IN-SITU FATIGUE DAMAGE ASSESSMENT OF CARBON-FIBRE REINFORCED POLYMER STRUCTURES USING ADVANCED EXPERIMENTAL TECHNIQUES

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Abstract

This study focused on the in-situ fatigue damage assessment of open-hole carbon/epoxy coupons using Acoustic Emission (AE) and Digital Image Correlation (DIC) techniques. Constant amplitude fatigue tests were performed and the main objective was to investigate the damage process, the degradation process of the fatigue modules and to identify features, derived from the experimental data, that can be used as sensitive-to-damage indexes. To this end, the two experimental techniques were reviewed as potential online monitoring tools for the fatigue damage assessment.

1. Introduction

Carbon Fibre Reinforced Plastic (CFRP) materials are widely used nowadays as primary structures (airwings, fuselage, etc.) in commercial aircrafts. The most recent example is the Airbus A350, which is in service since January 2015, and more than 50% of its structural weight made of composites. Despite the fact that aerospace industry promotes the use of composite materials, a comprehensive understanding of their mechanical behaviour in terms of fatigue damage analysis is missing.

The foundations of the current understanding of the fatigue processes of composite materials were set early in the decades of 1970's and 1980's [1] when the aerospace industry was eager to increase the use of composites. The way damage evolves in a general composite laminate was generally outlined after extensive experimental evidence although the consent is that the fatigue crack growth can be extremely complex dependent on the loading conditions and the orientation of the reinforcing fibres. The initial stage of damage development consists of multiple matrix cracking along fibers in the off-axis plies, leading progressively in a saturation state of cracking in individual plies. This is called the characteristic damage state (CDS) [2], characteristic of the lay-up and independent of the load value. In the stage following CDS, the ply cracks link up locally promoting interfacial related phenomena such as debonding, fibre pull-out etc. Further load cycling causes growth and coalescence of locally induced delaminations. The final stage of the damage process is characterized by fiber failures in the longitudinal plies and total failure. This phenomenology offers an insight of the physical processes that take place inside the material but still the knowledge of the precise behavior of a composite material under fatigue loading is far from complete. Thus, there is a need of a framework that combines a generalized physics based model, real time monitoring strategies and realistic loading scenarios should

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be developed in order to strengthen our understanding for fatigue damage mechanisms and fortify our confidence about composites materials.

The current exercise focuses on the real time monitoring strategies and explores the capabilities of two experimental techniques, Acoustic Emission (AE) and Digital Image Correlation (DIC) in the fatigue damage assessmnent of CFRP structures. Section 2 presents the experimental set-up, section 3 is devided in two parts; the strain and AE data analysis respectively. Finally, the paper conludes with the section 4 where the most critical observations of this exercise are emphasized.

2. Experimental set-up

Plates from carbon/epoxy prepregs with a stacking sequence $[0/\pm45/90]_{2S}$ were manufactured via the autoclave process. Rectangular coupons were cut in dimensions 300mm x 30mm and a central hole of 6 mm diameter was drilled. The experimental campaign consisted of 3 quasistatic tensile tests and 9 constant amplitude fatigue loading tests. The fatigue tests were executed with maximum amplitude 90% of the ultimate tensile load, loading frequency f=10 Hz and ratio R=0.

A stereovision system was used to perform 3D full field DIC measurements so as to measure strain distribution and calculate fatigue modules. The stereovision system consisted of two matched AVT stingray F-504 digital cameras, two matched Schneider Kreuznach Cinegon 1.4/23 mm lenses and a rigid cross member to minimize relative motion between cameras. In order to acquire pictures, the following steps executed: every 500 cycles the tests were interrupted, the specimens were loaded quasistatically up to the maximum amplitude within 1 sec where the load was kept constant for 2 sec so as to take pictures, then the specimens were unloaded within 1 sec and the fatigue tests continued.

An AMSY-6, 8 channel AE system, was used in order to perform the AE measurements. One wide-band piezoelectric sensor AE1045S-VS900M, with external 34 dB preamplifier and a band pass filter 20-1200 kHz, was attached on the surface of the coupon using a special clamping device., ultrasonic gel coupling was applied on the sensor surface, in order to maximize the conductivity between the sensor and the specimen. The AE system was continuously recording AE activity until the failure of the specimen. The sensor was placed in the lower part of the specimens in a distance of 80mm from the hole and a threshold of 55dB was selected.

Figure 1 presents the experimental set-up and the fatigue loading with the data acquisition process.

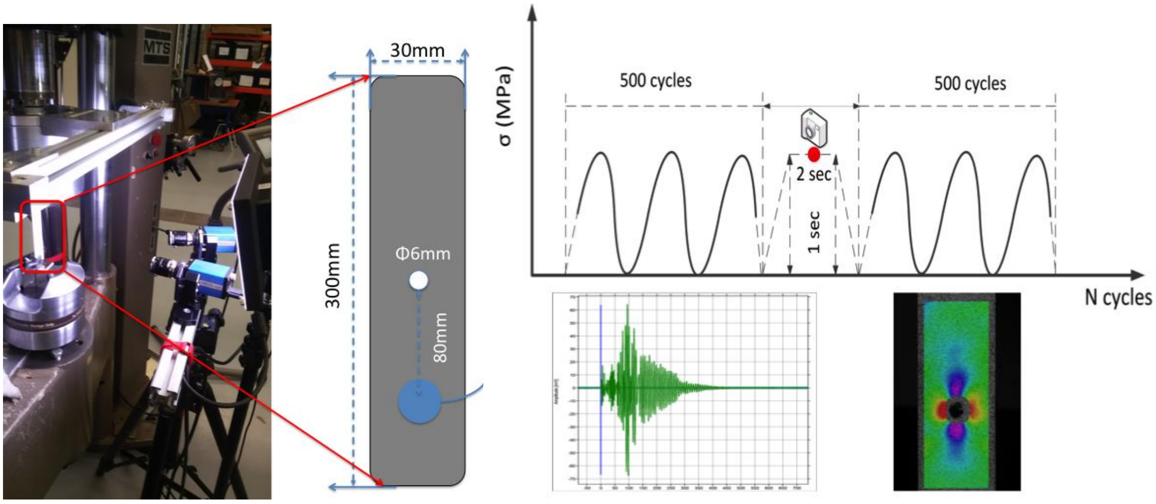

Figure 1. The experimental set-up and the acquisition data process.

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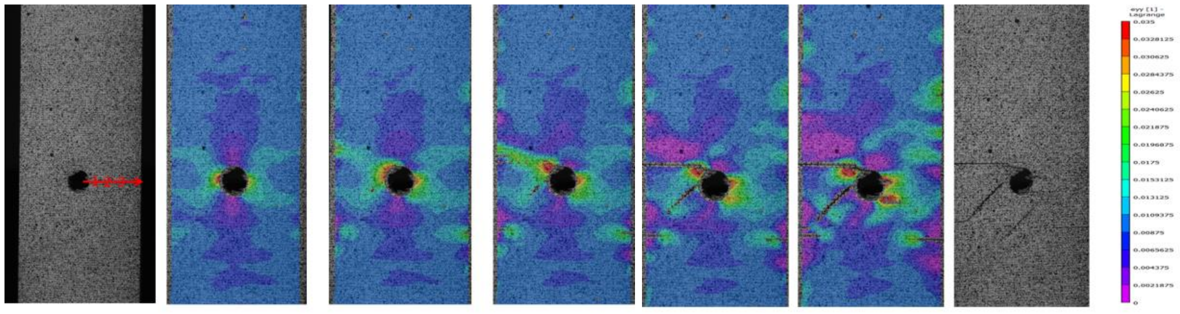
3. Results

3. Strain data analysis

The use of full-field DIC measurements enabled strain calculations in the entire surface of the specimen. Figure 2 presents the ε_{yy} strain (in the load direction) distribution as calculated at the maximum loading during the fatigue test of specimen 2.



0 cycles 5k cycles 10k cycles 15k cycles 20k cycles 23k cycles Failure

Figure 2. The ε_{yy} strain distribution (load direction).

Based on the analytical model of Lekhnitskii [3], which calculates the effect of a notch on the stress/strain distribution, three points were selected in order to calculate the fatigue module. The analytical model was reproduced in the MATLAB environment where the stresses in respect to the distance from the centre of the hole in the direction perpedincular and parallel to the load direction were calculated, see Figure 3. In addition, the strain evolution during the fatigue test for three points P1, P2 and P3 with a distance 4,6 and 8mm respectively from the centre of the hole of specimen 2, is presented in Figure 4.

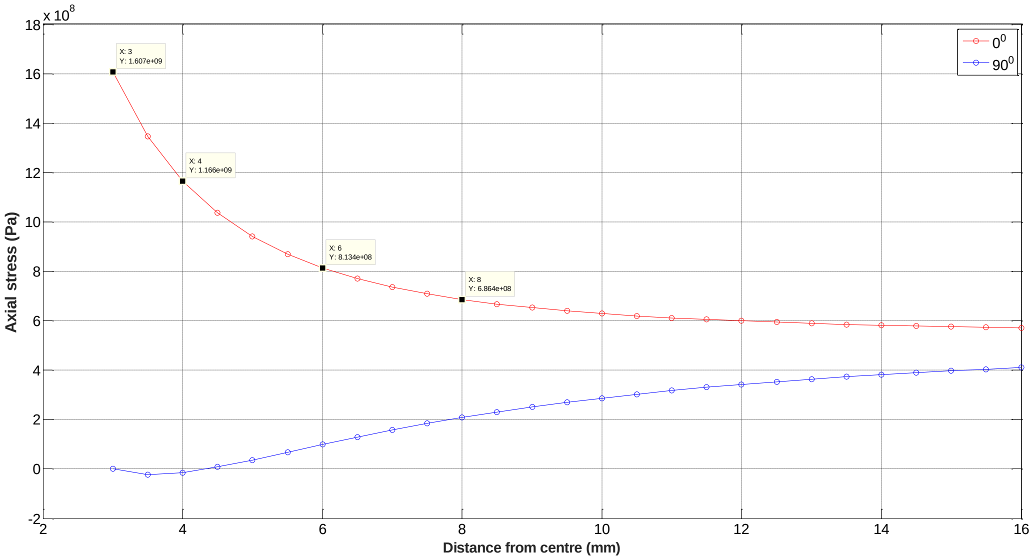


Figure 3. The stress in relation to the distance from the centre of the hole perpendicular and parallel in the load direction.

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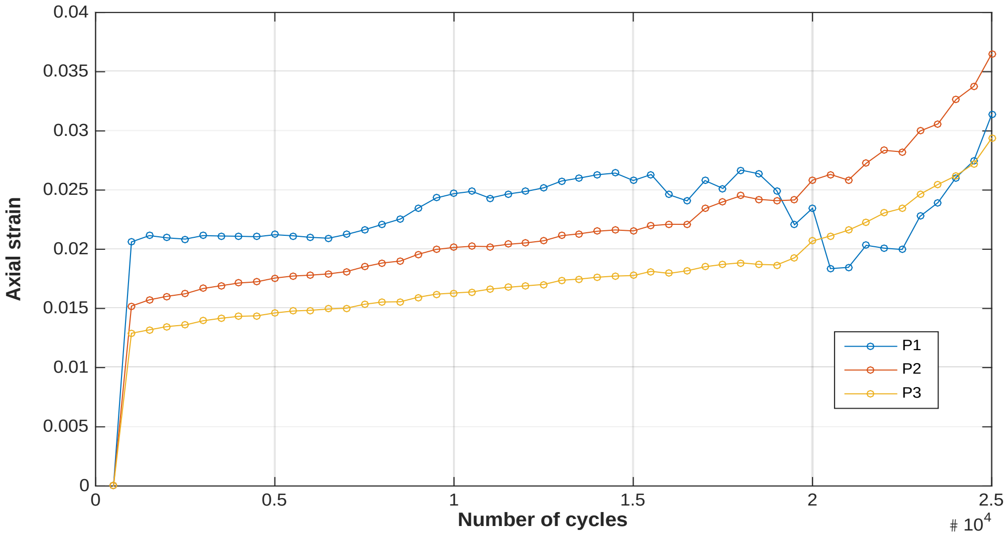

Figure 4. The strain evolution for points P1, P2 and P3 of specimen 2.

Figure 5 presents the degradation of fatigue module for the 3 selected points. Although the fatigue modules have different absolute values, the degradation processes have similar trends. It was noted that the fatigue module for point P1 increased between 17500 and 20000 cycles something that can be attributed to the inaccurate correlation during the strain analysis because, as it can be seen in Figure 2, damage occurred very close to point P1.

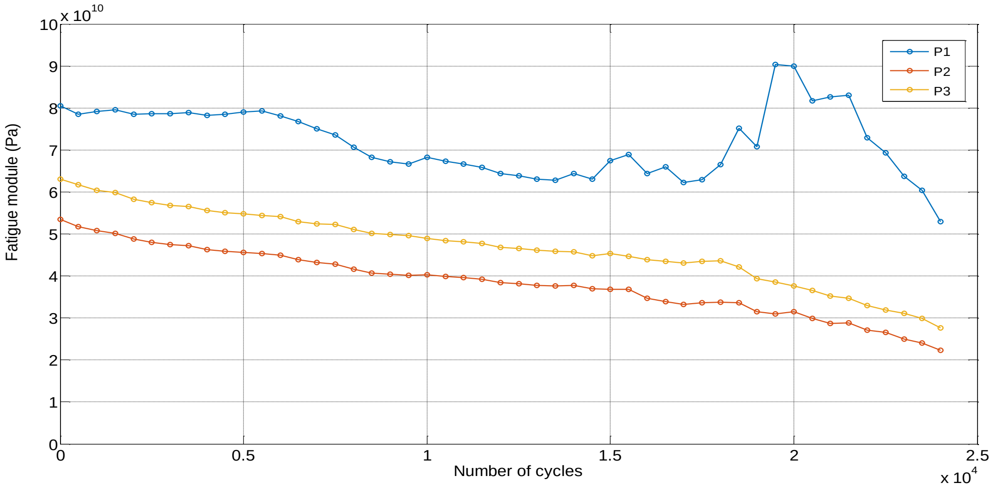

Figure 5. The fatigue module degradation for points P1, P2 and P3 of specimen 2.

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3.2. Acoustic Emission data analysis

The AE technique recorded both the signal waveforms and signals features such as peak amplitude, rise time, duration, burst signal energy etc. Advanced signal processing technique, such as wavelet analysis can be utilized in order to classify signals and link them with different failure modes. However, this process is out of the scope of the current exercise.

It is important to select features, sensitive to damage in order to describe the damage progress and previous results, see [4], demonstrated burst signal energy as an excellent candidate. Figure 6 presents the cumulative energy for all the specimens. It was observed that more than 50% of the AE energy was recorded before the 20% of the life time of the specimens. Then, the energy gradually increased where periods without significant AE activity was recorded, for example for specimen 6 - red line - between 1000 and 2000 sec and 2300 and 3300 sec.

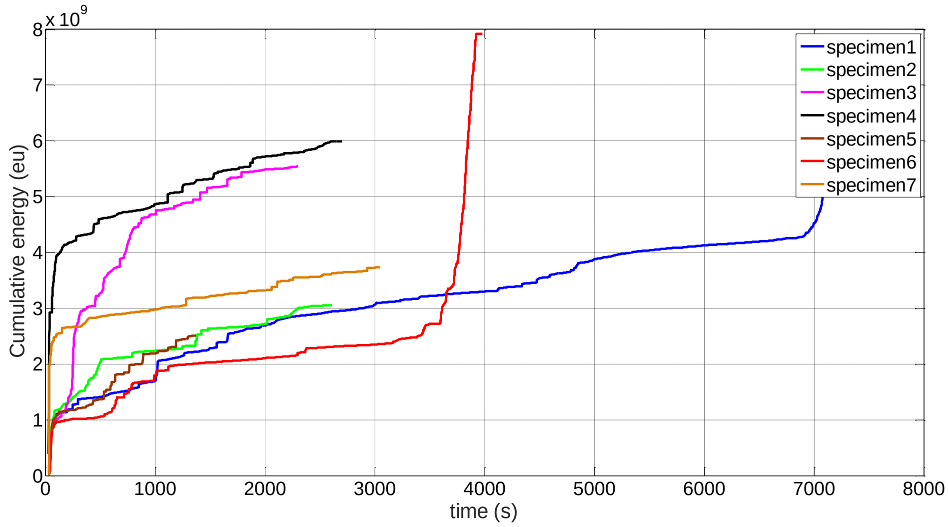

Figure 6. The cumulative AE energy.

The fatigue modules and the cumulative energy were compared so as to demonstrate the relevance between the damage process of the specimens during the fatigue loading and the AE activity. In order to highlight the degradation process, the cumulative energy was formulated as following; the cumulated energy at any given time was substracted by the total energy recorded at the end of each test. Figure 7 presents the comparison for every specimen and it was observed that the trends of the cumulative energy graphs described sufficiently the stiffness degradation process. The best correlation was achieved for specimen 1,3 and 5. It should be stated that AE technique recorded the AE energy emitted from the entire specimen volume while the fatigue modules were calculated based on strain values derived from a point. Thus, the comparison is not straightforward and a sensitive analysis for the selection of areas or points where the strain calculation should be performed is needed. Neverthelless, the cumulative AE energy is a promising feature that may describe the degradation of fatigue modules and the damage process of composite structures during fatigue loading.

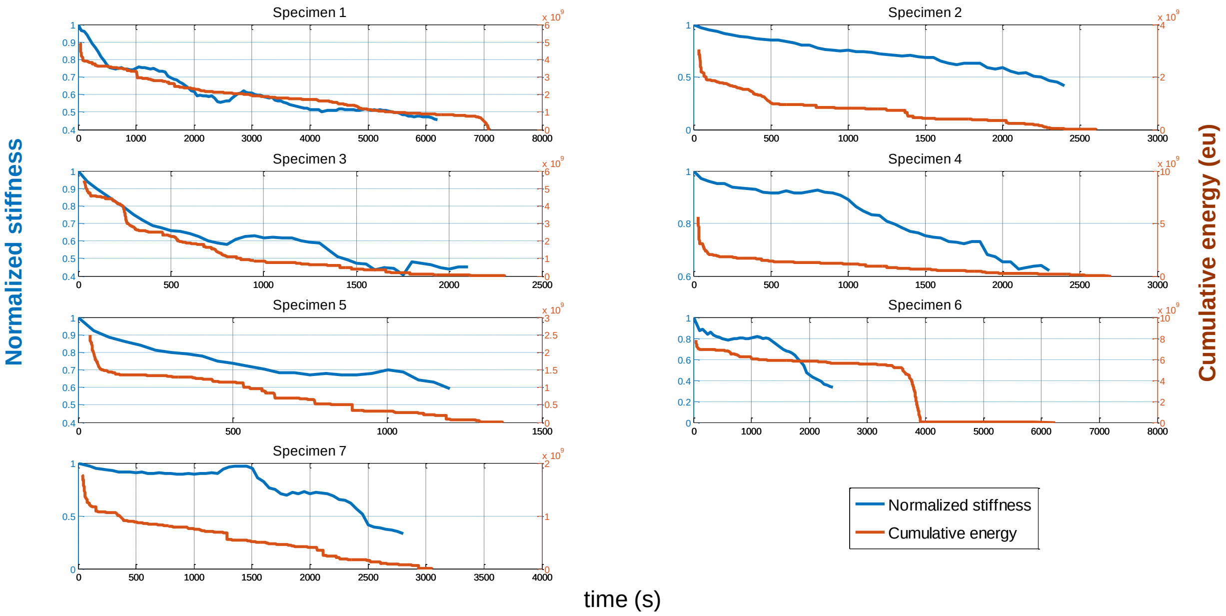

Figure 7. Comparison between the stiffness degradation and the cumulative AE energy.

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4. Conclusions

This study focused on the in-situ fatigue damage assessment of open-hole carbon/epoxy coupons. Constant amplitude fatigue tests were performed and DIC and AE techniques were employed in order to monitor the damage progression. Using DIC, full field strain calculations were performed and the strain fields were used to calculate the fatigue modules. The selection of points for extracting strain values was done based on Lekhnitskii's model which was used to calculate the stresses around the hole. It was observed that the selection may influence the calculations and lead to inaccurate results due to local damages in the specimens. A systematic methodology on how to extract points and areas for strain calculations is needed which will enable more realistic fatigue module calculations and strengthen the knowledge about damage progression during fatigue loading.

AE technique was used to record the transient waves as a result of the damage process caused by fatigue loading. AE features were extracted and burst signal energy was selected as a candidate to describe the damage process. The recorded AE energy, in form of cumulative energy, was compared to the degration of fatigue module and a good match was found indicating that cumulative energy is a sensitive to damage feature. These preliminary results are promising and strengthen the effort to provide capabilities for damage assessment and prediction of remaining useful mechanical properties to an online monitoring system.

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