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Assessing 3D shear stress–strain properties of composites using Digital Image Correlation and finite element analysis based optimization

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ABSTRACT

This work presents a method which uses the full-field measurement capability of Digital Image Correlation (DIC) for a simultaneous assessment of non-linear shear stress-–strain relations for composites in all three principal material planes. The method, which employs a small rectangular plate torsion specimen, advances our ability to measure 3D material properties compared to the previous methodology that was able to use only small regions of the specimen surfaces in the material characterization. The new methodology takes full advantage of the full-field measurement. Material stress–strain constitutive modeling is relying on the DIC data including the in-plane as well as out-of-plane strain components; and on iterative finite element model (FEM) updating based on the Levenberg–Marquardt algorithm for minimization of weighted least squares error between the DIC-measured and the FEM-predicted strains. Results include the in-plane and two interlaminar stress–strain curves simultaneously captured for a practical carbon/epoxy tape material system.

1. Introduction

The ability to accurately determine the basic material properties including 3D stress–strain constitutive relations, fully characterizing material behavior under mechanical loads, is essential for understanding complex deformation and failure mechanisms of structures manufactured from highly anisotropic polymeric composite materials [1–3]. The objective of this work is to advance such ability through enabling simultaneous full-field assessment of three-dimensional constitutive properties of composite materials, including nonlinear shear stress–strain response in all principal material planes, in a single experiment.

In pursuit of methods for measuring 3D mechanical properties of composites, the authors of this work have been developing techniques to capture the shear stress–strain curves in the principal material planes [4–6]. Earlier techniques, including a short-beam shear (SBS) method allowing for measuring most of the 3D stress–strain constitutive relations [5,6], fell short of capturing nonlinear interlaminar shear properties in the 2–3 principal material plane. Most recent results, published in Composites Science and Technology [4], include the ability to characterize shear stress–strain curves until material failure in both 1–3 and 2–3 interlaminar material planes based on a small rectangular plate torsion (plate-twist) specimen using DIC based deformation measurements. For reference, 1 indicates the fiber direction; 2 the in-ply transverse direction; and 3 the laminate thickness direction. The ability of unidirectional small-plate torsion specimens to simultaneously exhibit large shear strains in all principal material planes, including 2–3 interlaminar shear, advanced the state-of-the-art for measuring 3D mechanical properties of composites in a single experiment [4]. The interlaminar shear stress–strain relations were obtained through coupling DIC-based strain data with FEM-based stresses, using a stress-updating procedure where material properties in the FEM were updated until the change in the maximum FEM-based shear stress became negligible.

However, these previously developed techniques are able to use only small regions of the test specimen surfaces, approaching line segments or points, in the material characterization. In order to take full advantage of the full-field measurement, all DIC surface strain data must be utilized. The methodology developed in this work represents a major advancement in our ability to measure 3D material properties by utilizing DIC measurement from the entire surface. In particular, this work extends the small-plate torsion

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method to utilize the full-field measurement capability of DIC for simultaneous assessment of the non-linear shear stress–strain constitutive relations in all three principal material planes.

Full-field measurements, allowing for simultaneously determining multiple material properties in experimental setups not subject to limitations of conventional strain gage-based material characterization requiring uniform strain, are attractive for assessment of material constitutive properties of composites [7]. Among strategies developed to solve the inverse problem of determining the material constitutive parameters using the full field information, FEM updating (FEMU) method has been the most common approach and the virtual fields method (VFM) – the most recent alternative. An extensive overview of inverse methods is given in Ref. [8]. Most of the existing work using inverse methods and full-field measurements for material characterization of composites has been focused on the identification of linear elastic properties such as orthotropic material constants or rigidities of laminated plates [9–11]. Yet, the in-plane and interlaminar shear behavior of polymeric composites is widely recognized to be nonlinear [12]. It is worth noting that full-field measurements coupled with the VFM were used in Ref. [13] to determine nonlinear shear behavior of a glass-epoxy composite based on double V-notched shear tests. However, only in-plane shear material properties were identified and some restrictions inherent to the VFM, such as the complexity in choosing suitable virtual fields for arbitrary specimen configuration and test setup, could be mentioned.

In this work, an iterative FEMU method is presented for assessment of the nonlinear shear stress–strain relationships of composite materials using the full-field strain data from small-plate torsion specimens. The new method is able to determine the shear constitutive behavior in all three principal material planes simultaneously and therefore such method significantly reduces the number of FEM iterations compared to the previous methods handling one plane at a time. The basis of the inverse method is the minimization of the least square error between DIC-measured strains and FEM-predicted strains by fine-tuning the parameters of the material constitutive model. Full-field strain measurements in the three principal material planes (surfaces) of the small plate torsion specimen capture large strain gradients and allow for an efficient characterization of both linear and nonlinear material response regimes, using only a limited number of DIC images generated during the specimen loading. Results include the in-plane and two interlaminar stress–strain curves simultaneously captured for IM7/8552 carbon/epoxy material system. To the best of the authors' knowledge, a simultaneous full-field assessment of non-linear shear stress–strain relations for a composite material in all three principal material planes has been demonstrated in this work for the first time.

2. Experiment description

To enable simultaneous assessment of the shear stress–strain response in the in-plane (1–2) and interlaminar (2–3 and 1–3) principal material planes, 11 small rectangular plate specimens were machined from a 26-ply 4.26 mm (0.168 in.) thick IM7/8552 carbon/epoxy unidirectional tape panel cured at 350° F per prepreg manufacturer's specifications [15]. The specimen length and width are 25.4 mm (1.00 in.). Fig. 1 shows a small-plate torsion experiment setup and loading conditions.

The small-plate specimens were placed in a custom test fixture with 6.35 mm (0.25-in.) diameter hemispherical supports; and loaded in a servo-hydraulic load frame at a constant 0.05 in/min crosshead displacement rate until failure. The support length was 17.8 mm (0.7 in.). The tests were conducted at 72° F room-temperature ambient conditions. It is worth noting that design of the test fixture in Fig. 1, allowing for DIC measurement in all three material planes, is different from the design used in Ref. [4] to determine only interlaminar material properties.

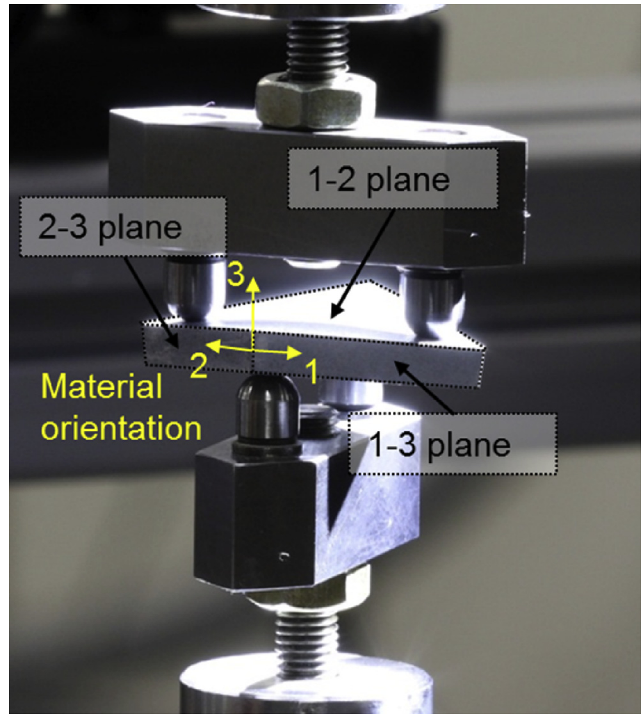

Fig. 1. A small-plate torsion experimental setup with custom test fixture.

DIC was used to assess the strain components on all principal material planes simultaneously. The reader is referred to Ref. [14] for a general description of the DIC technique; and to Refs. [4–6] for more specific details pertinent to this work. Three synchronized 16-megapixel stereo camera systems monitored strains in the 1–2, 2–3 and 1–3 principal material planes. Fig. 2 shows a setup for simultaneously monitoring surface strain. Fig. 3 shows typical engineering shear strain components measured before failure using the DIC technique. The strain analysis is performed in VIC-3D software [16] using a subset (data point) size of 35 × 35 pixels, corresponding to approximately 0.275 mm^2 for these particular tests. Data was obtained on 7 pixel centers, resulting in approximately 26,000 data points per load case.

Maximum in-plane and interlaminar shear strains greater than 5% are observed in both the 1–2 and 2–3 principal material planes, respectively and greater than 3% in the 1–3 principal material plane before failure. This method allows for a simultaneous assessment of shear strains in highly nonlinear stress–strain regime for polymeric composites in all material planes.

3. Inverse problem

3.1. Optimization algorithm

The FEMU method used in this work for assessment of the material constitutive properties of composites, including nonlinear shear behavior, is based on a non-linear least squares optimization procedure. The objective error function $C(p)$ for the optimization problem is defined as the sum of the weighted squares of the differences between DIC-measured and FEM-computed strains, as shown in the following equation