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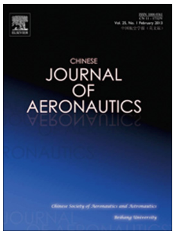

A new stress-based multi-scale failure criterion of composites and its validation in open hole tension tests

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Abstract A new stress-based multi-scale failure criterion is proposed based on a series of off-axis tension tests, and their corresponding fiber failure modes and matrix failure modes are determined at the microscopic level. It is a physical mechanism based, three-dimensional damage analysis criterion which takes into consideration the constituent properties on the macroscopic failure behavior of the composite laminates. A complete set of stress transformation, damage determination and evolution methods are established to realize the application of the multi-scale method in failure analysis. Open-hole tension (OHT) specimens of three material systems (CCF300/5228, CCF300/5428 and T700/5428) are tested according to ASTM standard D5766, and good agreements are found between the experimental results and the numerical predictions. It is found that fiber strength is a key factor influencing the ultimate strength of the laminates, while matrix failure alleviates the stress concentration around the hole. Different matchings of fiber and matrix result in different failure modes as well as ultimate strengths.

1. Introduction

Due to the high ratio of strength/stiffness to weight and good corrosion resistance, etc., fiber–reinforced composite materials are widely used in modern aero-plane structures. It has been demonstrated that primary aircraft structures made from carbon fiber composites can achieve weight savings of 20%–30% over similarly designed metal structures.[1] Airbus uses 25% composites in A380 structures and Boeing uses up to 50% in Boeing 787 structures, and the percentage of composite materials used in commercial jet aero-planes becomes a symbol of technology advantage and market competitiveness.[2] For its great importance to structure safety, failure behavior and strength prediction of composite materials have been reported extensively in the literature. After several decades of development, countless efforts have been made in this area, and substantial achievements have been obtained.[3] Some well-known failure criteria such as Tsai-Wu tensor criterion,[4] Hashin criterion,[5] etc. can effectively predict the failure strength of

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composites and have been widely used in engineering practice. The world-wide failure exercise (WWFE) sponsored by Hinton et al.[6] provides a good opportunity for comparison of all the participant failure theories against experimental results, and comprehensive assessment of 19 leading failure theories was presented, including their validities and shortfalls. All theories were ranked according to their abilities to predict a wide range of experimental results.

However, conventional failure models are almost phenomenological and rely on a number of parameters fitted with experimental results, whose physical meanings are not always well established.[7] They usually treat the fiber–matrix system as a whole and determine failure at the ply level, which can hardly distinguish whether failure occurs in fiber, matrix, or at fiber–matrix interface, even though some efforts have been made. In order to establish the link between the properties of composite constituents (fiber, matrix and interface) and macroscopic performance, the Accelerated Insertion of Materials-Composite Program (AIM-C) devised by Defense Advanced Research Projects Agency (DARPA) in 2001 suggested to develop physical mechanism based analysis methods and multi-scale failure models, which allow the designer to reliably predict damage and its growth down to the micromechanic level for a given design option, while simultaneously incorporating material and processing variability.[8]

In such a context, some failure theories based on micromechanics were developed. Gosse and Christensen[9] proposed strain invariant failure theory (SIFT) in 2001, which identifies fiber and matrix failure by two strain invariants in the micro-level, and attributes matrix failure to dilatation as well as distortion failure. The multi-continuum theory (MCT) by Mayes and Hansen,[10,11] in which the constitutive equations of fiber and matrix are formulated by stresses at a point, identifies their failures by quadratic stress failure criteria respectively. In Wang's theory,[12] the improved von Mises yield criterion is adopted to judge matrix failure, while the micro-buckling failure mode of fiber under compression is captured. Considering the failure of fiber, matrix and interface, the micro-mechanics of failure (MMF) criterion proposed by Ha et al.[13,14] formulates damage determination and evolution methods. Bednarcyk et al.[15,16] uses a micromechanics model called the generalized method of cells to evaluate failure criteria at the micro-level, and a corresponding analysis platform FEAMAC is presented. Gotsis et al.[17] and Huang[18] have also proposed other micromechanics-based failure criteria respectively. Up to now, multi-scale failure criteria have been used in fracture and durability analyses of composite structures,[19–22] and these criteria also make use of the analysis of residual thermal stresses and fiber volume fraction's effects on the mechanical behaviors of composite laminates.[23–25]

Meanwhile, the multi-scale failure analysis methods still require considerable improvements. For example, the SIFT criterion can only predict damage initiation while the MMF criterion always underestimates the shear strength of the laminate.[21] Problems such as the stress/strain transition between microscopic and macroscopic levels, and the determination and evolution of failure modes in micro-level, also need to be further investigated. Intending to solve the problems mentioned above, this paper proposes a new stress-based multi-scale failure model based on experimental observations, and the failure behaviors of fiber and matrix at microscopic level are properly defined. Square and hexagon representative volume elements (RVEs) are introduced to transform macroscopic stresses to microscopic stresses, and the corresponding damage evolution methods are established. In order to validate the multi-scale failure criterion, open-hole tension performance of three material systems (CCF300/5228, CCF300/5428, and T700/5428) are tested, and numerical models based on this failure theory are used to analyze the effect of constituent properties on the open-hole tension performance of carbon fiber reinforced plastics (CFRP) laminates.

2. Proposal of multi-scale failure model of composites

2.1. Transformation from macro stresses to micro stresses

As the average value between fiber and matrix, macroscopic stresses obtained by mechanical experiments in laminates can't describe the actual stress distribution in the microscopic level. However, under the arrangement assumption of fiber and matrix, stresses applied on the laminate can be equivalently transformed to the stresses applied on the RVE, as shown in Fig. 1. Therefore, microscopic stresses in fiber and matrix can be obtained by FE analysis on RVEs, which can be written using stress amplification factors:

$$\boldsymbol{\sigma} = \boldsymbol{M}_{\sigma}\bar{\boldsymbol{\sigma}} + \boldsymbol{A}_{\sigma}\Delta T \tag{1}$$

where $\boldsymbol{\sigma}$ and $\bar{\boldsymbol{\sigma}}$ (6×1) are the microscopic and macroscopic stress vectors respectively, $\boldsymbol{M}_{\sigma}$ (6×6) is the matrix of mechanical stress amplification factors caused by different mechanical properties of fiber and matrix, and $\boldsymbol{A}_{\sigma}$ (6×1) is the matrix of thermal stress amplification factors caused by their different thermal expansion coefficients.

Fig. 2 is the representative distributions of fiber and matrix considered in this paper. Square and hexagon RVEs are used to obtain stress amplification factors, where 1 describes fiber direction and 2, 3 the normal directions of the fiber. A set of reference points in the RVEs is chosen to analyze the stresses in fiber and matrix respectively. Due to the symmetrical stress distribution in the RVEs, all reference points are in the upper side of the model. The reference points chosen are the maximum stress points under different loading cases, which can cover the dangerous points in calculation. In the square RVE, 6 out of 16 reference points (F1–F6) are in the fiber and the other 10 (M1–M10) are in the matrix, while in the hexagon RVE, 8 out of 21 reference points (F1–F8) are in the fiber and the other 13 (M1–M13) are in the matrix. Mechanical and thermal stress amplification factors are calculated at each reference point of the RVEs. The relationship between macro stresses and micro stresses can be expressed as

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} & M_{16} \\ M_{21} & M_{22} & M_{23} & M_{24} & M_{25} & M_{26} \\ M_{31} & M_{32} & M_{33} & M_{34} & M_{35} & M_{36} \\ M_{41} & M_{42} & M_{43} & M_{44} & M_{45} & M_{46} \\ M_{51} & M_{52} & M_{53} & M_{54} & M_{55} & M_{56} \\ M_{61} & M_{62} & M_{63} & M_{64} & M_{65} & M_{66} \end{bmatrix} \begin{bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_3 \\ \bar{\sigma}_{12} \\ \bar{\sigma}_{13} \\ \bar{\sigma}_{23} \end{bmatrix} + \begin{bmatrix} A_{11} \\ A_{21} \\ A_{31} \\ A_{41} \\ A_{51} \\ A_{61} \end{bmatrix} \Delta T \tag{2}$$

In the aspect of $\boldsymbol{M}_{\sigma}$ calculation, normalized stresses are applied on the boundaries of the RVEs by nodes coupled with each face, seen in Fig. 3. When $\bar{\boldsymbol{\sigma}}_1$ is applied, micro stresses at each reference point can be obtained, and the first column of