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Crushing analysis and multiobjective crashworthiness optimization of foam-filled ellipse tubes under oblique impact loading

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A B S T R A C T

In this paper, a novel foam-filled ellipse tube (FET) is proposed and compared with other hollow and foam-filled tubes with different cross-sections under multiple loading angles, which include square, circle and rectangle. First, finite element analyses of these tubes reveal that the FET tube has the best crashworthiness under multiple loading angles. Second, design of experiments (DOE) was used to analyze the parameters that radial rate *f*, thickness of wall *t* and foam density ρ_f. Third, the Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to optimize the FET tube, in which the optimal parameter variation is sought for maximizing specific energy absorption (SEA) and minimizing peak crush force (PCF) under multiple loading angles. The optimized FET tube exhibits better crashworthiness than the origin FET tube and other tubes with different cross-section, indicating that the FET tube can be a potential energy absorber especially under oblique impact loading.

1. Introduction

With increased customer demand and government regulation, more and more attention has been recently drawn to improvement of structural crashworthiness for reducing occupant fatalities and injuries. On the other hand, growing concern in fuel consumption and environment sustainability pushes the vehicle structures lighter and lighter. As a result, thin-walled structures have drawn extensive attention on their excellent crashing behaviors and energy-absorbing characteristics for better performance and utilization of structural materials [1–8].

To improve energy absorption of the thin-walled columns without increasing volume and too much weight, cellular materials such as metallic [9–12] and polymer [13,14] foams are often used as fillers for such structures. Hanssen et al. conducted extensive experimental tests of square [10] and circular [16] columns with aluminum foam filler subjected to static and dynamic loads which suggest the prediction formulas about average force, maximum force and effective crushing distance. Ghamarian et al. [17] and Zarei et al. [18] studied the axial crushing behavior of foam-filled thin-walled structure. The study suggested that this structure has dramatic improvement over the conventional thin-walled tube. An [19] et al. focused on the crashworthiness design for foam-filled thin-walled structures with sheets and found that functionally lateral graded thickness tubs can produce more promising Pareto solutions than traditional uniform thickness counterparts. Recently, Fang et al. [20] used a multi-objective robust design optimization (MORDO) method to design the foam-filled bitubal structures.

However, most study above ignored the impact event in the real world and paid too much attention to crushing response and energy absorption characteristics of thin-walled structures under pure axial loads. The energy absorbers such as the shotguns and side rails experience oblique impact rather than pure axial or pure bending loads in the car crash. Under oblique impact, thin-walled tubes deform via a combination of both axial progressive and global bending modes. Compared to progressive axial collapse, the global bending deformation of a thin-walled structure is generally unstable with an associated reduction in impact energy absorption. Parametric studies of the tapered square tubes under the oblique impact were carried out by Yang [21] et al. The studies showed that multi-cell tapered tubes have better crashworthiness performance than multi-cell straight tubes under oblique impact regarding both specific energy absorption and peak crushing force. Reyes [22] et al. studied the quasi-static oblique loading behavior of both empty [23,24] and foam-filled [20] square aluminum columns and found that the energy absorption drops drastically when a global bending mode is initiated instead of progressive buckling, and it decreases further with increasing load angle. The energy absorption response of straight and tapered thin-walled rectangular tubes were studied by Nagel and Thambiratnam [25–27] under both axial and oblique quasi-static and dynamic impact loading. They concluded the tapered tubes have more advantages

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in applications under oblique impact. To seek the optimal specific energy absorption (SEA,absorbed energy per unit structural mass) and the peak crushing force (PCF) of thin-walled tubes, [28–38] used the structural optimization techniques.

In present study, a new class of foam-filled ellipse thin-walled tubes are proposed. These FET tubes are excepted to have high energy absorption efficiency and better capability of withstanding oblique impact loading than the tubes with other configuration section.The crushing responses of this type of thin-walled tubes under both axial and oblique impact loading are analyzed using the nonlinear explicit FEA code LS-DYNA. Towards this end, finite element (FE) models validated against theoretical and experimental results in the literature are established. Design information for such tubes as energy absorbers in oblique impact applications are developed through parametric study based on the sampling designs. A four-level full factorial design of experiments (DOE) method is used to determine those sampling design points. Also based on the DOE results, quartic polynomial functions are used to build response surface (RS) surrogate models that relate SEA and PCF to the geometric design variables associated with the FET tubes under oblique impact loading. Non-dominated Sorting Genetic Algorithm (NSGA-II) is used as the optimizer for solving the MOD problems.

2. Geometry and material

2.1. Geometrical description

The structure considered in this study is FET tube (Fig. 1) with the length L=250 mm, wall thickness t=2.0 mm and foam density p_f=0.27 g/cm^3. The FET tube could be mounted in the vehicle like tubes with other section-shapes and the larger diameter of the FET tube is horizontal. The bottom end of the tube is clamped, while the other end is impacted by a rigid wall with a constant velocity of V=10 m/s, which is typically encountered in passenger vehicle crash event. The normal of the rigid wall is in the X–Z plane and has an oblique angle α with the axis of the tube. The geometrical parameter of the cross-section can be get from the Fig. 2. And the

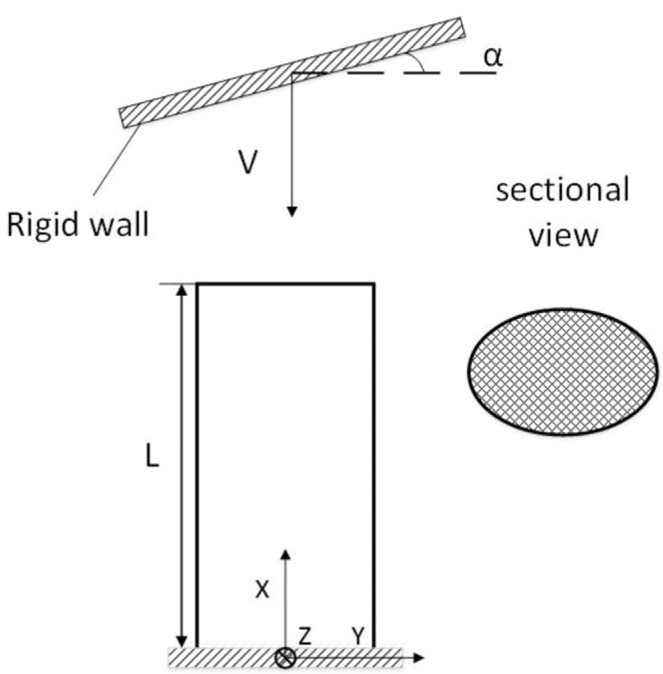

Fig. 1. schematic diagram of FET tube under oblique impact.

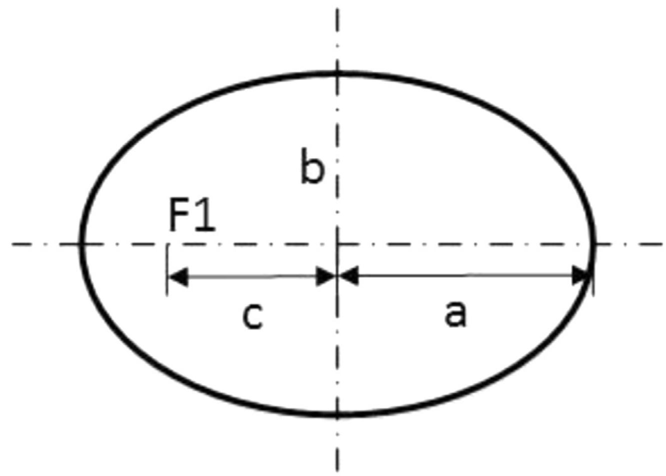

Fig. 2. schematic diagram of ellipse tub parameter.

radial rate f is defined as follows:

$$f = b/a \tag{1}$$

2.2. Material properties

The tube wall is made of aluminum alloy with density ρ= 2700 kg /m^3, Young's modulus E=68 GPa, and Poisson's ratio υ=0.3. Fig. 3 indicates the stress–strain curve of the tube material via uniaxial test. The constitutive law is based on an elastoplastic material model with von Mises's isotropic plasticity algorithm and plastic hardening [41]. Since the aluminum is insensitive to the strain rate, this strain-rate effect is neglected in the FE model [42].

The foam material is based on an isotropic uniform material model developed by Deshpande and Fleck [41,43,44]. The yield criterion of such a material is defined as follows:

$$\varphi = \hat{\sigma} - Y \le 0 \tag{2}$$

where Y is the yield stress, and the equivalent stress $\hat{\sigma}$ is given as

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

where σ_e represents the von Mises effective stress and σ_m is the

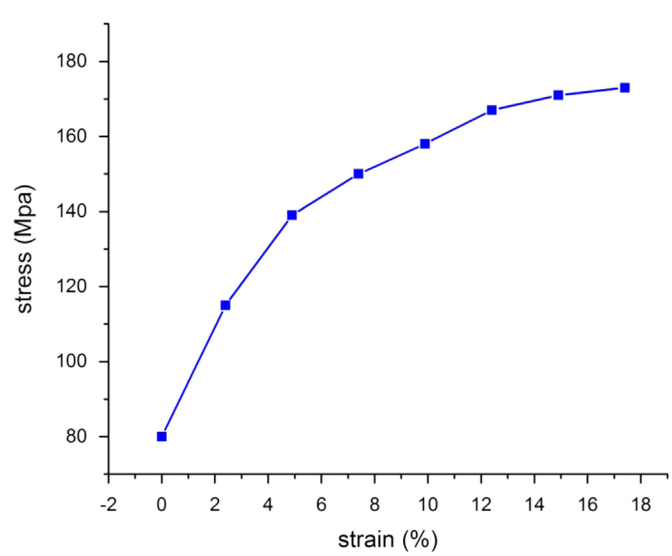

Fig. 3. Tensile stress–strain curve of AA6060 T4.