Composite Structures 184 (2018) 337–351

Contents lists available at ScienceDirect

Composite Structures

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

Uncertainty analysis in composite material properties characterization using digital image correlation and finite element model updating

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ARTICLE INFO

Keywords:
Uncertainty
Digital image correlation
Finite-element-model-updating
Reconstruction parameter
Global finite-element based approximation

ABSTRACT

This work presents an uncertainty analysis on composite material constitutive parameters, which are extracted using digital image correlation (DIC) and finite-element-model-updating (FEMU). The uncertainty is induced by the measurement system noise in the DIC technique and the approximation error in the displacements and strains smoothing algorithm. The covariance matrix of the extracted material constitutive parameters has been given explicitly. Six material constitutive parameters were identified from a customized short-shear experiment simultaneously using an estimated optimal reconstruction mesh size as an illustration. Sensitivity of measurement noise and reconstruction parameter on extracted material properties has been investigated. The effects of region of interest (ROI) and DIC image number on uncertainties of extracted material properties have been addressed. It is suggested that there exist an appropriate ROI and the number of images, from which reliable material parameters can be identified, but much more data used in identification process always lead to smaller standard deviation and COV. It is observed that the material constants used to characterize the in-plane shear stress-strain behavior show strong robustness to the measurement noise. However, the identified longitudinal Young's modulus is more sensitive to the measurement noise. Another key finding is that the reconstruction parameter in the global finite-element based approximation approach is critical for reliable material properties identification. Its value has to stay close to optimum for guaranteeing reliable identification of material properties.

1. Introduction

Composite materials with highly-anisotropic mechanical properties are becoming more essential for advanced structural designs. Growing worldwide demand has resulted in the rapid development of a wide range of composite materials, including glass-, carbon-reinforced polymer-matrix and multifunctional composites [1–3]. However, lack of accurate material properties required for understanding of deformation and failure mechanisms causes significant delays in qualification of composite materials for structural applications, and results in extremely conservative designs. Also, accuracy of finite element analysis (FEA) prediction strongly depends on the properties of materials evaluated experimentally. Improved three dimensional stress-strain constitutive relations are needed to more accurately characterize the mechanical response of advanced composites [4–9].

To enable efficient measurement of three-dimensional constitutive parameters of composite material behaviors, including nonlinear stress-strain relations, it is desirable to have a simple, yet effective method that can be used to extract multiple mechanical properties in constitutive relationships from a single test. Optical full-field measurement techniques such as reflection photoelasticity, moiré interferometer, grid method and digital image correlation (DIC), which can acquire displacements and strains over the entire surface of a specimen, are found very promising for the experimental stress/strain analysis of materials and structures [10–14]. This information can change the philosophy of the experimental method-from extracting a single material property to identification of multiple material properties in stress-strain relations from a single experiment. The experimental method will reduce the amount of testings required to qualify new composite structural components. Better knowledge of material structural characteristics will lead to increased reliability. Thus full-field measurements have the capability of greatly improving efficiency for constitutive parameter determination in advanced composites. Among them, DIC technique is easy to use, less sensitive to vibration, no heavy surface preparation, and it can be applied on any class of material [15].

Although optical full-field measurement techniques have found profound application in various domains, accuracy is a primary issue [16]. Errors in optical full-field displacement measurement, such as DIC

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http://dx.doi.org/10.1016/j.compstruct.2017.10.009
Received 5 July 2017; Received in revised form 26 September 2017; Accepted 2 October 2017
Available online 04 October 2017
0263-8223/

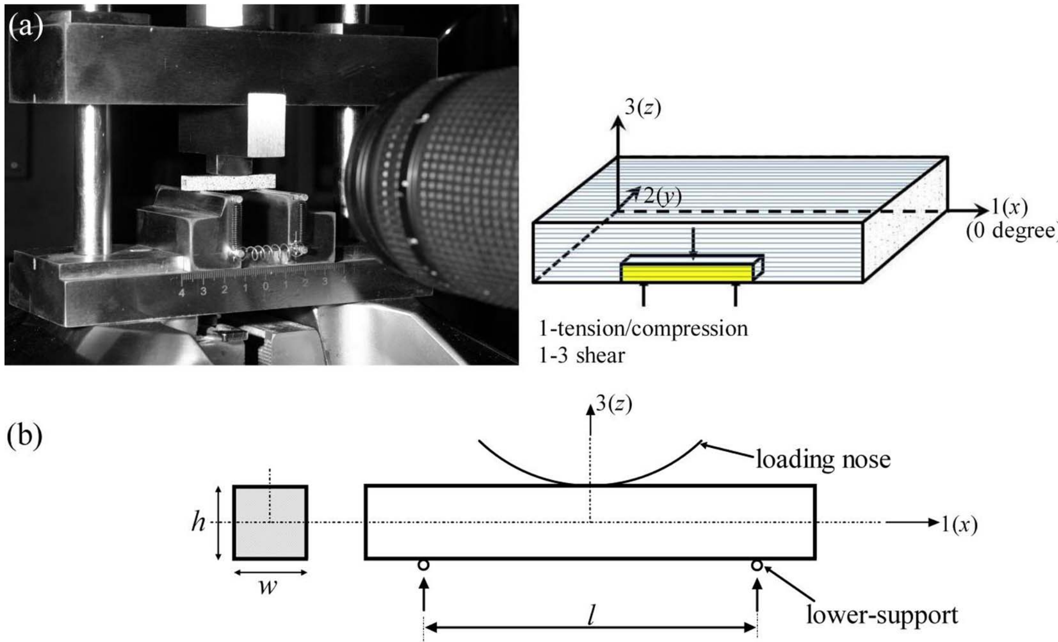

Fig. 1. (a) Short-beam shear (SBS) experimental setup combined with DIC full-field displacement measurement system to determine multiple constitutive parameters of composites from a single experiment. (b) Geometry of the SBS specimen.

could arise due to many sources such as illumination variations, quality of acquisition system, and image noises in the measurement system, or it could be due to the error associated with the implementation of correlation algorithm [17–20]. Then strains need to be computed from numerical differentiation of the estimated displacements. Unfortunately, the numerical differentiation can greatly amplify the noises contained in the displacements [17,18]. Thus, extensive research works concentrated on eliminating the noisy data of the displacement. For instance, a global finite element (FE) based reconstruction approach can be applied to generate a smooth displacement field and strain field [21]. A thin-plate spline (TPS) smooth method is another well-known global smoothing approach [22]. Radial basis functions (RBFs) can also be applied to improve accuracy of strain field estimation [21,23,24]. However all post-processing algorithms induce the approximation error inevitably.

In order to use the full-field deformation measurement technique for material characterization, identification techniques have been developed to extract multiple constitutive parameters of material behaviors. For instance, the Virtual Field Method [25], which is based on the principle of virtual work written with a particular virtual field, can be used for identification of parameters in linear or nonlinear constitutive relations for composites [26–30]. Finite-element-model-updating (FEMU) method can also be used to extract material parameters in a constitutive model. It allows the result of a numerical simulation to match the experimental field in the sense of a given norm. Based on various cost functions, such as constitutive equation gap or equilibrium gap, constitutive parameters can be identified as the minimum of the cost function by updating finite element model iteratively [11]. The FEMU methodology is *a priori* suited for a wide range of applications, featuring complex geometrical and loading configurations [31–35]. In previous studies, four orthotropic planar elasticity parameters have been identified from uniaxial test of an open-hole specimen using the FEMU method [31]. Elastic properties of monolithic ceramic were identified using a high-order polynomial displacement field in the FEMU method [35].

Even though researchers have started exploring the mechanical characterization of composites using the optical full-field measurement technique, a thorough investigation needs to be done to study the influence of various errors in optical full-field deformation measurement technique, such as DIC on material property estimation [36,37]. It is a key issue to evaluate quantitatively the uncertainty of identified constitutive parameters of material behaviors induced by the noise due to the deformation measurement system and the approximation error induced by the post-processing smoothing algorithm. The effect of region of interest (ROI), number of images, noise and smoothing algorithm parameter is of utmost importance and not many discussions are available in the literature [36].

It is the aim of the present study to give an uncertainty analysis on composite material constitutive parameters, which are extracted using DIC and FEMU. The combination of full field deformation measurements in conjunction with FEMU method is used to assess a set of reliable composite material constitutive parameters. A detailed methodology is given to identify multiple constitutive parameters of composite material behaviors including tensile, compressive, and nonlinear shear stress–strain relations in one of principal material planes simultaneously. A custom short-beam shear (SBS) test method combined with the full-field non-contact 3D DIC technique and the FEMU has been employed for this purpose [38–40]. A global finite-element based algorithm is applied to reconstruct displacements and strains to reduce measurement “noise” [41]. The uncertainty of the extracted constitutive parameters of material behaviors have been evaluated explicitly. The effects of the ROI, the number of images, the noise induced in the measurement system and the reconstruction parameter in the global FE smoothing algorithm on the identified material constitutive constants have been investigated thoroughly.

The material, the specimen geometry and the short beam shear test configuration are given in Section 2. Displacement fields are measured using a 3D-DIC system, which is described in Section 2. The identification method based on the FEMU is provided in Section 3. The global FE based smoothing algorithm used to reconstruct the displacements and strains is introduced in Section 4.1 and 4.2 respectively. Section 4.3 explains the uncertainty analysis on the extracted constitutive parameters of composite materials. Last, Section 5 deals with the reconstructed results and the corresponding uncertainties induced by the optical system noise and the smoothing algorithm. The influence of the ROI, the number of images, the noise in the measurement system and the approximation error induced by the smoothing algorithm on the uncertainty of the identified constitutive parameter has been discussed