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STRUCTURAL INTEGRITY EVALUATION OF WIND TURBINE BLADES USING PATTERN RECOGNITION ANALYSIS ON ACOUSTIC EMISSION DATA

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ABSTRACT

Current Wind Turbine (W/T) Blade certification practices require the conduction of static and fatigue tests on new blades, in order to assess whether the blade can sustain the applied loads. Within the scopes of a current EC-funded research project, Acoustic Emission (AE) monitoring has been extensively applied during testing of various W/T Blades of similar design. All blades were loaded to failure by, either, gradually increasing the static test loads, or fatiguing the blade until it failed. It has, already, been reported that AE could well locate the damage imposed on the blade during such tests (static and fatigue), and in most cases before the damage had become visible or audible, enhancing, thus, the assessment capabilities and the understanding of the failure process of the blades. Additionally, application of typical AE load-and-hold proof tests at intermediate loading stages, prior to failure, has enabled the assessment of the damage criticality for the particular proof load, denoted by high acoustic emission rates during load-holds. Furthermore, it has been observed that the AE behaviour of all tested blades during load-holds exhibited very similar trends right prior to failure, despite the fact that blades failed differently. The present paper reports on the use of (specially created for the Project) Pattern Recognition (PR) software which has revealed the existence of a "critical" class of AE data appearing close to failure. This has enabled the formulation of evaluation criteria used for the automated assessment of the blade's integrity, based on the amount of hits from critical classes appearing during the hold period. It is shown that, for similar blades, common grading criteria can be applied successfully, enabling a fast and effective "grading" (from "good" to "severely damaged"), and providing very successful warnings of impending failure. This is particularly important for an effective analysis of fatigue tests that have lasted for months and have produced huge amounts of AE data. The software and the automated blade evaluation will be verified with future tests on large, commercial scale blades.

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INTRODUCTION

Wind turbine (W/T) blades, while in operation, encounter very complex loading sequences, due to the stochastic nature of wind conditions on wind turbines sites. The suitability of a particular W/T blade to operate on a specific site is assessed through a certification procedure which entails the conduction of a series of static and fatigue laboratory tests on the W/T blade. The purpose of such tests is to ascertain that the blade can survive the applied (static and fatigue) loads as per the applicable design standards [1], [2], while the applied static loads aim to simulate the 1-in-50-years gust (and is applied on the blade for ten seconds during testing), followed by fatiguing the same blade for an accelerated 20-years fatigue lifetime test.

In the aforementioned procedures the pass/fail criteria for W/T blades have been based on deflection measurements and strain measurements on the blade's surface, during static loading. Damage characterisation is, usually, performed by visual inspection for evaluating surface damage. Audible sound emissions heard during such certification tests are considered as potential damage indications, however, on most occasions, the source of such noises cannot be located.

It has already been shown and reported[3]-[6] that application of AE monitoring during loading of W/T blades has offered considerable advantages towards the understanding of the complex damage mechanisms occurring on the blade, as the loading gets more severe, and, subsequently, has enhanced the tester's ability to evaluate the tested blade's condition. Damage occurring during certification testing (both static and fatigue) can be located with AE, while "weak" areas of the blade are pin-pointed at early loading stages. Additionally, the application of AE "proof-type" tests (with ten-minute load-holds) before and after each certification type static tests as well as before and during the fatigue tests (at various times during testing) has enabled the assessment of the criticality of the damage (if any) introduced by the test, based on the traditional "emission during load-hold" criterion.

Within the scope of a current, EC-funded research project (AEGIS) aiming to provide a reliable methodology for the assessment of W/T blades' structural integrity, Acoustic Emission (AE) monitoring was extensively applied during both static and fatigue certification type testing of W/T blades. Various proof tests have, also, been conducted for each blade and at various loading stages prior to failure, it has been verified that, as damage was propagating, and as the load was approaching the ultimate failure load, emission during load-hold demonstrated increasing trends. Furthermore, it has been observed that the qualitative characteristics of the recorded AE signals during load-holds (e.g. Amplitude, Duration, etc.) exhibited similar "patterns" close to failure loads. In general, the intensity of the recorded signals increased as damage was becoming more critical and as the loads were approaching the failure loads. The consistency in the presence of a distinguishable family of AE data right prior to failure has enabled the formulation of specific criteria for the assessment of the blade's ability to withstand specific loads. In other words, the absolute amount of intense AE data on a specific section of the blade during load-hold at a specific load has been proven to be a very good measure of weakness of this section of the blade to withstand such load.

With the use of a Pattern Recognition and Blade Grading software (AEGIS software), specially created for the Project, critical AE data can be automatically identified and quantified, for any given AE data set, and the tested blade can be sectionally (zonally) graded from "A" (minor damage) to "E" (severe damage) for a specific load, based on the number of critical AE data recorded per zone (i.e. per AE sensor) during the ten-minute load-hold.

EXPERIMENTAL PROCEDURE

In a series of ten (10) similar, small-scale blades, made of Fibre Reinforced Plastic (FRP), (Fig. 1), specifically manufactured for the project, various loading envelopes have been applied, while all blades were loaded up to final failure. Four blades were fatigued up to catastrophic failure, while six blades were deliberately loaded to failure by gradually increasing static loads, using various loading envelopes. The static testing loading envelopes varied and started from simple, monotonic, stepwise load increases (Fig. 2, top) up to failure with ten-minute load holds at various load levels, while, at later project stages, more complex loadings were applied, incorporating both “certification-type” loadings (ten seconds load increase, ten seconds load hold, load decrease) to gradually increasing loads until failure and, intermediately, ten-minute load-hold loadings (AE examination or “proof-type” tests) at, accordingly, increasing load levels, to certain percentages of the previously applied certification-type test load (Fig. 5, top).

In the present paper, results from the test to failure of three different blades will be presented. Blade #1 was monotonically loaded to failure with gradual load increases and 10-minute load holds. The results from this blade were used to “calibrate” the grading technique. Blade #7 was statically loaded to failure, following a complex loading envelope with “certification-type” tests of gradually increasing load and intermediate AE-proof tests with 10-minute load-holds which were used to grade the blade at various loading stages. Blade #8 was fatigue-loaded to failure, but before the application of the fatigue test, it had been subjected to AE-proof tests at two load levels, which were used to grade the blade.

The tested blades presented herein were manufactured by Geobiologiki S.A. and were tested to failure at the Centre for Renewable Energy Sources, while additional blades (not presented) were loaded at Delft University of Technology. For all tests presented, a 10-channel SPARTAN-2000 Acoustic Emission system by Physical Acoustics Corporation (PAC) was used, with PAC-R6I AE sensors.

UNSUPERVISED PATTERN RECOGNITION ON BLADE #1

The blade layout, sensor positions and load application point are presented in Figure 1. The applied loading envelope is shown in Figure 2. The blade final failure area was at 2300mm from the root, between sensors 7 and 8. Delamination was observed at the bottom section of the root area (sensor 2, not shown). The blade failed by buckling at 7KN load.

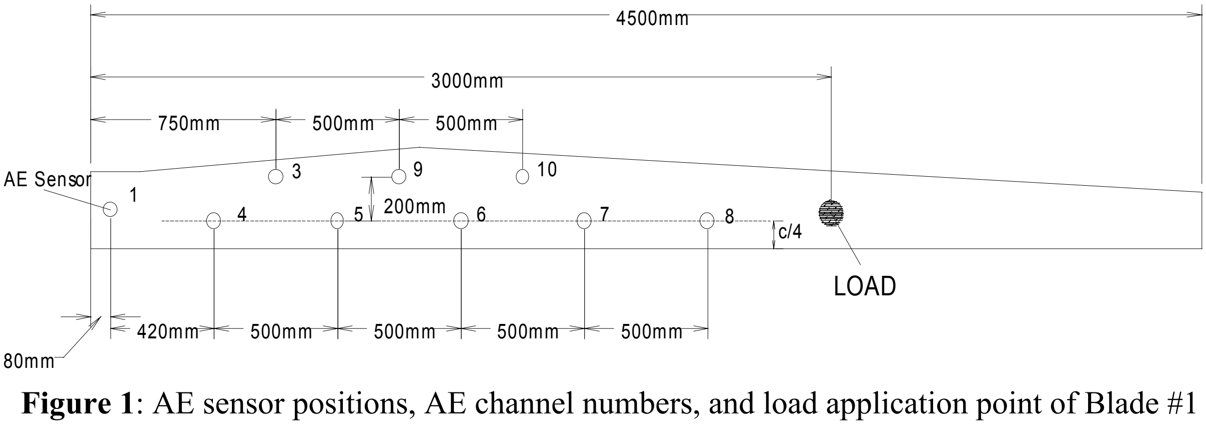


Figure 1: AE sensor positions, AE channel numbers, and load application point of Blade #1

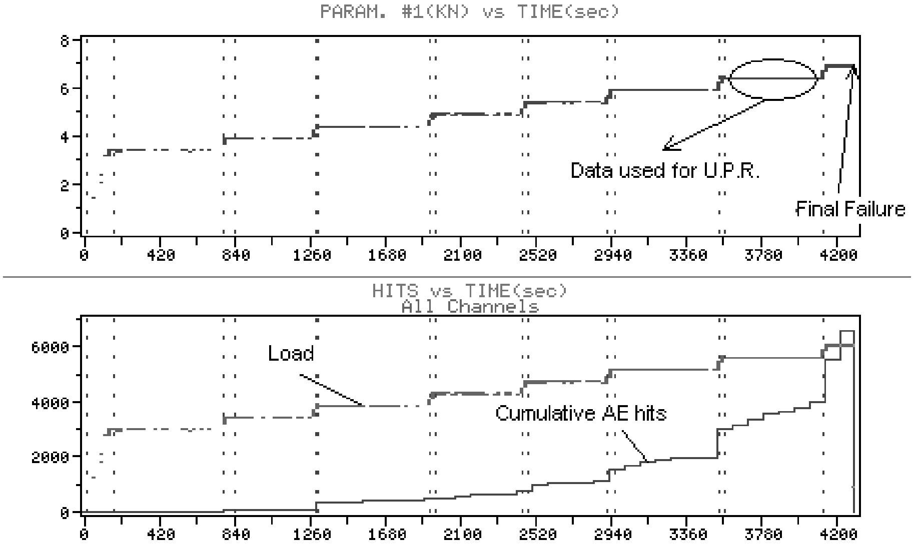


Figure 2: Applied loading envelope of Blade #1 (top) and cumulative AE hits vs. time (bottom), with load superimposed.

Unsupervised Pattern Recognition (UPR) was applied on the data of the last load-hold (at 6.5KN) prior to failure using the "AEGIS" Pattern Recognition software[7] especially developed for the Project. A "first-hit" analysis was followed. A representative set of AE features was used, comprising Counts to Peak, Energy, Duration, Amplitude and Average Frequency. Furthermore, all features were normalised individually to a range from 0 to 1, in order to avoid biasing the classification towards the feature exhibiting the highest physical dimensions. UPR was performed using the K-Means[8] algorithm and yielded three different classes of AE data.

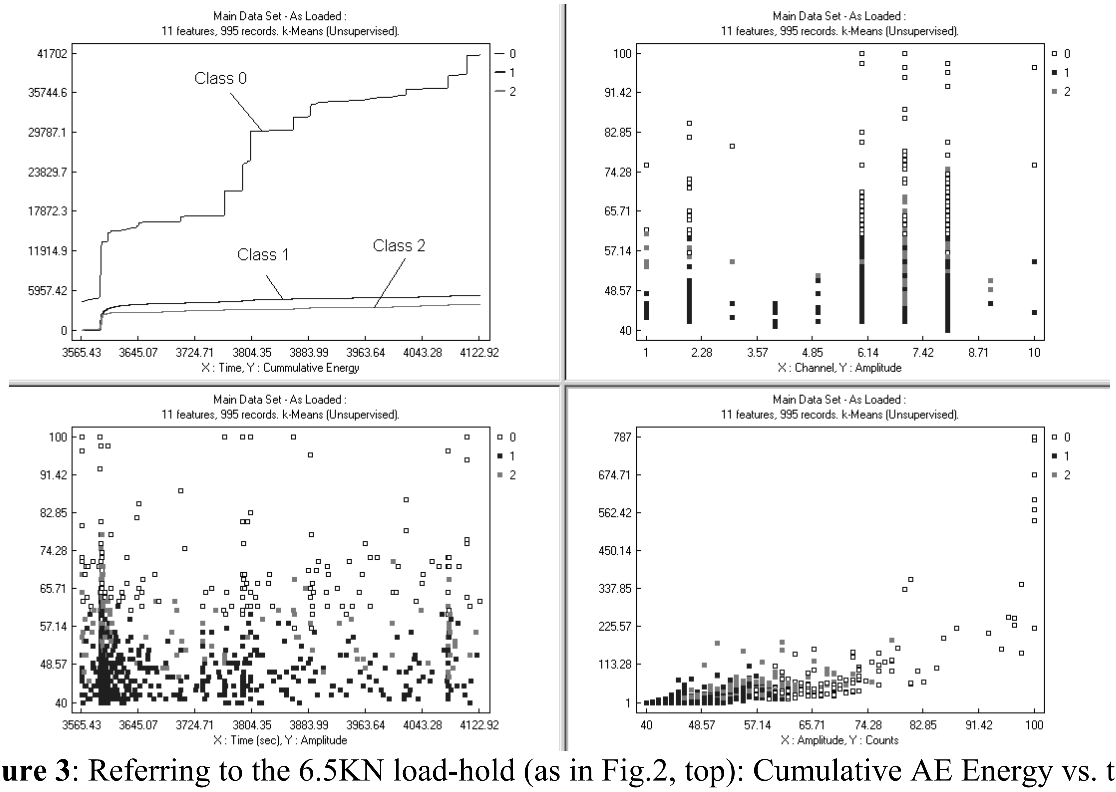


Figure 3: Referring to the 6.5KN load-hold (as in Fig.2, top): Cumulative AE Energy vs. time (top left), AE Amplitudes vs. Time (bottom left), AE Amplitudes vs. channel (top right) and Counts vs. Amplitude (bottom right)

Figure 3 refers to the data from the load-hold at 6.5KN, which was classified into three classes by UPR. A thorough examination of the data of Class “0” reveals the following:

a. Data has an intense rate of AE Energy throughout the load-hold, as opposed to the other classes (see Fig. 3, top left graph),

b. AE hits have high Amplitudes throughout the load-hold (Fig. 3, bottom left graph),

c. The class appears mainly in the channels close to the failure area (Fig. 3, top right graph),

d. The AE hits this Class have high Amplitude and Counts values (Fig. 3, bottom right graph).

Class “0” was characterized as the “critical” AE class; based on it, the grading strategy was formulated. Following the clustering performed by UPR on the 6.5KN load hold AE data, a “k-Nearest Neighbour” (k-NNC) Supervised Classifier[9] was trained to correspond AE hits, from any given data set, to one of the three classes based upon the values of their AE features. Subsequently, the data from each one of the load-holds of the loading envelope of Blade #1 (Fig. 2) was classified separately and the amount of data falling into the critical class was observed each time. As a result, a colour-coded grading strategy was formulated which grades the blade (for a specific load) based on the number of AE hits which are classified with the critical class. For example, for a channel to get a “B” grade, this channel must have recorded 10-25 critical class first-hits during the ten-minute load-hold. This same grading strategy was applied on subsequent blades’ load holds, (at various loading stages) and results from Blades #7 and 8 are presented below.

SUPERVISED PATTERN RECOGNITION AND GRADING OF BLADE #7

The blade layout, sensor positions and load application point are presented in Figure 4. The applied loading envelope is shown in Figure 5, where the loading stages and the sustained damage are, also, indicated. It can be observed that the loading envelope included both certification-type tests (e.g. the MTL11 test) and AE proof-type tests (e.g. tests AE7a to AE7d). Apart from an artificially imposed skin delamination which was located between 2m and 2.2m from the root, on the sensors’ line, the blade sustained damage during the test at various positions. Visual inspection during and after the test revealed (see also Fig. 5 bottom):

- Delamination at the root area, visible at later stages of the test,
- Two cracks at the compressive side, perpendicular to the blade axis, at 1.1m and 1.2 m from the root, visible after the MTL11 certification-type test, and,
- One crack at the compressive side, perpendicular to the blade axis, at 2.2m from the root, developed after the MTL11 certification-type test.

The blade failed at the position of the crack at 2.2m, during the MTL21 certification-type test at 22.8 KN, slightly before this load was achieved.

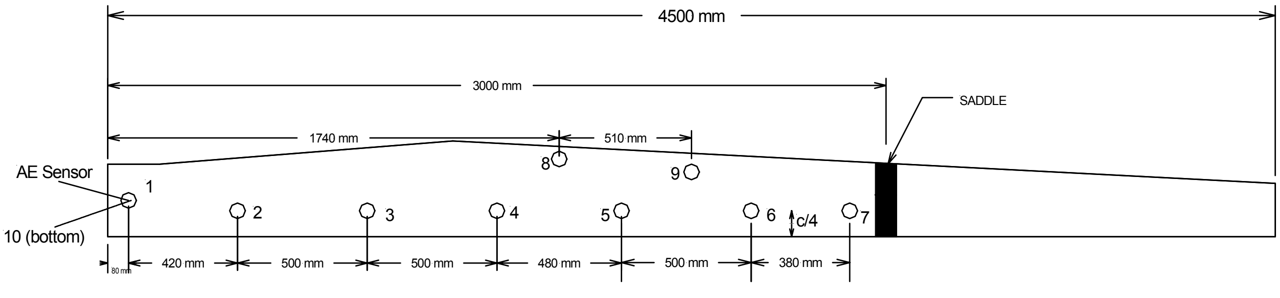


Figure 4: AE sensor positions, AE channel numbers, and load application point of Blade #7

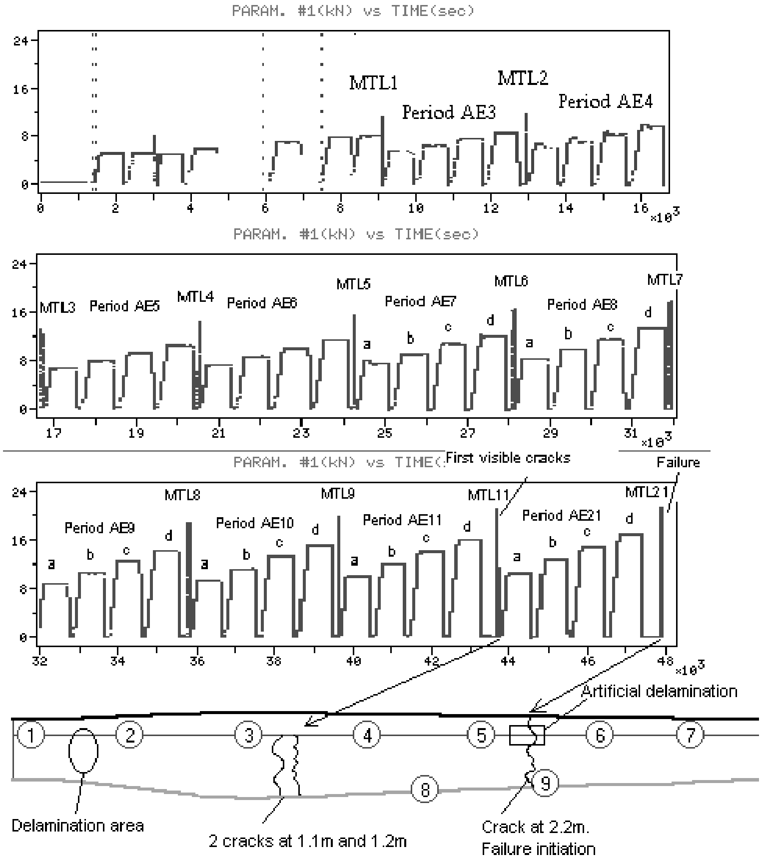
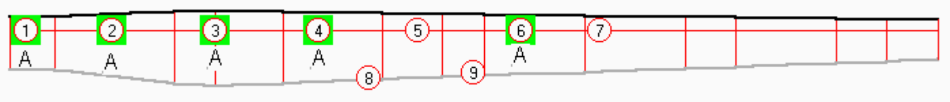
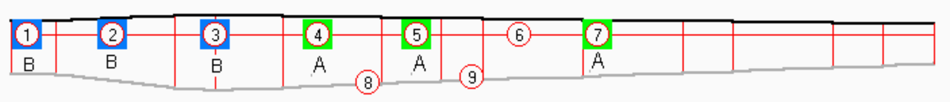
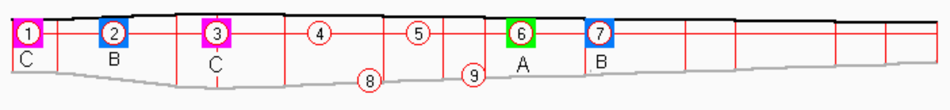
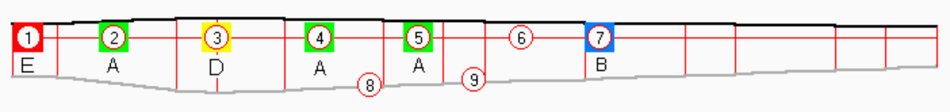
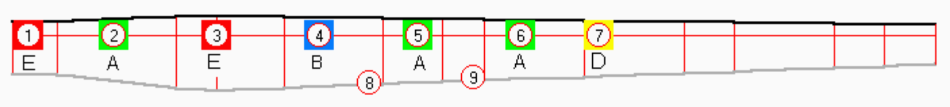
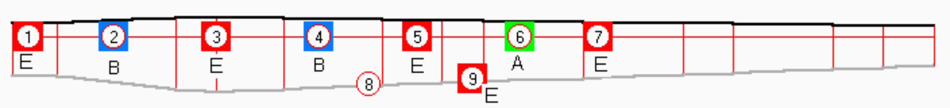


Figure 5: Loading envelope of Blade #7 indicating loading stages, and damage information

Each AE proof test was graded using the AEGIS software and the grading strategy defined in the previous paragraph, herein. Grading of some characteristic periods is presented in Table 1. It is worth noting that, prior to loading MTL5, the grading did not reveal any grades other than "A" or "no-grade", meaning complete absence of critical AE data and the blade did not exhibit any visible damage. The grading of sensor 1 (closest to the Delamination area) and sensor 3 (closest to the crack formed during MTL11 test) gradually increases from "A" (period AE7D) to "E" (period AE11E) giving a very good warning of the impending damage, i.e. the crack first seen after period MTL11. During the periods AE21A to E, sensor 5 was graded "E", while the blade failed catastrophically during the next test (MTL21) exactly in the area of sensor 5. Grading of the rest of the periods is not presented due to space limitations.

TABLE 1: GRADED BLADE #7 A B C D E	Period / Load-hold level (kN)
	AE7D 12.48 KN
	AE8D 13.44 KN
	AE9D 14.4 KN
	AE10D 15.36 KN
	AE11D 16.32 KN
	AE21D 17.28 KN

SUPERVISED PATTERN RECOGNITION AND GRADING OF BLADE #8

The blade layout, sensor positions and load application point of Blade #8 were identical to Blade #7 (see Figure 4). The blade was fatigue-tested with a sinusoidal load ranging from 1.2 KN to 12 KN, at a frequency of 1 Hz (Fig. 6 middle). Prior to fatigue testing, static AE proof type tests were applied to assess the ability of the blade to sustain fatigue loads. The applied static loading envelope is shown in Fig. 6, top, where the loading stages are, also, indicated. Apart from an artificially imposed skin delamination, located from 2m to 2.2m from the root, there was no other visible damage present on the blade during the last visual inspection prior to failure, which was estimated to have taken place less than one hour prior to failure. The blade failed after about 75K cycles into fatigue testing. Visual inspection after the test revealed that the blade failed with a crack on the compressive side between 1.8m and 2.0m from the root, close to sensor 5 (Fig. 6 bottom). Each preliminary AE proof test was graded using the AEGIS software and the grading strategy defined in the previous paragraph, herein. Grading results are presented in Table 2 and are summarized below:

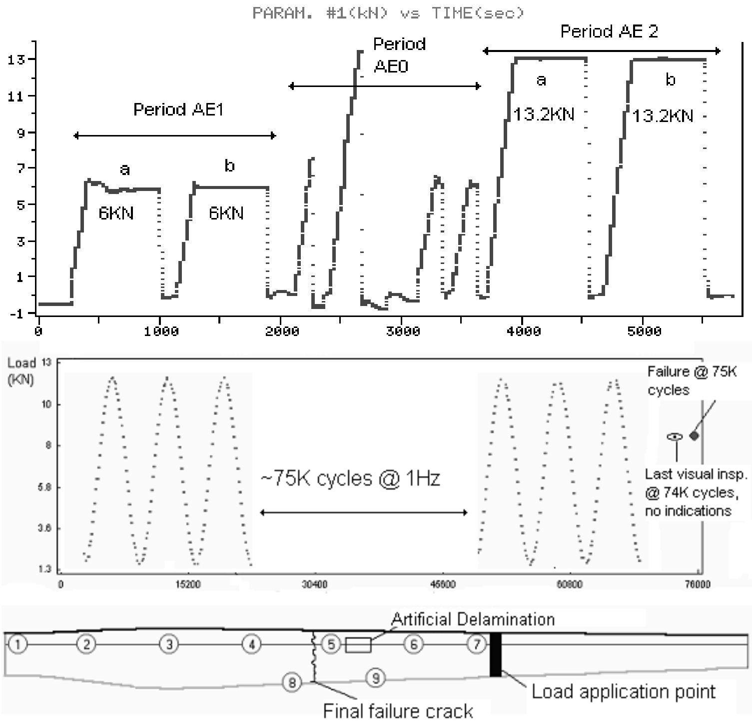
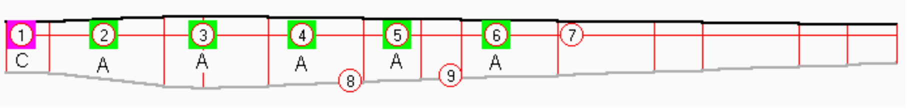
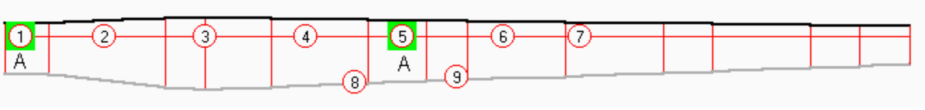
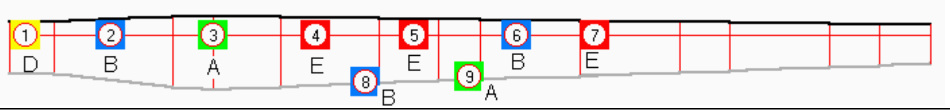
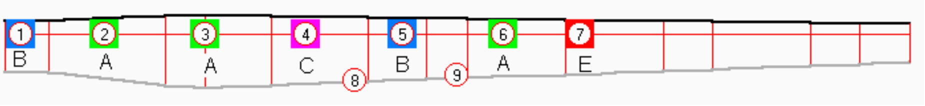


Figure 6: Static loading envelope of Blade #8 indicating loading stages (top), fatigue envelope (middle) and damage information (bottom)

TABLE 2: GRADED BLADE #8 A B C D E	Period / Load-hold level KN
	AE1a 6 KN (50% of max. fatigue)
	AE1b 6 KN (50% of max. fatigue)
	AE2a 13.2 KN (110% of max. fatigue)
	AE2b 13.2 KN (110% of max. fatigue)

a. Grading of Periods AE1a and b, does not yield any severe grade, indicating that the applied load (6KN) could probably be sustained by the blade.

b. Grading of Periods AE2a and AE2b, yield E grades, indicating that the applied load (13.2 KN) is severe for the blade.

CONCLUSIONS

An automated method for the assessment of the structural integrity of wind turbine blades and of their ability to withstand specific load levels has been developed and verified in a series of static and fatigue tests to failure of small-scale wind-turbine blades. The method involves static proof-loading of the blade and load-hold at the load of interest. AE activity during the load-hold is classified by a trained supervised classifier, to classes resulted from Unsupervised Pattern Recognition classification performed on the AE data obtained from the last load-hold prior to failure of the first tested blade. Each zone of the blade is, subsequently graded, from “A” to “E” based on the number of AE hits classified with the critical class (revealed from the first blade) of each corresponding AE sensor. A grade “A” indicates that there is minor or insignificant (for the specific load) damage on the blade, while an “E” grade indicates that the applied load causes severe damage on the blade and cannot be properly supported by it. The same grading strategy was applied on all tested small blades under the AEGIS project with very encouraging results, considering the fact that different blades failed in different ways (some of them very suddenly, with buckling) while different loading envelopes were applied. In the vast majority of the blades, including Blade #7, an “E” grade was assigned right prior to ultimate failure (or extreme damage), even during loading levels in which the blade did not exhibit any visible damage, and where it would have been otherwise unknown whether failure was pending. Additionally, the applied grading prior to fatiguing Blade #8, implied severity of the fatigue load levels and the blade failed after 75K cycles. Future work will include application of the same grading strategy during static and fatigue loading of large, commercial-scale blades, in order to assess whether the method can be applied to different blades, or further refinement and calibration of the method is required. A finalized version of such a method will provide manufacturers a tool to assist in blade design improvement and to users a fast and effective means for evaluating a blade’s condition (both new and in-service), increasing, thus, the overall reliability and cost effectiveness of Wind Turbines.

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