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Energy absorption analysis of a novel foam-filled corrugated composite tube under axial and oblique loadings

Mahshid Mahbod, Masoud Asgari*

Research Laboratory of Passive Safety Systems, Faculty of Mechanical Engineering, K. N. Toosi University of Technology, P. O. Box: 19395-1999, Tehran, Iran

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A B S T R A C T

Composite thin-walled structures are of much interest in differnet applications as well as energy absorption devices for their great crashworthiness and light weight. In this paper, a new corrugated composite cylindrical tube has been introduced in order to improve crashworthiness along with a stable crushing. In cylindrical composite tubes, the effects of corrugations regarding charactristics of energy absorption have underwent quasi-static axial and oblique loading investigations. For this reason, composite cylindrical tubes with different corrugation geometries were analyzed using finite element explicit code and the effects of corrugations on crush force effiency and specific energy absorption were comperhensively studied. The finite element model has been validated by experimental quasi-static compression tests. An efficient analytical solution for SEA during axial loading has been also derived and compared with FEM solution. Furthermore, a comparison of empty and foam-filled corrugated composite tubes has been done. Based on the obtained results, generating corrugated surfaces on tubes improved the crush force efficiency significantly in both axial and oblique crushings. Performing a parametric study on geometrical corrugation parameters of tubes has been indicated that the energy absorption of these structures depends strongly on the corrugation parameters. Furthermore the absorbed energy has been increased by using foams in both axial and oblique crushing. SEA increases by increasing the foam density while the CFE decreases.

1. Introduction

Safety is one of the vitally important challenges that vehicle designers face to accomplish high-performance products in the transportation industry. In order to avoid fatal or serious injuries, vehicle crashworthiness and occupant protection are considered in automotive designs. Crashworthiness is defined as the ability of a restraint system or component to withstand loads below a certain level and to reduce the damage caused in those cases involving excessive dynamic loads [1]. Simply, crashworthiness is the capability of a vehicle to protect the occupants from serious injury or even death in case of accidents which are potentially survivable [2]. Therefore the interest of using energy absorber devices with higher crashworthiness capacity has been increased [3]. These elements convert the kinetic energy of crash into strain energy through structural deformation [4]. Among various available models, thin-walled structures are known as the imperative components for energy absorption and therefore they play an important role in industrial transportation systems. The crush boxes are fabricated by a wide range of materials such as aluminum, steel and composites which are used in different shapes such as circular, triangular, conical, squared and polygonal tubes [5–9]. Up to now, a considerable number of theoretical, experimental and numerical researches have been investigated, focusing on crashworthiness of thin-walled structures [10–12].

One of the first studies on energy absorption of thin-walled structures was expressed by Alexander [13]. He derived an approximate theoretical model in order to estimate the crushing forces of steel circular tubes deforming in concertina mode. It is worth mentioning that the solution was improved by Abramowicz and Wierzbicki [14,15]. The extensive researches concerning the crashworthiness of energy absorbers demonstrate that composite tubes are one of the widespread structures used in various topologies due to their low density and high energy absorption capacity. Studies state that a composite structure can display higher energy absorption than that of metals [16,17]. Studies done by several researchers are reported with crushing behavior of thin-walled composite structures subject to axial and oblique impact loading [18–22]. However, the energy absorption of composite structures depends on a wide range of factors such as material characteristics, ply design, geometry, etc and a considerable amount of literature has been published on the energy absorption characteristics of composite

* Corresponding author.
E-mail address: asgari@kntu.ac.ir (M. Asgari).

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structures affected by these factors [17–20,23]. Due to the recent developments of composite manufacturing methodologies, carbon fiber reinforced polymer (CFRP) components are widely used and fabricated in automotive and aerospace industries [17–19]. It is illustrated by Jacob et al. [17] that in spite of lower density, energy absorption capacity of carbon fiber is much more than glass, and Kevlar fibers. Furthermore an in-depth analysis of different fiber performance indicates that carbon presents the better specific energy absorption compared with glass fiber [19]. Moreover, geometry is another imperative factor that affects the energy absorption capacity of composite structures significantly [20].

On the other hand, recent development of cost-effective processes for the production of low-density metallic cellular materials, such as aluminum foam, has cleared the way for using it in light-weight structural members [24]. Cellular materials, such as honeycomb, foam and lattice materials, have been widely used in protective structures for impact energy absorption and shock mitigation due to the capacity to dissipate energy by the progressive local crushing of its microstructure under dynamic loading [25]. Furthermore experimental studies [26,27] indicated that direct compressive strength of the foam and the interaction between the foam and wall column are the vitally important parameters which lead to significant increases in crushing force of energy absorbers. Toksoy and Güden [28] explored the energy absorption of partially aluminum square tubes by varying the wall thickness and foam density subjected to quasi-static and dynamic loadings. The results displayed the crushing force is increased by increasing the foam density and wall thickness. Darvizeh et al. [29] investigated the crushing behavior of polyurethane foam-filled grooved circular thick-walled tubes. It is shown the energy absorption is increased in foam-filled structures in comparison with empty ones. Santosa [30] studied the energy absorption of foam-filled square tubes under axial crushing. The results demonstrate that absorbed energy in structure is increased by increasing the foam density. Based on these facts, it seems that using foams as fillers in thin-walled tubes could be much effective in order to improve energy absorption behavior.

In a considerable number of papers related to composite materials crashworthiness, simple axisymmetric geometries were focused including revolutionary surfaces such as circular, elliptical, and conical surfaces, and flat surfaces such as square, rectangular, etc. Recently the corrugations are introduced in the tube to force the plastic deformation to occur at predetermined intervals along the tube generator as an effective and innovative solution [31–34]. The aims are to improve the uniformity of the load-displacement behavior of axially crushed tubes, predict and control the mode of collapse in each corrugation in order to optimize the energy absorption capacity of the tube. Eyvazian et al. [35] experimentally investigated the effect of corrugation on crushing behavior and energy absorption of aluminum circular tubes. The results displayed that tubes with corrugation have a uniform force-displacement curve without an initial peak load. Alkhatib et al. [36] numerically studied the crushing behavior and performance of corrugated tapered tubes (CTT) under oblique loading conditions. It was found that some CTTs can achieve higher specific energy absorption relative to their tapered conventional counterparts and increasing the impact angles lead to a reduction in performance. Elgalai et al. [37] experimentally analyzed crushing of composite corrugated tubes subjected to quasi-static loading. Results confirmed that changing corrugation angle and fiber type enhance the energy absorption performance of composite tube. Numerical study of energy absorption of cotton fiber/propylene corrugated tubes [38] also displays that the tube's energy absorption capability was affected significantly by varying the number of corrugation and aspect ratios. It is found that as the number of corrugations increases, the amount of absorbed energy significantly increases. Crushing behavior of corrugated metal-composite tube was examined experimentally under axial loading condition by Eyvazian et al. [39].

The results of investigations on corrugated tubes indicated that corrugation could enhance the energy absorption capacity of structures in comparison to traditional straight tubes. To the best of authors' knowledge, there are few papers on the crushing of corrugated composite tubes, most of these studies focused on axial crushing of corrugated tubes. So, in order to study the effect of corrugation on the crashworthiness of composite tubes, a comprehensive numerical analysis of corrugated carbon/Bismaleimide (BMI) tubes is performed under both axial and oblique loadings in this work. Furthermore, a comparison of empty and foam-filled corrugated composite tubes is done. To do this, different tubes by varying the radius and number of curvatures are modeled and analyzed using LS-DYNA explicit dynamic code. An efficient analytical solution has been developed for predicting specific absorbed energy of foam filled corrugated composite tubes. These models are validated with appropriate experimental and analytical solutions. Performing a parametric study on geometrical corrugation parameters of tubes indicates that the energy absorption of the structures depends strongly on the corrugation parameters. Based on the obtained results, generating corrugated surfaces on tubes improves the crush force efficiency significantly in both axial and oblique crushing.

2. Material and model

This study proposes corrugated composite tubes in order to offer better energy absorption in comparison with conventional straight tubes. It is interesting to note that corrugation is formed in rows of wavelike folds or basically shaped into a series of regular folds that look like waves [38]. The tube incorporated with and without foam filler as illustrated in Fig. 1. In all cases, tubes have 110 *mm* in length, 60 *mm* in outer diameter, and 2 *mm* in thickness as shown in Fig. 1b. As illustrated in this figure, the cylindrical aluminum foam filler has 57 *mm* in diameter and 110 *mm* in length. Corrugation is defined by the number of wave curvatures, n and the radius of curvatures, r as depicted in Fig. 1c. Each concave or convex of tube determines one curvature. For example in Fig. 1, sixteen curvatures are exist ($n = 16$). Furthermore the length of one curvature, L, is indicated in Fig. 1. The geometrical parameters were kept the same in parametric study in order to focus on effect of changing the corrugation parameters.

2.1. Finite element modeling

The present numerical investigation is performed using a non-linear explicit dynamic LS-DYNA code. The corrugated composite tubes are studied in axial crushing as well as oblique one. As illustrated in Fig. 2 the FE model consists of three main parts as: 1) the corrugated composite tube, 2) aluminum foam filler, and 3) the mass block. The mass block is modeled as a rigid body by 'RIGID_MAT' in LS-DYNA. It should be noted that the mass is considered 500 kg and also young's modulus is assigned as 200 GPa. It is also worth mentioning that the mass block is allowed to move in the z-axis only. The angle 15° selected for oblique crushing is indicated in Fig. 2. All the tubes are modeled with Belytschko-Tsay shell element with five integration points through the thickness. A mesh convergence analysis for a foam-filled composite tube leads to considering the element size of 2 *mm* and 5 *mm* for shells and foam, respectively.

The clamped boundary condition is applied at the bottom of the shell and foam. They are crushed at a constant velocity of 10 m/s by the rigid body which is defined by 'PRESCRIBED_MOTION_RIGID' in LS-DYNA. The appropriate specification of contact interface types is an important part of modeling process. Two types of contact algorithm are utilized for an in-depth analysis. The contacts between mass block and specimens and also between the specimens themselves are modeled by 'AUTOMATIC SURFACE TO SURFACE.' The self-contact of composite tube is defined by 'AUTOMATIC SINGLE SURFACE.' It should be noted that the static and dynamic friction coefficient is taken 0.2 in all cases. It should be also noted that foam and tube are not bonded while the related absorbed energy is represented by an interaction effect. In order