Composite Structures 100 (2013) 479–492

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

Flattening process of empty and polyurethane foam-filled E-glass/vinylester composite tubes – An experimental study

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ARTICLE INFO

Article history:
Available online 26 January 2013

Keywords:
E-glass/vinylester
Composite tube
Energy absorber
Flattening
Lateral compression
Polyurethane foam

ABSTRACT

This paper presents quasi-static crushing performance of empty and polyurethane foam-filled E-glass/vinylester composite tubes with different geometrical characteristics to use in sacrificial cladding structures. Some empty and foam-filled tubes were compressed laterally between two rigid plates. The effects of polyurethane foam-filler on the crushing characteristics and the corresponding energy absorption by the composite tubes are investigated. Composite tubes with three different fiber fabric layers were considered to study the influence of polyurethane foam on the crushing performance. Also, effects of different geometrical characteristics on energy absorption by different tubes are studied. Experimental results show that the presence of polyurethane foam inside the composite tubes suppresses the circumferential delimitation process and fiber fracturing; consequently, it increases the specific absorbed energy by the composite tubes during the flattening process. Also, it is resulted that injection of the polyurethane foam in the tubes causes the more regular deformation mode, comparing with the empty tubes. Finally, experimental results of the present work are compared with some of the previous articles that were investigated the foam-filled composite structures under the different loadings to suggest an optimized energy absorber.

1. Introduction

Crashworthiness of structure has been a major concern in vehicle design to ensure safety of passenger. In practice, thin-walled structures have been widely adopted as main energy absorber for crashing protection attributable to their high stiffness–weight ratio, deformation pattern and energy absorption capacity. As higher and higher design requirements being placed, increasing attention has been paid to new configurations for enhancing vehicle crashworthiness and structural performances [1]. With the fuel price increasing in recent years and in view of better fuel economics both in terms of cost and fuel reserves, there has been an increased interest in the development of lightweight transportation vehicles. This brought a shift in the types of materials used for manufacturing of such vehicles, where composite materials started making an entrance into the transportation industries. Nonetheless, by introducing new materials into vehicle design, such as composites, one has to consider an important design aspect, namely the crashworthiness of the material [2].

Mahdi et al. [3–11] and Mamalis et al. [12–18] made wide researches on crushing response of composite tubes using finite element and experimental methods. Based on previous researches, composite materials have the potential as good energy absorbers, but due to their brittleness, the force variation from the average crush force is large. These variations should be small in order to reduce the injuries, especially brain trauma to occupants. Ideally the post crush zone should be at a constant level of crush force. In view of this, to further enhance the crashworthiness of composite tubes, cellular materials such as foams were examined by making these structures as the sandwich structures. Tubes and especially cylindrical tubes have not limitations to their applications in structures due to their extremely high stiffness-to-weight ratio and high strength-to-weight ratio. Metallic or polymeric foams were studied extensively as fillers in steel, aluminum and brass tubular structures [2]. Niknejad et al. [19–23] performed vast researches on axial compression of tubular metal structures and columns that were filled by polyurethane foams with different densities. They presented some theoretical analyses to predict the crushing load and energy absorption capacity of these structures and compared their theoretical results with experiments. Also, Niknejad et al. [24] experimentally compared energy absorption capacity of empty and polyurethane foam-filled brazen tubes with different foam densities under the lateral compression between two rigid plates which is called flattening process. Hall et al. [25] tested the aluminum foam-filled and empty tubes made of aluminum, brass and

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http://dx.doi.org/10.1016/j.compstruct.2013.01.009

titanium during the lateral compression. Estimation based on initial crushing loads showed that for comparable energy absorption, filled tubes are lighter than thicker empty tubes. Fan et al. [26] demonstrated the advantage of sandwich tube. They studied deformation behavior of sandwich tubes under quasi-static lateral crushing, experimentally and simulated the experimental results by ABAQUS/Explicit and achieved good agreements between both results. It was found that the usage of aluminum foam tends to change the deformation mode of empty tubes from a non-sequential to a sequential folding mode due to the plateau region of the foam.

England and Gregory [27] considered the finite plane strain deformations of an elastic–plastic tube compressed between two rigid smooth parallel plates. The composite was assumed to be an ideal material which is inextensible in the fiber direction and is incompressible. Gupta and Abbas [28] introduced a detailed experimental investigation of the quasi-static lateral crushing of composite cylindrical tubes between flat platens. The employed tubes were made of glass fiber reinforced with epoxy and their diameter to thickness ratio varied from 7.33 to 39. Calme et al. [29] studied the static lateral compression of 3D braided carbon–epoxy composite rings. In the linear domain, the analytical modeling of elastic stresses giving the distribution of hoop and transverse shear stresses were validated thanks to a numerical finite element simulation. Abosbaia et al. [30] experimentally investigated the effects of segmentation on the crushing behavior of woven roving laminated tubes under quasi-static lateral compressive load.

Abdewi et al. [31] fabricated and tested circular composite tubes to study the effects of radial corrugation geometry on the crushing behavior and energy absorption of composite tubes, experimentally. The specimens were subjected to quasi-static axial as well as lateral compression load. Mahdi and Kadi [32] presented and discussed the experimental behavior and corresponding artificial neural networks predictions of circular and elliptical tubes subjected to lateral compression load. Taher et al. [33] experimentally evaluated the crashworthiness characteristics of a novel design for cost-effective crashworthy composite glass fiber-reinforced plastic (GFRP) sandwich structures. They described the design, manufacturing and crush testing of rectangular fabricated blocks. Palanivelu et al. [34] studied the effect of polyurethane foam-filler on the crushing performance of small-scale composite tubes under the axial loading. They found that the presence of polyurethane foam has provided an additional wall strengthening and stability to achieve uniform and progressive crushing failure modes in the tubes which failed catastrophically without polyurethane foam. Tarlochan et al. [35] investigated the crushing response of composite sandwich structures under quasi-static compressive loads. The aim of their study was to design and fabricate tubular sandwich structures that have potential as energy absorber devices under the axial loading. Mahdi and Hamouda [36] examined the energy absorption capability of 1-D composite hexagonal ring array and identified modes of energy dissipation mechanism. Their research resulted that when the ring angle increases the energy absorption capability increases, too.

2. Experimental setup

2.1. Geometry, material and fabrication process

Present work investigates crushing response of empty and polyurethane foam-filled composite tubes under quasi-static lateral compression between two rigid plates. The tubes were prepared with different geometrical characteristics that are detailed out in Table 1. The composite tubes were made of woven E-glass fiber and vinylester resin. The fiber fabric was weaved at a $30°/-30°$ configuration. Three different layers of fiber fabric are studied: 5 layers, 6 layers and 7 layers.

To study the effects of foam-filler and foam density on energy absorption capability of composite tubes, two different polyurethane foams were used to fill the tubes: a hard foam (Foam 1) and a soft foam (Foam 2). Densities of Foam 1 and Foam 2 are 250 and 190 kg/m^3, respectively. To study the effects of adhesion between the inner walls of the tubes and the polyurethane foam on energy absorption by the composite tubes, the tubes were filled by polyurethane foam in two ways: injection of foam inside the tubes and placing the expanded foams into the tubes.

Hand lay-up technique was used as the fabrication means with cylindrical mandrels. Tensioning was given during the fabrication process to ensure that all specimens have the desired thickness and that air is not trapped between wraps. The ends of the tubes were cut out to ensure that the tubes are free from burrs or uneven ends. The fabricated tubes were cut out to the desired lengths.

2.2. Test procedure

The energy absorption capability by different empty and polyurethane foam-filled composite tubes subjecting to quasi-static lateral compression load between two rigid plates was experimentally investigated. The tests were performed by a DMG machine Model 7166. In all of the experiments, the crosshead speed was kept at 10 mm/min. The load–displacement and energy–displacement diagrams of each specimen were sketched and the absorbed energy by tubular structures (the area under the load–displacement diagram) and the specific absorbed energy or energy absorption per unit of mass (SAE) were calculated.

3. Results and discussion

In this part, different results that are measured from the experimental study are represented. According to the experimental results, effects of diameter, length, number of layers, adhesion between the polyurethane foam and inner wall of composite tubes, and foam density on energy absorption capability by composite tubular structures are investigated. Eventually, some of the previous studies on energy absorption of foam-filled composite structures are introduced and their results are compared with the present experiments.

3.1. Effects of tube length

Fig. 1 illustrates lateral load–displacement diagram of two empty specimens with the same diameter and thickness and different lengths. Lengths of the specimens CVE-02 and CVE-03 are equal to 30 and 50 mm, respectively. Fig. 1b shows diagram of lateral load per unit of the tube length (load/length ratio) versus the displacement of these two specimens. According to Fig. 1b, the two graphs are close together. Thus, lateral load of the empty specimens has a direct relation versus the tubes length. The area under the load–displacement diagram of a specimen indicates the absorbed energy by the specimen. Therefore, the absorbed energy by the empty composite tubes subjected to the lateral compression load increases proportional to the tubes length. Also, a good agreement between the two curves in Fig. 1b shows that the lateral compression tests on the empty tubes had an acceptable accuracy. Fig. 2 compares absorbed energy by the specimens CVE-02 and CVE-03. According to the figure, the absorbed energy by the empty composite tubes subjected to the lateral compression load increases proportional to the tubes length.

Fig. 3a and b shows the lateral load–displacement and the load/length ratio versus the lateral displacement diagrams of three filled