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Multiobjective crashworthiness optimization design of functionally graded foam-filled tapered tube based on dynamic ensemble metamodel

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ABSTRACT

Foam-filled thin-walled structures have recently gained attention with increasing interest due to their excellent energy absorption capacity. In this study, a new type of foam-filled thin-walled structure called as functionally graded foam-filled tapered tube (FGFTT) is proposed. FGFTT consists of graded density foam and thin-walled tapered tube. In order to investigate the energy absorption characteristics of FGFTTs, the numerical simulations for two kinds of FGFTTs subjected to axial dynamical loading are carried out by nonlinear finite element code LS-DYNA. In addition, a new kind of multiobjective crashworthiness optimization method employing the dynamic ensemble metamodeling method together with the multiobjective particle swarm optimization (MOPSO) algorithm is presented. This new kind of multiobjective crashworthiness optimization method is then used to implement the crashworthiness optimization design of FGFTTs. Meanwhile, the crashworthiness optimization designs of FGFTTs are implemented by using traditional multiobjective crashworthiness optimization method, which employs metamodels such as polynomial response surface (PRS), radial basis function (RBF), kriging (KRG), support vector regression (SVR) or the ensemble with the static design of experiment (DOE). Finally, by comparing the optimal designs of FGFTTs obtained by using the new multiobjective crashworthiness optimization method and the traditional one, the results show that the proposed new crashworthiness optimization method is more feasible.

1. Introduction

Foam-filled thin-walled structure has been widely used in impact engineering such as vehicle crashworthiness for its excellent energy absorption and extraordinary light weight [1]. Thus, a lot of work on studying the energy absorption characteristics of foam-filled thin-walled structures by employing experimental, analytical and numerical methods [2–18] has been extensively investigated. According to the results reported, it can be found that foam-filled thin-walled structures can absorb more dynamic impact energy than the corresponding hollow thin-walled structures. The energy absorption of a foam-filled thin-walled structure is larger than the sum of the energy absorptions of individual filled foam and thin-walled structure. The improvement is due to an interaction between the foam and the thin wall. Among those different kinds of foam-filled thin-walled structures, the foam-filled tapered thin-walled structure has been gradually become a very attractive and newborn subject because it not only has excellent energy absorption capacity but also performs superior balance of crashing stability [19,20].

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 functionally graded foam (FGF) material is considered to replace the uniform foam (UF) material. For instance, Sun et al. [21] 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 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. [22] investigated the energy absorption characteristics of two kinds of functionally lateral graded foam (FLGF) filled square tubes. The investigation results show that FLGF-filled square tube has better energy absorption than UF-filled square tube with the same weight. Attia et al. [23] employed nonlinear finite element code LS-DYNA to

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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 can be found that the crashworthiness of FGF-filled thin-walled structures is usually better than that of their uniform density counterparts. FGF-filled tapered thin-walled structures are likely to be a good alternative energy absorber in vehicle engineering, because UF-filled tapered thin-walled structure performs better crashing stability. However, to our best knowledge, the FGF-filled tapered thin-walled structures had never been presented or investigated before.

Note that for both UF-filled structures and FGF-filled structures, the crashworthiness of foam-filled thin-walled structures is greatly affected by the design parameters such as structural size and foams density. In order to optimize the crashworthiness of foam-filled thin-walled structures, it is essential to develop some design methods to seek for the optimal parameters, see the references in [24–29]. It should be mentioned that some metamodels of optimal objectives were usually used in optimization design processes to reduce the computational cost. The metamodels were established mainly by using static design of experiment (DOE) methods [30,31] together with individual metamodeling methods [20] in these studies. Sun et al. [21] and Yin et al. [22] all established the metamodels of SEA and PCF for functionally graded foam (FGF) structures by means of separating the design space. However, it is very troublesome to establish the metamodels by separating the design space [21,22]. The optimal objectives such as specific energy absorption (SEA) and peak crushing force (PCF) of FGF-filled thin-walled structures always perform highly nonlinear characteristics because of the effect of density gradient [21–23]. Thus, it is still hard to establish accurate metamodels for these optimal objectives of FGF-filled thin-walled structures without separating the design space by using a certain number of design points [21,22].

In this paper, the new structure of functionally graded foam-filled tapered tubes (FGFTT) is firstly proposed and investigated by nonlinear finite element analysis (FEA) through LS-DYNA. Furthermore, in order to seek for the optimal designs of FGFTT, a new kind of multiobjective crashworthiness optimization method by jointly using the dynamic DOE method [32–35], the ensemble metamodeling method [36–38] and the multiobjective particle swarm optimization (MOPSO) algorithm is presented. In the optimization process of this new method, the accurate metamodels called as dynamic ensemble metamodel for the optimal objectives of FGFTTs are first established without separating the design space. Then, FGFTTs are optimized by employing the MOPSO algorithm to achieve maximum SEA and minimum PCF with the dynamic ensemble metamodels. After that, the Pareto fronts for the conflicting objectives SEA and PCF are obtained. From the Pareto fronts, we can obtain a series of optimal designs of FGFTTs which can satisfy different practical design conditions for crashworthiness.

2. Structural crashworthiness indicators

In order to study the crashworthiness of energy absorbed structures, it is essential to define the crashworthiness indicators. There are many different indicators available to evaluate the energy absorption capabilities of different structures [39]. Among these indicators, specific energy absorption (SEA) is usually used to estimate the energy absorption capacity of absorbers. SEA is defined as the ratio of the absorbed energy to the mass of the structure and it can be formulated as [40]:

$$\mathrm{SEA}(d) = \frac{\mathrm{EA}(d)}{M}, \tag{1}$$

where d is the axial crushing distance. M is the total mass of the structure and EA is total absorbed energy during crushing, which can be calculated as:

$$\mathrm{EA}(d) = \int_0^d F(x)\mathrm{d}x, \tag{2}$$

where F denotes the axial crushing force. Obviously, the higher the SEA, the better the energy absorption capacity of a structure.

In the design of energy absorption structures which is used to absorb the impact energy in collision, another important indicator is the peak crushing force (PCF) of the energy absorption structure. Taking the vehicle crashworthiness as example, the PCF of the absorber may determine the occupant survival rate when impact occurs. A large PCF often leads to a high deceleration and may cause severe injury or even death of occupant [41]. The axial crushing force–displacement curve of a typical foam-filled tapered structure is shown in Fig. 1 [20]. As shown in Fig. 1, the PCF occurs in the end of the curve, which is different from that of the hollow thin-walled structure. The Peak crushing forces of typical hollow thin-walled structure and foam-filled tapered thin-walled structure are respectively marked as the red solid circle 1 and 2 in Fig. 1, when the crushing distances at the left side of the dashed line are considered.

3. Finite element modeling of FGFTT

3.1. Finite element model

The geometrical configuration of the FGFTT considered in our study is shown in Fig. 2, which is actually a tapered cylinder tube filled with functionally graded aluminum foam. In our study, some structure parameters of a FGTT are fixed to illustrate the analysis process. The radius R_1 of the top circle and the radius R_2 of the bottom circle of the tapered cylinder tube are fixed as 40 mm and 60 mm, respectively. The thickness t and the length L of the tube are 2 mm and 240 mm, respectively. The geometry of the tube is determined from the dimensions of a typical lower rail of a passenger car [40]. In order to simulate the front crash of a passenger car, the functionally graded foam-filled tapered tube (FGFTT) impacts onto a rigid wall at an initial velocity of 15 m/s with an additional mass of 600 kg attached to its bottom end in our study as shown in Fig. 2.

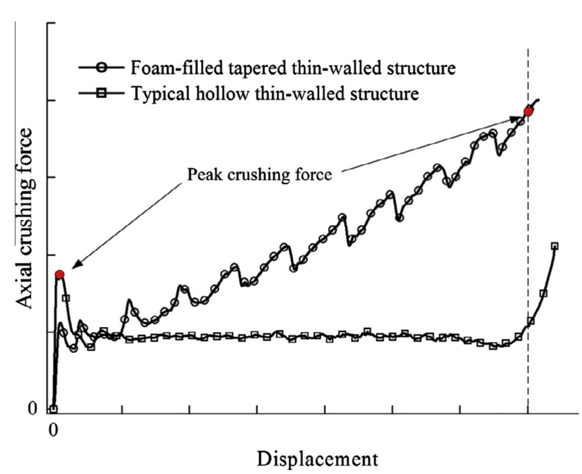

Fig. 1. Axial crushing force–displacement curves of energy absorbed structures.