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Experimental and theoretical study on crashworthiness of star-shaped tubes under axial compression

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ABSTRACT

Thin-walled tubes play a very important role in energy absorbing for car crash. Current studies mainly focus on the design theory and performance improvement by proposing different structures. However, the practical performances might be influenced by manufacturing process, but few studies on this aspect could be found. In this paper, the crashworthiness of several star-shaped tubes, i.e., the hexagonal, octagonal and twelve corners, which were made with different material and fabrication methods, are compared through the experimental analysis. It is found that the energy absorption of octagonal star-shaped tubes is the best and that of the twelve corners star-shaped tubes is the lowest. Under quasi-static compression, the P_m of the octagonal star-shaped tubes increases by 7.94% with respect to the hexagonal star-shaped tubes, while the P_m of star-shaped tubes with twelve corners decreases by 15.75% with respect to the octagonal star-shaped tubes. The star-shaped tubes manufactured by different processing methods have some influence on the deformation mode, but the effect on overall crashworthiness is limited. Finally, the axial mean crushing force of the star-shaped tubes was analyzed theoretically based on the simplified Super Folding Element theory. A theoretical solution for the mean crushing force of the star-shaped tubes was derived, and the theoretical solutions show an excellent agreement with the experimental results.

1. Introduction

The energy absorption of the structures under the impact load is an important research hotspot of automobile crashworthiness. Traditionally, energy-absorbing parts in automobile were mainly made with thin-walled structures to absorb the impact energy through plastic deformation. Thin-walled structures have become an important and widely used energy absorbers in engineering applications because of its low weight, high energy absorption efficiency and long impact stroke [1]. Extensive researches have been carried out on the thin-walled structures from the experiment [2–5], theoretical analysis [6–10], numerical simulation [11–13] and optimization [14–16], etc. The material, structure size, loading condition, and cross-sectional shapes all play important roles in the energy absorption of the structure, while the thin-walled structures with different cross-sectional shapes have become an important research field, including circular [3,17,18], square [6,7], polygonal [19,20] and multi-cellular [21–23] tubes.

Wierzbicki et al. [6,24] found that thin-walled metal tubes produced progressive folding deformation under axial impact, and the energy was mainly absorbed through plastic deformation in bending and membrane deformation. Usually, the plastic deformation in bending and membrane deformation near the corner of the tubes tends to be the most intense. So, to a large extent, the corner number of cross-section of the tubes determined the performance of energy absorption. Yamashita et al. [25] carried out an axial compression study of a regular polygon tube with numbers of sides varied from 4 to 96. It was found that the mean crushing force of the regular polygon tube is increased with the increasing of the number of corners, but when the number of sides is greater than 11, the energy absorption performance approached the point of saturation. This is mainly due to the increase of edges number, which in turn makes the angle of the corner increase accordingly. Similarly, Wierzbicki et al. [26] concluded that the energy absorption is the highest when the angle is between 90° and 120°. However, conventional convex polygon tubes cannot simultaneously satisfy that the number of corners increases while the angle keeps in the optimal range, i.e., between 90° and 120°. Therefore, the crashworthiness of thin-walled structures cannot be effectively improved only by increasing the number of corners. In view of the above-mentioned problems, Tang et al. [27] introduced a tube with some extra non-convex corners in the cross-section. This kind of structure makes it possible that the angle

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keeps between the optimal ranges when the number of corners is increased. Therefore, the energy absorption has been effectively improved. It was showed that the non-convex multi-corner thin-walled columns were superior to the conventional square tubes in that both the energy absorption and the load consistency become better. It is worth emphasizing that star-shaped tubes can also be regarded as non-convex tubes, but there are very few studies on star-shaped tubes.

Fan et al. [28] carried out experiment and numerical simulation on the crashworthiness of star-shaped tubes. It was found that star-shaped tubes had higher energy absorption but poorer load consistency than polygon tubes with the same number of convex corner under axial quasi-static compression. In addition to that, the star-shaped tubes had less deformation stability, and formed smaller number of folds during deformation. In our previous studies [29,30], the experimental and numerical investigations of the star-shaped tubes were carried out, and the mode classification chart of the star-shaped tubes with different sizes is obtained. Through the combination of star-shaped tubes and circular tube, a novel CSC-tube [30] was put forward, and the experiment and optimization design of CSC-tube were carried out. However, systematic experimental study and theoretical analysis of the star-shaped tubes have not been carried out yet, such as the quasi-static and dynamic impact experiments of different structures with the same material, the compression experiments of different materials with the same structure etc.

It should be noted that current existing thin-walled structures for crashworthiness are generally machined with the wire-electrode discharge machining (WEDM) technique. The basic machining principle is to use a continuously moving fine wire (called an electrode wire) as an electrode to cut the work piece with pulse spark discharge erosion. WEDM has some advantages such as small processing margin, high processing accuracy, high efficiency and low manufacturing cost. However, the wire-electrode machining will inevitably cause the hardening of the tubes wall, thus influencing the deformation mode and crashworthiness of thin-walled structures. It should address that current studies have paid little attention to the effect of different processing methods on structural crashworthiness and deformation modes. High-pressure water jet machining utilizes high-energy water jet that is generated from ordinary water through multi-level pressurized fine nozzle at a great speed of nearly one kilometer per second. Compared with wire-electrode discharge machining, it is characterized with none or very small input of heat source during machining. In this paper, two machining methods in producing thin-walled structures, i.e., the non-thermal cutting and thermal cutting methods are compared to analyze the effect of machining methods on the deformation mode and crashworthiness of thin-walled structures. In the meantime, the influence of materials on thin-walled structures is also discussed.

Based on the observation of the axial compression process of square tube, Wierzbicki first proposed an idealized model of the tubes breakage mechanism, and then he put forward the Super Folding Element theory [26]. A basic fold unit has two types: fixed hinge and moving hinge. The energy dissipation in each plastic zone is estimated to be absorbed by a basic folding element, and then the total energy dissipation can be calculated according to the number of folding elements. Zhang et al. [10] studied the deformation mode of multicellular tubes, and deduced a formula to calculate the mean crushing force of the multicellular tubes based on the simplified Super Folding Element theory [9]. In this paper, the axial impact force of the star-shaped tubes is deduced from the Super Folding Element theory, and the formula of the mean crushing force is obtained theoretically.

Through the above analysis, we can see that although there are many researches related to thin-walled tubes, they mainly studied thin-walled tubes with the same material and different structures. However, there are few studies on the crashworthiness of structures with different processing methods and materials. It is known within the scope of the author's knowledge that there is currently no theoretical solution for the mean crushing force of the star-shaped tubes. In order to solve the above problems, the quasi-static compression and dynamic impact experiments under different combinations of material, structure and processing, i.e., different structures with the same material, the same structure with different materials, and the same material and structure with different processing methods, are compared. Finally, the axial mean crushing force of the star-shaped tubes is analyzed theoretically based on the simplified Super Folding Element theory.

2. Crashworthiness indicators

In order to analyze crash performance of star-shaped tubes, the mean crushing force (P_m), specific energy absorption (SEA) and maximum impact force (P_{max}) are usually used to evaluate the crashworthiness of thin-walled structures. The definitions are as follows:

P_m is the mean force that reflects the whole energy absorption process, which is related to the energy absorption and compression distance, as defined in Eq. (1):

$$P_m = \frac{\int_0^d F(x)dx}{d} \tag{1}$$

where F(x) is the instantaneous compression force, and d is the compression distance.

SEA refers to the total energy absorbed (EA) by the given mass (m_t) of the structure, as defined in Eq. (2):

$$SEA = \frac{EA}{m_t} = \frac{\int_0^d F(x)dx}{m_t} \tag{2}$$

where P_{max} is the maximum reaction force of the structure in the compression process.

3. Experimental materials and methods

3.1. Sample preparation

In this paper, we mainly study the crashworthiness of star-shaped tubes made either with different materials or different processing methods of the same materials. The chosen samples are made of aluminum alloy AA6061T4, AA6061T6 and AA6063T5. The structure and size of the star-shaped tubes are shown in Fig. 1. Considering that welding might take a certain effect on the material performance of the bottom of the star-shaped tubes, all star-shaped tubes are assembled with bolts connection on the base, which is shown in Fig. 1b. The size of the cross-section for the star-shaped tubes is shown in Fig. 1c and the diameter D of all star-shaped tubes is 30 mm, where t represents the thickness of the tube wall. The length of the star-shaped tubes is 100 mm. Mounted on the base, its effective length is 90 mm, and the corresponding assembly diagram is shown in Fig. 1d. The fabrication methods are WEDM and high-pressure water jet. In order to help facilitate subsequent analysis, the sample follows the naming convention. In the case of "S06-A-WC", the first set of symbols represents the type of tubes, where S stands for "the star-shaped tubes", and 06 represents the number of corners. The second group of symbols denotes the type of material, where A stands for AA6061T4, B for AA6061T6, and C for AA6063T5. The third group of symbols shows the fabrication method of the tubes, where WC represents WEDM method; WJ represents high-pressure water jet method.

3.2. Material properties

Three kinds of material are chosen to make the comparison, which are aluminum alloy AA6061T4, AA6061T6 and AA6063T5. The tensile test specimens are prepared by using WEDM according to ASTM Standard E8M-04 and each material is prepared with a tensile test sample. The material properties through tensile tests are obtained and the sizes of the samples are inspected, shown in Fig. 2 respectively. The