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Crushing analysis of foam-filled single and bitubal polygonal thin-walled tubes

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ABSTRACT

Foam-filled thin-walled structures have drawn considerable attention and been widely applied in automotive and aerospace industries for their significant advantages in high energy absorption and light weight. This paper aims to compare the energy absorption characteristics of foam-filled single and bitubal polygonal tubes with different cross-sectional configurations under different axial crushing load conditions. The coupled finite element method (FEM) and element free Galerkin method (EFGM) are applied in modeling the foam-filled tubes for their interaction associated with large deformation, failure and damage. By the complex proportional assessment (COPRAS) technique – the multicriteria decision-making method, the comparisons of energy absorption characteristics of the considered single and bitubal polygonal tubes are conducted herein, respectively. The results show that the foam-filled circular bitubal column has outstanding energy absorption characteristics under all the conditions considered. It is found that the mean crushing force and energy absorbed generally increase with the increase in the edge number of foam-filled bitubal columns. The multiobjective optimization of foam-filled circular bitubal tube is finally conducted by using Non-dominated Sorting Genetic Algorithm (NSGA-II) for the maximization of specific energy absorption (SEA) and the minimization of peak crushing force (PCF).
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1. Introduction

Thin-walled structures have been widely used as energy absorbers in crashworthiness applications such as automotive and aeronautical industries to protect passengers from severe injury for their excellent energy absorption capacity and lightweight. The early investigation of energy absorbers concentrated on steel columns for their low costs and high ductility [1]. As the increasing importance of lightweight, the use of aluminum columns has become more and more predominant in the recent years [2]. To better understand crashing behaviors of aluminum columns, comprehensive studies have been conducted using theoretical, numerical and experimental methods. In this regard, Alexander [3] first derived an analytical solution to calculation of the axial mean crushing force of circular tubes, and then Wierzbicki and Abramowicz [4] proposed the close-form formulas to predict the axial crush response of aluminum thin-walled tubes under both static and dynamic loading conditions. The theoretical predictions were validated experimentally by Abramowicz and Jones [5,6] and Langseth and Hopperstad [7]. Zhang derived a theoretical solution for the mean crushing force of square multi-cell tubes based on the super folding element theory [8].

The impacting structures are expected to absorb maximum energy with minimum mass. To achieve lightweight design, cellular materials such as aluminum foams have exhibited superior capability of absorbing impact energy as they can undergo large deformation at nearly constant load. Generally, aluminum foam can offer a distinct plateau of almost constant stress up to nominal strain values of 70–80% [1]. From this perspective, aluminum foam is often taken as an ideal energy absorber. However, the strength of aluminum foam itself is relatively low, thus the amount of energy absorption is very limited when the aluminum foam is used alone. The shortcoming mentioned above limited the applications of aluminum foam to some extent. Though aluminum foam is not suggested to use alone for energy absorber, they can be taken as a filler material of thin-walled structures. Ahmad and Thambiratnam [9] pointed out that the presence of the foam-filler materials in thin-walled structure helps improve crushing stability and collapse mode of a structure, thereby increasing overall crashworthiness. In this regard, substantial effort has been devoted on the effect of foam-filler on the energy absorption characteristics. For example, Reid et al. [10] performed a comprehensive experimental study on the crashing behaviors of square foam-filled tubes under quasi-static and dynamic loadings. They found that the interaction between foam and inner skin of tube wall plays an important role in the process of structural crashing. Kavi et al. [11] investigated the energy absorption of a foam-filled thin-walled circular tube experimentally, from which it was found that foam filler

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changes the deformation of tube from diamond mode to concertina mode by varying the foam type and density. Quasi-static tests and non-linear dynamic finite element (FE) analyses were used to investigate the crash behavior of the empty and foam-filled end-capped conical tubes by Ghamarian et al. [12]. Abramowicz and Wierzbicki [13] developed a theoretical model to predict the progressive folding of foam filled prismatic columns. Hanssen et al. [14] presented the close-form formulas to predict the responses of foam filled aluminum tubes under both quasi-static and dynamic loading conditions. Their study showed that the total absorbing energy of foam-filled tube exceeds that of the sum of empty column and foam absorbed lonely attributable to the interaction effect. Mirfendereski et al. [15] used the finite element method to simulate the behavior of foam-filled tapered tubes under quasi-static and dynamic loadings. Aktay et al. [16] adopted PAM-CRASH to analyze the quasi-static crushing responses of foam-filled tubes. Zhang and Cheng [17] used nonlinear FE code LS-DYNA to conduct a comparative study on energy absorption between foam-filled square tubes and multi-cell square tubes. Gedikli [18] used both FE and smooth particle hydrodynamics methods to investigate the crashworthiness of empty and foam-filled tailor welded tubes.

Although foam-filled thin-walled columns can enhance the energy absorption, the energy absorption was found to be highly dependent on the foam density and tube geometry [19]. To further improve the energy absorption capability of foam-filled thin-walled structures, optimization techniques have been widely adopted in recent years. For example, Zarei and Kroger [20] combined multi-criteria design optimization (MDO) technique with the response surface method (RSM) to maximize the energy absorption and minimize the weight of foam-filled aluminum tubes. Hou et al. [21] optimized the foam-filled square tube using single and multiple crashworthiness criteria. Sun et al. [19] integrated particle swarm optimization (PSO) with surrogate models to conduct a crashworthiness optimization for functionally graded foam (FGF) filled column, which showed that the FGF structures provide a better crashworthiness performance than the uniform counterpart with the same mass. Later, Yin et al. [22] also conducted a similar investigation. The investigation mentioned above mainly focus on the single tube. Actually, the bitubal tubes could be superior to the single tubes in crashworthiness [1]. Thus the crashworthiness of bitubal tubes haves been recently gaining increasing attention. In this regards, Zhang et al. [23] conducted optimum design for energy absorption of bitubal hexagonal tubes with honeycomb core. Zhang et al. [24] used the genetic algorithm to optimize the crashworthiness of foam-filled bitubal square tube. While the foam-filled bitubal tubes could significantly improve the crashworthiness, the present studies largely limit to the foam-filled thin-walled structures with a single cross-sectional configuration under single loading. Li et al. [25] investigated the energy absorption of foam-filled single and bitubal tubes under oblique loading with different loading angles. It is shown that the energy absorption capacity of foam-filled double tubes is better than that of the empty and the foam-filled single tubes. To author's best knowledge, there are few reports available to comprehensively compare the crashworthiness of foam-filled structures with different cross-sectional configurations under different impacting velocities.

This paper aims at first investigating the energy absorption characteristics of foam-filled single and bitubal polygonal tubes with eight different cross-sectional configurations under three axial crushing load velocities by using LS-DYNA. The weights of crashworthiness characteristics of these tubes are assigned in a multicriteria decision-making procedure. Then a comprehensive evaluation on crashing behaviors of these tubes is conducted to select the most efficient one from these different configurations. The results indicated that the foam-filled bitubal tube is of excellent energy absorption characteristics of these considered cases. Finally, the foam-filled bitubal tube is optimized to achieve maximum specific energy absorption (SEA) and minimum peak crushing force (PCF), in which the foam density and wall thickness of tube are taken as design parameters. Through the multiobjective optimization, the Pareto fronts for the two conflicting objectives (SEA and PCF) are obtained, which provided us with a set of design schemes in line with different requirements.

The rest of the paper is organized as follows. Section 2 describes the FE modeling method of foam-filled thin-walled structure. Section 3 provides the FEA results and discussion. Section 4 conducts the multiobjective optimization for foam-filled bitubal tube and finally, and Section 5 draws some conclusions.

2. Finite element modeling

2.1. Crashworthiness criteria

There have been different indicators available to evaluate the crush characteristics and energy absorption of different structures [26,27]. Of these indicators, energy absorption (EA), specific energy absorption (SEA), mean crushing force (MCF), the peak force (PCF) (Fig. 1), the crash load efficiency (CLE) are commonly used. Taking an axial collision as an example, the energy absorption is determined by integration the crashing force with respect to displacement x as

$$\mathrm{E}(d) = \int_0^d \mathrm{F}(x)\, dx \tag{1}$$

where d denotes deformation distance and F is the axial impact force. As shown in the force–displacement curve in Fig. 1. The mean crushing force (MCF) for a given deformation d can be expressed as

$$\mathrm{MCF}(d) = \frac{\mathrm{E}(d)}{d} \tag{2}$$

The specific energy absorption (SEA) is a critical criterion to measure energy absorption capability of different materials and weights, defined by

$$\mathrm{SEA} = \frac{\mathrm{E}_{total}}{\mathrm{M}} \tag{3}$$

Obviously, the higher the SEA, the better the capacity of energy absorption.

The crash load efficiency (CLE) can be defined as the ratio of the mean crushing force to the peak crushing force

$$\mathrm{CLE} = \frac{\mathrm{MCF}}{\mathrm{PCF}} \tag{4}$$

where PCF represents the peak crushing force (see in Fig. 1). As an energy absorber, the structure with high CLE is preferred [26].

2.2. Geometrical description

A group of regular polygonal tubes with different cross-sectional configurations from triangle to nonagon, seen in Fig. 2, are considered here to investigate their crashworthiness with foam-filled single tubes. The diameter of circumscribed circle D is kept as a constant of 80 mm, and the length is 200 mm. The geometry is determined from typical dimensions of the front side rail of a passenger car [2]. When the number of the side walls increases, the shape of regular polygonal tube gradually approaches a circular tube. In addition, we also consider the foam-filled bitubal tubes. For the bitubal polygonal tubes, the circumcircle diameter of the inner tube (D_i) is taken as half of the outer tube's (D_o), and the wall thickness of the inner tube is the same as the outer tube (Fig. 2c).

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