FATIGUE DAMAGE ASSESSMENT OF UD CFRP COMPOSITE LAMINATES UNDER SPECTRUM LOADING USING ACOUSTIC EMISSION

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Abstract
Notched UD CFRP composite material laminates were subjected to tensile static loading and tension-tension fatigue loading under variable amplitude loading (VAL). VAL tests were constructed so that the effect of Peak Stress, Trough Stress, Frequency and Cycle-Mix can be investigated. Online fatigue damage recording was carried out using Acoustic Emission (AE). Damaged specimens were also investigated using ultrasonic c-scanning and microscopy to reveal extent of damage and correlate with recorded AE data. AE monitoring revealed significant matrix failure as early as 50% of UTS during static tests. This indication dictated the selection of maximum stress level for fatigue loading which was no more than 75% of matrix failure stress. Results suggest that fatigue baseline data for composite materials should ideally be based on multiple block tests with a wide representation of frequency of occurrence of the main load levels within a load spectrum. Also, AE energy showed that cyclic fatigue damage is reasonably linear at low cyclic stress levels up to the first “effective failure” state. The implication is that the use of representative Cycle-Mix base data and the relatively linear damage accumulation trends up to initial effective failure state suggest that VAL fatigue life to this state could be achieved with a simple damage accumulation rule such as Palmgren-Miner’s rule.

1 Introduction
CFRP composite materials are becoming the number one choice of material for many aerospace designers and manufacturers. However, fatigue damage and life prediction still rely on knowledge based on metal tests analysis which is inconsistent with how composite materials behave under fatigue loading. Matrix damage is known to occur under low cyclic stress/strain levels in composite materials [1] and hence, designers have opted for very low design stress/strain levels to eliminate the catastrophic effect of fatigue [2]. However, increasing these design levels would lead to important structural weight and cost savings but only if damage is understood and can be tolerated. In order to go down this route, composite damage needs to be accurately monitored. Researchers’ easiest damage detection technique under fatigue loading has always been stiffness degradation [3] which fails to pick up subtle matrix damage. On the other hand, AE technique is found to be one of the most sensitive methods that are proven to pick up early matrix damage in composite materials [4]. Most importantly, variable amplitude fatigue loading requires a higher level of damage detection sensitivity which AE is capable of achieving. However, the challenge with using AE remains in the amount of data that can be generated, distinguishing between the various types of AE hits and the possibility of randomness of damage in composite materials [5]. Also, there is the issue of failure criteria which is not as straight forward as in metals. One method of overcoming the failure criteria issue is to consider the specimen to have failed if AE signal energy reaches a user defined level which can then be confirmed by further NDT methods such ultrasonic c-scan [5]. While in service, components usually operate under a spectrum of loading hence, fatigue life prediction methods and models which rely on constant amplitude data that excludes any possible block effect may not be

applicable [6]. Therefore, there exists a need to investigate how the various components in a spectrum of loading may influence damage initiation and propagation.

2 Tests Specimens and Experimental Setup

2.1 Tests Specimens

913 CHTA-5-34 Unidirectional pre-impregnated CFRP used by Agusta-Westland Helicopters (UK) for helicopter blade manufacturing was used to prepare notched (***6 mm*** diameter holes) specimens (***270x30x2.42 mm***) with ***160 mm*** gauge length as per CRAG recommendation [7]. Vacuum bagging and autoclave processing were used to manufacture the material used to make the specimens. The latter's layup was $\boldsymbol{(+45_2, -45_2, 0_4, 90)_s}$ as used in helicopter rotor blades. To avoid grip wedges slippage and crushing of specimens, 2mm GRP end tabs were bonded to the specimens using Redux 810 epoxy adhesive. An illustration of the specimens is shown in figure 1.

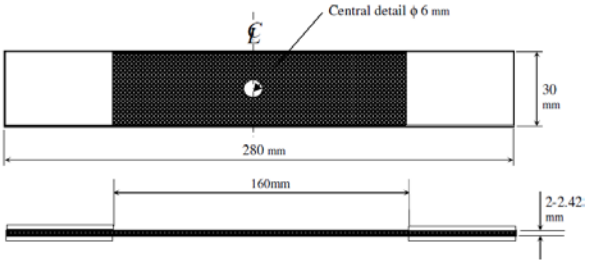

Fig.1. Schematic of test specimens.

2.2 Experimental Setup

Tests were carried out using Instron 1432 universal test machine fitted with Instron 8800 controller. Vallen AMSY5 two channels acoustic emission system was used for online damage monitoring. The AE system included two AEP4 preamplifiers with BNC input/output, wideband frequency (5 kHz to 3 MHz) and a gain of 40 dB. The preamplifiers were connected to two Pancom P15 sensors of 150 kHz Resonance.

Using Vallen VisualAE™ program, total AE signal energy per block is extracted for the various loading blocks within one specific test. Then, by using MATLAB®, accumulated block energies are illustrated over the test duration in cycles. The AE sensors (Transducers) were attached to the specimens gauge length 80 mm apart using TEC-Bond glue. Only AE hits that were located between the sensors were accounted for. Pencil-lead break tests were carried out as recommended by Hsu-Nielsen ASTM Standard E976-94 to calibrate the location capability of the AE system. All fatigue tests were carried out in load control mode.

2.3 VAL Fatigue Tests

The variables identified for spectrum loading investigation were: maximum (peak) stress effect (MxSE), minimum (trough) stress effect (MnSE), frequency effect (FrqE) and "cycle-mix" effect (CMxE). As observed by the author previously [4], investigation of static test damage with the use of AE monitoring revealed that significant damage can occur prior to total failure as shown in figure 2. The latter shows that as the applied load increases, AE hits start occurring along the gauge length at a stress level named here "crack initiation stress" then, AE activity intensifies with the severity of damage at a stress named "onset of damage stress" or "1st effective failure stress". Finally, the specimen fails at ultimate tensile stress (UTS) with possibly other "effective failure" states prior to UTS.

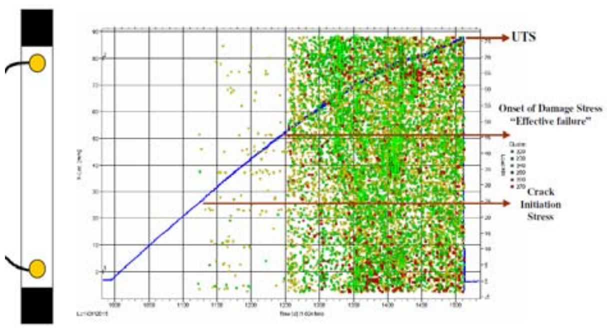

Fig.2. stress-strain curve overlaid with AE hits.

Consequently, an ideal fatigue test would have a maximum stress less than the first "effective" static failure or possibly even less than the crack initiation stress level. In this work, to avoid the destruction of damage accumulation relevant to service stress levels, the maximum stress used in all fatigue experiments was chosen to be at 75% of the first "effective" static failure stress level. Table 1 shows the properties of the various blocks of loading constructed for this investigation.

Loading Variable	Frequency Effect	Min Stress	Max Stress	Cycle Mix Effect
f_h, f_l	-	-	-	4,9
f_1, f_2, f_3	2,5,8	4,6,9	4,6,9	-
σ_{max1}, σ_{min1}(%)	75, 7.5	75, 7.5	75, 7.5	-
σ_{max2}, σ_{min2}(%)	75, 7.5	75, 30	52.5, 7.5	-
σ_{max3}, σ_{min3}(%)	75, 7.5	75, 45	37.5, 7.5	-
$H\sigma_{max}$, $H\sigma_{min}$(%)	-	-	-	75, 7.5
$L\sigma_{max}$, $L\sigma_{min}$(%)	-	-	-	37.5, 7.5
N_1	1000	1000	1000	-
N_2	1000	1000	1000	-
N_3	1000	1000	1000	-
N_{H1} , N_{L1}	-	-	-	1k, 1k
N_{H2} , N_{L2}	-	-	-	500, 500
N_{H3} , N_{L3}	-	-	-	250, 250

f: loading frequency (Hz). **σ**: loading stress (% of 1st effective failure stress, MPa). **N**: number of cycles. **H**: high range block. **L**: low range block

Table.1. Details of the four test types.

All possible combinations of the blocks were used (i.e. Hi-Med-Lo, Hi-Lo-Med, Med-Hi-Lo, Med-Lo-Hi, Lo-Hi-Med, Lo-Med-Hi). Sequences were repeated for 216,000 cycles after which AE activity usually indicated significant damage throughout the specimen gauge length. At this stage, edge delamination was also visually observable on the specimens. The aim of these tests was to extract AE energy emitted during each loading block and to determine how changes in loading affect the damage accumulation. This information can then be used to understand damage accumulation at more representative load levels. An initial ramp is included to start the sequence either at the minimum or the maximum stress level in all cyclic tests, depending on the type of test carried out. Four AE variables were identified for data analysis in this work which are:

- Number of AE hits (a hit being one single AE wave arriving at the sensors)
- Number of AE events (an event being a number of hits arriving at the sensor at the same time with a user specified time period)
- AE energy
- Amplitude of AE hits

Each multi-block test is allowed to run for a specific number of cycles (between 54,000 and 300,000 cycles and 3 to 9 18-block sequences, depending on the type of test). These tests durations were chosen as a result of initial trials that showed damage to continuously grow under the quoted stress levels in table 1. AE hits and their signature types are then collected at intervals.

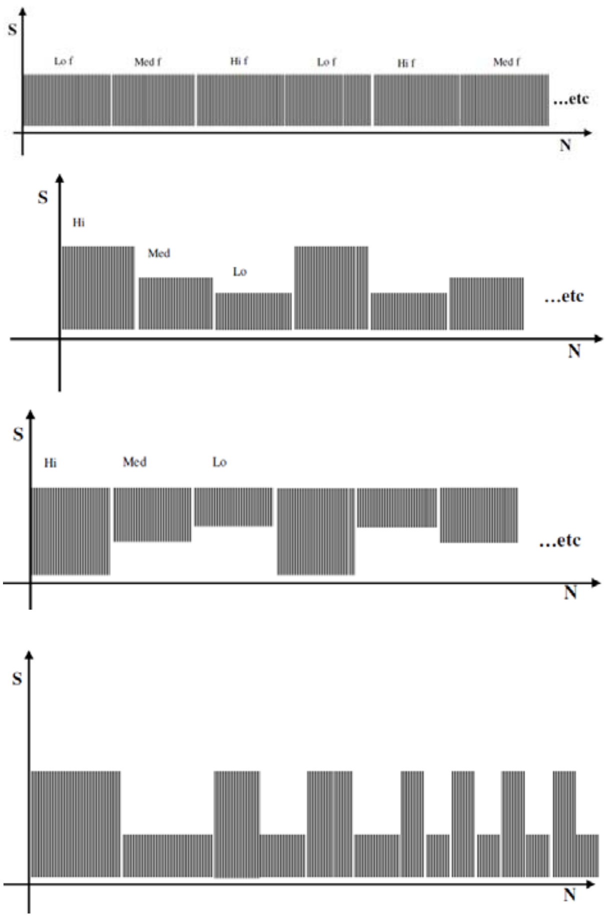

Fig.3. Illustrations of the four fatigue tests. From top to bottom: FrqE, MxSE, MnSE and CMxE.

The actual stress values applied in these fatigue tests are shown in table 2. MxSE, MnSE and CMxE tests were carried out at a loading rate of ***129.6 kN/s*** in order to maintain the same frequency.

Test Type	Block 1 σ_{max1},σ_{min1}	Block 2 σ_{max2},σ_{min2}	Block3 σ_{max3},σ_{min3}
FrqE	249, 24.9	249, 24.9	249, 24.9
MxSE	249, 24.9	174, 24.9	123, 24.9
MnSE	249, 24.9	249, 100	249, 152
CMxE	249, 24.9	123, 24.9	-

Stresses in MPa

Table.2. Applied stress levels for each test.

3 Results and Discussions

3.1 Tensile Static Tests

As reported by the author previously [8], the monitoring of damage using AE allowed us to define specific intermediate damage thresholds during static tests such as initiation of cracks and first “effective failure” state e.g. onset of delamiantion, second “effective failure” state e.g. interaction of notch-edge damage and finally “catastrophic failure” i.e. specimen separation. These patterns have been observed in all static tests in this work.

The number of located events (an event being a number of hits simultaneously occurring in a period of 0.1 ms in these tests) varies depending on the material and lay-up type [5]. In particular, as might be expected, high numbers of AE hits and events are noticed for delamination as indicated in figure 4.

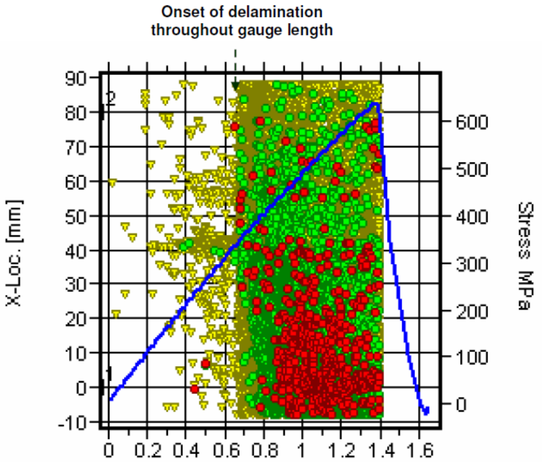

Fig.4. sensors 1 & 2 location vs strain (%, horizontal axis) vs stress.

The sharp increase in AE activity is also confirmed by the visible change in slope of the stress/strain curve shown in figure 4 where the slope can be seen dropping slightly after the increased AE activity along the gauge length. Correlations of AE hits with damage indicated that fiber breaks are found to generate AE hits with amplitude equal or greater than 90 dB (shown as circles in figure 4) while delamination generates hits with amplitude between 77 and 90 dB (shown as squares in figure 4). Whereas AE hits with amplitude below 77 dB are generally caused by matrix and fiber disbond cracks (shown as triangles in figure 4). These ranges are characteristic for the materials used for this work but may also be applicable to other materials. It is also possible to plot these graphs using the number of hits or their energy levels located within the sensors. Note, as expected figure 4 indicates that specimens initially show more AE activity at the notch zone than throughout the remainder of the gauge length before major damage occurs. In summary, the static test determined three important stress levels, crack initiation stress, 1st effective failure stress and 2nd effective failure stress.

3.2 FrqE Fatigue Tests

AE data generated from the fatigue tests was extracted block by block in terms of AE energy. Vallen “VisualAE^{TM}” software was configured to produce an average AE energy value for each block. The resulting AE energy history representing damage accumulation for each block was then plotted as cumulative AE signal energy versus the number of cycles. In the frequency effect tests, it was apparent that AE signal energy decreased with an increase in frequency as shown in figure 5. These findings meant that - as done in this work - the loading rate should be constant when studying the effect of peak or trough stress on fatigue damage.

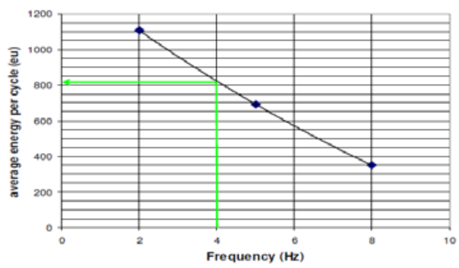

Fig.5. Effect of frequency on AE energy.

3.3 MxSE Fatigue Tests

Figures 6 to 8 show the results of MxSE tests for high, medium and low loading block respectively over 216,000 cycles (i.e. 72,000 per block type) while a summary of results is presented in figure 9. The figures show the cumulative AE signal energy (vertical axis, $\mathbf{x10^7}$) vs. number of cycles (horizontal axis, $\mathbf{x10^4}$) plotted as dots overlaid with a linear polynomial curve fit using the MATLAB® curve fitting tool (cftool). As seen in the figures, damage in the form of AE signal energy seems to be linear with only slight variation in slope throughout the fatigue life. As expected, the higher the peak stress the higher the AE signal energy. One interesting observation is the fact that the low block (123 MPa) generates little AE activity for the first 15,000 cycles. This observation is consistent with the static test results where matrix cracking started to occur at a stress level of around 135 MPa.

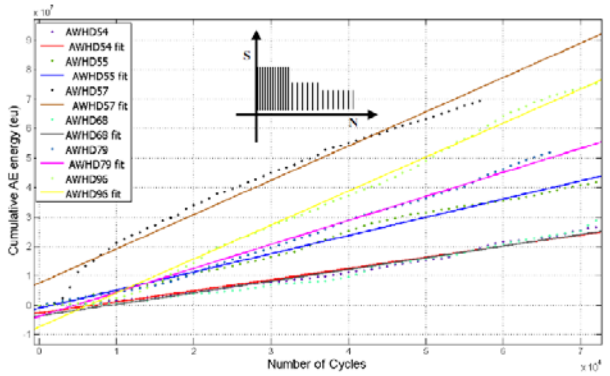

Fig.6. High loading range effect.

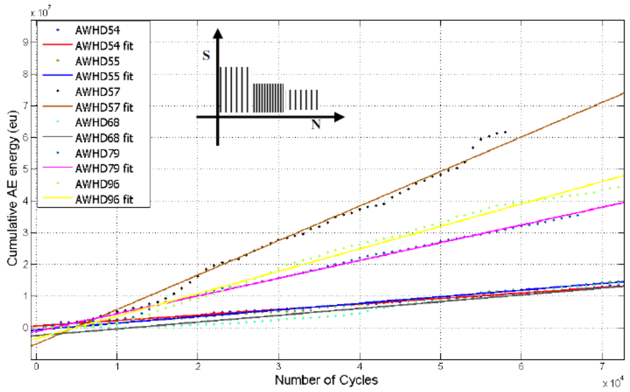

Fig.7. Medium loading range effect.

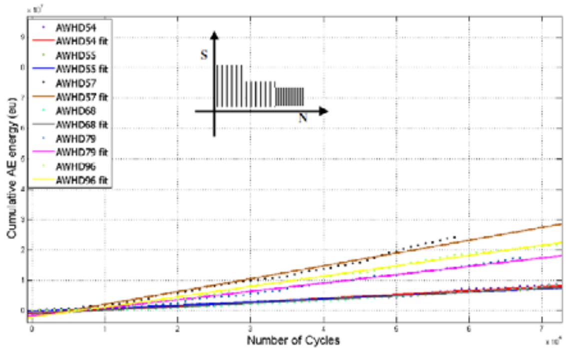

Fig.8. Low loading range effect.

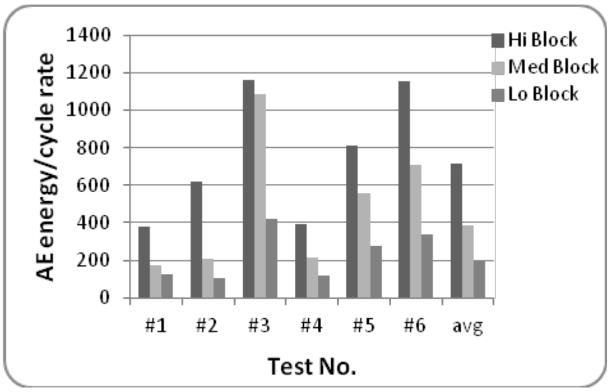

Fig.9. MxSE Extracted AE energy/cycle.

C-scan investigation showed that not only does damage grow at the notch but also at the edge as shown in figure 10. This observation highlights the difficulty in determining a failure criterion as damage keeps growing without total specimen failure.

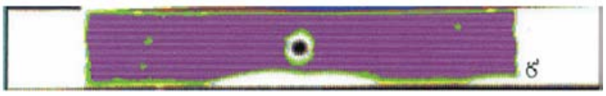

Fig.10. Fatigue damage as revealed by C-scan.

3.4 MnSE Fatigue Tests

AE energies for each of the three blocks that make up the results for this test are similar to those observed during the MxSE test where each block of loading had a different average AE energy/cycle rate as shown in figure 11. As in MxSE tests, the damage rate is almost linear and it increases with the increase in loading range but with less scatter than the MxSE tests, especially for the medium and low loading range blocks.

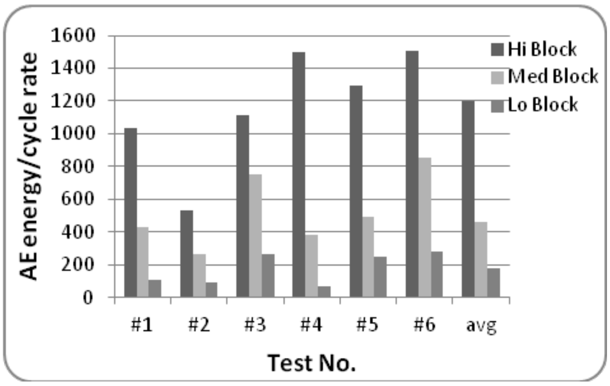

Fig.11. MnSE Extracted AE energy/cycle.

3.5 CMxE Fatigue Tests

The effect of cycle mix, as reported by the author earlier [4], where damage caused by a high loading block was found to continue accumulating under a lower peak stress block, indicates that a summation rule such as Palmgren-Miner's need to be used with care in variable amplitude loading spectrums. From results of this work we would advise a separate linear summation rule for each effective failure phase accounting for the damage accumulation rate in easch particular phase. It should be noted that the MxSE and MnSE tests already include some sort of cycle mix effect since all the possible block combinations were used in the test.

4 Conclusions

The main observation of the results presented in this work is that for cyclic loading less than the first "effective failure" static load level the damage accumulation under different load levels and ranges is generally linear. This is probably due to the singularity of the mode of damage e.g. matrix damage within the limited phase of damage accumulation studied. The damage in this phase accumulates and eventually leads to delamination which is regarded as a new phase of damage accumulation with a new damage accumulation characteristic. It is also noted that specimens show some scatter in the data due to the variation in locations of damage e.g. at the notch or the specimen edges. It has been shown in this investigation that the damage rate for a given block of loading is constant when repeated in the early stage of fatigue life. However, using the same block in a different combination i.e. within a group of blocks or spectrum may generate different damage rates depending on the amount of "cycle mixing" and the relative occurrence of high cycle ranges and peak stresses. It should be noted here that the maximum peak stress used for this investigation (32% UTS) although lower than conventional test levels is still close to the stress level at first "effective failure" (43% UTS) in static tests and is much higher than the stress level at which matrix cracks start to occur (18% UTS). To provide useful data to relate to service stress levels fatigue tests should ideally be carried out with a peak stress less than the static initiation level (e.g. < 18% UTS). This suggests longer test times but if the objective is to only run the tests to the first or second effective failure states then the test time should become acceptable.

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