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Fatigue behavior of laminated composites with a circular hole under in-plane multiaxial loading

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ABSTRACT

A modified fiber failure fatigue model is presented for characterizing the behavior of laminated composites with a central circular hole under in-plane multiaxial fatigue loading. The analytical model presented is based on minimum strength model and fiber failure criterion under static loading available in the literature. The analysis starts with the determination of location of a characteristic curve around the hole and the stress state along the characteristic curve under in-plane multiaxial fatigue loading. Number of cycles to failure and location of failure are determined under given fatigue loading condition. Based on ply-by-ply analysis, ultimate fatigue failure and the corresponding number of cycles are determined. Analytical predictions are compared with the experimental results for uniaxial and multiaxial fatigue loading cases. A good match is observed. Further, studies are carried out for different in-plane biaxial tension–tension and biaxial compression–compression loading cases.

1. Introduction

Fatigue damage in composite materials is a complex phenomenon involving several damage modes, such as matrix cracking, interfacial debonding, delamination and fiber fracture. These different forms of damages often develop simultaneously in a laminate and follow complex growth patterns. During growth, there can be mutual interaction of different damage modes. The damage modes and their growth pattern depend upon constituent material properties, stacking sequence and fatigue loading condition.

In many structural applications, notched composites are needed for different reasons such as weight reduction, joining and functional requirements. For the effective design of composite structures with notches, behavior of composites should be clearly known. Fluctuating load on composite structures is one of the critical conditions. Considering the importance of this subject, there are many studies on fatigue behavior of notched composites.

Typical experimental studies on fatigue behavior of notched composites are presented in [1–11]. Jen et al. [1] and Aymerich and Found [4] observed that increase in matrix strength and matrix–fiber bond strength decreases damage growth and increases fatigue life. Ferreira et al. [2] investigated the effects of frequency, stress ratio, temperature and stress concentration on the fatigue behavior of notched polypropylene/glass-fiber thermoplastic composites. Afghani et al. [3] observed that fatigue life of notched laminated composites was dependent on fiber–matrix interfacial adhesion.

Wang and Shin [5] and Shin and Wang [6] studied the fatigue behavior of notched quasi-isotropic and cross-ply AS4/PEEK laminated composites. They observed that the fatigue life of cross-ply laminates is higher than that of quasi-isotropic laminates.

Choi et al. [7] investigated the damage growth in notched AS4/3501-6 graphite/epoxy quasi-isotropic laminates under compression–compression and compression dominated spectrum fatigue loading. Jen et al. [8] studied the effect of material lay-up on fatigue life of AS4/PEEK notched laminates. They concluded that cross-ply laminates are more resistant to cyclic loading than quasi-isotropic laminates.

Khashaba et al. [9] carried out experimental studies on bending behavior of notched and unnotched $[0/\pm30/\pm60/90]_s$ glass fiber reinforced epoxy composites under static and fatigue loading. They investigated the influence of notch size on bending strength. Mall et al. [10] carried out experiments to study the fatigue behavior of both notched and unnotched carbon/epoxy composites manufactured from the H-VARTM process under tension–compression loading. Murdani et al. [11] carried out experimental studies on fatigue strength and fracture behavior of a notched carbon–carbon composite. The effect of fiber orientation and notch configuration on the fatigue behavior was examined.

Jen et al. [12] investigated failure surfaces, crack lengths and their corresponding growth directions, delamination areas and transverse delamination lengths in centrally notched Gr/Ep laminates subjected to fatigue tensile load.

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Nomenclature

b_0	characteristic length between characteristic curve and hole contour (mm)
E_1	modulus of elasticity along fiber direction (GPa)
E_2	modulus of elasticity across fiber direction (GPa)
f	frequency of load application in a fatigue stress cycle (Hz)
G_{12}	in-plane shear modulus of orthotropic lamina (GPa)
I	failure index
N	number of cycles during fatigue loading
N_f	number of cycles to failure for notched composite
R	stress ratio
r	radius of the circular hole (mm)
S	in-plane shear strength of lamina (MPa)
S^R	in-plane residual shear strength of lamina (MPa)
t	thickness of laminate (mm)
X_C	longitudinal compressive strength of lamina (MPa)
X_C^R	longitudinal residual compressive strength of lamina (MPa)
X_T	longitudinal tensile strength of lamina (MPa)
X_T^R	longitudinal residual tensile strength of lamina (MPa)
Y_C	transverse compressive strength of lamina (MPa)
Y_C^R	transverse residual compressive strength of lamina (MPa)
Y_T	transverse tensile strength of lamina (MPa)
Y_T^R	transverse residual tensile strength of lamina (MPa)
α	fatigue parameter
β	fatigue parameter
γ	smallest angle between the fiber direction and the loading direction (°)
θ	angle between 1-axis and the normal vector of the tangent at the hole contour (°)
v_{12}	in-plane Poisson's ratio of orthotropic lamina
σ_1	lamina stress in longitudinal direction (MPa)
σ_2	lamina stress in transverse direction (MPa)
σ_6	lamina in-plane shear stress (MPa)
σ_n	uniaxial notched strength of the laminate (MPa)
σ^R	residual strength of laminate during fatigue loading (MPa)
σ_u	static ultimate strength in the loading direction (MPa)
$\overline{\sigma_{Li}}$	laminate average stress (MPa)
$\overline{\sigma_i^0}$	stress component due to uniform stress field (MPa)
$\overline{\sigma_i^*}$	additional stress component due to a circular hole (MPa)
$\sigma_{\max}$	maximum applied fatigue stress (MPa)
$\overline{\sigma_i}, \sigma_{x\max}, \sigma_{y\max}, \tau_{xy\max}$	far field applied stress (MPa)
ψ	slant angle from the y-axis = 90° for a circular hole (°)

Rotem and Nelson [13] studied the fatigue response of T300/934 carbon/epoxy unnotched unidirectional composites under tension–compression loading. Jen and Lee [14,15] investigated static elastic and strength properties of unnotched AS4/PEEK APC-2 unidirectional composite. They also investigated fatigue properties and failure modes under tension–tension and compression–compression loading. Barron et al. [16] studied the effect of test frequency on fatigue behavior of T300/914C carbon/epoxy unidirectional lamina.

Huh and Hwang [17] developed life prediction models for the prediction of fatigue behavior of notched composites under uniaxial loading. Shokrieh and Lessard [18,19] proposed a model for life prediction of notched laminated composites made of AS4/3501-6 carbon/epoxy. In their studies, there is a need for repeating the experimental studies at lamina level for every different stress ratio and frequency.

Broughton et al. [20] presented experimental studies on open-hole tension fatigue behavior of quasi-isotropic glass fiber reinforced plastic laminates under constant and block amplitude loading. Kawai and Teranuma [21] presented a multiaxial experimental fatigue failure criterion based on principal constant life diagrams for unidirectional carbon/epoxy laminates.

Epaarachchi and Clausen [22] proposed a fatigue model for unnotched glass fiber-reinforced plastics taking into account the non-linear effect of stress ratio and loading frequency on fatigue life. Further, they extended the model for fatigue residual strength prediction [23]. Talreja [24] reviewed the mechanisms of fatigue damage, characterization of damage and its evolution, criticality of damage and prediction of fatigue life.

In our recent study [25], an analytical method is presented for fatigue behavior of notched composites under uniaxial random loading. The method is based on determining the stress state around the circular hole and then evaluating the fatigue behavior. Further, studies are presented on fatigue behavior of $[0n/90n]_s$ composite cantilever beams under tip impulse loading [26].

There are only limited studies on fatigue behavior of notched composites under multiaxial loading. Francis et al. [27] conducted tension–torsion fatigue tests on graphite/epoxy T300/1034 composite angle ply tubular structures containing a hole. They developed a theory based on Hill's failure criterion to determine the fatigue life. Hirscfeld and Herakovich [28] carried out experimental studies to investigate the crack growth in notched unidirectional graphite/epoxy tubes subjected to axial, torsional and combined loading. They carried out an analytical study using normal stress ratio theory to predict the stresses and the direction of crack growth.

Shen et al. [29] predicted the fatigue life of notched composite components subjected to multiaxial loading conditions. The model also predicts the location of fatigue crack initiation sites using the local fatigue parameter. They predicted the life of notched composite components from a limited amount of experimental data.

Fujii et al. [30] proposed an empirical approach to investigate the fatigue notch sensitivity of tubular specimens made of woven fabric composites having a circular hole subjected to tension/torsion biaxial loading. Quaresimin and Susmel [31] analyzed the influence of several design parameters such as biaxiality ratio and off-axis angle on the fatigue life of notched composites subjected to multi axial loading from the data available in literature.

From the literature, it can be seen that there are typical experimental and analytical studies on fatigue behavior of notched composites under uniaxial loading. Only limited experimental and analytical studies are available on fatigue behavior of notched composites under in-plane biaxial and multiaxial loading. Further studies are necessary on fatigue behavior of notched composites under in-plane biaxial and multiaxial loading.

The objective of the study is to present a model for the prediction of behavior of laminated composites with a central circular hole subjected to in-plane multiaxial fatigue loading. The model is referred to as modified fiber failure fatigue model for notched composites under in-plane multiaxial loading. The analytical