Acoustic Emission Analysis in the Dynamic Fatigue Testing of Fiber Composite Components

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Abstract. The main objective of dynamic fatigue tests is the initiation of slow-growing damages in composite structures. For this purpose, the load spectrum has to be adjusted accordingly when the first indications of damage occur. For damage detection, the acoustic emission analysis has been successfully used for small scale analyses of bonded joints applied for especially manufactured beam structures and dynamic tests of wind turbine rotor blades.

The acoustic emission testing is well accepted for static testing of fiber composite components, since high energetic acoustic emissions are initiated in fiber composites by fiber breaks and delamination processes during damaging. The challenge lies in the application of the method during dynamic fatigue tests, in filtering influences from the strong noise environment and in the unfavorable acoustic properties of composite materials. These requirements are met by an acoustic measurement system with high measurement dynamics, the storage and the assessment of the complete waveforms and specific evaluation and tracking algorithms which is presented in this paper.

The range of the detected acoustic waves is determined by the damping properties of the composite material. Therefore, a sensor network has been developed which monitors the highly stressed parts like the web connections of the blades. Depending on the blade type, 52 to 60 sensor nodes were installed for an array of 3 by 5 meters.

During the dynamic fatigue testing of the rotor blades on test plants, the growing damage of specific leaf elements has manifested itself as a result of the acoustic emission testing. Areas of increased AE event density were correlated to a damage of the cap-web bonding and undulations in the fiberglass spar caps by other non-destructive testing methods. The structural components failed after a specific time evolution of the acoustic emissions events.

1. Introduction

One of the goals of the joint research project "Model-based Structural Health Monitoring for rotor blades of wind turbines - SHM Wind" (project duration 2009 to 2012) was the upgrading of acoustic monitoring methods to the application as monitoring techniques at rotating wind turbines.

Within this framework, the fractural behavior of composite structures under dynamic loading tests was investigated. Thereby, the Fraunhofer Institute for Ceramic Technologies and Systems, Branch Materials Diagnostics Dresden IKTS-MD carried out a combination of acoustic measurements. This includes the active method Acousto

Ultrasonics (AU) and the passive method Acoustic Emission Analysis or Acoustic Emission Testing (AT).

The Acoustic Emission Analysis has been used successfully in material testing for many years to quickly and reliably localize areas that emit sound due to an external load of a component, e. g. due to crack growth. Conventional NDT methods allow the evaluation of the detected acoustic emissions. As a passive method, the Acoustic Emission Analysis requires relatively few sensors to evaluate a component with large volume entirely. It is essential to apply external loads for noise emission caused by damaged areas. The stored elastic energy is released by exceeding local strength properties, e. g. by cracking (even by friction and by structural change), and converted primarily into heat and sound energy. Each material transmits these waves with a material-specific speed. The attenuation of the acoustic waves is also specific for each material and furthermore influenced by environmental factors such as moisture. In case of heterogeneous materials such as carbon fiber laminates, the attenuation depends on the individual components such as epoxy resin and carbon fiber plate.

The radiating sound is recorded by acoustic sensors. Based on the travel time of the signals from the individual sound emitting sources (active cracks, faulty bondings, friction) to multiple sensors in the vicinity (at least three for planar tracking), the position of the active lesions can be calculated.

During dynamic fatigue tests of composite structures at a rotating system, the evaluation of acoustic emission measurements was carried out based on the acoustic emission rate, the spatial distribution of acoustic events and on the burst parameters such as energy and frequency content of the burst signals.

It is an aberrant basic course of the acoustic emission rate to be expected in relation to the damage of FRP materials than the damage of metals. It is a fundamental difference between GFRP materials and metals regarding the acoustic emission rate in relation to the development of damage in. In case of metal structures, noise emissions do not occur as long as a given maximum threshold of the load history is not exceeded (Kaiser Effect according to [3]). In contrast, composites already cause additional significant AE events below the given maximum threshold of the load history. This mechanism, introduced as Felicity effect, can be mainly explained by frictional processes in the pre-damaged composite material. Another advantage of fiber-reinforced composites lies in the fiber breakage and delamination processes and the corresponding very strong acoustic emissions. Therefore, the Acoustic Emission Analysis is successfully applied to fiber composite components for a wide range of applications.

2. Evaluation of Acoustic Emission Analysis with dynamic structural loading

Major challenges in the application of Acoustic Emission Analysis with dynamic structural loading are the strong ambient noise and the unfavorable acoustic properties of the composites. The acoustic measurement system meets these requirements by a high dynamic range, the storage and assessment of the complete waveforms and by special algorithms.

The separation of electromagnetic transients on the basis of their arrival times and the choice of channels to be stored in the vicinity of the trigger channel are already executed in the context of signal preprocessing. The triggering itself is carried out by the analysis of the hardware-based energy threshold of the burst signals. The offline processing comprises the automated onset detection of the burst signals in two stages. At first, the Akaike Information Criterion (AIC) is calculated in a time window as a static parameter that determines the boundary of two populations based on the signal variation. The location of the signal window for the AIC calculation is determined by means of an rms threshold which is automatically adjusted to the signal level of the measuring channel. Afterwards, the onset detection is improved by means of the correlation of signal windows or of the Hilbert envelope in these windows. A filtering of the measured signals prior to the onset detection of the bursts improves the signal-to-noise ratio. The precise localization in alternating composite materials is ensured by suppressing the high-frequency symmetric wave modes using a dynamic band filter adapted to the center frequency of the required signal. Afterwards, the localization is carried out by means of the low-frequency but high amplitude asymmetrical wave mode A0. Secondary minima are suppressed by low-pass filtering of the AIC value. This ensures an increased accuracy of the onset detection especially in the case of low-frequency bursts. The arrival times of both onset detection methods of are finally transferred to the localization algorithm.

Especially at a rotating system, the desired acoustic signals are superimposed by electromagnetic interferences. Their influence can be minimized by plausibility considerations in the planar localization of AE events. Within this process, hits with very short or very long travel time differences or a very short range of AIC variation and therefore very low burst energy are specified and separated. The singularity of the coefficient matrix (and hence the solvability of the equation system) is checked by examining the pivot elements in the context of hyperbolic localization. Finally, localizations with more than three sensors are separated, if the time residuals lie above a given threshold.

3. Case study: acoustic emission analysis in dynamic fatigue testing of test beams

In operation rotor blades of wind turbines are subject to complex stress conditions. Monitoring is extremely important for load-bearing areas. Special beams variants at the Fraunhofer IWES were designed to investigate the strength of the adhesive bond between the spar cap and the web. Dynamic fatigue tests of these beam variants were accompanied by acoustic emission analysis and thermography.

Figure 1 shows the shear web of the test beam instrumented with acoustic emission sensors. The bar is mounted with two glued bolts at one side (the friction surfaces are in bearings outside the beam) and by a pin connection to the load cylinder on the other side. The maximum shear stress along the adhesive joint occurs in the range of 650 mm to 840 mm bar length which coincidence with the theoretical calculations. Common defects at this bar variant are axial adhesive seam cracks which occur sporadically in the beginning of the experiment, spread and eventually accumulate. Another common type of damage is the separation of the adhesive from the laminate layers of the spar cap and/or shear web and the large-scale interfacial failure which is often the result of lateral cracking in the adhesive layer. **Figure 2** shows the material pairings of the test structure.

Figure 3 presents the results of the Acoustic Emission Analysis on the test beam in the end of the experiment after the structural failure including the thermographic recording visible in the background. The detachment of the upper adhesive layer from the web can be clearly seen right from the highest loaded area by the bulging of the upper spar cap. The thermogram shows highly stressed zones of the two adhesive, which correspond with the lateral position of crack braids detected by the acoustic emission tests. In addition to the results of the thermography, matching clusters of emissions from the adhesive layers and adjacent spar cap-/web-areas occur in addition to acoustic events on the line connecting the two main stress zones in the shear web laminate.

The localization was achieved with remarkably high accuracy in the centimeter range, far below the wavelength of the wave mode used in the decimeter range.

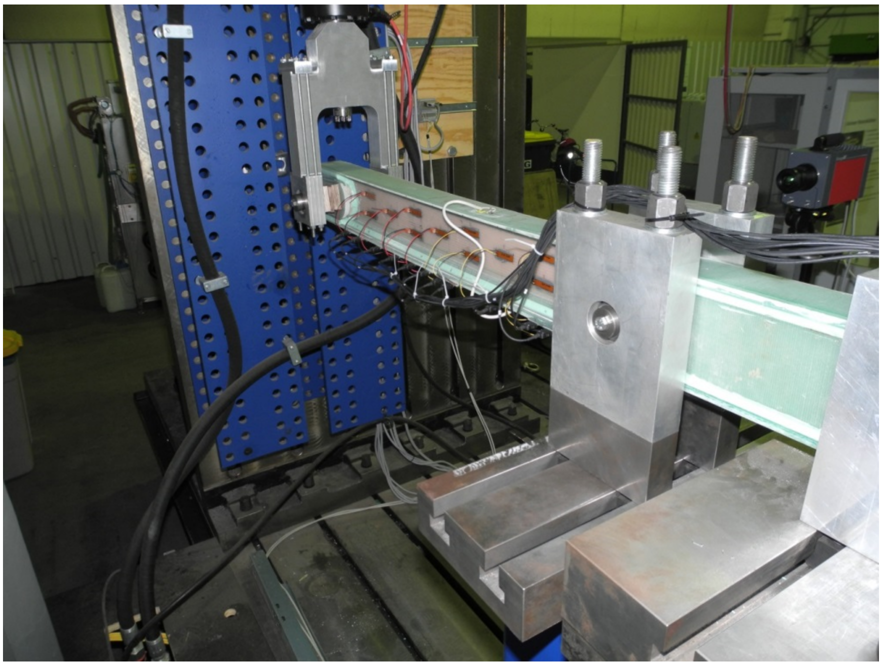

Figure 1. Test beam at the asymmetric three-point bending test, acoustic emission sensors (DuraAct patch transducers 11 x 41 mm) on the shear web,
Preamplifier on the underside of the bar, right: thermographic camera.

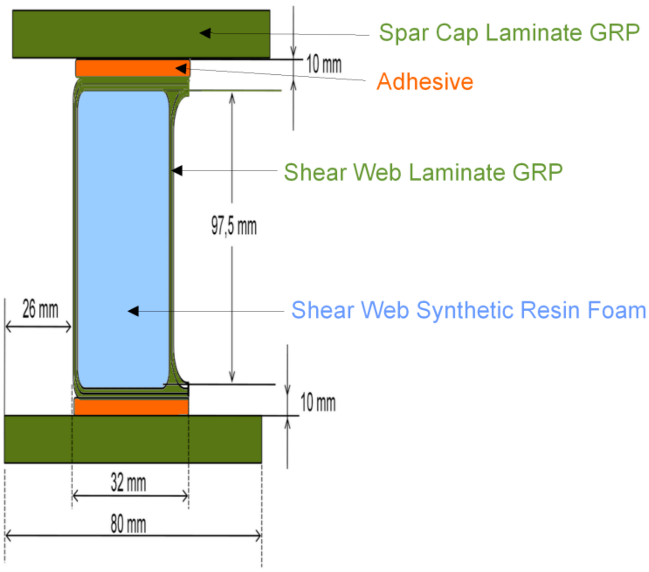

Figure 2. Structure of the test beam material, beam length: 1500 mm, test length: 1380 mm.

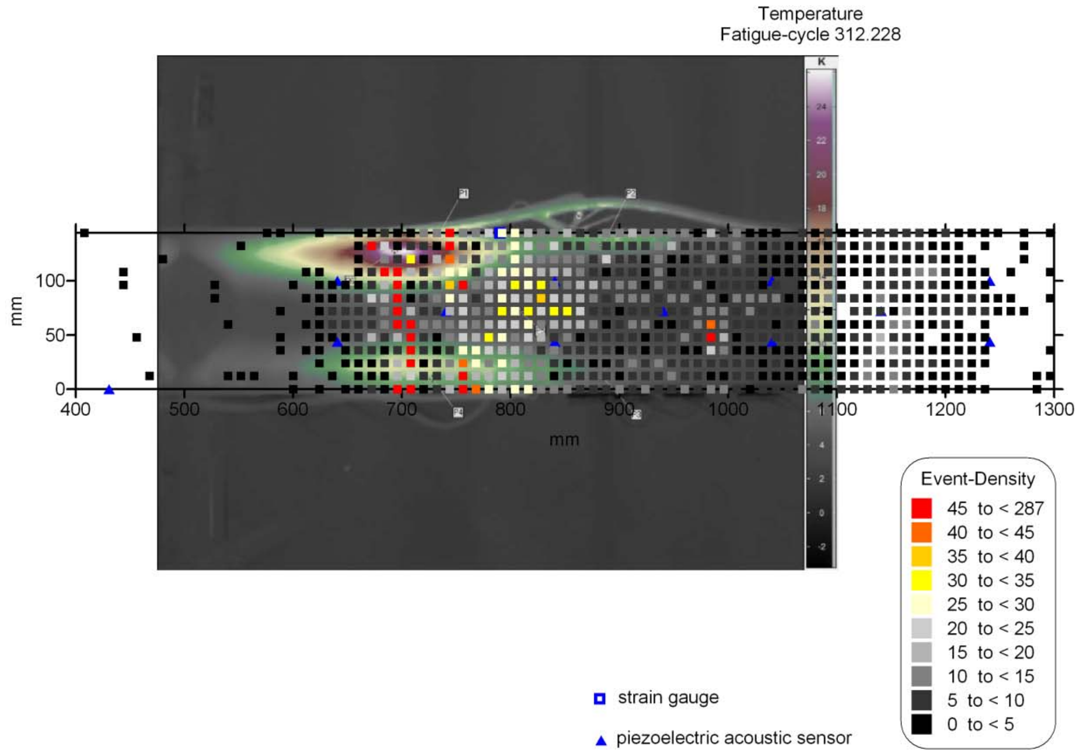

Figure 3. Test beam, acoustic emission event density per surface element of 1.2 cm x 1.2 cm in the oscillation cycle 249 384 and temperature distribution after the structural failure.

4 Case study: Spar cap rupture during flapwise dynamic fatigue test of a rotor blade

Rotor blades of wind turbines consist essentially of a two half shell sandwich construction and two shear webs or a spar box. In the considered case, the main straps in the outer shell, the shear webs and the spar box take the majority of the forces, while the remaining portions of the outer shells determine the aerodynamic shape of the blade and take only a small part of the load. The outer shells consist of bi-directional fiberglass layers and of the fiber spar caps or the sandwich areas depending on the expected load. The spar caps are usually unidirectional glass fiber scrim and also carbon fiber scrim for currently manufactured sheets, they absorb the tensile load from the blade root towards the tip of the rotor blade. Sandwich constructions with PVC foam or balsa wood are used as a support material in less stressed areas as a compromise between strength and weight. The spar webs are made of the same material. They support the two half-shells and serve as connecting elements next to the front and rear edges.

A typical rotor blade cross section with the basic structure and the aerodynamic shape of the rotor blade is shown in **Figure 4**. Depending on the manufacturer, material and location of the structural elements can vary significantly from this example.

The damage development of rotor blades was accompanied by Acoustic Emission Analysis and AU measurements during dynamic blade testing, and thus the sensor distances in the blade are determined according to the range of the acoustic waves which are mainly influenced by the damping properties of the above-mentioned various rotor blade materials. A sensor network consisting of an array of up to 64 sensors with spatial intervals of 3 to 5 m -was developed to monitor especially the highly stressed parts such as the spar caps.

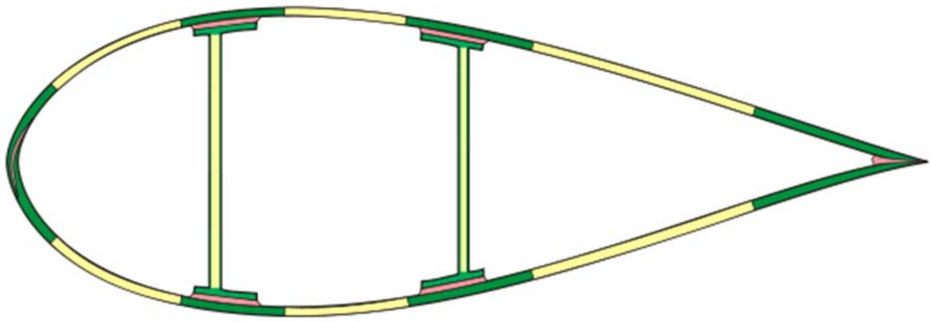

Figure 4. Typical cross-section of a rotor blade, GRP: green, balsa / foam: yellow, adhesive joints: pink.

Figure 5 shows an example of the sensor arrangement in a 38 m blade. Planar coordinates were used to generate localization planes from the 3D model of the rotor blade in order to calculate the source locations of the acoustic emissions efficiently and to implement the results of the source positions in the room model.

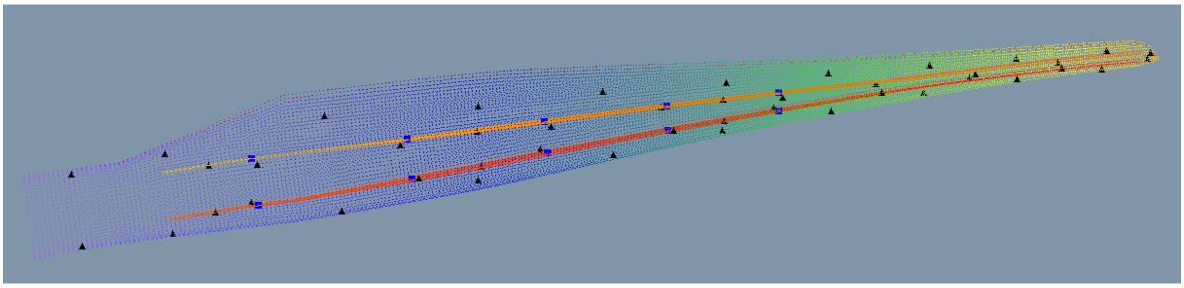

Figure 5. Array of 52 acoustic sensors (black triangles and blue squares) in a 38 m rotor blade.

The photo in the right of **Figure 6** shows color highlighted undulations in the glass fiber composite sheet of the leading edge spar cap at radius R = 20.5 m on the pressure side. As can be seen in the acoustic emission localization plot in **Figure 6** on the left that in this zone of weakness in the vicinity of the spar cap occurred increased acoustic events at edgewise excitation (in the plane of the blade). This points to single-fiber cracks and, consequently, increased friction processes in this area.

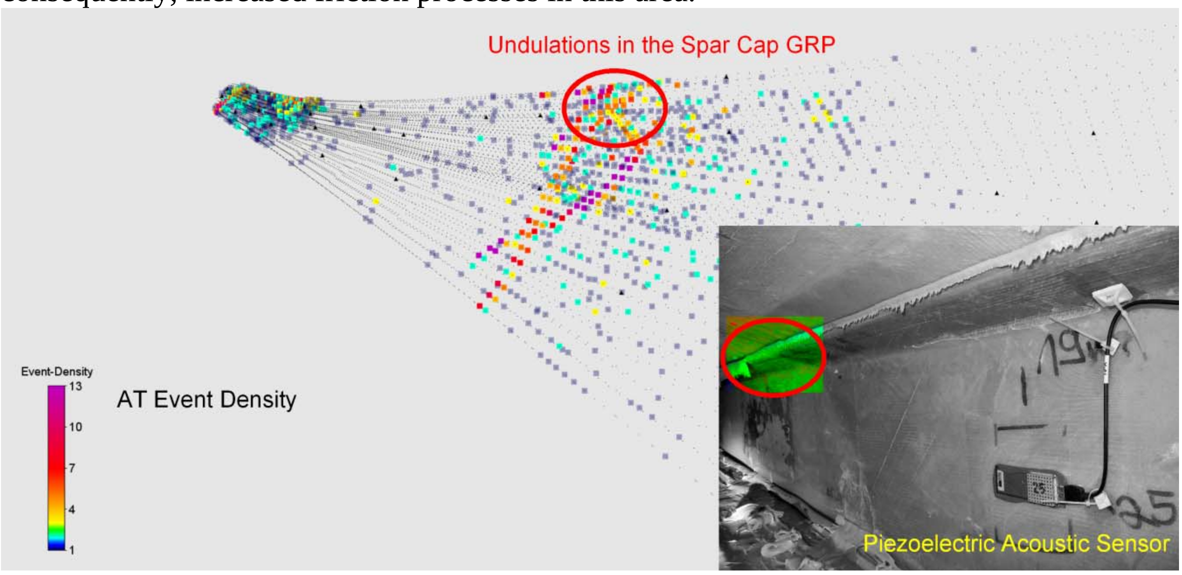

Figure 6. Left: acoustic emission localization plot, view at the pressure side, color coded event density during the flapwise excitation, right: the highlighted part of the photo shows undulations in the glass fiber composite of the leading edge spar cap at radius 20.5 m on the pressure face.

The AT- measurement image shows especially weaknesses in the quality of the fiberglass spar caps and adhesions of the spar caps during flapwise excitation (perpendicular to the blade plane). The trailing edge spar cap on the intake side was broken nearby blade radius R = 17.5 m at a target swing amplitude of 90 % after 680,000 cycles with resonant excitation in the flapwise direction.

As shown in the acoustic emission localization plot in **Figure 7**, the actual fracture events in the leading edge spar cap occurred only during the last 20,000 oscillation cycles, which are color coded. The fracture zone is flanked on both sides by areas that are characterized by an increased sound emission rate for long test times. At the blade tip above R=20.5 m, strong undulations in the GRP-spar cap are visible.

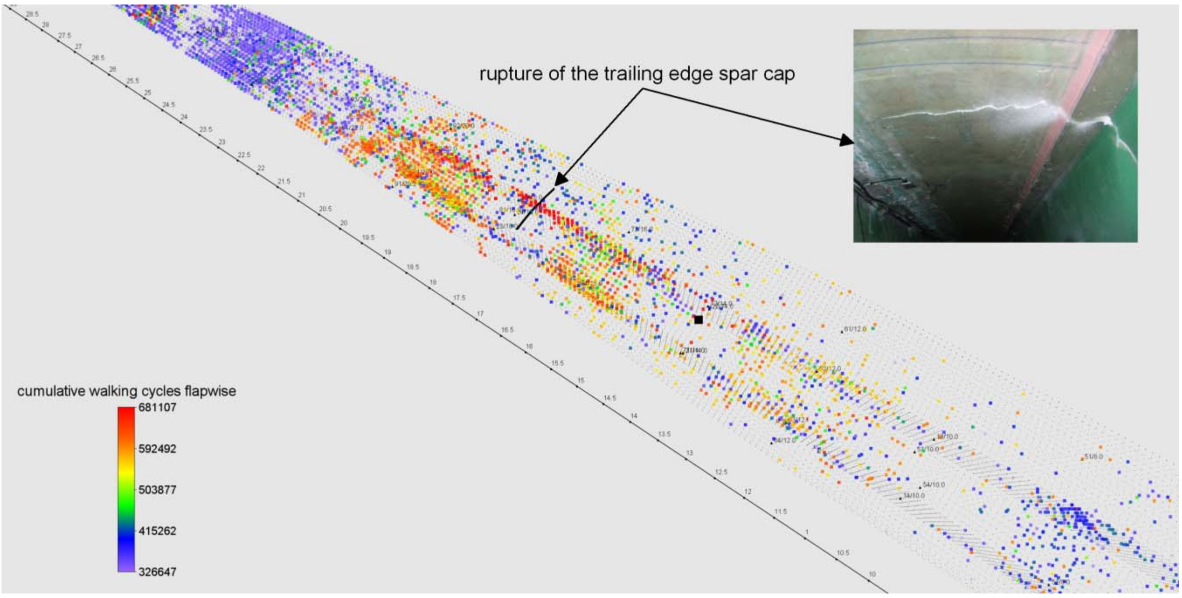

Figure 7. Acoustic emission localization plot, flapwise excitation, look at the intake side, color coded: cumulative walking cycles, photo: rupture of the trailing edge spar cap on the intake side at R = 17.5 m after 680,000 oscillation cycles, looking at the middle chamber.

To find the causes of the spar cap fracture, six samples of each of the two fiberglass spar cap strips at the intake site were examined with US-echo measurements. Hidden undulations in the glass fiber composite spar caps were detected in the B-scans (**Figure 8**). High sound emission frequencies correspond with strong undulations. The load-bearing fiberglass spar caps of the rotor blade are particularly high loaded during fatigue test in the flapwise direction. The material cannot absorb the calculated shear and compressive stresses in areas with undulations in spar cap fiberglass composites and the corresponding resin nests or cavities. In the present case, the more undulated leading edge spar cap could absorb less stresses than the less undulated trailing edge spar cap. The stiffer trailing edge spar cap broke in the area of the largest load increase because of a laterally narrow undulation of the fiberglass scrim.

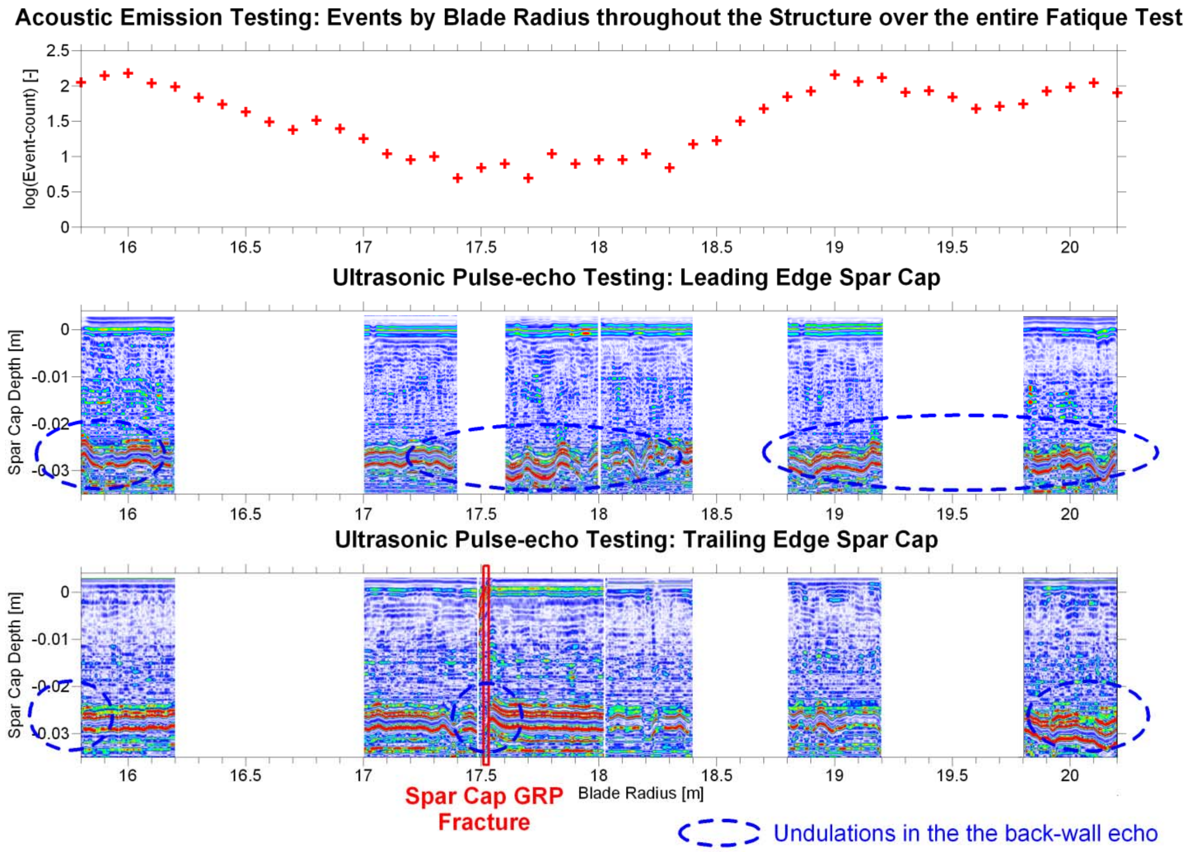

Figure 8. Logarithm of acoustic emission frequency on B-scans of US-echo measurements on spar cap samples.

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