ACOUSTIC EMISSION MONITORING DURING CERTIFICATION TESTING OF WIND TURBINE BLADES

A G Dutton[1], M J Blanch[1], P Vionis[2], D Lekou[2], D R V van Delft[3], P A Joosse[3], A Anastassopoulos[4], D Kouroussis[4], T Kossivas[5], T. P. Philippidis[6], Y. G. Kolaxis[6], G Fernando[7], A Proust[8]
[1]Energy Research Unit, CLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
[2]CRES, Wind Energy Department, 19th km Marathon Avenue, Pikermi 19009, Attiki, Greece
[3]Stevin II laboratory / WMC group, Delft University of Technology (CEG), Stevinweg 1, 2600 GA Delft, The Netherlands
[4]Envirocoustics Abee, El. Venizelou 7 & Delfon, Metamorphosi, Athens 14452, Attica, Greece
[5]Geobiologiki S.A., 62 Thrakomakedonon Str, 136 71 Acharnai, Attika, Greece
[6]Dept of Mechanical Engineering & Aeronautics, University of Patras, P.O.Box 1401,
Patras 265 00, Greece
[7]Engineering Systems Department, Cranfield University (RMCS), Shrivenham, Swindon SN6 8LA, UK
[8]Euro Physical Acoustics SA, ZAC des Portes de Sucy, 27 rue Magellan, Sucy-en-Brie F-94373, Val de Marne, France

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 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 presented for the application of the methodology.

Keywords : Blades : Materials-Composite : Non-destructive Testing : Condition Monitoring

1. 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 [1,2]. 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 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 such as 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.

The conventional approach to AE testing (see, for example, the procedure applied to FRP fan blades [3]) 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 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 an AE load-hold test.

A novel methodology had to be developed, therefore, to include AE monitoring during standard blade certification tests. This methodology has been used 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 [4].

2. STATIC CERTIFICATION TEST PROCEDURE

The load regime experienced by a wind turbine blade can be characterised by the nominal operating load (OL) and the maximum test load (MTL). The OL is the maximum sustained load that the blade will experience during normal operation. Clearly, the blade should not undergo critical damage when loaded up to the OL 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 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 (e.g. parked, gust or braking) conditions. 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.

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. Since such a short load-hold was initially perceived to be too short for AE damage criticality assessment, much effort has concentrated on extracting and characterising information from MTL tests. 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.

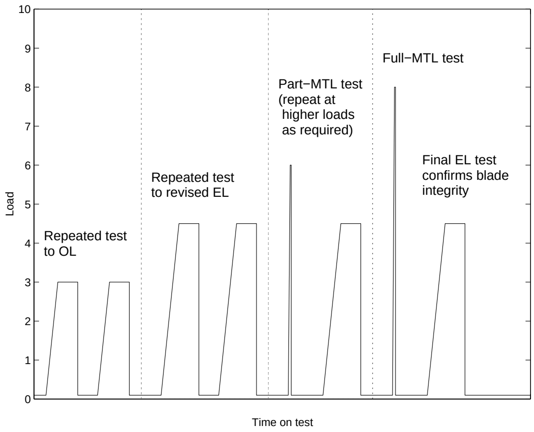
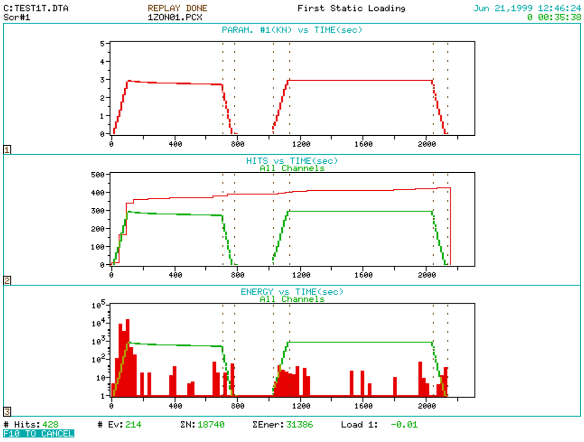


Figure 1 : AE static certification test load profile

3. THE AE EXAMINATION LOAD (EL)

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. If a higher EL has been agreed, this should be applied next in exactly the same way.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C:TEST1T.DTA       REPLAY DONE            First Static Loading      Jun 21,1999 12:46:24
Scr#1              1ZON01.PCX                                               0 00:35:38
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# Hits:428     # Ev:214     ΣN:18740     ΣEner:31386     Load 1:   -0.01
F10 TO CANCEL
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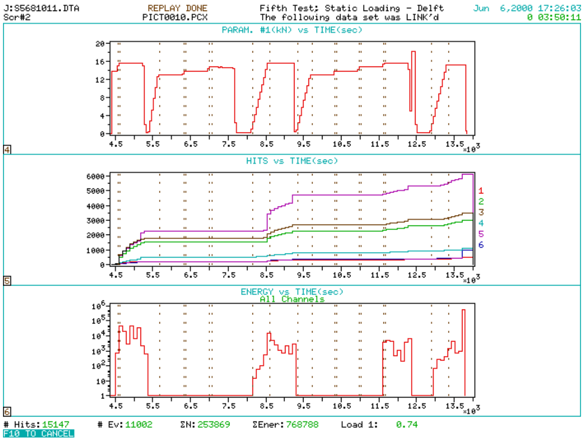
Figure 2 : Initial loading of virgin blade to OL and repeat - load profile (top); cumulative AE hits (centre); AE signal energy (bottom)

Figure 2 shows the typical burst of AE activity associated with the first loading to a given load level and the much quieter repeated loading.


```
J:S5681011.DTA     REPLAY DONE      Fifth Test; Static Loading - Delft      Jun  6,2000 17:26:03
Scr#2              PICT0010.PCX     The following data set was LINK'd               0 03:50:11
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# Hits:15147     # Ev:11002     ΣN:253869     ΣEner:768788     Load 1:   0.74
F10 TO CANCEL
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Figure 3 : Comparison of emission levels from 15 kN EL's during a static blade test to failure - load profile (top); hits per channel (centre); AE signal energy (bottom)

Figure 3 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. This blade finally failed close to sensor 5.

4. THE MAXIMUM TEST LOAD (MTL)

As discussed in section 2, the MTL for a blade test is typically estimated based on a single event: the 1 in 50 years gust. This event is generally reproduced as a rapid load "spike" with duration no longer than 10 s. Pass/fail certification criteria are based on the blade surviving this load. Load-holds of 3 minutes or more at sizeable fractions of the MTL are not acceptable to the blade manufacturers since they are perceived to be unrealistic loads that would not be seen in service and which might cause premature failure during the certification test.

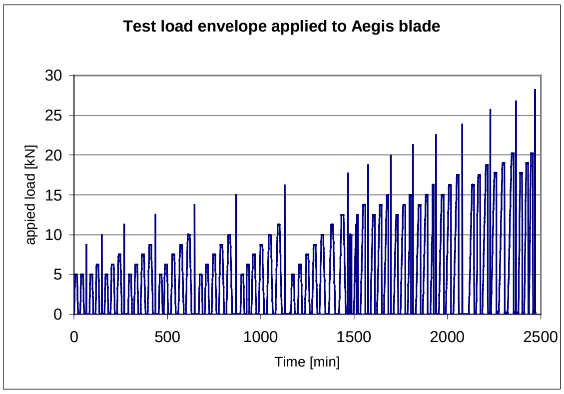
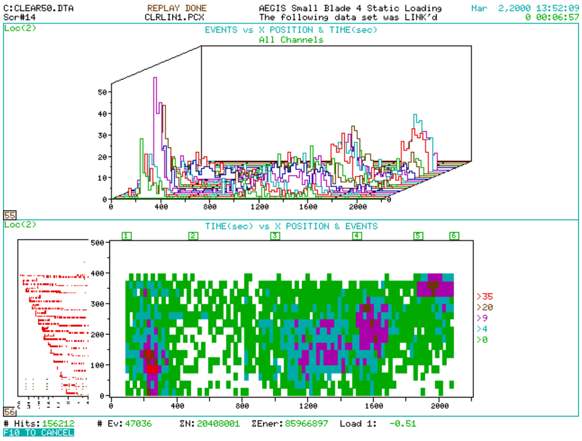


Figure 4 : Static load test envelope to evaluate AE procedures and EL and MTL sensitivity

It was necessary therefore to develop a load profile which incorporated the standard certification loading and to base the AE evaluation criteria on such tests. 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 4).

Results are presented in terms of number of located events for a typical static blade test in figures 5 and 6. 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 2000 mm, where the second large events peak is located.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Scr#14                 CLRLIN1.PCX       The following data set was LINK'd                0 00:06:57
# Hits:156212     # Ev:47036     ΣN:20408001   ΣEner:85966897   Load 1:   -0.51
F10 TO CANCEL
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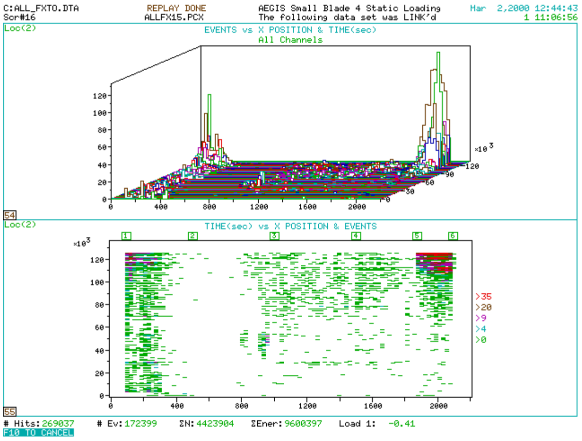
Figure 5 : Damage progression by linear location for sequence of MTL tests in terms of AE signal energy by position (x-axis) and time (z-axis - top; y-axis - bottom) with applied load inset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C:ALL_FXTO.DTA         REPLAY DONE       AEGIS Small Blade 4 Static Loading      Mar  2,2000 12:44:43
Scr#16                 ALLFX15.PCX       The following data set was LINK'd                1 11:06:56
# Hits:269037     # Ev:172399    ΣN:4423904    ΣEner:9600397    Load 1:   -0.41
F10 TO CANCEL
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Figure 6 : 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)

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.

5. 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 suggests 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 recorded during the 10 slow cycles in every 10,000 cycles, which were applied in order to check the compliance of the blade. 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, say, 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, say, 0.2 Hz) and during this interval the load-strain characteristic and the AE activity is monitored.

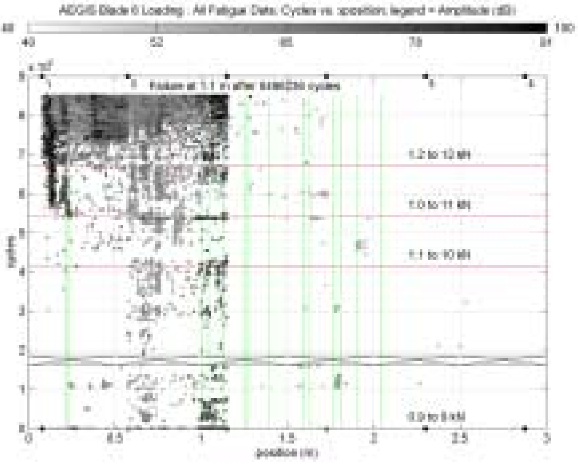

Figure 7 : Amplitude history of linearly located events during slow cycles for blade 6f

The AE data can be collected and collated into a plot of signal amplitude, energy, or some other AE parameter, as a function of position along the blade and number of applied load cycles. A particular example is shown in figure 7, where signal amplitude is plotted against number of cycles. Again, high amplitude events are found in the root area of the blade after the second load increase. However, this blade failed at the cluster of high amplitude events around 1.1 m. Also marked in the graph are the locations of several cracks in the foam section of the blade, many of which do not produce significant AE activity. The reasons for this are still being investigated.

6. PATTERN RECOGNITION SOFTWARE AND DAMAGE DETECTION

A particular achievement of the project is a suite of pattern recognition software, which uses clustering algorithms [5,6] to separate a collection of AE hits into classes, based on their AE features. The software can operate in either supervised or unsupervised mode and, when trained for a specific blade type, can be used to grade the structural integrity of various zones on the blade according to user-selectable criteria. Thus, the software can act as an early warning system against critical damage developing in specific regions of the blade, enabling more intensive observation of final failure mechanisms.

The software requires input of the blade geometry, the positions of the AE sensors, and the AE data. The user can define pass/fail criteria for separate areas of the blade, thereby enabling the software to differentiate between sections of different strength.

The software has been evaluated using the results from the blade tests carried out by the consortium. Blade 1 of the static test series failed by buckling in a weakened area created by shortening of the internal shear webs. Buckling is, of course, notoriously difficult to predict. Figure 8 shows the grading of the blade carried out during a load-hold at 6.5 kN (before raising the load to 7.0 kN, at which level the buckling failure occurred). Area 8 was given the most severe grading (E) at this load step and this load step only, indicating that a new class of failure-critical signals had been detected.

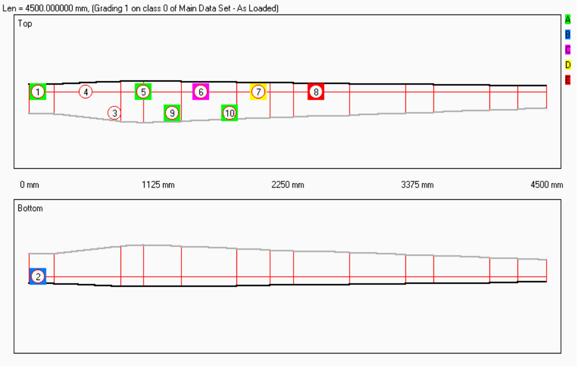

Figure 8 : AEGIS software grading of Blade 1 during load-hold preceding final failure

The AEGIS software, by identifying critical levels of AE parameters associated with different regions of the blade under specific loading conditions, could form the basis of an on-line blade condition monitoring system for an active wind turbine.

7. CONCLUSIONS

Methodologies for applying AE non-destructive test techniques during wind turbine blade certification tests (static and fatigue) have been 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. 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.

REFERENCES

[1] IEC 61400-1, *Wind turbine generator systems - part 1: safety requirements*, 1998

[2] IEC 61400-23 TS Ed.1: *Wind turbine generator systems - part 23: Full scale structural testing of rotor blades for WTGS's*, draft 1999

[3] ASTM E07.04.03-98/1 draft standard, FRP pressure vessels per ASME Code Section V, Art. 11

[4] Dutton, A.G., et al., *Acoustic emission monitoring from wind turbine blades undergoing static and fatigue testing*, 15th World Conference on Non-Destructive Testing, Roma, Italy, October 2000

[5] Anastassopoulos, A.A., Philippidis, T.P., *Pattern Recognition Analysis of AE from Composites*, Proceedings of EWGAE - 23rd European Conference on AE Testing, Vienna, 6-8 May 1998, pp. 15-20.

[6] Anastassopoulos, A.A., Philippidis, T.P., *Clustering Methodologies for the evaluation of AE from Composites*, J. of Acoustic Emission, Vol. 13, No 1/2, 1995, pp 11-21.

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