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Application of infrared thermography for the characterization of damage in braided carbon fiber reinforced polymer matrix composites

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ABSTRACT

The focus of this study is to assess, using infrared thermography, the fatigue behavior and the corresponding damage states of a textile polymeric composite plate, as a prerequisite step in the development of damage based life prediction models for such advanced composite materials. Monotonic (quasi-static) loading test results confirmed that the dominant damage mechanism is cracking in the braider yarns, which was monitored using thermographic images and confirmed by edge replication microscopic observations. Fatigue results confirmed that the saturation of braider yarn cracks during cyclic loading corresponded to changes in the stiffness degradation rate as well as the surface temperature profile. This was confirmed by edge replication and scanning electron microscopic analysis. The reported results and observations provide an important step in the validation of thermography as a powerful non-destructive evaluation tool for monitoring the development of fatigue damage as well as predicting the damage states of laminated composite materials in general, and braided polymeric composite materials in particular.

1. Introduction

In recent years, advanced fiber-reinforced polymer matrix composite (PMC) materials have been preferred for primary load bearing aerospace applications due to their excellent mechanical properties including superior strength-to-weight and stiffness-to-weight ratios. In fact, carbon fiber reinforced epoxy laminates consisting of multiple oriented unidirectional laminae have been predominantly utilized for these specific applications. Despite their substantial use, many manufacturing and performance disadvantages have been identified with unidirectional-ply PMC laminates, leading to highly conservative component designs [1]. This has consequently led to the recent development of fabric-reinforced PMC materials, which include woven, knitted and braided fabrics among others. Compared to conventional laminates, fabric reinforced PMC components boast a number of clear advantages [2,3]. Some of these advantages include having better overall through-the-thickness strength properties including superior impact damage resistance and delamination resistance, balanced in-plane performance, improved fatigue performance and lower notch sensitivity. In addition, producing complex shaped parts can be easier and lower cost due to the conformability of fabrics coupled with out-of-autoclave manufacturing processes such as resin transfer moulding (RTM).

In spite of the indicated advantages, the use of fabric reinforced PMC materials is only limited to a few applications in the aerospace industry to date. One of the issues restricting their wider use is that there have been few studies reported in the open literature which characterize the mechanical behavior of these PMC materials [4–7]. Damage and failure mechanisms are more complex for fabric PMCs and thus much more difficult to understand, partially due to a number of fabric geometric variables such as tow size, tow angle and braid/weave pattern. Generally, there is a lack in available fatigue life and fatigue strength data for these materials, which would otherwise be useful during the component design stage. Developing a comprehensive understanding of the material mechanical behavior is therefore crucial to ensure the widespread application of these advanced materials for manufacturing primary load bearing structural components.

When subjected to cyclic loading composite materials can prematurely fail at loads that are significantly lower than their ultimate strengths, which can limit their service life and damage tolerance capabilities. Therefore, assessing the fatigue behavior of composite materials by tracking damage progression and material property degradation is also imperative for developing corresponding tools to predict critical damage states or their fatigue life. An acquired ability to accurately monitor and quantify damage is in fact an essential prerequisite in the development of damage based

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life prediction models for advanced composite materials such as those that are the subject of this study. A number of non-destructive evaluation (NDE) techniques have been employed in the past with this aim. Some of these NDE techniques include acoustic emission [8], ultrasonic scanning [9] and X-ray tomography [10]. These methods may not necessarily be practical for in situ monitoring due mainly to the limitations of the testing apparatus. Recently, infrared thermography (IRT) has been established as a means to monitor the performance of composite components [11,12], providing a non-contact, in situ and a real-time assessment of these materials. In addition, IRT has recently been utilized for characterizing the microscopic damage behavior of fabric reinforced PMC plates with promising results [13–20]. It is therefore the objective of this study to utilize IRT for monitoring the development of damage in a tri-axially braided carbon fiber-reinforced PMC material. An infrared (IR) camera is used to not only monitor the surface temperature of the cyclically loaded plates, but to capture the crack saturation states that correspond to the exhibited material behavior. The subsequent sections outline the experimental details, present the results with the corresponding analysis and discussion, and summarize the main conclusions.

2. Experimental details

A thermosetting polyimide resin reinforced with a tri-axially braided carbon fiber fabric (T650/35-6K) with a 0°/±60° orientation was investigated (see Fig. 1(a)). The flat composite panels were manufactured using a RTM technique, resulting in panels with final dimensions of 362 mm (warp) by 350 mm. Each panel was cut along the warp direction (i.e., 0° yarn direction) into 12 coupons using an abrasive waterjet cutting technique. The coupons, which were equipped with 10° tapered aluminum end tabs to eliminate any potential issues with gripping induced failure, had nominal dimensions of 355 mm × 25 mm.

All uniaxial tensile monotonic and fatigue tests were conducted at room temperature on an MTS 322 test frame equipped with hydraulically operated wedge grips. A surface mounted extensometer was used to monitor the local axial strain and for calculation of the progressive material stiffness during the cyclic loading tests. A FLIR SC5000 infrared camera with a pixel resolution of 320 × 240 and a temperature sensitivity of <20 mK was used to monitor the test coupon surface temperature. The infrared camera was used without an external heat source, thus the specimens were only heated by mechanical loading. A photograph of the test setup with application of the IR camera is shown in Fig. 1(b). For the cyclic tests, the infrared camera was synchronized to the test controller in order to trigger the acquisition of images at the same point in each loading cycle, which was necessary to eliminate any variation of temperature due to cycling between maximum and minimum cyclic stresses [11]. In addition, edge replicas were taken for some of the fatigue test coupons using acetone and cellulose acetate film to track edge damage progression during cyclic loading. Scanning electron microscopy (SEM) was also utilized post *mortem* for additional damage observations, where specimen cross-sections were investigated and specimen axial-sections close to as well as further away from the edge were also investigated [1]. The ultimate strength tests were conducted in displacement control with a constant crosshead speed of 2 mm/min. Tension–tension fatigue tests were conducted in load control using a constant amplitude sinusoidal waveform, a loading frequency of 5 Hz and a stress ratio of 0.1 at various maximum applied stress levels.

3. Experimental results

3.1. Monotonic tests

A total of four ultimate strength tests were conducted initially to define the ultimate strength of the test specimens which was required for the fatigue tests, and to investigate the microscopic damage mechanisms under quasi-static loading conditions. Edge replicas were extracted for two monotonically loaded test specimens for the purpose of identifying the dominant damage modes and determining the evolving crack density. These tests were paused at various stress levels in a stepwise manner to extract the edge replicas while the load was held constant. After pausing the tests at load levels corresponding to 7%, 14%, 21%, 35%, 42%, 50%, 57%, 75% and 85% of the ultimate strength, loading resumed with the same constant rate. The IR camera was employed for two additional monotonic loading tests to continuously monitor the temperature profiles on the material surface as loading increased. Edge replication revealed that the dominant damage mechanism was transverse cracking in the braided yarns. Braider yarn cracks were also found to be the dominant damage modes for a similar tri-axially braided composite material quasi-statically loaded in tension [21]. This was confirmed by *post mortem* SEM analysis as shown in Fig. 2. Note that the 0° yarns are outlined for clarity in the image. There was no visible damage in the 0° yarns, and some localized cracking at the adjacent braider yarn interfaces. The evolution of the braider yarn cracks was continuous for the duration of the monotonic loading tests, reaching a higher propagation rate and thus a higher crack density during the latter stages of the loading.

Real-time images extracted using the IR camera confirm that the saturation of braider yarn cracks is in fact much higher during the latter stages of loading, and damage is widespread throughout the specimen length. Fig. 3(a–d) shows a series of these images for an ultimate strength test specimen. The initiation of damage in the braider yarns is indicated by the sudden temperature increase in the braider yarn regions at lower stress levels. As loading progresses, the initiated cracks begin to propagate along the braider

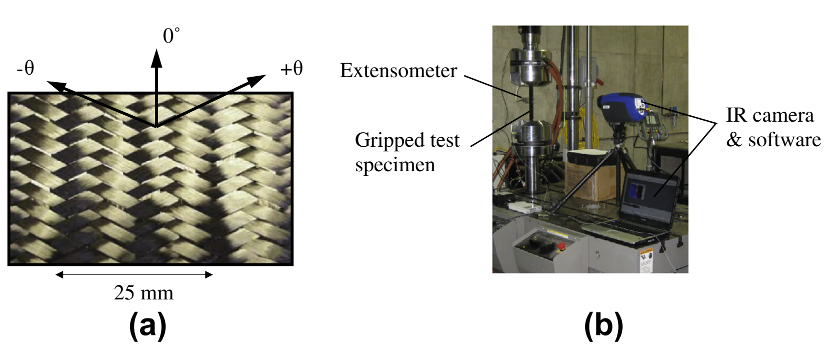

Fig. 1. Photograph of (a) braided fabric and (b) experimental setup with infrared camera.