



Full length article

Energy absorption mechanics for variable thickness thin-walled structures

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ABSTRACT

This paper introduces axial functionally graded thickness (AFGT) and lateral functionally graded thickness (LFGT) to thin-walled square structures separately, and then investigates their crashworthiness theoretically, numerically, experimentally under axial crushing load. The quasi-static axial crush experiments and the corresponding finite element models are first conducted to analysis the deformation mode and crushing force for uniform thickness (UT), AFGT and LFGT square tube under the same mass. Then, theoretical models predicting the mean crushing forces of AFGT and LFGT square tubes are established. The results show that both theoretical solutions and numerical results for FGT tubes agree well with the experimental results. Energy absorption characteristics between FGT and UT square tubes with same mass are compared based on the validated numerical models, which shows that AFGT square tube can effectively reduce the initial peak force compared to UT square tube while LFGT square tube remarkably surpasses the UT square tube in specific energy absorption (SEA) under axial crushing. Furthermore, parametric studies are performed to investigate the effects of gradient thickness variation on the energy absorption characteristics of AFGT and LFGT square tubes. The results again demonstrate that both AFGT and LFGT square tubes can improve the crashworthiness of thin-walled square tubes.

1. Introduction

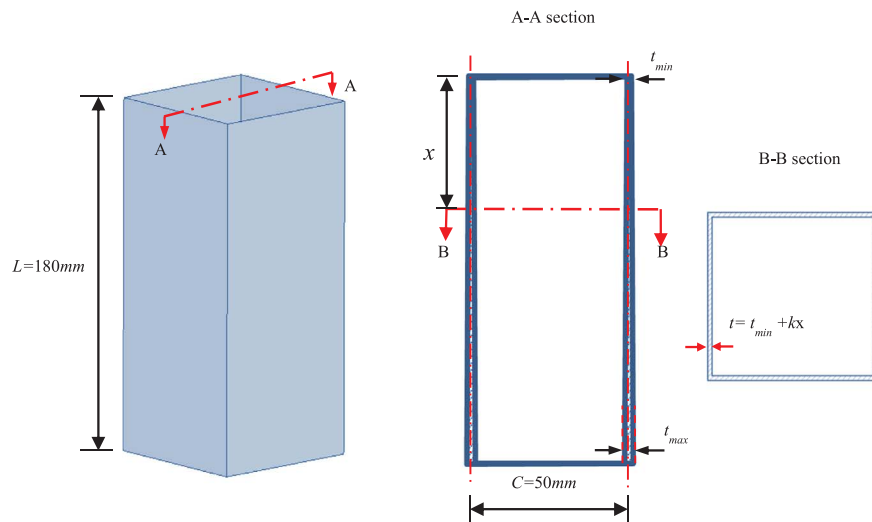
Over the past decades, thin-walled structures are widely used as energy absorbers in automobile industries and their crashworthiness has been investigated systematically and comprehensively through theoretical, experimental and numerical methods [1–6]. By undergoing large plastic deformation during collision, the energy absorbers dissipate substantial kinetic energy and therefore provide protection to the occupants. The cross-sections of traditional energy absorbers are mainly of circular or square/rectangular shape, thus, many early research efforts have been made to understand the collapse behavior of circular and square/rectangular tubes under static or dynamic axial loading. For example, Wierzbicki and Abramowicz [1] firstly proposed the super folding element method to study the crushing behavior of square tubes theoretically. Later, the theoretical predictions for static and dynamic progressive buckling of circular and square tubes were developed and validated with experiments by Abramowicz and Jones [2,7,8]. When the thin-walled structures are subjected to axial loading, a large undesirable initial peak force first generates, followed by fluctuation under lower level in the force-deformation response till densification [9,10]. The collapse mode of a square tube under axial crushing can be

divided into two main deformation modes, in which one is extensional mode and another is in-extensional mode. The design requirement for such device is usually to achieve high energy absorption while keeping the reaction force low enough to minimize the injury and damage to people and goods [11,12].

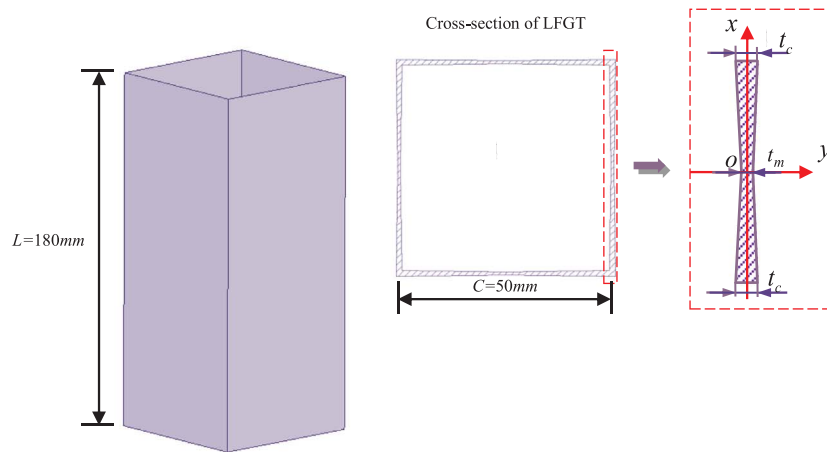
In reality, more and more concerns have been paid on both the crashworthiness and lightweight of the vehicles. Due to rapid increases in vehicle production, fuel consumption and environmental preservation have been increasing concern problems to push on the lightweight of vehicular structures. The statistics states that the 10% reduction of vehicle weight would lead to around 6–8% decrease in fuel consumption [13]. Thus, it is highly desirable to design lightweight structures without sacrificing crashworthiness. It is known that the vehicular structures are largely composed of thin-walled structural devices, which are typically made by forming process of traditional metal sheets with uniform thickness and single material. However, a uniform wall thickness does not necessarily make best use of material to absorb energy [14]. In other words, the structures with uniform wall thickness may not be a reasonable design to necessarily make best use of material for meeting the requirements of vehicular lightweight and safety [15,16]. Therefore, there is an urgent demand to develop new

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(a) Schematic of the AFGT square tube



(b) Schematic of LFGT square tube

Fig. 1. Thin-walled structures with varying thickness.

structural configurations with different material and/or thickness combinations for maximizing crushing capacities and material utilization.

According to Yang et al. [17], a metal sheet with varying thickness could be a more desirable structure because it not only uses material more efficiently, but also increases design flexibility considerably. For example, the tailored welded blanks (TWB) which consists of laser-welded sheet metals of different thicknesses and materials, provide a flexible combination of component materials and thicknesses, which has been adopted in vehicular floor component [18], B-pillar [19], front-end structure [20], and door inner panels etc. [21,22]. The main shortcoming of those blanks lies in that it consists of discrete thickness sections and may lead to stress concentration in the interfaces. To overcome such defects of TWB, a relatively new rolling process, named tailor rolled blank (TRB), has been developed. In the newly developed TRB process, the rolling gap can be varied, which leads to a continuous thickness variation in the workpiece. Varying sheet thickness can better meet more and more demanding design requirements, thereby enhancing utilization of material and/or thickness comparing with traditional stamping uniform sheets [23,24]. There have been some reports on the crashworthiness of thin-walled structures with tailoring capability [25–28]. Sun et al. [29] proposed a square tube with functionally

graded thickness (FGT) along axial direction and found that the specific energy absorption of FGT square tube is superior to that of its uniform thickness (UT) counterpart. Zhang et al. [30] showed that the square tube with graded thickness along lateral direction has an increase of 30–35% in *SEA* compared to the UT tube through experimental and numerical methods. The variation of wall thickness is found to have great influence on both deformation mode and force responses of the tubes [31,32]. The energy absorption characteristics of FGT circular tube under axial crushing loads was also studied and optimized [33,34]. All these works demonstrated that the thin-walled structures with functionally graded thickness can make more efficient use of material to achieve less weight and better crashworthiness.

To make use of thin-walled structures with variable thickness for impact engineering, it is essential to understand the energy absorption mechanics in comparison with those well-studied uniform thickness (UT) thin-walled structures. To the author's best knowledge, however, very limited studies on energy absorption mechanics of FGT thin-walled structures have been performed to date. Previous studies on thin-walled structures with functionally graded thickness were carried out mainly through the numerical and experimental approaches. Theoretical studies on the thin-walled structures under axial crushing loading are limited to those with simple geometric shapes and constant wall

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