Composite Structures 203 (2018) 523–538

Contents lists available at ScienceDirect

Composite Structures

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

Open hole and filled hole progressive damage and failure analysis of composite laminates with a countersunk hole

Ashith P.K. Joseph, Paul Davidson, Anthony M. Waas*

William E Boeing Department of Aeronautics and Astronautics, University of Washington, 3940, Benton Ln NE, Seattle, WA 98195, United States

ARTICLE INFO

Keywords:
Composite laminates
Progressive failure analysis
Virtual testing

ABSTRACT

Countersunk holes are used in bolted joints for creating non-protruding smooth surfaces. As a first step towards a detailed progressive damage and failure analysis of bolted joint configurations, a new model referred to as the Intra-inter crack band model (I2CBM) is used to study open hole tensile/compressive and filled hole tensile/compressive progressive damage and failure. The I2CBM is a unified approach for modeling intralaminar and interlaminar progressive damage and failure in polymer matrix composites. 3D finite elements in the I2CBM formulation can be adapted for modeling individual lamina elements or to model interface delamination elements. A path for communication between the intralaminar and interlaminar failure mechanisms is enabled in the model to overcome limitations associated with homogenized element modeling and to capture complex interactions in a physically correct manner. A non-local crack spacing method is implemented for tracking matrix cracks. Comparisons between test results and I2CBM predictions for the open hole tensile/compressive and filled hole tensile/compressive cases with a countersunk hole configuration are discussed. The effect of bolt pretension on the filled hole failure analysis case is also presented and the failure mechanisms are discussed.

1. Introduction

Progressive damage and failure analysis (PDA) of multi-bolt joints that connect fiber reinforced laminates is a computationally challenging task due to a number of competing material and geometric non-linearities including effects of interaction between different mechanisms of failure, [1–5]. Because of this, the development of new methods require tackling simpler problems that include features found in a multi-bolt joint. Recent studies related to progressive failure modeling of composite laminates including open hole and impact damage analyses have been reported in [6–17]. A virtual testing framework for composite laminates is presented in [17]. The model presented here is intended to be used as a virtual testing platform for composite laminates. Distinguishing features of the model used here are highlighted in the following sections. Importance of using ply-by-ply fiber aligned meshing strategy is also highlighted in [15,17]. This paper focuses on the development of the I2CBM model to address issues associated with bolted joints, and is validated against open hole and filled hole loading cases.

Experimental results from open hole and filled hole laminates subjected to remote tensile and compressive loading are used to motivate the development of the I2CBM model. The following effects are identified and studied systematically; (a) Effect of stress concentration due to a hole: Open hole tension and compression cases are standard ways of verifying that the PDA method can account for this. A countersunk hole simulation has additional challenges due to the 3D stress state around the hole. This can also produce local out of plane displacements complicating the failure mechanism, (b) Effect of bolt and pretension load: We need to understand how open hole failure is influenced by the presence of the bolt. Presence of the bolt adds spatial constraints and the pretension in the bolt introduces through-the-thickness stress which can influence the local failure events. One good way to study them is using filled hole tension and compression simulations. Details of bearing failure analysis using the I2CBM model can be found in Joseph et al. [18]. Discussion of open hole tension, filled hole tension, open hole compression and filled hole compression cases are included in this paper.

2. Intra-inter Crack Band Model (I2CBM)

The I2CBM is based on combining a pre-failure homogenized continuum model that includes distributed micro-damage, with a post-peak equivalent continuum model that captures macro-cracks. Pre-peak lamina response, which dictates the overall composite material response is non-linear, especially in shear, owing to formation of micro cracks in the matrix [19] (driven by local shear, Fig. 1). In I2CBM this

---

* Corresponding author.
E-mail address: awaas@aa.washington.edu (A.M. Waas).

https://doi.org/10.1016/j.compstruct.2018.06.120
Received 23 January 2018; Received in revised form 13 May 2018; Accepted 28 June 2018

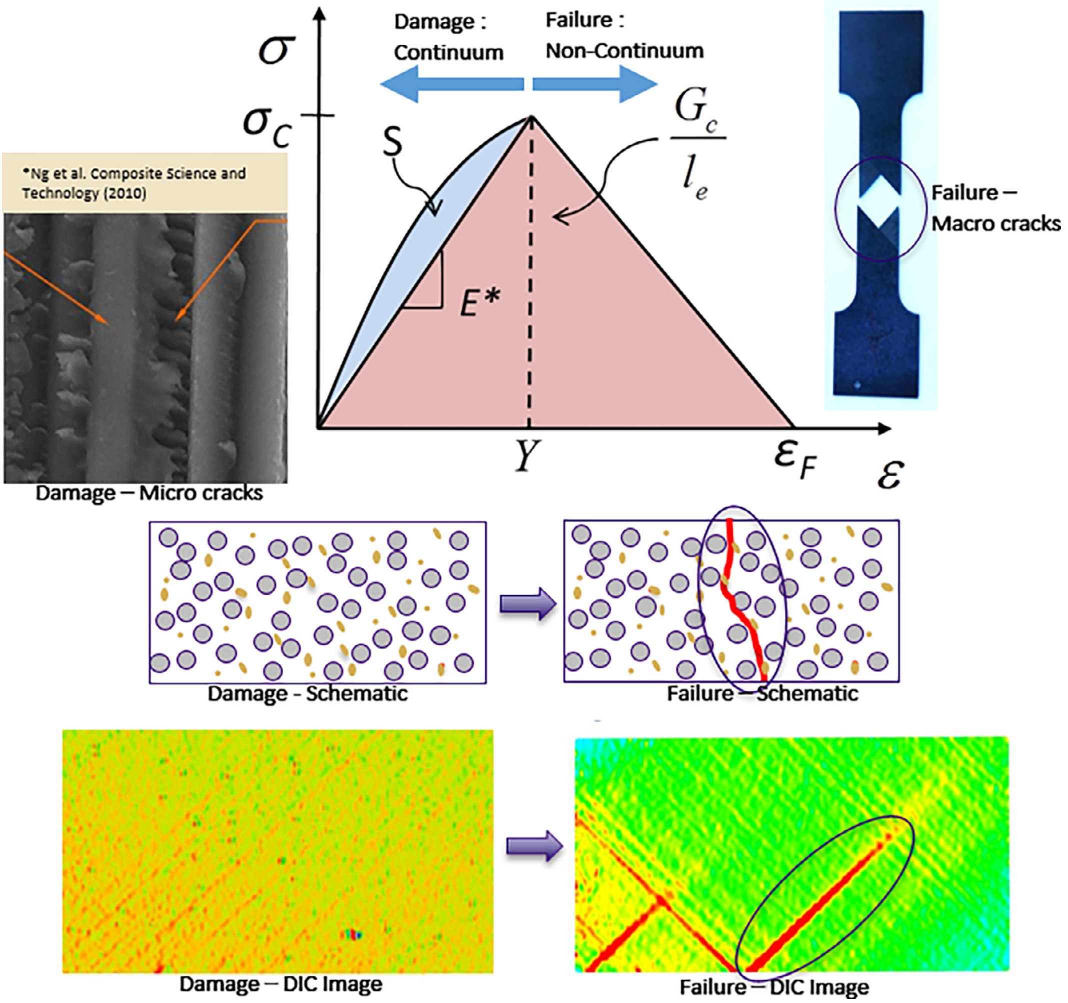

Fig. 1. Damage and Failure.

nonlinearity is modeled using Schapery Theory of micro damage [20]. Post-peak behavior, characterized by macroscopic fracture evolution is incorporated using a modified Crack Band Model. When an appropriate transition criterion is met (from pre-peak damage to post-peak failure), post peak softening region begins and the area enclosed by the post peak response is the corresponding toughness for that mode of failure, scaled by the element characteristic length [21,22]. This toughness is mechanism dependent and coupon level testing is used to obtain the parameters that govern the individual toughness values. Alternatively, micromechanics modeling can be used to infer these values.

Typical response of a stress-strain work conjugate pair implemented in I2CBM is shown in Fig. 1. As shown in the figure, at the lamina scale, damage is attributed to matrix microcracks and other sub-microcrack mechanisms which are invisible to naked eye, but that which contributed to dissipation leading to nonlinearity in observed coupon level testing, such as reported in [19]. Notice that the tangent stiffness of the stress–strain response is positive during damage evolution and the material obeys the laws of nonlinear continuum mechanics. The energy dissipated in microcrack formation is denoted by S as shown in Fig. 1. Failure is defined by a transition criterion and corresponds to a macroscopic event. For instance, in predominantly tensile stress states, microcracks coalesce to form a macrocrack. Marcocrack formation releases energy corresponding to the toughness of that particular failure mode. In addition to the above feature, additional important characteristics of the I2CBM model are as follows;1. A single finite element is used seamlessly throughout an analysis. There is no need for inserting or a priori deciding to insert cohesive elements (for example). 2. A coupled failure mechanism which links in-plane (intra-ply) failure to inter-ply (delamination) failure is used. This is based on the experimental observation that shows during in-plane loading of laminates, delamination due to failure of interface layer between two plies can only initiate if an intralaminar macrocrack forms within one of the plies. 3. To ensure correct energy dissipation during the post-peak regime and under mixed-mode conditions, the normal and shear surface tractions must vanish simultaneously at failure through cracking since a crack must have zero tractions on its surface. A novel incremental mixed mode evolution law has been implemented to achieve this. 4. The strength values are statistically distributed over the geometry of the test coupon. This approach takes the strength variation measured in the experiments, and helps to model localization of failure events and is representative of the physical nature of material strength (it is not constant throughout a volume). 5. For compressive mechanisms of failure, residual strength approach is used to account for post-kink banding strength retention under confined compression of zero degree plies. When the residual compressive strength level is reached, the stress state is fixed at that value for further increments of loading in the post-peak regime. The value of the residual strength is dependent on the material and can be affected by geometric features such as spatial constraints and bolt pretension. 6. Accurate calculation of element characteristic length is performed for various failure modes. Since I2CBM is implemented as a user subroutine in the commercial finite element code, the average characteristic lengths provided by the FE solver need not be correct and can lead to incorrect energy dissipation. The correct choice for characteristic lengths for each mode is calculated