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Crashworthiness design for foam-filled thin-walled structures with functionally lateral graded thickness sheets

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ABSTRACT

Crash components in automobiles are probably subjected to multiple loading conditions in real life, such as axial crushing and lateral bending. Unlike most of the existing work that solely focuses on the pure axial crushing or lateral bending, this paper attempts to accommodate both by proposing a novel structure, namely foam-filled thin-wall tube with functionally lateral graded thickness (FLGT). From numerical study of FLGT structures, they are found to exhibit noticeable advantage over the corresponding traditional uniform thickness (UT) structures with the same weight under both axial crushing and lateral bending. Moreover, the gradient governing the varying thickness shows significant influence on the crashworthiness performance of FLGT. To seek for the optimal gradient, a multi-objective optimization is carried out using multi-objective particle swarm optimization (MOPSO) algorithm, where response surface models are established to formulate the objectives functions, i.e. specific energy absorption (SEA) and peak impact force (F_{peak}). The optimization results show that the foam-filled structure with FLGT can produce more promising Pareto solutions than traditional UT counterparts. Therefore, the FLGT structure could have potential applications subjected to different loading conditions.

1. Introduction

Over the past decades, the design of crashworthy columns subjected to axial crushing has been extensively investigated. For example, Xiang et al. [1] performed crashworthiness optimization of spot-welded spacing of thin-walled hat section subjected to an axial crushing force. Tarigopula et al. [2] studied the energy-absorbing capacity of thin-walled high strength steel section and concluded that the energy-absorbing capability for thin-walled tube increased continuously with yield strength, sheet thickness and impact velocity. Bambach et al. [3] developed theoretical procedures to design the crashworthiness characteristics for the composite tubes. Alavi Nia and Haddad Hamedani [4] compared the axial energy absorption and deformations of thin-walled tubes with various section geometries. Najafi and Rais-Rohani [5] investigated mechanics of plastic collapse in the multi-cell, multi-corner crash tubes under axial crushing. Ghamarian et al. [6] and Zarei et al. [7] paid considerable interest on the axial crushing behavior of foam-filled thin-walled structure and found that this structure has dramatic improvement over the conventional thin-walled tube. Recently, Fang et al. [8] explored the design of foam-filled bitubal structures using a multi-objective robust design optimization (MORDO) method.

Besides axial loading, substantial studies on lateral bending have been conducted for crashworthiness design. In this regard, a rib-reinforced thin-walled hollow tube-like beam was presented for potential application in vehicle bumper [9]. Poonaya et al. [10] provided a theoretical model to predict the collapse mechanism of thin-walled circular tube subjected to pure bending. Ayhan et al. [11] investigated the bending behavior of the beam by the finite element method and dealt with the correlation between the energy absorption and transition displacements for geometric parameters. Qaiser et al. [12] endorsed the viability of using sinusoidal patterned beams in mainstream practical applications under lateral bending. Fang et al. [13] introduced a functionally graded foam-filled tube as potential crashworthy structure for lateral bending.

However, the crashworthy structures in vehicle can be subjected to various loading scenarios, such as frontal, side and rear collisions. As a result, the whole vehicle structure should have a good performance under multiple loading cases, which can be achieved by improving the crashworthiness of each component in particular cases. For example, frontal rail, crash box and other frontal components are expected to perform well in frontal crash, while side-door beam, door sill, B pillar and other side structures

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are required to absorb energy in side impact. However, majority of the existing abovementioned work for crashworthiness design solely focuses on either pure axial or lateral loading condition, which may narrow the applications of the structures studied.

To reduce the fuel consumption and preserve the environment, lightweight design has also been gaining considerable attention [14,15]. For a thin-walled structure, tailoring its thickness variations offers a more flexible way to make the best use of material. Yang et al. [16] pointed out that the sheet with varying thickness could be more promising structure in the area of crashworthiness. Sun et al. [17] introduced functionally graded structures with changing wall thickness along the longitudinal direction which showed potential advantage as absorber of crushing energy. Zhang et al. [18] revealed that tubes with graded thickness in cross-section, which can lead up to 30–35% increase in energy absorption under axial loading. With the advance in material processing technology, it is not difficult to fabricate metal sheet with varying thickness. Hirt and Dávalos-Julca [19] showed the feasibility of roll bending using tailor rolled strips to produce a tailored tube with varying thickness. Chuang et al. [20] pointed out that tailor rolled blank (TRB) technology allows continuous change in metal thickness thereby providing new opportunities for automotive design in weight reduction.

This paper introduces tube with functionally lateral graded thickness (FLGT) to foam-filled thin-wall structure for accommodating both axial crushing and lateral bending. First, it is essential to understand the crashworthiness characteristics of foam-filled FLGT tubes in comparison with conventional foam-filled thin-wall structure under axial crushing and lateral bending. The influence of the exponent parameter controlling the thickness gradient on crashworthiness performance of structure is also investigated. Then, a multi-objective optimization is formulated to seek for the optimal gradient, where a surrogate modeling technique is conducted for the designated crashworthiness indicators, i.e. specific energy absorption (SEA) and peak impact force (F_{peak}).

2. Finite element modeling of foam-filled thin-walled structures with functionally lateral graded thickness (FLGT) tube

2.1. Functionally lateral grade thickness (FLGT) tube

In a crashing structure, rolling and extensional deformation are usually confined in the corner regions. In order to increase the energy absorption efficiency, it is effective to add material to the corner regions and accordingly reduce that in other regions [18]. In this study, the thickness of the column wall varies along lateral direction in the cross section (Fig. 1). The thickness gradient m governs the thickness variation by the following power-law function:

$$t(x,m) = t_{min} + (t_{max} - t_{min})\left(\frac{x}{L}\right)^m \quad (1)$$

where t (x,m) is the graded varying thickness, and x denotes the distance to the middle point of the width, and L is the half-width of the section for FLGT (Fig. 1). t_{max} and t_{min} are the maximum and minimum thicknesses, respectively. We define another parameter $n = \log_{10}(m)$ so that Eq. (1) can be rewritten as Eq. (2). In this study, the gradient n is varied from -1 to 1. The variation of graded thickness along the width with gradient m (n) is shown in Fig. 2.

$$t(x,n) = t_{min} + (t_{max} - t_{min})\left(\frac{x}{L}\right)^{10^n} \quad (2)$$

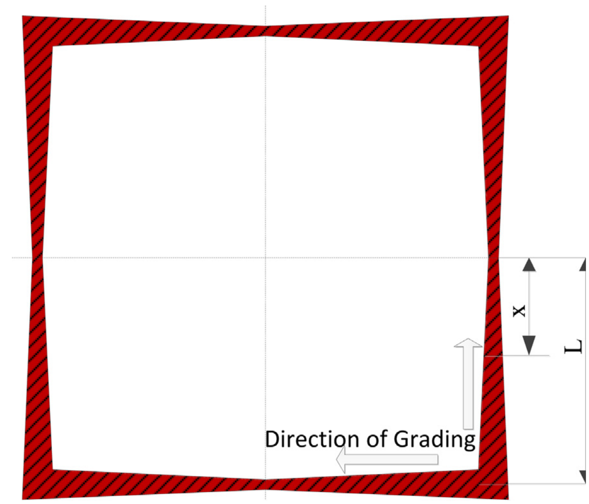

Fig. 1. Schematic showing thickness grading patterns in the lateral direction.

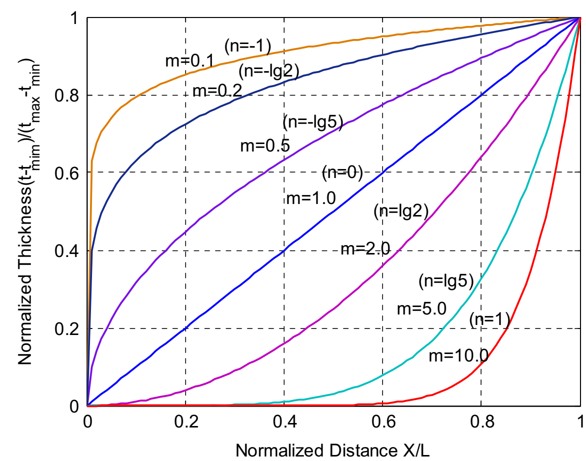

Fig. 2. Thickness variation versus normalized distance.

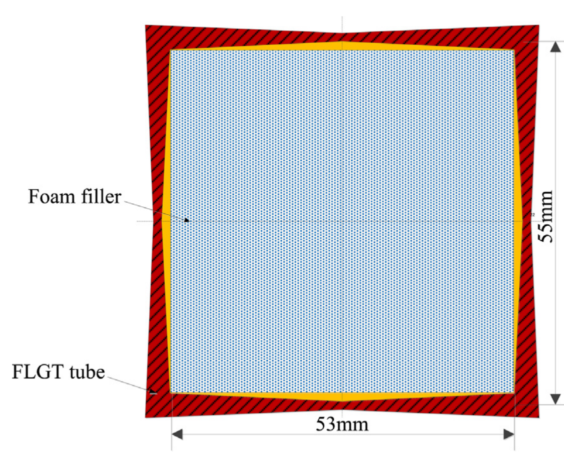

Fig. 3. Cross section description of foam-filled FLGT tube.

2.2. Geometrical description and details of the finite element model

The column considered in this paper is a foam-filled structure, whose section is 53 mm × 53 mm and 55 mm × 55 mm for the foam filler and column wall, respectively (Fig. 3). The total length of the column is 240 mm. As for the tube thickness, it varies from