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A review on functionally graded structures and materials for energy absorption

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ABSTRACT

In the past decades, there has been a constant aspiration for light-weight and highly efficient energy-absorbing structures and materials in vehicle and other industries. A large number of publications have shown that advanced configurations with functionally graded properties could collapse in a more controlled manner and have a remarkable energy-absorbing efficiency when compared with traditional uniform structures and materials. This paper mainly covers the state of the art of energy absorption of graded structures and materials, and discusses the effects of the graded properties on their crashworthiness. Those advanced energy-absorbing structures and materials include primarily thin-walled structures with variable diameter/width/wall thickness/strength, cellular materials with variable density and their filling structures, and other hybrid structures with multiple graded properties. It demonstrates that thin-walled structures and cellular materials could exhibit more efficient and effective energy-absorbing performance by introducing graded properties. Additionally, some advanced manufacturing and modeling technologies such as the 3D printing, multi-scale computation, etc. provide a much wider and more feasible conceptual design for graded structures and materials.

1. Motivation

In the past years, there has been an unremitting pursuit of lighter and safer energy-absorbing structural elements in many fields such as vehicle, ship and aerospace industries for better fuel economy, less gas emission, improving structural integrity and passenger safety. Recently, crashworthiness of advanced structures and materials with graded properties raised enormous concerns [1,2]. Introducing gradient to structures and materials could considerably reduce weight and at the same time improve performance by making reasonable designs of the gradient parameters.

The investigations on energy-absorbing configurations considering graded properties are quite extensive and abundant. Those structures/materials may be thin-walled components, cellular materials like foams or honeycombs, or composite materials/structures of these two [3,4]. The graded properties may arise from geometrical parameters such as diameter, width, wall thickness etc. Additionally, they can also be caused by variable material properties including density, strength and even material type. Note that the graded property could be a single factor alone, or multiple graded properties could take effect at the same time. What's more, the applied load conditions are also multifarious such as axial crushing, transverse or oblique loading, ball impact, etc.

In general, the introducing of gradients brings bigger flexibility and wider design domain in related energy-absorbing structures and materials. The crashworthiness performance of these structures and materials could definitely be further improved by appropriate design optimization [5]. There is no doubt that design optimization techniques would always play an important role in this process to obtain optimal solutions with different objectives, constraints and design variables.

However, it is worth noting that the introducing of gradients may result in some difficulties in fabrication or manufacturing of such structures and materials. Fortunately, this obstacle could be eliminated with the advance of manufacturing science and process technology. For example, various tailoring and forming technologies can be employed to fabricate the structures with graded properties. Thus, it would not be difficult anymore to obtain thin-walled structures with a graded property in most cases. Some mature production technologies, such as tailor-welded blank (TWB), tailor rolling blank (TRB) and tailor hot stamping (THS), etc., have been widely applied in various engineering fields, especially in the automotive industry. The components produced by

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those technologies are all representations of thin-walled structures with graded properties. Although the manufacturing of metal foams with graded density is still a challenging task, the progress is being made in this field.

The main motivation of this paper is to summarize the effects of graded properties on energy absorption of structures and materials in those published works. And it is also expected to inspire novel manufacturing, modeling and computational strategies for designing better load-bearing elements with higher energy-absorbing capacity. The relevant experimental, numerical, theoretical and optimization studies on the crashworthiness design of those advanced structures and materials will be comprehensively reviewed and summarized in the present work.

2. Thin-walled structures with graded diameter (width)

Thin-walled tapered tubes or frusta are the most simple and commonly-used structures with gradient property. They are always employed to endure axial or oblique impact loads. Note that a prior motivation of employing tapered tubes is to improve the load uniformity of energy absorbers during impact scenarios. As we all know, the crush response of thin-walled tubes is generally initiated with a high peak force, and then followed by a stable stage with a relatively low force. For a circular (square) tube, a decrease in the diameter (width) will lead to a reduction in the initial peak force. That's why the smaller end of tapered tubes is always placed proximal to the striker. The major problem is whether the energy absorption capacity of tapered tubes is also greatly reduced due to the decrease in diameter or width when compared to straight tubes.

According to the studies on the axial crush resistance of circular or square tubes, the dependence of crushing force on diameter or width is small. The expressions for the mean crushing force of a typical deformation mode of circular and square tubes are presented here. Axisymmetric concertina mode [6] and symmetric collapse mode [7] are selected for circular and square tubes, respectively. An illustration for the two representative modes is given in Fig. 1.

For concertina mode $$P_m = 7.935\sigma_0 D^{0.5} t^{1.5} \quad (1)$$

For symmetric mode $$P_m = 13.06\sigma_0 C^{\frac{1}{3}} t^{\frac{5}{3}} \quad (2)$$

where σ_0 is the flow stress of the structural material, t is the wall thickness. D and C are the mean diameter and width of circular and square tube, respectively.

As shown in both expressions, the exponent of D and C is equal to 0.5 and 0.33, respectively. Thus the mean force will keep 70–80% of the original value when D or C is reduced by half. In other words, the mean force decreases by about 20–30%. As we know, the mean force of a taper tube is approximately the average value of the two ends. For a circular/square tube, when the diameter/width in one end is reduced by half to form a tapered tube, the mean force is hence reduced by just about 10–15%. However, the peak force is approximately proportional to the sectional area of the material, and it would be reduced by about 50% when the diameter or width is cut in half. Definitely, the ratio of the mean force to the peak force is increased and hence the load uniformity is improved.

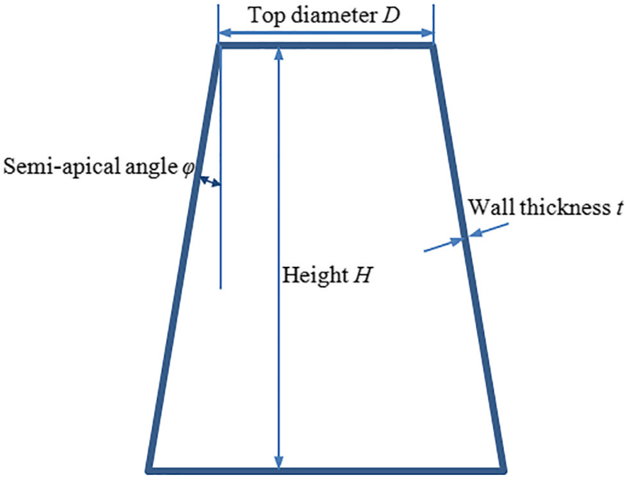

Fig. 2. A schematic diagram for a thin-wall frustum.

The early studies on the axial crushing of tapered tubes were performed by Mamalis and Johnson [8] and Mamalis et al. [9,10] in the 1980s. Based on the compression tests of thin-walled cylinders and frusta, empirical expressions of the mean crushing load were firstly derived for frusta with various semi-apical angle by fitting the results of frusta with various crumpling modes [8,9]. A theoretical model was then proposed to analyze the extensional mode of the frusta [10], and the mean force was correlated with the yield stress Y of material, wall thickness t, top diameter D and semi-apical angle φ of the frusta. A schematic diagram for the dimensions of a thin-walled frustum is shown in Fig. 2. The effects of end constraints on the energy absorption of frusta were investigated experimentally by Sobky et al. [11] and constraining the frusta at the top was reported to enhance the energy absorption capacity under both static and dynamic loading.

With the advance of computer technology, numerical simulation and surrogate optimization methods have been widely applied in the crashworthiness analysis and design of tapered tubes. For example, Nagel and Thambiratnam [12,13] investigated the energy absorption response of tapered thin-walled rectangular tubes numerically and compared with that of straight tubes (see Fig. 3). Influences of various factors including wall thickness, taper angle, impact mass and velocity were analyzed. In 2007, Avalle and Chiandussi [14] introduced a tapered initiator to a tubular component as the front structure or front longitudinal beam of a vehicle body (see Fig. 4). Experiment results showed that the tapered initiator could reduce the initial peak force and hence lower the maximum acceleration during impact events. Optimization with two variables, i.e., the diameter at one end and the tapering length, was performed by using the response surface method. Other optimization designs of tapered tubes were also carried out by Liu [15] and Hou et al. [16].

Besides improving load uniformity, another significant merit of tapered tubes is to resist oblique loads. In fact, the energy-absorbing


(a) (b)

Fig. 1. (a) Concertina mode of circular tubes [6] and (b) symmetric mode of square tubes.