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Analysis and life prediction of a composite laminate under cyclic loading

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A R T I C L E I N F O

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A thermographic approach is applied to study the fatigue behavior of a Glass/Epoxy (G10/FR4) composite laminate. A series of uniaxial tension–compression and fully-reversed bending fatigue tests are performed at different stress levels and load ratios with both constant and variable amplitude loading. It is found that under the conditions tested, there is a fairly linear correlation between the rate of temperature rise obtained from the specimen and the time rate of hysteresis energy generation. It is shown that the slope of temperature rise obtained from the specimen increases steadily as the damage accumulates due to cyclic loading. It is also found that the slope of temperature rise is a useful parameter for the characterization of composite fatigue life in constant as well as variable amplitude loading. Several validation tests are performed both constant and variable amplitude loading, and the results are found to be in good agreement to those obtained from the experiments.

1. Introduction

The application of composite materials has increased substantially over the last decade. Components made of these materials have several better mechanical and physical properties, e.g., strength-to-weight ratio, low thermal conductivity, etc., compared to their metallic counterparts. Nevertheless they are prone to irreversible damage when exposed to cyclic loading. Therefore, development of a technique for estimating the useful *remaining fatigue life* (RFL) of a composite structure is highly desirable.

Since composite materials are anisotropic and inhomogeneous, their underlying mechanisms of fatigue degradation are far more complicated than isotropic materials. In particular, the damage mechanism in a composite involves matrix cracking, delamination, fiber/matrix debonding, and fiber breakage [1–3]. These complexities hinder the application of damage estimation models developed for isotropic and homogeneous materials to composites [4,5].

Several approaches have been reported for the estimation of the fatigue life, N_f, of composite laminates [6–11]. However, only a few methods are available for the estimation of RFL [12,13]. These RFL prediction methods rely on the measurement of stiffness degradation and the application of Miner's rule to monitor the entire history of loading.

Recently, researchers developed a method to predict the RFL of metallic specimens by measuring the slope of temperature rise, R_θ, obtained from a short-time excitation (STE) test on a pre-fatigued specimen [14–16]. Liakat and Khonsari [17,18] showed that the evolution of material damage, thermodynamic entropy, and plastic strain energy of a metallic specimen with prior history of cyclic loading can be estimated by measuring the evolution of R_θ. This approach is shown to be capable of predicting the RFL of metallic specimens in a non-destructive (NDT) fashion. However, the application of this method to composite materials has not been reported.

In this work, the gradual progression of composite fatigue degradation is related to the thermal response obtained from a series of STE tests subjected to both constant amplitude cyclic loading (CACL) and variable amplitude cyclic loading (VACL). The principle of the conservation of energy is utilized to establish a correlation between R_θ and the time rate of hysteresis energy generation, $\dot{W}_H$, obtained from STE tests. An extensive series of uniaxial tension–compression and fully-reversed bending fatigue tests are performed with solid cylindrical and flat specimens made of G10/FR4 composite to determine the validity of the proposed RFL prediction method.

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Nomenclature

A_i	thermodynamic forces
C	specific heat (J kg^{-1} K^{-1})
f	frequency (Hz)
k	thermal conductivity (W m^{-1} K^{-1})
L_R	load ratio
n	cyclic rate of R_θ evolution (°C s^{-1} cycle^{-1})
n_k	value of n in kth-stage of loading (°C s^{-1} cycle^{-1})
$n_{k,\text{H-L}}$	value of n in kth-stage of loading in a high-to-low load sequence test (°C s^{-1} cycle^{-1})
$n_{k,\text{L-H}}$	value of n in kth-stage of loading in a low-to-high load sequence test (°C s^{-1} cycle^{-1})
N	number of load cycle
N_f	fatigue life (cycle)
N_k	number of load cycle at kth STE test
N_u	number of load cycle before STE test in the 2nd-stage of a validation test
R	radius (mm)
R_θ	slope of temperature rise (°C s^{-1})
$R_{\theta i}$	value of R_θ at ith STE test (°C s^{-1})
$R_{\theta 0}^{c}$	intercept of R_θ–N plot on R_θ axis (°C s^{-1})
T	absolute temperature at the middle of specimen gage section in fatigue test (K)
$\dot{T}$	time rate of T (K s^{-1})
V_i	internal variables
$\dot{W}_H$	hysteresis energy generation rate (MJ m^{-3} s^{-1})
$\dot{W}_p$	plastic strain energy generation rate (MJ m^{-3} s^{-1})
$\varDelta$	displacement amplitude (mm)
α	coefficient of linear expansion (K^{-1})
ε^e	elastic strain tensor
ε^p	plastic strain tensor
ρ	density (kg m^{-3})
$\boldsymbol{\sigma}$	stress tensor
σ	nominal stress (MPa)
ϕ	diameter (mm)
∇	Laplacian operator

2. Experimental details

2.1. Material and specimen preparation

The material tested is G10/FR4, a Glass/Epoxy composite laminate. This is an unbalanced woven fabric that consists of continuous filament glass cloths laminated with an epoxy resin binder. This material has high mechanical strength, low water absorption rate, and is resistant to corrosion. It is also flame resistant and offers several superior electrical characteristics compared to metals over a wide range of temperature and humidity. These properties allow a wide variety of applications such as aerospace structures, terminal boards, washers, sleeves, and electrical insulators. Some of the properties of this material useful for this work are reported in Table 1.

Fig. 1 presents the photograph of a solid cylindrical dogbone and a flat specimen made of G10/FR4 along with their dimensions. The continuous glass fibers are aligned along the longitudinal axis of the cylindrical specimens. Cylindrical specimens are prepared from cylindrical rods using a computer numerical control (CNC) machine and flat specimens are prepared from a sheet of G10/FR4 using a water jet machine, following the procedure reported in Refs. [11,20,21]. The gage section surfaces produced by machining are polished with sand papers progressing through 1500, 2000, and 2500 grit sizes. Uniaxial tension–compression and fully-reversed bending fatigue tests are carried out with solid cylindrical and flat specimens, respectively. The required dimensions of the solid cylindrical specimens are determined to ensure that they do not buckle within the range of compression loads considered in this work. The flat specimens are designed with hourglass gage section so that fracture occurs in that section. Fig. 2 shows the orientation of the warp (90°) and weft (0°) in each layer of the glass fibers in the sheet material. The fiber layers are aligned parallel to each other along the thickness of a sheet. Flat specimens are prepared at 45° off-axis stacking with respect to the weft (0°) direction. Specimen surfaces created by machining are polished longitudinally using sand papers with fine grit sizes.

The direction of the glass fibers is along the longitudinal axis of the cylindrical specimens. Therefore, its thermal conductivity in the longitudinal direction can be different than that of the radial direction. In the case of flat specimens, thermal conductivity along the thickness of the specimen is different than the directions of the fibers as shown in Fig. 2. However, the value of thermal conductivity reported in Table 1 is a bulk property of this material. Since the effect of anisotropy decreases with the accumulation of fatigue degradation [22], the difference between the thermal properties due to the anisotropy becomes less pronounced.

2.2. Equipment and experimental procedure

2.2.1. Uniaxial tension–compression tests

Load-controlled uniaxial fatigue tests are carried out at different stress levels, σ, load ratios, L_R, (defined as the ratio of minimum to the maximum stress in a load cycle), and test frequency $f = 5$, 10, and 15 Hz. In order to determine the effect of fatigue loading frequency on R_θ evolution, three tests are performed at 5, 10, and 15 Hz frequency with $\sigma = 145$ MPa and $L_R = -0.25$. The apparatus is a servo-hydraulic fatigue testing machine with the capability of a maximum of 50 kN axial load and 75 Hz frequency. The specimen is gripped between the jaws of the top and the bottom grips vertically and an extensometer is mounted on the gage section as shown in Fig. 3. The top grip remains stationary and the bottom grip oscillates vertically to generate uniaxial tension–compression load in the specimen. The extensometer used to record the strain in the gage section of the specimen has the gauge length of 25.4 mm and travel between −10% and +50% strain. It directly interfaces with the fatigue testing machine and a data acquisition system records the load and strain data during the fatigue test. Stress vs. strain plot provides hysteresis loops associated with each load cycle and the area contained within the boundaries of these loops is the measure

Table 1
Properties of G10/FR4 composite laminate [19].

Density, ρ (kg m^{-3})	Specific heat, C (J kg^{-1} K^{-1})	Thermal conductivity, k (W m^{-1} K^{-1})	Coefficient of linear expansion, α (K^{-1})
1635	850	0.4	50×10^{-6}