Thin-Walled Structures 59 (2012) 103–119

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

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

Crushing analysis and multiobjective crashworthiness optimization of tapered square tubes under oblique impact loading

Chang Qi, Shu Yang *, Fangliang Dong

State Key Laboratory of Structural Analysis for Industrial Equipment School of Automotive Engineering, Dalian University of Technology, B1211 Chuangxinyuan High-rise Building, No. 2 Linggong Road, Ganjingzi District, Dalian 116024, China

ARTICLE INFO

Article history:
Received 9 March 2012
Received in revised form
10 May 2012
Accepted 14 May 2012
Available online 14 June 2012

Keywords:
Tapered tube
Crashworthiness
Energy absorption
Multiobjective optimization
Oblique impact
Load uncertainty

ABSTRACT

In this paper, a class of axisymmetric thin-walled square (ATS) tubes with two types of geometries (straight and tapered) and two kinds of cross-sections (single-cell and multi-cell) are considered as energy absorbing components under oblique impact loading. The crash behavior of the four types of ATS tubes, namely single-cell straight (SCS), single-cell tapered (SCT), multi-cell straight (MCS) and multi-cell tapered (MCT), are first investigated by nonlinear finite element analysis through LS-DYNA. It is found that the MCT tube has the best crashworthiness performance under oblique impact regarding both specific energy absorption (SEA) and peak crushing force (PCF). Sampling designs of the MCT tube are created based on a four-level full factorial design of experiments (DoE) method. Parametric studies are performed using the DoE results to investigate the influences of the geometric parameters on the crash performance of such MCT tubes under oblique impact loading. In addition, multiobjective optimization design (MOD) of the MCT tube is performed by adopting multiobjective particle swarm optimization (MOPSO) algorithm to achieve maximum SEA capacity and minimum PCF with and without considering load angle uncertainty effect. During the MOD process, accurate surrogate models, more specifically, response surface (RS) models of SEA and PCF of the MCT tubes are established to reduce the computational cost of crash simulations by finite element method. It is found that the optimal designs of the MCT tubes are different under different load angles. It is also found that the weighting factors for different load angles are critical in the MOD of the MCT tubes with load angle uncertainty.

1. Introduction

Thin-walled metal tubes have been widely used as energy absorbing devices for decades in trains, passenger cars, ships and other high-volume industrial products since they are relatively cheap and weight efficient. For instance, the crash box of an automotive body in white (BIW) is often made of thin-walled tubes which can absorb the kinetic energy of the vehicle through plastic deformation during an impact event.

Extensive efforts have been made to investigate the crushing behavior of thin-walled tubes through analytical, numerical and experimental methods. Among those, some focused on tubes with various cross-sections including circular [1–3], polygonal (e.g. square, rectangular, etc.) [4–6] and top-hat like [7], while other researchers tried to improve the energy absorption of thin-walled tubes by filling them with different materials including metallic [8–11] and polymer foams [12,13]. Besides that, thin-walled tubes with multiple cells have been shown to have desirable energy absorption with weight efficiency [14,15]. Zhang and Cheng [16] showed through numerical simulations that the energy absorption efficiency of multi-cell (MC) columns was about 50%–100% higher than that of foam-filled columns. More recently, Tang et al. [17] further showed that by introducing more corners into the structure, the energy absorption of thin-walled tubes can be further increased.

All these above-mentioned studies have been focused on the crushing response and energy absorption characteristics of thin-walled structures under pure axial loads. However, in real-world impact event, especially in the context of automobile crashes, the energy absorbers such as the shotguns and side rails rarely experience pure axial or pure bending loads, rather they deform under a combination of axial and off-axis or oblique loads. Such loading causes the thin-walled tube to deform via a combination of both axial progressive and global bending modes. Compared to progressive axial collapse, the global bending deformation of a thin-walled structure is generally unstable with an associated reduction in impact energy absorption. The experimental and numerical analyses on the quasi-static oblique loading behavior

* Corresponding author. Tel./fax: +86 411 84706475.
E-mail address: yangshu@dlut.edu.cn (S. Yang).

0263-8231/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tws.2012.05.008

of both empty [18,19] and foam-filled [20] square aluminum columns were carried by Reyes et al. [20]. The studies showed that the energy absorption drops drastically when a global bending mode is initiated instead of progressive buckling, and it decreases further with increasing load angle. Another numerical investigation on the oblique crush behavior of square thin-walled column made of mild steel showed that there exists a critical load angle at which a transition takes place from the axial progressive collapse mode to the global bending collapse mode while the latter yields a significant reduction in the mean load [21]. In aware of this, increased focus has been given to tapered tubes, namely tapered rectangular and conical tubes, which have been found preferable to straight tubes since they are capable of withstanding oblique impact loads as effectively as axial loads, and appear to have fewer chances to fail via global bending [22]. Despite this, compared to straight tubes, information in the open literature on the oblique loading of tapered thin-walled energy absorbers is limited. Nagel and Thambiratnam [23–25] compared the energy absorption response of straight and tapered thin-walled rectangular tubes subjected to both axial and oblique quasi-static and dynamic impact loading. They showed the tapered tubes have more advantages in applications when oblique impact is inevitable. Ahmad et al. also [26] showed that foam-filled conical tubes appear to be advantageous in impact applications where oblique impact load is expected.

To seek the optimal configurations of empty and foam or honeycomb-filled thin-walled tubes, structural optimization techniques have been applied on the crashworthiness design of such components under either pure axial [27–34] or lateral loads [35,36]. The design objectives in theses crashworthiness optimizations usually include the specific energy absorption (SEA, absorbed energy per unit structural mass) and the peak crushing force (PCF). The SEA should always be maximized to improve energy absorption efficiency, while the PCF should be decreased for the safety of the passengers or goods protected by such structures. To deal with these multiple objectives, more recently, multiobjective optimization design (MOD) method has been employed in the crashworthiness design of tapered circular tubes under axial loads. Acar et al. [37] carried out MOD of tapered circular thin-walled tubes with axisymmetric indentations. The optimum values of the number of axisymmetric indentations, the taper angle and the tube thickness were sought for maximum crush force efficiency (CFE, the ratio of the average crushing load to the PCF), and maximum SEA. Hou et al. [38] optimized the energy absorption characteristic of tapered circular tubes with three different configurations. Moreover, surrogate modeling techniques, such as the response surface method (RSM), are often used in these studies in lieu of nonlinear finite element analysis (FEA) for fast iteration. However, in all these aforementioned optimization studies, only pure axial or lateral loading conditions were considered despite the fact that oblique loadings are much more common in real crash events. In other words, the load angle uncertainty effect has not been systematically considered in the crashworthiness design optimization of such thin-walled structures. To date, crashworthiness optimization of tapered tubes under oblique loading are not available in the literature to the best of authors' knowledge.

In the present study, a new class of tapered square tubes with MC cross-sections is proposed. These tubes are expected to have high energy absorptions efficiency as the MC straight tubes as well as better capability of withstanding oblique impact loading as shown by the tapered tubes. The crushing responses of this type of thin-walled tubes under both axial and oblique impact loading are analyzed using the nonlinear explicit FEA code LS-DYNA [39]. Towards this end, finite element (FE) models validated against theoretical and experimental results in the literature are established. Design information for such tubes as energy absorbers in oblique impact applications are developed through parametric study based on the sampling designs. A four-level full factorial design of experiments (DoE) method is used to determine those sampling design points. Also based on the DoE results, quartic polynomial functions are used to build response surface (RS) surrogate models that relate SEA and PCF to the geometric design variables associated with the MC tapered square tubes under oblique impact loading. Multiobjective particle swarm optimization (MOPSO) algorithm is used as the optimizer for solving the MOD problems both with and without load angle uncertainty.

2. Problem description

2.1. Structures of the crushing analysis under oblique impact loading

The structures considered in this study are tapered axisymmetric thin-walled square (ATS) tubes with single-cell (SC) and multi-cell (MC) cross-section configurations. For simplicity, they are named as SCT (abbreviate of single-cell tapered) tubes and MCT (abbreviate of multi-cell tapered) tubes afterwards, respectively. For comparison purposes, their counterparts of straight tubes are named as SCS and MCS tubes, which stand for single-cell straight and multi-cell straight tubes, respectively. All tubes have the same baseline geometry with length $L=250$ mm, largest cross-sectional side length $A=80$ mm and wall thickness $t=2.0$ mm besides that the tapered tubes have an angle $\theta=5^{\circ}$. This geometry is determined from typical dimensions of the front side rail of a passenger car [15] as well as similar thin-walled structures investigated in the literatures [25,26,37]. The schematic diagram of the computational model is shown in Fig. 1.

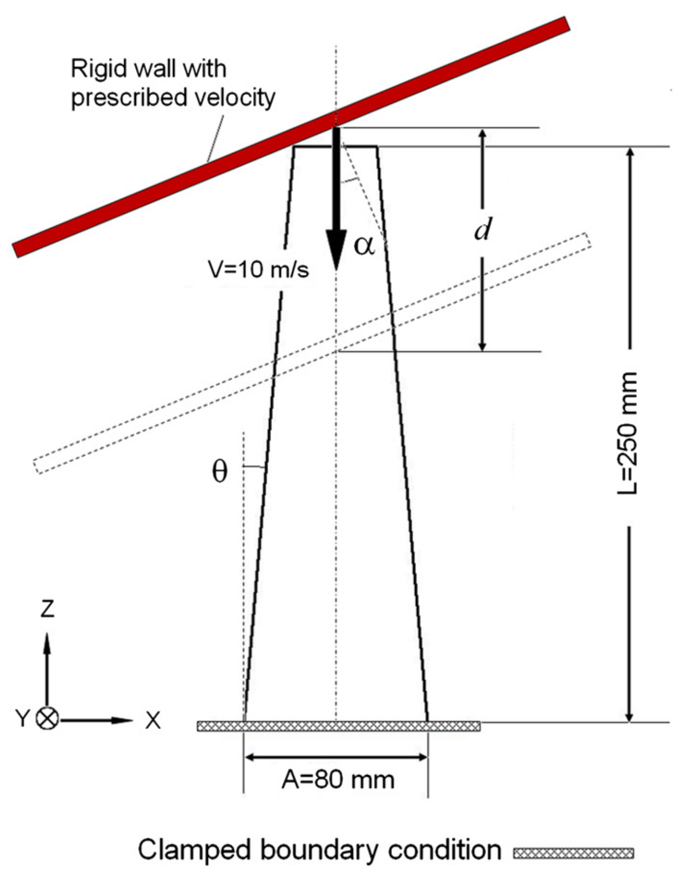

Fig. 1. Tube dimensions and schematic of the computational model.