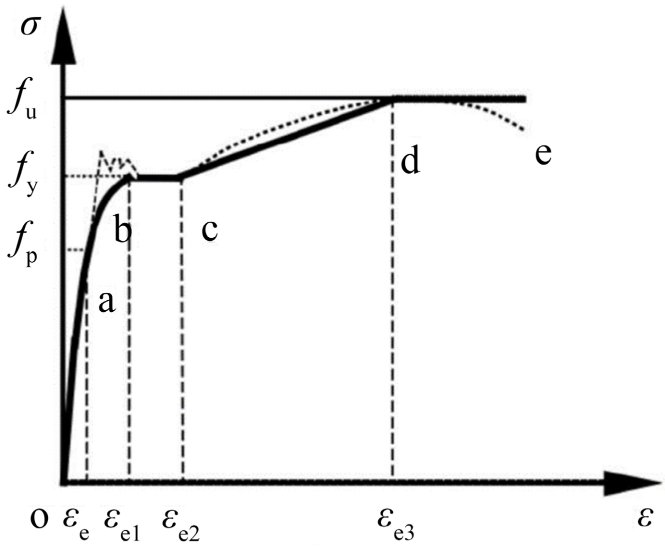


Figure 1. Constitutive relation of steel pipe.

Among them, f_p, f_y and f_u are the proportional limit, yield limit and tensile strength limit of steel respectively. Its mathematical model expression is shown below.

$$\sigma_s = \begin{cases} E_s \varepsilon_s & \varepsilon_s \le \varepsilon_e \\ -A\varepsilon_s^2 + B\varepsilon_s + C & \varepsilon_e \le \varepsilon_s \le \varepsilon_{e1} \\ 1.6 f_y & \varepsilon_{e1} \le \varepsilon_s \le \varepsilon_{e2} \\ f_y \left[1 + 0.6 \dfrac{\varepsilon_s - \varepsilon_{e2}}{\varepsilon_{e3} - \varepsilon_{e2}} \right] & \varepsilon_{e2} \le \varepsilon_s \le \varepsilon_{e3} \\ 1.6 f_y & \varepsilon_s \ge \varepsilon_{e3} \end{cases} \quad (1)$$

$$\varepsilon_e = 0.8 f_y / E_s \quad (2)$$

$$\varepsilon_{e1} = 1.5\varepsilon_e;\ \varepsilon_{e2} = 10\varepsilon_{e1};\ \varepsilon_{e3} = 100\varepsilon_{e1} \quad (3)$$

$$A = 0.2 f_y / \left(\varepsilon_{e1} - \varepsilon_e\right)^2 \quad (4)$$

$$B = 2A\varepsilon_{e1} \quad (5)$$

$$C = 0.8 f_y + A\varepsilon_e^2 - B\varepsilon_e \quad (6)$$

where f_y represents the yield strength of steel; E_s represents the elastic modulus of steel; ε_e is the strain value corresponding to the proportional limit; ε_{e1} is the strain value corresponding to the beginning of the yield stage; ε_{e2} is the strain value corresponding to the beginning of the strengthening stage; ε_{e3} is the strain value corresponding to the strength limit.

2.2. Constitutive Relation of Concrete

It is almost impossible to establish a general stress-strain relationship model of concrete due to the inhomogeneity of its constituent materials, the uncertainty of construction level and the diversity of stress state. Because the failure process of concrete is actually the expansion and penetration of micro cracks before the material is subjected to load, which develops into macro cracks and leads to instability and failure of concrete. Therefore, the plastic damage constitutive model of concrete is used in finite element simulation. In the core concrete model, it is necessary to consider the difference in mechanical properties between the internal and external steel tubes and ordinary concrete when considering their hooping effect. Therefore, it is necessary to correct the peak strain and decline section of the stress-strain curve of ordinary concrete under uniaxial compression. The mathematical expression is:

$$y = \begin{cases} 2x - x^2 & x \le 1 \\ \dfrac{x}{\beta_0 (x-1)^\eta + x} & x > 1 \end{cases} \tag{7}$$

$$x = \frac{\varepsilon}{\varepsilon_0}, \quad y = \frac{\sigma}{\sigma_0}, \quad \sigma_0 = f_c', \quad \varepsilon_0 = \varepsilon_c + 800\xi^{0.2} \times 10^{-6} \tag{8}$$

$$\varepsilon_c = (1300 + 12.2 f_c') \times 10^{-6} \tag{9}$$

$$\eta = \begin{cases} 2 & \text{Concrete filled circular steel tube} \\ 1.6 + 1.5/x & \text{Concrete filled steel rectangular tubes} \end{cases} \tag{10}$$

$$\beta_0 = \begin{cases} \left(2.36 \times 10^{-5}\right)^{\left[0.25 + (\xi - 0.5)^7\right]} \times \left(f_c'\right)^{0.5} \times 0.5 > 0.12 & \text{circular} \\ \dfrac{\left(f_c'\right)^{0.1}}{1.2\sqrt{1+\xi}} & \text{rectangular} \end{cases} \tag{11}$$

3. Establishment of Finite Element Model

3.1. Selection of Unit Type

Because the thickness of the steel tube is negligible in the length direction, in order to meet the accuracy requirements, the linear 4-node reduction integral S4R shell element is adopted. The core concrete and the upper and lower end plates adopt the solid element of 8-node linear shrinkage integral C3D8R. The recycled concrete adopts the plastic damage model due to the internal original damage, and the end plate is set as a rigid body.

3.2. Connection Settings between Model Components

In order to realize the equivalent shrinkage of the section, endplates are set at both ends of the model. Each specimen consists of five separate components: outer steel tube, inner steel tube, core concrete and top and bottom end plates. The interaction between components is defined by the surface. One surface is the main surface and the other is the slave surface. The difference between the main surface and the slave surface is that the former can bind multiple slave surfaces. The steel tube is selected as the main surface when it interacts with concrete, and the concrete and steel tube are selected as the surface when they contact with both ends of the plate. In the finite element software, the interface models of internal and external steel tubes and core concrete are composed of two parts. One part is the bond slip in the tangential direction. The contact interface is defined by the Coulomb friction model and defined by Penalty with the friction coefficient of 0.6. The interface is defined by surface-to-surface contact and the finite slip effect is considered. The other part is the contact in the normal direction, and the hard contact is used in the normal direction. Tie constraint is adopted between the end plate and the upper and lower interfaces of concrete and steel tube.

3.3. Mesh Subdivision

After the finite element model is established, the model needs to be meshed, the model is divided into a certain number and size of the unit, and each unit is connected by nodes. The grid division in this paper adopts the structured division method. The accuracy of calculation results will be affected by the fine degree of element meshing. The smaller the meshing unit is, the more accurate the calculation results will be. However, the calculation amount increases and the calculation time increases. In this paper, each component of the model is divided into hexahedral element grids with equal size and 15 mm edge length, which can reduce the calculation time while ensuring the calculation accuracy. Grid division as **Figure 2**.

3.4. Boundary Conditions and Loading Methods

The square steel tube recycled concrete column in this paper is a three-axis symmetrical structure, and the rigid end plate at the bottom of the column adopts a fixed constraint U1 = U2 = U3 = 0, that is, the end plate has no displacement in the three directions of space X, Y and Z, but can be wound. Constrain the direction of rotation. On the other hand, the top end plate center node does not experience any rotation and lateral displacement (x and y directions). The top end plate of the specimen is deformed only along the longitudinal (z) axis, along which the load is applied. In this paper, a displacement-controlled loading regime is used to apply loads. Set the reference point as the action point of the displacement and couple it to the end plate. See **Figure 3** for details:

3.5. Design Scheme of Specimen

The establishment of the finite element model in this paper adopts the above constitutive relationship and modeling method, the column length L = 500 mm, the outer side length of the column D = 165 mm, and different eccentric distances (0, 30, 50) and different outer steel tube wall thicknesses are used. (t = 4, 5), different section forms (square sleeve, square sleeve, square solid), different concrete strengths (C30, C35, C40), different steel strengths (Q235, Q345) are the changing parameters, using ABAQUS A model of 15 square steel tube recycled concrete short columns was established, and the model was calculated and analyzed. The dimensions of the specimens and specific design parameters are shown in **Table 1**.

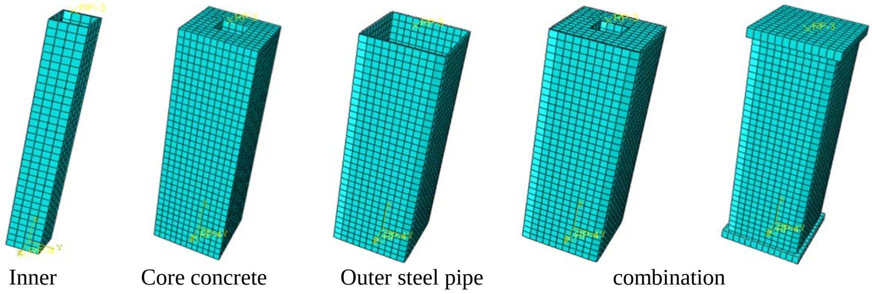


Figure 2. Grid generation.

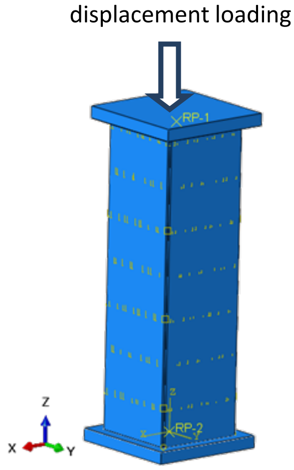


Figure 3. Boundary conditions and loading arrangement.

Table 1. Design parameters of specimens.

Specimen serial number	D/mm	f_y/Mpa	$f_{cu,k}$(N/mm^2)	t/mm	t_i/mm	$D_i(B_i)$/mm	e/mm
1-sds-$r_1t_1e_1$	165	235	30	4	3	60	0
2-sds-$r_1t_1e_2$	165	235	30	4	3	60	20
3-sds-$r_1t_1e_3$	165	235	30	4	3	60	40
4-sds-$r_2t_1e_1$	165	235	35	4	3	60	0
5-sds-$r_3t_1e_1$	165	235	40	4	3	60	0
6-sds-$r_1t_2e_1$	165	235	30	5	3	60	0
7-sdc-$r_1t_1e_1$	165	235	30	4	3	60	0
8-sdc-$r_1t_1e_2$	165	235	30	4	3	60	20
9-sdc-$r_1t_1e_3$	165	235	30	4	3	60	40
10-sdc-$r_2t_1e_1$	165	235	35	4	3	50	0
11-sdc-$r_3t_1e_1$	165	235	40	4	3	50	0
12-sdc-$r_1t_2e_1$	165	235	30	5	3	50	0
13-ss-$r_1t_1e_1$	165	235	30	4	3	0	0
14-sds-$r_1t_1e_1$-345	165	345	30	4	3	0	0
15-sdc-$r_1t_1e_1$-345	165	345	30	4	3	0	0

Where sds stands for square-sleeve square section, sdc stands for square-sleeve circular section, ss stands for square solid section; t_1, t_2 are wall thickness $t = 4, 5$; e_1, e_2, e_3 are eccentricity 0, 30, 50; t represents the wall thickness of the outer steel pipe; $D_i(B_i)$ represents the outer diameter or side length of the inner steel pipe; t_i represents the wall thickness of the inner steel pipe. r_1, r_2, r_3 are recycled concrete strength C30, C35, C40. 345 means the outer steel pipe is Q345.

4. Analysis of the Influence Factors of the Specimen

4.1. Influence of Concrete Strength

From Figure 4, it can be seen that recycled concrete filled square steel tube has little effect on the shape of load-axial displacement curve when eccentricity, steel strength and wall thickness of outer steel tube remain unchanged. At the beginning of loading, the initial stiffness of the specimen changed little; in the elastic-plastic stage, with the increase of concrete strength, the peak load of the specimen increases, and the downward trend of each specimen curve is basically consistent.

4.2. Influence of Eccentricity

Figure 5 shows the load-axial strain curves of 1-sds-$r_1t_1e_1$, 2-sds-$r_1t_1e_2$, 3-sds-$r_1t_1e_3$ and 7-sdc-$r_1t_1e_1$, 8-sdc-$r_1t_1e_2$, 9-sdc-$r_1t_1e_3$. It can be seen from the figure that when the concrete strength and the wall thickness of the steel tube are fixed, with the increase of eccentricity, the smaller the initial stiffness of the specimen, the lower the peak load, and the corresponding peak strain decreases. Compared with the model with eccentricity of 0 mm, the ultimate bearing capacity of the model with eccentricity of 30 mm and 50 mm of square hollow sandwich recycled concrete

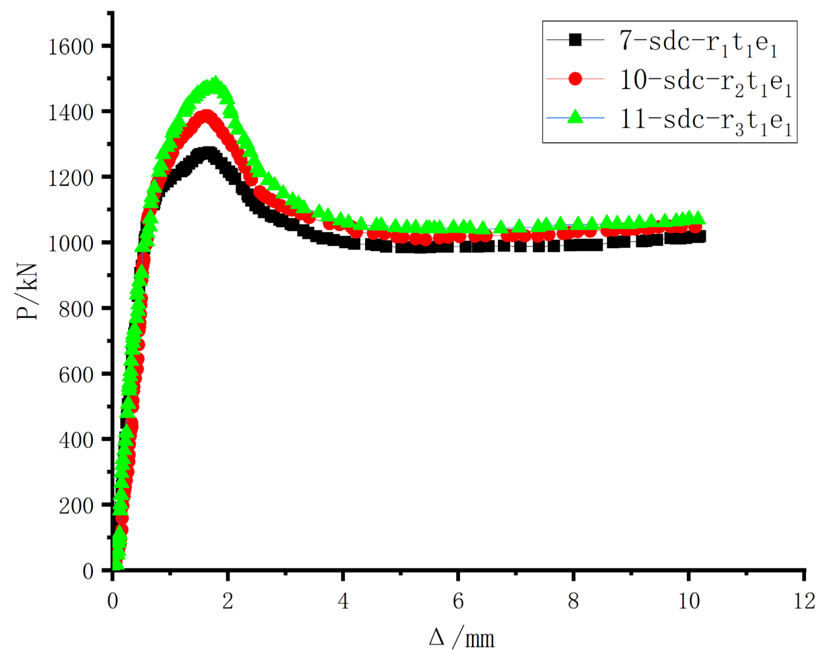
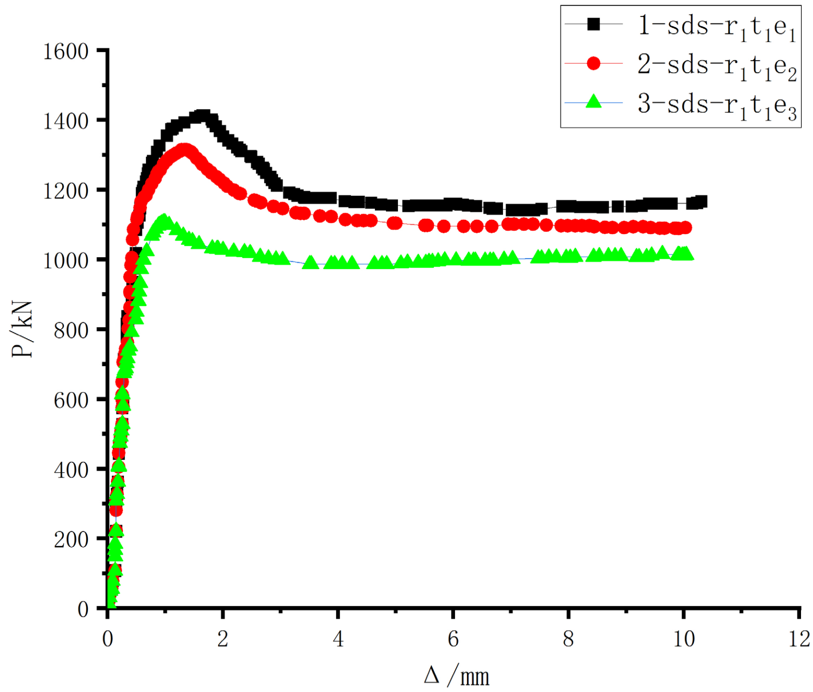
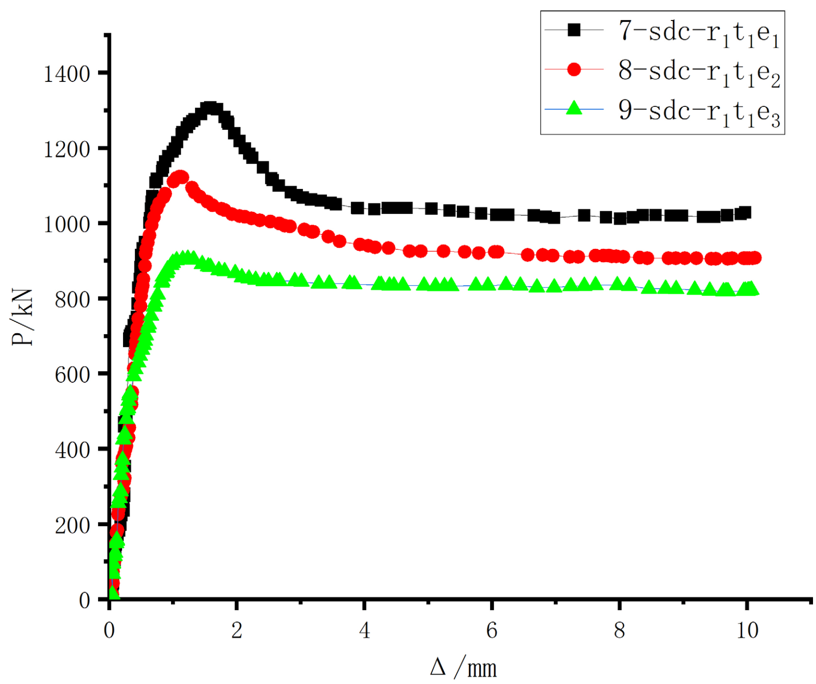


Figure 4. Load axial displacement curve of different recycled concrete strength.



(a)



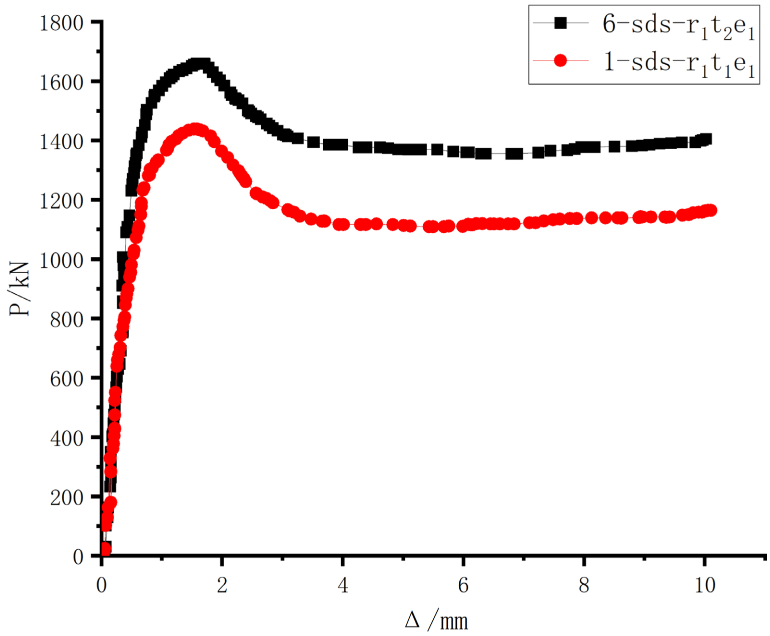
(b)

Figure 5. Load axial displacement curves with different eccentricities. (a) sds-r_1t_1e; (b) sdc-r_1t_1e.

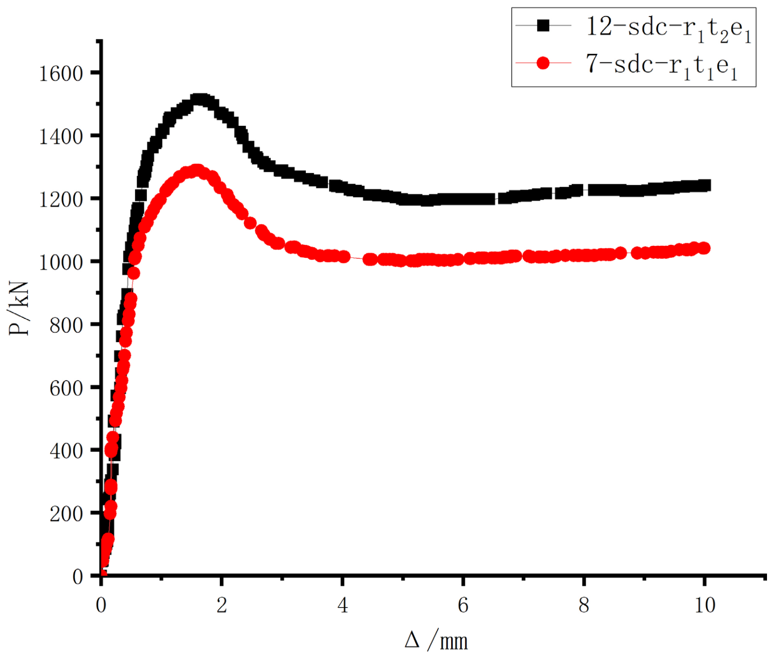
short columns decreased by 13.9% and 25.3%, respectively. It is proved that the change of ultimate bearing capacity and eccentricity of the model is nonlinear under the condition of certain concrete strength and steel tube wall thickness. After the peak value, although the bearing capacity of the specimens decreased, but eventually showed good ductility, indicating that the steel tube on recycled concrete constraints significantly, can effectively improve the deformation performance of recycled concrete.

4.3. Influence of Wall Thickness of External Steel Pipe

Figure 6 shows the load-longitudinal displacement curves of the finite element



(a)



(b)

Figure 6. Load axial displacement curve of different steel pipe wall thickness. (a) sds-r_1te_1; (b) sdc-r_1te_1.

models 1-sds-$r_1t_1e_1$, 6-sds-$r_1t_2e_1$ and 7-sdc-$r_1t_1e_1$, 12-sdc-$r_1t_2e_1$ of the square steel tube recycled concrete short column. It can be seen from the figure that the initial stiffness of the models 6-sds-$r_1t_2e_1$ and 12-sdc-$r_1t_2e_1$ with small wall thickness of the outer steel tube is slightly smaller than that of the models 1-sds-$r_1t_1e_1$ and 7-sdc-$r_1t_1e_1$ with thick wall thickness of the outer steel tube. With the increase of load, the stiffness of the specimen with small wall thickness of the outer steel tube degenerates earlier and yields first. With the increase of the wall thickness of the outer steel tube, the peak load of the specimen increases obviously, the trend of the decline section of the curve is basically the same, and the later curve shows an upward trend. The main reason for the formation of this curve is that at the initial loading stage of the specimen, the combined effect of steel tube and core recycled concrete has not yet played a role, and they bear loads respectively. The specimen with large wall thickness of the outer steel tube has large steel content and small deformation. With the increase of load, the combination effect between recycled concrete and steel pipe began to occur. The greater the thickness of the steel pipe wall, the stronger the hooping capacity, and the concrete strength was greatly improved. However, due to the existence of more micro cracks in the recycled aggregate itself, the micro cracks expanded under large load, so the downward trend of the curve did not decrease. It can be seen from the figure that the increase of the wall thickness of the outer steel tube of the square steel tube recycled concrete short column has a great effect on the improvement of the ultimate bearing capacity of the component.

4.4. Influence of Steel Strength

Figure 7 is the load axial displacement curve of square steel tube recycled concrete short column steel strength f_y 235, 345 Mpa. It can be seen from the figure that the influence of steel strength on the stiffness of the specimen is not obvious in the elastic stage. In the plastic stage, with the increase of steel strength, that is, the increase of hoop capacity, the stiffness of the specimen increases slightly, the stability is enhanced, the peak load of the specimen is significantly improved, the curve descending section is gentle, and a certain recovery occurs later.

4.5. The Influence of Different Cross-Section Forms

Figure 8 shows the load-axial displacement curves of recycled concrete filled square steel tubular stub columns with different section forms. It can be seen from the figure that at the beginning of loading, the curve was close to a straight line, and the deformation of the specimen was small. In the elastic-plastic stage, each specimen reaches the ultimate load, and the square sleeve 1-sds-$r_1t_1e_1$ specimen has the maximum ultimate load. In the plastic stage, each specimen showed good ductility. Under certain eccentricity, concrete strength and steel strength, the bearing capacity of square solid specimen is 1369 kN, and the bearing capacity of square hollow sandwich specimen is 1443 kN, which is increased by about 5.4%.

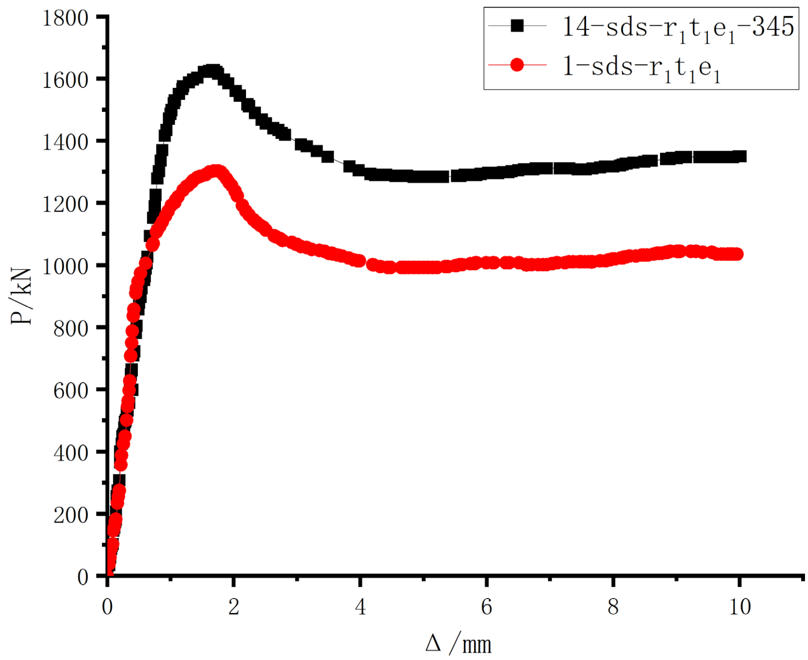


Figure 7. Load axial displacement curves of different steel strength.

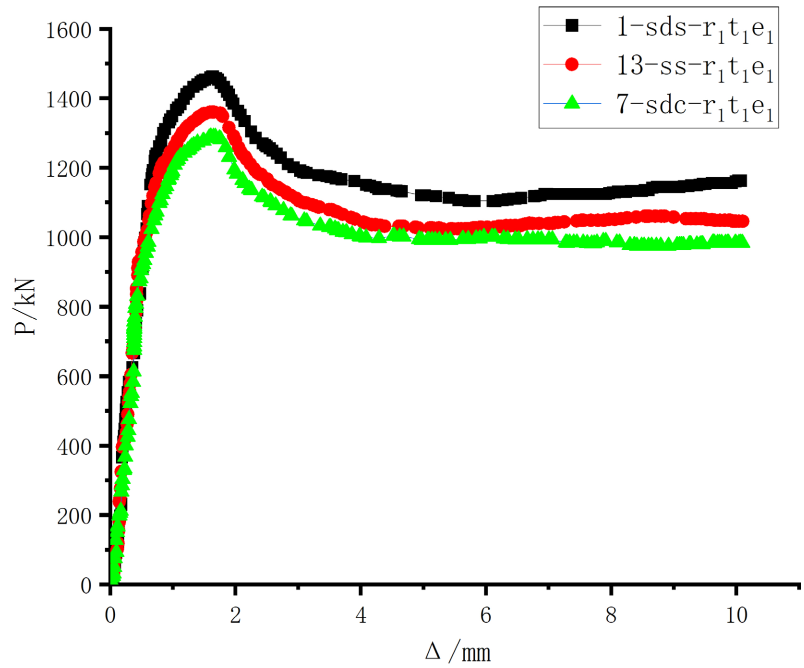


Figure 8. Load axial displacement curves of different section forms.

5. Conclusions

Through the simulation analysis of the parameters of 15 finite element models, the following conclusions can be obtained:

1) With the increase of concrete strength, the stiffness of the specimen changes little at the initial stage of loading. With the increase of load, the ultimate load of the specimen with higher concrete strength is larger, and the trend

of the descending curve is consistent. With the increase of eccentricity, the smaller the initial stiffness of the specimen is, the smaller the corresponding peak strain is, and the lower the peak load is, and the reduction is more obvious. The ultimate bearing capacity and eccentricity of the model are nonlinear, and the confinement effect of steel tube on recycled concrete is remarkable, which can effectively improve the deformation performance of recycled concrete.

2) With the increase of the wall thickness of the steel tube and the strength of the steel, that is, the confinement ability of the hoop is enhanced, the stiffness of the square steel tube recycled concrete short column specimen is improved, and the ultimate bearing capacity is significantly improved. The descending section of the curve is flat and the trend is basically the same, and the later curve shows an increase.

3) Among the specimens with different cross-section forms, the bearing capacity of the square hollow sandwich steel tube recycled concrete short column is the highest; the descending curve of square solid and square sleeve hollow section specimens almost coincides, that is, with the increase of load, the stress situation is almost consistent with the axial direction, and the specimens of each section form show good ductility.

Conflicts of Interest

The author declares no conflicts of interest.

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