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Characterization of strain-softening behavior and failure mechanisms of composites under tension and compression

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ABSTRACT

A methodology is presented to directly measure the damage properties and strain softening response of laminated composites by conducting over-height compact tension (OCT) and compact compression (CC) tests. Through the use of digital image correlation (DIC) technique, and analysis of the measured surface displacement/strain data, the strain-softening response of composites is constructed. This method leads to a direct determination of the Mode I translaminar fracture properties with the assumption that the shear stress is negligible around the damage zone and the crack growth occurs in the symmetric opening mode. Using this methodology, and by correlating the observed failure mechanisms with the strain-softening curves, the interaction of failure mechanisms leading to the final failure and also the distinction between the tensile and compressive failure mechanisms can be studied. The effectiveness of the method in accurate identification of the damage parameters is demonstrated through sectioning and deplying techniques. As a consistency check and further verification of the method, the obtained strain-softening curves are fed into a numerical damage mechanics model and successfully used to simulate the detailed response of the very same OCT and CC specimens from which the strain-softening curves were extracted.

1. Introduction

In quasi-brittle materials such as fiber composites, localization of damage in the failure process zone (FPZ) results in load redistribution and consequently local softening behavior. In composite laminates, the softening behavior is caused by localization of failure mechanisms such as fiber breakage, matrix cracking or delamination in the FPZ. Usually in these materials, unlike ideally brittle materials, the size of the FPZ cannot be neglected compared to the other dimensions of notched specimens or even structural components. As a result, characterizing the softening behavior of composite materials becomes a necessity in order to simulate their nonlinear damage behavior and predict the load bearing capacity of structural components made of such materials.

In several studies, failure mechanisms in composites and also micromechanical stages of damage propagation under tension [e.g. 1–8] and compression [e.g. 6–15] have been investigated. It has been shown that the sequence and evolution of these failure mechanisms may vary depending on various parameters, including the laminate stacking sequence or the lamina thickness [4]. Under tension, many studies have shown that fiber breakage, matrix cracking, splitting and delamination are the main failure mechanisms [e.g. 5]. Under compression, it has been shown that the kink band formation process is the main failure mechanism in unidirectional composites and a combination of kinking, delamination and matrix cracking constitute the main failure mechanisms in multidirectional composites [e.g. 5–17]. All of these failure mechanisms contribute to the loss of material stiffness and subsequently loss of structural load bearing capacity.

The current approach of continuum damage mechanics is to consider the degradation of material properties in a smeared band based on a strain-softening law to simulate the damage behavior of quasi-brittle materials. Since strain-softening response falls under a generalized continuum mechanics approach, it is compatible with finite element (FE) models and can therefore be readily implemented into nonlinear FE codes. In composites, for example, this approach has been successfully applied and its predictive capability in simulating the behavior of notched specimens has been demonstrated [e.g. 2,3,18–23].

In principle, the most direct approach for measuring the strain-softening response is to conduct uniaxial tensile or compressive tests that lead to a stable and self-similar damage growth. However, as noted in other studies [e.g. 24], such an approach has some major drawbacks that makes it difficult, if not impossible, to

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apply. This includes the fact that un-notched uniaxial tests are usually unstable after the peak stress which prohibits the observation and measurement of any softening response. Therefore, researchers have had to rely on notched geometries to create loading conditions that lead to a stable damage growth. However, this requires a priori assumptions for the shape of the strain-softening curve and application of indirect methods (or inverse methods) based on parametric fitting of the experimental data in order to extract the related parameters for the assumed strain-softening response. As a result, many solutions have been proposed for the shape of the strain-softening curve in composites and other quasi-brittle materials. These shapes range from simple linear and bilinear [24–25,28] to more complicated exponential [21,22,26,28] and multi-quadratic softening responses [2,27,28].

Based on an assumed shape for the constitutive response, one has to quantify the strain-softening curve by conducting several tests combined with a trial-and-error process [e.g. 18]. However, few research studies have been conducted on the validity of the assumption for the shape of the constitutive response, indirectly linked to the damage properties, and the effect that it might have on the predictions of the damage development in structural components.

Another important issue to note is the underlying tacit assumption for the homogeneity of the material response. Any voids or defects, introduced in the manufacturing process, can inherently change the local behavior of the material and consequently alter its strain-softening response. As shown in other studies [e.g. 29], in manufacturing of a laminate, repeatable inhomogeneity may be introduced at the scale of the fiber tows during automated fiber placement processes. This results in heterogeneous fiber failure and consequently an inhomogeneous softening law. In such cases, the strain-softening law should at least represent the average behavior of the damaged material.

In recent years, non-contact measurement techniques, such as Digital Image Correlation (DIC) method, have been used to measure damage related parameters of various materials using full-field measurement of displacement vectors [30]. In this paper, a methodology is presented to identify the translaminar damage properties of composite laminates for cases where damage grows in the symmetric opening mode (i.e. Mode I loading condition) using the DIC measurement technique. High resolution cameras combined with image analyses are used to obtain displacement vectors on the surface of notched specimens at different stages of loading. The acquired results are then combined with a numerical analysis that is based on the fundamental principles of mechanics (equilibrium and compatibility) to infer the strain-softening response of the laminate.

To validate the capability of the method for capturing the damage behavior of composites, a series of over-height compact tension (OCT) [5,19] and compact compression (CC) [5] tests are conducted on IM7/8552 CFRP laminates with a quasi-isotropic lay-up of $[90/45/0/-45]_{4S}$. The failure mechanisms under tension and compression are identified and their interactions are linked to the strain-softening curves obtained under tensile and compressive loading. Results obtained from destructive tests on the post-mortem specimens are used to confirm the validity of the strain-softening responses. To further demonstrate the effectiveness of the developed method, the tests are simulated using FE analyses of the specimens that employ the extracted strain-softening curves as inputs for the constitutive behavior of the laminated material.

2. Methodology

The methodology presented here uses full-field measurement of displacements to identify the damage properties and strain-softening response of composite laminates. Measurement of displacement vectors is performed using the DIC technique. In the DIC technique, a pair of digital images, obtained from the specimen surface before and after the load application, are compared in order to determine a displacement vector field for each image. During each test, high resolution cameras are used to capture images from the surface of the specimen while data is recorded using LaVision's DaVis software [31]. Through image processing techniques, full-field displacement vectors are obtained for virtual nodes inside the area of interest on the surface of the specimen. The displacement field is then used to calculate the surface strains.

In recent years, many different approaches have been proposed to indirectly identify constitutive parameters of a material using the DIC measurements. These include FE model updating method [32,33], constitutive equation gap method [34,35], virtual fields method [36], equilibrium gap method [37] and the reciprocity gap method [38]. The above approaches are based on an assumed shape for the strain-softening material response (e.g. linear softening) and then identifying the parameters for the selected strain-softening response.

The method used in this study, consists of conducting tests such as over-height compact tension (OCT) [5,19] and compact compression (CC) [5] tests as shown in Fig. 1. During these tests, the DIC technique is employed to measure the displacement field on the surface of the specimen within the identified zones. The details of the experiments are presented in Sections 3 and 4 for OCT and CC tests, respectively. The following three-step procedure is then followed wherein no prior assumption is made on the shape of the strain-softening response:

- *Step I:* Identification of the boundary of the damaged area. In this step, any of the existing and established approaches, without invoking any assumption on the shape of the strain-softening response, can be used [e.g. 30]. Based on the elastic properties of the composite laminate, an equilibrium-based approach is then used to identify the boundary of the damage zone.
- *Step II:* Determination of the approximate shape of the strain-softening response. Using an approximate methodology, for Mode I symmetric loading conditions where the shear stresses around the damage zone are negligible, the shape of the stress–strain curves within the damage zone are estimated. It is noteworthy that for those cases where delamination and splitting are the dominant failure modes thus violating the assumption for self-similar and symmetric opening mode, this method ceases to apply.

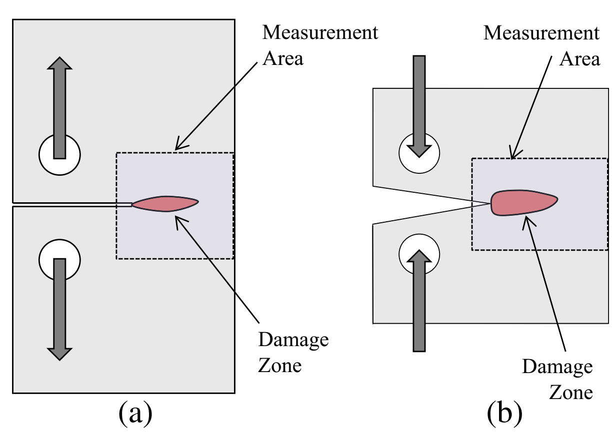

Fig. 1. (a) Schematic of the over-height compact tension (OCT) test; and (b) schematic of the compact compression (CC) test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)