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Crashworthiness design of functionally graded foam-filled multi-cell thin-walled structures

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ABSTRACT

Foam-filled thin-walled structure has recently gained attention due to its excellent crashworthiness. Based on the previous study, a new kind of foam-filled thin-walled structure called as functionally graded foam-filled thin-walled structure has more excellent crashworthiness than the traditional uniform foam-filled thin-walled structure. Moreover, as far as we know multi-cell thin-walled structure has more excellent crashworthiness than the traditional single-cell thin-walled structure. As an integrator of the above two kinds of excellent thin-walled structures, functionally graded foam-filled multi-cell thin-walled structure (FGFMTS) may has extremely excellent crashworthiness. Based on our study, the crashworthiness of the FGFMTSs is significantly affected by the design parameter of the graded functional parameter m. Thus, in order to obtain the optimal design parameters, the FGFMTSs with different cross sections and different wall materials are optimized using the multiobjective particle swarm optimization (MOPSO) algorithm to achieve maximum specific energy absorption (SEA) capacity and minimum peak crushing force (PCF). At the same time, the corresponding uniform foam-filled multi-cell thin-walled structures (UFMTS) which have the same weight as these FGFMTSs are also optimized in our study. In the multiobjective design optimization (MDO) process, polynomial functional metamodels of SEA and PCF of FGFMTSs are used to reduce the computational cost of crash simulations by finite element method. The MDO results show that the FGFMTS with PCF in the initial period of its crash not only has better crashworthiness than the traditional UFMTS with the same weight but also performs superior balance of crashing stability. Thus, the optimal design of the FGFMTS with PCF occurring in the initial crash is an extremely excellent energy absorber and can be used in the practical engineering.

1. Introduction

Foam-filled thin-walled structure has been widely used in impact engineering such as automotive, aerospace, military equipment and other industries for its excellent energy absorption and extraordinary light weight [1]. Compared with traditional hollow thin-walled structures, foam-filled thin-walled structures can absorb more impact energy without increasing too much total weight [2]. Recently, a lot of work on studying the energy absorption characteristics of foam-filled thin-walled structures has been carried out by experimental, analytical and numerical methods [2–19]. For instance, Reid et al. [2,3] performed an experimental study on the crushing behavior of squared foam-filled thin-walled structures under quasi-static and dynamic loadings. Hanssen et al. [6,7] presented the close-form formulas for predicting the crushing strength of aluminum foam-filled thin-walled tubes under both quasi-static and dynamic axial loading conditions. Shahbeyk et al. [18] investigated the effect of aluminum foam filler on the axial crushing resistances of a square column by numerical simulation. According to the results reported, it can be found that the energy absorption of a foam-filled thin-walled structure is larger than the sum of the energy absorptions of the individual components. This phenomenon is due to an interaction between the foam and the wall of the thin-walled structure during the deformation.

However, the investigations on foam-filled thin-walled structures in the existing literature mainly focus on the uniform density foams. Recently, for some popular foam-filled thin-walled structures, the uniform foam (UF) material is considered to be replaced by a new kind of foam filler material called as functionally graded foam (FGF) material. This new foam filler material has a graded density along a certain direction. Sun et al. [20] studied the energy absorption characteristics of FGF-filled square tubes in comparison with the UF-filled square tubes. It is found that the crashworthiness of FGF-filled

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tube is better than that of the corresponding UF-filled tube. In their work, the density of the filled foams of FGF-filled tubes changes along the axial direction of the tube. Yin et al. [21] investigated the energy absorption characteristics of two kinds of functionally lateral graded foam (FLGF) filled square tubes. Their investigation results indicate that FLGF-filled square tube has better energy absorption than UF-filled square tube with the same weight. Attia et al. [22] employed nonlinear finite element code LS-DYNA to investigate the crashworthiness of the FGF-filled square tubes, in which the foam density changes along both the axial and lateral directions of the tubes. The numerical results show relative improvement of 12% in specific energy absorption levels of FGF-filled structures over their uniform density counterparts with the same mass. Based on the above investigations, it is obvious that the crashworthiness of FGF-filled thin-walled structures is better than that of their uniform density counterparts with the same weight. Zhang and Zhang [23] investigated the functionally graded aluminum foam blocks under ball impact by using nonlinear finite element code LS-DYNA. They found that the block with linear decreasing density gradient possessed excellent perform in energy absorption and outperformed blocks with other density distributions.

Additionally, previous work on foam-filled thin-walled structures just concentrates on foam-filled single-cell thin-walled structures. Recently, thin-walled metal extrusions with multiple cells are found to be weight-efficient energy absorption structures and received extensive research interests [24–33]. Zhang and Zhang [24] studied the crashworthiness of multi-cell square tubes with different sections. They found that the multi-cell metal columns are much more efficient in energy absorption than single-cell columns under axial compression. Chen and Wierzbicki [25] investigated the axial crushing behaviors of multi-cell columns using both of analytical and numerical methods. A theoretical solution for the mean crushing force of multi-cell sections was derived, and the solution was shown to compare very well with the numerical predictions. Zhang et al. [26] modified Chen's theoretical formula for the mean crushing force of multi-cell sections. Their analytical solutions show an excellent agreement with the numerical results. Tang et al. [27] implemented numerical simulations for cylindrical multi-cell columns, and they found that cylindrical multi-cell column is more efficient than square column and square multi-cell column in energy absorption. From those investigations, we can found that the energy absorption capacity of the multi-cell thin-walled structure is better than that of the single-cell thin-walled structure. Thus, if the multi-cell thin-walled structure is filled with foam filler especially with FGF filler, its energy absorption characteristics will be greatly improved. Zhang et al. [28] investigated the crushing energy absorption of bitubal hexagonal aluminum columns with honeycomb core under dynamic axial crushing. The investigation results show that the specific energy absorption of bitubal hexagonal columns with honeycomb core is very excellent. Nevertheless, to our best knowledge, there are few research papers that investigate the crashworthiness of FGF-filled multi-cell structures up to now.

In this paper, the FGFMTSs with six kinds of cross sections and two kinds of wall materials under dynamic loading are studied. In order to compare the crashworthiness of these FGFMTSs with that of the corresponding UFMTSs, the UFMTSs with the same weight are also investigated. Based on the previous investigations, the energy absorption of these FGFMTSs will be greatly affected by the design parameter of the graded functional parameter m [20–22]. In order to seek for the optimal designs of FGFMTSs, multiobjective design optimizations (MDO) for the crashworthiness of the FGFMTSs and the corresponding UFMTSs are implemented jointly by using finite element analysis (FEA), metamodels and multiobjective particle swarm optimization (MOPSO) algorithm. The comparison between the Pareto fronts obtained by the MDO can give us which one is better between the FGFMTS and the corresponding UFMTS and can also tell us which kind of FGFMTS performs the best among these studied FGFMTSs with different cross sections. The optimal designs of FGFMTSs can be used as excellent energy absorbers in practical engineering.

2. Structures and crashworthiness indicators

2.1. Structures description

The structure considered in this paper is called as functionally graded foam-filled multi-cell thin-walled structure (FGFMTS), which is actually a multi-cell square tube filled with functionally graded aluminum foam. The length l and the outer width d of the multi-cell square tube are 240 mm and 80 mm, respectively. The wall thickness t of the multi-cell square tube is 2 mm. The FGFMTS impacts onto a rigid wall at an initial velocity of 15 m/s with an additional mass of 3000 kg attached to its end as shown in Fig. 1. This would generate an initial kinetic energy in accordance with the requirements for the front crash of a school bus. In this paper, we study six common multi-cell square tubes with cross-sectional cell number $n=1$, 2, 3, 4, 6 and 9. These multi-cell square tubes are all filled with graded aluminum foams. The sectional configurations of these FGFMTSs are shown in Fig. 2.

2.2. Crashworthiness indicators

In order to evaluate the crashworthiness of the FGFMTS, it is necessary to employ the crashworthiness indicators. As far as we know, energy absorption (EA), mean crushing force (MCF) and specific energy absorption (SEA) are frequently used as the important indicators for evaluating the crashworthiness [34]. The EA of a structure can be calculated as

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

where d is the crushing distance and F denotes the crushing force. The MCF for a given deformation can be expressed as

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

The SEA is defined as the ratio of the absorbed energy to the mass of the structure. So it can be written as [29]

$$\mathrm{SEA}(d) = \frac{\mathrm{EA}(d)}{M}, \tag{3}$$

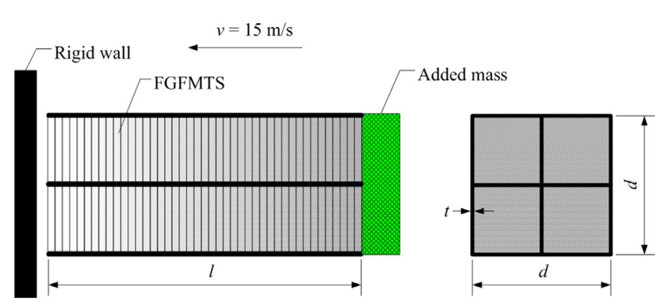

Fig. 1. Geometrical configuration of FGFMTS (here take $n=4$) and its loading condition.

Fig. 2. Different cross-sectional configurations of FGFMTSs.