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A constituent-behavior-motivated model for damage in fiber reinforced composites

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The aim of the work is to predict the onset and the progression of damage in the continuous fiber reinforced composite laminates taking into consideration the different mechanical behavior of the constituents in the composite under different loading conditions. The stresses in the constituents are obtained using a representative volume element (RVE) approach. Finite element analysis is carried out to extract the stresses in the constituents and the overall effective properties of the composite material. To consider the realistic behavior of the matrix of the composite material, a modified Drucker–Prager failure criterion is used. Direct test data on the individual constituents are used in this approach to model the failure of each of the constituents separately using the extracted stresses in the individual constituents. Failure envelope plotted for a unidirectional fiber reinforced composite material using the proposed model clearly shows that the initiation of damage is different in different constituents of the composite material. This is more realistic compared to the popularly used macroscopic criteria such as Tsai–Wu criterion. Propagation of failure in fiber reinforced composite is captured using a simple progressive damage model. It is also found that the hexagonal RVE has more predictive capabilities than the square RVE since the average distance between the fiber may play a major role in the strength prediction of composites.

1. Introduction

The fiber reinforced composite structures are lightweight with high strength and stiffness, which renders them favorable for a wide range of structural applications such as pressure vessels and storage tanks. Even a micro-crack in the pressure vessels may cause leakage and reduction of pressure, which necessitates the prediction of crack initiation at the microscopic level to avoid degradation of material properties in composites. The mechanical properties of the fiber and the matrix in the composite materials are different. So, the behavior of these constituents under the different loading conditions is complex, as the modes of failure related these constituents and their interaction are different.

Different modes of failure that occur in fiber reinforced composite materials are primarily, fiber breakage, matrix cracking/crushing and fiber/matrix interface failure [1]. Therefore, the prediction of damage for such a heterogeneous anisotropic material is a complex process. Initiation of damage occurs in a material when the applied stress, strain or the work done on the material reaches a threshold value. Given the complexity of the failure process, a number of new/modified failure criteria have been proposed in literature to predict the failure in fiber reinforced composite materials (see [2] for a comprehensive presentation of the various criteria). This work proposes a micromechanics based failure criterion for the prediction of the onset of damage and its progression in composites that handles the complexity in the behavior of material in simple way. Separate failure criteria are used for each constituent for predicting the onset of damage. The progression of failure is modeled using a simple progressive damage model that takes into consideration the reduction in the stiffness of the material due to damage accumulation.

The existing failure criteria are classified into different categories such as,

1. Non-interactive criteria: This criterion supposes the failure of the composite material to occur when the stress or strain induced in the material reaches a limiting value. Coupling of stress components or strain components are not considered in these criteria. Initiation of failure is generally caused by either longitudinal or transverse stress (or strain) that reaches a maximum value [3].
2. Interactive criteria: In this, the onset of failure is predicted using quantities that involve coupling of stress (or strain) components. One example of this type of failure criteria is the

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popular Tsai–Wu criterion which is a quadratic type failure criteria [4]. This is a widely used criterion for the failure of composites in which interaction of longitudinal, transverse and shear stress component is believed to be important.
3. Mode-dependent criteria: In this, not only is the onset of failure predicted but also the mode of failure. Puck and Schurmann [5] predicts the different modes of failure. For each constituent separate failure criterion is employed.
4. Mode-independent criteria: These criteria predict only the onset but not the mode of failure. Best example of this category is the Tsai Hill criterion which is used to predict only the onset of failure.

Initiation of failure occurs in individual constituents depending on (a) the stresses and strains experienced by the constituent and, (b) the failure behavior of the constituent. Most of the criteria proposed under the classes of failure criteria listed above consider either the entire composite as a homogenized medium or macro-stresses or strains for the prediction of onset of failure. Progression of failure is generally accounted for through a damage variable that increases with progress of failure [5–7]. In this work, an attempt is made to use failure criteria suitable for each of the individual constituent of the composite using the stresses or strains occurring in the constituents based on a micromechanical analysis. A simple damage progression is adopted to demonstrate the performance of the method.

Micromechanical failure criteria [8,9] are used to better predict the failure initiation in the individual constituents. Micro-stresses or strains induced in the fiber and the matrix cannot be measured accurately using experimental methods. Therefore, a micromechanical analysis using a representative volume element is carried out to extract the local stresses and strains induced in the individual constituents within the element. Analysis methods may range from analytical methods to finite element methods depending on the complexity of the RVE. The relationship between the micro and macromechanics of the composite laminate need to be studied. Ladeveze et al. [10] presented the complete relationship between the micro and meso-mechanics of the damaged composite laminates under out of plane loading condition and described that micro-cracks do not affect the damage behavior of the interface. Tran et al. [11] proposed a method of extracting the microscopic stress/strain details directly by analyzing the entire lamina typically using the finite element method for different loading conditions. However, this method is a time-consuming effort given that the microscopic stress–strain details have to be evaluated for a finite element model with a large number of degrees of freedom for various conditions of loading. To avoid repeated calculation in the elastic analysis for different stress or strain conditions, Ha et al. [6] proposed strain or stress amplification factors that connect the microscopic stresses/strains directly to the macroscopic stresses/strains and vice versa. The selection of the RVE depends on the distribution of the fibers in the matrix. To account for a general situation, typically, a square or a hexagonal cross-section prismatic volume is chosen as the RVE. These square and hexagonal RVEs are perceived to represent well the ranges of irregular spacing of fibers [12]. The advantage of the micromechanical analysis is that the effective properties of the composites can be evaluated by accounting for the irregularities such as debonding of fiber and matrix, irregular cross section and micro-cracks occurring within the RVE.

Different failure criteria suitable for the constituents that see the micromechanical stresses or strains have been used in literature. While some of the constituents may have directional dependence, some of them would be isotropic in nature. The failure in isotropic constituents are generally defined in terms of invariants of micro-stresses or micro-strains. Gosse and Christensen [13] used a strain invariant failure criterion to predict failure initiation in fiber and matrix using the first, second and third strain invariants. If any one of strain invariants exceeds an assigned critical value then onset of damage is assumed to occur accordingly in the fiber and matrix of the composite material. In the case of fiber/matrix interface with strong or weak bonding [14], the failure initiation is caused by either the plastic deformation of the surrounding matrix material or due to decohesion of the interface. In most cases, the contribution of fiber/matrix interface with perfect bond to failure is small, since the strength of fiber/matrix interface is generally higher than that of the failure strength of matrix. Ha et al. [6] developed a micromechanics based failure criterion for the prediction of failure initiation in a unidirectional ply. In order to calculate the constituent strength characteristics, they use the experimental test data at the macro-level to determine the critical micro-stresses that cause failure and assume such critical values for micromechanical failure criteria. Failure envelope of each constituent such as fiber, matrix and interface are superimposed to form the effective failure envelope.

When the unidirectional fiber reinforced composite materials undergo longitudinal tensile loading, most of the load is carried by the stiff and strong fibers. When a weak fiber starts to break and fails, the neighboring fibers start carrying the extra load due to the redistribution after the weak fiber failure and this causes others fiber to fail subsequently. Such processes also cause high stress concentrations on the surrounding material (such as matrix) which, in turn, fail [15]. Such a progression of damage can be effectively captured using a micromechanical failure theory. A detailed micromechanical analysis has been carried out by Murari and Upadhyay [16] to understand the influence of damage mechanism and volume fraction on the degradation of stiffness coefficient. The study shows that the volume fraction has some influence on the damage behavior on the unidirectional composites. Most of the degradation models use a damage variable to track the progression failure in composite materials. Puck and Schurmann [5] introduced a parameter for the degradation of material properties after the failure initiation that depends on three constants that are determined from the experiments. This parameter does not differentiate between damage in matrix, fiber or the interface. To capture the degradation in the different constituents of the composite, Lapczyk and Hurtado [7] captured the post failure of composites by introducing the damage variable separately for each constituent. The degradation is directly introduced into the elastic matrix of the material. [17] The degradation of laminate moduli and laminate coefficient of thermal expansion, as well as the degradation of lamina moduli and lamina coefficient of thermal expansion are captured as a function of crack density for the laminate with matrix crack. Singh and Talreja [18] have proposed a synergistic methodology that combines the continuum damage mechanics and the micro-mechanics approaches for predicting the stiffness degradation in the composite laminate by the transverse crack. Ha et al. [6] adopted a method in which when an element in the finite element model of the RVE fails, that element is deleted from the RVE finite element model for further analysis of the composite material.

In most of the failure criteria proposed in literature above for failure prediction of polymer matrix, hydrostatic part of the stress is considered dominant. Moreover, instead of using the indirect determination of critical strength parameters of individual constituents from the composite strength test data as in [6], it would be prudent to use the test data available for individual constituents. While calculating the effective property upon progression of damage, instead of removing the failed element in the RVE and recalculation of stresses, the degradation of stiffness of the constituent that essentially contributes to the overall macroscopic property change of the composite with damage could be directly introduced in the RVE. This stiffness reduction of the constituent for each