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Design of transversely-graded foam and wall thickness structures for crashworthiness criteria

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ABSTRACT

Foam-filled thin-wall structures have exhibited considerable advantages in energy absorption with light weight and have been widely used as energy absorber in engineering. Unlike existing uniform or mono-gradient structures, this paper introduces a novel dual functionally graded structure with changing both foam density and wall thickness along the transverse direction, namely transverse functionally graded foam-filled and functionally graded wall thickness (FGF-FGT) structures. According to different combinations of gradient directions in foam density and wall thickness, four different patterns are considered here. Based on the established surrogate models, the surface plots of crashworthiness criteria indicate that the combination of gradient patterns and the gradient exponents have significant effect on overall crashing performances. The multiobjective particle swarm optimization (MOPSO) algorithm is then adopted to seek optimal gradients of wall thickness and foam density, aiming to simultaneously improve the specific energy absorption (*SEA*) and reduce the maximum force (F_{max}). The optimization results indicate that the transverse FGF-FGT structures with ascending grading patterns in both FGF and FGT is superior to the uniform counterparts and other graded structures, providing the designer with the promising optima in a Pareto sense.

1. Introduction

Crashworthiness has become a significant topic of research for its close relevance to public safety and socioeconomic benefits. For example, despite the 25 percent decline in fatality due to the motor vehicle crashes from 2004 to 2013, the United States still lost 32,719 lives in crashes on roadways in 2013 [1], averaging around 90 fatalities each day. It was also reported that motor vehicle crashes caused economic cost of 277 billion dollars in the United States alone in 2010 [1], equivalent to nearly 897 dollars for each of 308.7 million people, and 1.9 percent of the 14.96 trillion dollars real Gross Domestic Product (GPD) in 2010. One way to tackle the road safety problem is to design crashworthy structures with better performance for absorbing as much kinematic energy as possible, so that the occupants can be protected from severe injuries and deaths as the energy transmitting from collision is reduced.

Foam materials are often used as lightweight fillers to thin-walled structures. Extensive literature has demonstrated that foam materials are ideal for achieving high energy absorption by improving crushing stability and load-carrying capacity of the structure, thereby increasing the overall crushing performances. In this regard, Hanssen et al. [2] explored the effect of foam-filler on the energy absorption behaviors for circular aluminum extrusions. Borvik et al. [3] found that foam filler is more influential on the mean crush force than on the peak load, which is important when using foam-filled structures as crash components. Song et al. [4] revealed that the foam–wall interaction could make the whole structure perform better than the sum of the empty tube and the foam alone. Rezadoust et al. [5] pointed out that in contrast to empty shells, foam-filled thin wall structures showed a more stable progressive crushing and a reverse trend in energy absorption with the cone angle. Ghamarian et al. [6] compared the energy absorption capabilities of foam-filled and empty conical tubes, and they also found that the energy absorption of the filled tube overtakes

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that of the combined effect of the empty tube and the foam alone under quasi-static loading. Other studies on crashworthiness of foam-filled structures can be widely found in literature, e.g. Refs. [7–9].

Although foam-filler can increase energy absorption in general, it may lower specific energy absorption (*SEA*) with certain mass penalty [10,11]. For this reason, design optimization is required to seek a more appropriate combination of foam material property and geometrical parameters of thin wall. In this regard, Zarei and Kroger [12] implemented multicriteria optimization technique to seek an optimal foam-filled tube, and they showed that the optimal filled tube can absorb the same energy as the optimal empty tube but has around 19% less weight. Hou et al. [13] applied both single and multiobjective optimization methods to optimize the square column with aluminum foam-filler. In their study, the SEA and peak crushing force (PCF) were taken as the design criteria, where the wall thickness and foam density were taken as the design variables. They found that while the two objectives of SEA and PCF strongly compete with each other, the multiobjective design of foam-filled column is more advantageous over the empty counterpart. Bi et al. [14] optimized foam-filled columns with respect to tube geometry and foam density for achieving the maximum SEA while maintaining a certain level of structural rigidity measured by the mean crushing force (MCF). Their optimization showed that the SEA tends to favor slender and thicker columns with a moderate foam density for both single- and triple-cell columns. Note that these abovementioned studies on foam-filled thin-wall structures have largely focused on the uniform wall thickness with uniform foam density.

Recently, functionally gradient structures have drawn extensive attention in research community. In this regard, Bruck [15] firstly investigated the stress wave propagation in gradient structures and pointed out the time delay effect for energy absorption applications. Surendranath et al. [16] optimized gradient configurations and found that the use of gradient parameters would accelerate the optimization process. Fares et al. [17] presented a multiobjective optimization problem to minimize the vibrational responses and maximize the buckling loads of functionally graded plates. To further excavate the energy absorption potential of foam-filled thin-wall structures, a novel foam filler material named functionally graded foam (FGF) material, which involves continuous variation of micro-scale cells in a predefined manner, has been proposed to replace the uniform foam (UF) material [18]. In this regard, Sun et al. [19] first investigated the energy absorption characteristics of FGF-filled square tube in comparison with the UF-filled square tube. It was found that the crashworthiness of FGF-filled tube is overall better than that of the corresponding UF-filled tube within a multiobjective optimization framework. In their work, the density of FGF changes along the axial direction of the tube. Later, Yin et al. [20] and Nouraei [21] extended the density variation of the foam filler from the axial direction to lateral direction of the tube. The optimal results indicated relative improvement of 12% in SEA of FGF-filled structures over the UF-filled counterparts with the same mass. As the UF-filled tapered thin-walled often performs better crashing stability, Yin et al. [22] presented a FGF-filled tapered tube and conducted a multiobjective optimization to simultaneously reduce PCF and enhance SEA. Fang et al. [23] optimized the crashing behaviors of three different FGF-filled thin-walled structures subjected to lateral impact. They successfully applied this novel structure to the design of automotive bumper beam [24]. All these above studies exhibited that the FGF filled structures are generally superior to the uniform counterpart in crashworthiness.

Recently, Sun et al. [25] extended the concept of functionally graded structure to the wall thickness and presented a class of novel functionally graded wall thickness (namely, FGT) structures. The crashworthiness of the FGT structures was examined under axial impact and the effects of the different thickness gradients on both SEA and PCF were evaluated in their work. It was showed that the FGT column is superior to the uniform thickness (UT) counterpart in terms of SAE and peak impact force. The advantages of FGT structures under lateral bending have also been also revealed recently [26,27]. From these abovementioned studies, it is concluded that the crashworthiness of FGF-filled and FGT-walled tube is respectively superior to the traditional UF-filled and UT-walled tubes. The question raised is how about if combine FGF with FGT configurations? Whether the structure can integrate their respective advantages? This study therefore aims to explore the crashworthiness of the transverse FGF-FGT structures. The finite element (FE) model of this FGF-FGT structure is first constructed in LS-DYNA. The crashworthiness of the transverse FGF-FGT structures is then compared with that of uniform counterparts. Finally, the multiobjective particle swarm optimization (MOPSO) algorithm is used to conduct the multiobjective optimization, where the transverse gradients of both foam density and wall thickness are taken as the design variables, and *SEA* and maximum crushing force ($F_{\max}$) as the design objectives.

2. Finite element modeling for a transverse FGF-FGT tube

2.1. Foam material

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 [28], in which the yield criterion of foam material is defined as:

$$\Phi = \hat{\sigma} - \sigma_y \leq 0 \tag{1}$$

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

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

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

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

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

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

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 follows,

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

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) [29,30].