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Effective calibration and validation of a nonlocal continuum damage model for laminated composites

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ABSTRACT

A combined experimental and numerical approach is presented to calibrate the parameters of a previously developed nonlocal damage model used to simulate the inelastic response of laminated composites within a macroscopic modelling framework. In this approach, a limited number of physically-based damage parameters are obtained by conducting tests on notched specimens while employing the Digital Image Correlation (DIC) technique. These parameters are then used to calibrate a non-local sub-laminate based damage mechanics model, CODAM2. Compared to available ply-based approaches; the sub-laminate damage model reduces the computational time significantly while capturing the overall damage behaviour of the laminate. The damage model is implemented as a built-in material model in the commercial finite element code, LS-DYNA (MAT_219) and also in the open-source object oriented finite element code, OOFEM. To validate this approach, experiments were conducted on notched tensile specimens with varying notch-tip radii that result in a range of behaviour from stable to unstable damage growth as this radius increases. The calibrated damage model was used to predict this transition.

1. Background and introduction

Advanced composite materials have seen a surge in popularity in the recent decade thanks to their vast utilization by the aerospace industry (e.g. Boeing 787 and Airbus A350) and, more recently, the move toward mass production in the automotive industry (e.g. BMW i3). Consequently, the need to develop a robust and computationally efficient damage model to simulate the nonlinear response of composite structures under extreme loading conditions has become more pronounced. Such a tool is essential for designers when simulating, for example, crashworthiness of composite structures.

Many numerical approaches have been proposed in the literature to simulate the damage behaviour of laminated composites [1–7]. Ranging from discrete to continuum to embedded crack approaches, these models attempt to capture the complex and multi-scale physics of the damage formation in composites. As the complexities of these models increase, so does their computational costs as well as the experimental costs associated with calibrating their parameters.

In recent years, efforts have been undertaken to arbitrate the validity of many available damage models in the literature and to arrive at a concise understanding of the applicability of these models [1]. Unfortunately, due to the complex and multi-scale nature of the damage formation in laminated composites, it has been widely recognized that there is a lack of a unique model applicable to a variety of loading conditions and geometries (e.g. [8]). In the midst of vigorous attempts in the scientific community to develop more robust damage models, the industry and regulatory bodies have perhaps taken a cautious detour by implementing a combined testing and analysis building block approach for substantiating composite structures [9,10].

Currently, ply-based models are popular approaches to simulate the damage behaviour of laminated composites (e.g. [11–14]). Plies connected with cohesive interfaces are the building blocks of such models. To calibrate these models, tests on unidirectional or cross-ply laminates are usually conducted to characterize individual plies and intra-laminar failure mechanisms. Interlaminar damage properties are characterized separately using standard test methods.

However, it should be noted that since a composite laminate is made by stacking unidirectional layers, the mismatch between the layers creates a complex local stress/strain field. The complexity increases when the damage is introduced to the system and damage modes start to interact at the smaller scales. The interaction between the layers and existence of various failure modes influence

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the behaviour of a ply within the laminate significantly. Therefore the behaviour observed in the tests performed on unidirectional or cross-ply coupons does not represent the effective behaviour of a layer in a laminated system. For example, the fracture energy of a composite laminate cannot be accurately estimated based on the properties of individual plies. Interaction of failure mechanisms such as delamination, splitting and fibre failure prevent such a simplified bottom-up approach to be adopted to characterize damage properties of laminated composites. Although this deficiency can be addressed by including the complex interactions of all plies in a numerical model, the approach does not offer a computationally practical method to simulate real-size structures.

The sub-laminate-based approach introduced by Williams et al. [15] offers an alternative framework to simulate the damage behaviour of composite components. This macro-scale approach takes the sub-laminate as the building block of the structure. The objective of the sub-laminate approach is to provide a model that predicts the effective and overall damage response of large coupons and structures while smearing the behaviour of individual failure mechanisms at the sub-laminate level.

Although the formation of matrix cracking, splitting, fibre breakage and delamination, all contribute to the damage behaviour of the laminate, in many cases, it is not necessary to simulate details of all of these failure modes to predict the overall response of the structure. By using a damage model that represents the overall behaviour of the material in terms of macro-scale indices, damage response of a large structure can be predicted effectively [2,16,17]. For example, it has been shown that a model as simple as the scalar damage model can be used to predict the load-displacement response of notched CFRP specimens fairly accurately (see [18] among others).

In this paper, a combined experimental and numerical investigation is presented that clearly outline the proposed methodology for calibrating the material parameters in the UBC sub-laminate based damage model, CODAM2 [2,19,20]. In this approach, initially, tests such as Over-height Compact Tension (OCT) [21] or Compact Compression (CC) [22] are conducted. Using the Digital Image Correlation technique (DIC), full-field strain vectors of the specimen surface are measured during each test. Based on the acquired data and using the known strain-to-failure values, damage properties of the composite laminate such as damage height and fracture energy can be extracted. These properties are then used as input to CODAM2, to simulate inelastic (damage) behaviour of composites. The CODAM2 model is equipped with an orthotropic non-local averaging scheme to inhibit the localization problem (mesh size and orientation dependencies) and improve the predicted damage patterns.

2. Methodology

2.1. Sub-laminate approach

The damage model implemented in this study, CODAM2, is based on the sub-laminate approach introduced by Williams et al. [15]. This approach requires the introduction of a representative volume element (RVE) as the zone to which homogenization is applied and over which the damage behaviour is smeared to obtain an equivalent strain-softening response for the composite material. By applying an axial deformation to the RVE (Fig. 1a), matrix cracking starts to grow (Fig. 1b) and stress-strain response of the RVE becomes nonlinear (Fig. 1e). Upon increasing the displacement further, fibres start to break (Fig. 1c) and that coincides with the onset of the RVE softening behaviour (i.e. strain-softening response) which eventually leads to complete failure when fibre breakage occurs through the entire thickness of the RVE (Fig. 1d). The strains under which matrix cracks start to grow, ε_m^i, and fibre breakage initiates, ε_f^i, are damage initiation parameters that can be measured experimentally. The area below the stress-strain curve, g_f (Fig. 1e), is a measure of the fracture energy density that is related to the fracture energy, G_f, and characteristic damage height, h_c, both of which can be determined experimentally.

In the current approach, experimentally obtained damage properties including the damage initiation strain, damage height, and the fracture energy are used to calibrate the strain-softening response of the sub-laminate. This calibrated response is then used as an input for the implemented damage model in a finite element code to simulate the damage behaviour of the composite laminate. In this paper, the experimental approach to obtain the required damage parameters is first presented. Next, the sequence of the numerical calculations and the calibration procedure are described.

2.2. Experimental approach

The experimental approach adopted in this study to calibrate the damage model is based on the methodology developed previ-

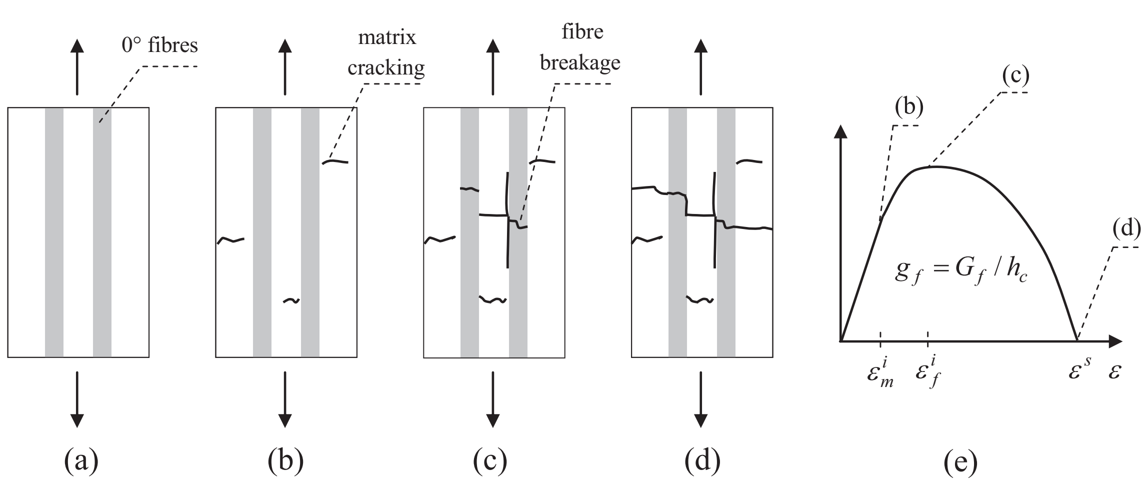

Fig. 1. (a) Representative Volume Element (RVE) of a composite laminate under tensile loading; (b) formation of matrix cracking in the RVE; (c) formation of fibre breakage in the RVE; (d) complete failure of the RVE due to matrix cracking, fibre breakage, debonding and delamination; and, (e) overall strain-softening response of the RVE under tension.