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Characterization of Fiber Failure Mechanism in T-700 Carbon Fiber Reinforced Epoxy Composites by Acoustic Emission Testing

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ABSTRACT: Acoustic emissions generated by a structure under stressed condition provide an insight in to the dynamic behaviour of flaws in the structure for characterization of failure modes. Fiber failure mechanism in T-700 carbon epoxy composites is characterized by testing unidirectional specimens in longitudinal mode. Acoustic emission parameters like amplitude, energy, duration, and signal strength have been recorded and studied with respect to the applied load to assess the fiber failure characteristics. The AE data is analyzed with different correlation plots for visual pattern recognition.Significant fiber breakage is observed at above 70% of the load. Bi-linear trend of the cumulative amplitude distribution curve indicates distinctively matrix and fiber failures.Matrix cracking failure mechanism dominated the entire loading cycle and is represented by AE hits of up to 85dB/90dB amplitude and the peak amplitude distribution is 58dB to 75dB. The wave forms of matrix cracking hits with less than 90dB and 100 units of energy are having up to 273 kHz frequency contents with a peak around 100 kHz. The wave forms of fiber breakage hits with more than 90dB and 100 units of energy have up to 448 kHz frequency contents and with a peak from 168 to 437 kHz.From the low amplitude filtering technique the border line for fiber breakage is observed from 89 to 92dB.

Keywords: Polymer Matrix Composites, Failure modes, Acoustic emission technique, Waveforms.

I. INTRODUCTION

The carbon epoxy composite materials are being widely used in aerospace industry as structural materials due to their high strength-to-weight ratio and corrosion resistance characteristics. One such application is carbon epoxy filament wound rocket motor casings of solid propulsion systems for aerospace and missile structures where the weight saving contributes to greater payload and range capabilities. Quality control of composites must be an on-going process and it needs continuing research in structural integrity assessment.Non-destructive testing has helped to improve the quality thereby structural integrity and the performance of composite structures.However non destruction evaluation (NDE) of composite structures is complex in terms of testing and interpretation of the data due to anisotropy and non-homogeneity of the material. Acoustic emission testing is a rapidly developing nondestructive tool which can effectively be used for real time structural health monitoring of complex composite structures under stress**[1-2].**The defects/ discontinuities in the structure would grow under stressed condition which can be evaluated by acoustic emission testing (AET). This technique has on line structural integrity assessment feature compare with conventional NDT techniques. It enables to evaluate the flaw type, location and damage severity in the structure under the applied stress.AE is defined as the class of phenomena where by transient elastic waves are generated by the rapid release of energy from localized sources within a material under stress [**1**]. AE signals, once generated, will be detected by the AE sensors, which are attached to the material, and sent to the AE data acquisition system for recording and processing.

The major failure modes in composites are observed in terms of matrix cracking, fiber breakage and de-laminations **[3-4]**. Therefore AE test data interpretation for composite systems is relatively complex due to different failure modes occurring simultaneously. Generation of extensive AE database on test coupon level and identifying AE signature of different failure mechanisms is essential for taking up AE testing of large composite structures like composite rocket motor casing. An attempt has been made in this study to characterize the fiber failure mechanism in T700 carbon epoxy composite material by generating AE data by tensile testing specimens from unidirectional laminate in along the fiber. The study has been done by employing (a) visual pattern recognition technique with the help of correlation plots of various AE parameters, (b) study of AE waveforms with FFT for frequency patterns and (c) low amplitude filtering technique.

I. Experimental Part

1.1 Sample preparation

T-700 carbon fiber impregnated with high temperature curing epoxy resin is used to prepare unidirectional composite laminate by filament winding process on a diamond shaped mandrel. The tensile specimens of 250 X 15 X 2 mm sizes cut from the laminate in the longitudinal direction to the fiber as per the ASTM standard **[5]** as shown in **Fig.1.**The aluminium tabs are bonded at both the ends for the tensile test specimens to ensure better gripping in the grips of universal testing machine (UTM).

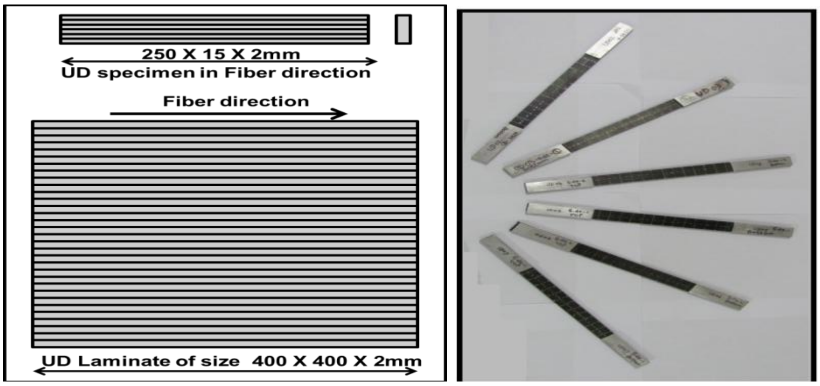

Fig.1.Unidirectional longitudinal tensile test specimens

1.2 Testing Procedure

M/s. Instron make, 100 kN universal testing machine with closed loop screw driven system is used for carrying out tensile testing and load versus displacement or strain curves are obtained independently. M/s. PAC, U.S.A, make acoustic emission system is used for on-line monitoring with suitable software and multichannel computerized AE system that performs AE waveform and signal measurement. M/s PAC make, R15D model resonant piezoelectric transducers and W15D model piezoelectric wide band sensors are used with external preamplifier to pick up the acoustic emissions and wave forms respectively from the specimens. R15D sensor has an operating bandwidth between 100 kHz and 500 kHz with resonant frequency of 150 kHz and W15D sensor has an operating band width of 10 kHz to 1 MHz.The following AE testing parameters are used during testing of samples.

i).Threshold: 40dB
ii). Peak definition time [PDT]: 20 µs
iii). Hit definition time [HDT]: 50 µs
iv). Hit lock time [HLT]: 300 µs

The AE test up is shown in **Fig.2**. The specimens are subjected to tensile loading gradually up to failure.The load versus strain and load versus acoustic emissions were measured simultaneously.

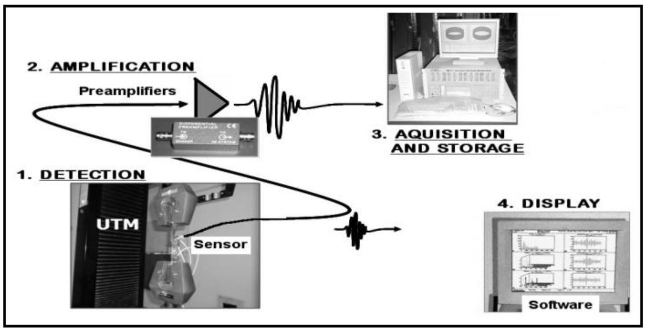

Fig.2 Acoustic emission test setup in UTM

II. RESULTS AND DISCUSSION

1.3 Mechanical testing results

Six numbers of specimens were tested and the data has been summarized in **Table.1**. The failure modes in the select specimens are shown in **Fig.3**. Load versus strain curves for two specimens are shown in **Fig.4**. The strain curves are found in linear trend with respect to load. In these specimens the principal failure mode is by fiber breakage and this happens towards the end of the test. However weak fiber failure is observed at the early stage of loading. As stated earlier the sample under mechanical load may exhibit three types of failure mechanisms **[6, 7]**occur in sequence as i) Matrix micro cracking is excessive during the initial phase of loading and is present during the entire loading phase.ii) Excessive matrix cracking leads to separation of bunch of fibres called delamination and iii) the fiber breakages cause ultimate failure of the specimen**[11**]. The ultimate failure load depends on the percentage dominance of de-lamination and fiber breakage.

Table.1 AE Test data for 6 specimens

S. No	Parameter	Range of values for 6 specimens
1	Failure load (kN0	42 – 69.5
2	No. of hits	1207 – 8922
3	Total energy	26340 – 430650
4	Energy range	2 - 43565
5	Total signal strength	1.15 E+09 – 3.24 E+09
6	Amplitude range (dB)	47 - 100
7	Duration range µs	28 – 292590
8	Rise time range µs	1 – 243

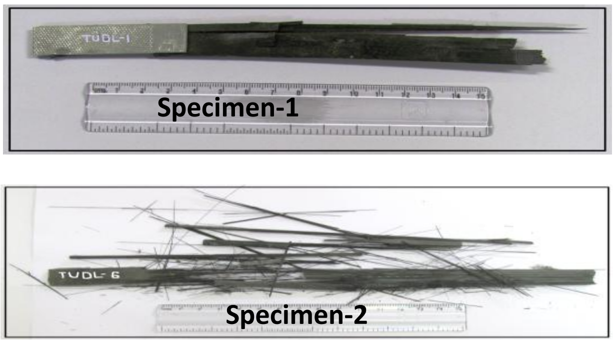

Fig.3 Failure modes in tested specimens

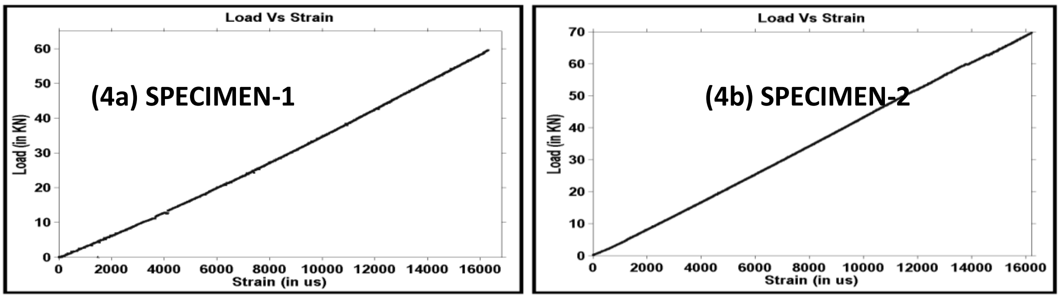

Fig.4. Load versus strain curves

1.4 visual pattern recognition with AE correlation plots

The AE data has been analysed by using various correlation plots. The raw acoustic emission signals obtained from six specimens during tensile test have been processed with Matlab program and various acoustic emission parameters are studied for fiber failure. Error in measurements has been minimized by normalization among the acoustic emission parameters like load, energy and signal strength.

1.4.1 Amplitude versus normalized load plots

These are the preliminary plots of AE testing which depicts the amplitude of acoustic emissions with respect to load and Fig.5 shows these plots for two select specimens. In general the emissions started at around 5% to 10% of the breaking load with marginal intensity. At above 60% of the load the emissions steeply increased with higher amplitudes and the same indicates initiation of failure of the samples.

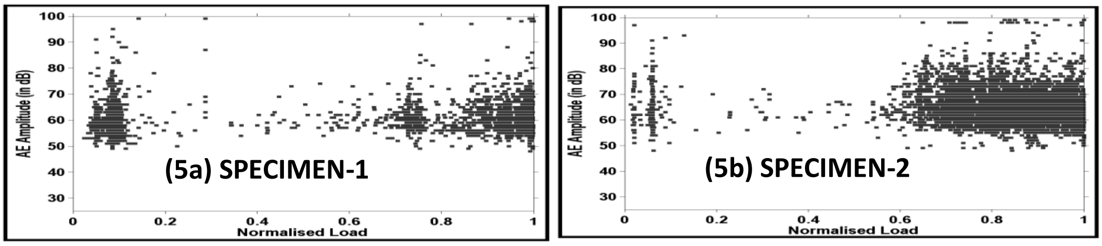

Fig.5. AE amplitude versus normalized load plots

1.4.2 Progressive amplitude distribution plots

Progressive amplitude distribution plots depict the number of AE hits with respect to amplitude at various load levels. These plots have been made at 20%, 40%, 60%, 80%, 90% and 100% of the failure load and the same are shown for two select specimens in **Fig.6**. The distribution is dominant between 55dB to 75dB which indicates that majority of the AE hits are attributed by such amplitude ranges. At above 80% of the failure load there is a steep increase in the amount of acoustic emissions which indicates the maximum safe limit of the load of the samples. There is an increase in the peak value of the normalized number of hits with increase in percentage of loading. But the amplitude at which the peak occurs is almost consistent for all percentage of loads for a given specimen. This trend is visible right from early stage of loading. The peak of the distribution lies between 58dB to 63dB. This indicates that the matrix cracking is more dominant in the entire loading cycle. The amplitude distribution plot for both the specimens is skewed towards lower amplitude side. The skewing of the amplitude distribution plot is a relative indication of the strength of specimen **[6]**. It can be seen that for specimen 1, the peak occurred at 58dB and for Specimen 2, the peak has occurred at 63dB. Hence the higher breaking load of Specimen 2 is substantiated.

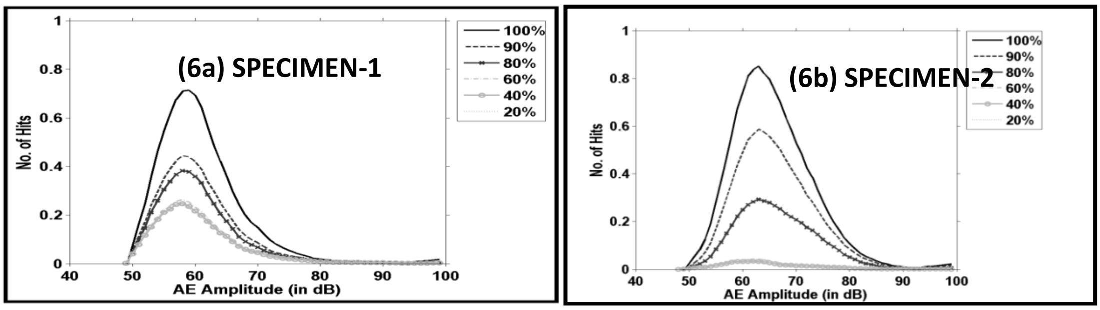

Fig.6. Progressive amplitude distribution curve

1.4.3 Progressive Cumulative amplitude distribution curves

The Progressive cumulative amplitude distribution curves depict the cumulative number of hits for the amplitudes at various percentage load levels and the plots for the select two specimens are shown in **Fig.7**. The cumulative amplitude distribution curves show bilinear nature at above 80% of failure load. It indicates that at lower loads the matrix cracking is dominant and above 80% of failure load both matrix cracking and fiber failure are dominant**[9]**. The transition load from single failure mechanism of matrix cracking to two failure mechanisms indicates safe loading limit of the specimens. The slope change at higher loads indicates transition of one mode of failure into another. The border line dB between matrix cracking and fiber failure is ranging from 85dB to 90dB.

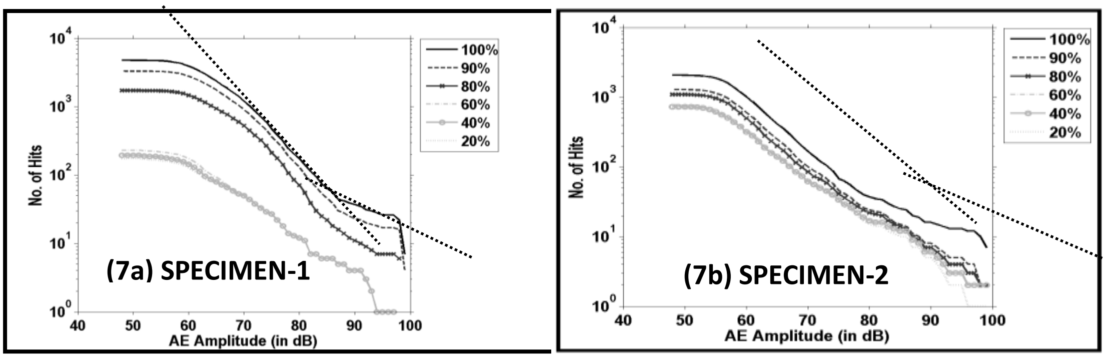

Fig.7. Progressive cumulative amplitude distribution curves

1.4.4 Acoustic Energy versus normalized load plots

The energy is the area represented by the rectified AE signal waveform and its magnitude indicates the damage potential of the AE event. The energy of the acoustic emissions with respect to load plots for the select two specimens are shown in**Fig. 8**.The energy of the AE hits is within 1000 units at the initial stage up to 70 to 80% of the failure load of the samples wherethe matrix cracking is dominant.Above this load the energy of the emissions are increasing up to 50000 units where the fibre failure is dominant and contributes the maximum amount of energy.

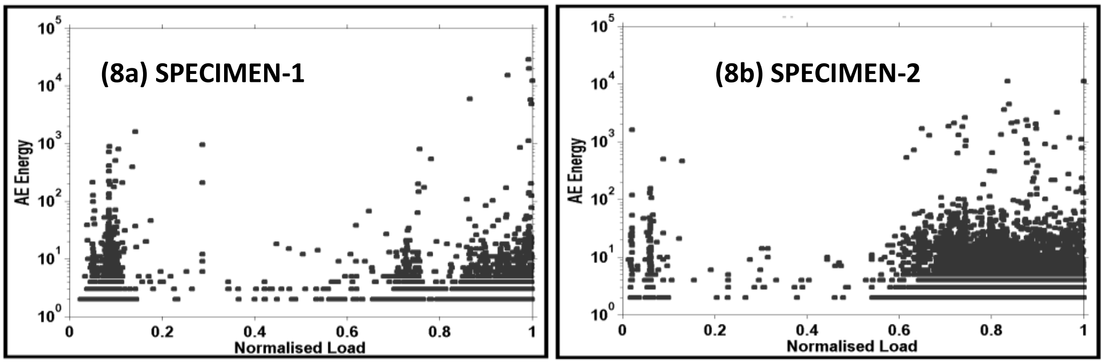

Fig. 8Energy versus normalised load plot

1.4.5 Amplitudes different energy groups versus Normalized load plots

These plots depict amplitudes of different energy groups with respect to load and the plots for the select two specimens are shown in **Fig.9**. The AE hits are divided in to 2 groups based on their energy content. First group contains AE hits up to 100 units of energy and second group contains with energies above 100 units. The plots indicate that the AE hits with less than 100 units of energy are more dominant in number and they are within 85 to 90dB amplitude across the various specimens and they represent micro matrix cracking. Hits with higher energy (energy >100) are spreading from 65dB and above. The high energy hits above 85 to 90dB is dominated by fibre breakage mechanism. Moderate energy hits from 65dB and above may represent matrix cracking at macro level and de-lamination.

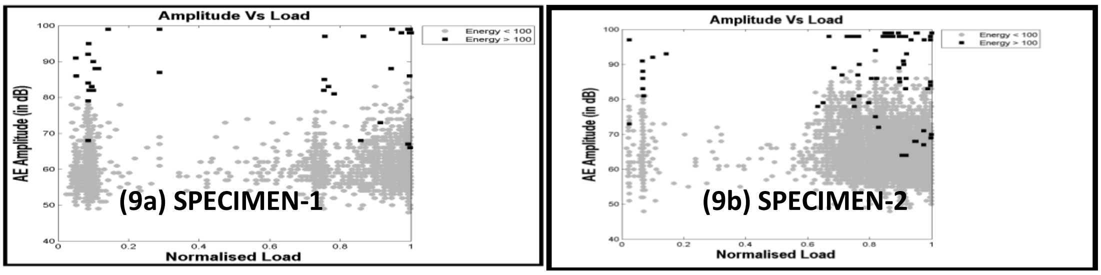

Fig.9 Amplitude versus normalized load curve

1.4.6 Cumulative signal strength and historic index versus normalized load plots

The cumulative signal strength and historic index as a function of normalized load for the select specimens is shown in **Fig.10**. The cumulative signal strength curve shows the total signal strength of all the AE hits at various percentages of failure loads.It is evident from the plots that up to 70% to 80% of the failure load where matrix cracking is dominant, the total signal strength is very low after which the curve is steeply increasing giving rise to a knee in the curves which is an indicator of initiation of fiber failure mechanism. The historic index plots indicate the change of signal strength per unit load at every interval of 0.5% of failure load. By studying these plots for all the specimens it is observed that when the historic index crosses 6 the onset of damage (fiber failure mechanism) initiates. The historic index is crossing 6 at about 70% to 90% of the failure load across the various specimens.

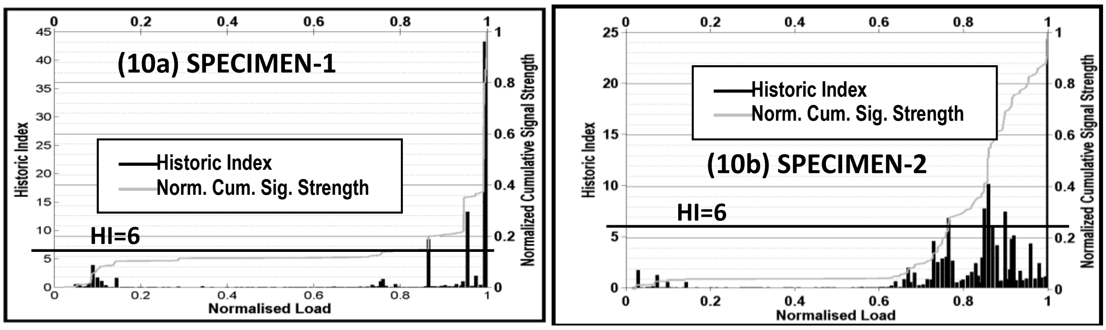

Fig.10 Cumulative signal strength and historic index as a function of normalized load

1.4.7 Acoustic signal duration plots

The duration of acoustic signal is the time from the first to the last threshold crossing in microseconds. The duration is acoustic characteristic feature for a given failure mechanism and is proportional to energy.The duration versus load plots for the select two specimens are shown in **Fig. 11**. These plots indicate that long duration hits with high energy content occur in the higher phase of loading which are contributed by fiber failure mechanism. The AE hits contributed by matrix cracking are within 10^4μs.

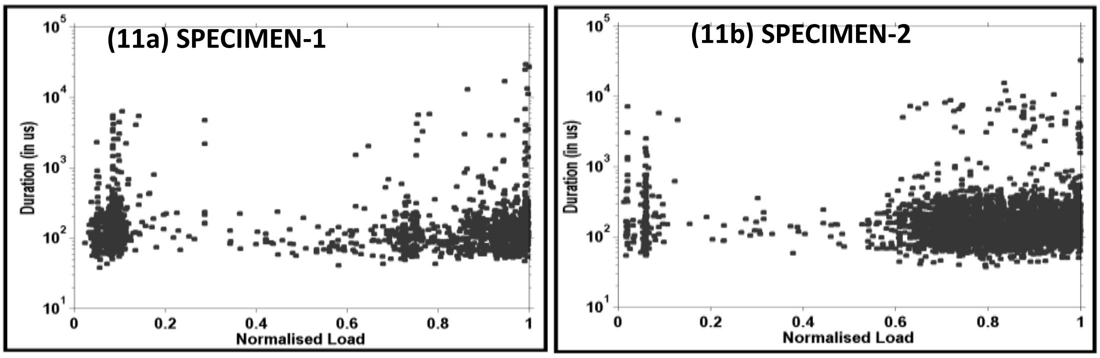

Fig.11. AE duration versus normalized load plots

1.5 Acoustic emission waveforms – FFT analysis

The time domain transient acoustic waveforms have been recorded with wide band sensor during tensile testing of specimens. For each raw wave form data the FFT analysis is carried out to obtain frequency domain power spectral density signal. In frequency domain, the peak frequency and range of significant frequencies have been derived. From FFT results it is observed that the waveforms of AE hits with low energy at below 90dB amplitude are showing different frequency patterns compared to waveforms of AE hits with high energy at above 90dB amplitude. Therefore the FFT wave patterns are classified in to two groups. i).The waveforms for low energy AE hits at below 90dB amplituderepresenting matrix cracking and two typical of them are shown in **Fig.12**.The range of frequency lies from 50 kHz to 275 kHz and peak frequency ranges from 97 kHz to 103 kHz. ii). The other group of waveforms represents fiber failure hits with frequency ranges from 57 kHz to 448 kHz and peak frequency range is from 168 kHz to 437 kHz. Two typical fiber failure wave forms are shown in **Fig.13**.

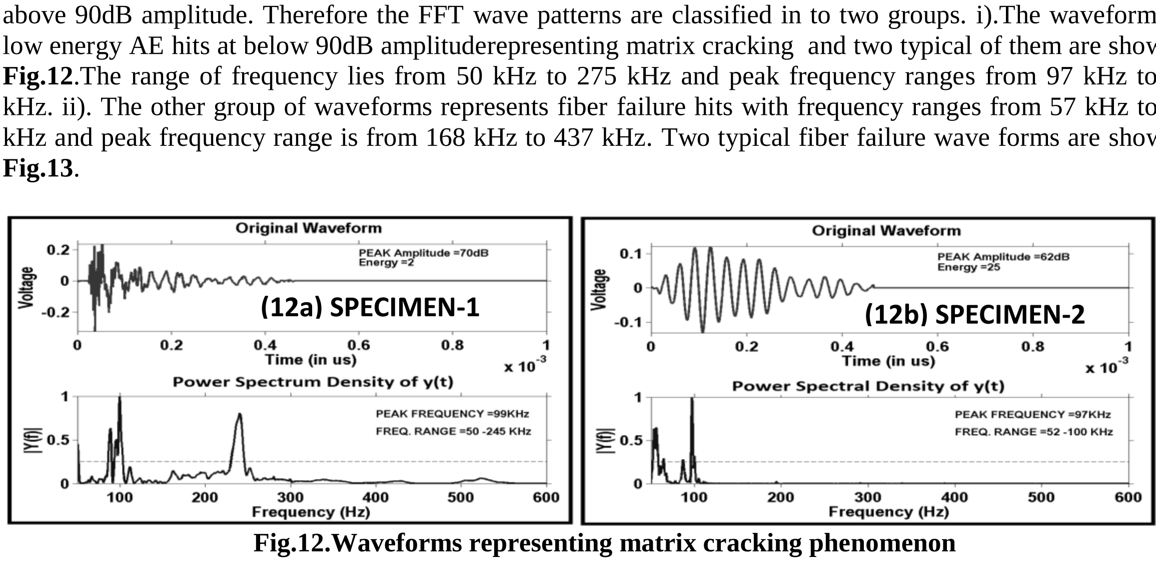

Fig.12.Waveforms representing matrix cracking phenomenon

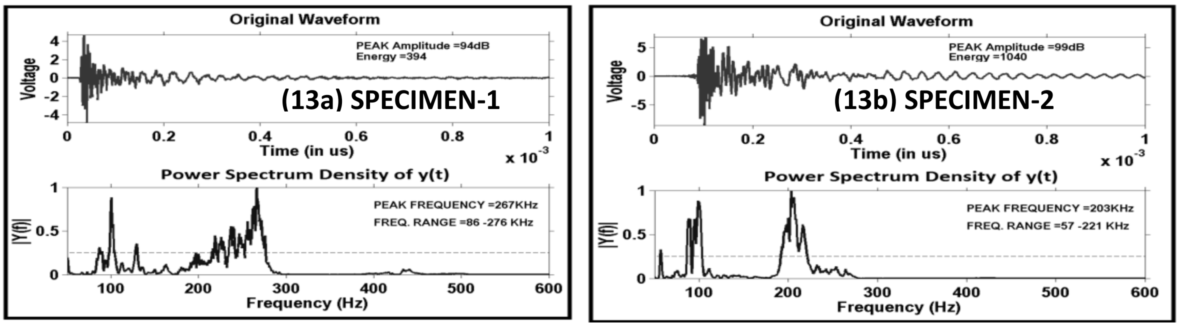

Fig.13. Waveforms representing fiber failure phenomenon

1.6 Low amplitude filtering technique – to identify fiber failure mechanism

The tensile testing of unidirectional carbon epoxy composite specimens in the longitudinal direction shows matrix cracking, fiber breakage, fiber/matrix de-bonding and delamination failure mechanisms. In the samples the Young's modulus and the tensile strength of the fibers are very much higher than the matrix. Therefore to utilize the full strength of the fiber, the ultimate strains of the fiber and matrix should be the same. The major release of strain energy during testing is due to fiber breakage, converts in to the AE signal strength.

Therefore the fiber failure is associated with high amplitude hits with high signal strength. Initially the failure is initiated at weak fiber and further the number of fiber breaks increases exponentially with respect to the applied load, attributed to the scattering of the fiber strength. To evaluate the number of fiber breaksversus applied load, a plot of cumulative signal strength versus load is most helpful. To evaluate the number of failure mechanisms a plot of cumulative hits versus load is most helpful. If the low amplitude hits (non-fiber break hits) are filtered out, the cumulative plot of the remaining hits versus load should follow the trend of the cumulative signal strength versus load plot. The lowest amplitude remaining after filtering is the borderline between the fiber break and non-fiber break hits [9]. The normalized cumulative signal strength and hits versus normalized load for specimen 1 is shown at before and after filtering in **Fig.14**.At below 91dB,the normalized cumulative hits plot is following closely the trend of normalized cumulative signal strength. By applying the low amplitude filtering technique for all specimens, the border line dB is observed between 89 to 92dB.

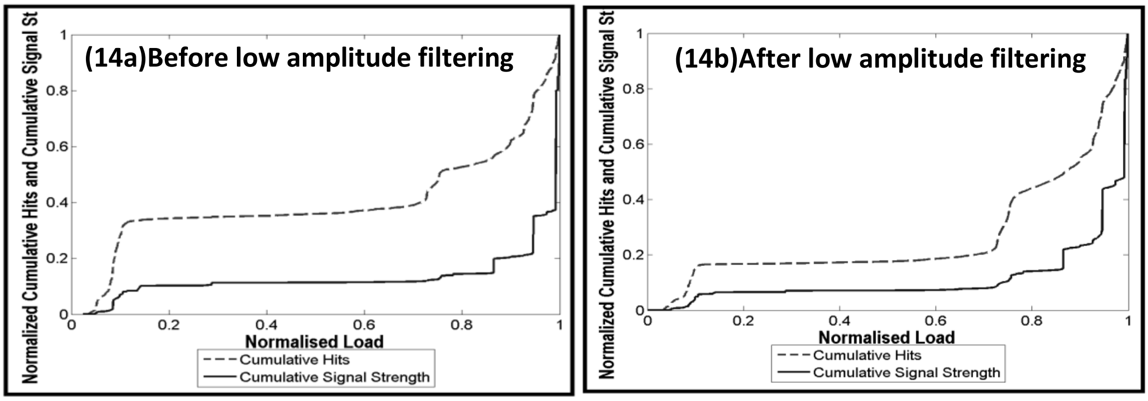

Fig. 14Cumulative hits and cumulative signal strength plots for specimen-1

1.7 Failure mechanisms versus normalized load plots

The experimental study carried out on T700 carbon epoxy UDLspecimens leads to a conclusion that around 90 dB as border line amplitude for fiber breakage mechanism and the initiation of damage in the specimens is observed at the knee location in cumulative signal strength plot where historic index is crossing 6**. Fig.15** shows the normalized cumulative signal strength and amplitude as a function of normalized load for the select two specimens which will explain the presence of different dominant failure mechanisms in the pictorial form. Up to around 70% to 80% of the load where the knee starts in the plot,matrix failure dominates by AE hits with amplitudes up to 90dB with a few fiber failures represented by at above 90dB amplitude hits. The later part of the loading consists of mixed failure mechanisms like matrix cracking, de-laminations and fiber pull out are observed with AE hits up to 90dB and fiber failure with AE hits beyond 90dB. The range of acoustic parameters for matrix and fiber failures from the test results are tabulated in **Table.2**

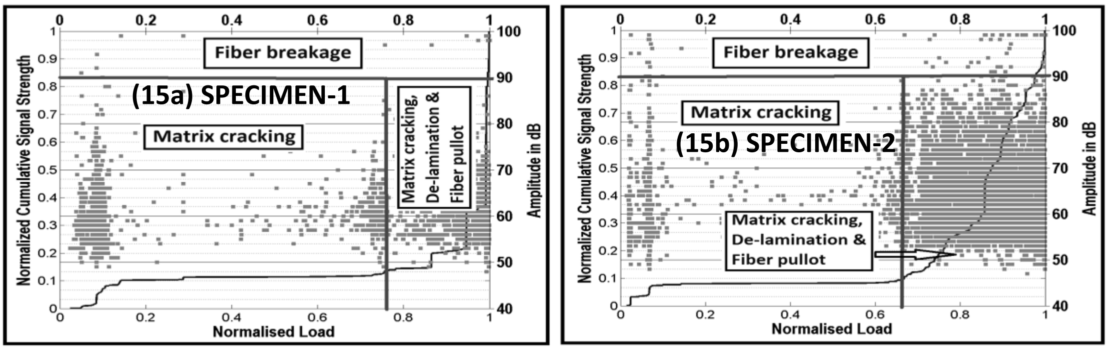

Fig.15. Pictorial representation of different failure regions

Table2 Range of AE parameters for matrix and fiber failures

Acoustic parameter	Range of values	
	Matrix failure	Fiber failure
Energy	<100 units for micro matrix cracking <1000 units for macro matrix cracking	>1000 and up to 41440 units
Signal strength	Up to 6.15 E+ 06	0.63E+06 to 3.73 E+08
Amplitude dB	<90	>90
Duration range µs	$<10^4$	$>10^4$ and up to 292590

III. CONCLUSIONS

Acoustic emission data was recorded for fiber failure analysis in the longitudinal direction of the T-700 carbon epoxy composite unidirectional laminate specimens. Significant fiber breakage is observed at above 70 to 80% of the load with historic index at above 6. Matrix cracking mechanism dominated the entire loading cycle and is represented by AE hits of up to 85 to 90dB amplitude with the peak amplitude distribution around 60dB. Bi-linear trend of the cumulative amplitude curve at above 80% of the load indicate matrix and fiber failures with a border line amplitude of 85 to 90dB. From the low amplitude filtering technique the border line for fiber breakage is observed from 89 to 92dB. The AE waveforms are distinctively classified for matrix and fiber failures with respect to frequency parameters. The matrix failure waveforms are with a frequency content ranging from 50 kHz to 275kHz and peak frequency at around 100 kHz. The fiber failure waveforms are with a frequency content ranging from 57 kHz to 448 kHz and peak frequency range is from 168 kHz to 437 kHz.

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