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Destructive Testing of Open Rotor Propeller Blades for Extreme Operation Conditions

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Abstract. Due to the complexity of composite material, accurate manufacturing is very complicated and carry over a large number of uncertainties, the process of optimization and validation being of primary importance.

In this paper as part of design technology for rotor blades, the process of mechanical testing against severe working conditions using Acoustic Emission (AE) is discussed. As part of this process, the dynamic behaviour is analysed with validation and model updating of the structure and material properties, followed by structural tests under loads specific to the operational conditions.

The results presented show how the appropriate AE technique has been implemented in order to obtain relevant data and focus on specific areas of interest for the design development, for correlation between modelling and experimental testing, the structure being tested to the ultimate load.

Keywords: Acoustic emission, Composites, Resonance Frequency, Tensile, Flexion

1. Introduction

In aerospace, future aircraft structures require airframes that are lighter, easier to maintain and more durable than those in current operation. All these requirements point out the use of composite materials, especially for the build of the primary structures, aiming for specific tailored properties and significant weight reduction. Currently laminated composite materials are largely used due to their properties, weight, stiffness and strength, being manufactured from unidirectional plies with thickness and specific angle of fibre orientation. Due to the complexity of these materials, accurate manufacturing is very complicated and carry over large number of uncertainties, due to misalignment of ply orientation, incomplete curing of the resin, and excess resin between plies, porosity resulting from machine, human, and manufacturing process inaccuracy. In addition to that, especially in the aerospace industry, the structure is pre-twisted to serve specific design purposes. For critical operational conditions, understanding the material behaviour, the damage initiation and propagation, and possible transition stages must be supported by both modelling and experimental programs combined with proper definition of the loading conditions to provide the highest level of confidence and improve the structural design and material development. Constrains such as mass, rotating speed, material specifications, length, geometry shock and impact require a robust design to increase the stability and fracture resistance this reflecting directly on the mass and volume of the structure. In addition, the environmental conditions with temperatures which can vary from -60oC to +90oC, rapid cooling and heating during the flight envelope, creating conditions for crack occurrence and propagations or critical structure failures. Additional factors that can affect blade performance are humidity, liquids (rain, snow or ice), as well as dust and debris in the air. Previous studies carried out on wind turbine blades have described the fatigue damage modes at the root of the blade Li,Wu and Zang [1] [2] [3] or Hak, Min and Park [4] as shown in Figure 1.

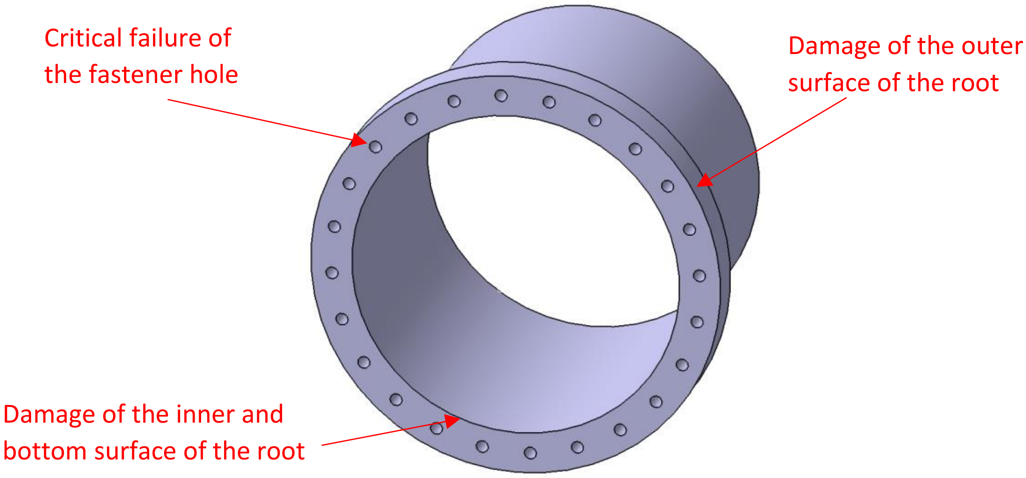

Figure 1: Failures at the end of the blade root

It was shown that the motion of the blade has resulted in different load distribution at different locations, which cannot be predicted accurately by the numerical simulations. As a result of the increased load, partial separation have been observed at the root end connection bolts which may cause the blade to be ripped off the turbine when in motion.

In this paper some phases of the testing program of a rotor blade structure is described highlighting the use of AE to monitor the structural behaviour under loads derived from operational conditions for High and Low Cycle Fatigue (HCF) life estimation. The test dynamic loads are based on the centrifugal, bending and twisting operational conditions with the objective of available stress margin estimation required for HCF avoidance. Some results obtained for two test cases are presented with the aim to present the use of AE measurements and its efficiency compared against the initial FEA analysis and predictions.

2. Experimental investigation and predictions

In the next section the preparation and the results obtained from a tensile test are described. The blade manufacturing characteristics require that the blade is adapted to the tensile machine in a specific manner. For this purpose a hole needs to be cut in the blade, using water jet cutting, to be able to allow the blade to go under tensile loading. Preliminary numerical modelling simulations were carried out to determine an optimal hole size and location with minimal stress concentration but at operational stresses as close as possible to reality. In all simulations equivalent material properties were used requiring the analysis of uncertainties and offsets when simulation results were compared with the experimental data. An AE calibration is carried out on a healthy blade before the introduction of the hole on the blade in order to check the wave velocity and determine a sensor set-up on the top and bottom surface of the blade. A final set of 10 sensors are used with a Vallen pulsing system (Figure 2).

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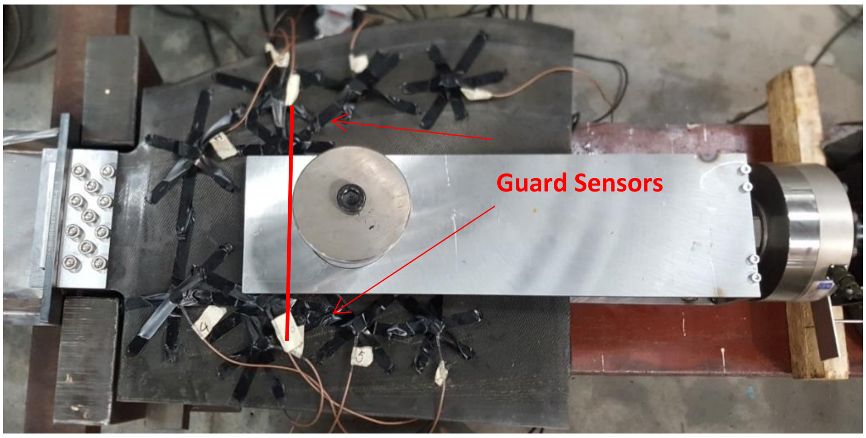
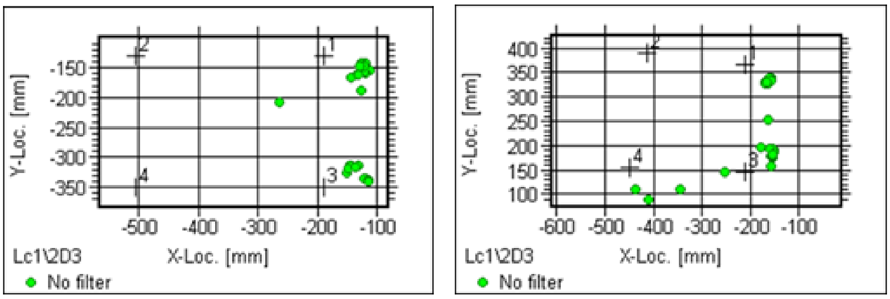


Figure2: Acoustic emission strategy for tensile test monitoring



a) Top face b) Bottom face

Figure 3: Calibration results for both surfaces of the blade

The test measures the velocity response between the mounted sensors by sending an impulse one to another through PLB and measuring the response with signal attenuation analysis and an average velocity calculation. The results of calibration localization of the generated events on both surfaces are accurate, validating the sensor set-up, as shown in Figure 3a, b. Four sensors are monitoring the root of the blade, where majority of the events are expected to occur based on initial analysis. Another set of four sensors are monitoring the mounting hole, the second most stressed area. Finally, two guarding sensors are introduced to be able to “split” the blade on two sections as shown with the red line on Figure 2. This is going to prevent signals to cross over and to be detected from both sets of sensors.

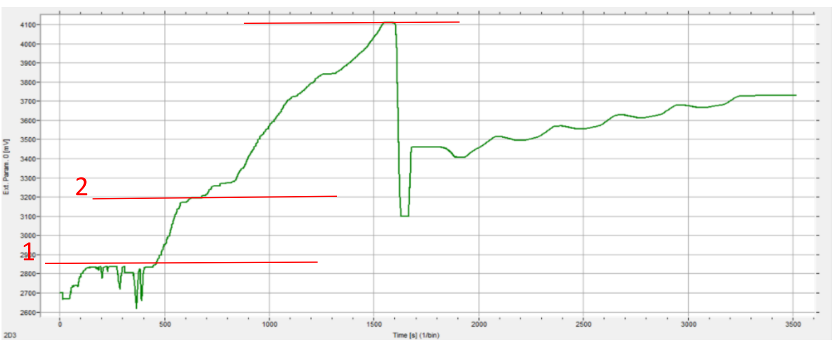


Figure 4: Loading schedule for tensile test

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The tensile test is performed on the blade with a step loading of 1kN schedule from an initial force of 18.42kN increased until safety factors of 3.5 and subsequently of 7 are achieved (Figure 4). In the AE signals the majority of the events detected appear at the root of the blade, with less than expected events detected at the top side of the blade, where most of the events cluster around the hole and may be a result of the contact at the pin connection with the blade. Unexpectedly, events appear at the trailing edge, which could possibly be explained with slightly twisted set-up for the test, which resulted in a stress slightly off the central axis of the blade due to the very complex shape of the blade.

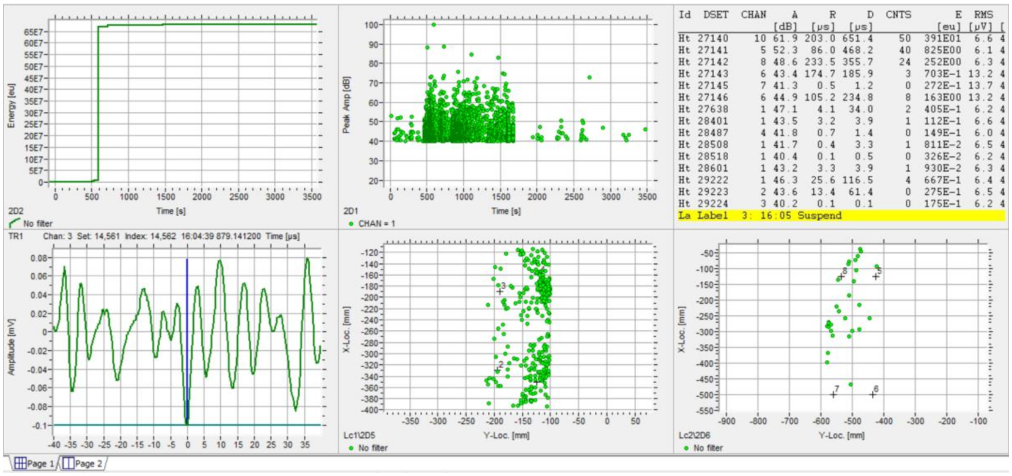

Figure 5: AE test results during the loading program

A second tensile test with a step of 5kN and the time of action of 40 seconds is presented in Figure 6.

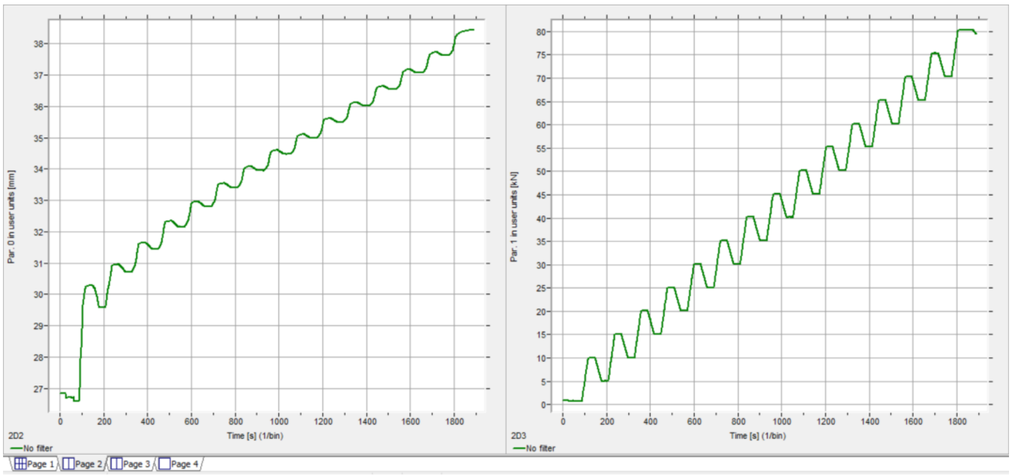

Figure 6: Second test tensile step loading

AE signal analysis results from this test are presented in Figure 7. As predicted, the majority of the events appear at the root of the blade. In contrast, the number of events detected in more

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controlled environment is much smaller. Noise and events associated to the pin contact are minimized under

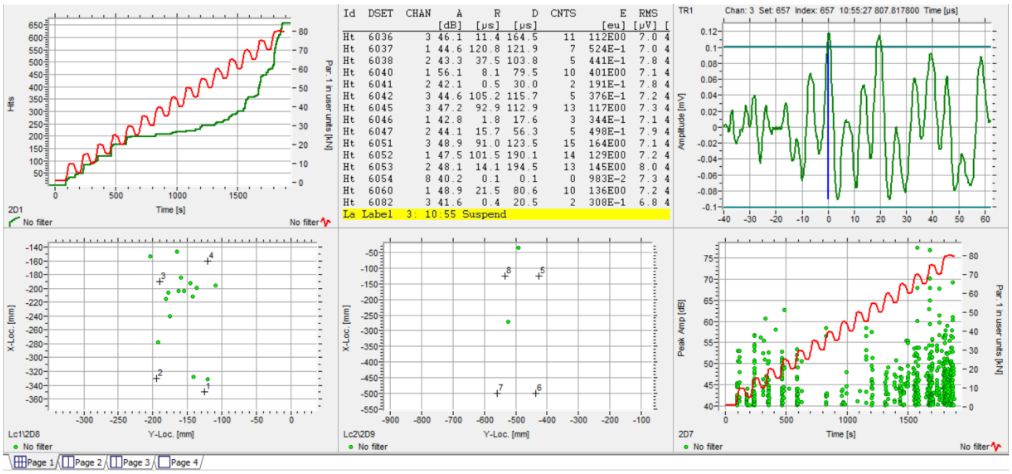

Figure 7: AE test results of the second tensile test

these test conditions. In the second phase a bending test was carried out, so that the blade can be validated with safety factor 3.5 with four sensors positioned to capture and locate any event that occurs in the root area (Figure 8).

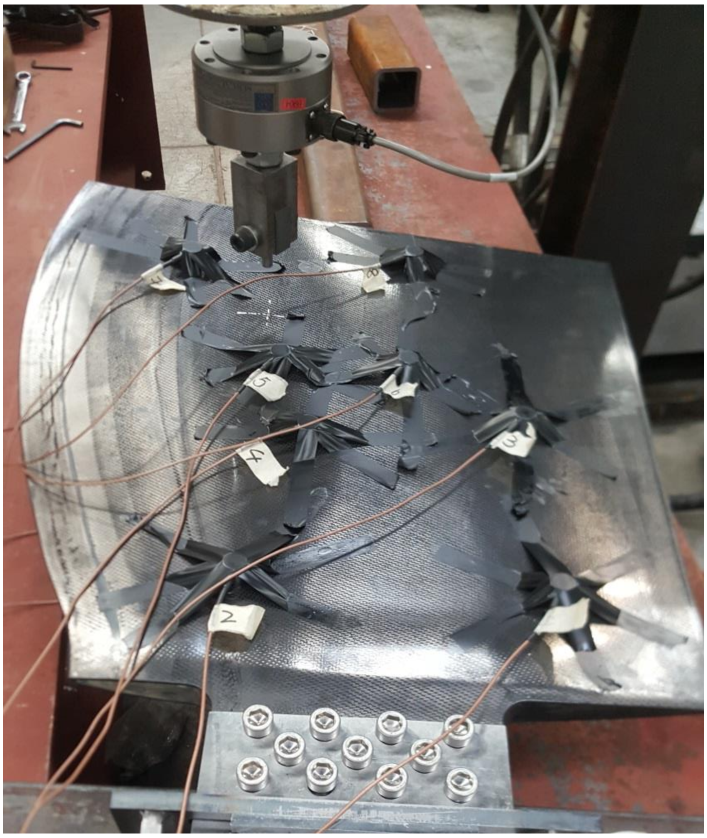

Figure 8: Test set-up and sensor configuration for the flexural test

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Because the load is going to be applied over relatively small area and the surface of the blade is not perfectly flat, noise can be produced in the area of contact, due to pin slip or damage as result of the concentrated stress. For that reason two guarding sensors, 5 and 6 in Figure 8, have been positioned above the main four, so any noise generated at the stress application point cannot be captured by the main sensors. Finally, two additional sensors 7 and 8 on Figure 8 have been added to monitor the top area of the blade, above the guard sensors, in case that event occur in an area not predicted by the numerical modelling simulation. A load program shown and the measured signals are shown in Figure 9.

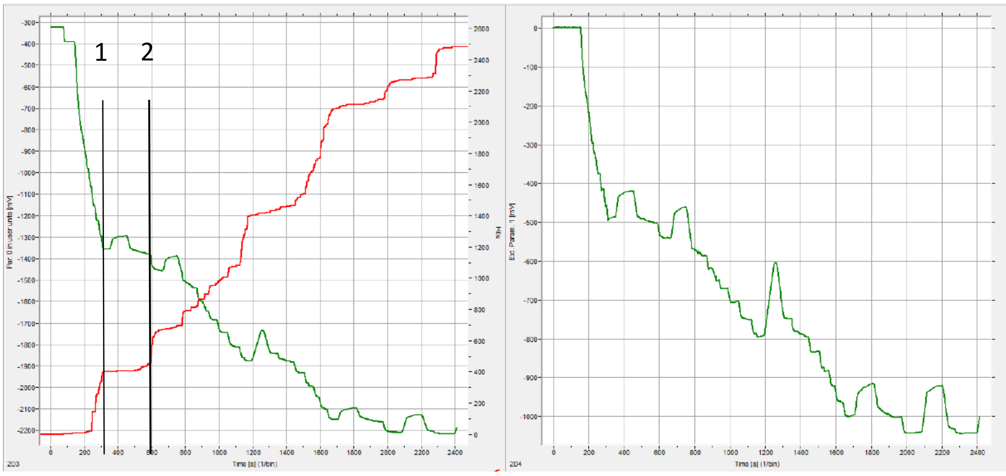

Figure 9: Load and AE cumulative hits variation with identification of the Kaiser Effect

These graphs allow a clear correlation of the AE signals with the load variation and the identification of the Kaiser Effect.

3. Conclusions

A rotor blade design has been validated successfully against a predefined tensile load program derived from the operational conditions of the system. The paper presents the use of the AE signal analysis in validation during testing of the predicted stress states using a 3.5 safety factor.
During the blade experiments, the Kaiser Effect was put in evidence, this being typically observed in testing of metallic elements but not usual for composites.

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