Construction and Building Materials 168 (2018) 633–649

Contents lists available at ScienceDirect

Construction and Building Materials

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

Crashworthiness design for bi-graded composite circular structures

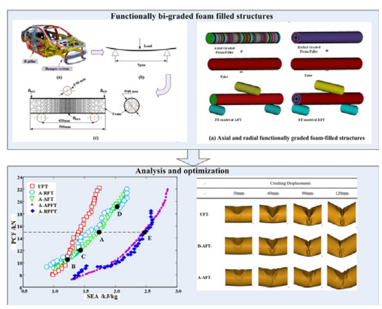
Yong Zhang [a,b,*], Xiang Xu [a], Shuran Liu [a], Tengteng Chen [a], Zhongwei Hu [a]

[a] College of Mechanical Engineering and Automation, Huaqiao University, Xiamen 361021, China
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, Australia

HIGHLIGHTS

- The bi-graded foam filled structures offer great potential to improve the crashworthiness under bending load.
- The graded direction is basis of bending collapse behavior for graded foam filled structures.
- Effective filled length is an important route to improve structural weight efficiency.
- Multiobjective optimization is used to seek optimal crashworthiness parameters for different foam filled structures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 September 2017
Received in revised form 11 February 2018
Accepted 21 February 2018

Keywords:
Functionally graded foam
Effective foam filled
Bending collapse
Multiobjective optimization

ABSTRACT

An innovative double functionally graded composite circular beam comprised of axial and radial graded foam filler is proposed to improve the safety of vehicle under lateral load. The numerical model is established and validated by three-point bending experimental testing. To explore the benefits of the novel functionally graded foam (FGF) material, graded foam filled circular beams with axial and radial graded directions are compared with homogenous foam filled counterparts. FGF filled beams are credited with primarily outward fold which leads to expanded crushing zone. Then, parametric studies are carried out to investigate the effect on thickness and yield stress of column wall of functionally graded circular beams. Furthermore, the bending behaviors of effective FGF filled circular beams are also investigated to improve the weight efficiency. Lastly, multiobjective optimizations of FGF filled beams, effective FGF filled beams and uniform foam filled beams are conducted to enhance crashworthiness. The optimization results show that FGF filled beams exhibit superior Pareto solutions to the uniform foam-filled beams. Especially, effective FGF filled configuration can significantly improve weight efficiency without compromising bearing capacity. The findings of this research offer a new route of designing novel lightweight bumper absorbers with improved crash characteristics.

1. Introduction

Thin-walled structures are widely used in automobiles and railway train to enhance the passive safety during crash events [1–2]. Over the years, the crashworthiness of some typical thin-walled structures including multi-cell structures [3–4], variable thickness thin-walled structures [5], tapered thin-walled structures [6–9], foam filled thin-walled structures [10–12], metal/composite hybrid structures [13–15] and hierarchical structures [16–17] under axial or oblique impact loading were extensively explored by utilizing analytical, numerical, experimental methods and design optimization. In this regard, Sun and his coauthors made a significant contribution to promote the development of energy absorber. Though progressive folding of thin-walled structures

* Corresponding author at: College of Mechanical Engineering and Automation, Huaqiao University, Xiamen 361021, China.

E-mail address: zhangyong@hqu.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.conbuildmat.2018.02.159
0950-0618/

was the most effective deformation mode in absorbing kinetic energy, most structural members of vehicles such as B-pillar [18], bumper [19], and roof rail [20], etc., often collapsed in bending mode. Therefore, it is of great engineering significance to study and improve the bending behaviors of thin-walled structures.

The researches on the bending behavior of thin-walled structures were mainly focus on the sectional shapes, dimension, thickness and materials. For example, Kotelko et al. [21] investigated four-point bending behavior for rectangular and trapezoidal cross-section beams. Kim et al. [22] introduced the concept of toroidal surface and further improved the model for thin-walled rectangular section tube. Huang et al. [23] presented an empirical formula for the bending moment of thin-walled square structures. Qi et al. [24] investigated the bending behavior of double hat beam with aluminum-steel hybrid materials, and found that the hybrid beam possessed better crashworthiness than the homogeneous beams. For the plastic bending fold of circular sections, Elchalakani et al. [25] presented a plastic mechanism analysis for thin-walled circular hollow section tubes deforming in a multi-lobe or diamond collapse mode under pure bending. Maduliat et al. [26] used Yield Line Mechanism (YLM) and developed an analytical solution to determine the rotation capacity for steel hollow circular sections. The aforementioned thin-walled structures were mainly made of uniform wall thickness. In order to improve the material utilization, Sun et al. [27–28] proposed a novel variable thickness thin-walled structure, and investigated their bending behaviors by comparing uniform thickness counterparts with the same mass. The results showed that the energy absorption of variable thickness thin-walled structures could be significantly enhanced under transverse loading.

However, the localized bending of single hollow structure resulted in inward folding of column wall, which made the bending resistance drop dramatically after small rotation angle [29]. To achieve higher bending resistance and weight efficiency, cellular foam materials were employed as filler materials for thin walled structures. Santosa et al. [30] investigated the bending crush behavior of thin-walled columns filled with closed-cell aluminum foam using experiments and numerical simulations, the results showed the aluminum foam filled structure was very attractive to avoid global failure for a component which undergoes combined bending and axial crushing. Chen et al. [31] studied on the bending collapse of thin-walled foam filled beams by simulation and optimization designs, the results showed potentials of significant weight saving and volume reduction by utilizing ultralight metal filler. Shahbeyk [32] compared the bending crash performance of empty and foam-filled box-beams, and found that aluminum foam filling is more preferable to thickening the tube wall. Li et al. [33] investigated the bending crashworthiness of empty and foam-filled thin-walled circular tubes through dynamic three-point bending experiments, and found foam-filled double circular structure had better dynamic bending resistance and energy-absorbing effectiveness than the empty tube.

Very recently, functionally graded foam with tuneable mechanical properties was proposed to replace uniform foam for energy absorption structures of engineering and building construction fields. For example, Fang et al. [34] studied the bending behavior of functionally graded foam filled (FGF) thin-walled structures, the results found that the FGF structures absorbs more energy than the uniform foam counterpart. Xiao et al. [19] explored the crashworthiness of a bumper beam filled with functionally graded foam, and found that the crashworthiness of graded foam filled bumper had much better than that of uniform foam filled bumper. Xia et al. [35] performed blast tests of graded density foams on reinforced concrete (RC) slabs to investigate the protective effectiveness of density-graded foams, and found that the ascending density from bottom to top could improve the blast resistance of the foam compared to the foam with uniform density.

However, the bending behavior of graded foam filled thin-walled structures still received less attentions, furthermore, the previous bending collapse studies of graded foam filled structures mainly focused on the square cross section. To the best of author's knowledge, the circular graded foam filled structures were seldom been studied and concerned before. Especially, the bending behavior of circular graded foam filled structures with different graded patterns and filled lengths was never been investigated.

Therefore, this paper investigates the bending collapse of functionally graded foam-filled circular beams against uniform foam-filled circular beams. Especially, two different graded patterns for foam fillers, namely axial graded direction and radial graded direction, are proposed and examined. The numerical model is first validated by 3-point bending experimental test. Then parametric studies are carried out to explore the effect on graded directions, thickness and yield stress of column wall and effective foam filled length. Lastly, multiobjective optimization design is implemented to seek the optimal parameters.

2. Numerical model

2.1. Functionally graded foam-filled circular tube (FGFCT)

Fig. 1**(a)** shows a typical bumper system and B pillar of vehicle [36], and bending collapse shown in Fig. 1**(b)** is formed to avoid serious injury of passenger subjected to front and lateral collision. Therefore, the schematic illustration of functionally graded foam filled circular tube is presented in Fig. 1**(c)** under the three-point bending load. The length and diameter of FGFCT are 500 mm and 60 mm, respectively. Two fixed cylindrical supports are placed under FGFCT with a length of 420 mm. A cylindrical punch is placed overhead of FGFCT. The diameter of punch and cylindrical support are 50 mm.

To capture the graded characteristics of foam, the continuously graded foam filler shown in Fig. 1**(c)** is discretized into a limited number of layers with uniform density (Fig. 2). Here, two graded patterns are studied, respectively the axial graded pattern and the radial graded pattern. For axial graded foam-filled tubes (AFTs), the foam density varies from two distal ends to the midsection of the tube, as depicted in Fig. 2**(a)**. If the density increases from the distal end to the mid-surface, such pattern is considered as ascending pattern, defined as ascending graded axial foam-filled tubes (A-AFT). On contrary, the descending pattern can be implemented for the descending graded axial foam-filled tubes (D-AFT). For radial graded foam-filled tubes (RFTs), the foam density varies along the radial direction from the peripheral to the central, as described in Fig. 2**(b)**. If the density increases from the central axis to the outermost layer, the structure is defined as ascending graded radial foam-filled tubes (A-RFT), and descending graded radial foam-filled tubes (D-RFT) is defined accordingly.

The graded variation of foam density for each layer is governed by the following power-law function:

$$\rho_f(x,m) = \begin{cases} \rho_{\min} + (\rho_{\max} - \rho_{\min})\left(\frac{x}{L}\right)^m \\ \rho_{\max} - (\rho_{\max} - \rho_{\min})\left(\frac{x}{L}\right)^m \end{cases} \quad (1)$$

where the maximum and the minimum density are ρ_{max} = 500 kg/m^3, ρ_{min} = 200 kg/m^3, respectively. Gradient exponent m varies from 0 to 10. x and L represented the length shown in Fig. 2**(a)** and **(b)**.

In addition, to compare the crashworthiness between FGFCT and the corresponding uniform foam-filled tube (UFT) with the same mass, the density of UFT is expressed as: