Thin-Walled Structures 94 (2015) 334–347

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length Article

Comparison of functionally-graded structures under multiple loading angles

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ARTICLE INFO

Article history:
Received 3 March 2015
Received in revised form
26 April 2015
Accepted 27 April 2015
Available online 16 May 2015

Keywords:
Functionally graded thickness
Foams
Optimization
Crashworthiness
Oblique load

ABSTRACT

This paper provides a comparative study on the crashworthiness of different functionally-graded thin-wall tubes under multiple loading angles, which include hollow uniform thickness (H-UT), hollow functionally graded thickness (H-FGT), foam-filled uniform thickness (F-UT) and foam-filled functionally graded thickness (F-FGT) configurations. First, finite element analyses of these differently graded circular tubes reveal that the F-FGT tube has the best crashworthiness under multiple loading angles. Second, parametric study on the F-FGT tube indicates that the thickness gradient and variation range significantly influence its crashworthiness. Third, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to optimize the F-FGT tube, in which the optimal thickness variation is sought for maximizing specific energy absorption (SEA) and minimizing initial peak force (IPF) under multiple loading angles. The optimized F-FGT tube exhibits better crashworthiness than other three equivalent tube configurations, indicating that the F-FGT tube can be a potential energy absorber when oblique impact loading is inevitable.

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1. Introduction

Environmental awareness and economic pressure force automobile manufacturers to decrease the weight of vehicles and achieve a highest possible safety and quality with minimum cost. Lightweight materials, such as aluminum and magnesium alloys, are gradually finding their place in vehicle engineering [1]. However, it is not always safe to reduce the weight of vehicle's components by sacrificing the crashworthiness, especially for critical protective components. Thin-walled structures, as effective energy-absorbing devices with high crashworthiness to weight ratio over other solid elements, have drawn extensive attention on their excellent crashing behaviors and energy-absorbing characteristics for better performance and utilization of structural materials [2–8].

To enhance energy absorption without much increase in mass, cellular materials, such as honeycombs, polyethylene and metal foams, have been widely used for filling the cavities of thin-walled structures. Amongst these filler materials, aluminum foam has been most commonly used. Recently, substantial effort has been devoted to understanding the effects of aluminum foam-filled structures on energy-absorbing characteristics using experimental, analytical and numerical methods. For example, Reddy et al. [9] conducted an experimental study on the crashing behaviors of foam-filled circular tubes under quasi-static and dynamic loadings. The deformation mode of such tubes was found to change from irregular diamond crumpling to axisymmetric folding, attributing to the filler interaction. Hanssen et al. [10,11] presented the close-form formulas to predict the behaviors of foam-filled aluminum tubes under both quasi-static and dynamic loading conditions. They showed that the total energy absorption of a foam-filled tube exceeded the sum of individual energies absorbed in empty column and form filler due to the interaction between foam and column wall. Ahmad et al. [12] used numerical methods to simulate the behavior of foam-filled conical tubes under quasi-static crush and they also found that energy-absorbing capacity of conical tubes was significantly enhanced due to foam filler. To make more effective use of various foam-filled thin-wall structure systems, Hou et al. [13,14] and Zhang et al. [15] attempted to simultaneously optimize foam density and wall thickness to seek best possible combination for enhancing crashworthiness. These above mentioned studies demonstrated that the presence of foam filler increases crushing stability, alters collapse mode, and improves overall crashworthiness in comparison with hollow thin-walled structures under certain loading conditions.

Working as energy-absorbing devices, however, thin-walled tubes could likely experience complex loading conditions with both axial and oblique impacts in real vehicle crash event. For this

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http://dx.doi.org/10.1016/j.tws.2015.04.030
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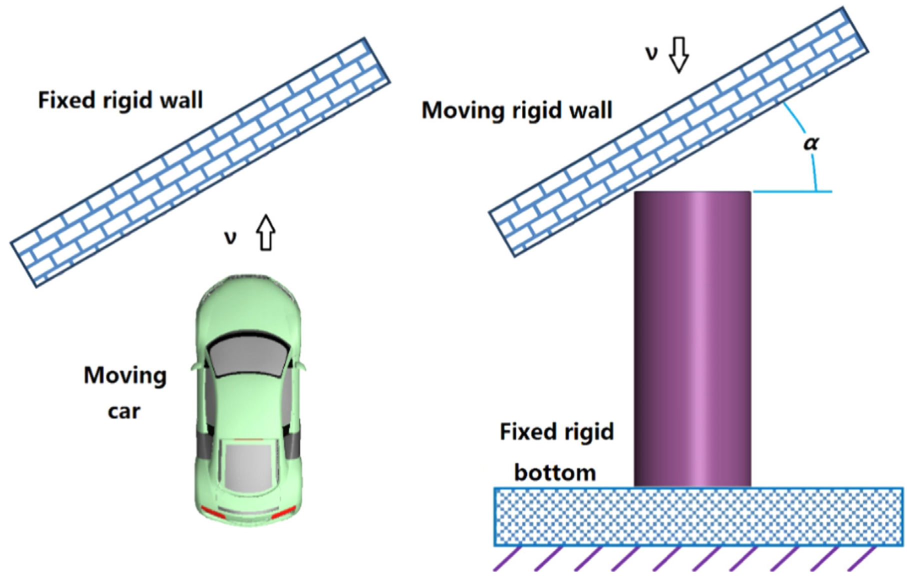

Fig. 1. Geometric configuration and boundary condition of tubes under oblique impact.

reason, the uniaxial impact analysis and design may lose its robustness in reality. According to the requirements of Federal Motor Vehicle Safety Standards 208 [16], the frontal impact of full vehicle should endure impacting angle up to 30° angle from the longitudinal axis. Such oblique loading condition could make energy-absorbing device deform in both axial progressive folding and lateral bending. Compared with the progressive folding mode, the lateral bending can be unstable with much less crash energy absorbed [17–24]. In this regard, Zhang et al. [25] optimized the hollow and foam-filled conical thin-walled tubes under oblique impacting loads, and they identified that the hollow tube could have better crashing performance than the foam-filled tube under relatively high impacting velocity and great loading angle. Yang and Qi [26] compared the crashworthiness of empty and foam-filled thin-walled square columns; and they found that the optimal foam-filled column had better crashworthiness than the empty column under pure axial loading, but lost its superiority under oblique impact. Furthermore, they also [27] studied conical tubes with or without foam-filler. Nevertheless, the results showed that the empty conical tube had the better performance in terms of both SEA and peak crashing force under axial loading, while the optimal foam-filled conical tube seemed better to be under any of oblique loading cases concerned. Ahmad et al. [28] investigated the responses of foam-filled conical tubes subjected to oblique impact loading, and they exhibited that such a configuration is able to withstand oblique impacting loads and can better maintain energy-absorbing capacity compared with the empty tubes when increasing the incidental angle of impact. In general, it is important to place energy absorber to various loading conditions rather than the axial impact, thereby figuring out whether and how the filled foam does enhance the crashworthiness under multiple loading angles.

To further improve energy-absorption of thin-walled tubes, some other novel attempts were made by switching the uniform wall thickness of tubes to graded thickness for tailoring specific functions. It is noted that the inherent shortcoming of uniform structures is that the usage of material may not exert its full capacity and the material distribution follows more manufacturing than functional requirements [29–31]. For this reason, it is reasonable to consider new structural configuration with varying wall thickness for maximizing materials usage. Tailor-welded blank (TWB) technology, which welds two or more metallic sheets with different thicknesses (and materials), is an example to achieve a changing thickness. Xu et al. [32] has experimentally investigated the crushing behaviors of TWB thin-walled structures; and demonstrated that with an optimal choice of different thicknesses and materials grades, crashing performance of the TWB components could be improved to a greater extent. Indeed, design of specific thin-walled components with desired thicknesses/materials in a more efficient manner creates new opportunity for further reducing weight and enhancing performance of the products. However, the main shortcoming of TWB structures lies in the welding sections which come with stepped thicknesses and heterogeneity of materials, potentially leading to considerable stress concentration in the interfaces.

To overcome such inherent defects of TWB components, a relatively new technology, named tailor rolled blank (TRB), had been developed [33–35]. In the rolling process, the roller gap can be varied, thereby leading to a continuous thickness variation in the TRB workpiece. On this basis, a new thin-walled structural configuration with functionally graded thickness (FGT) has been proposed by Sun et al. [36], who explored the crashing characteristics of FGT structures under axial impact. The results showed that the gradient exponent n which controlled the variation of thickness has a significant effect on crashworthiness, and the optimized results indicated that the FGT tube is superior to its uniform counterparts. Furthermore, Li et al. [37] performed a comparative study on FGT thin-walled structures and tapered tubes withstanding oblique impact loading. It was found that the FGT tubes are more preferable as an energy absorber attributing to their higher capacity of withstanding the oblique loads.

With the foam filled uniform structures and hollow functionally graded thickness structures in mind, it would be interesting to explore the hybrid structures by filling foam material to FGT (namely F-FGT) structures for multiple loading angles. First, finite element (FE) study is conducted under multiple impacts for a series of thin-walled circular tubes, specifically hollow uniform thickness (H-UT), hollow functionally graded thickness (H-FGT), foam-filled uniform thickness (F-UT) and foam-filled functionally graded thickness (F-FGT) tubes. It will show that the F-FGT configuration has the best crashing performance under oblique impact loads. Second, further investigation will be conducted for different thickness gradients to seek the optimal design of F-FGT tubes. The optimal design of the F-FGT tube demonstrates much better crashworthiness than the other three kinds of tubes with same geometric configuration, thereby indicating that the F-FGT

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