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A residual strain model for progressive fatigue damage analysis of composite structures

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ABSTRACT

A residual strain model was presented based on the fatigue-accumulated damage mechanisms of composite materials. By combining the proposed residual strain model with a residual stiffness model, the gradually degraded material properties due to the damage in fatigue cycles were characterized. Accompanying the residual strain based gradual material degradation model with a micromechanics-based sudden material degradation rule for describing the stiffness degradation in one fatigue cycle and an extended maximum strain criterion for evaluating failure of materials, a progressive fatigue damage model (PFDM) of a typical double-lap three-bolt joint made of T800 carbon/epoxy composites was developed. Compared with the residual strength model in a traditional PFDM, the residual strain model has consistent parameters with those in the residual stiffness model, which could be determined by non-destructive experiments. Fatigue tests of the double-lap three-bolt joint specimens under a stress ratio $R = -0.2$ and three-level load ratios $q = 0.7, 0.8, 0.9$ were performed. Good consistency between the experimental results and numerical predictions of the PFDM validates the efficiency of the proposed residual strain model and PFDM in accurately predicting the residual strength and fatigue life of composite structures.

1. Introduction

Carbon fiber reinforced polymers (CFRPs) have been widely utilized in aircraft structures due to their high specific stiffness/strength and superior fatigue performance, etc. Initially, CFRPs were mainly used in inessential or secondary aircraft structures with lower load capability. Thus, the fatigue in composite structures was generally enveloped by the static strength [1]. With the increasing application of CFRPs in primary aircraft structures, a high demand for structure efficiency and loading capability makes the fatigue properties of composite structures a focus of attention. Since the mechanical joints are always weak parts of composite structures, their fatigue behaviors have attracted much attention in the last decades.

The investigations on fatigue of composite mechanical joints can be classified as experimental tests and numerical simulations. Up to now, great efforts have been made to study the effects of different factors on the fatigue properties of composite mechanical joints with experimental tests [2–9]. These studies mainly focused on the fatigue life of the joints and only several of them qualitatively evaluated fatigue damage evolution and failure mechanisms of the joints through the limited measurement techniques, such as the strain gauge and extensometer method [2], the DIC method [3] and the infrared thermography [5,8]. In order to deeply explore the fatigue damage propagation and reveal the fatigue damage mechanism of composite mechanical joints, the numerical simulation techniques have been developed since the late 1980s [10–18]. Initially, a critical element model [10,11] was presented to predict fatigue behavior of composite hole laminates. In this model, residual strength of critical elements as well as residual stiffness of subcritical elements needs to be calculated. In later studies, a progressive fatigue damage model (PFDM) [12,13] was established to analyze fatigue failure of composite pin-loaded and bolt-loaded laminates. The PFDM can determine the damage state at different fatigue loading levels and different fatigue cycles, and predict the residual stiffness, residual strength and fatigue life of composite laminates with arbitrary geometry and lay-ups. To reduce the huge computational cost of the PFDM, a similar regional elements model [14] was further developed, where a 2D stress analysis model of

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Nomenclature

$E(n)$	residual stiffness or fatigue modulus
$\varepsilon^R(n)$	residual strain
ε_{ult}	ultimate strain
$\varepsilon(0)$	initial strain
$\varepsilon(n)$	resultant strain
$\Delta\varepsilon(n)$	irreversible fatigue-accumulated strain
E_{11}, E_{22}	longitudinal and transverse moduli
G_{12}	shear modulus
υ_{12}	Poisson ratio
X_T, Y_T	longitudinal and transverse tensile strengths
X_C, Y_C	longitudinal and transverse compressive strengths
S_{12}	shear strength
$\varepsilon^R_{11,t}(0)$, $\varepsilon^R_{22,t}(0)$	longitudinal and transverse ultimate tensile strains
$\varepsilon^R_{11,c}(0)$, $\varepsilon^R_{22,c}(0)$	longitudinal and transverse ultimate compressive strains
$\varepsilon^R_{12,s}(0)$	shear ultimate strain
R	stress ratio
q	load ratio
P_{max}	the maximum load
P_{min}	the minimum load
P_r	residual strength
N_f	fatigue life

representative region, residual strength of critical layers and residual stiffness of sub-critical layers were involved. Recently, Kaminski et al. [15] briefly introduced the PFDM developed by ONERA for predicting the fatigue of 3D woven composite structures and suggested the promising future of PFDM in fatigue analysis of composite structures. In order to overcome the deficiencies of the macro theories in aforementioned PFDM-type models, the micro-mechanics of failure (MMF) theory was extended to predict progressive fatigue failure of composite bolted joints [16], in which numerous fatigue tests of unidirectional laminates are required to obtain MMF critical parameters. Furthermore, to minimize the need for experimental material characterization, a model based on the kinetic theory of fracture for polymer matrices was developed to predict fatigue bearing failure of the hole laminates under the assumption that the initiation of the fatigue damage takes place in the matrix [17,18].

As discussed above, the PFDM is one of the most popular numerical techniques to investigate the fatigue of composite mechanical joints under arbitrary fatigue loading. In general, the PFDMs are combined by different stress analysis models, fatigue failure criteria and material degradation models to obtain accurate predictions. In particular, the material degradation models commonly involved the gradual material degradation stemmed from continuous fatigue cycles and the sudden material degradation resulted from the excessive strain/stress in one fatigue cycle, in which the latter has been maturely developed in static progressive failure analyses of composite joints [19–23]. With regard to the gradual material degradation rules, the researchers have proposed many residual stiffness models [24–30] and several residual strength models [31–33]. Generally, the basic parameters in the residual stiffness models are gained by nondestructive tests, while those in the residual strength models are difficult to be determined because the tests for strength are destructive and usually have a large dispersion.

To overcome this knottiness, a residual strain model was proposed based on the fatigue-accumulated damage mechanism of composite materials. In the proposed model, the parameters are always consistent with those in the residual stiffness model, for which only nondestructive tests are required. Moreover, a PFDM was established to predict the residual strength and fatigue life of a typical double-lap three-bolt joint made of T800 carbon/epoxy composites. In the PFDM, a detailed 3D finite element (FE) model of the joint was built to obtain accurate stress distribution. The proposed residual strain model companied by a residual stiffness model was utilized to represent the gradual material degradation during the fatigue cycles and a micromechanics-based material degradation rule [23] was adopted to characterize the sudden material degradation in one fatigue cycle. The maximum strain criterion was extended to describe fatigue failure of composite materials. To validate the proposed residual strain model and the developed PFDM, fatigue tests of composite double-lap three-bolt joints were carried out.

2. Residual strain based material degradation model in fatigue cycles

A residual stiffness model proposed by Hwang and Han [24] was introduced and a residual strain model replacing the traditional residual strength model was presented, both of which are essential components to establish a gradual material degradation model in fatigue cycles.

2.1. Residual stiffness model

Most researchers agree on the gradual stiffness degradation measured nondestructively is an important aspect to describe the material degradation properties in the fatigue cycles of composite materials. A typical fatigue modulus proposed by Hwang and Han [24] to describe the residual stiffness of composite materials is:

$$E(n) = \frac{\sigma_{max}}{\varepsilon(n)} = \frac{q\sigma_{ult}}{\varepsilon(n)} \tag{1}$$

where $E(n)$ and $\varepsilon(n)$ represent the fatigue modulus and resultant strain at the n^{th} cycle. σ_{max} is the maximum stress level in the fatigue loading spectrum and σ_{ult} is the ultimate strength. q is the load ratio, defined as the ratio of σ_{max} to σ_{ult}.

The boundary conditions are

$$\begin{cases} E(0) \approx E_0 \\ E(N) = \frac{q\sigma_{ult}}{\varepsilon(N)} = \frac{q\sigma_{ult}}{\varepsilon_{ult}} = qE_0 \end{cases} \tag{2}$$

where E_0 denotes the initial stiffness and ε_{ult} is the ultimate strain. They assumed that the final fatigue failure occurs when the resultant strain $\varepsilon(n)$ stemmed from fatigue-accumulated damage arrives at the ultimate strain ε_{ult}.

The stiffness degradation rate is described by [24]

$$\frac{dE(n)}{dn} = -Acn^{c-1} \tag{3}$$

where A and c are material constants.

The integration of Eq. (3) is written as:

$$E(n) - E(0) = -An^c \tag{4}$$

when the fatigue cycle reaches the fatigue life N, A can be expressed as:

$$A = -\frac{E(N) - E(0)}{N^c} \tag{5}$$