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Hypervelocity impact behavior and residual flexural strength of C/C composites

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ABSTRACT

This paper describes the hypervelocity impact behavior and the residual strength of carbon fiber reinforced carbon (C/C) composites under different impact velocity. Impact tests of 2.5D C/C composite samples have been performed using one stainless steel ball driven by solid explosive to detect correlations between the impact direction and damage distribution and the residual flexural strength of the composites. Results showed that the impact resistance of the C/C composites was affected by the impact velocity. Damage modes evolved from matrix cracking and fiber breakages to spallation and delamination along the impact direction. Furthermore, delamination occurs delamination occurred in mat plies and 90° plies, resulting from poor load-bearing capability of short mat layers and weak adhesion between fiber bundles. In addition, the residual strength of the damaged C/C composites decreased by 30.6–43.5% and 47.4–48.6% in the upper side and bottom side, respectively. The flexural stress-strain curves and fracture modes of post-impacted composites were various due to the diverse damage types in different areas.

1. Introduction

Nowadays, the total number of space debris in the earth orbit sharply increases with the development of aerospace activity. These debris all travel at hypervelocity enough for a relatively small piece of orbital debris to destroy a spacecraft, which seriously threatens the security of manned spacecraft [1,2]. Hypervelocity impact damage can potentially degrade performance, shorten the service life, or cause catastrophic accidents [3,4]. Hypervelocity impact behavior of novel materials used as spacecraft protecting structures have been researched, including aluminum matrix composites [5–8], metal/ceramic composites [9] and polymer composites [10–13].

Carbon/carbon (C/C) composites have garnered considerable attention owing to their advantages of high specific strength and stiffness, good thermal conductivity, low thermal expansion coefficient and superior ablation performances [14,15]. They are the main components of thermal protecting systems in airframes and reusable launch vehicles [4,16]. Most focus of studies has been put on the oxidation and ablation properties of coated and modified C/C composites under the static environment [17–20]. In our previous work, SiC coated C/C composites were designed to determine effects of hypervelocity impact on ablation behavior of coated C/C composites [21]. We discovered that the interfaces between SiC coating and the matrix have a great effect on the impact resistance of coated C/C composites. Once C/C composite structures used in vehicles were impacted by orbital debris, the strength of the composites would be deteriorated, providing a large number of potential threats to the safety of space vehicles. It is therefore necessary to investigate effects of the impact damage on the operational life and mechanical performance of C/C composites. Though extensive studies have been dedicated to understanding certain mechanical properties like strength and fatigue life [22–29], the knowledge about hypervelocity impact behavior of C/C composites is still incomplete. Xie et al. [30] studied the effects of hypervelocity impact on the structural integrity of thin C/C composite laminates for high temperature applications. Grujicic et al. [31] predicted the extent of damage and the probability for failure of the carbon-carbon/carbon-foam CAV panels during potential hypervelocity impact of space debris with the outer surface of the CAVs by a transient non-linear-dynamics-based analysis. Most

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researchers put their attention on the integrity of thin laminates, while impact behavior and strength reductions of thick C/C composites along thickness direction have not been clearly reported.

In the present work, hypervelocity impact tests using a steel projectile driven by explosives on 2.5D C/C composites with thickness of 10 mm at different velocities were performed. The main intentions were to investigate hypervelocity impact behavior and the residual flexural strength of C/C composite samples along thickness direction after various velocity impact tests. Besides, impact damage evolution of the C/C composite was discovered by the cross section images of post-impacted samples. At last, the relationship of residual strength and impact velocity and damage distribution were investigated.

2. Experimental procedure

2.1. Composites preparation

2.5D needled preform, as shown in Fig. 1, was made up of layers of 0° non-woven carbon fiber cloth, 90° non-woven carbon fiber cloth and short-cut mat layer after needle-punching in Z direction step by step. The preforms were densified using methane via isothermal chemical vapor infiltration (ICVI) process 1100 °C for 200 h [32], and the vacuum system of the CVI vessel must be operated at least 2 h and guarantee in-chamber high vacuum (≤−0.095 MPa). During heating, depositing and cooling processes of composites preparation, the high vacuum state of the CVI vessel must be kept as well. The as-prepared C/C composites possessed a high-textured pyrocarbon matrix and a density of 1.72 ± 0.01 g/cm^3. All of the composites were not heat treated.

2.2. Experimental methods

Samples used in impact tests were Φ70 × 10 mm^3 plates. Stainless steel balls with a weight of 0.89 g and a diameter of 6 mm were chosen as projectiles to perform hypervelocity impact tests driven by driven by pentaerythrite tetranitrate explosive. The explosive device could be found in our previous work [21]. A ZBS-10 multichannel intelligent explosive rate measuring instrument with precision of 0.1 μs was employed to measure impact velocity. Two types of velocities (2.5 km/s and 3.5 km/s) were designed to investigate the effects of impact velocity on damage modes and residual flexural strength of C/C composites under hypervelocity impact. For each selected velocity, five targets were tested to guarantee the results accuracy.

After hypervelocity impact tests, specimens with the size of 55 × 8 × 4 mm^3 were cut from the post-impacted plates to detect residual flexural strength of C/C composites according to the crater positions. Static three-point bending tests before and after hypervelocity impact tests were conducted by a servo-hydraulic testing machine (INSTRON 8872, INSTRON Co.) at a constant loading speed of 0.5 mm/min with the span of 40 mm. There were three types of testing samples, including un-impacted samples (sample-U), samples involved frontal surface damage (sample-F) and samples involved rear surface damage (sample-R). Flexural strength (σ_b, MPa) was calculated by Eq. (1):

$$\sigma_b = 3PL/2bh^2 \quad (1)$$

where P is the maximum load (N), L is the span length of flexural test (mm), b is the width of specimen (mm) and h is the thickness of specimen (mm).

The compressive strength of as-prepared C/C composite used in this study was measured by a SANS CMT5304 universal testing machine with sample dimensions of 10 × 10 × 10 mm^3 to compare with the impact pressure produced by impact projectiles. Compressive strength (σ_y, MPa) was calculated by Eq. (2):

$$\sigma_y = P/F \quad (2)$$

where P is the maximum load (N), F is the cross sectional area of tested sample (mm^2).

After impact tests, macrographs of front and rear surfaces of post-impacted samples were obtained by one digital camera (DSC-RX100 M3, SONY). Damage occurring on the front surface, rear surface and cross section were observed to identify the impact behavior of C/C composites. Defect images were observed by scanning electron microscopy (SEM, JOEL JSM-6460, Japan).

3. Results and discussion

3.1. Impact test results

After impact tests, two types of craters can be observed on the front surfaces (A1 and B1) of C/C composite targets, as shown in Fig. 2, I-crater is generated by the projectile and II-crater is produced by explosive debris. Comparing the front surfaces of two samples, the maximum depths and diameters of I-crater in sample-A and sample-B are 0.11 mm and 5.93 mm, 1.01 mm and 6.36 mm, respectively, which indicates that the maximum of depth and diameter of I-crater increase with the increase of impact velocity. Furthermore, sample-A has less II-crater than that of sample-B, revealing that the damage generated by explosive debris increases with the increasing velocity as well. On the rear surfaces (A2 and B2), cracking and delamination can be seen on all post-impacted samples. On the B2 surface, one slice was peeled off from the sample, while the spalling does not occur on the rear surface of sample-A. These results demonstrate that spallation

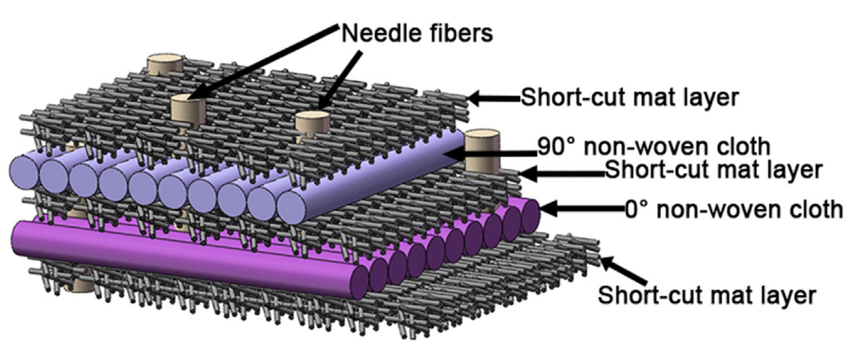

Fig. 1. Sketch of 2.5D C/C composite preform.