Advances in Engineering Software 99 (2016) 27–35

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Optimization of foam-filled double ellipse tubes under multiple loading cases

Qiang Gao[a], Liangmo Wang[a,*], Yuanlong Wang[a], Fuxiang Guo[b], Zunzhi Zhang[b]

[a] School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, P.R. China
[b] Nanjing Iveco Automobile Co. Ltd., Nanjing 210028, China

ARTICLE INFO

Article history:
Received 26 February 2016
Revised 7 April 2016
Accepted 1 May 2016

Keywords:
Foam-filled double ellipse tube
Crashwothiness
Multiobjective optimization
Multiple loading

ABSTRACT

In this paper, a novel foam-filled double ellipse tube (F-DET) is proposed. First, the circle and ellipse tubes with three different configurations(hollow, foam-filled, double foam-filled) are investigated under axial and oblique impact by using the nonlinear finite element code LS-DYNA. The numerical results showed that the F-DET tube has the best crashworthiness performance than tubes with other configurations. Then to optimize the F-DET tube, the Kriging model about the radial rate f, thickness of wall t and foam density ρ_f is constructed. Based on the Kriging model, the multiobjective particle swarm optimization (MOPSO) algorithm is utilized to achieve the optimized F-DET tube, foam-filled ellipse(F-ET) tube and foam-filled double circle(F-DCT) tube on the maximizing specific energy absorption (SEA) and minimizing peak crush force (PCF) under multiple loading angles. It can be found that the F-DET tube has better crashworthiness performance than F-ET tube and F-DCT tube. This indicates F-DET tube can be a potential energy absorber under the multiple loading cases.

1. Introduction

By development of technology, the number of vehicles and their speed have increased and the possibility of car crashes and human injuries has increased as a result. Therefore, the researchers focus more attention to the crashworthiness of the vehicle safety. At the same time, the fuel consumption is another aspect on the designing of the vehicle which could not be ignored. Thus, to improve the energy absorption of a material, the thin walled structures have been applied in many cases, especially thin walled tubes. Superior energy absorption capability of thin-walled tubes lays in the progressive and controllable plastic deformation modes. Extensive research efforts were conducted to investigate the crushing behavior of thin-walled tubes under quasi-static and dynamic loading [1].

To enhance energy absorption without much increase in mass, cellular materials or structures including metallic foams [2–8], synthetic foams [9–12], natural cellular materials [13] and honeycombs [14] are used to fill the tubes. Some other research focus on the multi-tube usage [14–18] and generating corrugated/grooved surfaces on the tubes. To predict the crashworthiness of the thin walled tubes, Hanssen et al. [19,20] presented the close-form formulas to predict the behaviors of foam-filled aluminum tubes under both quasi-static and dynamic loading conditions. They showed that the total energy absorption of a foam-filled tube exceeded the sum of individual energies absorbed in empty column and form filler due to the interaction between foam and column wall. Recently, considering the crashing performance of the vehicle in real world, the deformation mode of the tubes under the oblique loading has been analyzed and some novel structures are proposed. The crush behavior of mild steel square columns was analyzed by Han and Park [21], indicating that from the axial to the bending collapse mode, there was a critical load angle at the transition place. Li et al. [22] paid attention to the aluminum foam circular tubes and did some experiments. As for the tapered tubes, the tapered rectangle tubes had more advantages than straight tubes under an oblique impact has been concluded by Nagel and Thambiratnam [23–25]. To make more effective use of various foam-filled thin-wall structure systems, some researchers [26,27] attempted to simultaneously optimize foam density and wall thickness to seek best possible combination for enhancing crashworthiness.

Meanwhile, the double tubes gains increasing attention from the researchers due to the advantages on the crashworthiness under both axial and oblique impact. Goel [3] compared the energy absorption of empty and Al foam filled bi-tubular and tri-tubular configurations to empty and foam-filled single circular and square tubes numerically. The results revealed that energy absorption capacity of Al foam-filled bi-and tri-tubular structures were higher in contrast to single foam-filled tubes. Guo et al. [28] investigated the crashworthiness of double circular tubes under bending

---

* Corresponding author. Fax: +8684315425.
E-mail address: liangmowang_njust@163.com (L. Wang).

http://dx.doi.org/10.1016/j.advengsoft.2016.05.001
0965-9978/© 2016 Elsevier Ltd. All rights reserved.

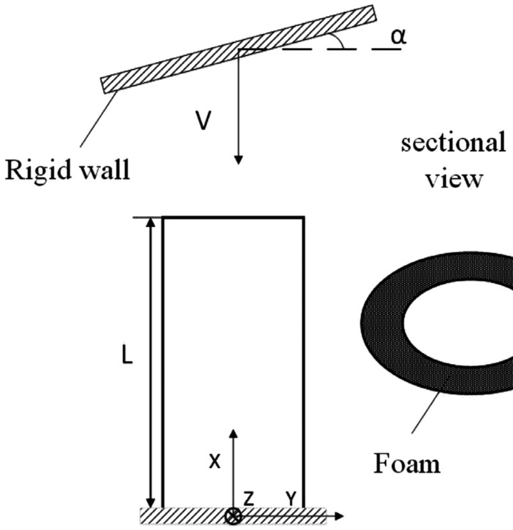

Fig. 1. Schematic diagram of tube under oblique impact.

conditions using experimental and numerical testing, which indicates the superiority of the ability absorbing the energy. Experimental and finite element analyses were performed on bitubular square thin-walled tubes with different arrangements under quasi-static axial compression loading by Kashani [29], and the effect of length difference in inner and outer tubes was studied.

In this paper, a novel foam-filled double ellipse tube is proposed. First, the hollow tubes (H-T), foam-filled tube (F-T), foam-filled double tube (F-DT) with two different cross-sections (circle, ellipse) are analyzed using the nonlinear explicit FEA code LS-DYNA about the crushing behavior. The specific energy absorption (SEA, absorbed energy per unit mass) and peak crushing force (PCF) under axial and oblique impact are compared. It will show that the foam-filled double ellipse tube (F-DET) has the best crashing performance under axial and minor oblique impact. To achieve the optimal F-DET tube, some geometry parameters are chosen to design the DOE experiments. Based on this, a Kriging approximation model is established to formulate the objective and constraint functions. Then the multiobjective particle swarm optimization (MOPSO) algorithm is used as the optimizer for solving the multiobjective optimization design (MOD) problems. Finally, the crashing performances of the optimal F-DET tube, the foam-filled ellipse tube(F-ET) and the foam-filled double circle(F-DCT) tube are compared to reveal the advantage of the F-DET tube.

2. Materials and methods

2.1. Description of geometrical features

To simplify the vehicle collision model, the thin walled tube (Fig. 1) is fixed on the bottom end and the rigid wall is given an initial velocity (v = 10 m/s). The structure considered in this study is F-DET tube with the length L = 250 mm, wall thickness t = 2.0 mm and foam density ρf = 0.206 g/cm^3. The inner tube and the outer tube share the same center. 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 radial rate f is defined as follows:

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

2.2. Material properties

Both the outer and inner tube wall is made of aluminum alloy with densityρ = 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 [30]. Since the aluminum is insensitive to the strain rate, this strain-rate effect is neglected in the FE model [31].The constitutive behavior of the aluminum column was modeled via the piece wise linear plasticity material model, Mat 24, in LS-DYNA.

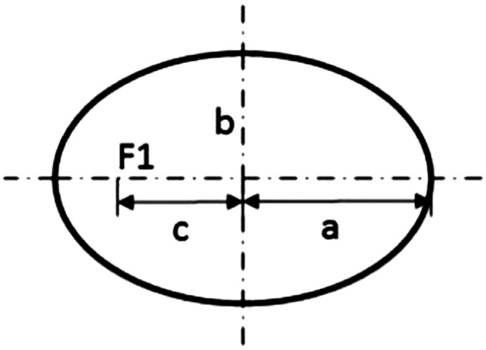

Fig. 2. Schematic diagram of ellipse tub parameter.

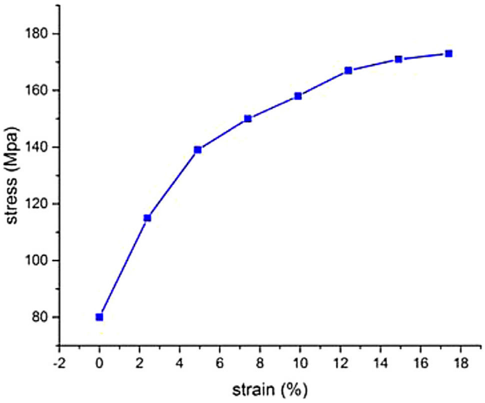

Fig. 3. Tensile stress–strain curve of AA6060.

The foam material is based on an isotropic uniform material model developed by Deshpande and Fleck [32]. 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 mean stress. For the aluminum foam, α = 2.12 is used.

The strain hardening rule is implemented in the material model as follows:

$$Y = \sigma_p + \gamma\frac{\hat{\varepsilon}}{\varepsilon_D} + \alpha^2\text{in}\left(\frac{1}{1 - (\hat{\varepsilon}/\varepsilon_D)^\beta}\right) \tag{4}$$

where $\hat{\varepsilon}$ is an equivalent strain. $\sigma_p, \alpha_2, \gamma, \frac{1}{\beta}, E_p$, and ε_D are the material parameters which are related to the foam density as [33]

$$\left(\sigma_p, \alpha_2, \gamma, \frac{1}{\beta}, E_p\right) = C_0 + C_1\left(\frac{\rho_f}{\rho_{f0}}\right)^\kappa$$

$$\varepsilon_D = -\ln\left(\frac{\rho_f}{\rho_{f0}}\right) \tag{5}$$

in which ρ_f is the foam density, ρ_{f0} the density of the base material, and C_0, C_1 and κ are the constants as listed in Table 1. In