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The shock and spallation behavior of a carbon fiber reinforced polymer composite

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ABSTRACT

In this work, the shock and spallation behavior of a carbon fiber reinforced polymer (CFRP) composite has been studied using the plate-impact technique. The free surface velocity of the sample was monitored by a dual-laser Doppler pin system (DPS). The results showed that a steady shock front can be achieved and propagated in the composites. However, due to the stress wave dispersion and attenuation, the peak particle velocity was attenuated with propagation distance and became even more apparent as impact velocity increased. In addition, the shock Hugoniot curves were computed and compared with experimental results, and the CFRP was found to be stiffer than the materials cited in the references in the range of 1.5–5.3 GPa. Meanwhile, the spall strengths of the composites were observed to increase with increasing strain rates within the test range. Finally, the soft recovered samples were examined by macroscopic and microscopic analysis and it was found that the fracture surface revealed an envelope of matrix and fiber/matrix interface delamination, indicating that both sites were equally prone to fracture.

1. Introduction

Fiber reinforced composites are widely used in aerospace, defense and other manufacturing industries where both light weight and high strength are critical design elements [1]. Consequently, detailed knowledge of this material behavior, especially under dynamic shock loading, is becoming ever more valuable for the design of engineered structures routinely subjected to severe impacts during in-service life [2].

The shock response of a composite laminate is known to vary significantly with constituent materials, shock duration [3], shock direction [4] and other microstructural details. In most cases, the loading axis has been perpendicular to the laminates. Dandekar et al. [5] investigated the shock response of a glass reinforced polymers (GFRP) material in the through-thickness direction by shock experiments and obtained a linear relation between shock velocity and particle velocity by dividing the coefficients in the quadratic fit. This linear relationship has also been observed by other researchers in a wide range of materials including carbon fiber-epoxy composites [1,6] and glass reinforced polymer composites [7]. Dattelbaum et al. [8] also examined the shock responses of two carbon fiber polymer composites in the through-thickness direction by plate-impact experiments. In their work, they tested the shock response of a fully dense carbon fiber-filled phenolic composite (CP) and a high degree of porosity filament-wound carbon fiber-epoxy composites (CE). By the reason of the microstructural and chemical differences of the constituent materials, the result showed that the shock wave structures were highly heterogeneous in the fiber-epoxy composite (CE) and the carbon fiber-filled phenolic composite (CP) was stiffer than the fiber-epoxy composite (CE).

In addition to the through-thickness shock, the researches on shock response along the in-fiber direction have been conducted. It is expected that the shock response along the in-fiber direction would be quite different from that through-thickness direction. Hazell et al. [9] investigated the shock behavior of Dyneema® by plate-impact experiments. In their work, they used a manganin stress gauge to measure the shock propagation in the specimen and found that the shock wave was composed of two different components consisting of a high-velocity two-part wave propagating along the fibers and a slower wave traveling through the matrix. Hazell et al. [10] also studied the effect of specimen thickness on the shock propagation of an aerospace-grade CFRP laminate along the in-fiber direction. They found that for a given shock pressure, changing the thickness of test specimen resulted in a change

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in the magnitude and duration of the ramped portion of the wave front. More recently, Millett et al. [11] examined the effect of orientation on the shock response of a carbon fiber-epoxy composite. They showed that the in-fiber direction shock response was significantly stiffer than the through-thickness orientation at low shock intensities; as the shock pressure increased, the Hugoniots of the two orientations converged. Thus, the orientation only affects the shock equation of state (EOS) at lower shock pressure.

The through-thickness tensile strength (spallation) property of a composite material [12–16] under shock loading is critical to structural performance. Gupta et al. [17] investigated the spall behavior of a woven carbon/carbon (C/C) and carbon/polyimide (C/P) composite laminates. The dynamic tensile strengths of the composite laminates were measured using a laser spallation technique. Dandekar et al. [18] and Yuan et al. [19] also studied the spall strength of a glass fiber reinforced polymer (GFRP) composite. Their results showed that with the increase of shock-induced shear the delamination strength (spall strength) of the composite was decreased. Recently, Lässig et al. [20] investigated the spall behavior of UHMWPE and revealed that the spall failure of UHMWPE composites was not restricted to a single crack plane. Instead, the spallation of the composite plates was accompanied by several delamination at ply interfaces, which were caused by intersections of subsequent release waves.

So far, only a limited number of experiments have been carried out to examine the shock behavior of carbon fiber-based composites, and especially how dynamic spall strength varies with strain rates. In the present study, we examined the shock and spallation response of a carbon fiber epoxy composite loading along the through-thickness direction. The results of the present study along with the shock compression data obtained from literature were used to better understand the shock equation of state (EOS) of our own test material. In addition, the effects of strain rate on spall strength were also investigated. Finally, macroscopic and microscopic examinations of the impacted samples were conducted to understand the failure morphology [21] and damage mechanism of the composites.

2. Experimental

2.1. Materials used

The materials used in the present research were unidirectional CFRP composite laminates that were fabricated by Harbin FRP Institute, China, from a commercially available prepreg made by Toray Industries, Inc. The carbon fiber was T700 and the epoxy matrix corresponded to TDE-85. The CFRP panel was 3 mm thick and made from 24 plies with quasi-isotropic layup $[0/45/90/\text{-}45]_{3s}$. This configuration is widely used when there is not a preferential load direction, which makes the laminate useful for many applications. In these experiments, the laminas were aligned such that they were parallel to the induced shock wave. The fabricated CFRP panel also has a flat specimen surface, which meets the requirement of one-dimensional shock-wave loading experiments. The longitudinal (c_L) and shear (c_S) sound velocities along the thickness direction were measured by a 10 MHz quartz transducer with an Olympus 5073 PR pulser/receiver in the pulse-echo configuration. The material properties of the CFRP shown in Table 1 were provided by the manufacturer, with the bulk sound speed c_B calculated using Eq. (1). The material properties of plates (OFHC copper) were taken from Ref. [22].

$$C_B = \sqrt{C_L^2 - \frac{4}{3}C_s^2} \tag{1}$$

Fig. 1 shows micrographs of the cross-sections of a prepared virgin target specimen in the through-thickness direction at two magnifications. The cutting plane was parallel to the fiber direction in the outmost ply. The carbon fibers were about 5 μm in diameter, and the fiber alignment was exceptionally unidirectional. Note that in this scanning electron micrograph, the loading axis was in the direction parallel to the page.

Table 1
Material properties of the CFRP and Copper.

Property	CFRP	Property	Copper
Fiber volume fraction	60%	Density, ρ (kg/m^3)	8930
Longitudinal stiffness, E_1 (GPa)	132	Young's modulus, E (GPa)	124
Transverse stiffness, E_2 (GPa)	11	Shear modulus, G (GPa)	47.7
Poisson's ratio, ν_{12}	0.29	Poisson's ratio, μ	0.34
Shear modulus, G_{12} (GPa)	5.2	Yield stress, A (MPa)	90
Longitudinal tensile strength, X_t (MPa)	2178	Pre-exponential factor, B (MPa)	292
Longitudinal compressive strength, X_c (MPa)	1039	Work-hardening exponent, n	0.31
Transverse tensile strength, Y_t (MPa)	24	Strain rate factor, c	0.025
Transverse compressive strength, Y_c (MPa)	168	Thermal softening exponent, m	1.09
Interlaminar shear strength, S (MPa)	81	Gruneisen,γ	2.02
Density, ρ (kg/m^3)	1600	C_0 (mm/μs)	3.94
Longitudinal sound velocity, c_L (mm/μs)	3.212		
Shear sound velocity, c_S (mm/μs)	1.472		
Bulk sound velocity, c_B (mm/μs)	2.725		

2.2. Experimental technique

A common way for measuring the shock Hugoniot and spall strength of materials is by conducting plate impact experiments. Fig. 2 shows the schematic of the plate impact experiment. Two sealing O-rings have been fitted into the groove on the sabot to keep a projectile from rotating as it was propelled. The flyer plate located in front of the sabot was accelerated toward the target by pressurized nitrogen gas. In order to avoid the ballistic deflection of flyer affected by air resistance, the target chamber has been evacuated to a partial vacuum of about 10Pa before impact. Projectile velocity measurements and triggering of the DPS recording oscilloscope were achieved with a series of electrically charged metal pins of known spacing. The waves transmitted through the CFRP laminates were monitored at the free surface of the CFRP laminates by a dual-laser Doppler pin system (DPS) [23], which is essentially a displacement interferometer like photon Doppler velocimeter. Two optical fibers (denoted as DPS#1 and DPS#2) were used as DPS probes to guide 1550-nm laser light to illuminate the target and receive the reflected light signals. The superposition of the reflected light (Doppler shifted) with the reference light from the laser source (unshifted) created an interference pattern, whose beat frequency was proportional to the target velocity [24]. DPS#1 and DPS#2 were fixed near the rear surface of the disk and rectangular plate, respectively. All optical signals were analyzed by the short time Fourier transform (STFT) technique, and a Hamming window of size 4096 samples with an overlapping step size 256 was used. The DPS probes tracked the particle velocity with an uncertainty better than 1%. The measured particle velocity profile was then used to obtain the shock and spallation characteristics of the composite specimens.

Samples made of two parts, a 30 mm diameter × 3 mm thick disk and a 25 mm × 15 mm × 3 mm rectangular plate, were machined from a sheet (300 mm × 300 mm × 3 mm) received from manufacturer by Wire cut Electrical Discharge Machining (WEDM) with a geometry tolerance of ± 0.1 mm for diameter, thickness, length and width of the feature. This was done to avoid the loss of the one dimensional shock conditions due to edge release during the experiments [1]. Then, two machined parts were stacked and glued together by a slow curing two-part epoxy adhesive to make a stepped specimen. The fabrication was carried out by the vacuum bag molding technique to eliminate the entrapped air and excess epoxy adhesive. As a result, the thickness of