Thin–Walled Structures 114 (2017) 1–10

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Theoretical study of absorbed energy by empty and foam-filled composite tubes under lateral compression

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ARTICLE INFO

Keywords:
Composite tubes
Energy absorption
Lateral compression
Polyurethane foam
Quasi-static loading

ABSTRACT

This paper is an attempt for introduction of new theoretical relations in order to predict energy absorption behavior of empty and polyurethane foam-filled composite tubes, which are made of woven fiber fabrics, during lateral compression between two rigid plates. Such theoretical relations can be used to specify portion of different deformations that are happened during crushing process in total energy absorption of the structures. Knowing these data may help the designers to reinforce the energy absorbers more effectively. Also, several experiments are conducted on empty and polyurethane foam-filled circular E-glass/Vinylester composite tubes in order to validate the theoretical relations. The specimens are laterally compressed between two rigid plates during a quasi-static process. According to experimental studies, the composite tubes collapse with different modes of deformation during lateral flattening. Different relations are introduced for prediction of the absorbed energy of tubes with different deformation modes. The theoretical and experimental energy-displacement diagrams and total absorbed energy by the composite tubes are compared and good agreements are found. Finally, theoretical relations are compared with each other and effects of different energy absorption mechanisms on total energy absorption are discussed based on the presented relations.

1. Introduction

Composites have long been used in personnel and vehicle protective/structural applications for protection against various ballistic and blast threats. Composite materials are well suited to this role because of their superior stiffness and strength-to-weight properties over many other classes of materials. Utilization of composite materials provides mass efficiency with enhanced survivability for various combat vehicles and protection devices [1]. Also, thin-walled plates and tubes made of metals or E-glass/vinylester laminates are used extensively in many different applications including the construction, infrastructure, aeronautical, aero-space, automotive, marine and sporting industries. In strength applications the advantage of using thin elements is the high strength and stiffness to weight ratios, and in energy absorbing applications the advantage is the high energy absorption to weight ratios (specific absorbed energies) [2].

A series of recent articles [3–8] about tubular metal and composite structures focused on axial compression of such structures, looking forward to design energy absorbers. A lateral compression test, however, allows highlighting the transverse behavior of the material, and even though this kind of tests is rather seldom, it is of high interest for the design of low-speed impact resistant structures (automotive, rail, etc.) [9]. With this aim, Abosbaia et al. [10] carried out an experimental investigation in order to study the effects of segmentation on the crushing behavior of quasi-static laterally compressed composite tubes. Load-deformation curves and failure mechanism histories of typical specimens were presented and discussed in their paper. Calme et al. [11] modeled elastic stress state inside RTM-molded braided composite cylinders under lateral compression, analytically. The experimental part of the paper describes the quasi-static delimitation under lateral compression of RTM-molded carbon/epoxy rings, made of braided two-dimensional (2D) tubular performs and DGEBA-IPD resin. Morris et al. [12] conducted experimental investigations into the compression of nested metal systems under two different loading conditions: the quasi-static lateral compression with vertical and inclined side constraints. Also, they examined the quasi-static analysis of nested circular and elliptical (non-circular) metal energy absorbers using experimental and numerical techniques and concluded that such energy absorbers may find application where they are subjected to compressive load under impact with the aim of bringing the moving mass to a controlled stop [13]. The implementation of artificial neural networks (ANN) technique in the prediction of the crushing behavior and energy absorption

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http://dx.doi.org/10.1016/j.tws.2017.01.029
Received 8 July 2016; Received in revised form 24 January 2017; Accepted 24 January 2017
Available online 31 January 2017

characteristics of laterally loaded glass fiber/epoxy composite elliptical tubes was studied by Mahdi and Kadi [14]. Their predictions results were compared with actual experimental data in terms of load carrying capacity and energy absorption capability and showed good agreement. Abdewi et al. [15] investigated the effect of radial corrugation geometry on the crushing behavior and energy absorption of composite tubes, experimentally and subjected three types of specimens to quasi-static axial as well as lateral compression load. Olabi et al. [16] performed dynamic lateral crushing tests on mild steel nested tube systems. The various nested tube systems consisted of one standard and one optimized design. Their crushing behavior and energy absorption capabilities were obtained and analyzed. Fan et al. [17] conducted systematic investigations into thin-walled circular tubes with Aluminum foam sandwiched under quasi-static lateral crushing. They studied the deformation behavior of sandwich tubes under quasi-static lateral crushing, experimentally and simulated the results by ABAQUS/Explicit. An extensive experimental investigation of in plane crushing of composite hexagonal ring system between platens has been carried out by Mahdi and Hamouda [18]. Behavior of ring as regards the initial crushing load, post crushing load, energy absorbed and mode of crushing has been presented and discussed in their paper. Niknejad et al. [19,20] studied the effects of polyurethane foam-filler on the lateral deformation in the circular brazen and composite tubes under radial quasi-static loading, experimentally. Also, they investigated the geometrical effects on energy absorption of empty and foam-filled metal and composite tubes. Niknejad et al. [21] investigated lateral compression of rectangular metal tubes, experimentally and theoretically. Gupta and Abbas [22] conducted a detailed experimental and theoretical investigation of the quasi-static lateral crushing of composite cylindrical tubes between flat platens. In their mathematical model it is assumed that the composite material is rigid perfectly plastic.

Baroutaji et al. [23] presented finite element analyses to investigate the energy absorption through the lateral collapse of the sandwich circular tubes, which consist of thin-walled circular tubes with aluminum foam core. In another research, the response surface method (RSM) for design of experiments (DOE) along with the finite element modeling (FEM) was used to explore the effects of geometrical factors such as thickness (t), diameter (D), and width (W) on the energy absorption responses of laterally crushed circular tube [24]. They also studied the responses of nested tube systems under quasi-static and dynamic lateral loading, experimentally and numerically. The finite element simulations were examined by experimental results and then a parametric study was performed using validated FE models. Furthermore, the effects of geometrical and loading parameters on the responses of the best nested tube system were explored [25].

According to previous researches, empty and polyurethane foam-filled E-glass/vinylester composite tubes deform with different modes under quasi-static lateral compression based on their geometrical characteristics [20]. In current research, mathematical models are developed for most common deformation modes of empty and foam-filled composite tubes in order to predict their energy absorption during lateral compression between two rigid plates. Also, empty and polyurethane foam-filled tubes with different geometries are investigated experimentally and their energy absorption behaviors are compared with theoretical results. After validation of the theoretical predictions, portion of different energy absorption mechanisms during lateral crushing of the tubes are discussed based on the presented theories.

2. Experiments

In order to validate the theoretical results of empty and foam-filled composite tubes under lateral compression, the tubes were fabricated from woven E-glass fiber and Vinylester resin and tested. The fiber fabric was weaved at a $60^{\circ}/-30^{\circ}$ configuration toward axis of the tubes and hand lay-up technique was used as the fabrication means with cylindrical mandrels. Tensioning was given during fabrication process to ensure that all specimens have the desired thicknesses and that air is not trapped between wraps. 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.

Table 1
Geometrical characteristics of empty and foam-filled composite tubes.

Specimen code	Inner diameter (mm)	No. of fiber-fabric layers	Length (mm)	Foam no.	Deformation mode
TCF-01	40	5	50	–	IE
TCF-02	66	5	50	–	IE
TCF-03	51	5	50	–	IE
TCF-04	40	5	50	Foam 2	IF
TCF-05	66	7	50	Foam 2	IF
TCF-06	66	5	50	Foam 1	IIF
TCF-07	51	7	50	Foam 1	IIF
TCF-08	40	6	50	Foam 1	IIIF
TCF-09	66	7	75	Foam 1	IIIF

Foam-filled specimens were filled with two kinds of polyurethane foams (Foam 1 and Foam 2). Polyurethane foams were injected inside the composite tubes. Plateau stresses of Foam 1 and Foam 2 are 2.25 and 4.17 MPa and their densities are 250 and 190 kg/m^3, respectively. Table 1 gives the geometrical characteristics of empty and foam-filled composite tubes.

Empty and polyurethane foam-filled tubes were laterally compressed between two rigid plates during a quasi-static process and the crosshead speed was kept at 10 mm/min. The compression tests were performed using a DMG machine model 7166 and their energy-displacement diagrams were sketched based on the testing machine data.

In order to determine the E-glass/Vinylester composite material properties, five specimens were tested during quasi-static uniaxial tension tests according to ASTM D638.2105.3517ISIRI10729 standard. Finally, average of the five tests results were calculated and used in theoretical relations for comparison with the experiments. Table 2 gives characteristics and tests results of the five samples and their averages.

3. Theory

According to Niknejad et al. [20], empty and polyurethane foam-filled composite tubes deform in different ways during flattening progress. Their investigated composite tubes were made of woven E-glass fiber and Vinylester resin. In this paper the absorbed energy by empty and polyurethane foam-filled composite tubes that deform through the most common deformation modes, are studied, theoretically. Fig. 1 shows a common deformation mode of empty tubes cross sections which is named model IE and a composite tube which deformed according to this deformation mode. Also, Fig. 2a, b and c show three common deformation modes of foam-filled tubes cross sections which are named model IF, model IIF and model IIIF and a tube for each model which deformed according to the mentioned models,

Table 2
Characteristics of E-glass/Vinylester composite samples.

Specimen no.	Width (mm)	Thickness (mm)	Maximum force (N)	Yield stress (MPa)	Elastic modulus (GPa)
1	24.65	0.80	6392	324	17.627
2	24.65	0.80	6740	342	17.889
3	24.65	0.80	6816	326	17.988
4	24.67	0.82	6025	298	17.729
5	24.68	0.78	6527	343	19.573
Average	24.66	0.80	6500	330.6	18.161