Thin-Walled Structures 87 (2015) 1–11

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Optimization of foam-filled double circular tubes under axial and oblique impact loading conditions

F. Djamaluddin, S. Abdullah *, A.K. Ariffin, Z.M. Nopiah

Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form
9 October 2014
Accepted 30 October 2014

Keywords:
Aluminium foam
Crashworthiness
Cylindrical tube
Optimization
Oblique impact

ABSTRACT

This paper presents the multi objective optimization of foam-filled tubular tubes under pure axial and oblique impact loadings. In this work, the double circular tubes, whose bottom is the boundary condition, while at the top, is the impacted rigid wall; with respect to the axis of the tubes. The optimal crash parameter solutions, namely the minimum peak crushing force and the maximum specific energy absorption, are constructed by the Non-dominated Sorting Genetic Algorithm-II and the Radial Basis Function. Different configurations of structures, such as empty empty double tube (EET), foam filled empty double tube (FET), and foam filled foam filled double tube (FFT), are identified for their crashworthiness performance indicators. The results show that the optimal foam filled foam filled tube (FFT) had better crashworthiness than the others under pure axial loading. However, the foam filled empty tube (FET) was the best choice for structures under an oblique loading.

1. Introduction

One aim of the automotive industry is to increase the crashworthiness capability of structures and decrease weight for save fuel. Finding new materials and designs plays a major role in achieving this target. Simulated testing was chosen over physical testing due to cost. To improve the energy absorption of a material, thin-walled behaviour, which considered the parameters of geometry, size, cross-section, and loading conditions of the tubes, was studied [1,2]. The energy absorption behaviour of thin-walled circular tubes under axial impact has been studied by several scholars [1–5]. The dynamic instability of different cross-sections, such as circular and square tubes, subjected to axial impact loading, was reported in a book authored by Jones [2]. However, the progressive buckling, inversion, and splitting of circular tubes were previously discussed by [3]. Furthermore, Alghamdi et al. [4] studied the different structure's collapsibility as energy absorbers, namely circular and square tubes. Without increasing volume and weight too much, to improve the crashworthiness capability of thin-walled tubes, some researchers [6–11] used cellular materials, namely foams and honeycombs. The energy absorption capability of empty filled foam circular tubes, using a double-cell profile, was studied by Seitzberger et al. [12,13] and Nurick et al. [14].

In a real-world vehicle collapse event, thin-walled tubes work, not only with pure axial or pure bending loads, but also with a combination of axial and oblique loadings; particularly in a bumper system. The energy absorption capabilities of thin-walled tubes reduce more under a combination of axial and oblique impacts, compared to pure axial loads. The crush behaviour of mild steel square columns was analysed by Han and Park [15], indicating that from the axial to the bending collapse mode, there was a critical load angle at the transition place. Reyes et al. [16–19] studied square aluminium extrusion response, square tubes with and without foam, and circular tubes subjected to oblique loading, and obtained both experiment and simulation results. In addition, Li et al. [20] carried out deformation and energy absorption testing, using the experiment results for aluminium foam circular tubes, subjected to an oblique quasi-static loading. For tapered thin-walled rectangular tubes, Nagel and Thambiratnam [21–23] showed that this structure had more advantages than straight tubes under an oblique impact. In other types of structure, Ahmad et al. [24] also investigated the benefits of using foam-filled conical tubes under an oblique impact. Meanwhile, double circular tubes under axial and bending conditions using experimental and numerical testing were investigated by Guo et al. [25–28]. All gave good promising findings towards the development of crashworthiness properties.

* Corresponding author. Tel.: +60 3 89118411; fax: +60 3 89259659.
E-mail addresses: fauzan@siswa.ukm.edu.my (F. Djamaluddin), shahrum@eng.ukm.my (S. Abdullah), kamal@eng.ukm.my (A.K. Ariffin), zmn@eng.ukm.my (Z.M. Nopiah).

http://dx.doi.org/10.1016/j.tws.2014.10.015
0263-8231/

In recent years, concerns have increased on the optimization techniques applied to structural designs; especially to optimize the configurations of foam or cellular material filled thin-walled columns and tubes. For instance, maximizing energy absorption and minimizing the weight of foam filled [29,30] and honeycomb [31] under axial loads was investigated by Zarei and Kröger. In addition, multi objective optimization was used [32] to maximize specific energy absorption (SEA) and minimize the Peak Crushing Force (PCF) of honeycomb filled single and bitubular polygonal tubes. Aluminium foam filled-filled monotubal and bitubal thin walled square columns were optimized [33,34] using multi objective optimization. The results showed the foam-filled bitubal configuration to have more energy absorption efficiently than empty and its aluminium foam filler. Acar et al. [35] identified the maximum Crush Force Efficiency (CFE) and maximum SEA of tapered circular thin-walled tubes using multi objective crashworthiness optimization. The crashworthiness designs of empty and foam filled thin-walled square columns under an oblique impact loading were performed and indicated better outcomes [36]. Different mathematical programming was used to seek optimal solutions, such as genetic algorithms (GA) [37,33]. Sun et al. [38,39] used Particle Swarm Optimization (PSO) to optimize, with a two stage multi fidelity method for honeycomb, and optimized the crashworthiness design of Functionally Grade Foam (FGF) structures using Multi Objective Particle Swarm Optimization (MOPSO).

For all of the above mentioned studies, there was a limited concern about the foam-filled configuration of the double circular tube; particularly under different loading conditions. Furthermore, because of their good capability in energy absorption, these structures should be explored more, in order to gain an optimal design [20,28]. The aim of this current study paper is to optimize the crashing behaviour of double circular tubes under pure axial and oblique impact loadings using three different tubes, namely empty-empty double tube (EET), Foam-filled Empty Tube (FET), and Foam-Filled double Tube (FFT). In the design's problems, crashworthiness criteria i.e., SEA and PCF, were considered as design variables, such as diameter of cross-section, thickness, material, yield stress of wall, and the foam density. This work used s Non-dominated Sorting Genetic Algorithm (NSGA-II), due to the effectiveness of the crashworthiness design [40,41], to compare the optimal crashworthiness of the structures.

2. Materials and methods

2.1. Crashworthiness indicator of double tubes under axial and oblique impact loadings

To evaluate the energy-absorbance of structures, it is necessary to define the crashworthiness indicators. The parameters for instance Energy Absorption (EA), SEA, and PCF can efficiently evaluate the crashworthiness of structures. Energy absorption can be calculated as:

$$\mathrm{EA} = \int_0^{\delta} F(\delta) d\delta \tag{1}$$

where $F(\delta)$ is the instantaneous crashing force with a function of the displacement δ.

SEA indicates the absorbed energy (EA_{total}) per unit mass (M_{total}) of a structure as:

$$\mathrm{SEA} = \frac{\mathrm{EA}_{total}}{M_{total}} \tag{2}$$

where M_{total} is the structure's total mass. In this case, a higher value indicates the higher energy absorption efficiency of a material.

The average crush force (F_{avg}) is the response parameter for the energy absorption capability:

$$F_{avg} = \frac{\mathrm{EA}_{total}}{\delta} \tag{3}$$

where energy is absorbed (EA_{total}) during collapse and displacement (δ).

Crush force efficiency is defined as the ratio of the average crush force (F_{agv}) to the peak crush force (F_{max}),

$$\mathrm{CFE} = \frac{F_{avg}}{F_{max}} \tag{4}$$

Peak Crushing Force (PCF) is another important indicator in the design of energy absorption structures to absorb the impact energy in collision. When impact occurs i.e., automotive, PCF is able to determine the occupant's survival rate; therefore, several occupants injuries or even death [40] are caused by a large PCF.

2.2. Finite element models of the structures

Fig. 1 shows the schematic of the tubes under different impact loadings in particular axial (0°) and oblique (30°) impacts. The highest loading in mean force occurred at 30° without major reduction; this value was therefore chosen in the oblique impact [32,42,43]. To model energy absorbing structures, aluminium foam filled double tubes of length $L = 250$ mm [32,34] were used to simulate the bumper beam of a passenger vehicle. Moreover, a stroke efficiency of 0.5 (as described by Chen et al. [44]) for all tubes was assumed at a maximum crash distance of 125 mm.

A rigid wall impacted the top of the tubes at an initial velocity of $v = 15$ m/s. This speed was obtained from the New Car Assessment Program (NCAP). The rigid body was modelled as a mass block. All translational and rotational degrees of freedom were fixed and only translational displacement was allowed to move. Futhermore, the mass block of 110 kg was attached to the top free end. The bumper beam was assumed to absorb a kinetic energy of

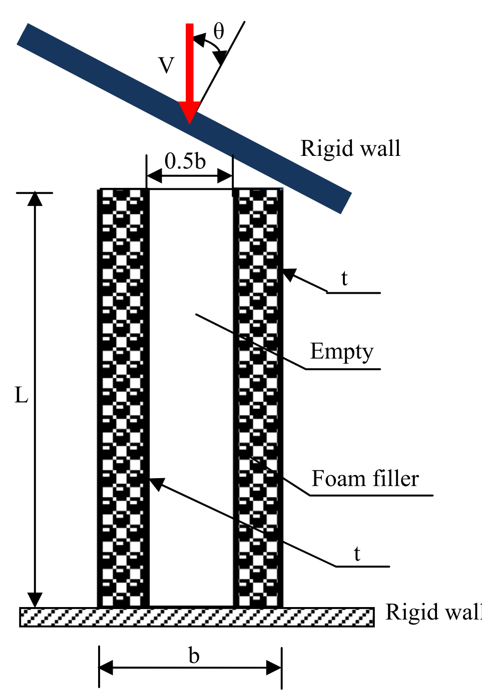

Fig. 1. Schematic of double circular tubes.