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Prediction of fatigue life of glass fiber reinforced polyester composites using modal testing

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ABSTRACT

The main objective of the present work is to investigate the capability of experimental modal analysis as a nondestructive tool to characterize and quantify the fatigue behavior of laminated composite beam with different lamina orientations and cantilevered boundary condition. In the present work, experimental modal analysis was conducted on the specimens previously subjected to fatigue loading to determine the modal parameters (natural frequency, damping ratio and mode shape). This was achieved through studying the response of modal testing with different specimens of different lamina orientations as a main factor affecting fatigue life. This correlates modal parameters such as: damping ratio, natural frequency and mode shape to fatigue behavior. The composite material used in experiments is glass fiber reinforced polyester (GFRP) laminate. Plane bending fatigue tests were performed on standard fatigue specimens. The fatigue test was interrupted at different fatigue life ratios (n/N_f) and modal testing was conducted to determine the change in modal parameters. The results showed that the changes of modal parameters provide a proper means for predicting the fatigue behavior of composite structures. From the experimental results of both dynamic and fatigue tests, curve fitting technique was used to correlate modal parameters to fatigue life. An exponential and quadratic equations have been obtained which correlate fatigue life ratio to damping ratio and resonant frequency respectively. It was noticed from the curves representing exponential and quadratic equations that the value of damping ratio ξ is more noticeable than the value of frequency, which means that the extent of fatigue damage determines the damping ratio, hence damping ratio could be said to be a good indicator of the fatigue life ratio.

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1. Introduction

Fatigue has been recognized as a unique and independent failure process in metals for more than 100 years. In metals, fatigue failures have generally been divided into three stages: crack initiation, crack propagation to a critical size, and unstable fracture of the remaining section. Widespread studies of fatigue failures have led to the conclusion that as many as 90% of all material failures are caused by fatigue. Thirty years ago, it was common for users of CFRP involved in Airbus program to express the belief that these advanced materials did not suffer from fatigue. Today, it is assumed by certain experts including Harris [1] that fatigue of CFRP should be one reason among others, explaining the crash of AA 587 on November 2001, near New York airport.

It is of interest to point out differences between metals and high performance composites in regard with the need of the designer. Many differences occur at the microscopic and at the macroscopic levels. In metals, the fatigue damage is strongly related to the cyclic plasticity that is to say the dislocation mobility and slip systems. Due to the environmental effect and the plane stress states, the initiation of fatigue damage is often localized near the surface of metals. The fatigue damage propagation in metal is a single crack. The fatigue of composite materials is quite different from metal fatigue. The simultaneous development of numerous cracks in composite materials makes it impossible to assess the fatigue damage based on a single crack. Moreover, the fatigue damage of composite materials depends on many other damage mechanisms such as fiber breakage, matrix cracking, delamination, and debonding. Combinations of these damage mechanisms may adversely affect some of the mechanical properties of composite materials such as strength and stiffness. Consequently, much of the cumulative damage research on composite materials is concerned mainly with the exploration of residual strength and stiffness degradation during the fatigue process.

Dyer and Isaac [2] studied fatigue behavior of continuous glass fiber reinforced composites. In their study, two matrix resins were tested: standard polyester and a polyurethane-vinyl-ester. Three different types of glass fiber fabrics were used for reinforcement: a conventional woven roving and two stitch-bonded cloths.

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Additionally, their study was undertaken to evaluate the micro-mechanisms that occurred during fatigue and how damage accumulated throughout the sample lifetime. This involved measuring stiffness changes during fatigue cycling, followed by microscopic study of the samples. They found that similar damage micromechanisms occurred in each lay-up regardless of resin and cloth type, and these included matrix cracking, delamination and fiber breakage, they observed, differences in the extent, location and rate of damage, and these were consistent with the variations seen in the fatigue strengths. Paepegem and Degrieck [3] presented an investigation of the fatigue performance of plain woven glass/epoxy composite materials in two configurations: $[0°]_8$ and $[45°]_8$. First, they discussed the experimental set-up developed for bending fatigue experiments which showed not only that the two specimen types, had a quite different damage behavior and that the stiffness degradation followed a different path but also indicated that stresses are continuously redistributed across the structure during fatigue life. Next, they presented a numerical model implemented in a mathematical software package and proved to be a useful tool to study the fatigue degradation behavior of composite materials. Prediction of the cyclic durability of classic-weave glass fiber vinylester laminate specimens produced by wet vacuum technology and cut at different angles to the principal axes was investigated by Tamuzs et al. [4]. They found that the final critical damage level before failure, defined by reduction in the cyclic modulus, did not depend on the durability (cycles to failure), but did vary in different loading directions, depending on the asymmetry (in ratio of minimum to maximum load) of cyclic loading. The invariance of critical damage level with respect to the durability provides a means of predicting the cyclic life time by monitoring the damage accumulation reflected by cyclic modulus. Lee and Shin' [5] introduced a frequency response function (FRF)-based structural damage identification method (SDIM) for beam structures. The damages within a beam structure were characterized by introducing a damage distribution function. It was shown that damages might induce the coupling between vibration modes. They also investigated numerically the effects of the damage induced coupling of vibration modes and the higher vibration modes omitted in the analysis on the accuracy of the predicted vibration characteristics of damaged beams. The feasibility of SDIM was verified through some numerically simulated damage identification tests. Moon et al. [6] developed a new nondestructive fatigue prediction model for composite laminates in which the natural frequencies of fatigue damaged laminates under extensional loading were related to the fatigue life of the laminates by establishing the equivalent flexural stiffness reduction as a function of the elastic properties of sub-laminates. Vibration tests were conducted on $[90_2/0_2]_s$ carbon/epoxy laminates to verify the natural-frequency reduction model. Correlations between the predictions of the model and experimental results were good. Bedewi and Kung [7] investigated global effects on modal parameters, natural frequencies and damping ratios during the fatigue process using a developed experimental method to predict the residual fatigue life of composite structures and continuously refine the prediction during the service life of these structures. Changes of modal parameters were correlated with the prediction of fatigue failure life for selected graphite/epoxy composite specimens. They recommended the use of damping changes to predict remaining life at later stages. They concluded that using damping ratios to predict fatigue life can be used as a backup approach to support predictions made using natural frequencies. Banerjee et al. [8] developed and subsequently used the dynamic stiffness matrix of a composite beam to investigate its free vibration characteristics. The formulation was based on Hamilton's principle leading to the governing differential equations of motion in free vibration, which were solved in closed analytical form for harmonic oscillation. Through the boundary conditions, the frequency dependent dynamic stiffness matrix that relates the amplitudes of loads to those of responses was then derived. The Wittrick–Williams algorithm was applied to the resulting dynamic stiffness matrix to compute the natural frequencies and mode shapes. The method is computationally efficient and numerically accurate and thus can be used as an aid to validate the finite element and other approximate methods. Damir et al. [9] investigated the capability of experimental modal analysis, as a nondestructive tool, to characterize and quantify fatigue behavior of materials by studying the response of modal parameters (damping ratio, natural frequency, and FRF magnitude) to variations in material microstructure, as a main factor affecting fatigue life. This correlates modal parameters to fatigue behavior. Cast iron family represented by grey cast iron, ductile cast iron and austempered ductile iron (ADI) was used in experiments as a case presenting considerable variations in microstructure. Modal testing was performed on specimens made of the selected materials in order to extract the corresponding modal parameters. Rotating bending fatigue test was performed on standard fatigue specimens to correlate the modal parameters to the fatigue behavior. This enabled the evaluation of the ability of modal testing to predict the fatigue life of mechanical components. Kim [10] established a vibration-based damage identification method for fiber-reinforced laminated composites and their sandwich construction. His new technique used the structural dynamic system reconstruction method exploiting the frequency response functions (FRFs) of a damaged structure. To verify the effectiveness of this method, the frequency responses obtained by vibration testing of fatigue-damaged laminated composites and honeycomb sandwich beams with debonding were examined according to the extent of the damage via the fatigue-damage load cycle for laminated composites, and via the debonding extent for honeycomb sandwich beams. He examined the changes of the peaks and valley of the FRFs according to the debonding extent and the fatigue load cycles. He also discussed the area changes in the FRFs as the damage index. The residual FRFs or the difference between intact and damaged FRFs are newly defined for application of the on-line damage identification method. Finally, he could identify the delamination extent for the sandwich beams and the fatigue damage level for the laminated composites in terms of the changes in natural frequencies and damping ratios of the reconstructed FRFs for these damaged composite structures. Giannoccaro et al. [11] dealt with the development of a technique based on the analysis of a particular set of modal data to which fatigue strength of elementary mechanical components can be correlated. The modal data was dealing with resonance and anti-resonance data associated to a certain set of specimens. The specimens have been submitted to a large number of fatigue tests and valuable correlations have been extracted between modal data changes and the evolution due to the relevant fatigue loads in the high-cycle regime. The high number of statistics involved in the experimental tests clearly showed how the previously mentioned modal data can forewarn a final failure. Chen et al. [12] developed a methodology that combines the vibration failure test, finite element analysis (FEA), and theoretical formulation for the calculation of the electronic component's fatigue life under vibration loading. A specially designed plastic ball grid array (PBGA) component with built-in daisy chain circuits was mounted on a printed wiring board (PWB) as the test vehicle for the vibration test. A formula for the prediction of the component failure cycle was deduced. It is also examined later by firstly predicting the fatigue failure cycle of a component and then conducting a vibration test for the same component for the verification purposes. The field test results have proven to be consistent with predicted results. It is then believed that the methodology is effective in predicting component's life and may be applied further in improving the reliability of electronic system. A statistical model for the prediction of the fatigue life of unidirectional composite laminae subjected to multiaxial fatigue loading was developed by Diao et al. [13]. The model is based on