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Strain rate-dependent compressive properties of C/C composites

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Abstract

To understand the strain rate sensitivity of compressive properties of carbon/carbon (C/C) composites, both the quasi-static and dynamic compressive tests of C/C composites were conducted using electronic universal testing machine and modified split Hopkinson pressure bar (MSHPB) with pulse shapers. The results indicated that the compressive strength and stiffness of the C/C composites were sensitive to the strain rate, and increased with the increase of strain rate. The samples failed by shearing under quasi-static loading, and by crushing under dynamic loading. The fiber failure was characteristic of extensive debonding within bundle and many small steps under quasi-static loads, where as, the fiber failure was characterized by fiber bundle multiple splitting with abrupt fracture surfaces under dynamic loads.

Keywords: C/C composites; Dynamic compression; SHPB; Strain rate sensitivity

1. Introduction

Carbon/carbon (C/C) composites are widely used in aeronautical and aerospace applications, due to their high specific stiffness, high specific strength up to temperature exceeding 2000 K and low density. When C/C composites were used as heat shields for space shuttles and hypersonic planes, structures may be subjected to impulsive loading such as the impact of debris during take off or landing [1,2]. Therefore, dynamic properties of the materials under impact loading are important, and failure characteristics under dynamic loading must be taken into account for material designs.

The split Hopkinson pressure bar (SHPB) technology, developed by Kolsky [3], has been widely used to determine the high strain rate response of materials under tension, compression and torsional loading as it can give the scope to test materials at high strain rates. Strain rate effect on materials has been studied experimentally by many researchers. Sarva and Nemat-Nasser [4] used a modified split Hopkinson pressure bar (MSHPB) to investigate the effect of the strain rate on the compressive characteristics of silicon carbide under uniaxial loading. They found a remarked increase in the compressive strength of silicon carbide at the strain rates above $10^2\ s^{-1}$. Hour et al. [5] studied the effect of dynamic loadings on the mechanical properties of carbon/epoxy laminate composites. Their results indicated that the dynamic compressive strength through the thickness direction of cross-ply laminates exhibited a reduction as compared with the quasi-static value. Songa et al. [6] investigated dynamic compressive behaviors of a polystyrene foam using a pulse-shaped SHPB setup, they concluded the elastic modulus and the collapse stress of the polystyrene foam were sensitive to strain rates.

Referring to the tensile properties of C/C composites, a wealth of literature including high-temperature behaviors has been reported [7–9]. However, little data on the compressive behavior of C/C composites is available [10]. Although many research efforts have been focused upon various composites dynamic properties [11–14], the compressive behavior of C/C composites under dynamic loading has not yet been reported in the open literature, to our best knowledge. The present work may be, thus, a first step to understand the effect of strain rate on compressive characteristics of C/C composites using a MSHPB.

2. Experimental procedures

2.1. Material

Preforms of the C/C composites used in this work were a commercially available 3K-PAN carbon felts (fiber diame-

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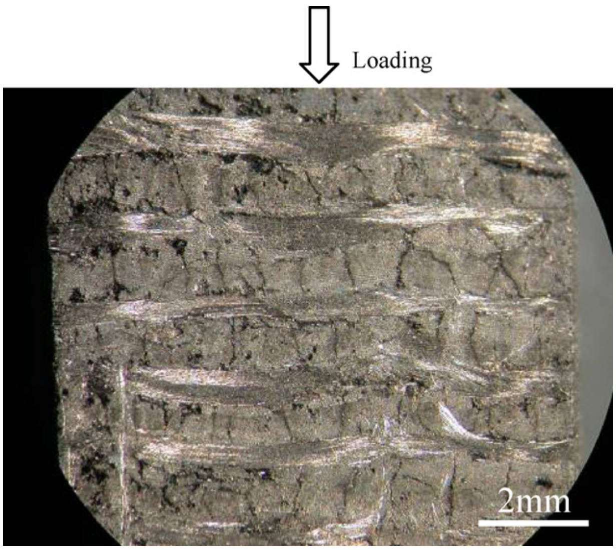

Fig. 1. Typical optical macrograph of longitudinal section of the as-received C/C composite showing pre-existing macroscopic cracks, voids.

ter: 6–8 μm) with the apparent density about 0.6 g/cm^3, which were manufactured by Yixing Tianniao Co. Ltd., China. Using a needle-punching technique, they were made up of layers of non-woven carbon fiber cloth and short-cut web laminated in plane direction at angles of 0/90°. The size of disk-shaped preforms was 300 mm o.d. × 100 mm i.d. × 35 mm thickness. The C/C composites were densified by the thermal gradient chemical vapor infiltration, followed by heat treatment at a temperature of 2400 K for graphitization in an inert environment. The carbon source gas used for infiltrations run was the natural gas (98% CH_4, 0.3% C_3H_8, 0.3% C_3H_4, 0.4% other hydrocarbons, 1% N_2). Further details of the processing technology see Ref. [15]. The volume fraction of carbon fiber was about 35%, and the density of the C/C composites was 1.55 ± 0.03 g/cm^3. The porosity rate for the C/C composites was about 18%. Fig. 1 indicates the typical optical macrograph of longitudinal section of the C/C composites prior to static and dynamic testing.

2.2. Dynamic tests

The dynamic compressive tests were conducted using a SHPB, comprising three 12.7 mm diameter steel bars: a striker bar (256 and 125 mm in length corresponding to the strain rates of 4.5×10^2 and 1.5×10^3), an incident bar (1200 mm in length) and a transmitter bar (1000 mm in length). The specimen was sandwiched between the input and output bars. The striker bar, propelled by pressurized gas, impacted against the input bar. Upon impact, a compressive stress pulse was generated in the striker and input bar. The duration of the loading pulse was equal to the time for stress wave to traverse back and forth once in the striker bar. The compressive stress pulse then impinged on the specimen sandwiched between the input and output bars. Part of the incident pulse was reflected back into the input bar from the input bar-specimen interface and part of it was transmitted through the specimen into the output bar. Strain gauges were mounted on the bars to measure the incident, reflected, and transmitted pulses. The output signals of strain gauges were recorded on a digital oscilloscope. One-dimensional elastic wave equations were then used to calculate the strain in the sample from the reflected pulse, and the corresponding stress from the transmitted pulse. Specifically, the stress, strain rate and strain histories were, respectively,

$$\sigma_s = E\left(\frac{A_b}{A_s}\right)\varepsilon_T(t) \tag{1}$$

$$\dot{\varepsilon}_s(t) = -\left(\frac{2C_0}{l_s}\right)\varepsilon_R(t) \tag{2}$$

$$\varepsilon_s(t) = -\left(\frac{2C_0}{l_s}\right)\int_0^t \varepsilon_R(t)\,dt \tag{3}$$

where ε_T (t) and ε_R (t) denote the amplitudes of the transmitted and reflected strain pulses. E, A_b and C_0 denote the Young's modulus, cross-sectional area and longitudinal wave speed of the bars. A_s and l_s are the cross-sectional area and length of the specimen, respectively. The history of stress according to Eq. (1) and the history of strain according to Eq. (3) were combined to yield the stress–strain relation of specimen.

Ideally, the stress and strain fields in the specimen should be homogeneous and the radial inertia effect of the specimen and friction effect between specimen and the bars should be negligible for a SHPB test. In order to provide higher analysis precision of SHPB experiments, specimen design is the most critical part. According to Gillespie and Meng's work [16,17], the aspect ratio of 1:1 for specimen is valid to achieve a stress homogeneous and suppress the influence of friction effect. Considering the quality of the specimens (Fig. 1), the relatively big sample dimension should be adopted for the testing if homogeneous properties are needed. So, the as-received material was machined into cylindrical specimens with a diameter of 10 mm and length of 9.5 mm. Top and bottom surfaces of the specimen were polished so as to be parallel each other. The accuracy was about 10 μm, in order to maintain uniaxial loading.

It was important to ensure that a nearly constant strain rate over most of the test duration was attained, especially for specimen with a relative larger diameter, because the effect of radial inertia was proportional to the square of the sample diameter. For the C/C composites specimen with an approximately linear response in compression up to the failure stress, the constant strain rate cannot be ensured using the traditional SHPB with an incident pulse of trapezium shape. To achieve the goal of a constant strain rate for dynamic test, a hard copper cushion designed by numerical simulation and experimental trials, also called the pulse-shaper [18–20] was placed at the impact end of the incident bar, to introduce a monotonically increasing ramp-like stress pulse in the incident bar. The dimensions for pulse shapers were Ø5.0 × 1.0 and Ø7.5 × 1.0 mm, corresponding to the strain rates of 4.5×10^2 and 1.5×10^3, respectively. All specimens were lubricated carefully by using MoS_2 in order to reduce this contact friction.