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Progressive failure analysis and energy-absorbing experiment of composite tubes under axial dynamic impact

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ABSTRACT

The crashworthiness testing of carbon/epoxy composite tubes is conducted in this study, and the corresponding energy-absorbing parameters and failure morphology are discussed. Considering the anisotropic constitutive relationships of composites, a stiffness degraded model that involves the extended Hashin failure criterion and damage evolution law based on the continuum damage mechanics is proposed to analyze the progressive failure of G803/5224 composite tubes. The progressive failure user subroutine is developed based on the transient dynamics software. The progressive failure numerical analysis combined with the failure criterion is also discussed. The relative error of specific energy absorption and average load is less than 6% compared that of the experimental results. This result indicates that the proposed method can be applied to estimate the energy-absorbing characteristics of composite tubes.

1. Introduction

Composite structures are widely used in the defense and civilian industry, especially in the aeronautic and astronautic fields, because of their high specific strength, specific stiffness, energy absorption capabilities, and designable ability. Crashworthiness is defined as the ability to protect the safety of occupants under a survivable crash or impact. The increasing requirements for aviation safety have led to the extensive research on the crashworthiness of aircraft structures. The study on energy absorption behavior of composite structures is significant in improving their energy-absorbing capability. Numerous energy-absorbing studies and applications of composite structures have been conducted in the past decades. Experimental studies [1,2] indicated that the energy-absorbing ability of composites is higher than that of light metal structures. Composites have an advantage in terms of their specific energy absorption (SEA), and they are easy to manufacture and maintain. The energy-absorbing mechanism of composites mainly depends on the reasonable structure configuration, ply design, loading, rate, and trigger mechanism [3,4]. Vladimir [5] simulated the crushing process of corrugated composite plates but did not consider the effect of shear characteristic on structural failure. Okano et al. [6] studied the energy absorption properties of a hybrid braided fiber-reinforced plastic (FRP) tube and found that the tube with a 60° braiding angle showed the highest energy-absorbing capability. Muhi et al. [7] studied the hybridization effect of the glass fiber-reinforced plastic (GFRP) behavior under high-velocity impact, and the result revealed that hybridization improves the laminate performance under dynamic penetration.

Recently, Wang et al. [8] studied the uniaxial compression behavior of luffa-filled tubes and found that the cross-sectional topology of the filler material has a negligible effect on the SEA per unit mass. Bandaru et al. [9] used hydrocode simulations to investigate the effect of hybridization on hybrid composite armors under ballistic impact. They found that the GF layer in the exterior and the CF layer on the front side offer good ballistic impact resistance when the KF layer is arranged at the rear side. Siromani et al. [10] developed a finite element modeling methodology to study the crushing behavior and energy absorption characteristics of graphite/epoxy laminated circular tubes, but the shear failure was not considered into the model.

At present, research into the crashworthiness of aircraft composite structures is a focus for some scholars. Marco et al. [11] analyzed the water dynamic impact response of composite skin panels. Duan et al. [12] studied the effect of the structure-optimized design of sinusoidal composite tape specimen on energy absorption and crush peak loading to improve the SEA and reduce the impact peak load. Composite tube is an important component of the

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energy-absorbing structure of aircraft. Thus, in-depth studies into the dynamic impact properties of crushing average load and total energy absorption are necessary. Currently, experimental studies on composite energy-absorbing structures are mainly concentrated on quasi-static axial loading condition [13,14], and experimental studies on transient dynamic axial impact are relatively lacking. Meanwhile, the effective numerical simulation method is proposed to predict the axial dynamic impact response of composite tubes and improve the limitations of long period and high cost of composite structures in dynamic impact tests. This method will be important in theory and practice.

Some researchers proposed different numerical simulation methods for energy-absorbing composite structures. Gong et al. [15] used the parameter equivalent method and considered the composite laminates as the equivalent elastic–plastic material. The dynamic impact response is simulated by the transient dynamic software MSC.Dytran, the corresponding load–displacement curves are obtained, and the simulation results are consistent with the experimental results. However, this method does not contain the anisotropic constitutive relationships of composites; it also ignores the microscopic damage model of composite materials and cannot accurately reflect the progressive damage model of composite structures. In Refs. [16,17], the axial impact test of composite square tubes is simulated through LS-DYNA software, which considers the continuum damage mechanics. However, only the maximum strain failure criterion is considered, and the influence of shear failure on fiber and matrix is ignored.

The present study aims to develop a new method to simulate the crashworthiness performance of composite tubes. First, the trigger mechanism of composite tubes is designed and the corresponding axial impact tests are performed. Considering the different failure modes and progressive damage evolution law of composite materials, stiffness degradation theory that concentrates on the analysis of crashworthiness damage for composite tubes is proposed combined with the improved Hashin damage criterion. Second, the finite element secondary subroutine of progressive damage analysis for carbon/epoxy tubes is developed and applied based on the MSC.Dytran platform, and the crashworthiness numerical simulation of carbon/epoxy tubes is conducted. Finally, the test and simulation results are comprehensively analyzed, which also demonstrates the application of this new method.

2. Experimental research

2.1. Experimental preparation

All the tubes used for the dynamic tests are manufactured (Beijing Institute of Aeronautical Materials, Beijing, China) through a winding process (FWM3000L, Asahi-Engineering Company). The corresponding production process for the specimens is as follows. First, the winding fibers are cured at 60 °C for 0.5 h and 120 °C for 2 h and then slowly cooled down to room temperature. Second, after the curing and de-molding process, the composite tubes are cut into specimens (Fig. 1) with appropriate dimensions for impact tests.

All the tested G803/5224 specimens in this study are cylindrical composite tubes that have a uniform length of 125 ± 0.2 mm and an internal diameter of 50 mm. The trigger mechanism is also set up at the top of the specimens. Three replicate specimens are tested at the same loading condition to guarantee the stability of energy-absorbing capability and ensure the validity of the dynamic impact tests on composite tubes. The typical configuration of specimens is shown in Fig. 1.

Experimental studies have shown that a reasonable trigger mechanism can reduce the maximum impact load and control the initial failure mode of energy-absorbing components so that progressive failure occurs at the dynamic impact process and improves the energy-absorbing capability of composite structures [18]. The chamfer trigger configuration in the present study is shown in Fig. 2. A 45° chamfer is set up on the top of the specimens and as the trigger mechanism to produce gradual crushing and obtain good energy-absorbing effectiveness of the circular tube in the axial loading. The overall collapse failure of tubes in axial impact is avoided to reduce the peak load and induce the occurrence of gradual crushing of the circular tube. In this process, t is the thickness of the composite tube, and θ is the angle between the bevel of the trigger mechanism and the axis of the circular tube.

The G803/5224 carbon/epoxy composite tube is made of bidirectional carbon-fiber-impregnated materials, of which a single layer is 0.1 mm thick, the total number of layers is 30, and the corresponding ply sequence is $[(\pm 45)_{15}]$. The basic material properties of the composite tube are listed in Table 1.

2.2. Experimental method and results

Dynamic impact tests are conducted based on a drop test system (DHR-9401, Fig. 3) and the auxiliary experimental equipment are based on the universal design specification of aircraft crashworthiness. The weight of the drop hammer is set as 81.5 kg, and the drop hammer is fixed at the height of 5.31 m to obtain the desired transient velocity of 10.2 m/s and ensure that each tube has 1/2–3/4 of its height participated in the crushing tests. The image and the data are obtained using a 2000 frame/sec high-speed camera (Fig. 3b) and a Tektronix digital oscilloscope (Fig. 3c). These equipments are used to record the evolution of the crushing mechanisms and to digitize the data, respectively.

The corresponding diagram of the experimental installation and testing procedure is shown in Fig. 4. The corresponding test procedure in the dynamic impact is as follows. First, the initial kinetic energy is obtained by the drop hammer device. A circular tube specimen is placed at the center of the drop hammer system and located at the bottom of the mass center of the drop hammer at the vertical direction. A force sensor (Fig. 4) is embedded in the bottom of the test base platform, and a laser range sensor is fixed on the ground to measure the distance from the hammer to the ground. Second, the drop hammer is released from the fixed height where it begins and falls on the specimen to trigger the deformation of the circular tube. The axial crushing force and displacement data in the crushing process are measured by the force and laser range sensors respectively. The acquisition data are collected through a Tektronix digital oscilloscope and are ultimately stored in a computer. Finally, the force–displacement curves are computed from the recorded data. A 2000 frame/sec high-speed camera is also used to record the deformation state in the dynamic impact process for parts of the tests.

Fig. 5 shows the progressive failure morphology of the G803/5224 carbon/epoxy tubes from the high-speed photography. The damage first emerges on the trigger mechanism with the increased displacement of the drop hammer. Meanwhile, a small amount of curled fiber bundle (Fig. 5b) is observed. The crushing displacement gradually increases with the increase in impactor loading. Consequently, the progressive failure is found as the crush displacement increases and some micro-fragments (Fig. 5c–e) splash out of the tube wall. Finally, the eventually crushing displacement reaches 95 mm, and the steady progressive failure is observed in whole from top to bottom because of the reasonable trigger mechanism setting. Similar to the simulation results, some fracture debris (Fig. 10d–h) also splash out of the tube wall in the progressive crushing process. Overall, the composite tubes express an excellent energy-absorbing capability.