FLEXURAL DAMAGE ASSESSMENT OF CARBON-EPOXY COMPOSITES WITH AND WITHOUT RESIN FLOW CHANNELS

Kariappa M. Karumbaiah[1], Christoph Kracke[2], Mark Battley[1], Simon Bickerton[1], Tom Allen[1]

[1] Centre for Advanced Composite Materials, University of Auckland, Auckland, New Zealand
m.kariappa@auckland.ac.nz
[2] BMW Group, Ohmstraße 2 84030 Landshut, Germany, Christoph.Kracke@bmw.de

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ABSTRACT

The integration of resin flow channels in Resin Transfer Moulding (RTM) aids the manufacturer in numerous ways. A reduction in the required injection pressure to fill the mould, increase in flow front and acting as an extended injection gate are some of its advantages. However, the presence of resin flow channels in the moulded composites results in local geometric variations and can affect fibre alignment, leading to changes in local stress fields. This study investigated static flexural performance of composite laminates with deliberately introduced resin flow channels. Four-point bending tests were carried out on three different specimen types, with single large channels, multiple small channels and reference specimens without channels. Acoustic Emission (AE) monitoring was used to characterise the initiation, propagation, and accumulation of damage and identify critical locations. Damage accumulation patterns and net cumulative hits of all three specimen types were different. Multiple channel specimens demonstrated high accumulation of AE signals when the channels were facing the compression side of the flexural loads. Damage also initiated at lower loads in multiple channel specimens compared to the reference and single channel specimens. With the resin flow channels in the compression face of the flexural tests, the reference and single channel specimens did not exceed 400 cumulative hits (accumulated damage) until 90% of the ultimate flexural load. In comparison, the specimens with multiple resin channels exceed 400 cumulative hits at 40% of the ultimate flexural load. Damage distribution along the length of the specimen was monitored. The reference and single channel specimens show similar damage patterns localised to particular positions. However, the majority of damage in the multiple channel specimens were distributed between the resin flow channels. The frequency of each distinct damage was monitored to categorise the damage, such as matrix cracking, debonding and fibre breakage. This study has aided in providing an insight to the damage mechanism of composites with and without resin flow channels.

1 INTRODUCTION

Composite materials are used in various fields of engineering, such as marine, wind energy, aerospace and automobile. The growth in use is mainly due to their performance advantages over conventional metals and the freedom in design. An example of increased commercial application of composites in large volumes is the i-Series vehicles currently produced by BMW. The increase in demand necessitates faster manufacturing techniques for composite structures. One of the recent development is the integration of resin flow channel(s) into resin transfer moulding tools spanning from the injection point [1]. A shape optimization of resin channels has been investigated previously [1]. Based on the effective permeability and finished weight it has been found that the best shape is the parabolic shape. The amount of undulation depends on the layup configuration and size of the resin channel(s). The cross-section of the single channel is shown in **Error! Reference source not found.** with the typical undulation of the load carrying layers. The specimens with single large channels have greater undulation compared to multiple small channels. Depending on the level of undulation there is a decrease in static tensile strength up to 70% [1]. The physics behind the damage evolution of these resin flow channels under static flexural loads is yet to be investigated.

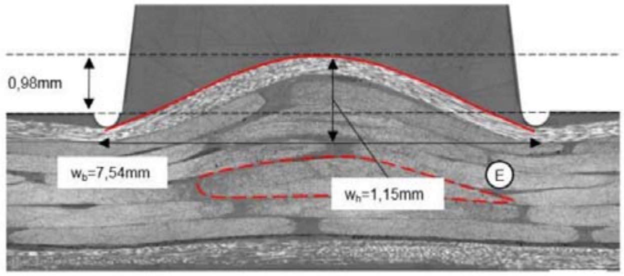


Figure 1: Fibre inwash into flow channel [1].

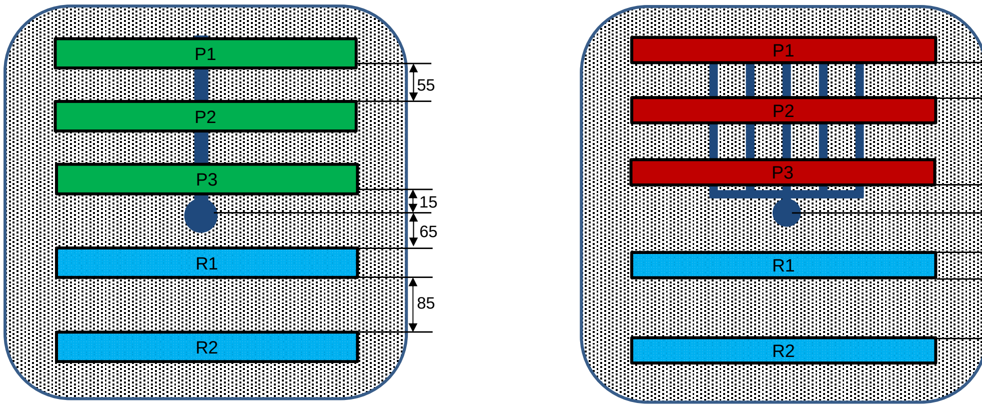
Acoustic Emission monitoring is a powerful technique to understand the failure behaviour of composites. The principle of the acoustic emission relies on detecting the transient release of elastic energy waves known as damage events [2, 3]. The damage events are recorded above a threshold selected based on the material type. 42 dB is considered a suitable threshold for carbon fibre reinforced composites [4, 5]. The recorded AE signals are subjected to signal processing, which involves signal enhancement, separation and analysis. Signal enhancement involves minimizing or removing noise. The removal of noise involves an application of suitable filters. Deterministic linear filtering includes band selection filtering such as lowpass, bandpass and highpass. This involves identifying the difference between signal and noise based on duration, count, rise time, amplitude and peak frequency [6].

The goal of AE is not limited to capturing the number of events; the source of the event can also be located. The use of multiple sensors aids in determining the location of an event and knowing the hit arrival time and the velocity of the wave to travel in the specific material the location can be identified [4]. The source detection technique is applicable with an assumption that the wave travels at constant velocity throughout the material [7]. The accuracy of the technique is affected by the reflection of waves and multiple wave modes. Hence, the geometry of the test specimen and the operating frequency plays an important role in the efficiency of the source location technique [8]. Peak amplitude, duration, counts, rise time, frequency and AE energy are the parameters that can be used to characterize the damage evolution of a structure [9-11].

While some research has been undertaken on the application and implementation of AE in composite materials, no research has been conducted on understanding the damage evolution of composites with the presence of deliberately introduced resin flow channels. Introducing resin flow channels in vacuum assisted resin transfer moulding is a relatively new manufacturing technique and its effects on the flexural damage evolution have not been investigated.

2 MATERIAL AND TEST SPECIMENS

Carbon fibre-epoxy laminates reinforced with non-crimp textiles, with deliberately introduced resin flow channels were used for testing. These composites were manufactured using an automated resin transfer moulding technique. Two different sets of specimens were manufactured: Specimens with the single resin flow channel (Figure 2-a) and multiple resin flow channels (Figure 2-b). Figure 3 shows the cross-section of the two resin channels. Each specimen is 400 x 25 x 2.7 mm. Dimensions were chosen to enable proper placement of the AE sensors to capture and locate AE events.



(a) (b)

All dimensions are in mm

Figure 2: Schematic of experimental RTM platen layout; (a) Single resin flow channel and (b) multiple resin flow channel

(a) (b)

Figure 3: Geometry of resin flow channels; (a) single and (b) multiple

3 METHODOLOGY

Four-point flexural tests were used to characterize the flexural strength of composite laminates with and without resin flow channels (Figure 4). Tests were conducted at room temperature on an Instron 1186 electro-mechanical universal testing machine with a load cell capacity of 200kN. The tests were conducted on three different specimen types, with single large channels, multiple small channels and reference specimens without channels. A support span of 140mm and a load span of 70mm were used. The cross-head speed for testing of all the specimens was maintained at 1 mm/min. Vallen AE-suite AMS3 was used to record the damage. Three AE sensors were attached to the specimens. One sensor was mounted in the centre and other two were mounted at a distance of 120mm from centre.

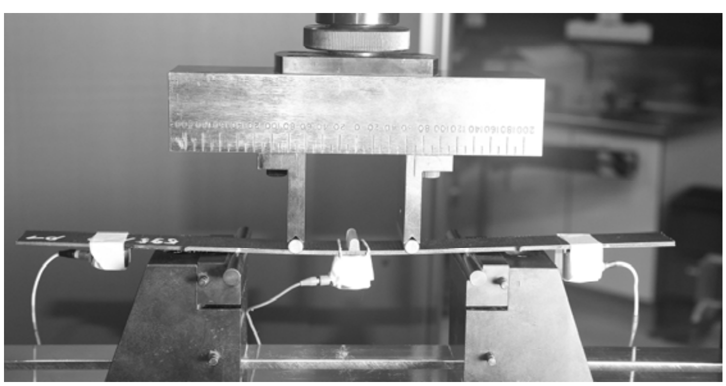


Figure 4: Experimental setup for four-point flexural tests

The purpose of AE was to analyze critical locations and number of events leading to the failure of the component. The data were recorded above the threshold of 42 dB. The piezo-electric sensors were used to detect and record events. These sensors have a sensitivity in the range of 25 kHz to 120 kHz and a secondary range of sensitivity from 130 kHz to approximately 230 kHz. The acoustic emission signal was bandpass filtered with a 30 kHz to 1 MHz preamplifier and the total system amplification maintained at 34 dB allowing processing of the preamplifier input signal up to 99.9 dB above 1 mV (±99 mV peak). The sensors were coupled with the specimen using petroleum jelly and connected to the data acquisition system via coaxial cables. Figure 5 shows the AE instrumentation setup. A performance check was conducted by carefully breaking pencil lead on the surface of the test specimen (ASTM E976-10) to ensure the AE data was reliable and the channel sensitivity was consistent. AE-signal were captured during the tests and signal descriptors such as duration, counts, rise time, amplitude, were stored in the Vallen AE system. The locations of the events were measured by the device based on the knowledge of wave velocity, the distance between the sensor and the first receiver of the release of the transient wave. However, the structural complexity such as holes and varying thickness may alter the wave propagation path and velocity [12].

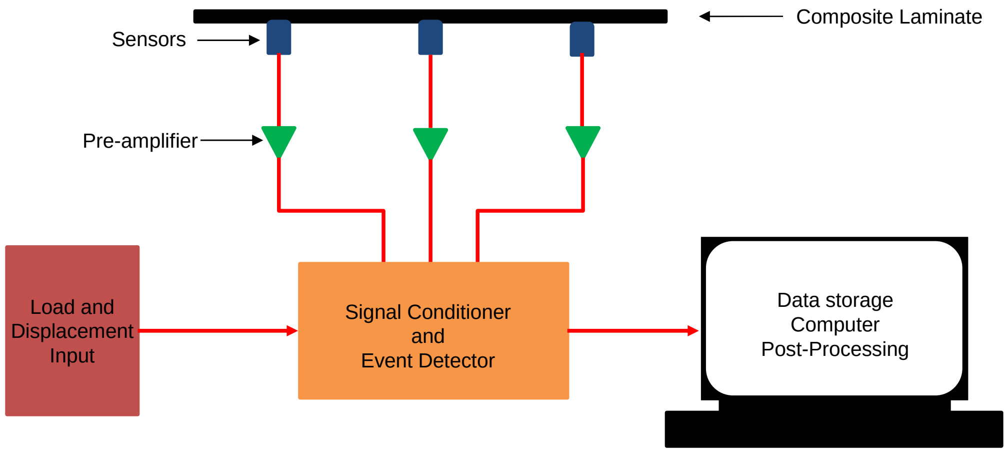


Figure 5: Acoustic Emission instrumentation setup

4 RESULTS AND DISCUSSIONS

A detailed study of failure mechanisms of specimens with and without resin flow channels is discussed below. The acquired AE parameters such as amplitude, rise time, frequency, counts, and duration were chosen as the input data to analyze the behaviour of the composites under quasi-static flexural loads. The AE parameters such as amplitude and cumulative-hits were analyzed to understand the trends and location of damage. Peak frequency was used to characterize the modes of damage.

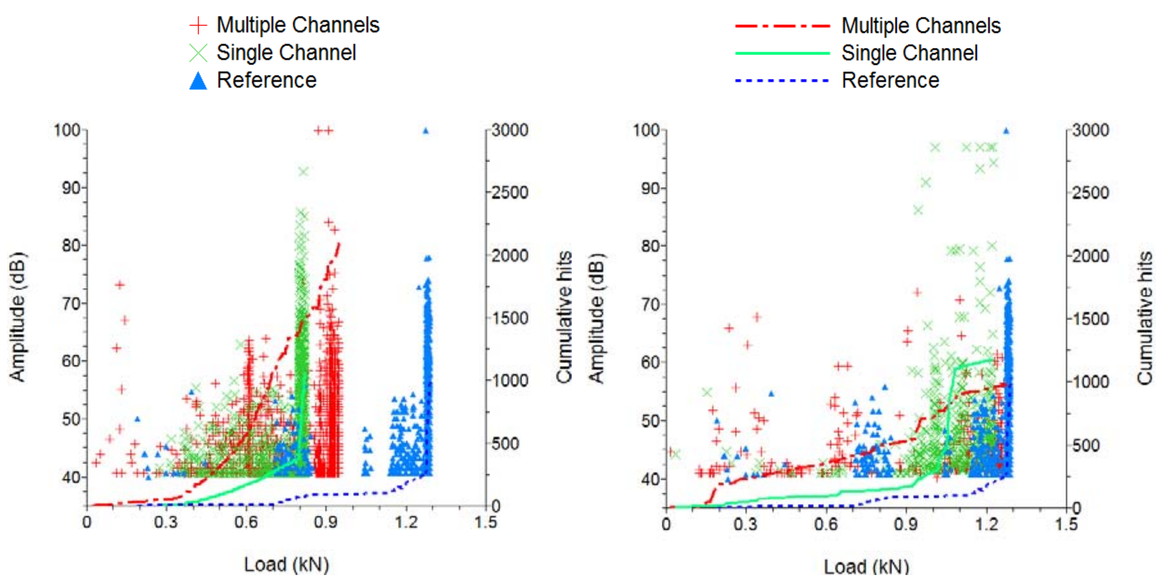
4.1 Damage assessment

The data analysis was performed in real time while the tests were being conducted and post-test. Signals were processed at multiple levels. Representative illustrations of cumulative AE hits/events (i.e., the sum of events of each successive acoustic signals) during quasi-static flexural loading are shown in Figure 6. Three specimen types were tested, Reference (R), large single channel specimens and small multiple channel specimens. Single and multiple channel specimens were tested in two different loading scenarios; placing the channels in the compression and tension face of the flexural tests. (Single channel specimens in compression face (SCC), in tension face (SCT) and multiple channel specimens in compression face (MCC) and in tension face (MCT).) Damage accumulation patterns and net cumulative AE events of all three specimen types were different.

The reference specimen shows fewer low amplitude events occurring at the beginning of the tests. After 80% of the failure load, an increase in the amplitude of the AE signals can be observed. 15% of the total AE signals were recorded for 60% of the load. No significant increase in the AE events was observed till 90% of the failure load. Hence, a rapid increase in the rate of accumulation of AE signals leading to failure can be observed above 90% of the load.

With the resin channels facing the tension side of the flexural tests, single channel specimens and multiple channels specimens shows a different trend in the accumulation of AE signals. An early initiation and greater accumulation of AE signals were observed in these specimens compared to reference specimens. Single channels specimens accumulate 20 % and multiple channels up to 50% of the total AE signals below 80% of the failure loads.

For specimens with resin channels facing the compression face, single channel specimens showed an increase in accumulation of events after crossing 50% of the load level. Moreover, a sudden increase in the accumulation of the events was observed above 90% of the failure load, and progressively increasing until the monotonic load approach the failure loads. Multiple channel specimens demonstrated greater accumulation of total AE signals leading to failure of the specimens compared to other specimen types. A slow and steady increase in the accumulation of AE signals was observed in multiple channel specimen above10% of the failure load. An exponential increase in AE events were observed above 40% of the failure load.



(a) (b)

Figure 6: Amplitude and cumulative hits vs load response during a 4-point bend tests: (a) resin channels on the compression face and (b) resin channels on the tension face

The total number of damage-related AE events were recorded and plotted in Figure 7 for different specimens and loading scenarios. Three specimens were tested for each loading scenario. The error bar demonstrates the standard deviation of total AE signals. These numbers represent filtered events, where a minimum threshold of 42 dB was applied to filter the noise, the electromagnetic interferences were filtered manually by applying linear AE signal filters. The number of AE events for each AE sensor was nearly same. The reference, single and multiple channel specimens with resin flow channels facing the tension face of the flexural test showed nearly same average total AE events. However, when the channels were facing compression face of the test, a difference in total AE events can be observed with average AE hits of 950, 1250 and 2250 in reference, single and multiple channels specimens, respectively. The multiple channels specimens in compression side exhibits more AE events.

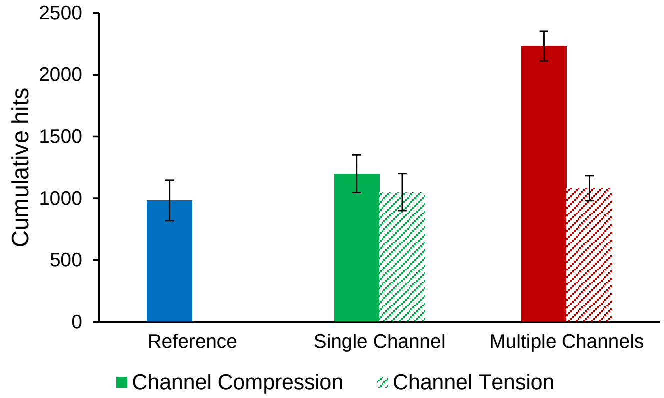
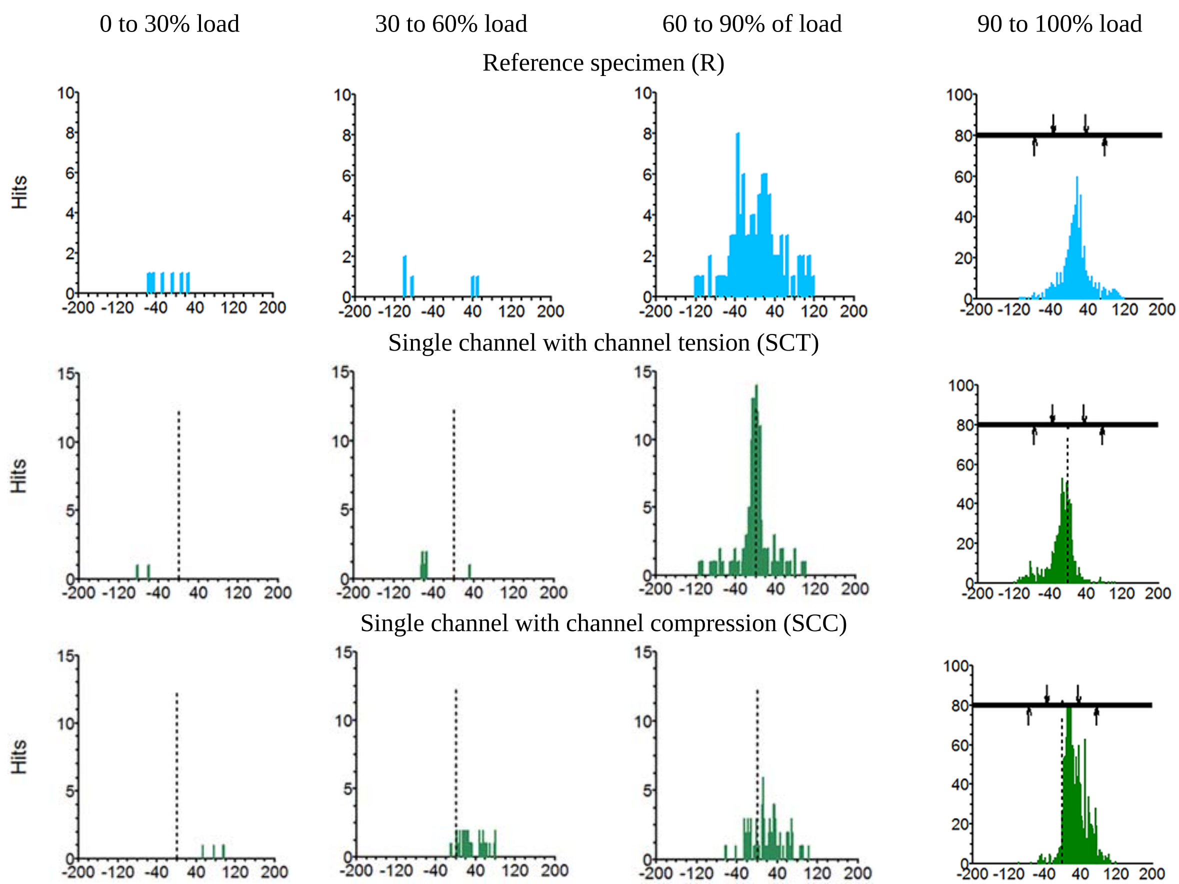


Figure 7: Total number of damage-related AE events under 4-point bend test

4.2 Location and Modes of Damage

Damage distribution along the length of the specimen was monitored. A series of plots were generated to identify the possible locations of the events leading to the failure. The locations were plotted at four different intervals of loads, 0 to 30%, 30 to 60%, 60 to 90% and 90 to 100% (Figure 8).

The location of AE events was identified from the difference in the first hit time of the AE signal and the wave velocity. First-threshold-crossing technique uses the arrival time when the transient wave cross the pre-defined threshold [13]. The current investigation showed accurate location results; the results from the pencil lead break were compared with its locations and found to be consistent and accurate.



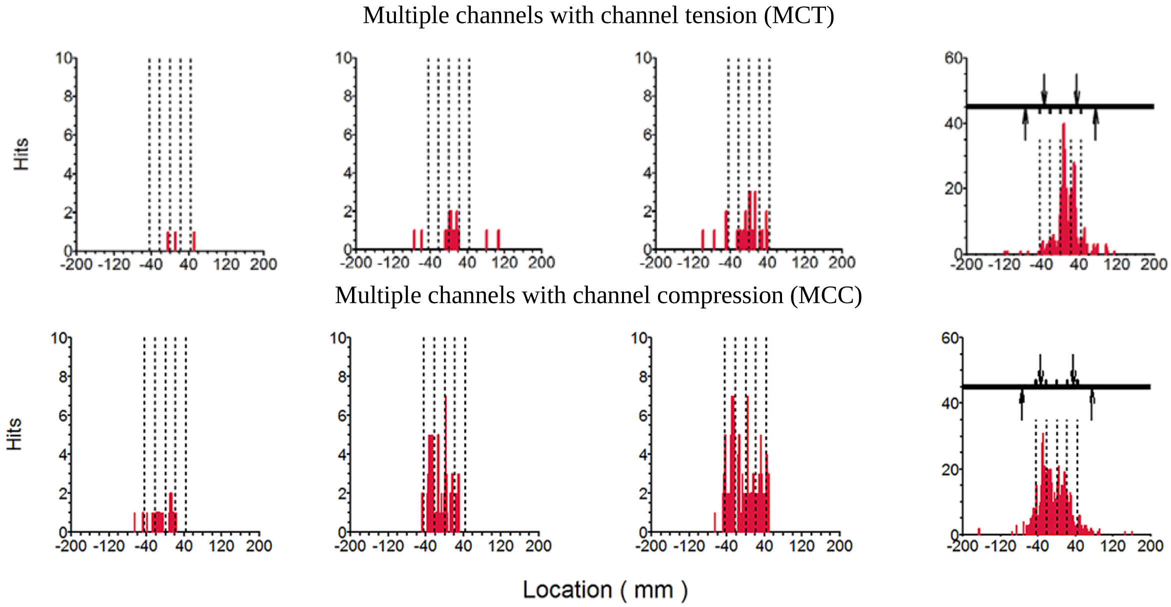


Figure 8: Damage distribution along the length of the specimen at different failure load intervals (dotted lines define the channel position)

For reference specimens, low-amplitude AE events started to occur close to the centre of the specimen at failure load range of 0 to 30%. Subsequently, few low amplitude events occur near the loading pins or between the loading and support pins. A concentrated region closer to the centre of the specimen (between the loading pins) exhibits high accumulation of low-amplitude AE events at the failure load range of 60 to 90%. High amplitude events continues to progress between the loading pins after 90% of the failure load, leading to the failure of the specimen.

With resin channels on the tension side of the flexural test, the single and multiple channel specimens showed a similar behaviour as the reference specimen up to 60% of the failure load. Damage was located close to the centre of the specimen. An increase in the damage propagation rate was observed after 60% of the failure load, similar to reference specimens. However, the single channel specimens accumulated AE signals with high-amplitude close to the resin channel. Multiple channel specimens had fewer high-amplitude AE signals spread between the resin channels.

The location plot of single channel specimens with resin channels facing the compression side showed an increase in AE signals above 30% of the failure load. More AE signals were distributed between the loading pins at the load range of 30 to 60%. The build-up of low-amplitude AE signals was observed to continue in the same location as the load increased up to 90%, finally leading to failure with high-amplitude AE events. Compared to single channel specimens facing the tension side, these specimen showed a wider distribution of accumulated AE signals between the loading pins. Multiple channel specimens with similar loading conditions showed the accumulation of AE signals between the resin channels at the load level 0 to 30%. A significant growth in the accumulation of high amplitude AE signals between the resin channels was be observed at every stage of loading leading to failure.

A pattern study of the AE signal was undertaken to classify the signals based on peak frequency distributions. From literature studies it is known that AE signals generated at fracture can be related to classifying the modes of damage [14]. Frequency analysis for different types of specimens tested to obtain the desired failure mode can be used to classify the types of damage [15]. Unidirectional fibre reinforced composite loaded in the direction of fibre can generate four types of damage. Loading at 10° to fibre orientation can result in no fibre breakage. Matrix cracking can be a dominating mode of failure when loaded at 90° to the fibre orientation, and double cantilever beam tests can be conducted to capture matrix cracking and debonding. The proposed classification is summarized based on the available literature [15] as shown in Figure 9. The common failure modes such as matrix cracking, delamination, debonding and fibre failure may occur with the frequency range of 0 to 50kHz, 50 to 150kHz, 200 to 300kHz and above 400kHz, respectively.

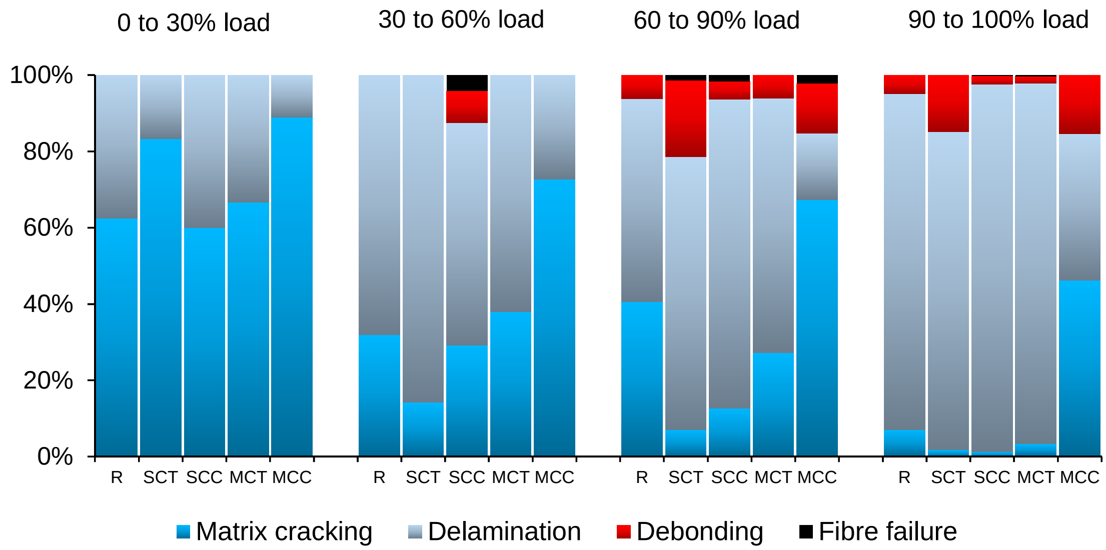


Figure 9: Frequency based failure modes at different intervals of failure loads

The result show that at the load range of 0 to 30%, all the specimen types and loading scenarios may have a large amount of matrix cracking and possibly some delamination. For the load range, 30 to 60% delamination may dominate over matrix cracking. However, multiple channel specimens facing the compression side (MCC) may continue to have a greater amount of matrix cracking compared to delamination. Single channel specimens with channels on compression face are the only type that may have fibre failure and debonding at this load range. Debonding and fibre failure may be expected to occur with matrix cracking and delamination in all specimens at load range of 60 to 90%. Additionally, MCC may continue to have more matrix cracking along other damage modes. A significant amount of delamination can be expected at the load range of 90 to 100% in reference, single channel specimens with channels facing both tension and compression side and multiple channel specimens with channels facing the tension side of the test. More matrix cracking at this load range may be only observed in multiple channels specimens with channels facing compression side of the flexural test.

5 CONCLUSIONS

The flexural damage mechanisms of specimens with and without resin flow channels was investigated. AE signals were recorded from the flexural tests and post-processed to appropriately understand the evolution of damage under flexural loads. The amount of recorded AE signals were found to be different in specimens tested with the resin channels in compression side of the flexural tests. The cumulative AE signal analysis showed that events leading to failure in multiple channel specimens with channels facing the compression side was 57% and 75% greater than the single channel and reference specimens. Specimens with resin channels in tension side of the flexural test showed a similar number of total AE signals leading to failure. The AE signal accumulation trends vary with the specimens, with the rate of accumulation varying along the applied loads. The location analysis demonstrated the damage evolution along the length of the specimen. The reference and single channel specimens show similar damage patterns localized to particular positions. However, the majority of damage in the multiple channel specimens were distributed between the resin flow channels. Characterizing failure modes using frequency content of AE signals appears to be promising. Further investigation is necessary to collect the signals from composites developed by the same manufacturing techniques in order to confirm the frequency range obtained from the literature.

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