Computers and Structures 191 (2017) 100–114

Contents lists available at ScienceDirect

Computers and Structures

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

Three-dimensional micromechanical analysis models of fiber reinforced composite plates with damage ☆

D.H. Li *, Q.R. Guo, D. Xu, X. Yang

College of Aeronautical Engineering, Civil Aviation University of China, Tianjin 300300, China

A R T I C L E I N F O

Article history:
Received 22 March 2017
Accepted 11 June 2017

Keywords:
Composite plates
Extended layerwise method
Transverse crack
Delamination
Fiber breakage

A B S T R A C T

A three-dimensional micromechanical analysis model was established to investigate the force-bearing mechanisms and damage in fiber reinforce composite plates. In the proposed model, the matrix and fibers were described by the extended layerwise method (XLWM) and the three-dimensional bar elements, respectively. The final governing equation of composite with damage was developed from combing the governing equations of matrix and fibers by the displacement compatibility conditions at the coupling interfaces. The equivalent material property of matrix calculated by the volume faction of fibers was used to remove the contribution of the redundant matrix shaved the overlapping region with fibers. In the numerical examples, the unidirectional composite plates with damage were investigated to validate the proposed model, and the results calculated by the proposed model are compared with those of the 3D elastic models developed in the general commercial finite element code. In addition, the effects of the damage on the stress distribution in fibers were investigated.

1. Introduction

The advanced fiber reinforced composite structures widely used in aerospace, automobiles, trains, ships and wind turbine blades are heavily subjected to large stochastic loads. Various failure modes may be provoked and continue to grow in the service period, and the damage evolution behavior depends on these failure modes seriously. The knowledge of the damage mechanisms plays one of the most important roles for the practical design of composite structures. Furthermore, the damage in fiber reinforced composite materials occur at a number of length scales, from the microsopic, barely observable fiber matrix debonding, to macroscopic matrix cracking and delamination. Therefore, the mechanisms, analytical and numerical modeling of the fiber reinforced composite with various damage are the subjects of intense research for over half a century.

The first type damage occurred in the fiber reinforced composites is the defects resulted from manufacturing. The incomplete wetting would form a imperfect bond between the fibers and matrix (fiber-matrix debonding) due to the resin shrinkage or residual thermal stress. Such defects are impossible to observe with the naked eye, and even with optical or other types of microscopy. The single fiber fragmentation test (SFFT) [1], which consists of a sufficiently long fiber surrounded by the polymeric matrix, is the first and one of most important methods for investigation of the fiber-matrix debonding [2–4]. But the researches based on SFFT are based on the simplified solutions of the stress state along the fiber-matrix interface, so the predicted interfacial strengths do not accurate for the debond propagation under different loading conditions. Another important approaches to characterize the fiber-matrix debonding are the energy-balance-based and fracture-mechanics-based methods. Using these methods, the fiber-matrix Mode II interfacial fracture toughness is obtained from the SFFT data, it results in an easier application of the measured failure properties to the distinct loading conditions [5–8].

Matrix cracking is probably the most serious type of damage in the fiber reinforced composites. In addition to reduce the mechanical properties, it also leads to other types of damage forms that can prove fatal fracture to the structures or components, such as the fiber breakage and delamination. Usually, the precursor to matrix cracking is the fiber-matrix debonding in off-axis plies. The strength-based and energy-based methods are two kinds of important techniques to predict matrix cracking progression as well. In the strength-based approaches, the point failure criterion is utilized for the matrix cracking initiation and multiplication, whereas the energy-based methods consider the balance of energy during crack formation and, are similar to the concept of energy

☆ Supported by the National Natural Science Foundations of China (11502286), Natural Science Foundations of Tianjin (17JCQNJC02600) and Fundamental Research Funds for the Central Universities (3122017021, 3122017034).

* Corresponding author.
E-mail address: lidinghe@163.com (D.H. Li).

http://dx.doi.org/10.1016/j.compstruc.2017.06.005
0045-7949/

release rate (ERR) in the linear-elastic fracture mechanics. The strength based shear lag model (SLM) is the first simple one-dimensional solution for the matrix cracking [9]. In this model the transverse ply is assumed to not carry any axial load in the crack-plane, while a part of this load is transferred back to the transverse ply through axial shear away from the matrix crack. Laws and Dvorak [10] carried out the first major energy analysis for progressive multiplication of ply cracks in cross ply laminates by introducing statistical concepts concerning spatial randomness of resistance to crack formation. Hashin [11] provided a two-dimensional solutions by using variational methods for the stress analysis of a cross-ply laminate with periodic cracks in 90° plies. And then, Vinogradov and Hashin [12] derived a highly accurate damage evolution model based on Hashin's original variational analysis method and the finite fracture mechanics [13]. This approach was extended to the case of angle-ply laminates with layup containing matrix cracks in middle layers as well [14]. Based on the concepts of fracture mechanics, the matrix crack multiplication process can also be studied using the virtual crack closure technique (VCCT) by supposing a virtual crack between two existing cracks [15–17].

Fiber reinforced composites are usually manufactured from bundles of fibers and the strength of each fiber within the bundle would not be the same but a Weibull distribution. When such fibers are used for a composites, they will fracture at different applied load and generally produce the isolated fiber fractures. Under the high strain conditions, the localized stress concentrations caused by isolated fiber fractures can induce failure in adjacent fibers, and leading to an accumulation of fiber fractures. The individual fiber fractures is difficult to predict for the existing methods. The fiber bundle model (FBM) developed initially by Daniels [18] considered a bundle of N fibers with identical elastic properties under uniform tensile stress. In this method the load transferred from the broken fiber is distributed equally over all the intact fibers, it also called as global load sharing. And then, the FBM was expanded, modified and generalized by many authors [19,20], even take into account the influences of the matrix and interfaces, the nonlinear behavior of fibers and matrix, and the real micromechanisms of composite failure [21,22].

The delamination in fiber reinforced composites is a consequence of the mismatch of elastic properties of adjacent plies. But the matrix cracking is almost always a necessary precursor for delamination initiation. To model the delaminations within the laminate structures, two methods based on the damage mechanics and the fracture mechanics were usually used. In the damage mechanics methods, the stresses regimes at the layer interfaces are used to predict the onset of delamination by macro-scopic damage initiation criteria, such as Choi-Wu [23–26]. The cumulative effect of delamination can be described by the material degradation models at failure material point. The implementation of the damage mechanics methods is very simple. Since the damage is incorporated within the constitutive model, the damage mechanics methods are easily adapted to numerical approaches such as the finite element method. But the real extension process of delamination cannot be observed in the damage mechanics methods. In the fracture mechanics methods, the linear elastic fracture mechanics (LEFM) is commonly applied for the problem of delamination [27–29]. The delamination propagation path can be also further simulated based on the other techniques, such as virtual crack closured technique (VCCT) [30–34], extended finite element method (XFEM) [35–40,34,41]. and cohesive zone model (CZM) [42–45].

The typical damage pattern of the fiber reinforced composite laminated structures is a complex three-dimensional crack with layered characteristics, and various damage forms always exist simultaneously, such as the matrix cracking, delamination, fiber breakage and debonding. It is necessary to develop a refined analysis method to take into account all of the typical damage forms in composites. In our previous studies [39,40,34,41], an extended layerwise method (XLWM) was developed for the composite laminated beams, plates and shells with multiple delaminations and transverse cracks. The XLWM cannot only perfectly describe the multiple delaminations together with the thick through or non-thick through transverse cracks, but also accurately obtain the displacement and stress fields of the transverse crack tips and delamination front. In addition, the modeling capabilities of the XLWM are essentially the same as the conventional 3D displacement finite element method, so the existing fracture mechanics method based on the conventional 3D displacement finite element method can be conveniently applied to XLWM [34]. Therefore, the XLWM is a ideal choice to established the aforementioned refined analysis method for all of the typical damage forms in composites.

In order to take account all of the typical damage forms in composites, a three-dimensional micromechanical analysis models was established in the proposed work under the framework of the XLWM. In the proposed models, the matrix is simulated by using the XLWM and the fibers are modeled by using three-dimensional bar elements. The final governing equation of the composite with damage can be obtain from combing the equations of matrix and fiber by using the displacement compatibility conditions in terms of the interpolation polynomials employed in the element of matrix to obviate remeshing when the fiber size and location change. The rest of this paper is organized as follows. In the next section, the force-bearing mechanisms of fibers in fiber reinforce composites is introduced. The modeling scheme of the proposed micromechanical model is presented in Section 3. The Hamilton principle of XLWM is introduced briefly for matrix in the composite plates with matrix crack and delamination in Section 4, and the finite element modeling of fiber is developed by 3D bar elements in Section 5. The Hamilton principle of the proposed three-dimensional micromechanical analysis models for the fiber reinforced composite plates with damage is deduced in Section 6, together with the final finite element governing equations, the assembly scheme of global stiffness matrix and the equivalent scheme of material properties of matrix. In Section 7, the unidirectional composite plates with damage were investigated to validate the proposed method, and the effects of the damage on the stress distribution in fibers were investigated as well. At last, some conclusions are drawn in Section 8.

2. Force-bearing mechanisms of fibers in fiber reinforce composites

The composites consisted of the fibers and matrix material is considered in the present work. The matrix serves to hold the fibers together and distributes the fiber loads, while the function of fibers is to carry the external loads. The matrix materials have bulk-form properties whereas fibers have directionally dependent properties. The basic mechanism of load transfer between the matrix and fiber takes place through shear stress, and it can be explained by considering a cylindrical bar of single fiber in a matrix material, see Fig. 1. When the applied load P subjected on the matrix is tensile, the shear stress τ develops on the outer surface of the fiber, and its magnitude decreases from a high value at the end of the fiber to zero at a distance from the end, see Fig. 1(a). The tensile stress σ in the fiber cross section has the opposite trend, see Fig. 1(b). The distance from the free end to the point at which the normal stress attains its maximum and shear stress becomes zero is known as the characteristic distance. The pure tensile state continues along the rest of the fiber.