Research on the Torsional Properties of Aluminum Foam-filled Steel Tube After Fire

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Abstract
Torsion tests of hollow steel tubes and aluminum foam-filled steel tubes after fire have been carried out. The influencing factors, on the static torsional behavior of aluminum foam-filled steel tubes after fire were also investigated, including the porosity rate of aluminum foam and steel rate. The research results suggested that aluminum foam filled in tube had systolic collapse after high temperature. The oxide layer of the steel tubes had an exfoliation phenomenon. The uniaxial torsional curves of aluminum foam-filled steel tubes after fire have a longer plastic collapse region, and have no obvious hardening stage. The ultimate torsional bearing capacity of the steel tubes filled with foam aluminum after fire is half of that before fire. Compared with hollow steel tubes, the deformation and ultimate torsional strength of steel tubes filled with foam aluminum after fire is improved.

Keywords: steel tube; aluminum foam; torsional carrying capacity; fire

1. Introduction

By introducing gas holes or bubbles into solid metal, foam metal with various kinds of pores (open, close) realizes the lightness and multifunction of structural material. These kinds of materials can achieve the maximum porosity rate of 90% above a relative density of 1 below (ρ≤1). Foam metal is more and more widely used in many fields because of its multifunction such as energy absorption, damping shock absorption, noise reduction, heat insulation, and electromagnetic shielding etc.1,2)

The plastic resistance of foam-filled steel tubes subjected to different loading conditions is of great interest in crashworthiness application. The load bearing capacity under torsion or combined loading was given much less attention than the corresponding axial crushing of tubes. Seitzberger studied the quasi-static axial crushing of steel columns filled with aluminum foam in experiments3; Hanssen investigated the static and dynamic crushing of circular aluminum extrusions with aluminum foam4; Xi studied the performance of a hollow cylindrical sandwich with high specific strength foamed Al alloy cores, including specific strength and stiffness5; Gui studied the energy absorption properties of a cylindrical metal foam-filled tube under quasi-static axial compressive load, as well as the influences of geometrical and material parameters on the specific absorption energy of the tube6; Tu researched the working and damping properties of an aluminum foam-filled steel tube7-10).

The force of a metal foam-filled steel tube is very complex in actual engineering, and it is a synthesis of several stress situations. Therefore, it is necessary to analyze the torsional properties of aluminum foam-filled steel tubes in order to understand their mechanical properties. The torsional properties of a metal foam-filled steel tube have not been shown. In this paper, based on previous research, torsion tests of hollow steel tubes and steel tubes filled with foam aluminum before and after fire have been carried out. The test results were further compared with those of hollow steel tubes between and after fire separately to research the influence of related parameters on the fire-resistant torsional properties of a metal foam-filled steel tube.

2. Experimental Test

2.1 Specimen Design

To analyze the torsional properties of an aluminum foam-filled steel tube after fire, samples in length of 120 mm and thickness of 1.2 mm, 2 mm and 2.5 mm, were prepared. They were provided with square cross sections with a side length of 40 mm. The length-
diameter rate of the samples was $l/d=3^8$.

The steel rate of the aluminum foam-filled steel tube is calculated by:

$$\alpha = A_s/A_f$$  \hspace{1cm} (1)$$

where $A_s$ denotes the cross section area of the outer steel tube; $A_f$ refers to the area of the aluminum foam filled in. In this test, the steel rates of the samples are 30.6%, 23.5% and 13.2% respectively.

The porosity rate of foam aluminum is obtained by\(^1\):

$$Pr = 1 - \frac{m}{V} \rho_s = 1 - \frac{\rho}{\rho_s}$$  \hspace{1cm} (2)$$

where, $\rho$ refers to the apparent density of porous metal foam; the density of aluminum $\rho_s$ is set as 2700 kg.m\(^{-3}\); $V$ is the volume of aluminum foam; the porosity rate of the aluminum foam used in this test lies in the 75%~90% range.

1.2 Sample Preparation

![Fig.1. Aluminum Foam Samples](image1)

The aluminum foam, which was fabricated by the Ultra Light Metal Laboratory of China Southeast University using the direct melt foaming method, was cut into samples of required size using a wire electric discharging machine, as shown in Fig.1.

The Q25 low-carbon steel tubes used in the test were purchased on the market. By putting the aluminum foam samples into the tubes, aluminum foam-filled steel tube samples were made, as shown in Fig.2. The main parameters of foam-filled steel tubes are shown in Table 1.

| L (mm) | B (mm) | $w_s$ (mm) | $Pr$ (%) | Number |
|-------|--------|------------|---------|--------|
| 120   | 40     | 1.2        | 75      | 6      |
|       |        |            | 80      | 6      |
|       |        |            | 90      | 6      |
| 2.0   |        |            | 75      | 6      |
|       |        |            | 80      | 6      |
|       |        |            | 90      | 6      |
| 2.5   |        |            | 75      | 6      |
|       |        |            | 80      | 6      |
|       |        |            | 90      | 6      |

1.3 Test Content and Test Load

![Fig.2. Samples of Hollow Steel Tube and Aluminum Foam-filled Steel Tube](image2)

The Q25 low-carbon steel tubes used in the test were purchased on the market. By putting the aluminum foam samples into the tubes, aluminum foam-filled steel tube samples were made, as shown in Fig.2. The main parameters of foam-filled steel tubes are shown in Table 1.

![Fig.3. Heating Curves](image3)

The samples were heated by a vertically openable electric furnace customized by Shanghai Yifeng Electric Furnace Company. The chamber of the furnace was made of 1400/300 fiber products and was 650 x 650 x 1050 mm in size (W x L x H). The heating elements were made of resistant wire (ceramic tube as an alternative) and provided an operation temperature of 1000°C. Temperature control was realized at three points through an SSR programmable 30-segment program meter with precision of $\pm 1.5^\circ$C.

The samples were put into the furnace and heated according to the experimental heating curve in Fig.3. to simulate the fire situation. After the test, they were naturally cooled in the furnace and then taken out for the torsion test.
The electronic torsion-testing machine (ndw2000) manufactured by Ji'nan Hengsishengda Instrument Co. Ltd. was employed to apply load in the torsion test. The rectangular-section torsion fixture was customized from a mold factory. Samples were loaded at the rate of $10^3$/min at controlled displacement. The load-displacement curve was recorded using the IMP data acquisition system, as shown in Fig.4.

2. Results and Discussion

2.1 Test Phenomena and Related Analysis

According to China's "Fire-resistant Tests-Elements of Building Construction", the heating curves in the furnace should agree well with the international standard IS0834 heating curve during the fire test. The equation is expressed as:

$$T - T_0 = 345\log(8t+1)$$

(3)

where, $T$ represents the temperature of the fire; $T_0$ is the initial environmental temperature and is set as 10°C in the test; $t$ denotes the heating time, in units of min.

However, the heating rate of the electric furnace was low during the early stage and it was hard to reach the requirements of the standard heating curve. Thus the experimental heating curve in Fig.3., which was different from the standard one to some extent, was utilized in the fire-resistant test. After the heating test, the samples were naturally cooled to room temperature.

2.1.1 The Phenomena of Samples after Fire

After the heating at 1000°C, the outer surfaces of the steel tubes turned blue and were heavily carbonized. In addition, part of the oxide layer was exfoliated from the surface (Fig.5.). Since the aluminum started to melt at 660.4°C, partial aluminum foam pores collapsed as the temperature reached 1000°C. As shown in the figure, the aluminum foam contracted in the steel tube. Moreover, the higher the porosity rate, the more obvious the contraction. At porosity of 87.7%, aluminum foam contracted by 18.4 mm and 14.6%; at the porosity of 80.44%, it contracted by 10.6 mm and 8.4%; at porosity of 73.4%, it contracted by 3.2 mm and 2.4%.

2.1.2 Test of Material Properties

In order to compare the effect of temperature change on the mechanical properties of steel and aluminum foam, the processed specimens were heated according to the heating curve shown in Fig.3. After the heating tests were finished, the specimens were removed and tested after natural cooling.
The tubes were made of Q235 steel. Those with a thickness of 2 mm therein were performed with tensile test according to the standard test method stipulated in China's "Tensile testing method of metallic materials" (GB228-87). The tensile curves of steel are shown in Fig.6. The aluminum foam samples were cut into miniature ones with a diameter of 20 mm and height of 30 mm using electrospark wire, which was then weighted by a balance with precision of 0.01 g. Subsequently, by taking three aluminum foam samples at each porosity rate, 9 samples were obtained. The compressive stress-strain curves of aluminum foam are shown in Fig.7.

![Fig.7. Compressive Stress-strain Curves of Aluminum Foam](image)

The mechanical properties of steel and aluminum foam are shown in Table 2.

| Table 2. Yield Strength of Steel and Aluminum Foam | Yield strength/Mpa |
|--------------------------------------------------|-------------------|
|                                                  | Before fire | After fire |
| Steel                                            | 215.5       | 120.7      |
| Aluminum foam                                    |             |            |
| 90%                                               | 3.59        | 1.06       |
| 80%                                               | 9.05        | 3.27       |
| 75%                                               | 16.27       | 6.18       |

2.1.3 The Torsion Test Phenomena and Related Analysis

![Fig.8. The Failure Mode of Aluminum Foam-filled Steel Tube](image)

The samples prepared above were twisted by a customized torsion fixture with square sections with an inner diameter of 40 x 40 mm.

Under the effect of torque, deformation was observed on both the hollow and aluminum foam-filled steel tubes. In the case of a small torsion angle, the carbonization layer on the outer surface of steel tubes started to be exfoliated. As the torsion angle increased, the exfoliation was intensified (Fig.8.).

2.2 Ultimate Torsional Bearing Capacity

The torsional bearing capacity of aluminum foam-filled steel tubes can be regarded as two parts: steel tubes and aluminum foam.

Torsion bearing capacity of square steel tubes

\[ T_s(t) = 2(B - w_r)^2w_r f_s(t) \]  (4)

Torsion bearing capacity of aluminum foam with square cross section

\[ T_{\text{foam}}(t) = 0.195 \tau_f(t) b^3 \]  (5)

The torsional bearing capacity of aluminum foam-filled steel tubes

\[ T(t) = T_s(t) + T_{\text{foam}}(t) \]  (6)

where \( B \), \( w_r \) — square cross sections in side length, thickness of steel tube; \( b=B-2w_r \) — section size of foam sandwich; \( f_s(t) = f_s(0)/\sqrt{3} \) — shear strength of steel; \( \tau_f(t) = 0.5 f_s(t) \) — shear strength of aluminum foam; \( f_s(t), f_f(t) \) — yield strength of steel and aluminum foam, are shown in Table 2.

2.3 The Torsional Properties of Aluminum Foam-filled Steel Tube after Fire

Fig.9. describes the uniaxial torsional curves (t-θ) of aluminum foam-filled steel tubes before and after fire. As shown in this figure, the tubes experience four phases in the torsion test before fire, including elastic torsion phase, yielding platform phase, strengthening phase, and declining phase. However, the curves of the tubes after fire are different to those before fire: they present a longer yielding platform phase with no obvious strengthening phase.

It can be seen from Fig.9. that the ultimate strength of an aluminum foam-filled steel tube after fire is significantly lower than that before fire. The ultimate strength of the aluminum foam-filled steel with tube thickness of 1.2 mm and foam porosity rate of 90% is measured as 415 N.m before fire, while that of the tube with close porosity is 167.6 N.m after fire.
Fig. 10. illustrates the torsional failure modes of hollow and aluminum foam-filled steel tubes after fire. As shown in this figure, both kinds of steel tubes present similar torsion modes, with obvious torsion angles at the end of the test.

In Fig. 11., fractures are apparent on part of the aluminum foam-filled steel tubes due to the large torsion angle in the torsion test. However, the aluminum foam-filled steel tubes show no fractures after fire in spite of obvious torsional deformation. This phenomenon manifests that high temperature weakens the strength of the aluminum foam-filled steel tubes, while the tubes keep the plastic deformation capacity higher.

2.4 Influences of Aluminum Foam on the Fire-resistant Torsional Properties of Aluminum Foam-filled Steel Tube

Fig. 12. shows the torsion curves of the hollow and aluminum foam-filled steel tubes with tube thickness of 1.2 mm after fire. It can be seen from the figure that the aluminum foam-filled steel tube shows significantly higher torsional bearing and deformation capacities after fire owing to the aluminum foam.

Aluminum foam improves the torsional deformation curve of steel tube. In Fig. 12., the torque of the hollow steel tube peaks at the torsion angel of about 20° after fire and then sharply declines with the intensifying of torsion. By contrast, the aluminum foam-filled
steel tube displays a long yielding platform as it reaches this phase. At the torsion angle of about 90°, strength decline is still not obvious, manifesting that the torsional properties of aluminum foam-filled steel tube are far more excellent than those of hollow steel tube. The reason lies in that, the interaction between the aluminum foam and steel tube continued to intensify with the increasing torsional deformation of the aluminum foam-filled steel tube. Aluminum foam prevents deformation of the outer steel tube.

Aluminum foam enhances the ultimate torsional strength of steel tube. The ultimate torsional strength of hollow steel tube is 122.3 $N\cdot m$ after fire, while that of steel tubes filled with aluminum foam with a porosity rate of 90% and 75% reach 166.1 $N\cdot m$ and 190.6 $N\cdot m$ respectively. Therefore, aluminum foam strengthens the torsional strength of steel tube. Moreover, the lower the porosity rate of the aluminum foam-filled tube, the higher its torsional strength.

The relationship between ultimate torsional strength and porosity of aluminum foam before and after fire are shown in Fig.13. The ultimate torsional strength decreases with the increase of porosity of aluminum foam. Formula 6 is consistent with the test results before and after the high temperature, but formula 6 is greater than the test result.

2.5 Influences of Steel Rate on the Fire-resistant Torsional Properties of Aluminum Foam-filled Steel Tube

Fig.14. interprets the relationship between steel rate and ultimate torsional strength of aluminum foam-filled steel tube before and after fire. From the test results, the ultimate torsional strength of aluminum foam-filled steel tube after fire is about 1/2 of that before fire. The ultimate torsional strength increases with the increase of steel rate. From Fig.14., with the increase of steel content, the difference between formula 6 and experimental results is increased.

3. Conclusions

Based on the fire-resistant torsion tests results of hollow and aluminum foam-filled steel tubes, the following results were obtained:

1) The aluminum foam in an aluminum foam-filled steel tube contracted and collapsed after fire. Meanwhile, the oxide layer was obviously exfoliated from the surface of the tube. Moreover, the exfoliation of the carbonized layer on the surface of the tube intensified as the torsion test proceeded.

2) The aluminum foam-filled steel tube presented a long yielding platform phase with no obvious strengthening phase after fire. In addition, the strength of the tube was significantly cut by 1/2 as compared to that before fire.

3) Aluminum foam-filled steel tubes showed significantly higher torsional strength and deformation capacity than hollow ones.

Acknowledgements

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