Dynamic Biaxial Compression of CFRP Laminates Using Electromagnetic Loading

Huaipu Kang · Jintao Liang · Yi Li · Hao Cui · Yulong Li

Abstract
The dynamic biaxial compression test for carbon-fiber-reinforced polymer (CFRP) laminates was carried out via synchronous electromagnetic loading in this study. During the experiments, four stress pulses transmitted along four incident bars, loading the square specimen simultaneously from four directions to keep the center of the specimen still. The dynamic mechanical behavior of CFRP was obtained employing the one-dimensional wave propagation theory, and the deformation and failure processes of the specimens were recorded by a high-speed camera. The effects of various biaxial stresses on the compressive strength were investigated in three biaxial and one uniaxial loading cases. For the CFRP laminates, the dynamic transverse compressive stress showed little effect on the longitudinal ultimate compressive strength. Numerical simulations were performed to understand the dynamic stress wave propagation. It showed that the employed loading device could guarantee good biaxial loading conditions until the ultimate failure of the specimens. This approach allows for the dynamic biaxial compression testing of various materials, which is of great significance in evaluating the dynamic impact performance of aeronautical composites.

Keywords Carbon-fiber-reinforced polymer (CFRP) · Dynamic loading · Biaxial testing · Electromagnetic loading

1 Introduction
Carbon-fiber-reinforced polymer (CFRP) laminates have been widely employed in the aerospace industry, and their compressive behavior has been one of the major concerns during the design and analysis phase. Significant work has been done to find out the compressive failure mechanisms of CFRP composites under uniaxial stress [1–5]. The compressive failure of CFRP composites was systematically introduced by Budiansky and Fleck [1], and the compressive failure mode was found to be dominated by plastic kinking. Pinho et al. [3] proposed a fiber compressive failure criterion which could accurately predict the failure behavior. Daniel et al. [2] conducted uniaxial compression tests on off-axis specimens over a wide range of strain rates and proposed a strain-rate-dependent failure criterion. Different specimen designs and laminate configurations for compression tests have been evaluated by Thomson et al. [4], and the cross-ply cuboidal specimens were recommended for testing the compressive strength of CFRP. Recently, Thomson et al. [5] also successfully performed dynamic longitudinal compression tests on cross-ply specimens, and a simple phenomenological approach was proposed to predict the rate-dependent fiber kinking strength of CFRP. To explore the failure response of composites in a complex stress domain representing engineering applications, testing of composite samples under biaxial loading is highly desirable [6].

For continuous fiber-reinforced polymers, it is challenging to determine the biaxial tensile strength in experiments because of the unavoidable premature failure [7–11]. Antoniou et al. [7] predicted the failure of the CFRP cruciform specimens and found that the initial fracture occurred outside the region of interest. Lamkanfi et al. [10] found that the unavoidable stress concentration at the edge of the thickness-tapered region may result in premature failure. In addition to
continuous fiber-reinforced polymers, Kang and coworkers [12] investigated the biaxial tensile failure behavior of short carbon-fiber-reinforced PEEK composites and obtained the failure envelope in the tension–tension regime via a combined experimental–numerical method. Reliable biaxial tests in the tension–compression and compression–compression regimes are relatively easier to achieve [13–15]. Gan et al. [13] investigated the influence of through-thickness compressive stress on the fiber-direction tensile strength, and the results revealed a linear decrease in fiber-direction strength with the increase in the applied through-thickness stress. Potter et al. [14] investigated the failure mechanisms and stress–strain behavior of cross-ply laminates under quasi-static in-plane biaxial compression by adopting a cruciform biaxial test frame, and the failure data conformed nicely to a Mohr–Coulomb-type shear failure law. Xu and coworkers [15] conducted quasi-static biaxial compression tests on the 3D carbon/carbon composites, and the experimentally obtained failure stress points traced an elliptical path in the principal stress space, which could be well represented by the Tsai–Wu criterion. The results of these studies show that the mechanical behavior of composites depends strongly on the hydrostatic pressure [5, 13, 14, 16]. Despite those reported studies on biaxial testing of composites in the quasi-static regime, the available biaxial testing systems are expensive and reliable results are not easy to obtain, and little work has been done on the biaxial failure of composites at high loading rates.

The main difficulty for biaxial loading at high strain rates is the accurate synchronization of dynamic loads. With hydraulic or pneumatic loading apparatus, generating synchronous stress pulses at high strain rates is nearly impossible due to the uncontrollable mechanical delay. To resolve this problem, an electromagnetic split-Hopkinson pressure bar was developed by Nie et al. [17], which has demonstrated its ability to generate synchronous stress pulses. With aid from the electromagnetic loading method, two symmetrical incident pulses can be accurately generated within several microseconds [18]. Consequently, the incident pulses can be transmitted along the incident bars and simultaneously load the specimen in both directions. Therefore, the excellent synchronization obtained with this electromagnetic loading method has shown its potential in achieving dynamic biaxial loading [19].

Our study aimed to develop a reliable dynamic biaxial compression testing method based on a biaxial electromagnetic Hopkinson bar system. The representative CFRP cross-ply laminates were chosen as the experimental material. In this paper, the experimental details and data processing methods are introduced first; and then the experimental results are provided and discussed; finally, conclusions are outlined for summary and outlook.

2 Material and Experimental Setup

It is extremely difficult to obtain reliable data for the unidirectional (UD) laminates from compression tests because the compressive failures of the UD laminates are sensitive to specimen geometry and boundary conditions. On the contrary, the compressive failures of cross-ply laminates are not noticeably affected by either specimen geometry or boundary conditions [4], so the cross-ply laminates were investigated in this work. The cross-ply CFRP laminates with a stacking sequence of [(90/0)s90l], were fabricated from Cytec™ T700/MTM28-1 carbon fiber prepreg according to the manufacturer’s specification, from which three cuboidal specimens were cut for each loading case. The laminates used for the specimens have a fiber volume fraction of 61% and a fiber density of 1522 kg/m³. The UD ply elastic properties for T700/MTM28-1 carbon/epoxy in the principal material axes were taken from [20]: \( E_{11} = 127 \) GPa, \( E_{22} = E_{33} = 8.4 \) GPa, \( G_{12} = G_{13} = 3.7 \) GPa, \( G_{23} = 3.0 \) GPa, \( v_{12} = v_{13} = 0.33 \) and \( v_{23} = 0.4 \). To begin with the dynamic biaxial exploration, the laminates with the simplest lay-up have been chosen as the testing material in this paper.

The schematic of the dynamic biaxial compression system is illustrated in Fig. 1a. The specimens were loaded by four Ti–6Al–4V (TC4) pads clinging to the end faces of four incident bars, and these bars were protected by four sleeves made of polytetrafluoroethylene (PTFE). The loading bar is 15 mm in diameter, so the size of the biaxial compression specimen was determined to be 13.4 mm × 13.4 mm to reserve sufficient space for the TC4 pads. To ensure good contact until ultimate failure, the adopted pads were 90% of the width and 165% of the thickness of the specimen. Due to the loading space limit, this approach is not suitable for measuring the biaxial compressive behavior of materials with large strains. However, this approach can investigate the biaxial compressive response if all the strain tensor components are less than 5%. This means it can be applied to various fiber or particle reinforced materials. Moreover, the synchronization was guaranteed by adopting four synchronous discharging electromagnetic stress pulse generators. These generators generated four synchronous semi-sine stress pulses due to the strong instantaneous repulsive forces between active and inductive coils [17, 18, 21]. The stress waves were recorded by an oscilloscope connected with four strain gauges (indicated by the symbol of ‘SG’ in Fig. 1a) mounted on the four loading bars. These strain gauges were 1.9 m away from the loading end, thus complete incident and reflected stress pulses were recorded. Once dynamic stress equilibrium was established, the stresses and strains were obtained using the one-dimensional wave propagation theory. Same as the symmetrical dynamic uniaxial loading test, the compressive stress (\( \sigma \)), compressive strain rate (\( \dot{\varepsilon} \)) and average
transverse strain ($\varepsilon$) in each direction can be calculated using Eqs. (1)-(3) [18].

$$\sigma = \frac{n_{ij}}{A} = \frac{1}{A} E \left( \varepsilon_{inc,i} + \varepsilon_{inc,j} + \varepsilon_{ref,i} + \varepsilon_{ref,j} \right) \quad (i, j = 1, 3 \text{ or } 2, 4) \quad (1)$$

$$\dot{\varepsilon} = \frac{n_{ij}}{A} = \frac{C_{ls}}{l_s} \left( \varepsilon_{inc,i} + \varepsilon_{inc,j} - \varepsilon_{ref,i} - \varepsilon_{ref,j} \right) \quad (i, j = 1, 3 \text{ or } 2, 4) \quad (2)$$

$$\varepsilon = \int_0^t \dot{\varepsilon} \, dt = \frac{C_{ls}}{l_s} \int_0^t \left( \varepsilon_{inc,i} + \varepsilon_{inc,j} - \varepsilon_{ref,i} - \varepsilon_{ref,j} \right) \, dt \quad (i, j = 1, 3 \text{ or } 2, 4) \quad (3)$$

where $l_s = 13.4 \text{ mm}$ is the side length of the square specimen; $A = 176.71 \text{ mm}^2$ and $A_s = 56.95 \text{ mm}^2$ are the cross-sectional areas of four bars and the specimen, respectively; $E = 113.6 \text{ GPa}$ and $C = 4940 \text{ m/s}$ are Young’s modulus and elastic wave speed of these bars.

The uniaxial symmetrical loading system has effectively reduced the time to reach stress equilibrium under dynamic loading [18]. This is true for dynamic biaxial loading with four electromagnetic stress pulse generators. Meanwhile, the stress pulse amplitudes and widths can be adjusted by varying the charging capacitance and voltage, and the dual charge–discharge systems in Fig. 1a allow different biaxial loading ratios. In this work, two 2 mF capacitors were adopted, and the biaxial loading ratios were controlled by varying the charging voltages in the two charge–discharge systems. Three dynamic compression tests were conducted for each loading case. The strain signals were measured in all four incident bars, and the data were acquired with an HBM GEN 3i Genesis high-speed data acquisition oscilloscope at 10 MS/s and filtered using a low-pass filter with a 100 kHz cutoff. The dynamic strain signals were also used to trigger the Kirana high-speed camera equipped with a Nikon 105 mm f/2.5 lens and two flashes (shown in Fig. 1b) at 500,000 fps and a resolution of 924 x 768 pixels. A fine speckle pattern (see Fig. 1b) was prepared on all specimens, and the full strain field data were obtained using the commercial software XTDIC. With aid from this, the deformation of specimens until ultimate failure was recorded, and the failure processes were also captured.

### 3 Results and Discussion

The typical stress pulse from each loading bar is shown in Fig. 2. The dynamic loading combinations varied from symmetrical uniaxial compression to equally proportional biaxial compression, and the charging voltage combinations were determined for these loading cases based on the proportional transformation of the electric and elastic energy. To ensure sufficient dynamic stress equilibrium time, the major charging voltage was set to 1500 V as a reference value for desired stress pulse amplitudes. All the specimens failed within the rising edge of the stress waves, and the stress pulses demonstrated very good synchronous performances before the ultimate failure of specimens. The differences in stress pulse amplitudes were caused by various voltage combinations, making variable-ratio tests possible. To make a better comparison, the only variable was the charging voltage of one charge–discharge system, and the charging voltage values were determined based on the equation below:

$$W = \frac{1}{2} C U^2 \quad (4)$$

where $W$ is the stored electric energy; $C$ and $U$ are the capacitance and the charging voltage, respectively.

High-speed imaging photographs of the failure process and specimen debris are given in Fig. 3. The corresponding captured time for these images is indicated by the vertical dashed lines in Fig. 2. The loading directions and the surface layer directions are also indicated in Fig. 3. Four stages before ultimate failure and the failure modes are also shown here. With the help of DIC, full strain distributions before failure
can be calculated, and the fields of normal strain along the 1–3 direction ($\varepsilon_{13}$) have been plotted on the specimens in Fig. 3. The strain field data of stage 5 were not available because the speckle patterns moved out of the scope of field depth. All four loading cases demonstrated similar strain distributions, and strain inhomogeneity became more severe with the increase in dynamic loading. In the ultimate stage 5, the specimens experienced severe collapse deformation, and the delaminated layers gradually moved out of the biaxial loading area. For a better comparison, the symmetrical uniaxial compression tests were conducted using the same boundary conditions along the 1–3 direction. As shown in Fig. 3a, the specimen went through a stable deformation stage; then, the gradual delamination was caused by the failure of certain layers. For biaxial loading cases in Fig. 3b–d, these specimens also underwent a gradual deformation stage till the final failure of certain layers. Significant delamination was observed among all the results, and the level of failure increased with the dynamic loading along the 2–4 direction.

To better explain the specimen failure process, the failure mechanisms of the specimens under dynamic compression are illustrated in Fig. 4. At the initial loading stages, the specimen underwent a stable deformation process. Then, the initial delamination was mainly triggered because of the miss-match of stiffness between layers. Finally, extensive delamination became the typical failure feature for the CFRP laminates under dynamic compressive loads. The failure mode in Fig. 3d is much more severe than the rest three loading cases, which was caused by the accumulation of failures along two loading directions. Specifically, the biaxial dynamic loads were sufficiently strong to cause the initial fiber breakage in both loading directions only for the loading case of 2mF–1500 V–1500 V, so massive fiber fracture features were observed in the debris.
To calculate the dynamic compressive stresses and strains, Eqs. (1) and (3) have been proposed for symmetrical loading cases [18]. The specimen stress in Eq. (1) is determined from the average loads of the ends on two concentric incident bars, while the specimen strain in Eq. (3) is obtained from the relative displacement of these ends. For the dynamic biaxial compression setup illustrated in Fig. 1a, TC4 pads were used to transfer the dynamic loads, and the stress states in the specimens were successfully calculated using Eq. (1). However, the strain could not be calculated from Eq. (3), because the relative displacement of two ends consisted of the deformations in both the specimens and the pads. With aid from DIC, the strains on the specimens were obtained via analyzing the variations of the speckle patterns.

The stress–strain curves along the 1–3 and 2–4 directions for four loading cases are illustrated in Fig. 5, and the corresponding time in Fig. 2 is presented as vertical dashed lines in these stress–strain curves. The initial nonlinear segments of these stress–strain curves were caused by the dynamic stress equilibrium process in the specimens. Once the dynamic equilibrium was established for each test, these dynamic stress–strain curves of CFRP can be used to represent its mechanical behavior [5]. These stress–strain curves demonstrate an apparent nonlinear trend, which can be attributed to the viscoelasticity of the matrix under compression. With the increase in the charging voltage, the stress component along the 2–4 direction gradually increased from zero to its ultimate strength, whereas the failure stresses along the 1–3 direction almost remained constant. The through-thickness compressive stress has been found to have a noticeable influence on the longitudinal ultimate tensile strength [13]. Still, the transverse compressive stress has no discernible effect on the longitudinal ultimate compression strength in this work. The distinct results were caused by the different failure mechanisms and stress states. The Poisson effects caused different rates of change for stresses and strains, and the strain values along the 2–4 direction in Fig. 5b even became positive.

According to Eq. (1), all the failure loads along the 1–3 or 2–4 directions were computed using the recorded stress pulse signals. All the global biaxial compression strengths are collected in Fig. 6a, and the results showed good repeatability for various biaxial loading cases. The uniaxial compression
Fig. 4 Specimen failure mechanisms for the CFRP laminates under dynamic compressive loads

strength of the cross-ply laminates is plotted for comparison, and the global failure stress along the 1–3 direction is almost constant as the load increases in the 2–4 direction. Using the elastic data, the principal stress components in 0° and 90° piles (see Fig. 6b–c) were calculated using classical laminate theory, and the UD fiber-direction compressive strength has been presented for comparison. The transverse stresses in 0° piles are much lower than the longitudinal ones because most of the loads along the 2–4 direction were carried by the fibers in 90° piles. The ultimate failure of the first three loading cases was caused by the compressive failure in 0° plies, while the 0° and 90° piles almost failed simultaneously in the last loading case (2mF–1500 V–1500 V). Due to the high degree of anisotropy, the longitudinal stress component is dominant for all the plies. Consequently, the compressive failure behavior of the studied laminates is insensitive to the applied vertical load changes.

To understand the dynamic stress wave propagation, a 3D finite element model was built in ABAQUS/Explicit, using 8 node hexahedral elements with the reduced integration scheme (type: C3D8R). As shown in Fig. 7a, the incident pulses in Fig. 2 were applied as uniformly distributed surface loads to the distal end of these bars. All components in the numerical model were assumed to undergo linear elastic deformation. The Young’s moduli and Poisson’s ratios of the TC4 and PTFE are 113.6 GPa, 0.34 and 0.5 GPa, 0.4, respectively, while the UD ply elastic properties for the specimen have been introduced in Sect. 2. After a mesh sensitivity study, the average element size of the specimen was determined to be 0.3 mm, and the meshes used in the numerical simulation are illustrated in Fig. 7b. The numerical stress fields in stage 4 for four dynamic biaxial compression loading cases are shown in Fig. 8, revealing the stress distribution along the 1–3 direction (S11: the stress component along the UD fiber direction). Although the contact between the TC4 pad and the specimen causes a slight stress concentration, the overall stress distribution in the specimen is relatively uniform. Hence, accurate biaxial strength data can be obtained with this dynamic biaxial compression method.

In general, the feasibility of dynamic biaxial compression utilizing electromagnetic loading has been systematically verified, and the methods to obtain stresses, strains and strain rates have been determined. The stress values were computed using the one-dimensional wave propagation theory, while the full-field strain data were obtained with the help of DIC measurement.
4 Conclusions

A novel dynamic biaxial compression testing approach has been proposed in this paper with a biaxial electromagnetic Hopkinson bar. A high-speed camera was employed to capture the deformation and failure processes of the specimens, and the full strain fields were obtained with DIC. The strain distributions revealed the deformation characteristics of the samples, and their inhomogeneity became more severe with the increase in loads. For the CFRP laminates, the dynamic transverse compressive stress has been found to have little effect on the longitudinal ultimate compressive strength. The results in this work demonstrate that the biaxial electromagnetic Hopkinson bar has the potential to determine the failure envelopes of composite materials. Moreover, not only are the failure data in the compression–compression stress regime available but also those of tension–tension or tension–compression ones can be obtained with appropriate specimen designs, providing much more reference data for investigating the failure mechanisms of composite materials.
Fig. 6 Biaxial compressive strengths: a global biaxial compressive strengths; b principal stress components in $0^\circ$ plies; c principal stress components in $90^\circ$ plies

Fig. 7 Numerical model of the dynamic biaxial compression tests
Fig. 8 The numerical stress fields for four dynamic biaxial compression tests in stage 4

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Declarations

Conflict of interest The authors declare no competing interests.

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