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Stress analysis and damage evolution in individual plies of notched composite laminates subjected to in-plane loads

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Abstract This work aims to investigate local stress distribution, damage evolution and failure of notched composite laminates under in-plane loads. An analytic method containing uniformed boundary equations using a complex variable approach is developed to present layer-by-layer stresses around the notch. The uniformed boundary equations established in series together with conformal mapping functions are capable of dealing with irregular boundary issues around the notch and at infinity. Stress results are employed to evaluate the damage initiation and propagation of notched composites by progressive damage analysis (PDA). A user-defined subroutine is developed in the finite element (FE) model based on coupling theories for mixed failure criteria and damage mechanics to efficiently investigate damage evolution as well as failure modes. Carbon/epoxy laminates with a stacking sequence of $[45^\circ/0^\circ/-60^\circ/90^\circ]_s$ are used to investigate surface strains, in-plane load capacity and microstructure of failure zones to provide analytic and FE methods with strong validation. Good agreement is observed between the analytic method, the FE model and experiments in terms of the stress (strain) distributions, damage evaluation and ultimate strength, and the layer-by-layer stress components vary according to a combination effect of fiber orientation and loading type, causing diverse failure modes in individuals.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are widely used in all fields of aerospace, automobile, electronic power, and mechanical engineering for several advantages offered over metals, ceramics, and plastics. These include low

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density, robust specific strength, low thermal expansion, corrosion resistance and designable characteristics for lightweight, efficient structures. Cutouts, especially circular and elliptical shapes, commonly appear in composite structural components due to requirements for stability, maneuverability, low weight optimization and accessibility of other systems. This is often the case in aircraft where composite structures such as wing spars and thin walls are drilled for electronic wires and hydraulic pipes[1] or to facilitate assembly operations.[2] Other instances occur not as part of the initial design of essential structures but due to material defects or unexpected damage during a service cycle.[3] These are serious and dangerous cases since they are not supposed to be there. Whatever their reasons for being, the integrity and continuity of fiber and matrix in the composite are destroyed; this makes the notch region the weakest part of the structure and causes serious local stress concentrations in the vicinity. As a consequence, structural capacity is reduced and uncertain reactions to external loads may occur and lead to unexpected fractures in service. In order to avoid potential safety hazards, accurate analysis of local stress levels and damage evolution of notched laminates are of great significance to the utilization of the material and lay the foundation for engineering applications.

The determination of stress fields in notched anisotropic plates has been the focus of many scholars for a long time. Muskhelishvili[4] first introduced complex potential theory to the isotropic elastic plates and successfully obtained an accurate solution of stress distribution. Analytical solutions for the stress distribution around holes of different shapes in anisotropic plates were given by Lekhnitskii[5] using series methods. Savin[6] presented a much simpler approach by conformal mapping of Cauchy integrals. Gao[7] used a biaxial loading factor together with an arbitrary orientation angle previously used to solve the problem of a plate with biaxial loading at infinity, avoiding the superposition of a solution with two uniaxial loading problems. The stress analysis research above established the base for later study of notched composite laminates. Ukadgaonker et al. developed a general solution for stress around oval holes,[8] triangular holes[9] with rounded corners[10] and irregular shaped holes[11] in cross-ply and angle-ply orthotropic plates under in-plane loading by superposition of two stage solutions for boundary conditions. The stresses were employed together with a series of failure criteria, which were an extension of the Von Mises criterion for quadratic interaction, to calculate the first ply failure (FPF) strength. Similar solutions around a rectangular hole in an infinite isotropic and anisotropic plate were given by Pan et al.[12] and Rao et al.,[13] respectively, using the complex variable method. Sharma[14] suggested general solutions for determining the stress distribution around polygonal holes and investigated the effect of hole geometry and loading pattern on the stress concentration factor. Batista[15] used a modified solution to solve problems of stress distribution around polygonal holes of complex geometry in an infinite plate subjected to uniform loading at infinity. Remeepazhand and Jafari[16] also studied the central polygonal hole problem in composite plates using two simple equations with parameters λ, c, n and w controlling the size, shape and bluntness of corners. Toubal et al.[17] experimentally investigated the tensile strain field of composite plates in the presence of stress concentration caused by geometrical cutouts consisting of circular holes by Electronic Speckle Pattern Interferometer (ESPI). The stress obtained in experiments is consistently lower than the analytical and numerical models.

This literature mostly concentrated on stress distribution in anisotropic plates as well as laminated composites, which are equivalent anisotropic plates, thus the stresses around cutouts were simplified to be uniform throughout, regardless of thickness. It should be noted that composite laminates contain several plies which possess dissimilar properties due to different fiber orientations, so the stress distribution in individual plies should be thoroughly investigated.

The above stress research methodologies and conclusions establish a theoretical basis for damage and failure of anisotropic plates. As for failure analysis, the damage propagation process is often depicted based on progressive damage analysis (PDA) utilizing numerical and experimental methods.[18] Lapczyk and Hurtado[19] proposed an anisotropic damage model suitable for predicating failure and post-failure behavior in fiber-reinforced materials. The plane stress formulation is used and the response of the undamaged material is assumed to be linearly elastic. The evaluation law is based on fracture energy dissipation and implemented in a finite element code. Zahari and EI-Zafrany[20] developed a progressive analysis algorithm based on Tsai-Hill failure to model the non-linear material behavior and capture the compressive response of woven glass/epoxy composite plates via non-linear finite element analysis. Rakesh et al.[21] introduced a generic finite element model to investigate the failure of unidirectional glass fiber reinforced plastic (UD-GFRP) composite laminates with drilled holes under tensile testing and compared the results with experimental work done earlier. Effects of joint geometry and stacking sequence on the bearing strength and damage mode were investigated by Ondurucu et al.[22] and specimens were examined for failure modes using a scanning electron microscope (SEM). Kim et al.[23] employed rosette strain gauges to measure the strain around the joint hole during insertion of stainless steel pins into glass fiber reinforced plastic (GFRP) specimens, and results were compared with the finite element method. Satapathy et al.[24] presented a modified fiber failure fatigue model to characterize the behavior of laminated composites with a central circular hole under in-plane fatigue loading. Martins et al.[25] studied the influence of diameter and thickness on failure pressure during tube burst tests and employed the progressive failure analysis using a damage model by a user subroutine (UMAT) implemented in ABAQUS software to understand the behavior of composite tubes under internal pressure. Lee et al.[26] proposed an evaluation method for the progressive failure of composite laminates built upon Puck failure criterion by implanted UMAT to efficiently analyze the progressive failure phenomenon in glass/carbon fiber-reinforced composite laminates. Compression tests were performed by Aljibori et al.[27] on 16 fiber-glass laminated plates with and without circular cut-outs to investigate the effects of varying the centrally located circular cut-out sizes and fiber angle-ply orientations on the ultimate load. Similar experiments were also conducted by Abu et al.[28] to investigate the influence of cut-outs on multi-layer Kevlar-29/epoxy composite laminated plates.

These remarkable works contribute a lot to the failure analysis of notched anisotropic composites whose layups are quasi-isotropic, cross-ply, and angle-ply. At the same time, numerical and advanced experimental methods for progressive failure have greatly developed. However, the failure criteria employed

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