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The mechanical behavior of thin-walled tube filled with hollow metal spheres

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ABSTRACT

The present work focuses on the quasi-static axial crush performance of the thin-walled tubes filled with hollow metal spheres (TWT-HMS) and their individual components (thin-walled tubes and hollow metal spheres) under axial compressive loads. All structures were compared in terms of the load–displacement and/or load–strain curves, energy absorption and energy absorbing efficiency curves. The results indicate that hollow metal spheres and thin-walled tubes are promising energy absorbing materials. The hollow metal spheres improve the axial bearing capability of thin-walled tube, and the biggest improvement scale can be 300%; due to the superimposed effect, TWT-HMS has more excellent properties than the hollow metal sphere and thin-walled tube. Thus, TWT-HMS is an energy absorbing structure with excellent properties and it has a promising application prospect.

1. Introduction

When foam material and thin tube structure are combined, there is an important interaction effect phenomenon in energy absorption. It means that under the same load, the compound structure absorbs more energy than foam material and thin tube structure. Besides, when under shock wave loading, the empty space in the compound material has the diffraction and segregation effect [1] on the stress waves. It not only reduces the weight of the compound material, but also helps to diffuse and weaken the stress waves.

The combined structure of foam material and thin tube structure is mainly achieved through the use of internally refilled material and metal material with good peripheral ductility. With the development of technology and science, all kinds of new foam material are frequently developed. Many researches about new refilled material have been carried out by scholars [2–6]. However, the current experiments and studies about it are mainly focused on several limited materials, like aluminum foam [7–9], polyurethane foam and so on. And these materials have certain limits. For example, aluminum foam requires high producing technology and is hard to make; as for polyurethane foam, its porosity is too high and the elasticity modulus of the matrix solid-phase material is too low, which will give no obvious imposition effect. Metallic hollow sphere structures (MHSS) [10,11] and Advanced Pore Morphology (APM) foam elements [12,13] are the hot topics on foam materials in the world, and these new foam materials have excellent energy absorption characteristics; Although the manufacturing cost is high, and the preparation technology for MHSS and APM foam elements are complex, but the emergence of these new foam materials shows new ideas to resolve the existing deficiency.

Based on the above research situations, thin-walled tubes filled with hollow metal spheres (TWT-HMS) were produced creatively by combining hollow metal spheres (HMS) and thin-walled tubes (TWT). The static compression tests of hollow metal spheres, thin-walled tubes and TWT-HMS were carried out, the load–displacement curves and the load–strain curves were obtained, and then the energy absorption and quasi-static ideal energy-absorbing efficiency curves were analyzed. Based on this, the superimposed effect was studied by contrast.

2. Materials and methods

The thin-walled tubes filled with hollow metal spheres were prepared by pouring the hollow metal spheres (Fig. 1a) into a thin-walled tube (Fig. 1b).

Hollow metal spheres made of 201 stainless steel (7Cr–4.5Ni–6Mn–N) with different diameters (22 mm; 48 mm;

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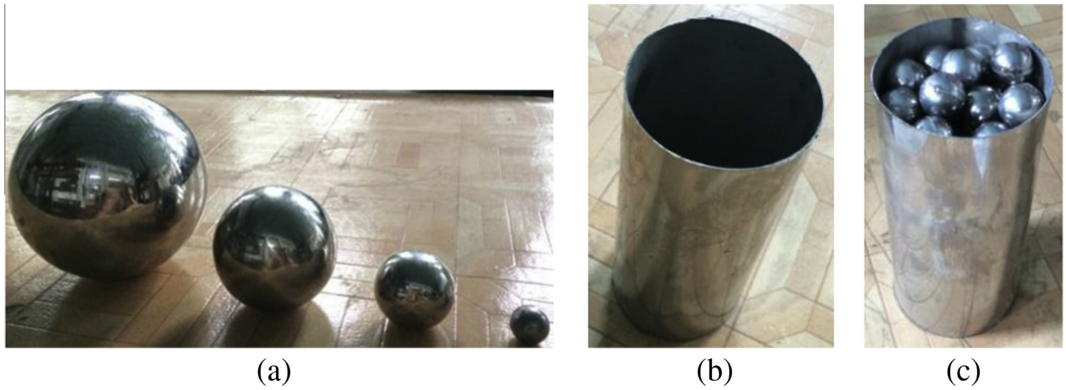

Fig. 1. (a) Hollow metal spheres with different diameters (22 mm; 48 mm; 83 mm and 136 mm); (b) thin-walled tubes; (c) thin-walled tubes filled with hollow metal spheres.

83 mm and 136 mm) and wall thickness of 0.5 mm were used in this work (Fig. 1a). The physical properties of this 201 stainless steel are as follows [14]: the elongation is 60%, the tensile strength is 520 MPa, the yield strength is 275 MPa, and the elasticity modulus is 203 GPa.

The thin-walled tubes filled with hollow metal spheres (Fig. 1c) were prepared by pouring the hollow metal spheres (Fig. 1a) into a thin-walled tube (Fig. 1b), as shown in Fig. 1. Thin-walled tubes made of 304 stainless steel (18Cr–9Ni) with an outer diameter of 89 mm, a wall-thickness of 0.7 mm and a length of 200 mm were used in this work (Fig. 1b). The physical properties of this 304 stainless steel are as follows [15]: the elongation is 42%, the tensile strength is 580 MPa, the yield strength is 255 MPa, and the elasticity modulus is 193 GPa. The quasi-static uniaxial compression tests of HMS, TMCT and TWT-HMS were made with the improved HHY series electro-hydraulic servo system according to the Chinese Standard GB/T 50081-2002 (Standard for test method of mechanical properties on ordinary concrete). The loaded strain speeds should be constant, which can be converted into strain rates ($1 \times 10^{-5} s^{-1}$). Three specimens were tested for each mechanical condition. And the load–displacement data were converted to load–strain and/or stress–strain data using the dimensions of the specimens.

Two methods were applied to describe the energy absorption properties of studied materials. One is the energy absorption (E_A), which is calculated by integrating the area under the load–displacement curve, as given by Eq. (1) [16].

$$E_A = \int_0^{S_c} F\,dS \quad (unit:\ \mathrm{kN \cdot mm}) \tag{1}$$

where F is the load, S is the displacement, and S_c is the displacement that the specimen is destroyed or compacted completely.

Another is the ideal energy-absorbing efficiency (I) [17,18]. I compares the deformation energy absorbed by a real material or component with that of an "ideal" energy absorber. An "ideal" absorber shows a rectangular March of the load–displacement curve, i.e. it reaches the maximum admissible strain and keeps it constant during the whole deformation process. The efficiency is defined as ratio of the actually absorbed energy after a compression strain s and the energy absorption of the ideal absorber, given by Eq. (2).

$$I = \frac{\int_0^S F(s')ds'}{F_{\max}(S) \cdot ds} \tag{2}$$

where the $F_{\max}$ is the highest force occurring up to the strain s. As all real materials show a varying strain under compression, the calculated efficiency also changes during the deformation process and therefore depends on the nature of the load–displacement compression curve.

3. Results and discussion

3.1. Hollow metal sphere

Fig. 2 shows the deformation mode of a hollow metal sphere with 22 mm of diameter under quasi-static compressive loading condition.

According to Fig. 2, hollow metal sphere changed its shape under combined internal pressure and axial compressive load. With the increase of compression deformation, the shape of hollow metal sphere changed from circular to a diamond mode, because of the asymmetric buckling of hollow metal sphere after high degree of deformation.

Fig. 3 shows the load–strain curves for hollow metal spheres with a diameter of 22 mm.

It is evident that the differences among the quasi-static load-strain curves of the four spheres are very tiny, which indicates the quasi-static mechanical properties of hollow metal sphere have good repeatability. According to Fig. 3, the load on the sphere remained unchanged during the long compression stage, which means the load–strain curve of hollow metal spheres has a stable plateau stage. And its densification strain is around 0.9. So, hollow metal sphere is a promising energy absorbing material.

Fig. 4 shows the quasi-static ideal energy-absorbing efficiency curves which were determined through Eq. (2) using the load–strain curves.

The I_{average} is defined as the average value of the ideal energy-absorbing efficiency curve over the certain strain when the load–strain curve is on the stable plateau stage. According to Fig. 4, the I_{average} of the four hollow metal spheres are respectively 0.66, 0.67, 0.62 and 0.66; the maximum values are respectively 0.79, 0.78, 0.72 and 0.81, and the correspondent strain are respectively 0.549, 0.478, 0.669 and 0.331.

Fig. 5 shows the load–displacement curves and load–strain curves of hollow metal spheres with different diameters (22 mm; 48 mm; 83 mm; 136 mm).

Based on the load–displacement curve, the E_A of hollow metal spheres was determined through Eq. (1). The E_A of the hollow metal spheres with a diameter of 22 mm, 48 mm, 83 mm and 136 mm over the whole strain zone are respectively 208.15 kN · mm, 651.43 kN · mm, 1348.72 kN · mm and 1880.01 kN · mm. Thus, the bigger the diameter of hollow metal sphere, the more energy it can absorb. The hollow metal sphere with a big diameter can absorb more energy that can be dissipated.