Thin-Walled Structures 95 (2015) 115–126

Contents lists available at ScienceDirect

Thin-Walled Structures

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

On design of multi-cell tubes under axial and oblique impact loads

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form
16 June 2015
Accepted 2 July 2015
Available online 9 July 2015

Keywords:
Multi-cell tube
Oblique impact
Crashworthiness
Complex proportional assessment
Multiobjective optimization

ABSTRACT

Multi-cell tubes have been drawn increasing attention for their excellent energy-absorbing ability. However, the effect of cell number and oblique loads on crashing behaviors has seldom been studied to date. In this paper, a group of multi-cell tubes with different cell numbers were comprehensively investigated under both axial and oblique loads. The finite element models were first established and then validated by experimental tests. The simulation results showed that the increase in cell number can be beneficial to the energy absorption (*EA*) but detrimental due to increase in peak force (F_{max}) under axial load. When the oblique loads were taken into account, the tubes could undergo global bending, which is an inefficient deformation mode. By applying complex proportional assessment (COPRAS) method, the 7×7 tube was selected as the best based on multi-criteria under multiple loading angles. Then the Kriging modeling technique and multiobjective particle optimization (MOPSO) algorithm were integrated to address the optimization problems, where *EA* and F_{max} were taken as objectives and tube sizes as design variables. The results demonstrated that different loading angles have different requirements on cell allocation and optimizations of multiple load cases (MLC) can yield better solutions in a weighted average fashion, whereas the optimization for separate single load cases (SLC) could result in inferior performance under other load cases.

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1. Introduction

Thin-walled structures such as front longitudinal rails are widely used to dissipate the vehicle's kinetic energy in terms of plastic deformation in case of the frontal collision. To better understand axial crushing behaviors of thin-walled structures, substantial efforts have been made by using analytical, numerical and experimental methods. In this regard, Alexander [1] conducted the pioneering research on the axial crushing for thin cylindrical shells and derived an approximate analytical formulas for average crushing force. Later, substantial experimental and theoretical studies by Wierzbicki and Abramowicz [2], Abramowicz and Jones [3,4] and others were carried on the studies on the axial crushing of square and circular tubes subjected to static and dynamic loads. It is generally known that the number of angular elements (e.g. corner configuration) on a tube's cross-section largely affects the energy absorption and crashing behaviors [2,5]. For this reason, it is expected to design thin-walled tubes with multiple cells and internal webs for achieving better energy-absorbing characteristics. For example, Kim [6] proposed a new multi-cell tube with four square cells at the corners and found that this structure has dramatic improvement in energy absorption over the conventional square box column. Based on the super folding element theory, Zhang et al. [7] derived an analytical solution for the mean crushing force of multi-cell sections, which agrees well with the numerical results. Later, Alavi Nia and Parsapour [8] demonstrated that for a 3×3 cellular tube, adding the partitions at corners can enhance energy absorption and thereby corrected Zhang et al.'s formula of mean crushing load for multi-cell tubes with unequally sized compartment. To maximize the energy absorption and minimize the peak force, Hou et al. [9] used response surface method to perform the design optimizations for single, double, triple and quadruple cell sectional columns. Tang et al. [10] devised a circular multi-cell column and verified its superiority to conventional square structure. Zhang and Zhang [11] studied the quasi-static axial crushing experimentally and analytically for multi-cell stub columns with different sectional configurations.

In automotive engineering, the bumper system requires to endure a load with up to 30° loading angle to the longitudinal axis [12]. Under this condition, thin-walled structures always undergo a combined deformation of bending and axial crushing, rather than pure axial collapse that is designed as an efficient deformation mode for energy absorption. Due to the presence of global

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http://dx.doi.org/10.1016/j.tws.2015.07.002
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bending, the energy absorption of thin-walled structures can be reduced dramatically. For this reason, oblique loading has to be considered in crashworthiness design. For this purpose, Han and Park [13] investigated the crush behavior of a square column subjected to oblique loads and found that the loading angle has considerable effect on deformation pattern from the axial buckling to global bending. Reyes et al. [12,14,15] studied the crashworthiness performance of hollow and foam-filled aluminum tubes under quasi-static oblique loads by using experimental and numerical methods. Zarei and Kröger [16] performed axial and oblique impact tests on empty and aluminum honeycomb filled square tubes and they observed a dramatic decrease in the first peak load during the oblique impact test. Tarlochan et al. [17] proposed a design process for the thin-walled structure subjected to both axial and oblique loads and they found that the hexagonal profile was a better choice for energy absorption application. Yang and Qi [18] developed an optimization procedure for design of the empty and foam-filled square columns under oblique loading and the results showed that compared with the foam-filled tubes, the empty column can behave better under oblique impact but worse under pure axial loading. And they also investigated the crashworthiness and lightweight design for conical tubes under oblique impact [19]. To the author's best knowledge, there have been very limited studies on multi-cell tubes by taking into account the oblique loads so far. Qi et al. [20] employed LS-DYNA to predict the crashing behaviors of four tubes with different cellular configurations under oblique loads, and they found that multi-cell tapered tube has the best crashworthiness performance. Song and Guo [21] found that the effectiveness of multi-cell configuration for improving tubes' energy absorption reduces as the load angle increases, and multi-cell tubes can even have worse performance if they collapse in global bending mode.

From the abovementioned studies, it is known that comprehensive comparison of the crashworthiness of multi-cell structures with different cell numbers remains under-studied thus far. Furthermore, how does the cell number affect the crashworthiness under oblique loads? How to select a multi-cell tube for optimizing its crashworthiness when both oblique and axial loads are presented? This study aims to address these issues. The remainder of this paper will be organized as follows. Section 2 introduces the finite element modeling of multi-cell tubes and its experimental validation. Section 3 describes complex proportional assessment theory. Section 4 studies the crashworthiness of multi-cells under oblique loads. Section 5 conducts multiobjective optimizations, followed by the conclusions in Section 6.

2. Numerical modeling

2.1. Finite element (FE) model

As shown in Fig. 1, the structures to be analyzed here comprise a group of thin-wall multi-cell square tubes with the same axial length of $L=200$ mm and the same width of $b=75$ mm subjected to oblique impact loading. These square tubes have different cell numbers (i.e., $N\times N=1\times 1$, 2×2, 3×3, …, 10×10), and are assigned different thicknesses in order to investigate these tubes with the same mass (Fig. 1). As shown in Fig. 2, a rigid wall with a mass of 600 kg and an incident angle θ impacts on the top end of the tubes at an initial velocity of $v=15$ m/s. the bottom ends of the tube is attached to the fixed rigid ground.

In this study, the numerical models were developed using explicit non-linear finite element code LS-DYNA. The Belytschko-Lin-Tsay reduced integration shell elements with five integration points through the thickness were employed to model the tubes. Stiffness-based hourglass control was employed to avoid spurious zero energy deformation modes and reduced integration was used to avoid volumetric locking. The interfaces between the tube and rigid wall and between the tube and rigid ground were both modeled as an "automatic node to surface". "Automatic single surface" contact was also prescribed to the tube to avoid interpenetration during tube folding. For both static and dynamic friction, the friction coefficient of 0.2 was adopted for all contact conditions [10,22,23].

The tube was modeled through a piecewise linear elastic-plastic behavior with strain hardening (material model 24 in LS-DYNA). The thin wall material was aluminum alloy AA6063-O with the density = 2700 kg/m^3, Poisson's ratio = 0.3, and Young's modulus = 70 GPa, initial yield stress = 46.5 MPa and ultimate stress = 103 MPa. The material model was considered insensitive

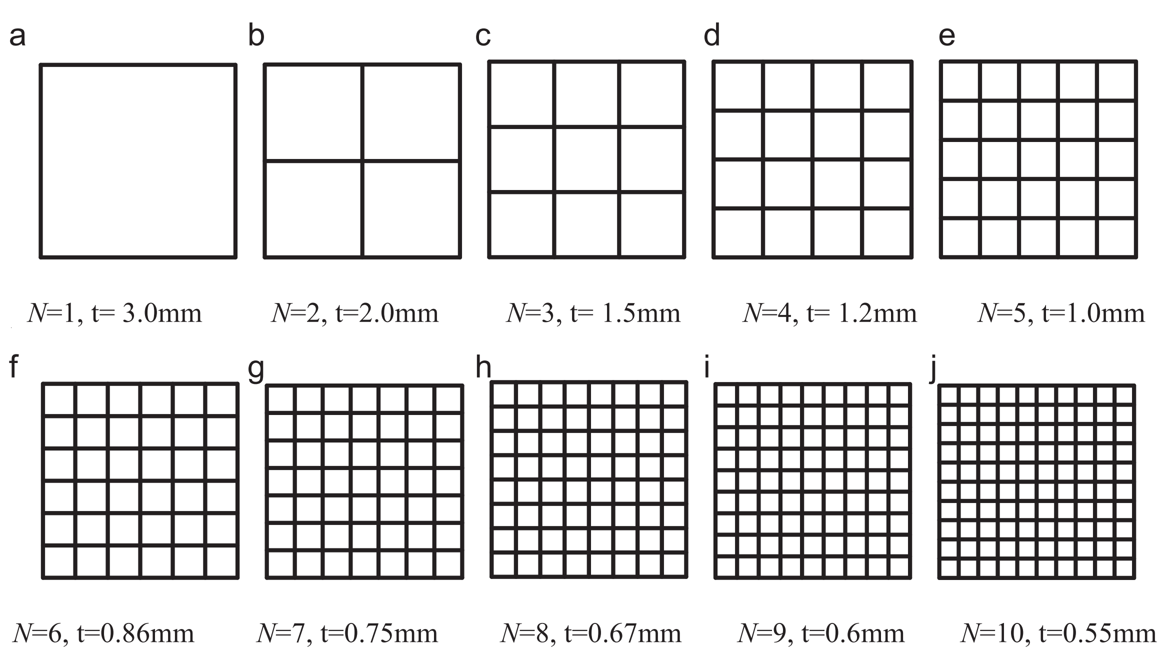

Fig. 1. Cross-sections of multi-cell tubes with the same mass but different wall thicknesses.

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