ACOUSTIC EMISSION MONITORING OF SMALL WIND TURBINE BLADES

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ABSTRACT

Wind turbine blade certification tests, comprising a static test, a fatigue test, and finally a residual strength test, often involve sudden audible cracking sounds from somewhere within the blade, without the operators being able to locate the noise source, or to determine whether damage (minor or major) has occurred. A current EC-funded research project is looking at the possibility of using acoustic emission (AE) monitoring during testing of fibre composite blades to detect such events and assess the blade condition. AE can both locate and characterise damage processes in blades, starting with non-audible signals occurring due to damage propagation at relatively low loads. The test methodology is discussed in the context of the blade certification procedure and results are presented from a series of static and fatigue blade tests to failure in the laboratory. Inferences are drawn about small differences in the manufacture of the nominally identical blades and conclusions are presented for the application of the methodology.

INTRODUCTION

Static and fatigue tests are routinely conducted as part of the certification process for wind turbine blades. These tests are designed to ensure that all parts of the blade can withstand extreme load cases as defined in the wind turbine design and testing standards [4,5]. It is usual practice to conduct one or more static tests up to an extreme load value, which typically may represent the 1 in 50 years gust, and then to use the same blade for an accelerated 20 years fatigue lifetime test. It is common for there to be sudden, audible acoustic emission during the static phase of the test, but without proper equipment it is impossible to locate the emission source. It is clearly important to discover the location and severity of any damage which occurs during the static test in order to be able to improve blade design and also to monitor such areas during the ensuing fatigue test.

In acoustic emission (AE) monitoring, surface mounted piezoelectric sensors detect and locate the origin of sound waves within a structure. The system is very sensitive and can detect much weaker signals than those normally audible to test engineers. The signals can be characterised in terms of features like Amplitude and Energy and inferences made about the kinds of damage process taking place in the blade. AE monitoring can determine the location and sometimes the kind of damage which is taking place; it can also be used to determine damage criticality, but conventionally this has required the application of high, sustained loads.

AE has been used by several parties (e.g. [2], [7] and [6]) to monitor wind turbine blades during static and fatigue testing. In these cases the measurement techniques have been used during a ‘conventional’ test. One of the aims of the present project is, to include AE monitoring during standard blade certification tests by developing a dedicated testing methodology. This methodology has been developed and verified during a series of tests on small, glass/polyester blades. The blades were specially designed for the project and comprised an outer, load-bearing skin with a pair of internal shear webs. Additional results from these tests can be found in [3].

FORMULATION OF TEST PROCEDURES

State Of The Art Procedures

The conventional approach to AE testing (see, for example, the procedure applied to FRP fan blades [1]) involves loading a structure to slightly above the highest service load and holding that load for around 10 minutes - the so-called "load-hold" test. For a typical, undamaged fibre composite structure, emission will occur the very first time it is loaded above a given level, but it will not then re-emit significantly on subsequent loading to that level. Sustained emission during a load-hold is thus indicative of damage. Unfortunately, wind turbine blades can be subjected to very high, but short duration loads (e.g. the 50 year gust), which cannot be sustained for the length of time required for a conventional AE load-hold test.

Static Certification Test Procedure

In a simplified form the wind turbine blade load regime can be characterised by the nominal operating load (OL) and the maximum test load (MTL). The ***OL*** is the maximum sustained load during normal operation. Clearly, at this load the blade should not undergo critical damage and so multiple tests can be performed at this level and it is expected that the AE signal level will be very low. However, if the blade is damaged sufficiently, such that further damage propagates at the OL, then AE signals should be detected. In most cases, however, damage of lower criticality can be expected, which only propagates under higher load conditions.

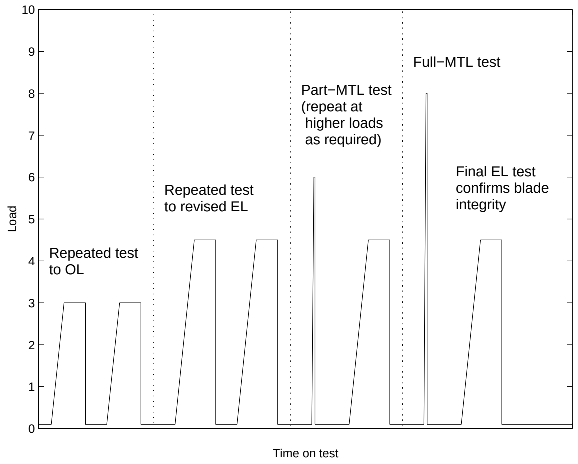

figure 1 : AE static certification test load profile

The ***MTL*** will normally correspond to the once in 50 years gust and will therefore be applied as a "spike" load with a hold of no longer than 10s. Pass/fail certification criteria are based on the blade surviving this load. Such a short load-hold was initially perceived to be too short for AE damage criticality assessment. On the other hand, load-holds of 3 minutes or more at sizeable fractions of the MTL are not acceptable to the blade manufacturers since load-holds at these high load levels might cause premature failure (creep) during the certification test. Thus, it is desirable to define an appropriate proof load for the AE method, which is above the OL but which is still at a safe level for undamaged blades. This will be referred to as the AE examination load (***EL***). There is clearly a potential conflict between the requirement to have the examination load at a high enough level to cause emission and enable judgement of damage criticality, but low enough that an undamaged blade can withstand the sustained load. Much work has gone into determining the appropriate level for the examination load.

Depending on the procedure being followed, there may be one or more part-MTL tests, before the final full-MTL test; it is important that the EL is applied after each load stage. The key points of the proposed static certification test procedure are shown in figure 1.

Fatigue Test Procedure

For a long test (wind turbine blade fatigue tests typically take between 2-6 months) the quantity of non-critical AE data can become a major problem. To keep the data to a manageable amount, some kind of heavy filtering or sampling technique is required. The AEGIS consortium concluded that time driven data (i.e. external parameters such as load and number of cycles, average AE signal level, and absolute energy) should be continuously recorded, and the recording of hits initiated for 10-100 cycles in every 10,000. For the AEGIS blade tests, hits data was usually recorded during the 10 slow cycles in every 10,000 cycles, which were applied in order to check the compliance of the blade. While testing blade 10, hits data have been recorded during 100 fast cycles to make evaluation of the frequency effect possible The use of slow cycles is analogous to load-holds in a static test and might be expected to produce accelerated damage rates due to longer dwell time at the peak loads. (A converse argument might be that damage is dependent on load rate, in which case the slow cycles may be less severe.) The sensor threshold must be set higher at 55 dB (compared to 40 dB in the static test), due to the higher noise floor in a dynamic test. This is not a significant drawback since major damage events, such as fibre breakage, are characterised by high amplitude signals. The AE fatigue test therefore consists of four load stages:

I : initial static loading to OL and repeat (AE hits data recorded).

II : static test loading at start and after every 500000 cycles to 10% above the peak fatigue load (AE hits data recorded) - this value may be chosen to be identical to the EL.

III : fast cycles (at e.g. 2 Hz) to the peak fatigue load (parametrics only - no AE hits data).

IV : after every 10000 cycles, the load application rate is reduced to give ten slower cycles (at e.g. 0.2 Hz) and during this interval the load-strain characteristic and the AE activity is monitored.

SMALL BLADE DESIGNS

A total of 10 small blades were tested in this project: 6 baseline tests and 4 on blades with defects.

The 4.5 meter blades were designed by the University of Patras. The blade structure consists of 2 shear webs, with a foam sandwich at the blade trailing edge (figure 2). The blade root connection consist of steel inserts. The glass/polyester blades were produced by the Greek blade manufacturer Geobiologiki, using hand-lay-up.

figure 2: Inside view of blade (post mortem)

The first four blades were manufactured with short shear webs (0.8-2.1 m radius) in order to ensure that AE activity would occur by buckling in a predictable region of the blade. The next two blades (5 and 6) were designed to meet the IEC-61400-1 standard, shear webs running to 3.1 m radius.

Table 1: Summary of blade designs

blade	design	type of test	other features
1	enhanced buckling	static	
2	enhanced buckling	static	
3	standard	fatigue	
4	standard	static	
5	standard	static	
6	standard	fatigue	
7	standard	static	defect type 1
8	standard	fatigue	defect type 1
9	standard	static	defect type 2
10	standard	fatigue	defect type 2

Two pairs of nominally identical blades were manufactured to the original blade design, except that each pair of blades contained a deliberately induced defect. Blades 7 and 8 contain a ply delamination between 2.0 m and 2.2 m (defect type 1). Blades 9 and 10 contained debonds in both shear webs between 2.0 m and 2.2 m and at the trailing edge at the maximum chord area (0.9 m to 1.1 m). The effect of these defects on the predicted static and buckling strength is very limited.

It should be noted that when ‘radius’ is used in this paper, the distance to the blade root plane is meant.

BLADE INSTRUMENTATION

All blades were instrumented with strain gauges at various radial positions to monitor the surface strains.

Acoustical emissions were monitored with surface mounted sensors, in most cases using the PAC-R6I, with 40 dB internal preamplifier. For measurement and evaluation, systems from Physical Acoustics Corporation were used. During the tests at CRES a SPARTAN 2000 (10 channels) was used; CLRC-RAL used a Mistras 2001 system (6 and occasionally 8 channels). During the tests at CRES, sensors were located on the blade in such a way as to be able to use triangular location. For most tests accomplished by CLRC-RAL at TU Delft, linear location was used. The sensors were located at the ¼ cord line, at the side with compressive strains (figure 3).

At the start of each test (and at certain intervals during the fatigue tests) lead break tests were performed to check the mounting of the sensors. In later tests the ‘AST’ option was used in which each sensor pulses sequentially. The results of the AST can then be compared to previous tests.

The blades were loaded uni-axial, in the flapwise direction. Most blades were tested in load control mode. The load was introduced using a wooden saddle, at 3.0 m radius (except for blade 4, which was statically loaded at 2.0 m).

The last two blades have also been monitored using embedded optical stain gauges and optical AE sensors. This interesting part of the R&D project however, will not be discussed in this paper.

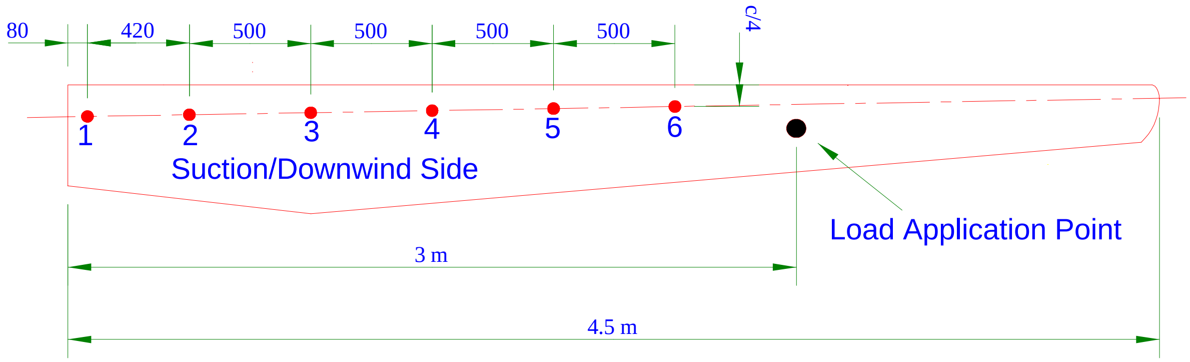

figure 3: Instrumentation plan for some of the DUT/RAL tests

STATIC TESTS

The Operating Load

At the start of any blade test, the blade should be loaded to the OL, the load held for 10 minutes, then the blade unloaded, and the procedure repeated.

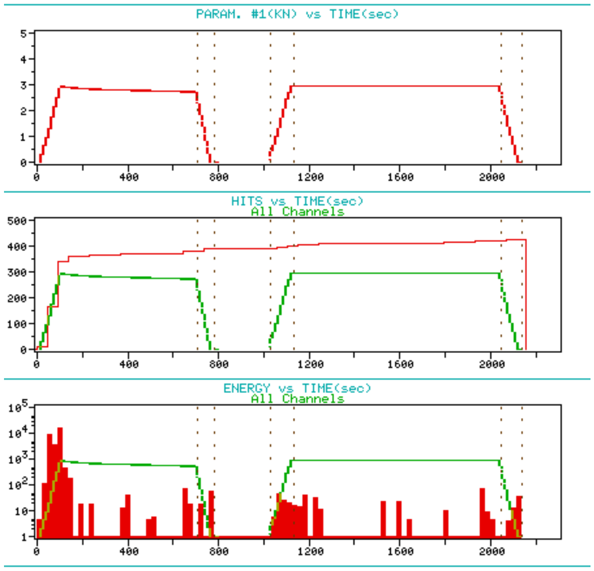

figure 4 : Initial loading of virgin blade 1 to OL and repeat - load profile (top); cumulative AE hits (centre); AE signal energy (bottom)

Figure 4 shows the typical burst of AE activity associated with the first loading to a given load level and the much quieter repeated loading. Based on the absence of significant load-hold activity, it was assessed that both blades could withstand the test load (3 kN). This was verified, since the blade failed in buckling at 7 kN.

It should be noted that AE activity does not always imply critical damage. In all tests a lot of AE activity occurred in the root area; this is probably due to the steel insert in the composite structure. None of the blades failed at the root, although considerable damage could be observed during the fatigue tests (see e.g. figure 15).

The AE Examination Load (EL)

The AE examination loads are proof loads at a lower level than the spike loads, but with a 10 minutes load-hold. The main aim of these EL loads is to see whether AE activity continues during the load-hold period, since this would indicate progressive damage. The level of activity during loading and unloading can also yield some useful information.

figure 5 gives an example of unstable behaviour indicative of critical damage during a sequence of similar EL's at a higher load level. Note that even on the first EL there is significant emission (hits - middle graph) registered on sensor 5 (top line), which do not stabilise during the load-hold. At lower load-hold values the blade is stable, but on re-loading to the critical EL, there is further strong emission, associated with high energy signals (lower graph). These results show that unstable behaviour could have been predicted at the first application of this EL.

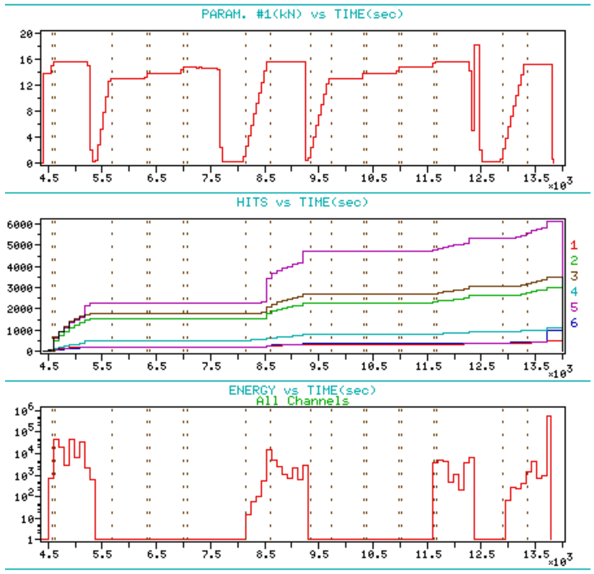

figure 5 : Comparison of emission levels from 15 kN EL's during the blade static blade test to failure - load profile (top); hits per channel (centre); AE signal energy (bottom)

Another approach to testing the integrity of a blade is to look at the transmission of sound waves through the structure. This can be achieved by using an additional pulsar, or by using the self-test facility of the sensors. This test is carried out before the blade is loaded (to check functionality and coupling of sensors) and again after each load-hold cycle. Since the test is carried out at zero load, possible effects due to blade curvature are eliminated.

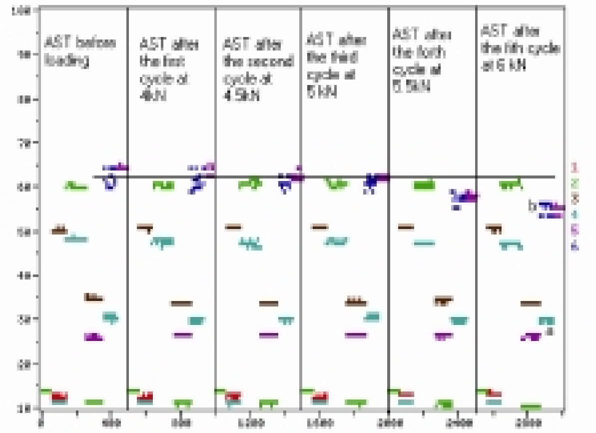

figure 6: AST energy at receiving channel at start of test and after each load-hold cycle (blade 2)

In the Auto Sensor Test (AST), the energy at the receiving channel is plotted against hit number (figure 6). All signals remain at essentially the same level, except for transmission between sensors 5 and 6, which drops markedly after the 5.5 kN load-cycle and further still after blade failure (marked b). The transmission received at sensor 4 from sensor 5 (marked a) remains consistent. For these tests therefore, it can be concluded that changes detected in the AST indicate a meaningful change in the blade.

Locating Events

With the software, locations of event sources can be determined. On most of the blades, cracks formed in the foam sandwich on the compressive side. On blade 5 eight discrete cracks, ranging between 25 mm and 115 mm long, had formed before failure (see e.g. figure 7).

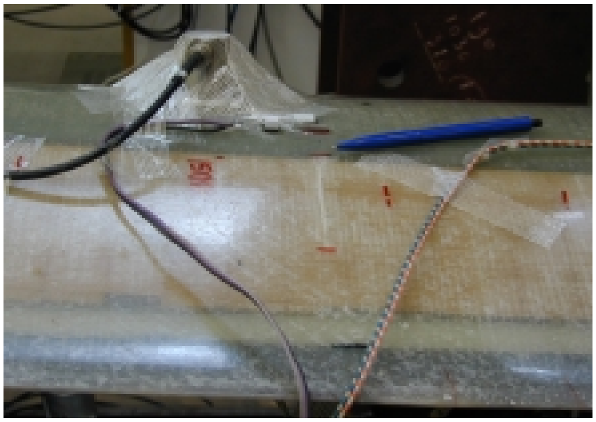

figure 7: Crack at 1.7 m radius (blade 5)

AE activity was identified from most of these locations and the cracks were successfully located. On several occasions, the crack was located first by the AE and only later by visual inspection. However, in certain cases some cracks were not located properly from the AE data and work is continuing to clarify the reasons for this.

EL Evaluation At Buckling Failure

The first blades failed by catastrophic buckling, starting at about 2.3 m radius, just outboard from the ends of the two shear webs. Although this was intended, the sudden nature of buckling made it impossible to give a warning in time for the operators to realize failure was about to occur. However evaluating the data after failure reveals that there were indications of impending failure.

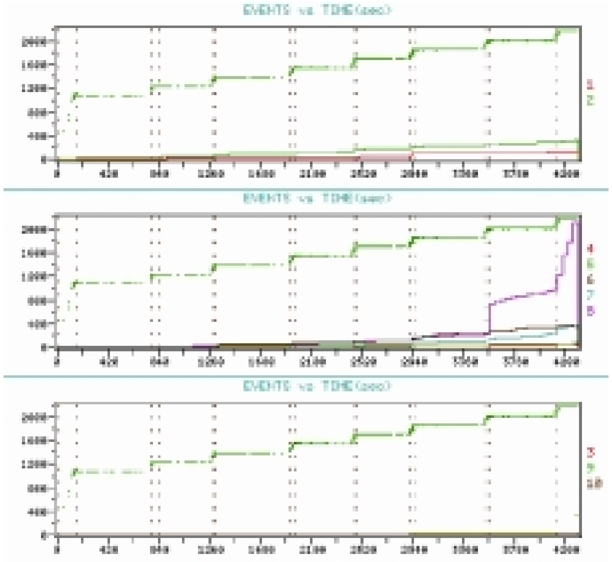

figure 8: Comparison of step load tests to failure on blade 1

Figure 8 shows events v time during the step load tests to failure. (An event is defined as the first hit of one or more hits caused by one single AE occurrence, i.e. the hit corresponding to the sensor that first detected this AE.) The test load is shown superimposed on the upper trace. From the graph it can be seen that AE activity increases significantly as the load level increases. On the load-hold prior to failure, AE is continuous and does not stabilize at the sensors nearest the final failure points (sensor 8). This is a clear indication of progressing damage during the load-hold and is characteristic of impending failure. The activity at the critical channels (i.e. number of events) is higher than on the other channels.

The Maximum Test Load (MTL)

Since the MTL is designed to mimic the extreme load the blade might experience in service, it is desirable to determine after the event whether the loading has caused damage within the blade - a further use for the EL procedure. To evaluate this procedure several blade tests were performed using a sequence of increasing EL's applied to the blade after each MTL to determine the minimum load level at which AE could be detected (figure 9).

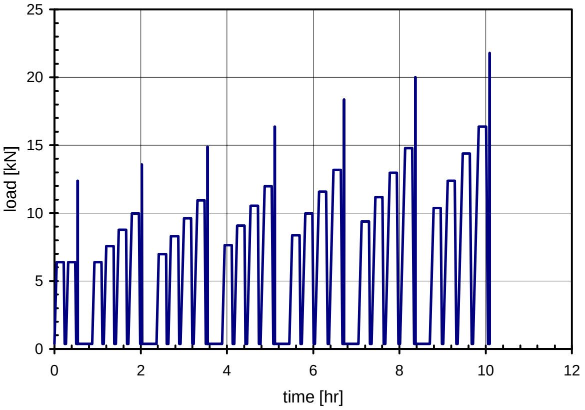

figure 9: Example for static load test envelope to evaluate AE procedures and EL and MTL sensitivity

Results are presented in terms of number of located events for a typical static blade test in figure 10 and figure 11. A large number of events are generated in the root at an early stage in the test; this was typical of all the blades tested and may be partly attributable to the transition between steel and GRP parts. Minor visible damage did develop in the root area, but the major failure occurred at a radius of about 2.0 m, where the second large events peak is located.

It can be concluded that the sequence of MTL's provides information about damage location from the number and distribution of events. Consideration of other AE parameters such as signal amplitude and energy, compared with the strength distribution of the blade, can be used to provide a qualitative indication of damage severity.

Damage criticality can be obtained from the EL sequence by considering stabilisation of the AE signals during the load-hold periods, *if* the applied load is high enough to propagate further (minor) damage, but clear-cut results by this technique require relatively high loads.

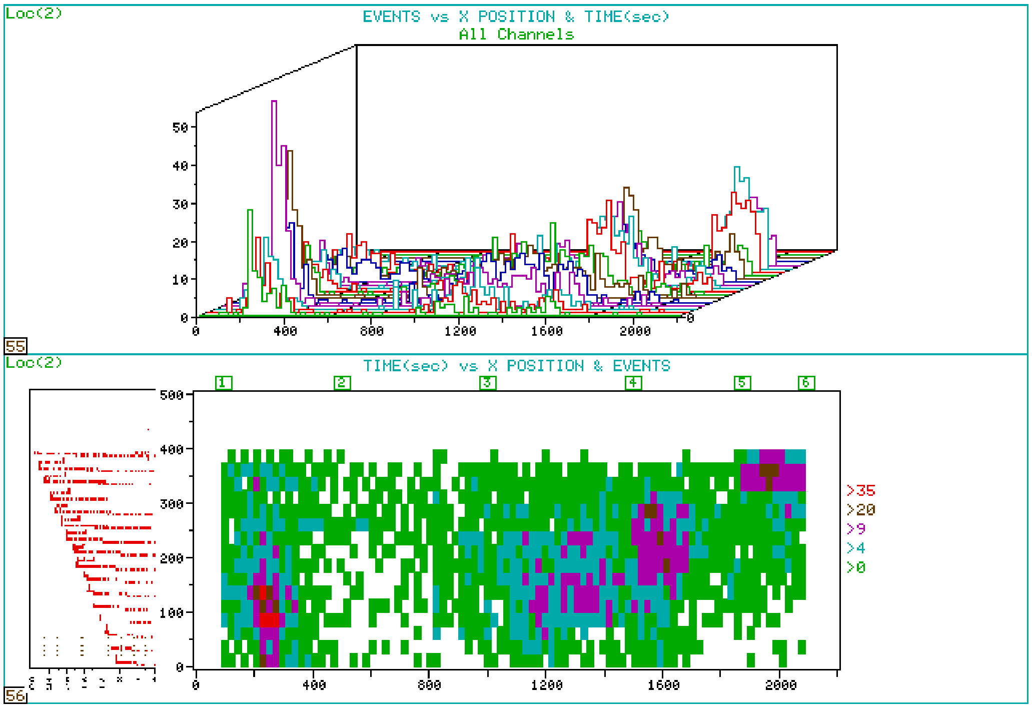

figure 10: Damage progression by linear location for sequence of MTL tests in terms of AE signal energy by position (x-axis) and time (z-axis - top; y-axis - bottom) with applied load inset

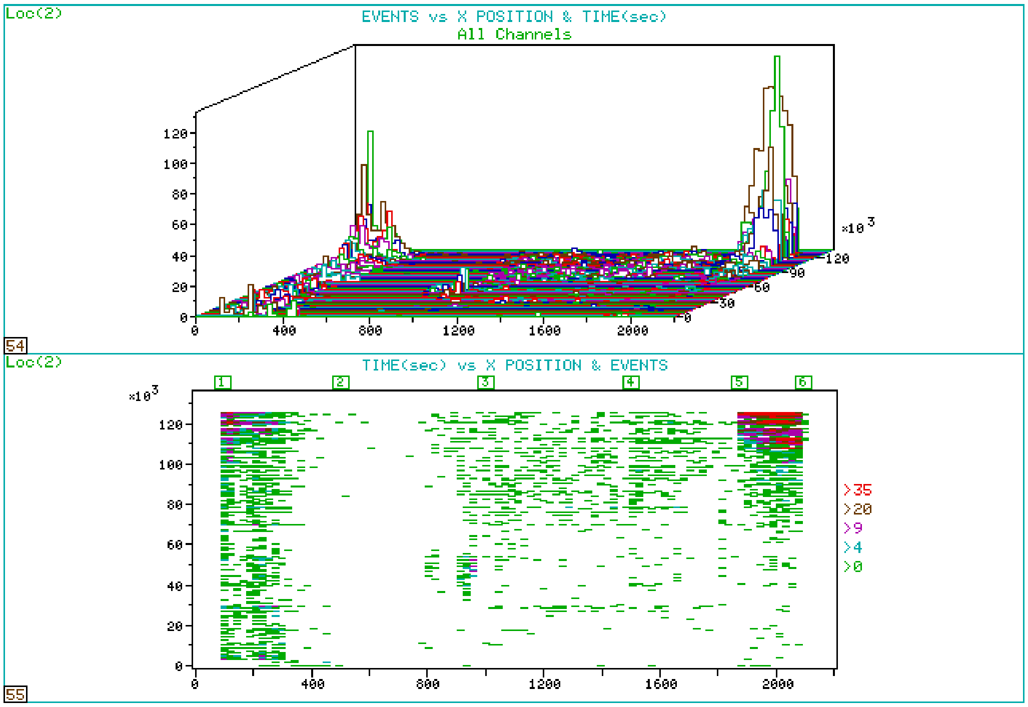

figure 11: Damage progression by linear location for sequence of EL tests in terms of AE signal energy by position (x-axis) and time (z-axis - top; y-axis - bottom)

The blades with defects that are considered typical for wind turbine rotor blades were tested with the aim to follow the damage increase. At this moment the evaluation of the AE signals is not completed, so only preliminary conclusions can be drawn.

figure 12: Blade fractured in static loading at the defect zone

Damage growth and final failure occurred at the defect zones. For blade 9 the delaminated shear web clearly caused the final failure, as can be seen in figure 12. Damage growth could not be observed visually, but the AE data indicate that the location of the AE events move during the test. A defect at the trailing edge showed some crack growth, which stabilised during the test.

FATIGUE TESTS

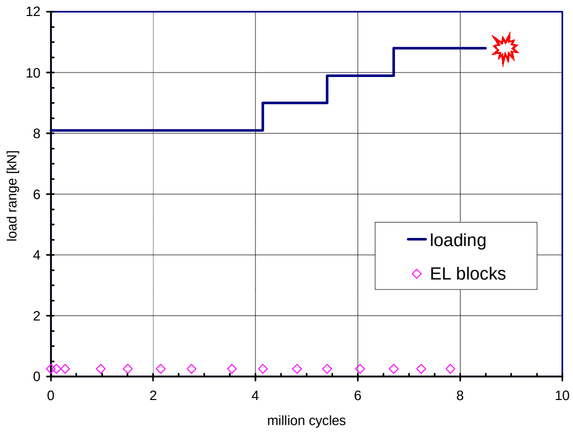

figure 13: Idealised load history of blade 6

A total of four fatigue tests were accomplished during the project. The aim of these fatigue tests was to have gradual increasing damage, to be monitored by the AE system, in a limited time. The fatigue load has been increased in steps to realise failure, since the actual strain levels and material fatigue behaviour are not known correctly. As an example, the idealised fatigue spectrum for blade 6 is shown in figure 13.

The first blades were designed to fail in (static) buckling. For this reason fatigue failure only occurred at very high loads, in a type of buckling mode. The next blades, to the standard IEC-61400-1 design, developed many cracks in the sandwich part of the blade. Two of those cracks (at 1.1 m from the root, initiated already before 100,000 cycles) eventually converged and propagated across the main structural part of the blade (figure 14).

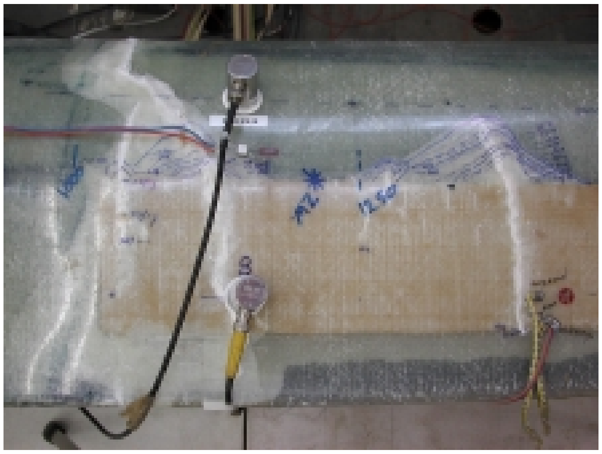

figure 14: Failed section of blade 6

At the blade root, damage had grown over a large area during a long period. Although a long crack was formed (figure 15), this was not a critical damage. Post-mortem inspection showed that only a few layers at the surface had failed. Due to the blade root configuration used for this blade, the major part of the layers were not damaged.
For the later fatigue tests the compression side of the blade was photographed over the entire length every half million cycles to record the damage.

Since both failures occurred during fast cycle loading only the parameters ‘Average Signal Level’ and ‘Absolute Energy’ were being recorded at the time. It is therefore necessary to look back at the most recent static and slow cycle fatigue data for evidence of impending failure.

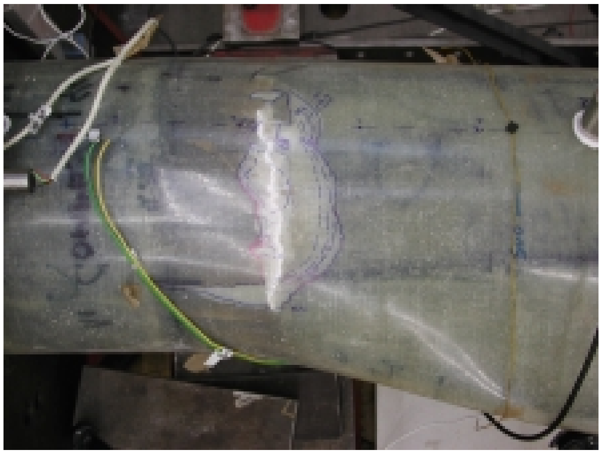

figure 15: Non-critical damage at blade root (fatigue)

For the evaluation of the fatigue tests, information from the static load blocks (labelled 'EL-blocks' in figure 13) can be used, or from the slow cycles, recorded every 10,000 cycles.

A total of 2.5 Gbyte of AE data was generated during the fatigue tests. Due to restrictions in the manufacturer's software, it proved impossible to manipulate the data in order to merge files and produce 3D plots of AE parameters against cycles and x-position along the blade. In the early stages of the project, drawing software was used to provide plots of filtered data in this form. A software plotting suite for the AE output data has been developed by RAL.

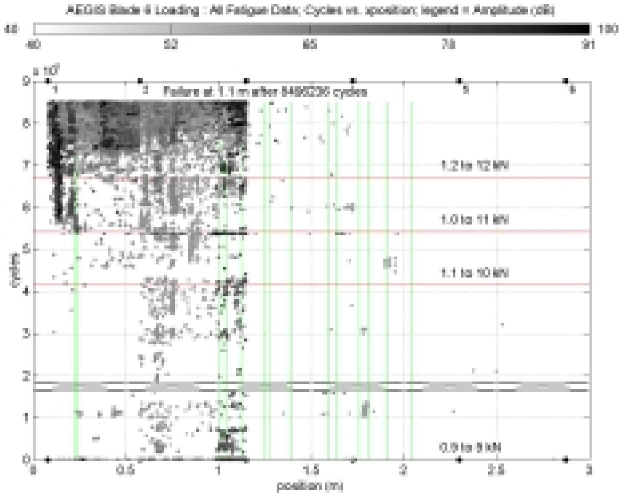

figure 16: Amplitude history of linearly located events during slow cycles for blade 6

A typical presentation of results showing the amplitude data for blade 6 is plotted in figure 16. A cluster of high amplitude events can be seen at the 1.1 m failure point. Other clusters of high amplitude events occur at 0.1-0.2 m in the root and at 0.4 m. figure 16 also shows the nominal location of other cracks (vertical lines) which appeared in the sandwich part of the blade at various stages of the test. Many of these are not well located by high amplitude (or high energy) events and require further investigation. Clearly, the number and severity of high amplitude events must be assessed in relation to the blade strength distribution to decide on the criticality of particular AE behaviour. This is the role of the Pattern Recognition software, which will now be used to carry out a multivariate assessment of the results and hence grade the criticality of damage found during the test.

AE EVALUATION USING FILTERING

The amount of data generated during a fatigue test is that large that extensive filtering is necessary. At present CLRC-RAL is working on filtering the data using structural information.

As a first step filtering has been done on the calculated maximum strain level at the location, for the external load. For this approach it is assumed that only normal strains are important. The Strain Weighting curve-fit is given in figure 17 and shows that the highest strains are expected to occur at 1.8 m.

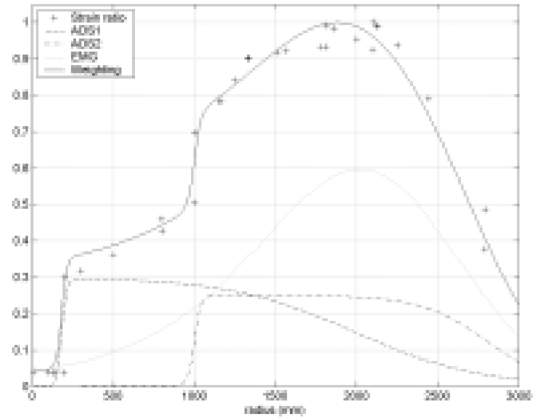

figure 17: Derivation of the Strain Weighting curve fit for blades 2 and 3.

The AE parameters which change the most as the blade damage increases throughout the test, are Energy, Amplitude and ASL. In figure 18, Energy is therefore used as an example to colour the plot of cycles versus location. Already at 2 million cycles, high values are recorded in the failure area (2.25 m), but also at 1.25 and 1.45 m and at the blade root.

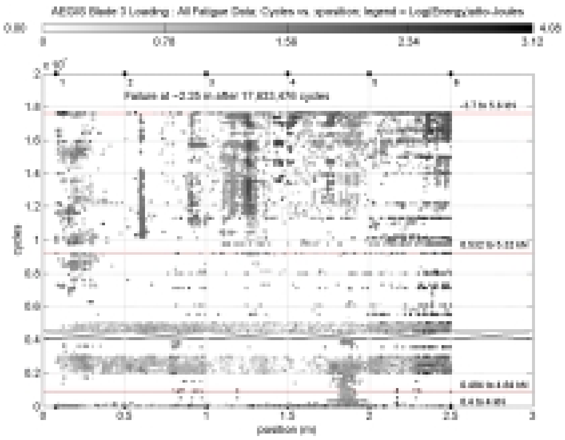

figure 18: Linear location of AE Energy during the fatigue test (raw data)

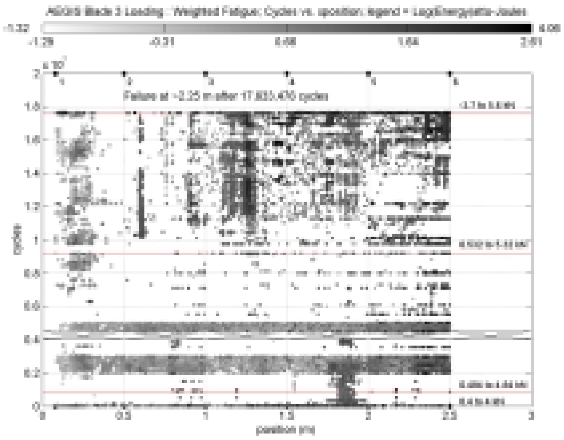

figure 19: Linear location of AE Energy during the fatigue test (filtered data)

The result of using the Strain Weighting as a multiplication factor is shown in figure 19. The filtering concentrates the high emission in the area of failure. This is despite the fact that the emission in the failure area itself was reduced relatively to inboard sections by the weighting. At the bolt ends the emissions have almost completely disappeared. High energy activity can still be observed at 1.25 and 1.45 m radius, but not clustered to the same degree as for the failure area.

Although being tentative only, these first results on blade 3 are encouraging. The same filtering philosophy will be applied for the other blade tests. In parallel a discussion is on-going on the adequacy of filtering by normal strains: for most blades that have been tested in this project, failure was initiated by delamination at the rear sandwich panel.

CONCLUSIONS

Methodologies for applying AE non-destructive test techniques during wind turbine blade certification tests (static and fatigue) were developed and demonstrated during a series of tests on a set of small blades.

The applicability of a proof test, using an AE examination loading, has been demonstrated, in that blades passing this test (i.e. exhibiting little or no emission during a second load step) can be expected to survive continuous loading at this level.

Critical areas can be identified (usually by lack of stabilisation of the AE hits on a given channel), and the damage graded using pattern recognition software, at load-holds close to ultimate failure levels.
In tests representative of current, state of the art blade certification procedures, data from successively increasing maximum test loads (MTL) has been shown to identify damage areas and can be used to indicate the likely location of failure.

Damage location can be achieved and this may be particularly useful in allowing other techniques to be applied to the suspect area.

The development of a methodology appropriate to fatigue tests has been more difficult due to the potentially huge data files and the necessity of sampling the data in some way. Pattern recognition software and /or filtering e.g. by strains is necessary for evaluation. Nonetheless, detection of high amplitude and high energy events appears to be highly significant in terms of predicting failure and gives some support to the hope that a field monitoring technique may one day be realised.

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