Materials and Design 63 (2014) 446–459

Contents lists available at ScienceDirect

Materials and Design

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

Investigating the quasi-static axial crushing behavior of polymeric foam-filled composite pultrusion square tubes

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ARTICLE INFO

Article history:
Received 21 October 2013
Accepted 10 June 2014
Available online 24 June 2014

Keywords:
Composite polymer matrix
Pultrusion
Delamination
Crashworthiness

ABSTRACT

The capability of structures to absorb large amounts of energy is a crucial factor, particularly for structural components of vehicles, in reducing injury in case of collision. In this study, an experimental investigation was conducted to study the crashworthiness of polymeric foam-filled structures to the pultruded square cross-section E-Glass fiber-reinforced polyester composite tube profiles. Quasi-static compression was applied axially to composite tubes to determine the response of the quasi-static load displacement curve during progressive damage. Three pultruded composite tube wall thicknesses at different sizes were examined, and the effects of crushing behavior and failure modes were analyzed and discussed. Experimental results indicated that the foam-filled profile is superior to the non-filled foam composite tube profile in terms of the capacity to absorb specific energy.

1. Introduction

Composite materials are generally characterized by high strength, light weight, and low cost. Recent developments have considered composite materials as design solutions to address the increasing cost of traditional materials, such as steel, aluminum, and wood. Advances in manufacturing methods make such composites an attractive alternative [1]. Several properties of composites, such as their non-conductivity, strength, stiffness, light weight, corrosion resistance, and low coefficient of thermal expansion, make them attractive design options for many structural, marine, automotive, and aerospace applications [2]. High initial costs and other unique properties are major considerations that prevent the widespread use of composite materials [3–5]. Pultrusion is a manufacturing method in which wetted fibers are drawn through a heated curing die to produce high-performance constant cross-section composites at low cost. Pultruded goods have numerous potential applications, depending on their fulfillment of certain design criteria. Pultruded composites have been used for automotive components, aerospace structures, and commercial products, as well as for other biomedical and construction applications [6].

Mamalis et al. [3] conducted research on the compressive behavior of composite panels under axial loading. They stated that composite panels fail in column buckling and that the ratio of crush force efficiency was low. These authors also observed that the main criterion to evaluate the compressive damage of specimens was the internal reinforcement of the foam material. Structural composites can provide better crashworthiness performance compared with metallic materials owing to their manufacturing process [2,7]. Moreover, structural composites exhibit relatively better performance in terms of specific energy absorption, ease of manufacturing, and maintenance compared with metallic materials [7]. However, crashworthiness performance not only depends on the cross-section form of the specimens [8], but also on the energy absorption process, which depends on the mechanical properties of the fiber and the resin, fiber and resin volume fractions, laminate stacking sequence, fiber orientation, and geometry of the tube [8]. Failed tubes exhibit delamination, bending, axial cracking, and fiber fracturing modes during crash events [9].

Few studies have been conducted on the effect of manufacturing process on the crushing performance of pultruded composites. No comprehensive quasi-static analyses of foam-filled pultruded polymeric composites on axial loading can be found in the literature, although many such studies have been published for metallic materials. Of the few investigations reported, one discussed quasi-static loading applied axially on pultruded composites to determine the response of load–displacement during progressive collapses. Sivakumar et al. [10] conducted a study to determine the effectiveness and sustainability of polyurethane foam (PU) as filler material reinforcement along quasi-static axial compressive modes on a composite tube. They found that the use of filler

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http://dx.doi.org/10.1016/j.matdes.2014.06.020
0261-3069/

material reduced the capability to absorb energy per unit mass. Tarlochan et al. [11] determined the axial compressive response of a sandwiched round tube shape with a variable number of laminate composites and a variable arrangement of inner tube wall diameters using polystyrene foam as core material. They found that the influence of core material inserted onto a sandwiched round tube facilitated an improvement in the capability to absorb specific energy.

Mamalis et al. [12] determined that structural materials based on composites in the form of hollow shapes fail and crushed in different forms for different material specimens. In another study, Mamalis et al. [13] analyzed the crashworthiness of filler materials inserted into an S-shaped composite with strengthened internally laminated reinforced polymer hollow cross-section. They found that the use of hybrid lamination of FRP tubes was advantageous for the crashworthiness parameters and capabilities of composite materials. Ataollahi et al. [14] conducted a study to determine the crushing behavior of silk fiber-reinforced epoxy square tube profile with different numbers of laminated structures. They found that the influence of different laminates improves the absorbed specific energy and crush force efficiency.

This study aims considers energy absorption performance for the design improvement of both empty and foam-filled pultruded square composite tubes under quasi-static loading. This research further aims to analyze the effect of different wall thicknesses on E-Glass/polyester pultruded composite square tubes as well as the effect of the introduction of polyurethane foam (PU) fillers with different rigid foam densities on pultruded composites when subjected to crushing loads and with constant cross-section geometries such as length, width, and height of tubing. A triggering mechanism was used as a crash initiator to facilitate the progressive crushing of tube structures. Moreover, this study aims to analyze the progressive energy absorption of empty and foam-filled structures as well as the effects of the variable density of the foam inserted into internal composite tubes.

2. Experimental procedure

2.1. Overview

Two types of square pultruded composites are analyzed in this study: an empty pultruded composite tube and a pultruded composite internally filled with polyurethane foam (PU) with variable densities of 50, 90, and 140 kg/m^3. The low-density rigid foam was used as a filler material for its weight reduction property and significant flexibility, which facilitate deformation and energy absorption upon impact. However, well-established test methods for the accurate measurement of this property for pultruded composites filled with polyurethane foam (PU) materials are currently unavailable. In this study, square cross-sections of pultruded composites with E-Glass/polyester geometry and different wall thicknesses are experimentally examined. Polyurethane foam (PU) with variable density was used as filler material. Several failure modes were defined. The progressive crushing of composite materials with microfragmentation, is designated as Mode I. Brittle fractures of the components, which result in catastrophic failure with minimal energy absorption, characterize Mode II. Finally, progressive folding and hinging, similar to the crushing behavior of thin-walled metal and plastic tubes, with moderate energy-absorbing capacity describes Mode III. Structural crashworthiness refers to the impact performance of a structure, particularly resistance, which enables a structure to protect its occupants from accidents during collision [1]. Ensuring that a structure is capable of withstanding impact forces and is capable of absorbing energy is necessary [3,5].

2.2. Test specimens preparation

For this investigation, square cross-section composite tubes were fabricated using E-Glass fiber-reinforced polyester resin with a fiber matt volume of 50.8% and a resin volume fraction of 49.2%. As recommended by Thorton and Jeryan [2], the linear density (mass per unit length) of the tube was set to achieve the progressive failure of the composite tubes. The resin and fiber volume fractions were calculated according ASTM: D2584-11. The materials were manufactured using a pultrusion process. This process draws fiber mats through a resin bath to wet the fibers and then draws the fibers through a hot die to form the desired final shape. Finally, the composite profile is passed through a tunnel oven to accelerate curing, and the composite is cut into the desired length. Twelve specimens were used for the test, with dimensions kept constant at 150 mm length (L) and 50.8 mm width (W). Hamada and Ramakrishna [15] conducted energy absorption on a round cross-section and indicated that a tube with a t/D ratio of less than 0.015 will fail catastrophically (where t is the thickness of the tube, and D is the diameter of the tube). Therefore, for square-pultruded composite tube profiles, t/W ratios of 0.0275, 0.0315, and 0.0393 were obtained for wall thicknesses of 2.1, 2.4, and 3.0 mm, as recorded in Table 1 and shown in Fig. 1, respectively.

2.3. Specimen triggering as a crush initiator

Chamfering angles were introduced to the front ends of specimens to serve as a crush initiator, and one end of each tube was chamfered at 45°. This type of triggering was selected because the initial contact will be uniform along the tubes during the crush event. This angle was machined using a dry grinding machine to produce identical angles. Low feeding rates were used during machining to reduce residual stress and cracking. Chamfering served as a collapse trigger mechanism that initiated stable progressive crushing while preventing catastrophic failure.

2.4. Compression test

Quasi-static testing can be defined as a test performed on the specimen at a constant speed that may range from 1.5×10^{-3} m/min to 0.02 m/min. The standard experiment test on quasi-static loading was conducted based on ASTM: D6264-12. The test specimens were compressed between parallel flat plates. Quasi-static tests are easy to control and do not require expensive equipment compared with other forms of testing because the energy absorption capability of crashworthy structures is highly dependent on the speed at which they are crushed. The compression test was conducted using a GOTECH 100-kN universal testing machine and standard experiment test, as shown in Fig. 2.

From Table 2, the wall thickness of the square pultruded composite tubes was categorized based on four types of foam-filler density. A wall thickness of 2.1 mm was used for specimen numbers 1a–1d, 2.41 mm was used for specimen numbers 2a–2d, and 3.0 mm was used for specimen numbers 3a–3d, all of which were based on foam densities of 50, 90, and 140 kg/m^3, respectively. The width and breadth of specimens were fixed at 50.8 mm. The dimensions of length, width, and breadth were fixed for specimens to meet design constraints and for easier comparison among specimens. Polyurethane foam (PU) samples ($50 \times 50 \times 50$ mm) were tested under compressive loading at a loading condition speed of 0.02 mm/min to study the quasi-static absorbed energy at densities of 50, 90, and 140 kg/m^3. Fig. 3 shows the compressive test results as a nominal stress–strain curve for the different densities. The compressive testing of polyurethane foam (PU) was conducted based on ASTM: D1621-10. The exact dimensions of all tested