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On functionally graded composite structures for crashworthiness

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ABSTRACT

The foam-filled thin-walled composite structures have proven an ideal energy absorber in automotive engineering for its extraordinary energy absorption ability and lightweight features. Unlike existing uniform foam and thickness (UFT) structure, this paper introduces functionally graded foam (FGF) to fill into functionally graded thickness (FGT) thin-walled structure, named as double functionally graded (DFG) tube, where different configurations of foam and wall thickness gradients are taken into account. To systematically explore the crashworthiness of DFG structures, first, experimental results were performed to validate finite element (FE) models. Second, a comparison of crashworthiness was carried out for (1) four different DFG structures, (2) four single functionally-graded (SFG) structures and (3) one traditional UFT structure. The results showed that the DFG structures have better energy absorption capacity than the SFG and UFT structures, especially with a convex gradient configuration. In addition, the specific energy absorption (SEA) values of these four DFG structures are fairly close to each other, while their loading responses highly depend on the combination of gradients. Of these DFG structures, Ascending–Ascending configuration exhibits best overall crashworthiness characteristics. Finally, parametric studies were performed and the results indicated that widening the ranges of foam density and tube wall thickness can improve the energy absorption of the Ascending–Ascending DFG structures without increasing the initial peak load. Therefore, the DFG structure of Ascending–Ascending gradient is recommended for a potential absorber.

1. Introduction

Energy absorber plays a critical role in protecting occupant and good's safety when vehicular collision occurs. As a class of typical energy absorbing devices, thin-walled structures are considered superior and one of most common energy absorbers for crashing protection attributable to its well-controlled deformation pattern of progressive folding. Different types of thin-walled structures, such as circular [1,2], square [2], top-hat and double-hat tubes [3,4], have received extensive attention. The previous studies demonstrated that cross-sectional configurations have critical influences in energy absorption capacity of thin-walled columns. Specifically, circular profile was found to be more effective in progressive folding than other cross sectional profiles [1,2]. For this reason, the study on crashworthiness of circular thin-walled tubes is of considerable interests.

Recently, such cellular materials as metallic foams have received extensive attention because they can undergo large deformation at nearly constant plateau load. Therefore, metallic foams have led to increased applications as filler materials in thin-walled structures to increase energy absorption without sacrificing too much weight. For example, Seitzberger et al. [5] performed quasi-static experiments and identified that foam filler greatly improved weight efficiency with respect to energy absorption. Hanssen and his coworkers [6,7] carried out axial crushing tests and derived some close-form formulas for prediction of average force, maximum force and effective crushing distance of foam-filled tubes. They also identified the strong interaction between foam and tube wall, which explained the reason why the structure absorbs more energy than the sum of empty tube and foam themselves [6,8]. Furthermore, Reddy and Wall [9] found that low density foam prevents irregular buckling of thin-walled tubes and leads to more symmetric buckling deformation, thus improving stability of crushing process. Nevertheless, Seitzberger et al. [10] pointed out that filling the circular tube with high density foam could result in global buckling and somehow reduce SEA of foam-filled structures. For this reason, design optimization is

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required to seek a best possible combination of foam material parameters and geometric configuration for foam-filled structures. In this regard, Hou et al. [11] exploited various surrogate modeling techniques to seek optimal design of uniform foam-filled thin-wall structures for crashworthiness. Zarei and Kroger [12,13], Nariman-Zadeh [14] and Zhang et al. [15] also adopted optimization techniques to maximize energy absorption and minimize the weight of uniformly foam-filled aluminum tubes.

Although the UFT columns have improved crashworthiness to a considerable extent, such configuration may not exert their maximum capacities in material usage. In other words, the uniform structures may not make best use of material for meeting the requirements of vehicular lightweight [16]. There is an urgent need to develop new structural configurations with non-uniform distributions of material and/or thickness for maximizing crashworthiness and material usage. Recently, functionally graded materials (FGMs), where microstructural details are spatially varied through a non-uniform pattern, are drawing increasing attention attributable to their tailored multifunctional behaviors. These advanced materials with engineered gradients of composition, structure or specific properties in the preferred direction/orientation are superior to homogeneous materials made of the same constituents and uniform geometry. For FGMs, the resultant mechanical properties such as Young's modulus, Poisson's ratio, shear modulus and material density can vary in preferred directions [17]. In nature, FGM structures widely exist, from bamboos (Fig 1(a)) [18] and cuttlebone consisting of horizontal lamellae separated by vertical pillars [19] (Fig. 1(b)), to the spongy trabecular bone [20]. In the biomimetic context, the gradient concept has been taken into account in a wide range of engineering applications, where optimal use of materials is essential, e.g. functionally graded piezoelectric materials, dental implants [21], heat exchanger [22], and novel concrete structures [23], etc.

To further improve crashworthiness of foam-filled thin-wall structures, graded foam material and tube wall thickness have shown certain benefits. In this respect, functionally graded foam (FGF) materials [24,25], where foam density varies continuously in a predefined form, have been attempted to replace uniform foam fillers. Several studies were conducted to investigate the energy absorption performance of FGF configurations. Cui et al. [26] proposed a FGF model, and showed that FGFs have superior energy-absorbing capability than uniform foam. Sun et al. [27] explored the crashworthiness of FGF filled square tube with axial gradient, and they found that FGF is superior to its uniform counterparts in overall crash behaviors. Yin et al. [28] studied the axial crushing behavior of FGF filled tapered tube. Fang et al. [29] explored the crashworthiness of the FGF column under lateral impact. Yin et al. [30] and Attia et al. [31] subsequently extended the foam filler from axial density gradient to lateral density gradient.

Furthermore, to improve the utilization of wall materials, functionally graded thickness (FGT) was proposed, in which the Tailored Rolling Blanks (TRB) technology has been used to produce sheet metal for continuously changing wall thickness [32]. In this regard, Sun et al. [16] first explored the crushing characteristics of FGT square tubes and found that FGT tube is superior to its uniform counterpart in overall crashing behaviors. More recently, Li et al. [33] compared the novel FGT tube with the conventional tapered tube for withstanding oblique impacting, and found that FGT tube is more beneficial within a given spatial constraint. These studies showed that the column with a graded wall thickness is more preferred than with a uniform thickness for its stable load-deformation responses and reduced risk of global buckling.

Nevertheless, these previous studies on functionally graded structures largely focused on single gradient for either column wall thickness or foam filler. To the author's best knowledge there has been no report available for taking into account the dual gradients for foam filler and wall thickness. This paper presents a novel composite structure, named as double functionally graded (DFG) configuration. To explore crashworthiness of DFG structures, a comparative study on the four different FGF-FGT circular columns, four corresponding SFG structures and one UFT structure with the same weight, is conducted here, in which SEA and Initial Peak Load (IPL) are selected as the indicators to evaluating crashworthiness.

2. DFG structure and finite element modeling

2.1. Single functionally-graded structures

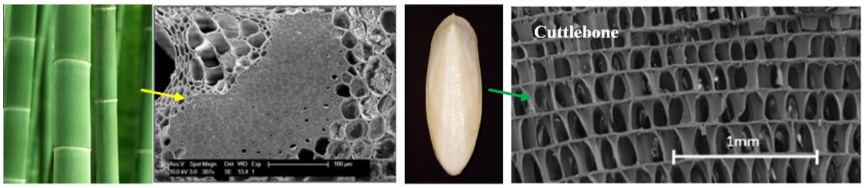
Previously explored functionally graded structures have been largely restricted to the SFG structures, where only one component, either outer tube wall or inner foam filler, uses functionally-graded configuration. Fig. 2 illustrates the SFG structures proposed in literature, namely longitudinally graded wall thickness (Fig. 2(a) [16,33]) and foam density (Fig. 2(b) [27,28,31]); as well as laterally-graded wall thickness (Fig. 2(d)) and foam density (Fig 2(c) [29–31]). This paper proposes a novel DFG configuration, combining graded wall thickness and graded foam density in longitudinal direction.

2.2. Double functionally-graded structures

To adapt the functional requirements for crashworthiness, novel processing methods such as friction stir processing [34,35], aluminum melt direct foaming route [36] have made it possible to fabricate foam in a desired gradient with continuous varying density along a certain direction [27]. To model the axially graded foam filler, the continuous gradient configuration was discretized with a limited number of layers, and the foam density of each layer was regarded uniform [16,27]. Fig. 3(a) is a schematic of such a FGF configuration, and foam density ρ is determined by the following power-law function.

$$\rho(x,m) = \begin{cases} \rho_{\min} + (\rho_{\max} - \rho_{\min})\left(\frac{x}{L}\right)^{10^m} & \text{ascending pattern} \\ \rho_{\max} - (\rho_{\max} - \rho_{\min})\left(\frac{x}{L}\right)^{10^m} & \text{descending pattern} \end{cases} \quad (1)$$

where ρ represents foam density of each layer, $\rho_{\min}$ and $\rho_{\max}$ are the minimum and maximum densities, respectively; m denotes the gradient parameter that governs the variation pattern of foam density; x and L are the distance from the fixed end (rigid wall) and axial length of the tube shown in Fig. 3(a), respectively. The direction



(a) (b)

Fig. 1. Examples of FGMs in nature and engineering (a) bamboo (b) cuttlebone and SEM image of the transverse cross section of cuttlebone.