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Full Length Research Paper

Comparison of acoustic emission parameters for fiber breakage and de-lamination failure mechanisms in carbon epoxy composites

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Acoustic emissions (AE) generated by a structure under stressed condition provide a passive method to understand the flaw growth phenomenon. In complex structures, such as composites, characterisation of AE signals generated by various failure mechanisms enhances such understanding. Sample level tests have been carried out on carbon epoxy unidirectional laminate in longitudinal direction of fiber to study the AE characteristics of different failure mechanisms, namely, fiber breakage and inter layer de-lamination. The AE parameters such as amplitude, energy, duration, rise time and signal strength have been acquired and analysed using various correlation plots. The fiber breakage is represented by high energy and longer duration hits with an amplitude of above 90 dB. The de-lamination mechanism is producing AE hits of medium energy of about 1000 units and long duration up to 10^6 µs. The duration per unit energy and the rise time per unit energy graphs portray a vivid picture of the occurrence of fibre breakage and delamination.

Key words: Carbon-epoxy composites, failure modes, acoustic emission (AE).

INTRODUCTION

Composites are widely being used as structural members in the aerospace industry, because of its high specific strength, stiffness and good corrosion resistance. Structural integrity assessment and quality control of composite structures have been a challenging task. Experience has shown that using non-destructive testing (NDT) for structural integrity assessment has greatly improved the quality and performance of composite systems. Non destruction evaluation (NDE) of composite structures is complex in terms of testing and data interpretation owing to its anisotropy and non-homogeneity.

Currently, Acoustic Emission (AE) testing is found to be a reliable and cost effective non-destructive tool for use with composite structures for on line structural health monitoring (American Society for Non-destructive Testing, 2005). The rapid release of strain energy at localized stress concentration points of microscopic or macroscopic defects within the structure under strain generates acoustic emissions. By mounting piezoelectric

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Table 1. Specifications of carbon fiber T 700.

S/N	Parameter	Specified value
1	Grade	T 700 (PAN based)
2	Tow size	12 k
3	Tex	800 g/km (minimum)
4	Fiber diameter	6 - 8 microns
5	Specific gravity	1.7 - 1.8
6	Carbon Content	94% (minimum)
7	Tensile Strength	4.0 GPa (minimum)
8	Tensile Modulus	200 Gpa (minimum)
9	% Elongation	2.1%
10	Sizing	Epoxy compatible (size content 0.7 - 1.0%)

Table 2. Specifications of epoxy resin LY556.

S/N	Parameter	Specified value
1	Grade	LY556
2	Color	Pale yellow, clear liquid
3	Specific gravity at RT	1.10 - 1.20
4	Viscosity at 25°C , cPs	8000 - 12000
5	Epoxy content, Eq/Kg	5.0 - 5.9
6	Volatile content, by weight	0.75% (maximum)

transducers on the structure, emissions are detected and sent to AE data acquisition system for recording and processing. This technique can monitor the dynamic behaviour of the flaws within the stressed structure and provides information with respect to classification and location of flaws as well as damage severity. High sensitivity, less preparation time, cost effectiveness, global coverage and online testing features are the merits of AE technique when compared with conventional NDT techniques.

There are many research papers describing the various types of damage mechanisms in composite structures (Chen et al., 1992; Suzuki et al., 2000). The predominant failure modes observed in composites are matrix cracking, fiber breakage and de-laminations (Giordano et al., 1998). During testing of composites, different failure modes occur simultaneously, thereby giving rise to different AE signals. Therefore, the challenge lies in skilful data interpretation. Extensive testing on specially designed specimens for characterising different failure modes is essential before adapting the AE technique for complex structures.

AE data has been generated at sample level for carbon epoxy composite laminates and the same has been analysed with respect to different correlation plots by comparing various parameters such as amplitude, energy, signal strength, duration, and rise time. These parameters have been used for characterising fibre failure and de-lamination mechanisms; thereby, the differentiating features of these two failure mechanisms have been studied. Tensile testing of unidirectional T700 carbon epoxy specimens with fibres in longitudinal (parallel to tensile axis) is used for evaluating the fibre breakage. Three point bend testing of unidirectional laminate specimens with fibre parallel to the bending plane is employed for evaluation of inter layer de-lamination phenomenon.

EXPERIMENTAL PROCEDURE

T700 carbon fiber laminates were prepared using LY556 based epoxy resin with HY5200 hardener. The aforementioned combination is most suitable for preparation of advanced composites by filament winding method due to its longer pot life at process temperature and better mechanical properties. The specifications of the carbon fiber T-700, Epoxy resin LY556 and Hardener (HY 5200) are shown in Tables 1 to 3.

Test specimen preparation

High temperature cured uni-directional T-700 carbon fibre laminates were prepared using filament winding process where the roving is wetted with the epoxy resin and wound over a rotating diamond shaped mandrel. The specially designed diamond shaped mandrel for the purpose is shown in Figure 1a. Finally, wet winding of carbon fiber (LY556+HY5200) system was followed by curing process in electrical oven. The detailed specimen preparation

Table 3. Specifications of hardener HY 5200.

S/N	Parameter	Specified value
1	Grade	HY5200
2	Colour	brown, clear liquid
3	Viscosity at 25°C, cPs	150 - 180
4	Specific gravity at RT	1.0 - 1.1

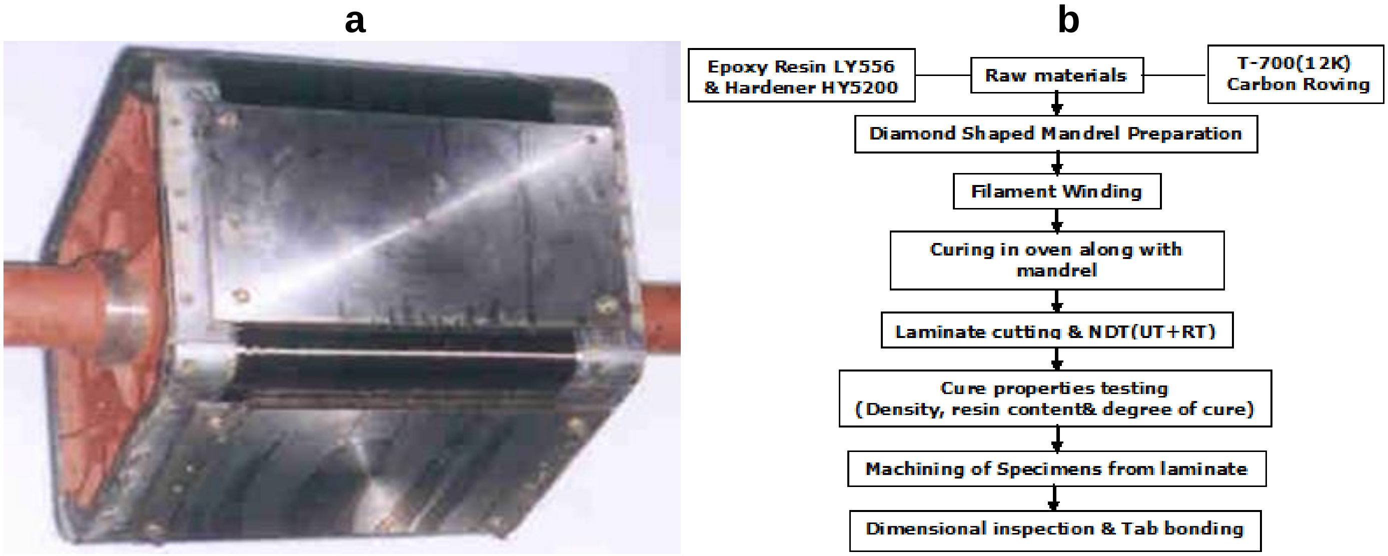

Figure 1. (a) Diamond shaped Mandrel used for laminate preparation. (b) Process flow chart for laminate preparation.

scheme is as shown in Figure 1b.

The tensile specimens made from the unidirectional laminate having fibres loaded in the longitudinal direction (same fibre and load directions) is designated as UDL(T) and are of size 250 × 15 × 2 mm. Aluminium tabs are bonded to the tensile specimens with high shear strength adhesive to facilitate the gripping in universal testing machine (UTM). The bending specimens made from the unidirectional laminate and having fibres loaded in the longitudinal direction (same fibre and load directions) is designated as UDL(B) and are of size 85 × 30 × 4 mm. Tensile and bend test specimens were as per the AS TM standards (ASTM Standard 2000, 2003) and are as shown in Figure 2a and b.

Experimental setup

M/s Instron make, 100 KN UTM with closed loop screw driven system was used for carrying out tensile testing and three point bend testing. M/s PAC, USA, make AE system is used for on-line monitoring. M/s PAC make, R15D model resonant piezoelectric transducers are used with external preamplifier for sensing the acoustic emissions from the specimen. The following AE settings have been used for the test:

Threshold: 40 dB
Peak definition time [PDT]: 20 µs
Hit definition time [HDT]: 50 µs
Hit lock time [HLT]: 300 µs

The AE test set up for tensile testing of UDL(T) specimens and three point bend testing of UDL(B) specimens in UTM is as shown in Figure 3. The specimens are subjected to loading gradually up to failure. The load versus displacement/strain and load versus AE were measured simultaneously. Six specimens have been tested in each category.

RESULTS AND DISCUSSION

Test data

The failure modes of the specimens after the tests are as shown in Figure 4. The AE test data for all the specimens is summarised in Table 4.

The observations on the failure modes of the specimens and AE test data are as follows:

Fibre breakage is the principal failure mode in the longitudinal tensile specimens [UDL(T)] and hence they have shown the highest failure loads. Matrix cracking is dominant in the early phase of loading cycle which is then taken over by fibre breakage mechanism in latter part with scant presence of the other failure mechanisms like

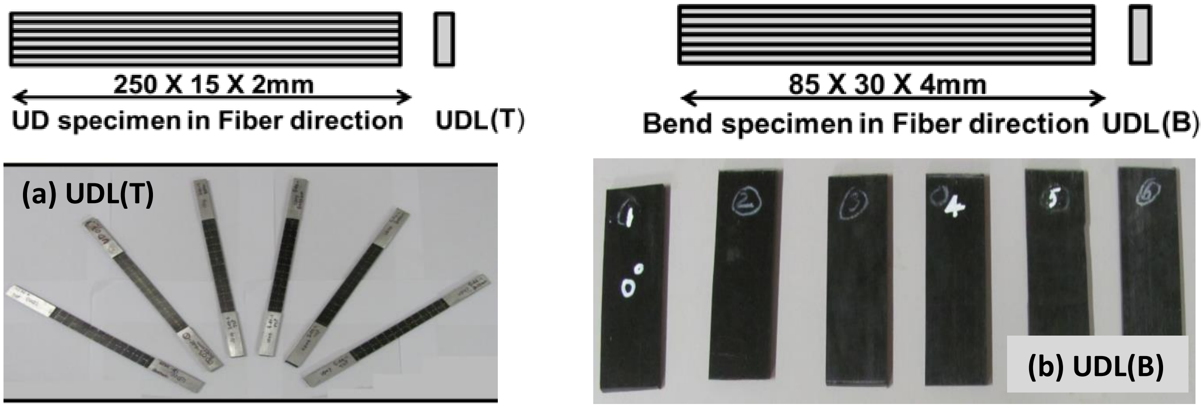

Figure 2. Test specimens for AE testing.

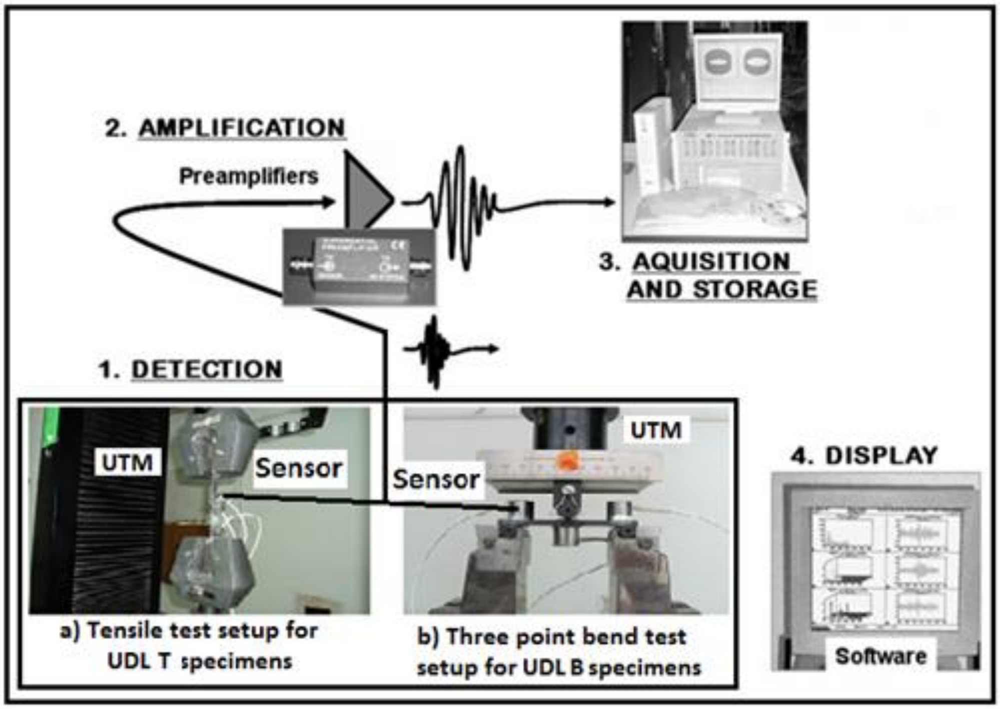

Figure 3. AE test setup.

de-lamination. These specimens have shown very large number of AE hits, high energy and signal strength. The duration of the AE hits are higher attributing to the higher energy content.

The longitudinal specimens [UDL(B)] in three point bend test have shown the failure loads much lower than that of UDL(T) specimens. The bending load is taken by the fibres with de-lamination as the principal failure mechanism. Accordingly the number of AE hits, energy and signal strength are lower than that of UDL(T) specimens. The durations recorded in UDL(B) specimens are much higher than those recorded with UDL(T) specimens indicating that the principal failure mode of inter layer de-lamination possesses the characteristic feature of medium energy and signal strength with very long durations.

Though the range of absolute rise time is higher in case of UDL(T) specimens, the parameter of rise time per unit energy is much shorter when compared with UDL(B) specimens. Hence, the fibre breakage mechanism shows sharp rise time when compared with de-lamination.

AE correlation plots

The AE data for all types of specimens has been post

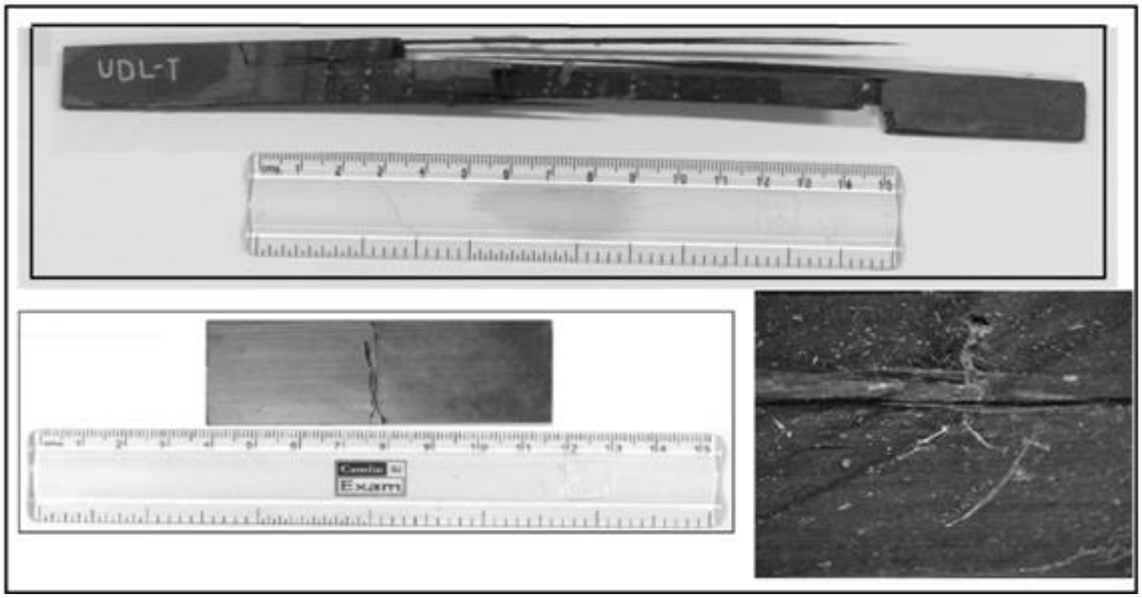

Figure 4. Failure modes of the test specimens.

Table 4. AE test data for different failure mechanisms

S/N	Parameter	UDL(T) specimens	UDL(B) specimens
1	Failure Load (KN)	42 - 69.5	4.35 - 4.79
2	No. of hits	1207 - 8922	97 - 210
3	Total energy	26340 - 430650	2815 - 5240
4	Energy range	2 - 43565	1 - 2435
4	Total signal strength	1.15×10^9 - 3.24×10^9	1.8×10^8 - 3.3×10^8
5	Amplitude range (dB)	47 - 100	47 - 99
6	Duration range (µs)	28 - 292590	522 - 699780
7	Rise time range (µs)	1 - 243	1 - 149

processed with MATLAB software and various correlation plots involving different AE parameters have been generated. These plots have been employed to carry out visual pattern recognition in order to segregate different failure mechanisms. Since different specimens have failed within a spectrum of various loads (owing to non-uniformity in fabrication and realisation process), normalized load is taken as the reference for representing the x-axis. Hence, a value of 1 indicates failure load of that particular specimen and also conveniently represents the stress state of the specimen at that corresponding load. AE plots for select UDL(T) and UDL(B) specimens are shown with distinctive observations for each failure mechanism as the following.

AE amplitude and cumulative signal strength vs. normalised load plots

The amplitude of an AE hit is the highest point of the signal waveform and is represented in dB. The signal strength of an AE hit represents area under the envelope of the analog voltage signal and a steep increase in cumulative signal strength indicates the initiation of higher failure mechanisms like fibre failure. Plot of amplitude and cumulative signal strength as a function of load for typical UDL(T) and UDL(B) specimens are shown in Figure 5. In the UDL(T) specimens, acoustic emissions have started right from the beginning of the loading (around 5% of the failure load) with marginal intensity and after about 60% of the load the same has steeply increased leading to the final failure. The high amplitude hits are more significant after about 70 to 80% of the failure load which contributed significantly to the total signal strength and the same represents the activation of fibre failure mechanism. In UDL(B) specimens, the acoustic emissions started after about 80 to 90% of the breaking load with amplitude in the range of 47 to 99 dB (Graphs in Figures 7 to 9 for UDL(B) specimens have exhibited significant AE activity in the normalised load

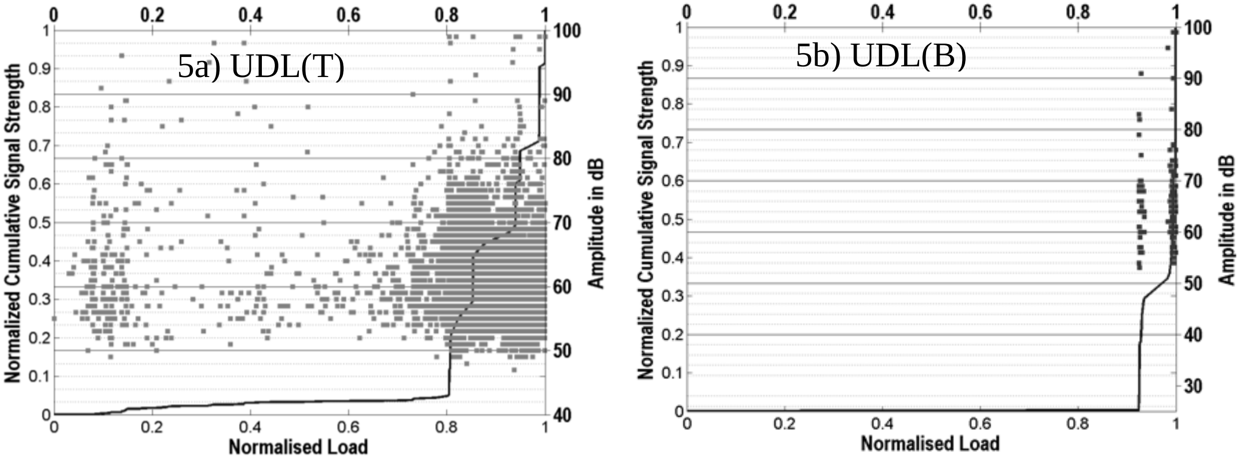

Figure 5. Amplitude and cumulative signal strength vs. normalised load plots.

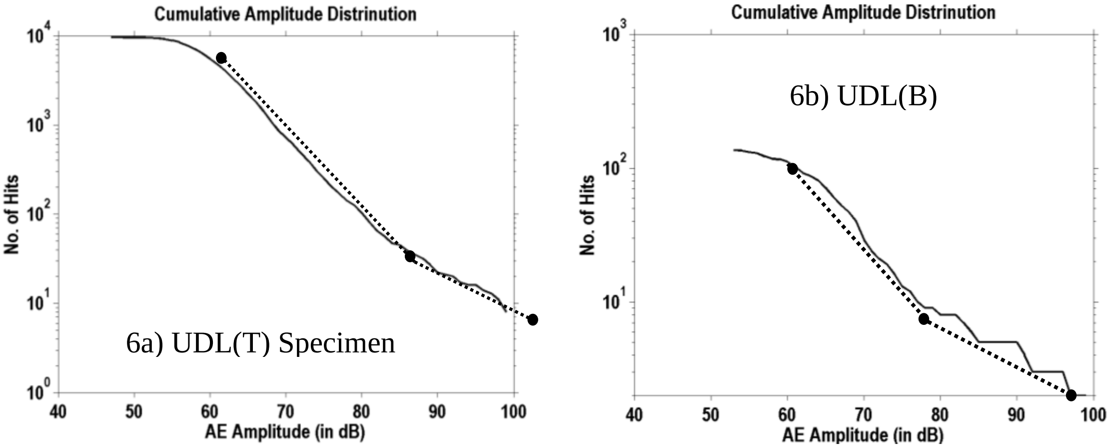

Figure 6. Cumulative amplitude distribution plots.

range of 0.9 to 1.0 only). In comparison with UDL(T) specimens, UDL(B) specimens have portrayed less AE due to the fact that, global matrix cracking is less in bending mode as compared to the tensile mode testing. The hits with amplitude more than 90dB are very few varying from 3 to 5 across the specimens and mostly they are towards the end of the loading cycle which is attributed to isolated fibre failures.

Cumulative amplitude distribution plots

The cumulative amplitude distribution curve helps in identifying the dominant failure mechanisms present in the failure of the given specimen based on number of slopes (Ativitavas, 2002). Figure 6 shows the typical cumulative amplitude distribution plots for both the specimens. The cumulative amplitude distribution curves of both the UDL(T) and UDL(B) specimens are bilinear indicating the presence of two dominant failure mechanisms, that is, matrix cracking and fibre breakage for UDL(T) specimens with border line amplitude of 85 dB. Matrix cracking and de-lamination are the dominant failure mechanisms for UDL(B) specimens with border line amplitude of 80 dB.

Energy vs. load plots and normalised signal strength vs. load plots

The magnitude of energy and signal strength of an AE hit indicates its damage potential and hence higher failure modes like fibre failure are associated with high energy/high signal. Figures 7 and 8 show these plots for UDL(T) and UDL(B) specimens. UDL(T) specimens have shown the highest energy content AE hits due to the

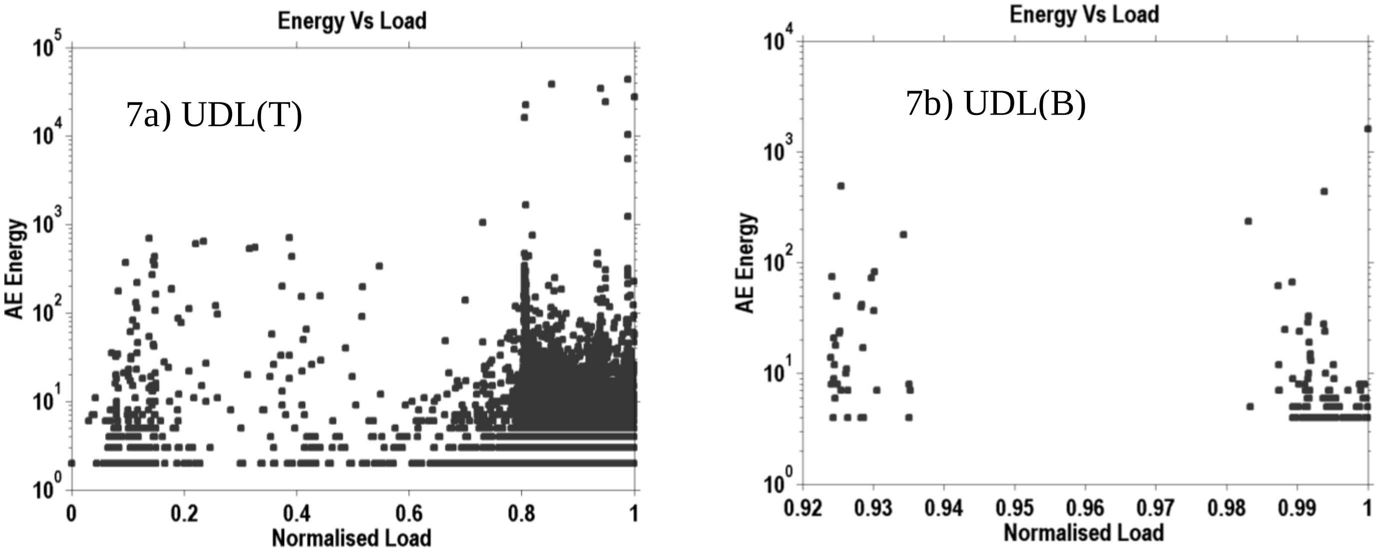

Figure 7. Energy versus load plots.

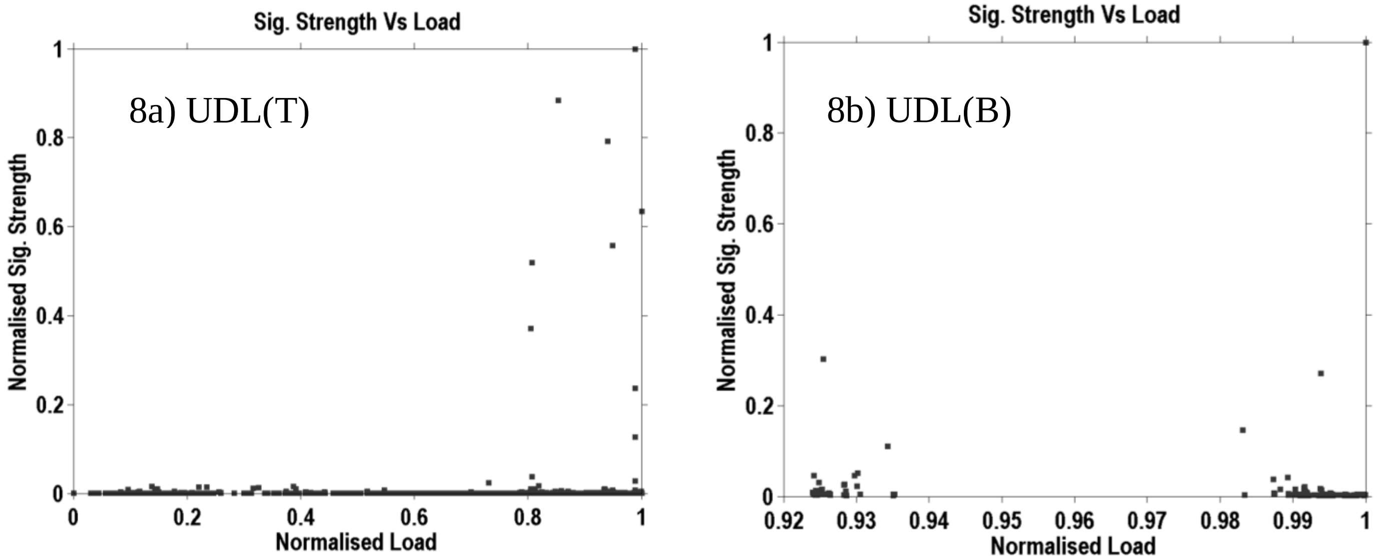

Figure 8. Normalised signal strength versus load plots.

presence of fibre breakage mechanism. The higher energy fibre breakage hits are dominant after about 70 to 80% of the loading. The AE hits of fibre breakage mechanism have contributed significant signal strength. The de-lamination failure mechanism in UDL(B) specimens has exhibited medium energy AE hits which are around 1000 units.

Acoustic signal duration plots

The duration of acoustic signal is the time between the first and the last threshold crossing in microseconds. The duration is an acoustic characteristic feature for a given failure mechanism and is proportional to energy. Typical duration versus load plots and duration distribution plots are as shown in Figures 9 and 10, respectively for both types of specimens. In UDL (T) specimens, the AE hits in the initial phase of loading have a duration of less than 10^4 µs and in the later part of the loading the fibre breakage hits of high energy content have longer durations up to 10^5 µs. In UDL(B) specimens, the AE hits of de-lamination which have a medium energy content of around 1000 units have registered very long durations up

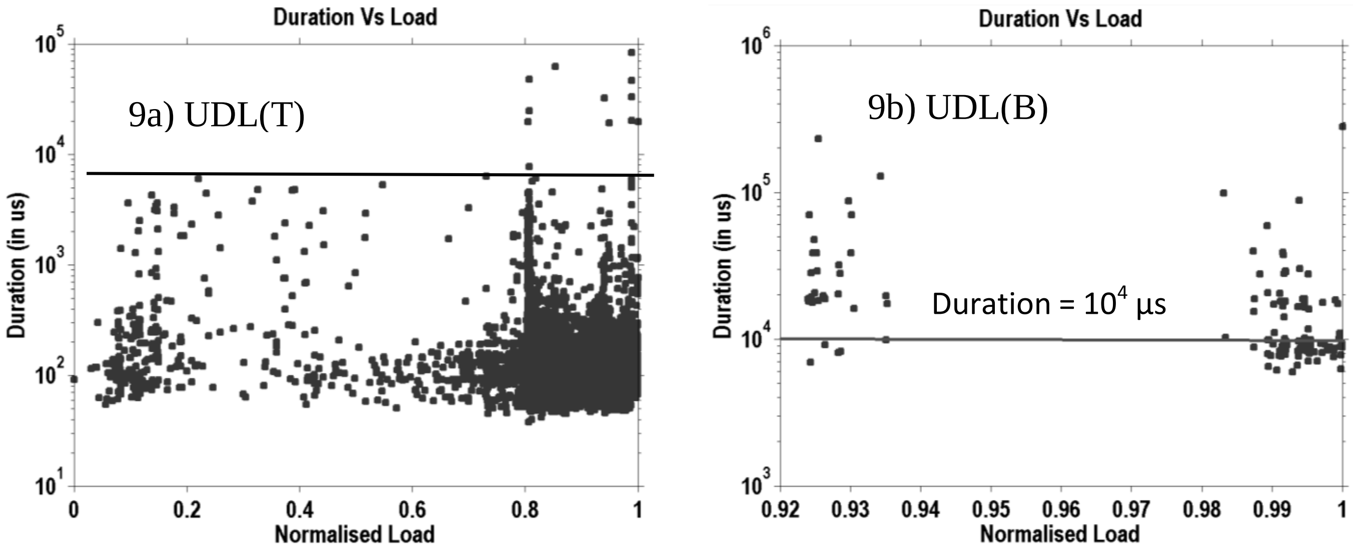

Figure 9. Duration versus load plots.

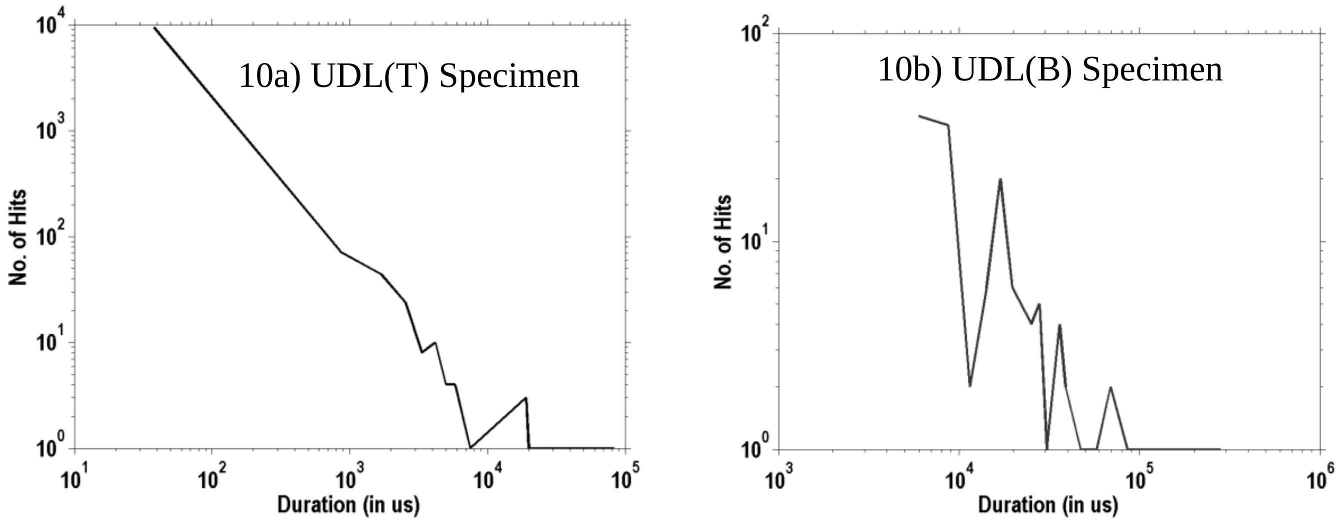

Figure 10. Duration distribution plots.

to 10^6 µs. The higher duration hits are more significant in number in UDL(B) specimens. The same is evident from the duration distribution plots.

Duration and rise time per unit energy vs. load plots

Duration and rise time per unit energy plots for both the specimens are as shown in Figures 11 and 12, respectively. These plots have been made for the AE hits with more than 3000 units of energy and higher than 90 dB amplitude representing fibre failure and lower than 90 dB with duration longer than 10^4 µs representing delamination. The plots show that UDL(T) specimens contributed dominant fibre failures and UDL(B) specimens contributed dominant de-laminations (Kim and Som, 1984). It can also be inferred that fibre failure hits are with shorter duration and sharper rise time when compared with de-lamination.

Conclusions

The experiments were carried out on carbon-epoxy T700 UD laminate longitudinal specimens by tensile testing and three points bend testing. AE signatures corresponding to failure mechanisms of fibre breakage

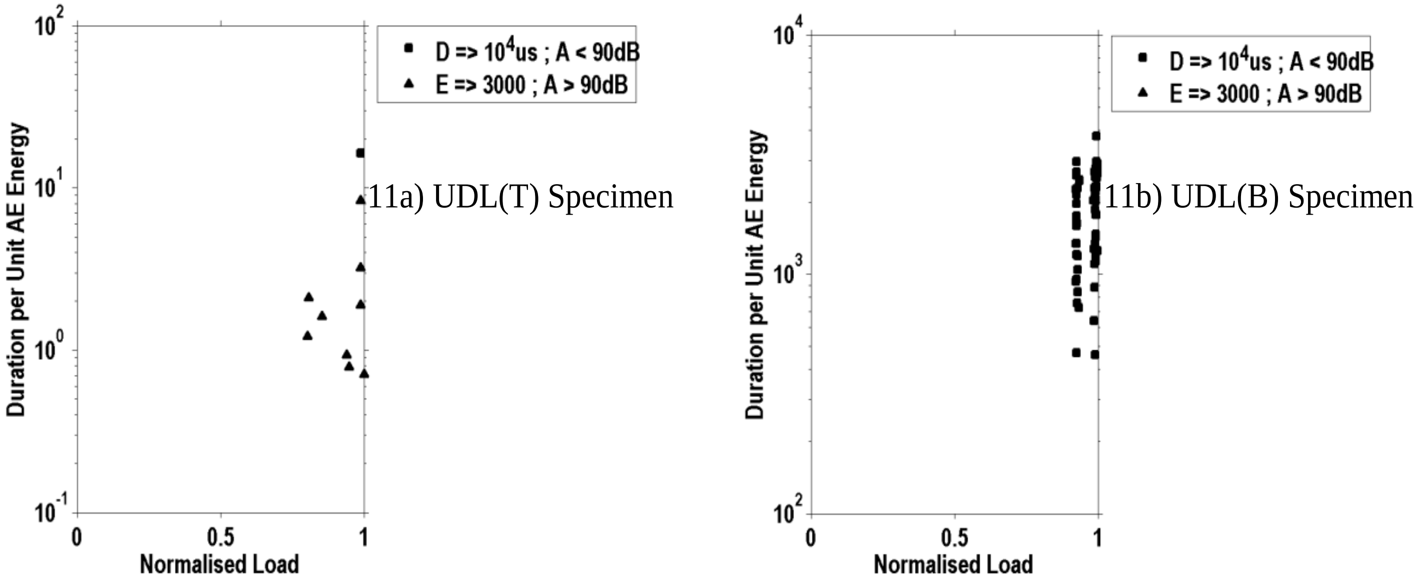

Figure 11. Duration per unit energy versus load plots.

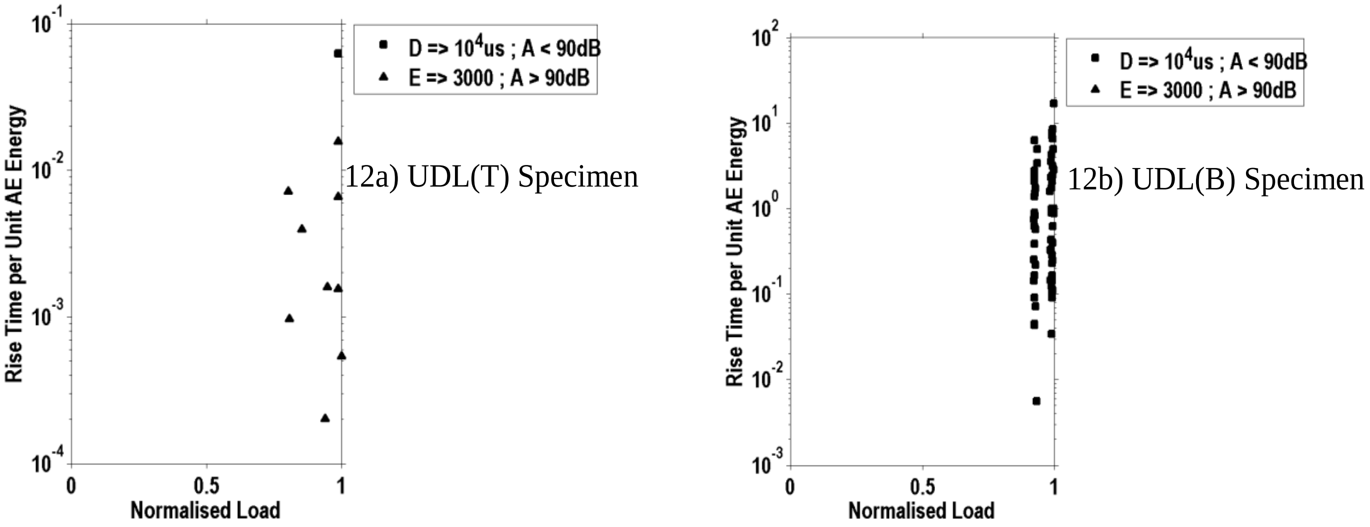

Figure 12. Rise time per unit energy versus load plots.

and de-lamination have been evaluated in terms of amplitudes, energy content and durations. The presence of multiple slopes in the cumulative amplitude distribution curve represents the presence of different failure mechanisms.

The lower valued slope indicates fibre failure in UDL(T) and de-lamination in UDL(B) specimens. The border line amplitude is 85 to 90 dB for fibre failure and 70 to 80 dB for de-lamination. The total signal strength recorded in UDL(T) specimens is contributed by fibre breakage mechanism to a larger extent. A steep change in signal strength is noticed after about 70 to 80% of the failure load. The de-lamination AE hits are characterised with medium energy content with durations up to 10^6 µs, longer than fibre breakage hits.

The fibre breakage AE hits are with sharp rise time compared to de-lamination mechanism. The comparison of AE parameters for both the failure mechanisms is shown in Table 5.

Conflict of Interests

The authors have not declared any conflict of interests.

Table 5. Comparison of fibre failure and matrix cracking.

S/N	AE parameter	Failure mechanisms	
		Fibre breakage	**De-lamination**
1	Amplitude range dB	>90 dB	65 - 90 dB
2	Energy range	Up to 43565 units	Up to 2435 units
3	Duration range	Up to 292590 µs	Up to 699780 µs
4	Duration per unit energy	Up to 10	Up to 4000
5	Rise time range	Up to 243 µs	Up to 149 µs
6	Rise time per unit energy	Up to 10^{-2}	Up to 10

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