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Parametric analysis and multiobjective optimization for functionally graded foam-filled thin-wall tube under lateral impact

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ABSTRACT

Foam-filled thin-walled tubes have proven an ideal energy absorber in automotive industry for its extraordinary energy-absorbing ability and lightweight potential. Unlike existing uniform foam (UF), this paper introduces functionally graded foam (FGF) to fill into the thin-walled structure subjected to lateral impact loading, where different configurations of foam grading (axial FGF and two transverse FGFs) are considered. To systematically investigate the bending behavior of this novel structure, numerical model is established using nonlinear finite element analysis code LS-DYNA and then is validated against the experiment. Through parametric study, it is found that the FGF tube absorbs more energy but may produce larger force than the UF counterpart. In addition, various parameters have a considerable effect on the crashworthiness performance of the FGF filled tube. Finally, multiobjective optimizations of UF and FGF filled columns are conducted, aiming to improve the specific energy absorption (SEA) and reduce the maximum impact force simultaneously, based upon the multiobjective particle optimization (MOPSO) algorithm and Kriging modeling technique. The optimization results show that all the FGF filled tubes can produce better Pareto solutions than the ordinary UF counterpart. Furthermore, the axial FGF tube provides better energy absorption characteristics than the two types of transverse FGF tubes.

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1. Introduction

In vehicular systems, bumpers are expected to protect the driver and passengers when frontal crash occurs. The collision energy is absorbed by the bumpers subjected to bending condition. Likewise, side door beams or B-pillars are required to provide enough load-carrying capacity in the event of side impact. Therefore, it is of significance to investigate the bending behavior of thin-walled structures under lateral impact. Recently, cellular materials, especially metallic foams have aroused increasing attention for their extraordinary energy absorption capacity and lightweight potential in automotive industry. Inclusion of lightweight foam-fillers into thin-walled sections has proven an effective way to help increase the load-carry capacity and energy absorption. In this regard, several studies have been conducted on bending behavior of foam-filled thin-walled structures. For example, Santosa and Wierzbicki [1] explored the effect of ultralight metal fillers on the bending collapse behavior of thin-walled columns and pointed out that filling aluminum honeycomb or foam core is preferable to thickening the column wall in order to enhance the energy-absorbing efficiency. Chen [2] performed numerical simulations and experiments to study the crush behavior of thin-walled columns filled with aluminum foam and found the foam filler is capable of avoiding global failure thereby improving the load carrying capacity. Shahbeyk et al. [3] exploited the effect of various parameters, including spot welding failure, flange location, sheet metal thickness, glue presence and foam filling on the crash performance of empty and foam-filled box-beams. They concluded that aluminum foam filling can significantly change the bending behavior in terms of energy absorption and deformation patterns. Zarei and Kröger [4] applied crashworthiness optimization to maximize the specific energy absorption (*SEA*) of the squared empty and foam-filled columns with the constraint on the energy absorption and the results showed that the filled column can absorb the same energy as the optimal empty column but with a 28.1% lower weight. Guo and Yu [5] studied the dynamic response of foam-filled double cylindrical tubes under three-point bending experimentally and numerically. Compared to the traditional

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foam-filled single tube, this new structure has a steadier load carrying capacity and much higher energy absorption efficiency under bending conditions. Besides, the maximum equivalent plastic strain of this structure increases much slower, which can provide a larger displacement to absorb more energy.

The above-mentioned studies are mainly restricted to uniform foam (UF) filled thin-walled structures. In order to further improve the crashworthiness of foam-filled structures, the functionally graded foam (FGF) material was recently used as an alternative to uniform foam (UF) material. Sun et al. [6] investigated the crash characteristics of FGF columns and first implemented the optimization procedure to seek optimum designs. Nouraei et al. [7] utilized nonlinear finite element code LS-DYNA to explore the crush behavior of FGF-filled columns under axial loading. Yin et al. [8] studied two kinds of functionally lateral graded foam-filled structures and the optimization was also performed to seek the optimal gradient exponential parameter. Most recently, based on dynamic ensemble metamodel, Yin et al. [9] conducted multiobjective crashworthiness optimization for a FGF filled tapered tube in order to simultaneously reduce the peak crushing force (*PCF*) and enhance the *SEA*. To the authors' best knowledge, however, previous studies on FGF-filled thin-walled structures did not take into account the bending behavior under lateral impact, which is a significant crashworthiness performance for thin-walled structures. Moreover, the effect of different grading directions (i.e., transverse and axial) on bending behavior was not investigated and compared in literature.

In this paper, the energy absorption characteristics of FGF filled tubes (including transverse and axial grading directions) under lateral impact loading are investigated by using nonlinear finite element code LS-DYNA. After the validation of finite element model, the effect of various parameters in the foam and wall on the crashworthiness performance is analyzed. Finally, multiobjective optimizations of UF filled tube and different types of FGF filled tubes are performed to simultaneously maximize the *SEA* and minimize the maximum impact force (F_{max}) by combining multiobjective particle optimization (MOPSO) algorithm with Kriging modeling technique.

2. Numerical modeling

2.1. Material modeling

The model selected to represent the material behavior of aluminum foam filler is Deshpande-Fleck foam (Material Model 154) which has been implemented as a user subroutine in LS-DYNA. The model was proposed by Deshpande and Fleck [10], in which the yield criterion of foam material is defined as follows:

$$\Phi = \hat{\sigma} - \sigma_y \leqslant 0 \quad (1)$$

where σ_y is the yield stress and the equivalent stress $\hat{\sigma}$ is given as:

$$\hat{\sigma}^2 = \frac{1}{[1 + (\alpha/3)^2]}[\sigma_e^3 + \alpha^2\sigma_m^2] \quad (2)$$

where σ_e is the von Mises effective stress and σ_m the mean stress. Parameter α controlling the shape of the yield surface is a function of the plastic Poisson's ratio υ_p, given as:

$$\alpha^2 = \frac{9(1 - 2\upsilon_p)}{2(1 + \upsilon_p)} \quad (3)$$

It is easily derived from Eq. (3) that $\alpha = 2.12$ when $\upsilon_p = 0$. The strain hardening rule is implemented in this material model as:

$$\sigma_y = \sigma_p + \gamma\frac{\hat{\varepsilon}}{\varepsilon_D} + \alpha_2 \ln\left[\frac{1}{1 - (\hat{\varepsilon}/\varepsilon_D)^\beta}\right] \quad (4)$$

where $\hat{\varepsilon}$ is equivalent strain, σ_p, α_2, γ, β and ε_D are the material parameters and can be related to the foam density as

$$\begin{cases} \left(\sigma_p, \alpha_2, \gamma, \frac{1}{\beta}, E_p\right) = C_0 + C_1\left(\frac{\rho_f}{\rho_{f0}}\right)^\kappa \\ \varepsilon_D = -\ln\left(\frac{\rho_f}{\rho_{f0}}\right) \end{cases} \quad (5)$$

where ρ_f is the foam density and ρ_{f0} the density of base material. C_0, C_1 and κ are the constants as listed in Table 1. Note that the Young's modulus of foam material E_p is also a function of ρ_f as shown in Eq. (5) [11].

In this study, both axial and transverse FGF materials are considered, where the foam is discretized to several layers and in each layer the density is uniform. Fig. 1 depicts the grading pattern for the axial FGF, whose density changes along the axis and has symmetry about the mid-span plane of the beam. Fig. 2a and b displays the grading patterns for the transverse FGF, where the foam density changes along the height direction of the beam section and is symmetrical about the horizontal mid-plane, and along the two directions of the beam section respectively. The density gradient is determined by the following power-law functions:

$$\rho_f(x, m) = \begin{cases} \rho_{min} + (\rho_{max} - \rho_{min})\left(\frac{x}{L}\right)^m & \text{for an ascending pattern} \\ \rho_{max} - (\rho_{max} - \rho_{min})\left(\frac{x}{L}\right)^m & \text{for a descending pattern} \end{cases} \quad (6)$$

where ρ_{min} and ρ_{max} are the minimum and maximum densities, respectively. x and L represent the distances shown in Figs. 1 and 2. m denotes the gradient exponent parameter that governs the variation of foam density. Fig. 3a and b shows the variation of foam density along the grading direction for ascending and descending pattern respectively. In our case of bending tube to be explained in detail, the beam has a large bending deformation at the contact area with the punch (Fig. 4) whereas other parts undergo a rigid body rotation. Since the strong interaction between the tube wall and FGF has a positive influence on the energy absorption characteristics, the large stiffness of foam is expected at the large deformation area [7]. That is to say, the outermost layer should have the maximum density for transverse FGF and the middle section for the axial FGF in our specific case. Accordingly, the ascending pattern is selected for the axial FGF and the descending pattern for the two types of transverse FGF.

Regarding the material modeling of the tube wall, a bilinear elastic–plastic behavior with strain hardening (material model 24 in LS-DYNA) was adopted. The thin wall material was aluminum alloy AlMg0.5F22 with the following mechanical properties: density $\rho = 2700$ kg/m^3, Poisson's ratio $\nu = 0.29$, Young's modulus $E = 68{,}566$ MPa, initial yielding stress $\sigma_y = 227$ MPa and tangential

Table 1
Material constants for aluminum foam [11,12].

Parameter	σ_p (MPa)	α_2 (MPa)	$1/\beta$	γ (MPa)	E_p (MPa)
C_0 (MPa)	0	0	0.22	0	0
C_1 (MPa)	720	140	320	42	0.33×10^6
κ	2.33	0.45	4.66	1.42	2.45

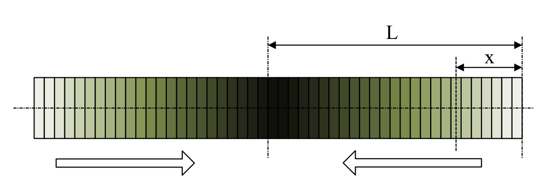

Fig. 1. Schematic showing grading patterns in axial direction.

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