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On design of graded honeycomb filler and tubal wall thickness for multiple load cases

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A R T I C L E I N F O

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A B S T R A C T

Circular tube filled with cellular materials becomes a fairly attractive structural option in energy absorbing devices, such as crash box and front rail in vehicle. This paper introduces a novel configuration, namely double functionally graded (DFG) structure, which comprises of a functionally graded honeycomb filler in a functionally graded thickness (FGT) tube. Based on the validated finite element (FE) models, a comparative study on the DFG tube, single functionally graded (SFG) tube, and traditional uniform honeycomb filled uniform thickness (H-UT) tube were carried out to explore the crashing behaviors of different structures under multiple load cases. It is found that as crushing displacement increases, DFG structure exhibits superior capacity of energy absorption over other configurations and this trend is positively related to the impact angles. In addition, the comparisons of deformation modes and critical crushing angles clearly indicate that the DFG structure is of better and more stable crashing characteristics, being a crashworthy structure. Following the configurational comparison, further parametric studies on the DFG structures were conducted to explore the effects of tubal thickness range and honeycomb thickness range on the crashworthiness. It is found that the tube thickness range is more important to crashworthiness, which provides a basis for structural optimization.

1. Introduction

Over the past few decades, thin-walled structures have been widely used as an energy-absorber to protect occupants from injury in automotive engineering for their extraordinary capability of energy absorption to lightweight. During a crash incident, thin-walled structure coverts part of impact kinetic energy into inelastic energy through severe plastic deformation and energy dissipation. To investigate the crashing characteristics of thin-walled structures, exhaustive studies have been conducted through the theoretical, experimental and numerical approaches. Alexander [1] first proposed an empirical model to predict average axial crushing force of circular tube. Wierzbicki and Abramowicz [2] derived the theoretical formulas to approximate crushing responses of square and circular tubes under both static and dynamic loading. These theoretical models were validated experimentally by Langseth et al. [3] and Abramowicz et al. [4,5]. Nevertheless, it remains difficult to develop accurate empirical models to predict crushing responses of thin-walled structures with more sophisticated configurations. Fortunately, finite element methods provide us with a powerful tool to simulate highly nonlinear dynamic response of complex thin-walled structures effectively [6–8].

Generally speaking, a well-designed crashworthy structure should be able to absorb maximum energy with minimum mass under different loading cases. In order to improve energy absorption of crash structures without much rise in weight, cellular materials, such as metallic honeycombs and foams, have been usually taken as filler inside thin-walled columns for their superior crashing characteristics. It has proven that the energy absorption of filled structure exceeds the summation of the energy absorptions of filler and thin-walled column due to complex interaction between them during progressive plastic collapse [9–11]. For this reason, the crushing performance of the thin-walled column with filler has drawn increasing attention. In this regard, Hanssen et al. [12,13] studied the axial deformation of the tubes filled with aluminum foam under both quasi-static and dynamic loading conditions. Through analyzing the experimental results, they proposed the theoretical formulas to predict average force, maximum force and effective crushing distance. A comparative study on different thin-walled structures, including empty tubes, foam-filled single tubes and foam-filled double tubes, had been evaluated through three points bending tests by Li et al. [14]. They found that the foam-filled double circular tube is of the best energy-absorbing effectiveness and is more suitable to be a crashworthy structure. Yin et al. [15] explored the

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crashworthiness of honeycomb-filled single and bi-tubular polygonal tubes by finite element analysis (FEA); and they found that these tubes have promising energy absorption characteristics for several cases considered. Mirfendereski et al. [16] investigated the crushing behavior of foam-filled tubes under both static and dynamic loadings; and they further carried out a parametric study on the influence of different design parameters on energy absorption. All these abovementioned studies indicated that as a filler, cellular materials are able to improve crushing stability and collapse mode of whole structure, thus considerably enhancing its crashworthiness.

Although these filled thin-walled structures have a positive bearing in energy absorption, they may generate a higher peak crushing force during impact and moreover, their material utilization may not reach an optimum. To meet the growing requirements of lightweight and crash safety, a new class of configuration, namely functionally graded structures, has been recently introduced, which can be further classified into two categories: functionally graded filler and functionally graded wall thickness. In this regard, Cui et al. [17] fabricated a functionally graded foam (FGF) material, whose density changed continuously in one direction. They showed that the FGF material, as a new type of filling materials, has significant advantages over traditional homogeneous foam. Sun et al. [18] explored the crushing behavior of functionally graded foam filled square tube by optimizing the graded apparent density for achieving best possible crushing behavior of a FGF structure. Yin et al. [19,20] further studied the crashworthiness characteristics of FGF-filled tapered tube and FGF-filled multi-cell thin-walled structures.

More recently, a functionally graded thickness (FGT) or named as tailor rolled blank (TRB) is developed to attain better crashworthiness, which allows varying the thickness of metallic plate in a continuous fashion. As such, the utilization of sheet materials can be further optimized by distributing wall thickness most efficiently. In this regard, Sun et al. [21,22] explored energy absorption characteristics of FGT tubes under dynamic axial and lateral impact loading respectively. They found that the tube absorbs more energy but generates a lower initial peak force compared with the uniform thickness (UT) tube with the same weight. And they also showed that the crashworthiness of FGT tube largely relies on the material gradient and variation range of wall thickness.

These abovementioned studies have focused on crushing characteristics under either pure axial or pure lateral loading. However, a practical structure often needs to withstand oblique loads. In other words, a well-designed energy absorbing device should meet the crashworthiness requirements for different impacting angles. In this regard, Reyes et al. [23] studied the crushing behavior and energy-absorbing capability of square columns under oblique impacting loads. They found that the oblique impacting loads can lead to unstable deformation mode, which drastically reduces the energy- absorbing capability of structures. Li et al. [24] compared the collapse behaviors of empty, foam-filled single and double tubes under different impacting angles through the quasi-static tests. They found that the foam-filled double tubes have the best crashing performance. Yang et al. [25] optimized the crashworthiness of empty and foam-filled square columns for oblique impact loading using multiobjective optimization. They revealed that the foam filled column would have better crashworthiness under pure axial loading; whereas the optimized empty column would be of more room to enhance the crashworthiness under oblique impact. Zarei et al. [26] explored the crushing behavior of empty and honeycomb filled aluminum square tubes under axial and oblique impact loading. Their study indicated that cellular filler materials generally improve the crashworthiness of whole structure, but when the density of filler is higher than a critical value, the structure would lose its weight advantages. Hence, it is important to select the appropriate filler density for improving crashworthiness characteristics. Han and Park [27] investigated the oblique crushing behavior of square steel column. They concluded that deformation changed from a progressive collapse mode to a global bending mode as loading angle increases. Li et al. [28] explored energy absorption characteristics for FGT, tapered uniform thickness and straight uniform thickness tubes subjected to oblique impact loading. They revealed that for a high load angle, the crash behavior of FGT tube is most stable. Mohammadiha et al. [29] simulated dynamic crash response of crash box filled with functionally graded honeycomb under oblique impact and investigated the effect of the gradient parameter on the crashworthiness. Li et al. [30] analyzed the crashworthiness of different functionally graded tubes under multiple loading angles and showed that the foam filled FGT tube is more advantageous over other configurations under multiple loading angles. Sun et al. [31] recently proposed a novel structure, named as double functionally graded (DFG) structure, which is composed of FGF to fill into FGT thin-walled structure, and investigated the crushing behaviors of DFG structures subjected to axial impact loading. They explored that the DFG structures have higher energy absorption capacity than the single functionally graded (SFG) and uniform structures, especially with a convex gradient configuration.

From the abovementioned studies, it is known that functionally graded structures have a greater potential over uniform counterparts in crashworthiness for bearing both axial and oblique loads. However, to the authors' best knowledge, there have been no reports available regarding the crushing behaviors of the DFG structure under multiple load cases. This paper introduces a novel DFG structure, which is composed of functionally graded honeycomb filler and functionally graded thickness column. To explore its advantages, a comparative study on the DFG, SFG, and traditional honeycomb filled uniform thickness (H-UT) tube is first carried out, in which the deformation modes and critical crashing angles are investigated. Further, some key features of DFG are selected for parametric study. The study is expected to provide some insights into the future design of DFG structures under multiple loading cases.

2. Problem description

2.1. Crushing under multiple impact angles

Vehicle collision can be simplified as an energy absorption problem of its representative key component under multiple load cases. This paper considers a circular tube filled with honeycomb as illustrated in Fig. 1. It is assumed that the bottom end of the tube is fully fixed and the top end is impacted by a rigid block with 600 kg attached mass and an initial impact velocity of 15 m/s. The impacting angle of the rigid block varies from 0° to 30°.

2.2. Crashworthiness indicators

The general goal for designing a crashworthy structure is to reduce occupant injury through sufficient deformation to absorb the impact energy. The energy absorbed during the crushing process can be calculated as follows:

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

where EA is energy absorption; d denotes crushing distance and $F(x)$ is crushing force.

To evaluate energy-absorbing efficiency of a lightweight structure, the specific energy absorption (SEA) is often used, defined as:

$$SEA=\frac{EA}{m} \tag{2}$$

where m is the mass of the crash structure. A higher SEA indicates a higher energy-absorbing efficiency of the structural mass [32].

Peak crushing force (PCF) extracted from the force-displacement