Composite Structures 140 (2016) 84–93

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Characterization of stress–strain behavior of composites using digital image correlation and finite element analysis

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ARTICLE INFO

Article history:
Available online 30 December 2015

Keywords:
Polymer–matrix composites
Digital image correlation
Finite-element-method-updating
Mechanical properties

ABSTRACT

This work presents a cost–effective method taking advantage of the full-field measurement capability of digital image correlation (DIC) for a simultaneous assessment of multiple stress–strain relations for fiber-reinforced composites in a principal material plane. The method is based on combining a finite element model based stress calculation and a full-field surface strain measurement in a custom short-beam shear (SBS) test. The unknown constitutive properties are determined through minimization of the square difference between the DIC-measured and the FEM-calculated strains. The robustness of the proposed method has been evaluated using different initial approximations of material constitutive parameters. Explicit derivation and evaluation of the sensitive matrix are not required in the method. Due to geometric nature of stress distribution in the unidirectional short-beam specimen loaded in a principal material plane, the optimization procedure converges rapidly, and is not sensitive to the formulation and parameters in the initial approximation of the constitutive model.

1. Introduction

Composite materials with highly-anisotropic mechanical properties can offer many benefits including the ability to tailor stiffness, strength, and fatigue performance characteristics, which become more and more essential in advanced structural designs. However, to achieve the greatest benefit of composite structures, accurate and reliable structural finite element analysis models are required [1–3]. The models need to capture the physics of material behavior, including complex deformation and failure mechanisms to generate realistic failure predictions; therefore accurate three-dimensional material characterizations are necessary as the basis of the FEM analysis models. The lack of accurate material properties causes significant delays in qualification of composite materials for structural applications, and results in extremely conservative designs.

Measuring the mechanical properties of advanced composite materials could be challenging due to their anisotropy and complex failure mechanisms, which result in a large number of different traditional test methods and test specimen types required to assess a complete set of three-dimensional constitutive relations and qualify the composites materials. Full-field displacement measurements are well suited for characterizing the mechanical properties of composite materials because of the complexity of their deformation [4]. To determine stress–strain constitutive relations simultaneously, experimental techniques must be based on multi-axial full-field strain/stress fields. In this case, full-field deformation measurement techniques such as digital image correlation (DIC) are needed. Multiple material constitutive properties are simultaneously involved in the stress–strain response of a single test specimen and a robust optimization strategy extracting the unknown three-dimensional stress–strain constitutive model from the multi-axial full-field measurement is required [4,5]. Constitutive parameter identification is often referred to as an inverse problem [6].

In order to determine multiple mechanical properties in a single experiment, characterization of parameters in the material stress–strain constitutive model has been the focus of many recent investigations. Pierron et al. [7–10] proposed the virtual fields method (VFM) on the basis of the principle of virtual work to identify constitutive parameters of composites from full-field displacement measurements. The assumed constitutive model formulation is utilized to express strain energy in terms of the strain components as well as the constitutive model parameters. For instance, full-field measurements coupled with the VFM were used to determine nonlinear shear behavior of a glass–epoxy composite based on double V-notched shear tests [10]. However, the complexity

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http://dx.doi.org/10.1016/j.compstruct.2015.12.018
0263-8223/

in choosing suitable virtual fields for arbitrary specimen configuration and test setup could be noted. A significant improvement of the method has been proposed through an automatic determination of these virtual fields with stability criterion [11,12].

The finite element method provides displacement/strain–stress fields for arbitrary loading conditions, specimen geometry and material properties. It has been used as a tool for solving the inverse problem iteratively, leading to finite-element-model-updating (FEMU) method [13–17]. FEMU consists in performing iterative finite element simulations of the test to find constitutive parameters that achieve the best match between the calculated and actual measurements. The FEMU methodology is a priori suited for a wide range of applications, featuring complex geometrical and loading configurations [6]. For instance, FEMU has been applied to the identification of parameters driving the elasto-plastic behavior for metals from tensile tests of notched specimens. The nonuniform stress states with the DIC measured full-field displacements and the total tensile force were used in the identification procedure [18,19]. Large strain elastoplasticity is considered in [20], where the material parameters are estimated for a piecewise-linear plasticity model and a parabolic hardening model.

Makeev et al. introduced a custom short-beam shear (SBS) test method combined with the digital image correlation (DIC) full-field deformation measurement technique to determine multiple material properties including tensile, compressive, and nonlinear shear stress–strain relations for composites [21–24]. The basis for the assessment of the constitutive properties along the principal material directions from unidirectional SBS tests was identification of the region which exhibits simple stress and strain states that can be used to extract the individual components of the stress–strain behavior until material failure. The stresses were calculated based upon a high-fidelity three-dimensional finite element model (FEM). A small line segment along the neutral axis midway the loading nose and support locations was used to extract the shear stress–strain curves; and cross-sections in a narrow region in the middle of the loading nose and support locations were used to determine the axial tensile and compressive modulus values. Subsequently, a small rectangular plate torsion (plate-twist) specimen using DIC based deformation measurements was proposed to assess shear interlaminar stress–strain curve until material failure in 2–3 principal material plane in addition to 1–3 material plane [25].

However, despite the strain assessment throughout the whole surface of the short-beam coupon in the plane of loading, only the small region, such as a small line segment along the neutral axis, which exhibits simple stress and strain states, were used to extract the constitutive parameters of composites. Most of strain data have been ignored. In order to take full advantage of the full-field measurement, all DIC surface strain data should be used [26]. Besides, no objective function, which is constructed through the squared difference between the full-field measured and numerical calculated stain components, has been given to evaluate the fidelity of the determined constitutive parameters from the small region [21].

The purpose of this work is to expand the method introduced by Makeev [21] and take the advantage of the full-field measurements of the strain in the short-beam specimen. The methodology developed in this work represents a major advancement in our ability to characterize the constitutive properties along the principal material directions from unidirectional SBS tests by utilizing DIC based measurement on the entire surface. The constitutive model, which generalizes the multi-axial stress–strain relations simultaneously in the SBS specimen along the principal material direction, has been identified in this work throughout the whole surface region of strain assessment. A squared difference objective function has been constructed to evaluate the agreement between the measured strains and the strains generated using FE analysis throughout the whole surface. The minimization of the objective function was achieved through a linear least square regression method. The work is demonstrated on unidirectional carbon/epoxy SBS specimens loading in 1–3 and 1–2 principal material planes. The procedure shows to be efficient in assessing the stress–strain relations between the measured strain vector and the calculated stress vector. The obtained material constitutive model has been verified by the remarkable agreement between the measured and calculated strain fields throughout the specimen surface through iterative evaluation of the objective function. Geometric nature of stress distribution in the short-beam specimen accelerates the optimization process and makes it not sensitive to initial approximation of the stress–strain behavior.

2. Experiment

2.1. Short-beam shear experiment

This section provides essential background for short-beam shear testing. SBS specimens are prismatic coupons with uniform rectangular cross-sections and are subjected to three-point bending. The support length equal to four to five times the thickness. Fig. 1 shows a test setup and schematic of the short-beam specimen configurations. A unidirectional tape panel can be utilized to machine the short-beam coupons in the zero-degree and 90-degree material directions; and apply loading in the 1–2 (in-ply), 1–3 (interlaminar), and 2–3 (interlaminar) principal material planes to characterize multiple basic constitutive relations for a composite material along principal material directions. For reference, the fiber direction is denoted as 1 (zero-degree); the in-ply transverse direction as 2 (90-degree); and the laminate thickness direction as 3 (the interlaminar principal material direction).

In this work, the SBS specimens were machined from a 6.4 mm-thick panel cured at 350°F based on the manufacturer's specification [27]. The SBS specimens were placed in a servo hydraulic load

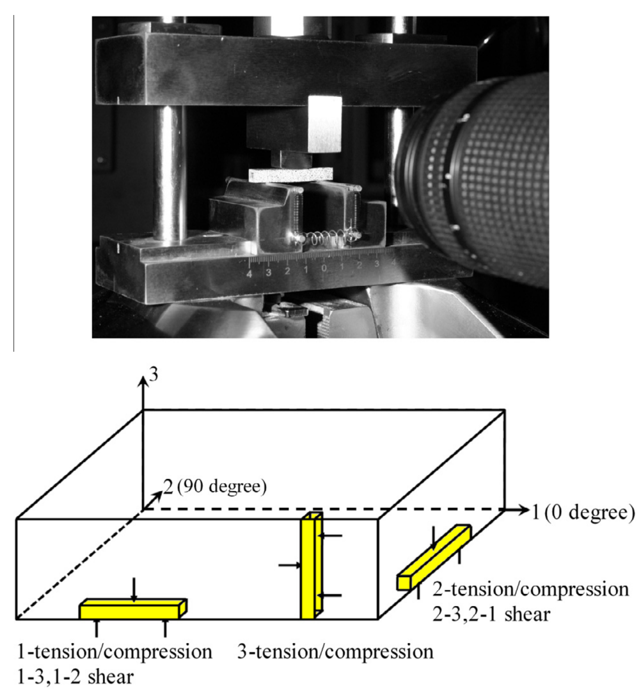

Fig. 1. A short-beam method to measure multiple stress–strain properties of composites in a single experiment: test setup and specimen configurations.