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Progressive damage assessment of centrally notched composite specimens in fatigue

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ABSTRACT

The aim of this study is to assess the residual properties and the corresponding damage states within centrally notched quasi-isotropic $[0/-45/+45/90]_S$ T650/F584 (Hexcel) carbon-fiber/epoxy composites subjected to fatigue loading using Digital Image Correlation (DIC), radiography, and a non-contact vibration measurement technique. Quasi-static tests were performed on virgin samples using DIC to determine the full-field in-plane strains at different applied load levels. Fatigue tests were interrupted during the fatigue lifetimes in order to perform quasi-static tests with DIC measurements. Non-contact vibration measurements were performed to investigate the effect of fatigue damage on residual frequency responses. X-ray computed tomography was used to determine the type, location, and extent of fatigue damage development. The results provide an important step in the validation of DIC and vibration response as a powerful combined non-destructive evaluation tool for monitoring the development of fatigue damage as well as predicting the damage level of notched composite materials.

1. Introduction

The increased and extended use of fiber reinforced composite materials in aerospace, submarine, wind turbine, automotive, civil engineering structures and other applications, can be attributed to the myriad of advantages these materials provide compared to isotropic materials such as steel, aluminum, concrete and even anisotropic wood. Indeed, fiber reinforced composite materials are characterized by high stiffness and strength with relative light weight, corrosion resistance and excellent fatigue properties. Although composite materials are expected to have excellent fatigue lifetimes especially when compared to metallic materials, researchers must consider fatigue as a crucial aspect in performance calculations during design processes, particularly for structures that undergo cyclic loading during their service time. The anisotropic nature of FRP composite materials renders their experimental fatigue damage characterization a complicated task since these materials exhibit different damage modes at different locations at the same time. The principal types of damage that can be developed during fatigue life are matrix cracks, delamination, matrix and fiber debonding and fiber breakage [1–3]. In addition, the interaction between these failure modes contributes significantly to the complexity of the damage characterization task. Moreover, the multitude of material configurations resulting from the variability of fibers, matrices, manufacturing methods, lamination stacking sequences and geometries makes the development of a commonly accepted method to cover all these variations difficult [4].

Several experimental techniques have been used to obtain valuable information on the micro-structural level as well as on the macro-structural level damage development during fatigue loading. Nevertheless, each work has been focused in one or more aspects for studying fatigue damage effects on composite material during its fatigue lifetime. Early fatigue studies used many non-destructive techniques for the identification of damage patterns on the surface of and also inside fatigued composite materials. The most common methods used were X-rays, acoustic emission, surface observation during fatigue loading or post mortem observation using scanning electron microscope, ultrasounds and surface replicas [5–9]. However, the generally accelerated enhancement of the hardware (mechanical and electronic aspects), the software (Data processing and display) and the development of modern embedded systems lead to a significant improvement of the results obtained by the aforementioned techniques and the development of new other techniques. For instance, recent advances in digital photography and computer technology have led to the development of digital image correlation (DIC) as an effective non-contact method of measuring deformation.

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de Vasconcellos et al. [10] have combined different techniques to analyze fatigue damage mechanisms of a woven hemp fiber reinforced epoxy composites for two different stacking sequences ($[0/90]_7$ and $[\pm45]_7$): optical microscopy, X-ray micro-tomography observations, temperature field measurement by infrared camera and acoustic emission monitoring. All these techniques permitted a complete description of damage mechanisms developing in these hemp/epoxy composites. El Sawi et al. [11] used infrared (IR) thermography to build a simple predictive model of fatigue life in two configurations of flax/epoxy composites layup ($[0]_{16}$ and $[\pm45]_{4S}$) by establishing a direct correlation between the temperature increase and the number of cycles to failure at the same stress level. They also used SEM to monitor crack density for a stress level at different damage stages. In the case of $[0]_{16}$ laminates, the dynamic modulus was found to increase with increasing number of cycles. This hardening behavior has been observed exclusively in flax/epoxy composite laminate that have plant-based fibers. Montesano et al. [12] also used infrared thermography technique to determine the stress-life curve and the fatigue threshold of a triaxially braided carbon fiber composite material. They established a direct correlation between the increase in temperature at stabilization, the intrinsic dissipation energy (hysteresis) and the number of cycles to failure. Other studies based on infrared thermographic techniques (passive and active approaches) are carried out to characterize the fatigue damage of CFRP composites [13,14].

Dattoma and Giancane [15] evaluated fatigue damage from a theoretical viewpoint of energy balance during the test by evaluating the hysteresis area, dissipated and accumulated heat and then calculating the fatigue damage energy. Their work was performed on double notched specimen made from E-glass/epoxy using two different full-field techniques thermography (via a FLIR 7500 camera) and digital image correlation (via a high speed camera with an image resolution of 320×256 pixel^2).

Broughton et al. [16] used various measurement techniques including digital image correlation, to monitor local and global strains throughout the fatigue lifetime of open-hole composites machined from quasi-isotropic $[45/0/-45/90]_{4s}$ E-glass/913 epoxy laminates, and multiplexed fiber Bragg grating (FBG) sensors to measure the residual stiffness resulting from the increasing of number of cycles. However, the study was restricted to monitoring longitudinal strain, specifically at the mid-section of the notched samples for a single stress level. The images were recorded during statically reloading the specimen to a constant load at a frequency of 1 Hz using a single megapixel camera after stopping the fatigue testing at set intervals of 10,000 cycles.

Sisodia et al. [17] used DIC for full-field strain measurement of composites under fatigue loading with the help of a high speed camera that captures images at a peak load level for every cycle. They also used microscopy to track the micro-cracks formation at certain milestone levels of load cycles.

The aforementioned studies represent the very limited number of existing studies in the literature that used DIC to describe the fatigue behavior of composites generally. Even for monotonic tests, there are only a few studies that used DIC to characterize the damage progression in notched composites during tensile loading [18–21].

Frequency response methods have been used as reliable and cost-effective damage detection techniques when utilizing composite materials. Indeed, they are found to be a great tool for identifying even small amounts of damage in composite structures through the change in natural frequencies, mode shapes, and damping ratios. Nevertheless, the potentially important information about damage type, shape, size, location and orientation were lost since various combinations of these parameters may engender similar frequency responses. However, a multitude of experimental studies were carried out on composite structures containing initially embedded defects. Each study represents only one type of damage: delamination, transverse matrix cracks, cutouts or impact failures with possible different locations and severities [22–26].

Nonetheless, only a restricted number of studies have focused on establishing relationships between fatigue damage, fatigue life, and changes in the modal vibration responses of composite structures [27–30]. Bedewi and Kung [27] conducted experiments to determine the effects of changes of modal parameters, natural frequencies, and damping ratios on the fatigue life of composite samples. They correlated these changes with the prediction of fatigue failure life for selected composite specimens. They selected modes 5 and 6 to predict fatigue life due to the apparent sensitivity of these modes to the induced damage. They also suggested the use of damping ratios to predict fatigue life as a backup approach to support predictions made using natural frequencies. Abo-Elkhier et al. [28] performed plane bending fatigue tests on glass fiber polyester composites with different lamina orientation: $[0°]_3$, $[45°]_3$ and $[90°]_3$. The fatigue tests were interrupted at different fatigue life ratios and modal testing was conducted to determine the change in modal parameters. The results showed that these changes offer a means for predicting the fatigue life of composite structures. However, the latter two studies involve the effects of out of plane bending fatigue on the modal properties of composite structures. Moon et al. [29] developed a non-destructive fatigue prediction model for matrix-dominated fatigue damage of composite laminates. They related the natural frequencies of cross-ply laminates under tension–tension fatigue loading to the equivalent flexural stiffness reduction which is a function of the elastic properties of sublaminates and the number of cycles. In this method, only the 90° plies undergo stiffness reduction while the 0° plies remain intact. This relation indicates that there is an equivalence relation between a residual natural frequency and extensional stiffness reduction. They also conducted vibration tests on $[90°_2/0°_2]_s$ carbon epoxy laminates to verify the natural frequency-reduction model. Kim [30] established a vibration-based damage identification for cross-ply carbon fiber epoxy laminates under fatigue loading. This structural damage identification uses the structural dynamic system reconstruction method by using the frequency response functions of damaged structure. The two previous studies represent the only available studies in the literature to study the effect of axial-fatigue testing damage on the modal parameters of composite structures during their fatigue life.

This study has carried out an extensive experimental program to investigate and quantify the damage development by measuring the residual properties throughout the fatigue life of open-hole quasi-isotropic $[0/-45/+45/90]_S$ T650/F584 (Hexcel) carbon-fiber/epoxy laminates loaded in tension–tension fatigue. The current work focuses on the application of (a) the Digital Image Correlation (DIC) technique to determine the strain profiles at selected locations of fatigued and non-fatigued specimens and (b) vibration tests to determine the frequency response of undamaged and fatigued specimens. X-ray scans are performed to partially fatigued samples to investigate damage details throughout the fatigue lifetime.

2. Material processing and experimental methods

2.1. Tested materials

Seven composite plates measuring 305 mm × 305 mm were autoclave manufactured using carbon fiber epoxy Hexcel T650/F584 pre-impregnated tapes with a quasi-isotropic $[0°/-45°/+45°/90°]_S$ lay-up. The plates were cured according to the