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Non contact inspection of the fatigue damage state of carbon fiber reinforced polymer by optical surface roughness measurements

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ABSTRACT

This work presents the evaluation of a new non-contact technique to assess the fatigue damage state of CFRP structures by measuring surface roughness parameters. Surface roughness and stiffness degradation have been measured in CFRP coupons cycled with constant amplitude loads, and a Pearson's correlation of 0.79 was obtained between both variables. Results suggest that changes on the surface roughness measured in strategic zones of components made of the evaluated CFRP, could be indicative of the level of damage due to fatigue loads. This methodology could be useful for other FRP due to similarities in the fatigue damage process.

1. Introduction

The growing use of composite materials in aircraft structures, mainly Carbon Fiber Reinforced Polymer (CFRP), makes essential the knowledge of the fatigue damage state, when these structures are subjected to cycling loads of any nature. Examples of these cycling loads include the spectrum loads for wings or constant amplitude loads for fuselages (due to internal pressurization) [1]. A better knowledge of the damage state due to fatigue is useful to optimize the maintenance procedures (repair or replacement) of structural components, keeping the integrity of the structure components in safe conditions.

Conventional techniques to determine the fatigue state of an aircraft structure are based mostly on measurement of structural loads throughout the service life by electric strain gauge sensors, which present some disadvantages. One is that these sensors are affected by extreme environmental conditions such as fatigue loads, electromagnetic fields, etc., in such a way that these sensors require an exhaustive maintenance program. A second disadvantage is that the stiffness degradation of the composite materials due to the accumulated damage on the structure could lead to a non-realistic stress–strain relation on the strain gauge sensors. A third disadvantage is that the accumulated fatigue damage determined by load history, is conventionally calculated from linear models initially developed for homogeneous material, where Palmgren–Miner rule is the most extensively used method [2]. Experimental studies show inaccurate and non-conservative predictions when Palmgren–Miner rule is applied to composite materials under spectrum loads [3–5].

There are numerous models developed for fatigue damage accumulation of composite materials, including strength and stiffness degradation [3,4], but due to the complexity of the damage mechanisms on composite materials, models developed are only applicable for specific conditions of loads and materials, and are based on fitting experimental values. The most relevant property to quantify the fatigue damage state of a structure (fatigue damage metric), is the strength degradation of the material due to the accumulated damage (commonly known as residual strength). This relevancy is because there exists a direct relation that the failure is produced when the residual strength becomes equal or lower than the maximum stress applied during cycling (S_{max}). Models have been developed to predict the fatigue life of Fiber Reinforced Polymers (FRP) based on strength degradation and several are summarized in the review study developed by Post et al. [3]. In practice, residual strength is a property that cannot be used to determine the fatigue damage state of an in-service structure, because of the impossibility of measuring the strength of a material with non-destructive tests. A second problem is that it is difficult to obtain adequate data to validate models based on strength degradation, because of the combination of two sources of scattering in the experimental data, the first one is the scattering of the initial strength and the second is the scattering of the fatigue

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life. This combination produces a significant scattering on the residual strength measurements [6].

An alternative damage metric to the residual strength method, is to measure the stiffness degradation of the material. Some authors take the stiffness as a fatigue damage metric and establish a relation with the residual strength [7–10]. Stiffness can be measured with non-destructive tests, making easier to follow the evolution of this property throughout the cycles. One disadvantage is that a controlled load should be applied to the structure with a dedicated test setup. A second disadvantage is, as mentioned before, that conventional techniques to measure the stiffness with sensors installed on the component, are affected by fatigue loads and environmental conditions.

Alternative techniques based on phenomenological changes on the composite materials are presented to measure damage due to fatigue loads such as ultrasonic techniques, acoustic emissions [11–13], infrared imaging [14], electrical resistance [15]. Others include non-contact techniques such as thermography, digital image correlation [16,17] and X-ray Tomography [18].

The present work is focused on the evaluation of a new technique to assess the fatigue state of CFRP structures, by means of the evaluation of surface topography variations due to fatigue damage with non-contact measurements. Techniques for evaluating the fatigue state via surface assessment have been developed for structural metals and the conclusion is that the metals undergo a surface transition related to metallurgical effects of their crystal structure [19–22]. A previous approach to evaluate the evolution of surface parameters on CFRP due to fatigue loads was done by the authors [23], where visual inspections show that the change in surface roughness in CFRP materials is a result of micro- or macro-surface cracking of the matrix material and changes of the surface shape due to internal delaminations. In this first study a relation between the evolution of roughness parameters and fatigue cycles at constant amplitude load of 60% of the ultimate tensile strength (S_{ut}) has been evaluated [22]. The present study is focused on the evaluation of the evolution of roughness parameters due to the fatigue cycles at different levels of loads and the comparison with a conventional damage metrics such as stiffness degradation.

Roughness parameters have been selected to characterize the topography of the surface, because it is a property that can be measured precisely in the laboratory with nanometer resolution optical perfilometers, such as confocal microscopes, and could be measured in the field by optical techniques such as speckle or portable optical perfilometers [24–27].

2. Methodology

2.1. Materials

The material selected for the present study is a CFRP type MTM-45-1/IM7 from Advanced Composite Group, ACG, which is a relatively new composite material used for aeronautic structures. Two panels of 2 mm of thickness in a quasi-isotropic stacking sequence of $((45,90,-45,0)_s)_2$, have been manufactured. The panels have been cured in an autoclave at 6 bars and 130 °C and their quality were verified by standard C-scan ultrasonic test. The ultimate tensile strength (S_{ut}) of the material is 938 MPa and was statistically estimated in a previous study [23].

For the present study, 13 coupons with dog bone geometry shown in Fig. 1 were extracted from the panels. GFRP tabs were bounded at both ends with film adhesive MTA240 from ACG, in order to obtain a better load introduction and to protect the coupon against the gripping forces of the test machine. The notched geometry of the coupon tests with a gage zone of $10 \times 10 \times 2$ mm^3 was designed and verified by finite element analysis, in order to guarantee the highest level of strains uniformly distributed at the inspection zone and also to avoid failure due to stress concentration at the interface with the test machine. Finite element results in Fig. 2 are drawn in a normalized scale and show a uniform distribution of strains (ε) in the direction of the load with variations around 5% in the gage zone when a tensile load is applied to the coupon.

A test machine (MTS 810 from MTS systems) operated at room temperature under load controlled conditions, was used for the fatigue tests and to extract the stiffness information from the coupons. The surface topography was obtained by a confocal microscope (PLμ Confocal Imaging Profiler, from Sensofar) with an objective zoom of 50 × and a resolution of 5 nm.

2.2. Fatigue tests and stiffness measurements

Cycling loads were applied to 13 specimens under constant amplitude load with a stress ratio of $R=0.1$ (tension–tension load). Different levels of maximum stress (S_{max}) between 47% and 66% of the S_{ut} were applied to obtain the stress life curve (S–N) shown in Fig. 3. A cycle frequency of 5 Hz has been selected to prevent overheating. The fatigue tests have been interrupted periodically before failure in order to perform the measurement of the surface parameters.

During the fatigue cycles, the stiffness of the coupons has been measured by the displacement of the test machine and the applied load according to Hooke's law. The machine data was treated in order to obtain the stiffness variations in terms of percentage of the initial stiffness (En/Eo), where Eo is the initial stiffness and En is the stiffness at cycle n.

2.3. Surface parameters measurements

Surface topography inspection has been done on both faces of the specimen in an area of 1.55×1.49 mm^2 near to the center of the face as shown in the Fig. 1. Due to the stacking sequence, the layer inspected is at 45° respect to the load direction. The size has been chosen to assess an area with a dimension similar to the area evaluated by laser speckle techniques, in order to have similar statistic and scale. An arbitrary position near to the center of the face has been selected because there is a uniform damage distribution expected along the gage zone of the specimen. The confocal microscope with an objective of 50 × zoom has been used to obtain the topography of the evaluated area, measuring

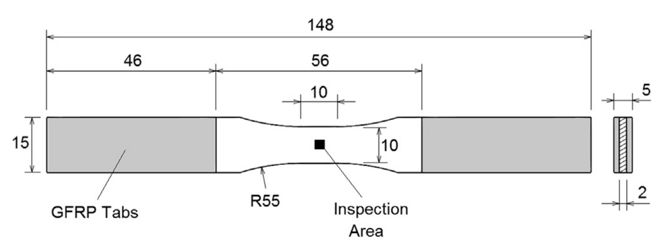

Fig. 1. Coupon geometry, surface inspection area.

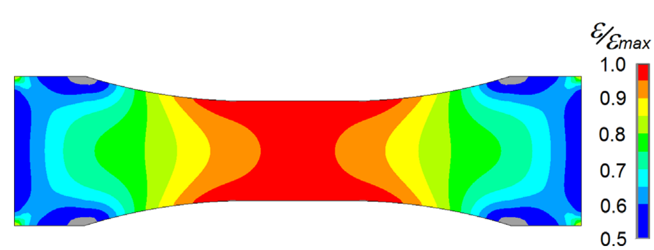

Fig. 2. Normalized strain distribution in the direction of the tensile load by finite element analysis. Variations lower than 5% of the maximum strain in the gage zone.