ACOUSTIC EMISSION STUDY OF DAMAGE ACCUMULATION IN CFRP COMPOSITES UNDER BLOCK LOADING

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ABSTRACT

Damage development in carbon fibre reinforced composite laminates has been studied under different two-block fatigue loading regimes using Acoustic Emission (AE). AE results were found to correlate with damage indicated by ultrasonic C-scanning, supporting the use of AE results to represent damage states in composites. AE results also confirmed that an increased mix of loading blocks (with a constant ratio of cycles in each block) can have a significant effect on damage accumulation and ultimately on the lifetime to failure of the specimen. More generally, results showed that AE damage monitoring can be used to determine damage events, types of damage, location of damage, onset of damage and effective life of the specimen before catastrophic failure. Based on this capability a fatigue prediction method is proposed that accounts for the damaging effect of load cycles according to the material's current sensitivity.

1. INTRODUCTION

Composites are low-density materials, which, if used correctly, provide a number of beneficial properties, primarily, high specific stiffness, high specific strength and fatigue resistance. However, design of composite structures over the years has been dominated by impact and static notch performance [1], making fatigue life prediction of composite materials generally a secondary issue in the design process. Typical ultimate design strain levels encountered in airframe design are in the region of 4000 $\mu\varepsilon$ (0.4%) while propeller and helicopter rotor designs typically do not exceed 1500 $\mu\varepsilon$ (0.15%). At these low strain levels composite materials allegedly can withstand large numbers of fatigue cycles while maintaining damage-tolerant design. One of the main reasons that designers do not want to exceed these levels is the absence of an accurate fatigue life prediction method.

Researchers have recognised the existence of a “cycle mix” effect in the fatigue life of composite under random loading but at most only arbitrary account for this in their fatigue damage accumulation models [2-5]. In order to specifically account for “cycle mix” effect it is necessary to define what causes the accumulation in the first place and how it is influenced by load interaction. Filis et al [3] have gone a long way in doing that but the assumption that a cycle mix event causes the same damage throughout life has to be investigated further. So, rather then exhausting the research effort in the manipulation of data to derive a prediction model, the definition of damage events is a necessary stepping-stone to go over.

An initial pilot study using a Vallen AMSY4 AE system has shown to good effect that analysis of the information coming from AE could lead to useful quantitative procedures for fatigue life prediction under variable amplitude of loading. Consequently, a detailed investigation is now underway at the University of Bristol to explore the “cycle mix” and complex loading effect on damage accumulation using AE as the main NDT/NDE method.

2. FATIGUE LIFE PREDICTION METHODOLOGIES

Since composite materials exhibit many mechanisms of damage accumulation and different modes of failure, researchers over the years have considered it difficult to incorporate all of them into the life prediction process.

Much effort in designing a reliable composite fatigue life prediction method has centred on constant amplitude and two-block loading due to the complexity of variable amplitude loading conditions. However, only a few models have addressed the case of variable amplitude loading [5-11].

Over the last three decades, a number of models have been presented but generally representing specific stacking sequences and loading conditions. For a more general review on fatigue life prediction models, the reader is referred to Degrieck and Van Paepegem [12].

2. EXPERIMENT SETUP AND PROCEDURE

Specimens were manufactured using 913C HTA - 5 - 34% pre-impregnated material supplied by Agusta-Westland Helicopters. They were prepared as per CRAG recommendations [13] with a $[-45_2, +45_2, 90_4, 0]_S$ lay-up consisting of 18 plies (ply thickness is 0.125 mm) and 280x30x2.42 mm in geometry with a gauge length of 160 mm. All specimens were end tabbed with 2.3mm thick Scotch-ply glass fibre end-tabs using Redux-810 epoxy adhesive.

Table 1 shows details of the pilot test programme carried out. Static tests were undertaken at a displacement rate of 0.48 mm/min and fatigue tests at a frequency of 4Hz. The fatigue loading ratio (R=Min. Stress/Max. Stress) was 0.1 i.e. tension-tension.

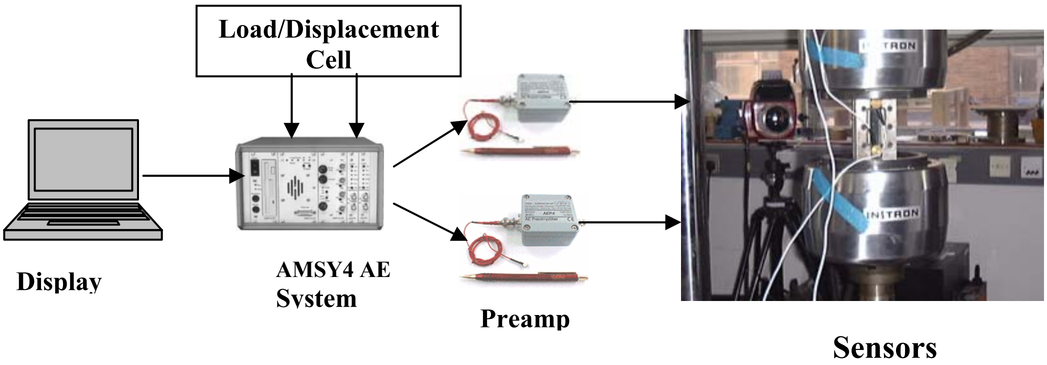
"**Table 1.** Test Programme Details."

Test Type	Specimen Name	Test Details
Static, tensile	AWHLB1, AWHLB5, AWHLC1, AWHLC5	AE data for AWHLB5 & AWHLC5
Fatigue, constant amplitude (Hi block)	AWHLB4, AWHLC8	σ_{max} = 145.5 MN/m^2 - Hi block -
Fatigue, constant amplitude (Lo block)	AWHLB11, AWHLC10	σ_{max} = 72.75 MN/m^2 - Lo block -
Fatigue, 2-block of loading (Low-Mix)	AWHLB7, AWHLB8, AWHLC7	100 Hi block : 500 Lo block
Fatigue, 2-block of loading (Medium-mix)	AWHLB10, AWHLC4, AWHLC6	50 Hi block : 250 Lo block
Fatigue, 2-block of loading (Hi-Mix)	AWHLB6, AWHLB9, AWHLC12	25 Hi block : 125 Lo block

Testing was performed using an Instron 1342 servo-hydraulic machine controlled via a Dartec controller with plate guides (anti-buckling guide) to limit unrepresentative edge peel.

An average of 14.7 psi per 1 kN of load was typically used for grip pressure applied at the specimen ends. Dartec data acquisition software (Data Manager) was used to log displacement and load during static tests. Only specific captures were taken for fatigue tests due to the amount of data available.

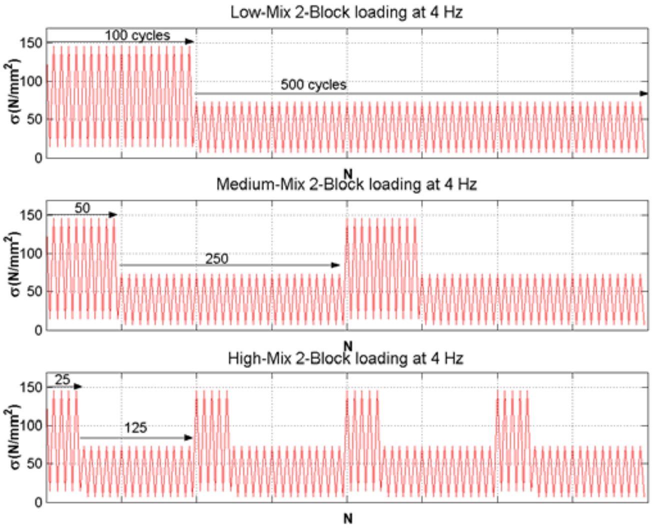
The AE system, as shown in Fig. 1, was used to record damage accumulation events ('hits') during the tests.



"**Fig. 1.** Experimental set-up of fatigue testing with AE as an NDE technique."

The system is made up of two AE channels and four parametric channels (one parametric channel was used to log the load). Two AEP4 preamplifiers with BNC input & output, wideband frequency (5 kHz to 3 MHz) and a gain of 40 dB. The preamplifiers receive AE 'hits' recorded by two Pancom P15 sensors (150 kHz Resonance) to the built in hard-drive. The system also includes location, filtering and pattern recognition software.
The sensors were placed 80 mm apart. The system software was used to locate 'hits' and those that were recorded in between the sensors were of particular interest since this was the location where the specimen is likely to incur most of the damage, although there were 'hits' recorded outside the sensors.

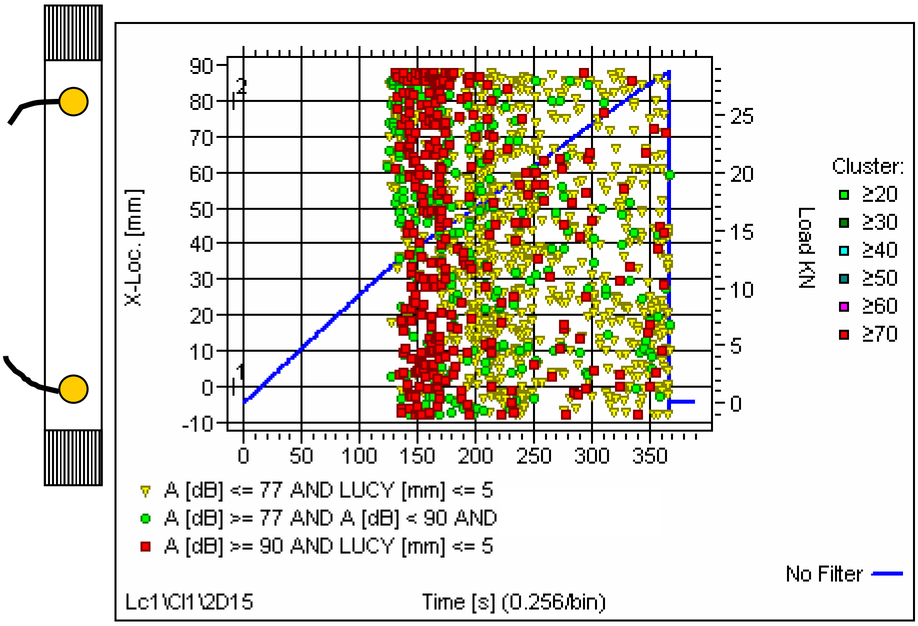
A set of specimens was tested under three loading regimes. The first of which can be described as a Low-Mix 2-Block loading where a high amplitude block of 100 cycles followed by a low amplitude block of 500 cycles is continuously repeated until the end of test. The second load regime (Medium-Mix) is similar to the first but with the number of block cycles halved. The third load regime (High-Mix) has the block cycles number halved further i.e. 25 Hi to 125 Lo. Fig. 2 gives a schematic illustration of these tests.



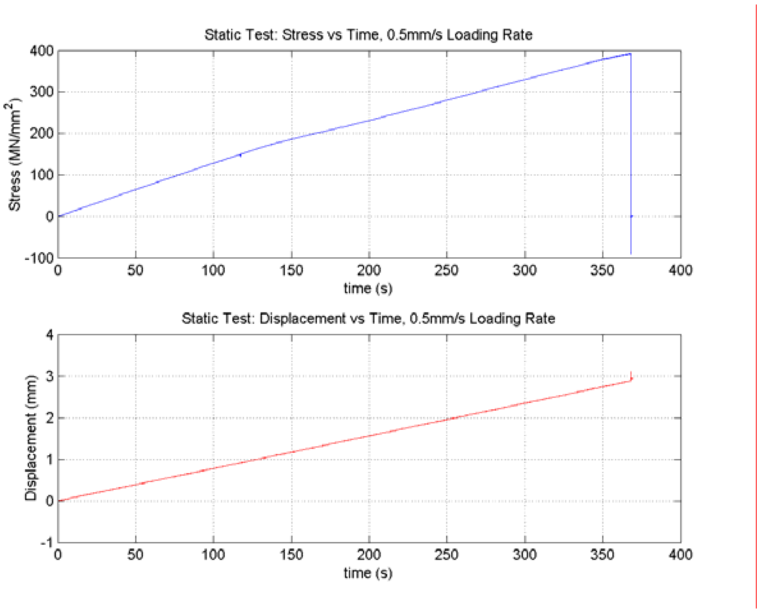
"**Fig. 2.** Illustration of cycle mix phenomenon in a two-block loading spectrum."

2. RESULTS AND DISCUSSIONS

Fig. 3 and Fig. 4 show the static test result on specimen AWHLC5 as recorded by AE and Dartec controller. Recording of AE 'hits' was set at a threshold of 60dB i.e. 'hits' with an amplitude level of 60dB or less were found to include background noise. As can be seen at the bottom of Fig. 3, AE 'hits' are shown in yellow triangles (60<= amplitude (dB) <77), green circles (77<= amplitude (dB) <90) and in red squares (amplitude (dB) >=90). The onset of damage is found to occur at approximately 44% of the ultimate failure stress level (385.4 MN/m^2).

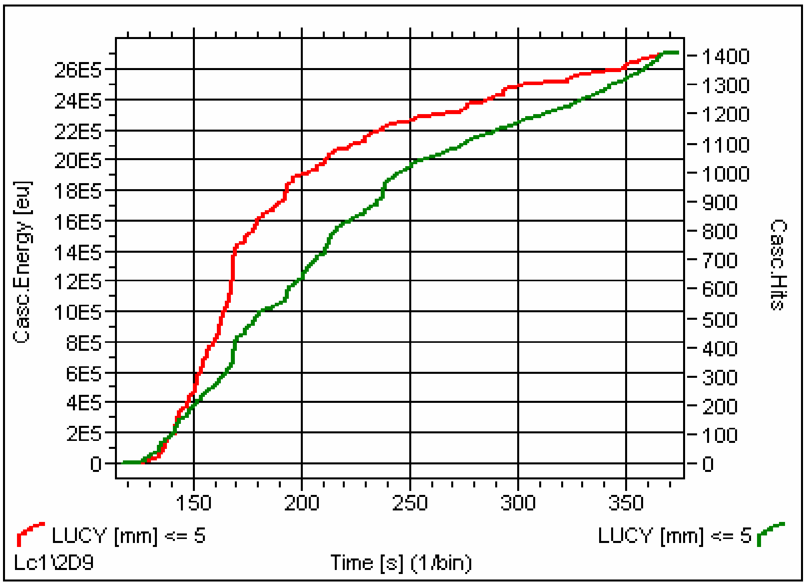


“**Fig. 3.** AWHLC5 static test showing onset of damage at around 44% of UTS.”



“**Fig. 4.** AWHLC5 static test in stress and displacement vs. time.”

The matrix was found to crack initially in the 90^0 layers (as was observed by a microscope) leading to their delamination. Eventually, sudden fibre failure of the 0^0 layers would result in final catastrophic laminate failure. This can be clearly seen in Fig. 3 above and more precisely in Fig. 5 where damage is indicated by the AE cumulative energy resulting from the specimen cracking. A high AE cumulative energy rate was observed early on in the test (caused by matrix damage and delamination) which becomes more moderate towards the end of test where the 0^0 fibres are carrying the majority of load.



"**Fig. 5.** AE cascaded energy (red) and 'hits' (green) growth rate at the static test. "

Fatigue tests results are listed in Table 2 where four stages have been defined during a fatigue test. Wear-in stage, where initial AE 'hits' were recorded from the first cycle for a short period before they dissipated; a slow damage growth rate, stage where there is little AE activity; a high damage growth rate stage, at which there was an onset of damage; and finally, a steady damage growth rate. AE energy after 100,000 cycles is also included in Table 2 to compare the effect of increasing the "cycle mix" ratio.

Tests were stopped when significant AE 'hits' indicated a critical state of damage. This was particularly the case when there was AE activity throughout the gauge length of the laminate. AE energy levels shown in Table 2 are relevant to the 'hits' recorded between the sensors.

"**Table 2.** Test Programme Details."

Test Type	Specimen Name	Wear-in Stage		Slow Damage Growth Rate Stage		High Damage Growth Rate Stage		At 100k Cycles	Number of Cycles at End of Test
		Cycles	AE Energy	Cycles	AE Energy	Cycles	AE Energy	AE Energy	
Constant Amplitude σ_{max} = 145.5 MN/m^2	AWHLB4	4000	20000	15480	55000	20000	10e+6	2.05e+8 *	52864
	AWHLC8	4000	30000	19200	230000	44000	30e+6	9.911+7 **	94556
Constant Amplitude σ_{max} = 72.75 MN/m^2	AWHLB11	N/A	Negligible	N/A	Negligible	N/A	Negligible	Negligible	1249290
	AWHLC10	N/A	Negligible	N/A	Negligible	N/A	Negligible	Negligible	2090006
2-block loading (Low-Mix)	AWHLB7	16000	250000	32400	250000	39200	2e+6	1.458e+7	177001
	AWHLB8	16000	40000	48000	70000	69000	1.5e+6	7127684	150496
	AWHLC7	16000	200000	86400	300000	92000	4e+6	8642721	175003
2-block loading (Medium-mix)	AWHLB10	12000	40000	29600	65000	54000	4.5e+6	5.512e+7	304590
	AWHLC4	12000	150000	70000	700000	80000	3.5e+6	7128149	109999
	AWHLC6	12000	30000	50000	80000	62000	6e+6	3.148e+7	155888
2-block loading (Hi-Mix)	AWHLB6	24000	30000	86000	35000	90000	600000	735447.7	152000
	AWHLB9	10000	40000	36000	800000	55600	15e+6	2.904e+7	144000
	AWHLC12	12000	200000	71000	400000	96000	15e+6	1.82e+7	315030

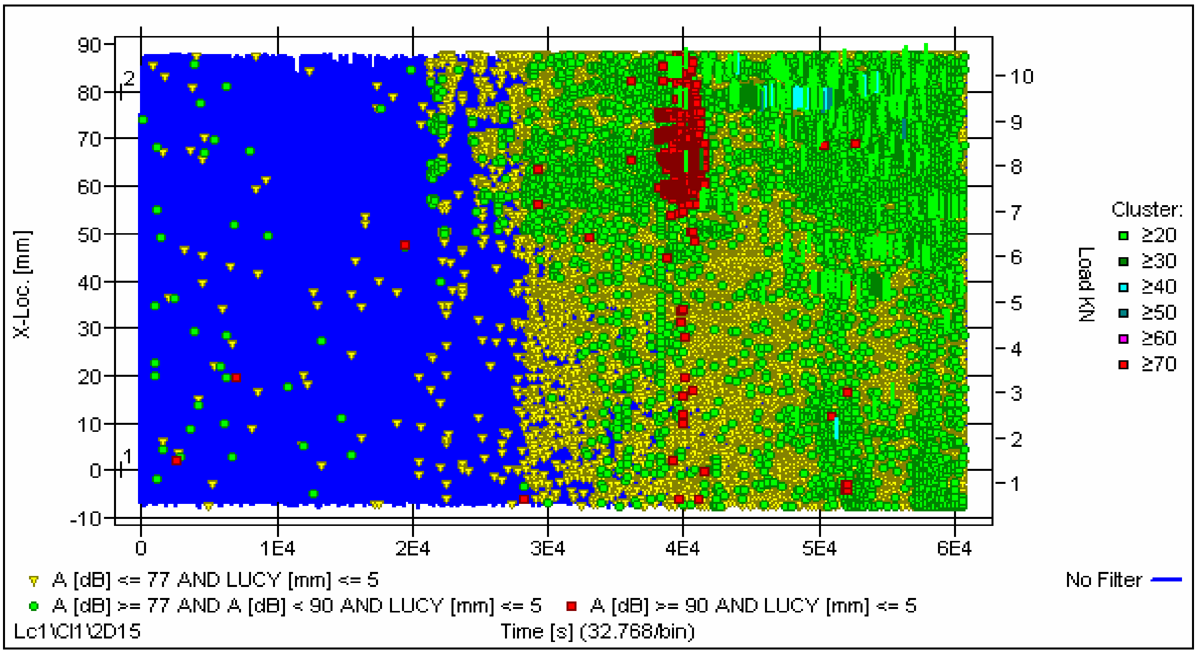
* At 52864 cycles as this is when the test was stopped. ** At 94556 cycles as this is when the test was stopped

Conflicting reports have been observed in the literature with regard to the relationship between the AE ‘hits’ amplitude levels and the mechanisms of damage. Wevers *et al.* [14] concluded that low energy ‘hits’ correspond to matrix cracks, medium energy levels to delamination and high energy levels to fibre breaks while Ono [15] observed that low amplitude ‘hits’ (<50 dB) are caused by fibre fracture and related medium amplitude ‘hits’ (50 ~ 70 dB) to initiation and growth of delamination. He also found that rapid advances in delamination cause high amplitude AE ‘hits’ (>70 dB).

In the case of static tests, it is clearly seen in Fig. 3 that high AE cumulative energy (with ‘hit’ amplitude >90 dB) was caused by initial rapid matrix cracks leading to delamination (medium amplitude ‘hits’, <70 dB). Fibre breaks, which would occur suddenly at the static tests, do not seem to be recorded. However, during fatigue tests, observations of the AE ‘hits’ amplitude gives more support to Wevers *et al.* findings.

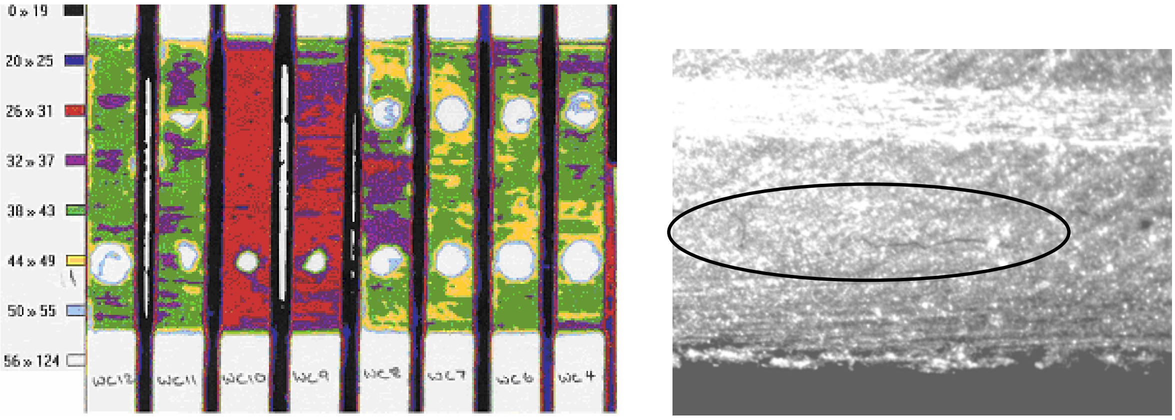
3. DAMAGE ACCUMULATION AND DAMAGE EVENT DEFINTION

It is known that Palmgren-Miner’s rule although simple to use, is generally unconservative and unreliable for composite materials. However, modifications that account for defined damage events can lead to an improved version as already reported by Farrow [2]. Results of this investigation, as seen in Fig. 6, shows that as soon as zones in the laminate reach the material’s elastic limit cracks begin to form releasing elastic energy waves that are recorded as AE ‘hits’. In this way, only damage that is found to be the result of fatigue will then be accounted for in the fatigue prediction process rather than assumed damage, a major failing of Palmgren-Miner’s rule for variable amplitude loading.



“**Fig. 6 -** Damage accumulation in AWHLC12 subjected to hi-mix two block fatigue loading showing location of damage and amplitude level of ‘hits’.”

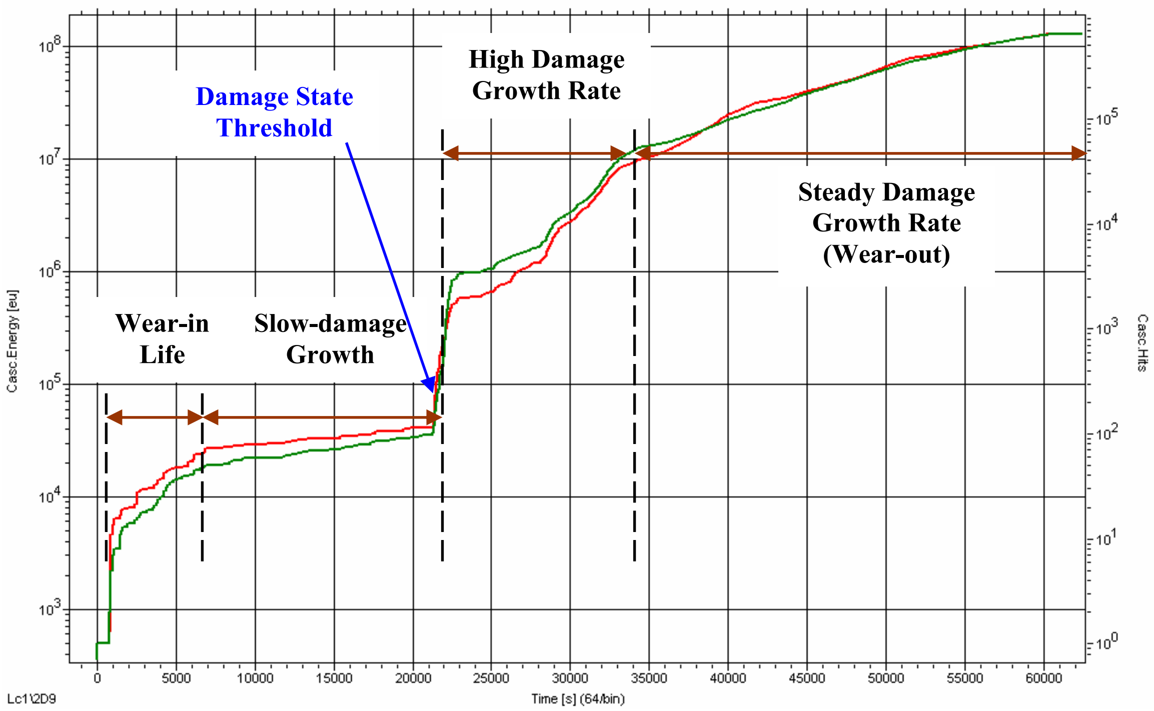
Correlations were achieved with C-scan and microscopic investigation results as shown in Fig. 7 where for example, AWHLC12 is shown to be more damaged than AWHLC10. The latter was found to emit little AE ‘hits’ while subjected to constant amplitude fatigue test for over 2 million cycles.



(a) (b)

“**Fig. 7.** Fatigue damage as revealed by: a) C-scan and b) Microscope (Specimen AWHLC4).”

The way damage accumulates is illustrated in Fig. 8 where thresholds are revealed by the AE energy accumulation. After the first cycle, cracks occur throughout the laminate (wear-in) before settling whereupon damage growth becomes slower. Onset of damage is then noted to occur throughout the laminate with a high growth rate. This is mainly caused by matrix cracking in the 90^0 layers as observed by microscopic investigation seen in Fig. 7(b). Once significant damage is done to the matrix, the 0^0 fibres become the main load carrying element resulting in a steady damage growth rate (wear-out) which lasts longer. While analysing this data, it became evident that it is not necessary to run tests until total specimen failure. AE was able to reveal significant intra-lamina (within a layer) and inter-laminar (in between layers) matrix damage that was subsequently found to lead to delamination.

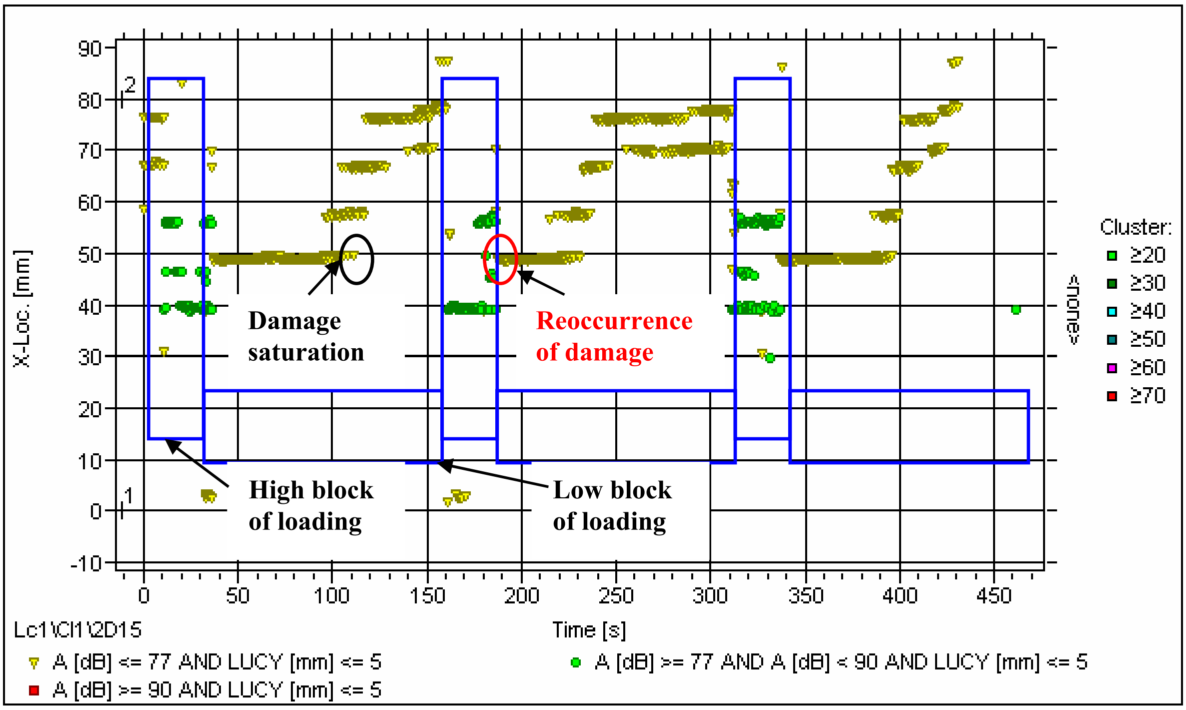


“**Fig. 8.** Damage accumulation in AWHLC12 as revealed by AE energy.”

5. LOAD INTERACTION (CYCLE MIX) EFFECT

It is likely that 'in-service' loading spectra include many interactions between blocks of loading of different cycles. Interaction effects could be significant if the specimen is either sensitive to a loading rate effect or transient rate.

This test was able to reveal that High-Mix 2-block loading tests appear to be more damaging, with the onset of damage occurring earlier than less mixed tests, as can be seen in Table 2. However, a closer investigation of the emitted AE 'hits', Fig. 9, provided evidence for the first time that damage seems to wear-in after a specific numbers of cycles. If changes in loading occur before the damage wear-in then greater damage may be caused as illustrated in Fig 9.

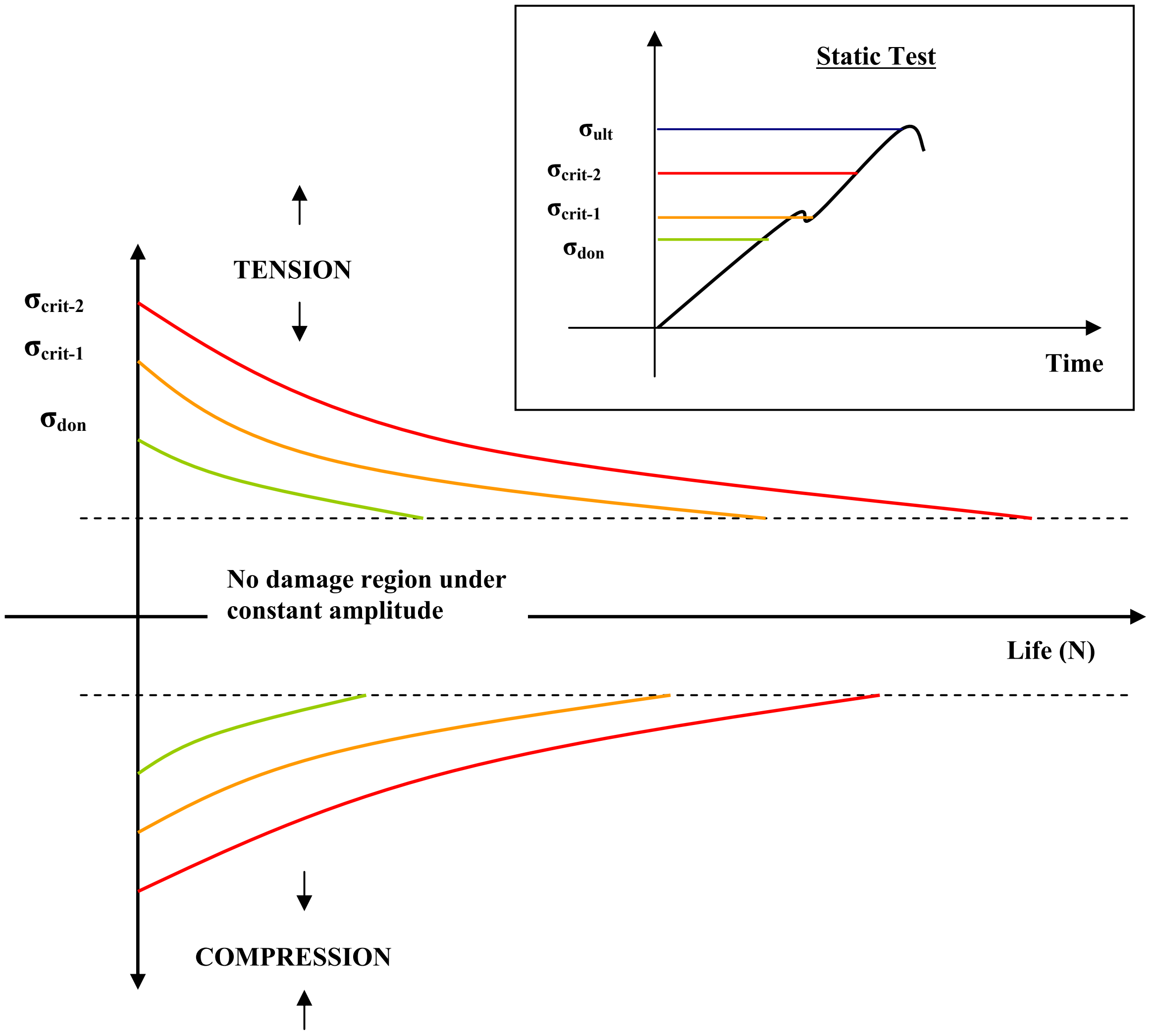


"**Fig. 9.** Load interaction effect as observed by AE technique."

6. A NEW FATIGUE METHODOLOGY

From the investigation carried out thus far, it is feasible to use AE techniques for the construction of a fatigue life prediction procedure that comprises the following:

1. Undertaking static tests in tension and compression to reveal the damage onset σ/ε_{don} levels and any other thresholds before ultimate failure.
2. Analysis of the static test data, to facilitate design for fatigue based on one of the critical thresholds observed during static tests i.e. first or second major failure, $\sigma/\varepsilon_{crit-1}$ or $\sigma/\varepsilon_{crit-2}$.
3. Undertaking a series of constant amplitude tests to establish the most damaging R ratio of the intended application spectrum of loading. These constant amplitude tests will be used to construct an S-N curve, as shown in Fig. 10. It will also reveal the various damage mechanisms that the laminate will endure. Other means of NDT such as C-scan can be used to verify damage mechanisms.



“**Fig. 10.** S/N fatigue curves based on emitted AE data at static tests.”

4. Undertake a series of combined variable amplitude loading tests to reveal whether the laminate is sensitive to loading rate i.e. tests may have to be carried at constant rate so that a different frequency is applied at the event of moving from one loading block to the other. Within these tests, the time taken for a specimen to dissipate damage under certain loading conditions (max $\boldsymbol{\sigma/\varepsilon}$, min $\boldsymbol{\sigma/\varepsilon}$ and loading sense) is then derived resulting in time dependent sensitivity factors for various damage mechanisms before the end of the fatigue life.

7. CONCLUSIONS

The Acoustic Emission damage monitoring technique has been shown to provide valuable information to understand how a composite laminate accumulates damage when subjected to static loading, constant amplitude fatigue loading or variable amplitude fatigue loading.

Using Acoustic Emission as an NDT/NDE method to evaluate fatigue damage is found to have a great potential to understand fatigue accumulation in composites and to assess design strain levels with confidence and presents suitable information for the basis of fatigue life prediction.

AE ‘hits’, energy and their amplitude levels can be used to study damage growth rate at the cycle level, block level and spectrum level since all of the emitted data can be saved and post-processed.

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