FULL-SCALE BLADE TESTING ENHANCED BY ACOUSTIC EMISSION MONITORING

D. J. Lekou[1*], P. Vionis[1], P. A. Joosse[2#], D. R. V. van Delft[2], D. Kouroussis[3], A. Anastasopoulos[3], M. J. Blanch[4], A. G. Dutton[4], A. Proust[5]

[1]CRES, Wind Energy Dept., 19th km Marathonos Ave., Pikermi 19009, Greece

[2]Knowledge Centre WMC (Delft University of Technology), P.O. Box 523, 2600 AM Delft, The Netherlands

[3]Envirocoustics ABEE, El. Venizelou 7 & Delfon, Metamorfosi, Athens 14452, Greece

[4]Energy Research Unit, CLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

[5]Euro Physical Acoustics SA, ZAC des Portes de Sucy, 27 rue Magellan, Sucy-en-Brie F-94373, Val de Marne, France

SUMMARY

To ensure that the static and fatigue design loads are sustained, current wind turbine blade certification procedures require full-scale tests on the prototype blade. During these tests sudden audible cracking sounds from within the blade are often generated, without the operators being able to locate the noise source or to evaluate the existence or extent of any damage. As blade structures continue to grow in size, the detection of any damage becomes a daunting task for the test engineer. Moreover, it is also important to have a forewarning of any impending failure, due to the enormous energy release in larger blades. Both these issues can be improved by the use of acoustic emission (AE) monitoring in parallel with standard testing procedures. Within the framework of an EU-funded project, AEGIS, a comprehensive assessment of the application of AE monitoring complementing structural testing of composite material blades was conducted and respective methodologies were developed. The testing procedure developed for small blades was applied to commercial quality and size blades, following current certification testing procedures, enhanced, however, through the quasi on-line analysis of the AE data. On-line analysis of AE data included damage location and criticality assessment by use of pattern recognition software previously calibrated through tests on small blades. Results from tests on two 16m blades are presented and the methodology is assessed, investigating the possibility of including AE monitoring during standard blade certification tests. The outcome of these experiments reveals that the critical areas can be effectively identified and assessed with respect to the blade's structural integrity, thus reducing the likelihood of untraceable damage.

Keywords: wind turbine blades; non-destructive testing; damage assessment

1. INTRODUCTION

An integral part of current wind turbine blade certification procedure is the static and fatigue test of a full-scale blade, in order to ensure that the blade can sustain the design loads and to assess its behavior during service life [1], [2]. Success or failure of the blade to sustain the design loads during these tests is judged by the non detection or detection of possible damage, respectively [3], usually by visual inspection. Nevertheless, it is recognized [3] that the detection of possible damage or failure during the test can be difficult, because of the complex structure of the blades (important structural elements are hidden and difficult to inspect and monitor) and, more importantly, the blade material can suffer local damage without showing it. It is obvious, that the up to now qualitative distinction of failure modes, needs improvement, so that the quality assessment of blade design and manufacturing becomes more objective. Non-destructive inspection (NDI) methods in combination with the currently applied testing procedure may well contribute to this necessity [3]. Acoustic emission (AE) monitoring, in parallel with standard testing procedures, has proven to be a suitable method, amongst others since it provides the means to both localize the damage, [4] and [5] and assess its criticality [6].

Within the framework of an EU-funded project, AEGIS, a comprehensive assessment of the application of AE monitoring complementing structural testing of composite material blades was conducted and respective methodologies were developed [7]. The AE testing procedures developed for small blades earlier in this project, have been applied to commercial quality and size blades with the aim to demonstrate and verify these. Although the selected size of the blade (16m) was a compromise to the state of the art blades, typically of 25m lengths, it was expected that the effects of scale and material could be verified correctly.

The two 16m blades were driven to failure through a static and a fatigue test, respectively, following current certification testing procedures, enhanced, however, through the quasi on-line analysis of the AE data. This on-line analysis of AE data included damage location and criticality assessment by use of pattern recognition software,

---

[*] Corresponding author: tel. +30 210 6603300, fax. +30 210 6603301, e-mail: dlekou@cres.gr

[#] Presently at: Composite Technology Centre, P.O. Box 103, 7600 AC Almelo, The Netherlands previously developed in this project and calibrated through tests on small Gl/P blades [8]. Acoustic emission occurs as a result of damage growth in the structure. The characteristics and intensity of the measured AE signals have been used in the pattern recognition software to grade the signals. Scope of these tests was the enhancement of current certification tests by the use of AE monitoring to facilitate the test operator in locating and evaluating any damage on the blade during testing.

Results from both these 16m blade tests are presented herein, revealing that the developed methodology can be successfully applied to large commercial blades. Although the grading of the pattern recognition software might need some refinement when passing from smaller to larger blades, due to some size and material related issues, results from both tests show that critical areas can be effectively identified and assessed with respect to the blade's structural integrity. Especially by standard measuring methods during blade testing with AE monitoring, the test operator is less likely to be confronted with untraceable damage.

2. DESCRIPTION OF TEST SETUP

The selected 16m blades were manufactured by NOI Scotland Ltd. (UK) following the original production specifications and design of the APX33 blade of AERPAC (NL). The static test of the Glass/Epoxy blade was carried out by CRES, with support from ENVIROCOUSTICS for the AE measurements, while the fatigue test of the second blade was carried out by TU Delft with CLRC and Euro Physical Acoustics supporting the AE measurements.

For both static and fatigue loading, the blade was loaded in the flap direction with the suction side of the blade under compression. During static testing, loading was applied at two positions at 8m and 10m from the blade root respectively, under load control following the load envelope defined for the static test procedure. The fatigue test was conducted in two parts: Part 1 with the blade loaded at 9.0m from the blade root and Part 2 with the blade loaded at 8.0m. During the fatigue testing of the blade, loading was performed under displacement control and since stiffness change of the blade was negligible, no fine-tuning of the displacement was necessary during testing. The load magnitudes of each load envelope used during both static and fatigue testing, were defined by TU Delft according to the structural characteristics of the blade and the target test load definition according to IEC 61400-23 [3]. For the fatigue test, the target test loads were defined so that the blade would fail at approximately 5million fatigue cycles.

When applying the procedure developed for AE monitoring [7], [9]the basic load envelope for the static test consists of a traditionally applied certification static test load (TL), which is both preceded and followed by a trapezium-shaped acoustic emission examination load (AEL). The AEL block involves a load-hold period of 10min following AE testing procedures, with an applied load corresponding to the maximum load of normal operating design load cases of the blade, while the TL is applied as a spike load with a load-hold period of 10s corresponding to the maximum load of extreme design load cases as described in IEC 61400-23 [3]. Fig. 1 illustrates the basic load envelope for the static case. It is necessary to repeat the initial AEL block, since AE always occurs when the virgin composite material structure is loaded for the first time above a given level, but won't appear if it is re-loaded to that or lower level, unless the structure is damaged. The basic load envelope was repeated several times, each time increasing the TL, up to the final failure of the 16m blade. Fig. 2 presents the load envelope applied during the static test of the first 16m blade.

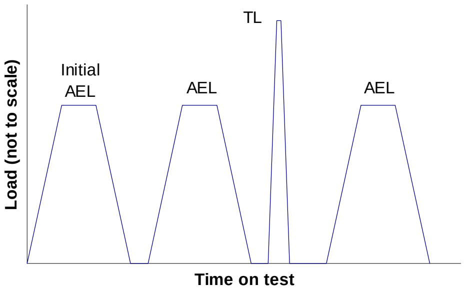

Fig. 1 Basic loading envelope during static testing

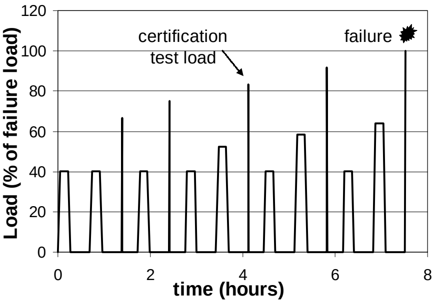

Fig. 2 Applied load envelope during static test

The difference of the traditionally applied fatigue test according to IEC 61400-23 [3] with the fatigue test incorporating AE monitoring [7], [10] is that initial and periodic AEL static tests to 5% above the peak fatigue load are foreseen, as well as slow data collection fatigue load blocks. Fig. 3 presents the load envelope for the fatigue case. Since the fatigue test is much more time consuming than the static test, in order to evaluate the already developed procedure, the fatigue load was calculated from the beginning to drive the blade to failure at a predetermined number of cycles.

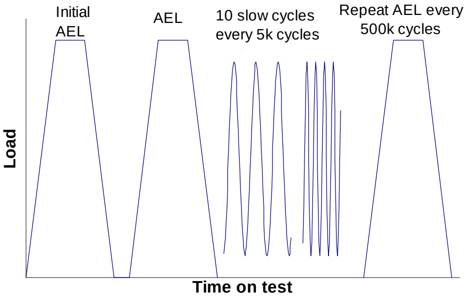

Fig. 3 Basic fatigue load envelope

For both the static and fatigue test, the monitoring included strains in pre-selected positions along the blade length, applied loads, blade deflection and AE data. During the static test, AE was monitored using a Physical Acoustics Corporation (PAC) 18-channel SPARTAN 2000 system. During Part 1 of the fatigue test, a PAC 10-channel SPARTAN 2000 system and a PAC 6-channel MISTRAS system were used in combination, while for Part 2 of the fatigue test only the 10-channel SPARTAN system was used.

During the static test, all measured quantities were continuously monitored and recorded, while due to the time-length of the fatigue test, data were continuously recorded during the AEL proof tests performed every 500,000 cycles, the 10 slow fatigue cycles and the first 10 fast cycles performed after the slow ones every 5,000 cycles. During the normal fatigue cycles the data acquisition was performed only during the top 10% of the fatigue loading.

Both the static and fatigue test procedures also included a quasi-on-line application of the AEGIS pattern recognition software, previously developed within the project [8], carrying out grading for each AE test, prior to the subsequent TL certification-type test, or fatigue block test, for the corresponding test, in order to quantify the severity of any existing damage and to assess whether the applied load is critical for the blade. This procedure aimed to facilitate the decision process as the whether the following loading (either static or fatigue) would be expected to be sustained by the blade or could lead to failure.

3. EXPERIMENTAL RESULTS

During the static test a total of five TL "spike" loads were applied, with the corresponding five intervening sequences of AE Load-hold tests, including the initial AEL proof tests as shown in Fig. 2. The blade failed rather suddenly during the fifth TL test (TL5), immediately after the corresponding target load was reached, probably by a buckling type mechanism, which started close to the load application point at 8m and eventually encompassed an area from about 6.7m to 9.0m from the blade root.

Concerning the AEL tests, location of AE throughout testing indicated that the area around the root-most load application point (8m from the blade root) and certain areas in the root section were emissive from the first load stages and, thus, may be characterized as potentially weak areas, since AE is a result of damage growth. Similar observation could be made from the TL tests. Visual inspection of the blade after each TL and AEL test revealed no significant visible damage prior to failure, although linear location in the final failure area close to the root-most saddle was very persistent throughout the test, especially after the first AEL test, giving a warning that this area was the critical one for the blade (see Fig. 4). The other source of AE near the root was the result of bubbles and small cracks visually identified in that area after TL1 & TL2, respectively, which did not progress till the final failure of the blade. Analysis of AE data gathered during the applied AEL before each TL gave a forewarning for this damage development. Should this test be a standard certification test, the test operator would have the opportunity to closely monitor both emissive areas of the blade in order to track down the damage development.

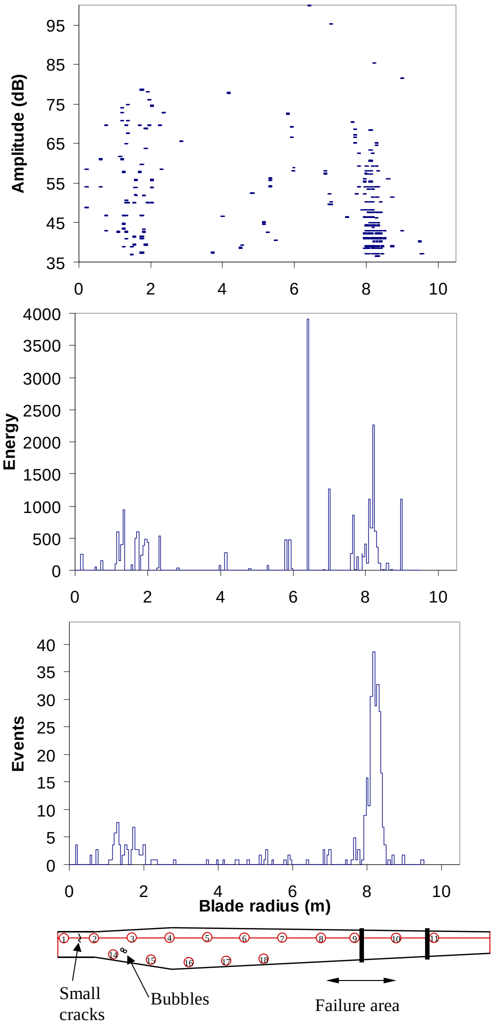

Fig. 4 Overall linear location during static test (blade superimposed)

The grading strategy that was applied for the quasi on line assessment of damage criticality was the same as previously developed for the small blades. Gradings range from none, via "A" to "E", the latter being the most severe. The grading of the last available load-hold prior to failure showed "A" grades near the failure area and left the rest of the blade with no grade, as shown in Fig. 5. This may have been appropriate, since up to the last load-hold level, the blade did not suffer from any visible damage. However, it might also be argued that the low number of "critical" AE data from the large blade is due to behavioral differences of glass/epoxy compared to glass/polyester, which were implicitly ignored in applying the grading strategy developed for the small blade series. Additional research is needed in this aspect, using the current test available AE data as trainers for a modification of the already developed pattern recognition software.

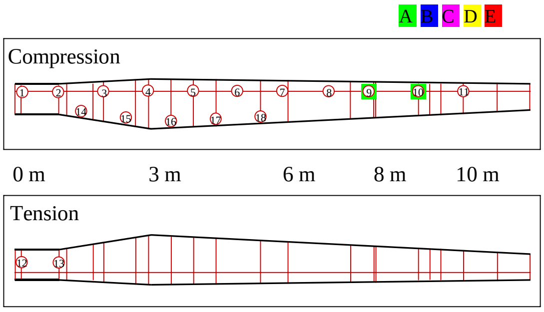

Fig. 5 Pattern recognition applied for AEL prior to TL5

During standard certification static testing, where the test load is applied only once, the change in the blade response is not accounted for. Usually, strain recordings are compared to design values (or simulation data) and the small inconsistencies are attributed either to incomplete modeling, or to expected differences between simulation and practice. During the currently applied test procedure, the results of the AEL blocks offered the test operator the opportunity to monitor and compare the blade's response prior to and after the application of the certification test load, in order to identify possible signs of material or other failure. For example, in Fig. 6 the difference is shown in strain measurements and actuator displacements during AEL load hold period of the same load level prior and after TL4, along the blade length in percent. As can be seen from this figure no significant changes were observed, while minor changes can be attributed to the temperature change during the test and the accuracy of strain measurement. Strain gauge reading at 5.5m from the root in the compressive side of the blade stands out due to the significant difference. As this strain gauge was the closest to the failure region, this change could be an indication that some damage had occurred in the area between the saddle at 8m from the blade root and 5.5m during TL4. However, visual inspection of the area immediately after TL4 did not reveal any external damage on the blade. It should also be reminded that the certification load for the blade was TL3, where after no sign of significant stiffness change was observed.

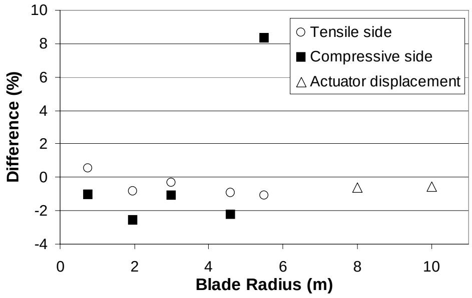

Fig. 6 Difference in load-hold values prior and after TL4

For the fatigue test, the analysis of AE data collected during the AEL blocks results in similar conclusions as for the static test. Namely, the location of critical areas is clearly identifiable, while use of the AEGIS pattern recognition (PR) software as trained by the data set from a small Glass/Polyester blade, gave underestimating grades for the criticality of the following fatigue load. Specifically, the first part of the test with the actuator at 9m from the blade root resulted in failure after 26.5k cycles at the same area as the static test without the test operator having a forewarning of the imminent failure. As for the static test of the first blade, pattern recognition applied to the AE data collected during the AEL prior to the fatigue loading showed an "A" grading for the failure area and for the root area (see Fig. 7a). Nevertheless, after the visual identification of the damage at 18.8k cycles the AEGIS PR applied on the AEL block clearly indicates that the area close to the identified damage exhibits a severe damage criticality (Fig. 7b).

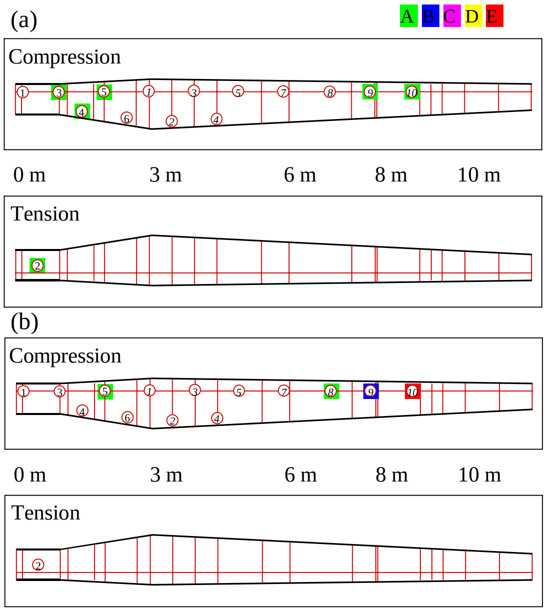

Fig. 7 Pattern recognition applied for AEL prior to fatigue loading (a) and before failure at 22k cycles (b)

Part II of the fatigue test was used to further evaluate the application of the procedure developed previously, since the damaged area of the blade was concentrated only near the 9m load application point, while the rest of the blade was intact. Nevertheless, although during part II the failure of the blade occurred after 5095k fatigue cycles, the same remarks as for the prior tests can be made. Strain and deflection observations during the fatigue test showed very slow stiffness degradation, almost up to the final failure of the blade, except for measurements from one strain gauge near the root of the blade where a delamination was developed after 1200k cycles. This damage development was correctly identified prior to any visual indication through the analysis of AE data.

4. CONCLUSIONS

Current certification testing procedures include monitoring of developed strain and deflection along the blade length. Although changes in the blade's response due to damage development can be clearly identified by use of standard monitoring techniques, e.g. strain gauge readings, this can be used only during a fatigue test, where the damage is progressively leading to failure. During a static test for certification, however, where the test load is applied only once, the change in the blade response cannot be monitored and damage cannot be accounted for except by visual inspection.

The basic AE testing methodology developed in the early phases of the AEGIS project was successfully transferred to a larger structure. Notably, the AEGIS pattern recognition was used quasi-on-line during the test to produce a grading for the structure at each stage, although, since this was the first test on a glass/epoxy blade, an appropriate training data set was not available.

AE monitoring at this stage was used to identify those parts of the large structure that seemed to be weaker than the rest and have more interest for the test operator. This was performed for both the static and fatigue test in consistent manner, allowing for closer inspection of the test areas prior to final failure. During both types of test performed, significant located AE activity was evident at the ultimate failure location from the very first stages of the test. If these had been genuine certification tests, then the findings from the AE data analysis would have afforded ample opportunity for closer investigation of the critical zones.

Pattern recognition software has also been applied to grade the damage of the blade, so as to warn the test operator for the criticality of the applied load. In this aspect more work is needed. For the static testing, the grading methodology just prior to the final TL (TL5) should give results with gradings at least D or E. The same holds true for the grading of the AE blocks prior to the fatigue cycling. Both grading procedures, however, resulted in grades A or B, whereas E would be expected. Nevertheless, the currently available AE data sets for the failures in static and fatigue testing of the two blades will be used in a subsequent work, to improve the training data set of the AEGIS pattern recognition software, which was used for the damage criticality assessment. Improvement of the grading strategy available in the software will then have to be proven on additional full scale testing.

In any case, experimental results show that use of AE monitoring techniques in addition to the standard certification testing procedure could enhance the full-scale testing procedure and in a more developed stage, that is with a larger data base, could eventually lead to lowering the applied forces, i.e. lead to use of proof loading, in order to get the same insight for the blade as with application of full extreme loading or application of the full fatigue life.

5. REFERENCES

[1] IEC 61400-1. *Wind Turbine Generator Systems-Part 1: Safety Requirements*, 1999

[2] Germanischer Lloyd. *Rules and Regulations, IV- Non-Marine Technology – Part 1 Wind Energy, Regulations for the certification of Wind Energy Conversion System*, Chapters 1-10, Supplement No.2, 1998

[3] IEC 61400-23. *Wind Turbine Generator Systems-Part 23:Full Scale Structural Testing of Rotor Blades for WTGS's*, Draft, Ed.1, 1999

[4] Beattie AG. Acoustic Emission Monitoring of a Wind Turbine Blade During a Fatigue Test. *A collection of the 1997 ASME Wind Energy Symposium Technical Papers*. AIAA, Reno 6-9 January 1997; 239-248

[5] Vionis PS, Anastassopoulos AA, Kolovos VK, Kouroussis DA. Non-destructive testing of full scale W/T blade by means of acoustic emission monitoring during controlled static loading. *European Wind Energy Conference and Exhibition Proc.*, Nice, France, 1-5 March 1999; 691-694

[6] Blanch MJ, Kouroussis DA, Anastassopoulos AA, Nikolaidis VN, Proust A, Dutton AG, Jones LE, Vionis P, Lekou DJ, van Delft DRV, Joosse PA, Philippidis TP, Kossivas T, Fernando G. Damage characterisation of acoustic emission data from ten small wind turbine blade tests. *Proc. of Global Windpower Conf.*, Paris, France, 2-5 April 2002

[7] Joosse PA, Blanch MJ, Dutton AG, Kouroussis DA, Philippidis TP, Vionis PS. Acoustic Emission Monitoring of Small Wind Turbine Blades. *Journal of Solar Energy Engineering* 2002; **124**: 446-454

[8] Anastassopoulos AA, Kouroussis DA, Nikolaidis VN, Proust A, Dutton AG, Blanch MJ, Jones LE, Vionis P, Lekou DJ, van Delft DRV, Joosse PA, Philippidis TP, Kossivas T, Fernando G. Structural Integrity Evaluation of Wind Turbine Blades using Pattern Recognition Analysis on Acoustic Emission Data. *Presentation at the 25th European Conference on Acoustic Emission Testing* – EWGAE 2002, Prague, Czech Republic, 11-13 September 2002

[9] Anastassopoulos AA, Kouroussis DA, Proust A, Blanch MJ. *Guidelines for carrying out acoustic emission test on wind turbine blades during static certification testing*. AEGIS Technical report 072. Envirocoustics S.A., Athens, January 2003

[10] Proust A, Anastassopoulos AA, Kouroussis DA, Blanch MJ, Dutton AG, Joosse PA. *Acoustic Emission Test Guidelines for fatigue of wind turbine blades*. AEGIS Technical Report 073, Euro Physical Acoustics, France, January 2003

AKNOWLEDGEMENTS

This research was supported by EC Non-nuclear Energy Program under contract number JOR3-CT98-0283.