Analysis of circular steel tubular columns under the coupling of fire and impact

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Abstract: Aiming at the coupling of a pair of sliding circular steel tubular columns with one end fixed by fire and impact, this paper analyzes the model by finite element software ABAQUS. The impact load is applied to the mid-span of the test piece. Through the analysis of the displacement of the mid-section of the test piece, the following three points are clarified: 1) The circular steel pipe column absorbs energy through integral plastic deformation and local plastic deformation; 2) The displacement of the end of the circular steel tubular column and the displacement and displacement of the upper and lower surfaces of the span depend on the axial compression ratio, the impact velocity and the temperature; 3) Under the coupling of fire and impact, the safe area of the column member depends on the temperature and axial compression ratio; the greater the temperature and axial compression ratio, the smaller the safety zone. In order to study the concrete-filled steel tube under the coupling of fire and impact.

1. Introduction

Concrete-filled steel tubular members may be subjected to impact loads due to natural or deliberate human factors. In recent years, domestic and foreign scholars have shown that the concrete-filled steel tubular members have excellent impact resistance [1-4]. Bambach et al. [5] carried out impact experiments on three different square steel tubes with width-to-thickness ratios of 31, 22 and 13 respectively. It was found that under the impact load, the round steel tube column would have plastic hinges at the ends and spans, between adjacent plastic hinges. There is basically no deformation, and the local deformation of the mid-span is accompanied by the bending deformation of the whole round steel tubular column, and the tearing damage occurs on the upper surface of the end first when the event occurs. Wang et al. [6] found through experiments and simulations that the concrete-filled steel tubular specimens undergo ductile failure when the ferrule coefficient is large, absorb more energy, and brittle fracture occurs when the ferrule coefficient is small, and the energy absorbed is less. The energy required to break the specimen increases as the axial compression ratio increases. Wang et al. [7] and Aghdamy et al. [8] found that the hollow ratio can significantly change the peak value of the impact force time history curve through the experiment and simulation of double-walled steel tube concrete. The peak value of the peak stage is related to the hollow ratio and the transverse deformation of the concrete filled steel tubular specimen. The size is related to the hollow ratio, the yield strength of the steel, and the compressive strength of the concrete.

The static loading test and the impact test of the existing steel pipes are all studies on the material properties and impact resistance at normal temperature. The fire test is a study on the impact resistance of the test piece during static heating and the cooling after cooling. However, after the fire in the
structure of the project, the bearing capacity of the structural members is reduced, the upper heavy objects fall, and the lower members need to bear the actual working conditions of the coupling of the fire load and the impact load.

In this paper, numerical analysis of circular steel tubular columns is carried out by experiments and ABAQUS finite element software. Through the parameter analysis, the effects of impact kinetic energy and temperature on the dynamic response mode of the circular steel tubular column under the impact and fire coupling environment were investigated. This paper provides a reference for the study of the response mode of CFST under the coupling of fire and impact.

The assumptions made in this paper are:
1) The deformation of the circular steel tubular column conforms to the flat section assumption, ignoring the influence of shear force on the yield of the section;
2) The steel material is an ideal elast-plastic material, ignoring the strain rate effect of the material;
3) The impactor is a rigid block, ignoring the deformation effect during the impact.

2. Finite element analysis under impact load

2.1. Calculation parameters

The ABAQUS/Explicit solver was used for the analysis of the impact load alone. The steel pipe adopts S4R unit, the inner diameter of the round steel pipe column is R=23mm, the wall thickness is t=2mm, and the length is L=1100mm. The round steel pipe column adopts the boundary condition of one end sliding and one end fixed. The load is applied by a certain mass and impact speed of a given rigid block in the mid-span of the test piece, as shown in Fig.1. The material constants of steel materials are shown in Table 1.

![Fig.1 Schematic diagram of impact force of circular steel tubular column](image)

| Steel material constant | $f_y/(MPa)$ | $E_s/(GPa)$ | $\nu_s$ | $\rho_s/(kg/m^3)$ |
|-------------------------|-------------|-------------|---------|------------------|
| 300                     | 205         | 0.3         | 7850    |

2.2. Calculation results

![Fig.2 Collapsed cloud diagram of round steel tube column at normal temperature](image)

Figure 2 is the final deformation cloud diagram of the round steel tubular column under $\mu_\nu = 0.1$, $v=10m/s$ conditions. Under the impact load, the circular steel pipe column will produce overall bending deformation. Due to the existence of axial force, the round steel pipe column cannot maintain
its own stability on the basis of large overall deformation, and collapse occurs. It can be seen from the stress cloud diagram that most of the area of the round steel pipe column at the time of collapse has reached its own yield strength.

2.3. End displacement and mid-span displacement

![Fig.3 End displacement of a circular steel pipe column with different axial compression ratios](image)

Figures 3a and b are displacement diagrams of the end of a circular steel pipe column with axial compression ratios $\mu_N = 0.1$ and $\mu_N = 0.3$, respectively. It can be seen from the figure that when the axial compression ratio is the same, the displacement of the end increases with the increase of the impact velocity; when the velocity is at a certain critical value, the displacement of the end gradually converges to a constant value after a sharp increase. The final displacement depends on the plastic bending deformation of the circular steel tubular column; however, when the velocity exceeds a certain critical value, the end displacement always increases with time and does not converge. Comparing Fig.3a, b, it can be seen that when $\mu_N = 0.1$ is used, the speed at which the end displacement does not converge is 10m/s, and when $\mu_N = 0.3$ is 4.8m/s, which is significantly smaller than the former. From this, we conclude that the end displacement of the round steel pipe column is highly dependent on the impact velocity and the end axial force.

![Fig.4 Displacement of the upper and lower sections of the round steel pipe column at different axial compression ratios](image)
Fig. 5 Displacement difference between the upper and lower sections of a round steel tubular column at different axial compression ratios

Figures 4a and b are displacement diagrams of the upper and lower surfaces of a round steel tubular column in axial compression ratios $\mu_n = 0.1$ and $\mu_n = 0.3$, respectively. In the figure, $Sur \_B$ is the mid-span surface, and $Sur \_T$ is the mid-upper surface. It can be seen from Fig. 5a and b that at the same axial compression ratio, as the impact velocity increases, the displacement of the upper and lower surfaces of the round steel tubular column increases, indicating that the overall plastic deformation is greater, thereby absorbing more energy.

Figure 5 shows the difference in displacement between the upper and lower sections of a round steel tubular column at different axial compression ratios. It can be seen from the figure that with the same axial compression ratio, as the speed increases, the displacement difference increases, that is, the local plastic deformation increases, so that more energy can be absorbed. Referring to Figures 4 and 5, we conclude that the circular steel tubular column absorbs energy mainly by integral plastic deformation and local plastic deformation.

3. Finite element analysis of circular steel tubular columns under the coupling of fire and impact

3.1. Calculation parameters

Using the ABAQUS software to analyze the finite element analysis of the round steel pipe column after the first warming, firstly add the axial force analysis in the ABAQUS/Explicit module, and then introduce the model with the axial force into the ABAQUS/Explicit module for heating through the transfer results technique. After analysis, the temperature analysis results were again introduced into the ABAQUS/Explicit module for impact analysis by transfer results technique. The properties of the steel materials in this section are the same as those in the case of individual impact.

3.2. Calculation results

3.2.1. Stress cloud map
Fig.6 Stress cloud diagram of impacted empty steel pipe column after first adding fire

\( (\mu_e = 0.1, \quad v = 9 \text{m/s}, \quad T = 400^\circ C) \)

Fig.6 is a stress cloud diagram of the collapsed force when the axial force is applied and the impact after the fire. From Fig.6a: \( t = 0 \text{ms} \), it can be seen that stress concentration occurs at the fixed end position due to the axial force and temperature. It can be seen from the figure that similar to the impact of the round steel pipe column at normal temperature, when the impact body is in contact with the circular steel pipe column, stress concentration occurs on the upper surface of the impact region, and then local deformation of the impact region occurs. When the internal force of the impact region is transmitted to the two fixed ends, a tensile force is generated at the upper end of the fixed end, and a tensile force is also generated at the bottom of the impact region, and the sliding end is displaced along with the overall deformation of the circular steel tubular column.

That is, the circular steel pipe column is accompanied by local deformation of the impact region, and overall bending deformation occurs, and finally the test piece collapses. As can be seen from Fig.6, the deformation of the round steel tubular column at the time of impact at a high temperature is similar to that at normal temperature.

3.2.2. End displacement

Fig.7a, b and c are the displacements at the ends of hollow steel tube columns with \( T=20^\circ C, T=400^\circ C \) and \( T=600^\circ C \) at \( \mu_e = 0.1 \), respectively. Comparing the three figures, it can be seen that although the temperature rise will change the critical speed at which the round steel column collapses, the change trend of the end displacement is similar.

\( (\mu_e = 0.1) \)

Fig.7 End displacement of empty steel pipe column at different temperatures when \( \mu_w = 0.1 \)

(a: \( T = 20^\circ C \); b: \( T = 400^\circ C \); c: \( T = 600^\circ C \))
Figure 8 is the displacement of the end of the steel pipe column at different axial pressure ratios at $T = 600^\circ C$, $v = 5m / s$.

It can be seen from Fig.8 that in the case where the temperature and the impact velocity are the same, an increase in the axial pressure ratio causes the displacement of the end portion of the circular steel pipe column to change from convergence to non-convergence. From Fig.7 and Fig.8, it is concluded that the axial compression ratio and temperature can significantly change the end displacement of the round steel tubular column.

### 3.3. Critical energy ratio

The critical speed is the speed at which the cylindrical steel pipe column just collapses when the axial pressure ratio and temperature are constant. Symonds and Fleming [8] et al. proposed energy ratios to describe the relevant analytical parameters.

$$ R = \frac{GV_0^2EI}{M_0^2L} $$

Where $V_0$ is the impact velocity of the impactor, $M_0$ is the plastic limit bending moment, and $L$ is the length of the test piece. Through simulation analysis, we draw Figure 9 and Figure 10.

Figure 9 is a graph showing the relationship between energy ratio and axial pressure ratio at different temperatures. It can be seen from the figure that when the temperature is constant, the $R$ value decreases as the axial pressure ratio increases. Comparing the three curves in the figure, it shows that the increase in temperature leads to degradation of material properties, which reduces the $R$ value. Figure 10 is a graph showing the energy ratio versus temperature for different axial pressure ratios. It can be seen from the figure that when the axial pressure ratio is constant, the $R$ value decreases as the temperature increases. Comparing the three curves in the figure, it shows that the increase of the axial pressure ratio reduces the value.

In Fig.9 and Fig.10, each curve is bounded by a certain area with the coordinate axis, which is a safe area, that is, in the safe area, the column member does not collapse; outside the safety area, the
column collapse occurred. From Fig.9 and Fig.10, as the temperature and axial pressure ratio increase, the safety area becomes smaller and smaller. We can conclude that the temperature and axial pressure ratio significantly affect the safe area of the column member.

4. Conclusion
This paper analyzes the finite element software ABAQUS and draws the following conclusions:

1) The circular steel pipe column absorbs energy through integral plastic deformation and local plastic deformation;

2) Only under impact load, the end and mid-span displacement of the round steel tubular column, as well as the difference in displacement between the upper and lower surfaces, depends on the axial compression ratio and the impact velocity;

3) Under the coupling of fire and impact, the displacement of the end of the round steel tubular column and the displacement and displacement of the upper and lower surfaces of the span are dependent on the axial compression ratio, the impact velocity and the temperature;

4) Under the coupling of fire and impact, the safe area of the column member depends on the temperature and axial compression ratio; the larger the temperature and axial compression ratio, the smaller the safety area. The bearing capacity of the column members should be designed in a safe area.

Acknowledgments
Thanks to my classmates Chunting Li and Qiuyue Zhang, this article was done with their help. I also thank my tutor for helping me with this article.

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