FLEXURAL FATIGUE PERFORMANCE OF CARBON EPOXY COMPOSITES WITH AND WITHOUT RESIN FLOW CHANNELS

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Abstract

The increasing use of composites in high-volume sectors such as automotive necessitates faster manufacturing techniques, such as high-pressure resin transfer moulding (HP-RTM). The integration of resin flow channels into the HP-RTM moulds can assist with the production of complex geometry parts by reducing total flow resistance, allowing faster filling and providing the capability to guide the flow of resin in the mould. This research aims to characterise the flexural fatigue performance of carbon-epoxy laminates reinforced with non-crimp textiles, with deliberately introduced resin flow channels. Acoustic Emission (AE) monitoring was used to characterise the initiation, propagation, and accumulation of damage and identify critical locations. Load/reload and full-cycle flexural fatigue tests were carried out on three different specimen types, with single large channels (SC), multiple small channels (MC) and reference (R) specimens without channels. Full-cycle fatigue tests were conducted on an Instron 8802 hydraulic universal testing machine at a frequency of 2Hz and stress ratio of 0.2 at room temperature. Flexural fatigue performance and damage accumulation patterns were different between specimen types. The reference specimen did not show a significant stiffness degradation after million load cycles. Post-fatigue, reference specimens showed a decrease in static flexural strength. However, SC specimens and MC specimens failed at lower cycle numbers.

1. Introduction

Carbon-fibre reinforced plastics (CFRPs) are widely used in high-performance structures in the aeronautical and automobile fields due to their excellent mechanical properties. The use of composite materials over metal has been a developmental trend in many automobile industries, including the use of CFRP's in BMW's i-Project. The requirement for high volume production necessitates faster manufacturing techniques for composite structures. One approach to reduce cycle times is the integration of resin flow channel(s) spanning from the injection point in resin transfer moulding tools [1-6]. Shape optimization of resin channels has been investigated previously [1]. A parabolic sectional shape has been shown to be optimal for maximising effective permeability and finished part weight. A degree of fibre undulation can occur adjacent to a resin channel depending on the local fibre preform lay-up, specimen position and size of the resin channel.

A micrograph of a sample cross-section at the base of a single channel is shown in Figure 1, demonstrating typical undulation of the lamina in the region of the channel. Differences in the undulation of lamina were observed for specimens cut at positions P1, P2 and P3, each being a different distance from the injection point. Specimen P3 (closest to the injection point) showed a greater undulation compared to P1 and P2.

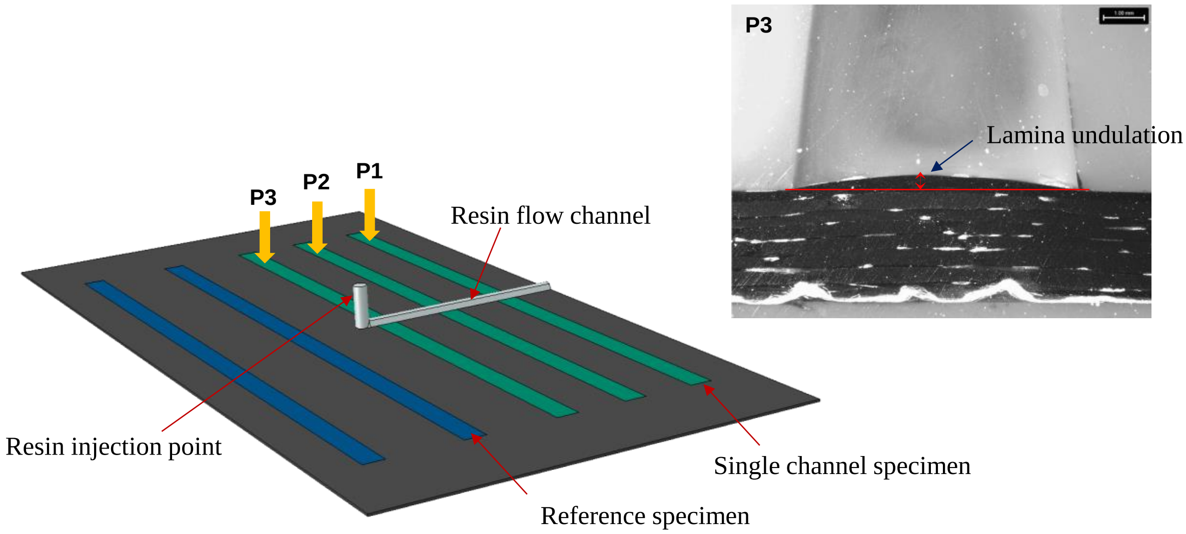


Figure 1. Schematic and microscopic representation of resin flow channels

This research has been conducted to understand the difference in mechanical performance of specimens with a single large channel and small multiple resin channels of equal effective flow. Specimens with single large channels create greater fibre undulation as compared to multiple small channels. Depending on the level of undulation there is a decrease in static tensile strength up to 70% [1], but the reasons for these strength reductions and the associated failure mechanics has not been investigated for fatigue loads.

The fatigue properties of composites are different than metals; generally, the performance of composites under cyclic loading is better than metals [7], particularly in tension. However, under fatigue loads, extensive damage occurs throughout the specimen volume [8]. This leads to failure being caused by general degradation of materials. Composite materials do not fail because of a single predominant crack under fatigue loads [8]. Composites typically exhibit four basic failure mechanisms: delamination, matrix cracking, interfacial debonding and fibre breakage [9]. The combination of different failure modes, complex stress fields, inherent anisotropies and tailored architecture limits the ability to understand the nature of fatigue failure.

Acoustic Emission (AE) monitoring is a technique used to understand the failure behaviour of composites. The principle of AE relies on detecting the transient release of elastic energy waves during damage events [10, 11]. These damage events are captured via AE sensors in contact with the surface of the structure under load. Thresholding is utilised to limit the data obtained to only those elastic energy waves of relevance. The threshold value used is based on the material type, with 42dB being commonly used for carbon fibre reinforced plastics [12, 13]. 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 [14]. Once the signal is enhanced individual events can be separated and factors such as duration, counts, energy, and rise time can be examined. This wealth of data provides a clear understanding of the recorded damage signal and can later be used to classify and locate the damage.

In this paper, the performance and future interests in the optimisation of composites with resin flow channels under load/reload and full-cycle fatigue loads are discussed. AE monitoring has been adapted to understand the initiation and propagation of damage under load/reload tests.

2. Material and Experimental Procedure

The specimens were manufactured by the BMW Group using a typical automated HP-RTM 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).

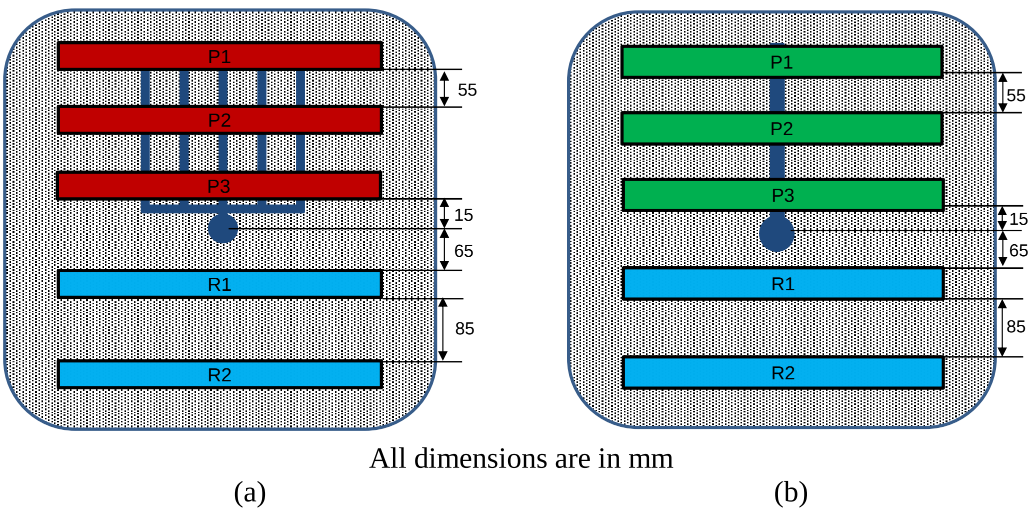


Figure 2. Schematic of experimental HP-RTM platen layout; (a) Single resin flow channel and (b) multiple resin flow channels

The composite coupons are made of carbon-epoxy laminates reinforced with non-crimp textiles. Figure 3 shows the cross-section of the two types of resin channel. Each specimen is of 400mm length, 25mm width and 2.7mm thickness. The preform layup configuration is $[90,0,45,-45]_S$.

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

The damage initiation process has been investigated using load/reload tests. This testing involves consecutive loading of a specimen for 5 times with an increase in strain for each cycle. The strain at 90% load for the reference specimens without flow channels was used as the target maximum strain for the fifth loading cycle for all of the different specimen types. The purpose of this test is to identify the strain level at which the damage affecting the life of a specimen starts to occur.

Fatigue tests were performed under flexural cyclic loading with constant stress amplitude. The loading frequency was 2 Hz to avoid any temperature influence on mechanical and failure properties. Fatigue tests were stopped if one of the following conditions occurred; the specimen fractured, or the specimen sustained a million cycles of loading. Stress unloading stages were used during all fatigue tests to measure the stiffness decrease of specimens due to damage. The lateral and transverse movements of the specimen were constrained using heat shrink polymer layers and a slot in the loading pins. The use of heat shrink material also aided in preventing local surface abrasion of the specimen during the cyclic loading (Figure 4).

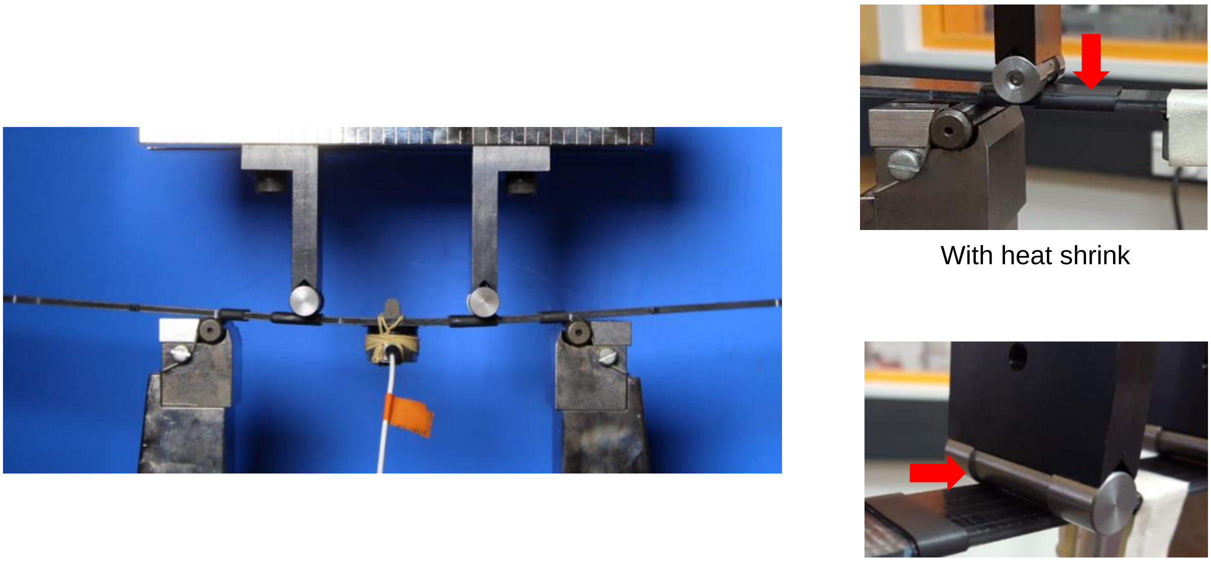


Figure 4. Experimental setup of flexural fatigue tests.

Initially, the reference specimens were loaded up to 80% of the load with the stress ratio of 0.2. It was observed that the reference specimen withstood a million load cycles. When a multiple channel specimen was tested for the same loading parameters, it failed at only 12 load cycles. When tested to 70% of maximum load, another multiple channel specimen could only sustain 28 load cycles. Hence a further reduction of loads was used to 60% of maximum load. For this case, the multiple channel specimen withstood 2200 cycles, which can give considerable information on stiffness degradation, hence further testing of specimens was carried out at the 60% load level.

4. Results and Discussions

A detailed study of damage behaviour of specimens with and without resin flow channels under cyclic loads is discussed below. AE parameters such as cumulative hits, amplitude, rise time, frequency and time were used to analyse the damage evolution.

4.1. Load/reload tests

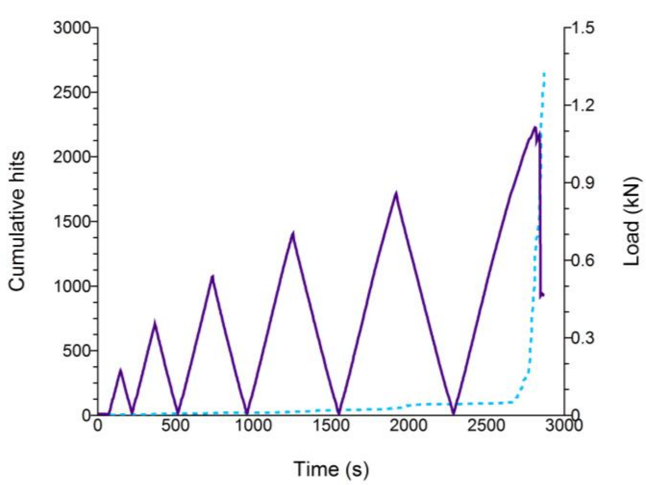
Figure 5 presents the load-time history, along with the cumulative hits from AE for load/reload tests. AE responses of the composite laminate were observed to be consistent for repeated tests. However, the consistency is limited to the similar test conditions, such as material, geometry, sensor type, user-defined hardware acquisition setting. These results were also used to investigate the damage initiation, propagation and patterns of accumulation. 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 failure. The locations were plotted for every load cycle. The location of AE events was identified from the difference in the first hit time of the AE signal and the wave velocity. The first-threshold-crossing technique uses the arrival time when the transient wave cross the pre-defined threshold [15]. The current investigation showed accurate location results; the results from a pencil lead break were compared with its locations and found to be consistent and accurate.

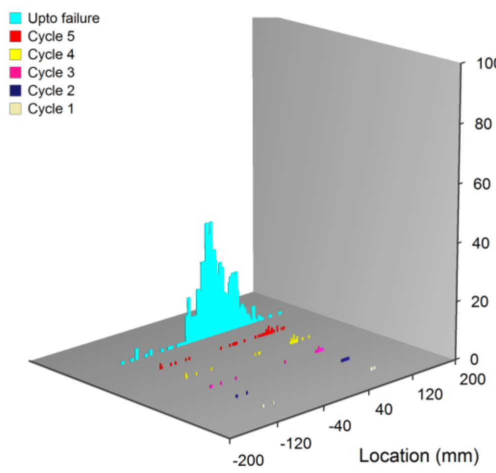
A total of 1600, 2400 and 2500 events were captured for the reference, single channel and multiple channel specimens respectively. Based on the Kaiser effect [12, 16, 17], the total number of events in the monotonic and load/reload tests should be equal, however, the total number of events for the load/reload tests was higher, possibly due to friction between damaged elements (matrix and fibre) [18]. A load of 420 N, 250 N and 150 N was sufficient to initiate the damage in reference, single channel and multiple channel specimens, respectively. This behaviour of the composite laminate was observed to be consistent across multiple tests.

For reference specimens (Figure 5-a), under the 5-cycle increase in strain tests, the first cycle generates only a few tens of hits, while during the 5th cycle thousands of hits were recorded. The increase is expected because as the load increases, apart from matrix micro-cracking many other failure modes, such as delamination, fibre breakage and debonding start to occur. Moreover, the rate at which events are recorded is also high. This is mainly due to increase in the rate of different fracture modes in the specimens. Initial events were observed to occur near the loading and support pins; this is mainly due to the settling of specimens. The reference specimen did not show any accumulation trend until the fifth loading cycle, and only during the 5th cycle, the damage is observed to accumulate near the centre of the specimen.

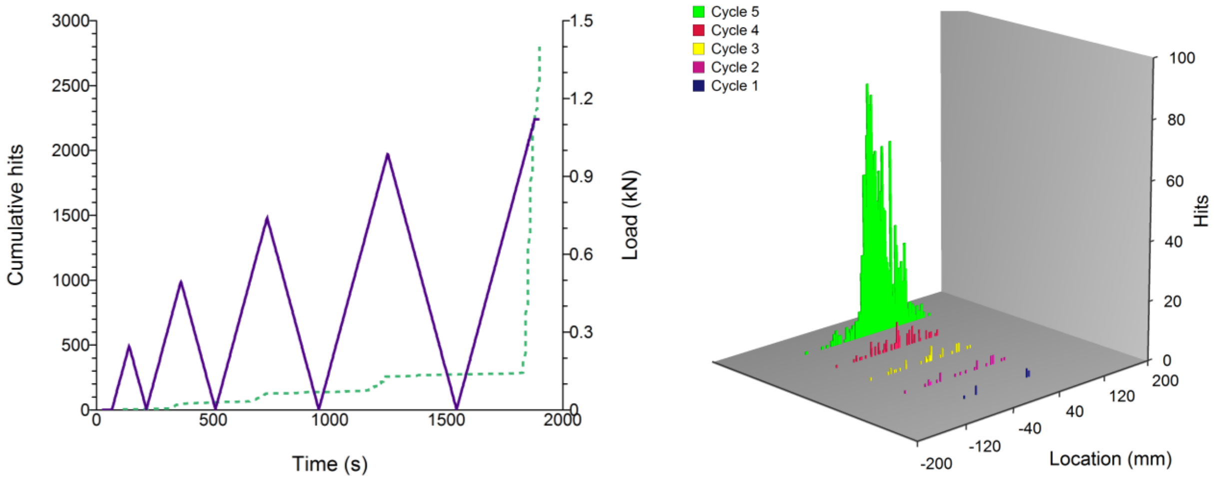
Single channel specimens (Figure 5-b) demonstrated an early initiation of damage compared to the reference specimens. A continuous increase in AE accumulation was observed for the 3rd and 4th load cycles. Similar to the reference specimens, single channel specimens showed a greater accumulation of AE hits in the 5th cycle. However, these specimens did not complete the 5th load cycle, they failed before reaching the target strain. For single channel specimens, a critical initiation of damage was observed at the second cycle. The same damage location was observed to accumulate more damage in the following load cycles.

Multiple channel specimens (Figure 5-c) exhibited different damage trends compared to the single channel and reference specimens. Damage was initiated at lower strains, as compared to the other specimens types. This damage was observed to be distributed among the flow channels. A greater accumulation of AE signals was observed at the second load cycle, and this accumulation was observed to increase with the increase in strain. This difference in the initiation and accumulation pattern of damage is observed to have a greater influence on the full-cycle fatigue life.

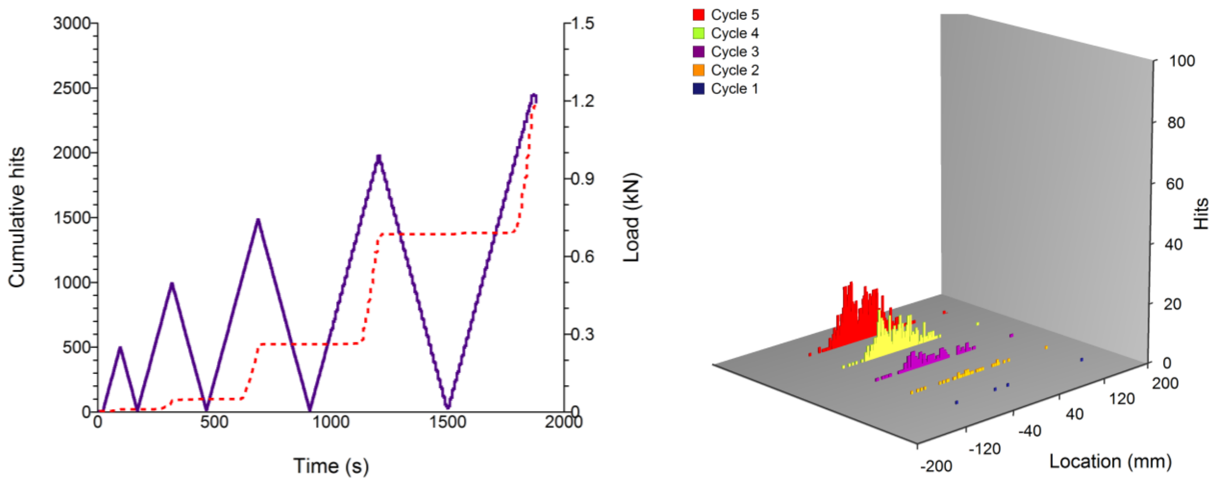




(a)



(b)



(c)

Figure 5. Load-time history along cumulative hits and damage distribution along the length of the specimens for load/reload tests: (a) reference specimen, (b) single channel specimen, and (c) multiple channels specimen

4.2. Fatigue life and damage evolution

The fatigue tests were carried out with a constant stress amplitude for a stress ratio of 0.1. The results are presented in Table 1 for specimens tested at 60% of the maximum load. These preliminary results show a clear influence of resin flow channels under cyclic loads. The reference specimen did not fail under cyclic loading and completed a million cycles. Post-fatigue static flexural test results showed a decrease in flexural strength of up to 12%. However, the single and multiple channels specimens showed a decrease in the number of cycles to failure. The single channel specimen failed at 109863 load cycles and the multiple channels specimen had a large decrease in fatigue life, failing at 2200 load cycles. This is due to a greater accumulation of damage in the multiple channel specimens compared to the single channel or reference specimens.

Table 1. Fatigue failure cycles.

Specimen Type	Maximum number of cycles
Reference	1000000
Single Channel	109863
Multiple Channels	2200

5. Conclusions

The flexural fatigue damage mechanisms of specimens with and without resin flow channels were investigated. AE signals were recorded from load/reload tests and post-processed to understand the evolution of damage under flexural cyclic loads. The amount of recorded AE signals were found to be different in specimens tested with and without the resin channels. The total accumulation of AE signals was found to be greater in load/reload tests compared to static tests. Multiple channel specimens demonstrated early damage initiation and a greater damage accumulation trend as compared to the reference and single channel specimens. Single and multiple channel specimens generated only a few tens of hits in the early cycles of the load, while during the 5th cycle thousands of AE signals were recorded. The location analysis demonstrated the damage evolution along the length of the specimen. The reference and single channel specimens showed similar damage patterns localized to particular positions. However, the majority of damage in the multiple channel specimens were distributed between the resin flow channels. The presence of geometric features and the associated variation in the lamina architecture were shown to have a significant influence on the fatigue performance of composites. The multiple channel specimen and the single channel specimen significantly reduced fatigue cycles compared to the reference specimen. These results demonstrate that resin flow channels and associated changes in local laminate architecture can influence the damage initiation and fatigue performance of composites. Work is underway to understand the failure mechanisms that underpin these effects. This study has been conducted on small size specimens, it would be useful to investigate how these effects translate to the fatigue performance of a full structural component.

Acknowledgements

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