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Crashworthiness behavior of Koch fractal structures

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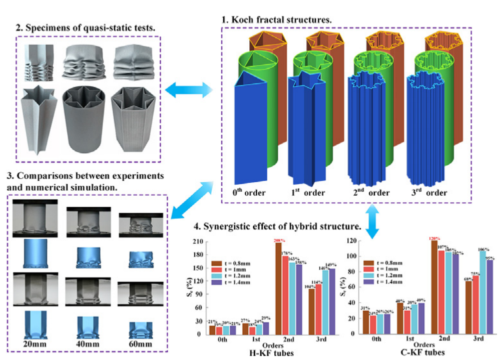
HIGHLIGHTS

- Thin-walled structures of Koch fractal cross-sections offer great potential to improve the crashworthiness.
- Fractal orders and thin-walled thicknesses have remarkable effect on specific energy absorption.
- Synergistic behavior of hybrid design obviously improves the energy absorption performance.
- The 2nd order Koch fractal design outperforms a wide range of multi-cell structures with the same mass.

GRAPHICAL ABSTRACT



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ABSTRACT

Thin-walled structures are currently used in automotive and aerospace fields due to their excellent lightweight and crashworthiness properties. This paper describes a new crush absorber design based on the Koch fractal (KF) geometry to improve energy absorption performance. The crash performance of three Koch fractal designs, one single-wall and two hybrid (double-wall), with different Koch fractal orders and wall thicknesses are investigated by experimental testing and computational modelling. Computational models of 1st order basic Koch and hybrid Koch structures are developed, with the predictions being compared with the experimental data. The computational simulations reveal a significant synergistic effect in the hybrid Koch structure, stemming from the interaction between the inner Koch wall and the external wall. Among the three designs of Koch structures, the 2nd order hybrid Koch absorbers give the highest specific energy absorption performance. Furthermore, these 2nd order hybrid Koch absorbers outperform a wide range of multi-cell structures of the same mass. The findings of this research open up a new route of designing novel lightweight energy absorbers with improved crash characteristics.

1. Introduction

Lightweight crash energy absorbers are of great importance to a wide range of applications to attenuate impact, limit maximum load, and provide over-travel protection. A broad range of new designs are emerging to replace traditional single-cell structures. For example, multi-cell thin-walled structures have been shown to absorb more energy than single cell structures of the same weight [1,2]. Kim et al. [3] proposed a new multi-cell tube with four square cells at the corners and found that this structure offered dramatic improvement in energy absorption over the conventional square box column. Wu et al. [4] investigated the effect of the number of cells and the topological configurations of multi-cell structures on their crashworthiness characteristics, and found that five-cell structure showed the best energy absorption

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characteristics compared with other multi-cell tubes. Zheng and Sun et al. [5] made significant contribution on crashworthiness of the laterally variable thickness (LVT) multi-cell square tubes, and they investigated the crushing behavior of the LVT multi-cell square tubes by experimental tests and analytical solution. The results showed that the LVT multi-cell square tubes could significantly improve the efficiency of material utilization for thin-walled structures. To improve energy absorption and to decrease peak crushing force, optimization designs [6,7] had been applied to identify the best configuration and dimension for multi-cell thin-walled structures, and found that the numerical optimization design was an effective method to improve the crashworthiness of thin-walled structures and obtain optimal parameter configurations.

In thin-walled energy absorbers, the cross-sectional shape also affects the energy absorption characteristics, for both single-walled and multi-walled structures. Sun et al. [8] investigated the crashworthiness of the criss-cross sectional tube shown in Fig. 1(a) and found that the energy absorption of crisscross tube with spline curve connection was about 150% higher than that of square column of the same weight. Wu et al. [9] proposed a series of novel Fourier varying sectional tubes, and found that the specific energy absorption of an optimum design of Fourier tube ($C_1 = 0.2$ and $C_2 = -0.3$) (referring to Fig. 1(b)), is 62.9% more than the equivalent weight circular tube.

Liu et al. [10] studied the dynamic impacting performances of thin-walled structures with *star*-shaped and polygon cross-sections shown in Fig. 1(c). Their numerical results showed tube of combing the star-shaped and polygon cross-sections gave a 40% higher energy absorption than traditional polygon tubes. Another concept to improve crash performance of the thin-walled tubes is to introduce internal ribs, double-walled, and multi-corner constructions. Jusuf et al. [11] compared the crashworthiness of the single-walled and double-walled multi-cell columns subjected to dynamic axial impact, the results showed that the energy absorption efficiency was significantly improved by introducing internal ribs to the double-walled column (Fig. 1(d)). Liu et al. [12] explored the energy absorption characteristics of a double-walled structure with star shaped cross section core shown in Fig. 1(e), and found that this new type of structure significantly increased the crashworthiness through the interaction effect between the core and the two walls. Furthermore, Tang et al. [13] found that the thin-walled columns with non-convex multi-corner in the cross section shown in Fig. 1(f) had higher energy absorption capacity than the conventional square box column, and it was also an effective strategy to improve the energy absorption efficiency of thin-walled columns.

Recently, a specific multi-corner fractal structure inspired by Koch topology has attracted strong interest in physics and engineering applications. Horvath et al. [14] reviewed Koch fractals and their diffraction behavior in physical optics, and pointed out that fractals could replace the modulators of light. Zarrabi et al. [15] combined Koch fractals and T-shaped stub to design a triple-notch ultra-wideband monopole antenna. The results showed that this antenna offered better transmission than circular monopole antenna. Xia et al. [16] developed a high-performance microwave absorber using carbon fibre felts shaped in the form of Koch fractals. They investigated the effects of the unit cell spacing and Koch parameters on the microwave absorption performance and found an optimal spacing for a given frequency band. For structural applications, Alberto et al. [17] analyzed and compared resonant frequencies between a Koch (order = 3) cantilever beam and a rectilinear cantilever beam, and results showed the Koch fractals design offered certain advantages.

Motivated by these promising findings, in this work we present a first study of the crash energy absorption performance of thin-wall structures with Koch fractal cross-sections. Section 2 first gives a brief summary of Koch fractal theory and then introduces three new absorber designs inspired by the Koch fractal geometry. Experimental tests are presented in Section 3. To facilitate design optimization and parametric analysis, Section 4 describes numerical models of Koch structures up to 3rd order. Computational analysis of the various designs is described in Section 5, from which an optimal design of Koch fractal energy absorber is identified.

2. Design based on Koch fractals

2.1. Koch fractal method

Fractal theory is an emerging discipline on geometrical design in recent years [18], with Koch fractal [19,20] being one of the most classical

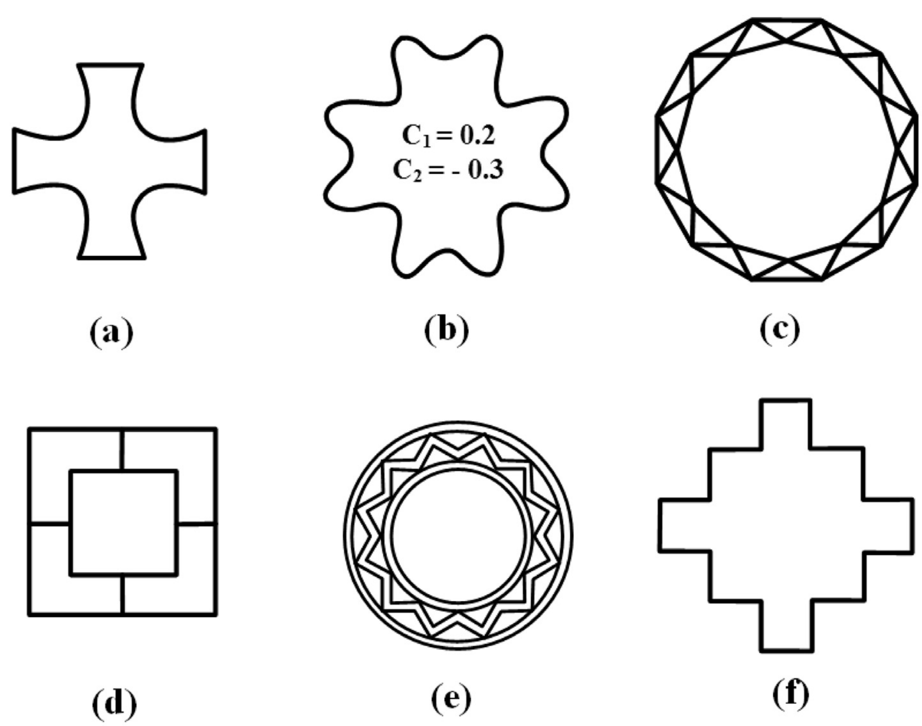

Fig. 1. Thin-walled structures with different cross sections: (a) criss-cross tube [8]; (b) Fourier varying sectional tube [9]; (c) tube combined *star*-shape and polygon [10]; (d) double-walled tube with middle ribs [11]; (e) double-walled circular tube with star-shaped core [12]; (f) multi-corner column [13].