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Controllable energy absorption of double sided corrugated tubes under axial crushing

Hozhabr Mozafari [a], Shengmao Lin [b], Gary C.P. Tsui [c], Linxia Gu [a, *]

[a] *Department of Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588-0656, United States*
[b] *School of Civil Engineering and Architecture, Xiamen University of Technology, PR China*
[c] *Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, PR China*

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To maximize the controllable energy absorption of corrugation troughs as observed in the single sided corrugated (SSC) tube, we proposed and tested a new structure design, i.e., double-sided corrugated (DSC) tube made of Al 6060-T6 aluminum alloy or CF1263 carbon/epoxy composite. Finite element models were developed to test the mechanical advantage of the DSC tube in comparison with both SSC and classical straight (S) tubes under axial crushing. Results have shown that the total absorbed energy of the DSC aluminum tube with 14 corrugations was 330% and 32% higher than that of the SSC tube with 14 corrugations and the S-tube, respectively. The initiation and progression of the crushing process for different tube configurations were characterized, leading to the mechanism of energy absorption. Plastic deformation in terms of PPEQ is the key parameter correlating with the energy absorption capacity. To overcome the lower specific absorbed energy (SAE) in the DSC tube compared to that in the S-tube, the CF1263 carbon/epoxy composite laminate was adopted and the corresponding SAE was 5.9 times higher than that of the aluminum one. Moreover, the influence of the number of corrugations on the crushing behaviors of the DSC tube was also inspected. A minimal straight tube section was suggested for a controllable smooth crushing behavior regardless of its advantage in SAE. This work might shed light on designing future thin-walled energy absorber devices with better control of crushing behaviors for minimal injuries and damages.

1. Introduction

Structural crashworthiness is an extensive research area in optimizing the behaviors of energy absorbing systems. Subjected to external crushing, permanent plastic deformations were introduced in crashworthy components to dissipate dynamic energy, which depends on material compositions, various geometrical shapes, and fabrication processes. Specially thin-walled structures have attracted much attention due to their low cost, ease of fabrication and superior energy absorption efficiency [1–3]. Previous works have looked into cross-sectional shapes [1,4], composite materials [5–7], and multi-step energy absorbing devices [8,9]. Thin-walled structures filled with aluminum honeycombs [10–16] and polymeric or metallic foams [17–20] as well as multi-cell tubes [21–25] have been suggested for better crashworthiness properties of energy absorbers. Composite materials have also demonstrated the mechanical advantages of crashworthiness over classical metals [26], i.e., crushing energy absorption per unit of mass [27–29]. For example, energy absorber devices made of carbon fiber reinforced plastic (CFRP) performed exceptionally well subjected to crushing loads [30]. Due to its lower density, higher specific strength, and superior crushing resistance, the CFRP has been widely utilized in high-end sports and/or electric vehicles [31–35]. Sun et al. [36] compared the crashworthiness of empty circular CFRP with CFRP/aluminum/steel tubes filled with aluminum foam or aluminum honeycomb under axial quasi static crushing. It was found that most of the foam filled tubes collapse in a progressive mode, exhibiting noticeable merits in crashworthiness. Moreover, it was noted that the specific energy absorption of CFRP tubes filled with honeycomb was slightly lower than the empty counterparts but far better than those of all metal specimens. Hussein et al. [37] conducted experimental investigations to study the axial crushing behavior of aluminum honeycomb-filled square CFRP tubes. The mean crushing force and energy absorption by honeycomb-filled

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[*] Corresponding author.
E-mail address: lgu2@unl.edu (L. Gu).

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CFRP tubes were larger than those of corresponding hollow CFRP tubes. On the other hand, the specific energy absorption of aluminum honeycomb-filled CFRP tubes were found to be less than that of a hollow CFRP tube. Liu et al. [38] studied the effects of expanded polypropylene (EPP) foam filling on the mechanical properties of aluminum honeycomb panels. It was showed that the mean crushing strength and total absorbed energy in the axial tests increased with the foam filler; and the higher foam density the greater filling effect, whereas the specific absorbed energy remained unchanged with increase in the foam density. They also [39] deigned a lightweight EV body structure made of CFRP and evaluated its performance using a multiscale approach and the crashworthiness was compared with an identical body made of GFRP. The CFRP body structure was 28% lighter than the GFRP, and the crashworthiness of the body structure increased. The carbon fiber composites also demonstrated their capacity as crushing energy absorbers with larger specific stiffness in a Formula SAE car [30].

Moreover, geometric modification from a straight tube (S-tube) to a single-sided radial corrugated tube (SSC) has shown a desirable smooth load-displacement behavior with minimal fluctuations [40–47]. The introduction of corrugations helped in directing the crushing energy to the corrugation trough. Eyvazian et al. [48] showed that an SSC aluminum tube can enhance energy absorption up to 228% compared with an S-tube under lateral loading conditions. The energy absorption capacity of a S-tube subject to axial loading is approximately ten times, more than that under lateral loading conditions [49]. Wu et al. [50] performed a parametric study on collapse mode and energy absorption of corrugated tubes. However, it has been observed that the energy absorption of the SSC tube was even much less than an S-tube under axial loading conditions [40]. This was expected, due that the formation of plastic hinges in the S-tube demanded much more energy than guiding the deformation of corrugation troughs. Chen and Ozaki [49] have further illustrated that the patterns vary with the shape of the corrugations and the geometry of the structure. For a fixed length, the axisymmetric hinge formation could absorb more energy than the asymmetric one. Considering the controllable energy absorption of the SSC tube under axial loading, more attention was focused on the means to improve the energy absorption capacity of the SSC.

In this work, we proposed an innovative structure design, referred to as double-sided corrugated tube (DSC), with the aim to provide more plastic deformation subjected to axial crushing and preserve the controllable energy absorption of the corrugation troughs. Within this regard, numerical models were developed to test the new tube designs following their validation against analytical solutions. A parametric study had been made in terms of geometry and materials through finite element analysis. Specifically, the axial crushing responses of DSC, SSC and S-tube made of classical aluminum alloy were compared. The DSC tube made of CF1263 carbon/epoxy composite, denoted as DSC-C, was characterized to show its crashworthy advantage. Moreover, the influence of the number of corrugations on the load-displacement behaviors of DSC tubes was investigated.

2. Finite element model

Nominal tube dimensions were adopted at 112 mm in length, 80 mm in diameter and 1 mm in thickness [49], regardless of detailed shape configurations, as shown in Fig. 1. Corrugations were considered to be in sinusoidal form with corrugation length λ_c and corrugation amplitude a. Since the tube was fully corrugated with 14 corrugations along the tube length, SSC, DSC or DSC-C tubes were also referred to as SSC-14, DSC-14, or DSC-14-C respectively.

Both ends of the tube were confined by two rigid plates. The top plate was fixed and the bottom one allowed the Y-direction translation only, with a displacement rate of 5 mm/min. The general frictionless node-to-surface contact was prescribed between the rigid plates and the tube. All tubes, except the composite one, were made of Al 6060-T6 aluminum alloy with Young's modulus of 71 GPa, Poisson's ratio of 0.33, density of 2700 kg/m^3, yield strength of 160 MPa, and ultimate tensile strength of 200 MPa. The elasto-plastic constitutive material model was adopted. For the composite DSC-14-C tube, CF1263 carbon/epoxy composite layup was chosen [51] with materials properties listed in Table 1. The Hashin progressive damage model was adopted and the damage is determined at the point when each of several damage criteria was met. Each damage criteria compares the calculated stresses against the strength properties of the respective material. Energy-based damage evolution was employed to encompass strain softening response of CFRP composite. The stacking sequence of the composite tube was [±45] with the thickness of each layer at 0.25 mm. The laminate had four layers and a thickness of 1 mm in total. All tubes were meshed using S4R linear shell elements with five integration points. The shell element provides accurate modeling without greatly increasing the computational time needed for each run. Mesh convergence analysis were conducted (Fig. 2) and the 1 mm element size was chosen.

3. Results and discussions

3.1. Verification of FE model

The analytical solution for an S-tube based on the kinetic approach [49] was used to validate our FE model results. The average compressive force over the whole crushing process could be calculated by

$$\lambda = 0.920\sqrt{2Rt} \tag{1}$$

$$\frac{P_{ave}}{M_o} = \frac{25.23\sqrt{2R/t} + 11.9}{0.86 - 0.568\sqrt{t/2R}} \tag{2}$$

Where $M_0 = \frac{\sigma_0 t^2}{4}$ is the fully plastic moment per unit length, σ_0 is the energy equivalent flow stress which is estimated as the 0.2% of yield strength [52], σ_u is the ultimate strength, and λ is the half-wavelength of the wrinkle. R and t are radius and thickness of tube, respectively.

The average compressive force P_{ave} from our model was calculated by dividing the total absorbed energy, i.e., the area under the load-displacement diagram (Fig. 3), by the displacement magnitude just before the densification point [49].

Moreover, λ was obtained by measuring the half-formed wrinkle length of the hinge. The calculated reaction force and the half-formed wrinkle length for the S-tube were 12.84 kN and 9.26 mm, respectively. The corresponding analytical results from Eqs. (1&2) were 14.91 kN and 8.228 mm. The differences between the simulation and the analytical solutions were 16% and 12.5%, respectively. These variations could be explained by the assumptions used in the kinetic approach [30]. In addition, the modeling framework for composite materials was validated in our previous work [7,53].

3.2. Mechanical advantage of double-sided corrugated tube

To improve the energy absorption capacity of the SSC without scarifying its controllable energy absorption of corrugation troughs,