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Enhancing material efficiency of energy absorbers through graded thickness structures

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ABSTRACT

At present, there has been constant aspiration of advanced thin-walled structures in vehicular industries for more efficient usage of materials to achieve much lighter weight and even higher energy absorption. In this paper, functionally graded thickness (FGT) tubes with a varying wall thickness are introduced and their energy-absorbing efficiency is enhanced. Apart from the geometrical parameters such as diameter and length, the gradient exponent that controls the variation of thickness distributions has also a significant effect on the increase in absorbed-energy. Numerical model is validated by performed crashing experiments of FGT tube. Parametric analysis demonstrates that the FGT column is superior to the uniform thickness (UT) column. Further, the multiobjective optimization (MOO) of FGT tubes is conducted for axial impacting by considering specific energy absorption (SEA) and crashing force efficiency (CFE) as objectives, and the diameter, initial length and gradient exponent of thickness variation as the design variables. The multiobjective particle swarm optimization algorithm (MOPSO) is applied to obtain the Pareto optimal solutions. In addition, a comparative study on different surrogate models, such as response surface method (RSM), Kriging method (KRM), and radial basis function (RBF), is also carried out to gain insights into their relative performance and features in computational modeling and design optimization. It is indicated that the performance of FGT tubes can be significantly improved by optimizing the geometrical parameters and gradient exponent.

1. Introduction

Lured by significant advantages of efficient energy absorption and low cost of manufacturing, a range of thin-walled metal tubes have been widely utilized in transportation and defense industries as one of the most important energy absorbers in different ways [1]. Over the past decades, two critical characteristics of lightweight and crashworthiness have drawn increasing attentions through analytical, experimental and numerical approaches to understanding of collapse mode, peak force, mean force and the energy-absorption [2–11]. The axial crashing behavior of thin-walled structures has been a key topic with great interest for many researchers.

The automobile body structures are largely composed of thin-walled structural parts, which are typically made by forming process of traditional metal sheets with uniform thickness. Crashworthiness of such sheet metal formed thin-walled structures has been of great interests for improving the material utilization and vehicle safety. Exhaustive studies were performed for developing different hollow or foam-filled structural configurations [12]. For example, Tang et al. [13] proposed a cylindrical multi-cell column to improve energy absorption. Ghamarian et al. [14] compared the crashworthiness of end-capped cylindrical and conical tubes using experimental and numerical approaches to searching more efficient and lighter energy absorbers. Marzbanrad et al. [15] systematically studied square, circular, and elliptic tubes of steel and aluminum tubes with different geometric dimensions by using finite element simulation. Acar et al. [16] investigated the crashing behaviors of tapered tubes using multiobjective optimization. Zhang et al. [17] evaluated the energy absorption characteristics of regular polygonal and rhombi columns under quasi-static axial compression.

Despite its significance, all those abovementioned thin-walled structures were made of uniform materials and/or the same wall thickness. The main drawbacks lie in that such structures may not exert their maximum capacities of crashworthiness. In other words, the tubes with uniform wall thickness may not necessarily make best use of materials for meeting the requirements of vehicular lightweight [18–20]. Therefore, there is an urgent demand

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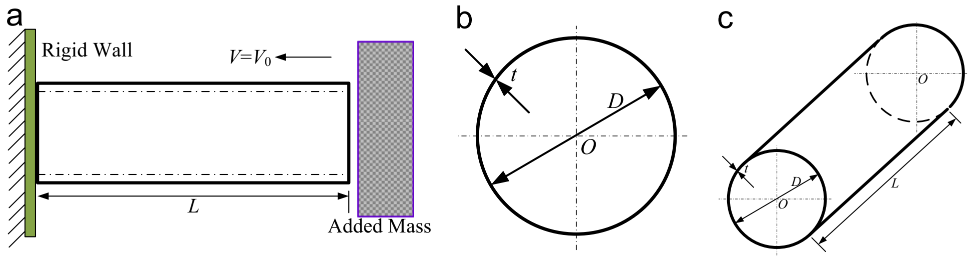

Fig. 1. Geometrical details of the circular column with uniform thickness used in axial crashing.

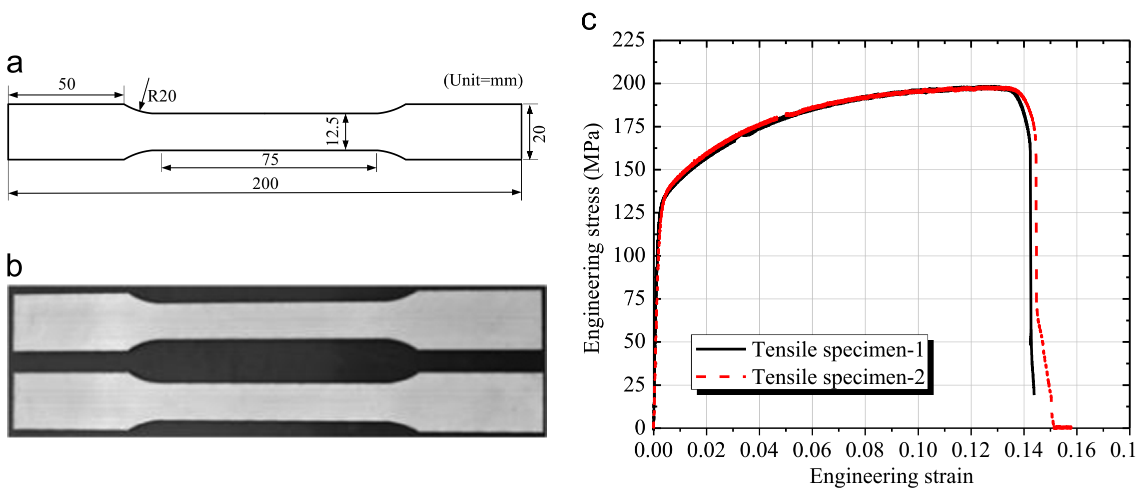

Fig. 2. (a) Standard specimens specified in the ASTM; (b) Tensile coupon test specimen; (c) Engineering stress and engineering strain relationship of metal aluminum material.

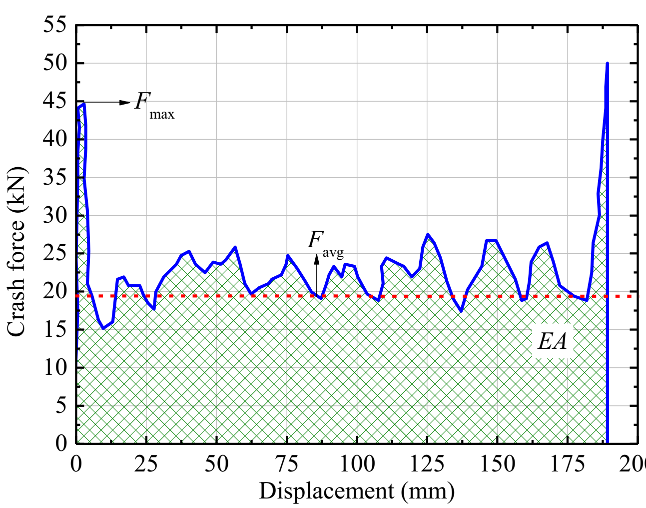

Fig. 3. A typical relationship between force versus displacement of axial crashing behavior of circular tubes [35].

to develop new structural configurations with different material and/or thickness combinations for maximizing crashing capacities and material utilization.

It has been proven that crashworthiness of non-uniform components could be improved by an optimal design of different materials and/or thicknesses [21]. Of various technologies to combine different materials or thickness, tailor-welded blank (TWB) structures have drawn major attentions over the recent years. They are fabricated by welding metal sheets with different thicknesses and/or materials first and then formed to be the desired thin-walled structures. Thus, it provides a more flexible combination of different sheets and allows better utilizing materials for improving the crashworthiness characteristics. For this reason, such structures have been extensively adopted in vehicular floor component, B-pillar, front-end structure, and door inner panels etc. [22–26]. However, the main shortcoming of those welded blanks lies in that they need to combine the sheets with different thickness/materials, and the material properties in the welding zone can be rather different from those in the base materials, potentially causing stress concentration in the interfaces. To overcome such defects of TWB, a new rolling technology, namely tailor rolling blank (TRB), which leads to a continuous thickness variation in the workpiece, has been developed in recent years [27]. From the study by Yang et al. [27,28], a metal sheet with variations of thickness would be a more desirable because the technology not only uses material more efficiently, but also makes design more flexible. As such, thin-walled structures with varying sheet thicknesses can better meet different design requirements, thereby providing enhanced material/thickness utilization comparing with those made of traditional uniform sheets [29–31]. Besides that, such special structures enable to absorb energy in a more controlled manner during a crashing situation.

To date, there have been some published reports available concerning TRB technology. For example, Urban et al. [32] developed a design tool by combining numerical simulation and optimization algorithm to improve the formability of TRB. Meyer et al. [33] used TRB to increase the maximum drawing depth compared with constant thickness. Zhang et al. [34] investigated the effects of the transition zone length, the blank thickness variation, friction coefficient and die clearance on the springback of TRB component. Nevertheless, those published works focused mainly on the design