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Experimental investigation into dynamic axial impact responses of double hat shaped CFRP tubes

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ABSTRACT

This paper aims to explore the dynamic responses and crashing characteristics of double hat shaped tubes made of weave carbon fiber reinforced plastic (CFRP). Experimental investigations were carried out into three different thicknesses and lengths of the composite tubes fabricated by the bladder molding process. Three distinct failure modes, classified as progressive end crushing, mid-length collapse and overlap opening, were observed in the dynamic crushing tests. Unlike continuous splaying fronds observed in the quasi-static tests, dynamic tests exhibited a number of fragment segments in the progressive end crushing mode. It is shown that the ply number was a critical parameter affecting the failure mode and energy absorption capability. The increase in ply number led to increases in the peak load and specific energy absorption (SEA); whereas the tubal length seemed insensitive to energy absorption capability. Compared to the quasi-static cases, the dynamic impact tests resulted in the higher peak load (increased from 46 % to 125 %) and lower SEA (reduced from 21 % to 33 %) for the tested tubes.

1. Introduction

Carbon fiber reinforced plastic (CFRP) gains increasing popularity in aerospace and automobile structures attributable to its lightweight, high specific stiffness, energy absorption capability and easy manufacturing [1]. Particularly for an electric vehicle (EV), the range that EV can travel without recharge has been below satisfaction yet due mainly to the restriction of energy storage in battery. Weight reduction of vehicle has been one way of solving this problem. BMW and some other automobile companies are developing their lightweight electric vehicles by extensively utilizing CFRP materials [2]. For achieving lightweight design while maintaining the increased safety requirements of vehicle, the crashworthiness of novel CFRP structures is therefore of particular importance [3].

A number of investigations have been conducted on the static axial crushing responses and energy absorption of some regular closed or open sectional CFRP components (c.f. Fig. 1). For example, Mamalis et al. [4] observed different modes of brittle collapse for the CFRP square tubes subjected to static axial compressive loading; and they analyzed the influence of structural geometries, such as the tubal length and sectional aspect ratio, on the compressive responses and collapse modes. Hull [5] summarized the main features of progressive folding in the circular tubes subjected to axial compression, and discussed the effect of fiber arrangement on progressive crushing in carbon fiber-epoxy unidirectional laminated tubes and woven glass cloth epoxy tubes. Huang et al. [6] performed numerical and experimental quasi-static tests on circular CFRP tubes to examine their axial crushing responses; and they found that based on the Chang–Chang failure criteria the two-layer finite element (FE) model was fairly effective in characterizing the energy absorption and crushing failure modes of the tubular composite specimens. Ochelski and Gotowicki [7] analyzed the energy absorption capability of conical tubes made of carbon-epoxy and glass-epoxy composites, and they revealed that the circumferentially oriented fibers in the specimens had critical influence on the increase of energy absorption and the decrease in the number of interlayer cracks. Jia et al. [8] analyzed the effect of geometric factor and winding angle on crushing behavior of CFRP cylinder, and they found that the compressive strength, compressive modulus and crack length decreased with

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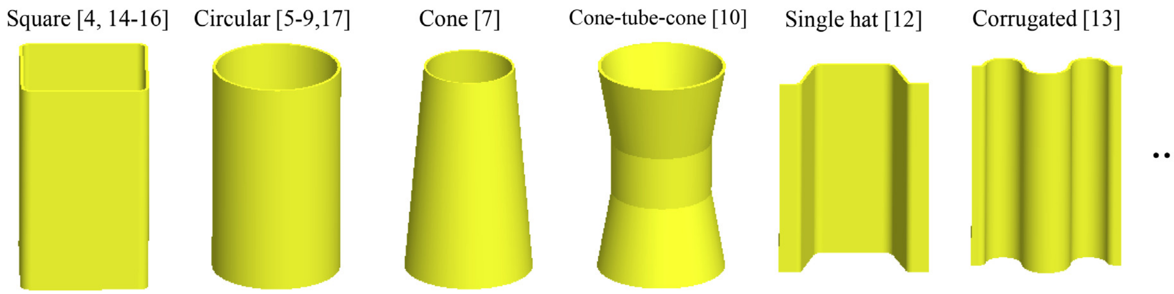

Fig. 1. Schematic of some regular sectional CFRP tubes.

the increasing winding angle. Siromani et al. [9] developed a finite element modeling methodology to study the crushing behavior and energy absorption characteristics of thin-walled circular CFRP tubes under axial compression, and they showed that the modeling methodology using multiple layers of shell elements and tiebreak contact accurately predicted the overall crushing behavior. Mahdi et al. [10] studied the quasi-static crushing behavior of axially compressed cone-tube-cone composite system, and they showed that structures with ratios (tube height to total height) between 0.06 and 0.11 exhibited a higher crashworthiness performance. Elgalai et al. [11] examined the crushing responses of corrugated tubes made of carbon-epoxy and glass-epoxy composites under quasi-static axial loading, and they reported that introduction of corrugation pattern could significantly enhance the energy absorption capability of composite tubes. Joosten et al. [12] used the explicit finite element code PAM-CRASH to predict the crushing failure for the carbon epoxy composite hat shaped energy absorber; and they found that a four-layer, stacked-shell FE model of the hat shaped composite element, was capable of closely capturing the failure modes and load–displacement (L-d) behavior obtained in the experiments. Feraboli et al. [13] evaluated the suitability of a progressive failure material model used to simulate the quasi-static axial crushing of CFRP tape sinusoidal specimen; they reported that LS-DYNA material model MAT 54 could successfully reproduce experimental results after assessing the sensitivity of input parameters to MAT 54. Bussadori et al. [14] developed two different numerical models to reproduce experimental crush test on square CFRP tube and showed the advantages of the crushing zone model compared to the stacked shell model. These above static studies provided us with important data for the design of CFRP components.

Relatively speaking, few studies have been carried out on the dynamic crushing characteristics of CFRP components. McGregor et al. [15] simulated the damage propagation, failure morphology and energy absorption in square braided CFRP tubes under axial impact, they reported that the developed continuum damage model implemented in LS-DYNA agreed well with the experiments. Mamilis et al. [16] compared the crashworthiness characteristics of the square CFRP tubes between the dynamic and static axial compression tests, and they found that the peak load in quasi-static tests was lower than that of the dynamic counterpart by 51%–91%. Farley [17] studied the effect of crushing speed on the energy absorption of circular CFRP tubes, and found that the magnitude of the change in energy absorption with respect to change in crushing speed of Thornel 300/Fiberite 934 specimens was related to ply orientation. Jackson et al. [18] investigated the laminate design on crush performance of open sectional CFRP specimens by dynamic and quasi-static crushing tests, and they reported that dynamic test of the selected laminate designs resulted in a reduction in SEA from 6% to 15% compared to the quasi-static case. Waimer et al. [19] explored the dynamic failure behavior of CFRP aircraft components under axial crushing, and they quantified the influences of design parameters on failure modes and load–displacement (L-d) characteristics. Boria et al. [20] carried out experimental and numerical investigations into the impact behavior of a composite impact attenuator for a Formula SAE racing car to pass the homologation requirements.

From the past research, much of work has been related mainly to regular cross sectional CFRP tubes, including the square, circular, cone, cone–cone, single hat and corrugated tubes, which are fabricated by the hand-lay up or filament winding techniques, as shown in Fig. 1. It remains under studied for some more sophisticated non-conventional CFRP tubes prepared from novel manufacturing process [21]. Moreover, limited dynamic crushing tests have been reported on determining the crashworthiness characteristics of CFRP components. While quasi-static tests can provide good qualitative assessment as to the effect of different variables on energy absorption; dynamic tests are indispensable for the structural crashworthy design of composite vehicle body.

Thus the aim of this study is to gain a comprehensive understanding of the dynamic impact responses and crashworthiness characteristics of double hat shaped CFRP tubes representative of the novel EV body structure, which structurally differ from the regular sectional tubes and are fabricated by a different process, namely bladder molding. In this paper, the typical load–displacement curves and failure modes are identified; the effects of thickness, length and impact velocity on crashworthiness characteristics are explored in detail. Following this, the differences of dynamic and quasi-static energy absorption capabilities are quantified for comparison.

2. Experiments

2.1. Geometry

The double hat shaped CFRP tube is a commonly used component for novel electric vehicle body structures, such as the side pillars or top pillars [22]. As shown in Fig. 2, the side B pillar consists of two segments of complex surface, which are bonded together at the overlap areas, and these overlap areas are used to support the door accessories. In this study, the width, height, overlap length of the specimen section are taken as the constants of 84, 38 and 15 mm, respectively. Three sets of varying parameters are considered in the tests, respectively: the first is the length of specimens with 50, 75 or 100 mm (L50-L100 in Table 1); the second is the ply number of 3, 6 or 9 plies (P3–P9 in Table 1); the third is the impact velocity of 3, 3.5 or 4 m/s (V1–V3 in Table 1). The specific dimensions of the tested tubular specimens described here are summarized in Table 1.

2.2. Fabrication

Unlike the filament winding process, the bladder molding process can be used to fabricate the specimens with complex shapes.