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On impacting mechanical behaviors of side fractal structures

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ABSTRACT

To enhance the impacting mechanical performance of the thin-walled structure, this paper proposes three new side fractal structures and investigates their crashworthiness by the experimental testing, simulation analysis and theoretical prediction. The energy absorption characteristics of the side fractal structure are characterized by quasistatic axial crushing experiment to verify the accuracy of the corresponding simulation models. Theoretical models of the side fractal structures are developed to predict the mean crushing force and the energy absorption. The accuracy of the theoretical model is verified by the simulation analysis, and the maximum error is 10.4%. Moreover, crashworthiness comparative studies are performed to investigate the mechanical behaviors of the side fractal structures by simulation analysis. The research results show that the maximum increment of the specific energy absorption of the hexagonal side fractal structure are higher 48.8% and 58.8% than those of the triangular and square side fractal structures with the same mass, respectively. The parameter study of the hexagonal side fractal structure is also conducted based on the theoretical model. Both the wall thickness t and the fractal factor N have important effects on the crashworthiness of the hexagonal side fractal structures. The research findings provide a good guidance for the design of an energy absorber of the protective system.

1. Introduction

Due to the advantages of the multi-cell thin-walled structures in energy absorption and lightweight, their crashworthiness designs have been widely carried out by theoretical analysis [1–5], experiment testing [6–9] and simulation [10–17]. For theoretical analysis, Kim et al. [18] studied the impact resistance of four different shapes of multicell square tubes and derived the theoretical model of the mean crushing force of each configuration. The result showed that the specific absorption energy of the multi-cell square corner tube is about 100% higher than that of the single square tube. Zhang et al. [19] derived an analytical solution of the mean crushing force for the square multi-cell section based on the super folding element (SFE) theory, and found that energy absorption efficiency of a single-cell column can be increased by 50% when the section was divided into 3×3 cells. Bai et al. [20] developed a new analytical model of mean crushing force for hexagonal multi-cell thin-walled structures under quasi-static crushing. The result showed that the proposed analytical model had higher accuracy than the traditional theoretical models. In addition, the theoretical expressions of the mean crushing force of the polygonal single tube and tubes with arbitrary sides are derived by Yin et al. [21]The results showed that the bitubular tube with 18 edges has the best energy absorption capacity. Besides, many experimental studies have also been carried out to investigate the crashworthiness of the multicell tube. For example, Wang et al. [22] carried out dynamic impact test on the multi-cell square tube and found the multi-cell square tube had more stable folding mode and more shorter folding wavelength than the single square tube. Liu et al. [23] studied the energy absorption of the bonded multi-cell square tubes by several compared experiments. The results indicated that increasing the number of cells could effectively improve energy absorption efficiency. Chen et al. [24] studied the crashworthiness of a novel five-cell tube with circular corners by experimental tests and found that the impact resistance of the multi-cell structures was sensitive to the size of the circular corners. In terms of the simulation analysis, Pirmohammad et al. [25] explored the crashworthiness of the multi-cell thin-walled structures with inner tubes under the oblique load, and found that adding the inner tube can effectively enhance the stability under the multiple impact conditions. Wang et al. [26] proposed and investigated the impacting mechanical capability of a Koch multi-cell structure. Simulation analysis results indicated the 2nd Koch multi-cell structure had more prominent in energy absorption than the general multi-cell structure. Altin et al. performed the crashworthiness studies of

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multi-cell tubes with different cross sections [27–29]. The results indicated that the cross section had important influence on the impact crashworthiness of the structure. The impact resistance of a new type of embedded multi-cell tube was simulated and analyzed by Zhang et al. [30], and found that the mechanical crushing capability of the embedded multi-cell tubes was better than that of the single-walled structures. Xiang et al. [31] proposed several key evaluation indicators and concluded that cell number is an important factor affecting the impact resistance of thin-walled structures. These studies indicated that multi-cell structures had prominent advantage for energy absorption compared to corresponding single walled structures and the number of cell and vertex have positive effect on the energy absorption capacity of the thin-walled structure.

To improve the mechanical performance of the multicell thin-walled structures, the hierarchical structure with more cell and vertex and high efficient energy absorption has attracted wide attention and interest in recent years. Zhang et al. proposed a vertex fractal design for hexagonal [32] and circular [33] structure. The result revealed that hierarchical structures had higher energy absorption efficiency than single-walled structure. Sun et al. [34] investigated the impact resistance of the vertex hierarchical honeycomb under dynamic load. Compared with the traditional honeycomb, the SEA of 1st and 2nd hierarchical honeycomb increased by 81.3% and 185.7%, respectively. Wang et al. [35] investigated the crashworthiness of the square multi-cell vertex hierarchical tube by means of the numerical and theoretical analysis, and indicating that the hierarchical design can effectively promote the crushing resistance capacity of the square multi-cell structure. Tsang et al. [36] proposed a tubular hierarchical structure based on the nanoarchitecture of biological materials. The result indicated that the mechanical properties of the structure were mainly determined by the geometrical hierarchical arrangement. In addition, Zhang et al. [37] established a theoretical model and investigated the energy absorption for the hexagonal vertex fractal hierarchical structure, and found that hierarchical order was an important factor affecting the energy absorption efficiency. Fan et al. [38,39] carried out the crashworthiness study of the hierarchical square structure and hierarchical triangle structure to explore their in-plane compression behavior, and found that the hierarchical structures also had good energy absorption under in-plane impact condition. Lu et al. [40] studied the energy absorption efficiency of the anti-tetrachiral and the hexachiral hierarchical structure respectively. The results showed that the anti-tetrachiral structure can produce higher platform stress and better energy absorption efficiency than the hexachiral structure. Abovementioned studies found that the hierarchical design can improve the energy absorption efficiency of the multicell structure.

However, previous studies mainly focused on crashworthiness of the vertex fractal structures, few researches were conducted on different fractal methods to design the new thin-walled structure with better mechanical behaviors. Therefore, this paper attempts to propose a novel side fractal design to enhance the crashworthiness of thin-walled structures. The description of the side fractal design and the experimental process are presented in Section 2. The numerical models are proposed and verified by experimental and analytical methods in Section 3. Section 4 derives relevant theoretical models to evaluate the mean crushing force of all side fractal structures. Section 5 performs the comparative study of crashworthiness of side fractal structures. Parameter study of the hexagonal side fractal design is carried out by the modified theoretical prediction model using the simplified super folding element (SSFE) theory.

2. Structural design and experimental testing

2.1. Description of the side fractal design

Fig. 1 shows the schematic diagram of the side fractal design. A straight side is replaced by a sub polygon, then, the corresponding higher-order structures are formed by increasing the number N of the sub polygon. The evolutionary process from 1st order to N^{th} order of side fractal designs is also presented in Fig. 1. The replaced straight sides are shown by dotted lines.

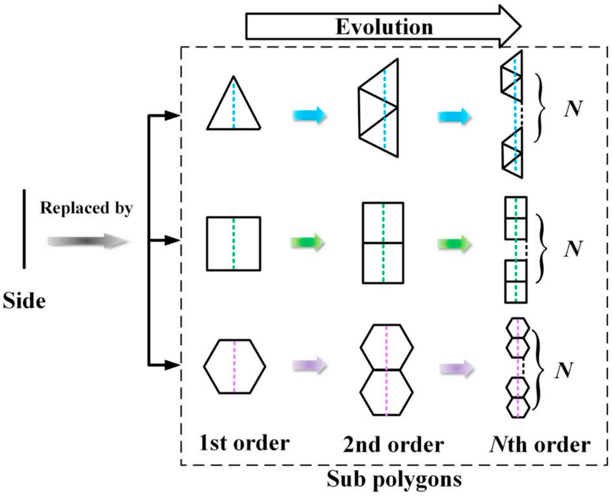

Fig. 1. Schematic diagram of side fractal design.

According to the principle of the side fractal design shown in Figs. 1 and 2 (a) proposes three side fractal structures with the triangular, square and hexagonal cross section. The sides of base polygons (triangle, square and hexagon) are replaced by the sub polygons with self-similar property. High order structures (2nd to 5th) are generated by fractal principle along the directions of sides of base polygons (dotted lines in Fig. 2(a)). The side fractal structures of the triangular, square and hexagonal are named as TSFS (Triangular side fractal structure), SSFS (Square side fractal structure) and HSFS (Hexagonal side fractal structure), respectively, and the digital subscript represents the corresponding fractal order. For example, the $SSFS_4$ denotes the 4th order square side fractal structure. All structures have the same circumcircle diameter of $D = 90$ mm, the thickness of these side fractal structures is t.

To explore the crushing performance of the side fractal structures. An axial impacting schematic diagram is established in Fig. 2(b). The length L of all side fractal structures is 160 mm (a typical length of energy absorber for vehicle), and their bottoms are fixed in a rigid wall. An impactor with mass 500 kg impacts the side fractal structure at velocity of 10 m/s.

2.2. The specimen preparation and evaluation of the crashworthiness

In order to characterize the crushing mechanical behaviors of the side fractal structure, three experimental specimens of the $TSFS_3$, $SSFS_3$ and $HSFS_3$ (as shown in Fig. 3) were produced based on the wire electrical discharge machining (WEDM) method respectively. This method is to take advantage of the continuous moving electrode wire to generate pulse spark discharge etching the materials. Table 1 presents geometric parameters of three experimental specimens. It was noted that the length of the $TSFS_3$, $SSFS_3$ and $HSFS_3$ was 110 mm, which is the maximum length obtained by the WEDM machine in this fabricating process, in addition, the $TSFS_3$, $SSFS_3$ and $HSFS_3$ were machined with two different wall thickness to ensure the diversity of experimental testing. The material of the $TSFS_3$, $SSFS_3$ and $HSFS_3$ is the 6061-O aluminum alloy. The base mechanical properties of the 6061-O aluminum alloy are shown in Table 2. The universal material testing machine (Fig. 4(a)) was used to characterize the stress and strain relationship of the aluminum alloy 6061-O. The tensile specimens were also cut from a 6061-O alloy aluminum block to accurately extract the performance of the material. The dimensions of the tensile specimens are shown in Fig. 5, and the engineering stress-strain curve with strain hardening properties is also shown in Fig. 5.

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