Available online at www.sciencedirect.com
ScienceDirect
Comput. Methods Appl. Mech. Engrg. 278 (2014) 543–566
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Regularized virtual fields method for mechanical properties identification of composite materials

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Received 27 September 2013; received in revised form 4 April 2014; accepted 7 May 2014
Available online 12 June 2014

Abstract

This paper presents a new material parameters identification method based on the Virtual Fields Method (VFM) where a regularization term coming from a micromechanical model has been added. In this Regularized Virtual Fields Method (RVFM), the system of equations associated to the VFM is solved within a constrained optimization framework. The method was applied to virtual Scanning Electron Microscope in-situ tests aiming at determining the local properties of uni-directional composites loaded in the transverse direction and for which the strain fields were obtained through Digital Image Correlation (DIC). The method was tested for composites with various volume fractions and properties contrasts and under different boundary conditions. The potentials and limitations of the algorithm in the presence of noisy images were investigated and compared to that of the VFM and the other finite element based methods. The corresponding results indicate that the proposed RVFM is more efficient than the other identification techniques in terms of both accuracy and computational time. An optimum size of region of interest was also determined by taking into account DIC magnification requirements and based on the accuracy of the identified parameters. This kind of study can be very useful for determining, a priori, the level of resolution in the imaging system required for a favorable accuracy of the identified parameters.

Keywords: Parameters identification; Virtual fields method; Regularization; Homogenization model; Constrained optimization; Full-field measurement

1. Introduction

Classical approaches of material characterization, such as standard tensile tests, are capable of determining the effective properties of materials under the assumption of homogeneous stress/strain fields. Full-field measurement techniques, such as Digital Image Correlation (DIC) [1] and Digital Volume Correlation (DVC) [2], are increasingly

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http://dx.doi.org/10.1016/j.cma.2014.05.010
0045-7825/

used in the field of mechanical properties identification. These techniques can provide displacement or strain fields on the surface, or even inside, opaque materials subjected to external loadings. Thanks to the experimental availability of such rich information, several identification techniques, either in the form of an inverse problem or direct methods have been developed. Unlike standard tests, these approaches allow the simultaneous identification of a set of mechanical properties in heterogeneous materials with a single, carefully designed, test. The Finite Element Model Updating (FEMU) [3–5] is the most commonly used approach. The Adjoint-Weighted Equation (AWE) method first proposed by Barbone et al. [6] was used as a direct solution to solve inverse problems of incompressible isotropic plane-stress elasticity [7]. Different approaches have also been developed by exploiting the intrinsic constitutive theory formulation for a wide range of materials. Gockenbach et al. [8] proposed an equation error approach based on the minimization of the discrepancy in the equilibrium equation of materials subjected to regularization schemes. Studies have also been conducted to estimate local material properties based on Error in Constitutive Equation (ECE) method. In this regard, Moussawi et al. [9] identified linearly elastic isotropic material parameters on the basis of compatibility of the stress field and relying on measured strain fields. Furthermore, in a more recent application an improved version of this methodology, referred to as Modified ECE (MECE) method [10], has been developed. This method aims at minimizing an ECE functional while treating the discrepancy between measured and computed displacement fields as a penalty term. Several studies have also been carried out for obtaining material parameters by relying on their average response when subjected to applied loads [11,12]. They were developed with the assumption of homogeneous deformation state and the direct problem output is obtained either using FE method [11] or solving the respective boundary-value Partial Differential Equations (PDEs) [13]. The practical advantage of these methods is that they require neither imaging setup nor full-field kinematic quantities measurements and their derivative calculation. Other classical identification techniques, named least squares methods [14], were deployed based on minimizing the L_2 norm of discrepancy between measured and predicted displacement fields in which predicted data must satisfy the equilibrium equation of material under deformation.

An alternative to these methods is the Virtual Fields Method (VFM) [15,16], being known as a direct (i.e., non iterative) identification approach. The VFM was first proposed by Grédiac [17] and has been successfully exploited in various applications [18–20]. The method has been applied to identify bending [21,22] and in-plane [23,24] properties of composite materials. Through-thickness characterization of composites, either with a linearly elastic or a nonlinear behavior, have also been studied. For example, Pierron et al. [25] and Moulart et al. [26] determined the stiffness constants of orthotropic laminated composites from full-field measurements through different test configurations. Grédiac et al. [27] used the VFM for simultaneous identification of through-thickness properties governing nonlinear shear behavior of composites during an Iosipescu test. Moreover, a methodology based on piecewise virtual fields was proposed [28] for detecting heterogeneities in functionally graded materials and determining local mechanical properties. Other studies, such as those conducted by Chalal et al. [29], dealt with the determination of damage parameters in composites. Unlike some of inverse methods, the VFM does not require specimen geometry modeling nor finite element calculations, and delivers materials parameters directly. The VFM is also less sensitive to noise than the other existing techniques, as investigated for instance by Avril et al. [30,31]. Incorporating strain data in the VFM induces further uncertainties and requires more computations when compared with other inverse identification methods, such as FEMU and least squares approaches, that rely on displacement data. However, providing images using new imaging systems delivers lower intrinsic noises and considerable progresses have been made in obtaining realistic strain fields, in 2D and 3D [32,33].

In-situ mechanical testing consists of observing the local kinematic quantities in the constituents of heterogeneous materials submitted to external loadings. In-situ mechanical testing can be carried out in a dedicated tensile testing machine embedded into a Scanning Electron Microscope (SEM) [34] or into a micro Computed Tomography (μCT) scanner [35]. Combination of these observations with DIC or DVC and an identification strategy could provide a means to measure local properties such as interface strength, in-situ local properties, etc. However, as shown in Fig. 1, the Region of Interest (ROI) (i.e., real physical observation zone) in such techniques is much smaller than the sample itself and the load boundary conditions on the boundaries of this area (F'_x and F'_y) are unknown. Assuming homogeneous or any other type of boundary conditions could have an effect on the resulting properties. Finally, current SEM and μCT introduce important noise and artifacts that can affect the quality of the full field measurements.

Additional constrains can be added as regularization scheme to the problem for stabilizing the identification procedure. Different regularization strategies relying on constitutive relation error [36], global variance analysis [37] and Tikhonov regularization [38] have already been studied in the literature. An improved FEMU strategy, named