Numerical Study on Temperature Field of Recycled Aggregate Concrete-Filled Steel Tubular Columns Under Fire

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Abstract: In order to study the characteristics of the temperature field and variation law of steel pipe recycled aggregate concrete column in a fire hazard, this paper takes the thickness of steel pipe and the type of concrete material as the main parameters to carry out fire resistance test of six concrete steel columns simulated by ABAQUS and conducts finite element analysis of the temperature field inside the test piece. The result shows that both the steel pipe recycled concrete column and the ordinary steel tube concrete column have a temperature platform during heating, and their temperature rise is feature hysteresis; the thickness of the steel pipe has little effect on the internal temperature rise while the concrete material is the main factor affecting the heating rate, so steel pipe recycled aggregate concrete column is better fire-resistant. The constitutive model based on the modified parameters in European EC4 specification is used for finite element analysis, and the FEM simulation result is well fitted with the experimental data.

1. Introduction

As a green material, recycled concrete can help to protect the ecological environment by handling a large amount of improperly disposed waste concrete. In addition, recycling construction waste can reduce the exploration of natural sandstone, alleviating the pressure of increasingly scarce of natural aggregates, thus avoiding ecological damage caused by over-exploitation and protecting the environment, which reflects the idea of sustainable development.

The steel pipe recycled concrete column is strong and has good ductility. The steel pipe provides restraint to the central concrete, and the two materials work together to be earthquake resistant and practical in use. At present, domestic and foreign scholars have carried out a lot of research on its performance. Liu [1] analyzed the bearing capacity and deformation capacity of recycled aggregate concrete-filled steel columns before and after fire based on the steel content and concrete material. Luo [2] has deduced and verified the calculation formula of axial bearing capacity of steel pipe recycled concrete column at normal and high temperature. Hou [3] has proposed a simplified calculation formula of elastic modulus and bearing capacity of steel tube recycled concrete under constant high temperature by testing its mechanical properties. Mohanraj [4] studied the mechanical behavior of slender steel pipe recycled concrete columns, and compared the result with the European
EC4 specification. Kodur [5] established a simple calculation formula of the fire endurance of concrete steel tubular columns with circular and square sections and verified it through experiment.

However, the research on the temperature field of steel pipe recycled aggregate concrete column is relatively scarce. Therefore, this paper will conduct the finite element analysis of the distribution of temperature field steel pipe recycled concrete column in a fire disaster so as to provide reference for its refractory design.

2. Test overview

2.1 Specimen
This test designs six seamless round steel tube concrete specimens and sets the thickness and concrete material type as the main parameters. The thicknesses are 4 mm and 5 mm respectively while the material is divided into ordinary concrete (N), semi-recycled concrete with coarse aggregate replacement rate of 100% (Ra), and full-recycled concrete with fine aggregate replacement rate of 100% (Rb). The parameters of the test piece are shown in Table 1. D is the outer diameter, t is the thickness of the steel pipe, L is the height, RP_{RCA} is the replacement ratio of the coarse aggregate of recycled concrete, and RP_{RFA} is the replacement rate of the fine aggregate of recycled concrete.

| NO.   | D/mm | t/mm | L/mm | RP_{RCA}/% | RP_{RFA}/% |
|-------|------|------|------|------------|------------|
| FC-N-T1 | 100  | 4    | 500  | 0          | 0          |
| FC-N-T2 | 100  | 5    | 500  | 0          | 0          |
| FC-Ra-T1 | 100 | 4    | 500  | 100        | 0          |
| FC-Ra-T2 | 100 | 5    | 500  | 100        | 0          |
| FC-Rb-T1 | 100 | 4    | 500  | 100        | 100        |
| FC-Rb-T2 | 100 | 5    | 500  | 100        | 100        |

2.2 Arrangement of measuring point
Three K-type thermocouple measuring points are set at the center depth of the test piece at 250 mm to collect the temperature change of the test piece and obtain the temperature field curve. The position and number of the cross-section of the thermocouple measuring point are shown in Figure 1.

2.3 Overview of fire test
The fire test takes the ISO-834 international standard heating curve to simulate the whole process of fire disaster. The test piece was only fired on the side, while the top and the bottom are covered with rock wool for isolation. The six specimens are simultaneously burnt in the small vertical fire furnace for 1 h. The testing phenomenon can be observed and recorded through the furnace viewport. After the test, the specimens are cooled naturally.
The temperature curve of ISO-834 international standard and the measured temperature curve of furnace are shown in Figure 3. It can be seen that the two curves agree with each other, indicating that this test can better simulate the situation of the components in real fire.

2.4 Specimen damage characteristics and temperature field monitoring results
This test monitors the temperature field changes of the internal measuring points of the six test pieces by taking the thickness of the steel pipe and the type of concrete material as the influencing factors. Figure 4 is the temperature field distribution curve of the test pieces with a thickness of 4 mm (FC-N-T1, FC-Ra-T1, and FC-Rb-T1) and the test piece with a thickness of 5 mm (FC-Rb-T2).

![Temperature-time curves of specimens](image)

It can be seen from Figure 4 that when the fire lasts 25–30 minutes, the curve stays at about 150–200 °C, which is called the temperature platform. When the fire stops, the internal temperature of the specimen continues to rise with FC-N-T1, FC-Ra-T1 and FC-Rb-T1 reaching the maximum temperature at 62.5~67 minutes. Then their temperature starts to drop, indicating the rising of temperature field is delayed.

The maximum temperatures of FC-N-T1, FC-Ra-T1, and FC-Rb-T1 are 782.5 °C, 732 °C, and 667.3 °C respectively. With the increase of recycled concrete replacement ratio, the internal temperature gradually decreases, indicating the internal heating efficiency of concrete is lower and the internal temperature conduction speed is slower. Therefore, it can be seen that the fire resistance of recycled concrete is better than that of ordinary concrete.

3. Finite element analysis of internal temperature field of RACFST column

3.1 Constitutive relationship of the material
The thermal parameters of the steel are calculated using the results provided by Lie [6]. The thermal conductivity and specific heat capacity of recycled concrete are selected according to Huang Yunbiao [7] and Zhang Feng [8] and verified based on the European EC4 specification [9]. Since the recycled coarse aggregate and fine aggregate have high water content, the corrected density and specific heat product $\rho C_v$ are adopted [10-11]. Since the outer surface of the steel pipe belongs to the third type of...
boundary condition, taking into consideration the thermal radiation of the surface [2], the heat transfer coefficient \( h \) is set as 1500 W/(m\(^2\)K) for the surface exposed to fire and 540 W/(m\(^2\)K) for the unexposed surface.

### 3.2 Establishment of finite element model

This paper solves the temperature field of steel pipe recycled concrete columns by adopting the ABAQUS/Standard module. The outer steel tube adopts DS4 four-node heat transfer quadrilateral shell, and in order to improve calculation accuracy, the Simpson 9 integral points are used along the thickness direction. The recycled concrete adopts DC3D8 eight-node linear heat transfer solid element, which is divided by green structural grid. The outer surface of the concrete and the inner surface of the steel tube are bound together so that the heat can be transferred to the interior of the concrete. The finite element analysis model is shown in Figure 5.

![Meshing of steel tube](image1)
![Meshing of RAC](image2)
![Meshing of specimen](image3)

**Figure 5.** Finite element analysis model of specimen.

### 3.3 Finite element simulation results and analysis

ABAQUS finite element analysis software is used to calculate and simulate the internal temperature field of steel pipe recycled concrete specimens, thereby obtaining the time-temperature curve from 0 to 60min. The calculated temperature of center point of different columns (axial depth of 250 mm, radial center of 50 mm) is compared with the test results, see Figure 6.

![Temperature curves](image4)

**Figure 6.** Comparison of calculated temperature curves and measured curves of specimens.

It can be seen from Figure 6 that the error between the calculation and the test result is controlled between 6.31% and 13.5%. The calculation of ordinary concrete specimen is slightly higher than the test result because the influence of moisture is not considered, and internal heating rate is faster. As for the other two specimens, the calculation results are close to the test results, especially for Rb, indicating that the constitutive relationship of the recycled concrete with the internal moisture content of taken into consideration can more accurately reflect the internal temperature rise of the recycled steel column.

In order to analyze the temperature distribution inside the steel pipe recycled concrete column, this
paper analyzes the temperature cloud diagram of the specimen at different cross-section positions (Figure 7) at 60 min by taking FC-Rb-T2 as an example. The axial section temperature cloud diagram is shown in Figure 8; the cross-sectional temperature cloud diagram is shown in Figure 9.

It can be seen from Figure 8 and Figure 9 that the temperature distribution characteristics of the recycled concrete steel column are: the closer to the center in the axial direction and the radial direction, the lower the temperature is; staircase distribution; the temperature of outermost surface can reach 871 °C, while that at the center is only about 387 °C. Due to the fact that the convective heat transfer coefficient at the unexposed side is small, its temperature rise is relatively slower. The temperature transfer inside the recycled concrete mainly depends on the thermal radiation and thermal convection of the external steel tube (the surface exposed to fire).
4. Conclusion
(1) A temperature platform (temperature is maintained at 100–150 °C) exists in the internal temperature field of steel pipe recycled concrete column and ordinary steel tube concrete column. The heating process is featured with hysteresis.
(2) The maximum temperature of FC-Rb-T1 test piece is 14.7% lower than that of FC-N-T1, which indicates that the internal temperature rise of steel pipe recycled coagulation column is slower, thus good fire resistance.
(3) The thickness of the steel pipe has little effect on the internal temperature rise while the concrete material is the main influencing factor affecting the final temperature.
(4) The error between FEM calculation and test result is 6.31%–13.5%. The calculation of internal temperature field of steel pipe recycled concrete column is well fitted with the test result. The internal temperature rise of the steel pipe recycled concrete column can be more accurately reflected based on constitutive relationship of recycled concrete while taking into consideration the internal moisture content of the test piece.

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