Experimental Analysis of Damage Development in Carbon Fiber Reinforced Composites under Cyclic Loading

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Abstract
There is a global need to design low weight structures for strategic, business, and social purposes. Reducing weight is critical for improving energy consumption as well as addressing range, performance, size, and cost challenges associated with structural design, especially in the automotive and aerospace industries. In recognition of this need, advances are being made in replacing high strength steels, magnesium and aluminum alloys with carbon fiber reinforced epoxy composites. These have many merits which include weight reduction for lower fuel consumption, resistance to environmental degradation and better aesthetic appeal. For most applications, the carbon fiber reinforced epoxy composites are exposed to cyclic loading leading to fatigue failure. High cycle fatigue in metals usually evolves by the single crack initiation which propagates until catastrophic failure. In contrast to metals, damage development in carbon fiber reinforced epoxy composites occurs in a complex global fashion which occupies an under-researched field. To enable better design, there is a need for a better understanding of carbon fiber reinforced epoxy composites, in particular, damage progression during cyclic loading. The aim of this paper is to investigate damage development during fatigue loading in carbon fiber reinforced epoxy composites. To this end, carbon fiber/epoxy composites produced from a bi-axial carbon material with a fiber volume fraction of 30% were investigated. The specimens were prepared using a hand layup molding technique. The results showed the first two of the three common stages observed during fatigue damage development. The first stage involved rapid damage, followed by stage two which is gradual, and the final stage which is rapid was not observed. The obtained results clearly show the fatigue damage mechanisms in carbon fiber reinforced epoxy composite materials.

Keywords
Carbon Fiber Reinforced Composites (CFRC), Damage Development, Epoxy resin, Low Cycle Fatigue

1 INTRODUCTION

In recent years, there is a growing scientific and economic interest in carbon fiber reinforced composite materials (CFRC). This is due to the quest for low weight structures. CFRCs offer substantial improvement over metals. These improvements include high stiffness-to-weight ratio, low weight, corrosion resistance and high resistance to fatigue. Carbon fiber composites have become indispensable in industries such as sporting, aerospace, marine and automotive [1].

Carbon fiber composites are manufactured by embedding carbon fibers in a polymer matrix.

Focusing on their fatigue behaviour, several studies have been done on the fatigue behaviour of CFRCs. Early notable literature on fatigue response of composites include that of Owen et al [2], followed by Harris et al [3]. These early studies mainly focused on the development of S-N curves. However, damage development under fatigue is very important and acts as a foundation for predicting component life.

Damage development in CFRC materials under fatigue is more complex than that of metals. Damage development in metals is mainly characterised by the propagation of a single crack. The damage process in CFRCs occurs by general degradation with multiple damage mechanisms occurring simultaneously rather than having a single predominant crack [1]. Damage development in composites under cyclic loading may be divided into three stages. Stage one is rapid and involves the formation of multiple crack zones sometimes referred to as damage zones. This initial damage starts early and occurs after a few hundred cycles. This stage involves a sharp decline in the composite stiffness. The second stage is more gradual and involves decline in composite stiffness. More serious damage occurs in the final stage which is also rapid and results in final fracture [4].

There are mainly four damage mechanisms involved in a composite exposed to a cyclic loading. These are matrix cracking, delamination, fiber pullout and fiber-matrix interface failure. Matrix cracking is mainly involved in stage one. Stage two has a mixture of these mechanisms while fiber pullout is dominant in stage three [1, 2, 5].

Liang *et al* [6] investigated damage evolution for four different loading levels monitoring the strain evolution. These loading levels were 0.8, 0.7, 0.6 and 0.5 of the ultimate tensile strength of the material. All three damage stages were observed. Koricho *et al* [7] reported observing the three damage stages at a load level of 75% of the ultimate flexural strength. Rapid damage was observed in the initial stages.

Although analysis has been done on carbon fiber composites exposed to cyclic loadings, detailed analysis, as per authors' knowledge, has not been thorough on damage evolution of biaxial carbon fiber composites exposed to cyclic loading.

2 SPECIMEN FABRICATION

The material used for the investigation was biaxial carbon fiber -45/+45 with a fabric weight of 154 gsm (grams per cubic centimeter). The material used for the matrix phase was a two part epoxy resin, Ampreg 21 resin mixed with 0.33 Ampreg 21 hardener. The laminates were produced using a hand layup moulding process with a stacking sequence $[\pm 45]_7$. This stacking sequence of seven layers gives a fiber content of 30% by volume calculated using the law of mixtures. The plates had a nominal thickness of 4mm.

Specimen fabrication was done using recommendations from ASTM D5687, Standard Guide for Preparation of Flat Composites Panels with Processing Guidelines for Specimen Preparation [8]. During the manufacturing process the two part epoxy resin was mixed by weight and degassed by settling it. A debonding wax was applied to the surface of the mould for easy removal of the plate. Using a paintbrush and small roller, the mixed two part resin was applied to the carbon fiber layer wetting it completely. This was done layer-by-layer until the required number of layers was achieved. The plate was left for 24 hours to dry. A hand layup moulding process was chosen as it enables better control of resin mixing with the fiber compared to other manufacturing processes. Use of a mould also provides better dimensional control.

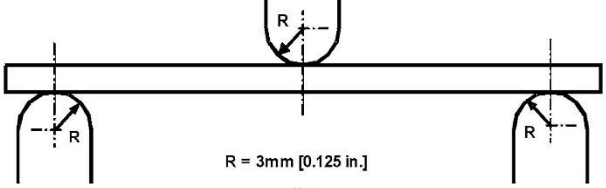
The composite plates were cut into test specimens using Computer Numerical Control (CNC) machining. A 3-D CAD model of the testing plates was initially generated using Solidworks. This CAD model was converted into a G-Code, a numerical control programming language, which is used to drive the CNC machine to do the cutting. After cutting the specimens into required shapes, the specimens were ready for the testing phase.

3 EXPERIMENTAL PROGRAMME

3.1 Static Tensile Tests

In order to determine the stress level to be used in fatigue, it was important to conduct static tensile tests. Displacement control tensile tests were conducted on the Instron 1195 machine driven by Bluehill software 2 (Figure 1 (a)). The machine is equipped with a standard load cell of 100kN capacity and a crosshead displacement measuring device. The tests were conducted according to ASTM D3039, which recommends that failure occurs within 10 mins, hence a stroke rate of 2mm/min was chosen [9]. The tensile test specimen setup is as shown in figure 1 (a).

(a)



(b)

Figure 1: (a) Tensile test setup (b) Three-Point Flexural test schematic

3.2 Flexural Tests

Three point flexural tests were conducted using the same Instron 1195 machine used during the static tensile tests. The specimen geometry is the same as the specimen geometry used for fatigue testing. The tests were again conducted at a stroke rate of 2mm/min. However, this time a 10kN load cell was used in order to improve accuracy of the applied load. The schematic for flexural testing is as shown in Figure 1(b).

3.3 Fatigue Testing

A displacement controlled bending fatigue test was conducted. The machine is displacement controlled by the use of a crank and link mechanism as shown in Figure 2(a). This setup gives a sinusoidal displacement and hence load waveform. 350 Ohm HBM strain gauges with gauge factor of 2.04 were attached to the top of the specimen as shown in Figure 2 (b). These would measure strain variations during fatigue tests. Strain logging was conducted using the National Instruments Compact DAQ with

NI 9234 data acquisition module at a sampling frequency of 200Hz. Fatigue loading was applied under cantilever configuration inducing a stress ratio (R) of -1, tension-compression loading. Load levels applied during the tests were 25% and 50% of ultimate flexural strength of the specimen as obtained experimentally. Load cycling was done at a frequency of 24Hz. All tests were terminated after reaching one million cycles (10^6).

(a) (b)

Figure 2: (a) Fatigue test setup (b) Specimen with attached strain gage

4 RESULTS

4.1 Tensile Static Tests

Figure 3 shows the stress-strain response of the tensile specimens. A total of 6 specimens were tested in accordance with ASTM D3039 [9]. Static tensile tests show two stages of linear response which are shown as region 1 and region 2 in Figure 3. This kind of response is known as bilinear response. According to ASTM D3039, a material exhibiting a bilinear response will have a secondary tensile modulus [9]. The first region repesents the behaviour of the composite prior to first stage failure while the second region is associated with matrix delamination and fiber pullout failure which is dominant in the second stage. Figure 4(a) shows a sample of a failed specimen.

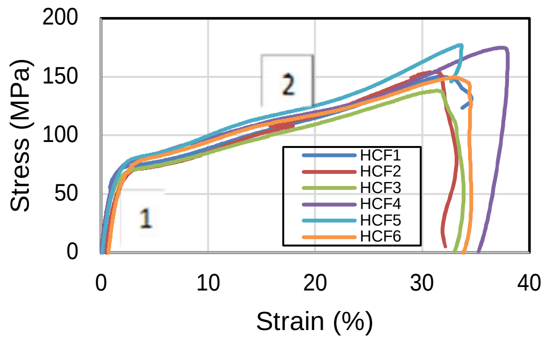
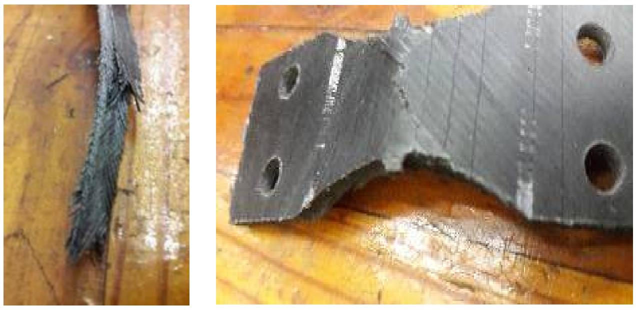


Figure 3: Tensile stress-strain response.

UTS (MPa)	TM1 (GPa)	TM2 (GPa)
157.23	0.828	0.129

Table 1: Tensile test properties

The results of of the tests are summarised in Table 1. The average ultimate tensile strength (UTS) was found to be 157.23 MPa. The average Tensile Moduli (TM) for the two regions are calculated and also presented in Table 1. The difference in tensile moduli for the two regions identifies the two failure modes.



(a) (b)

Figure 4: (a) Failed tensile specimen showing delamination and fiber pullout (b) Failed flexural specimen.

4.2 Flexural Tests

Figure 5 shows the stress-strain response of the biaxial composite under flexural loading. The test was conducted using 3 point bending in accordance with ASTM D7264 [10]. A 0.2% strain offset was used to determine the limit of proportionality by generating a 5th degree polynomial fit (dashed curve) to the curves. A linear curve was constructed parallel to this fit. The point of intersection was taken as the limit. In this case, a single failure mode is observed. The limit was found to be 157.9 MPa. 25% and 50% of this was chosen as the load level to be applied to the material during the cyclic loading.

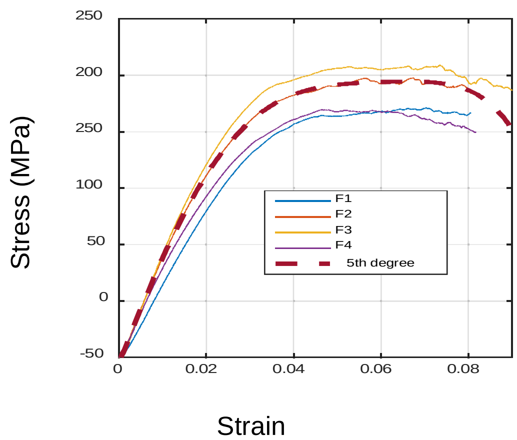


Figure 5: Flexural stress-strain response.

The results obtained from the flexural tests are summarised in Table 2 showing the ultimate flexural strength, the bending modulus and the proportionality limit.

UFS (MPa)	Bending Modulus (GPa)	Proportionality Limit (MPa)
221.1	9.5	157.9

Table 2: Flexural test properties.

4.3 Fatigue Tests

Figure 6 shows the strain evolution as the time proceeds up to the cut off point (10^6 cycles). Both of these show evolution at a loading of 25% of the ultimate flexural strength (UFS). Testing was stopped after one million cycles. Figure 7 shows the stress versus the time at 25% loading level. This is the general cyclic signal obtained from an applied cyclic displacement showing the good quality of the cyclic loading applied to the specimen. Figure 8 shows the extracted measured maximum strains revealing the variation of applied strain with time for the 25% load level. The same is shown in Figure 9 for the 50% load. In this case there is clear sudden failure of the composite at a certain number of cycles.

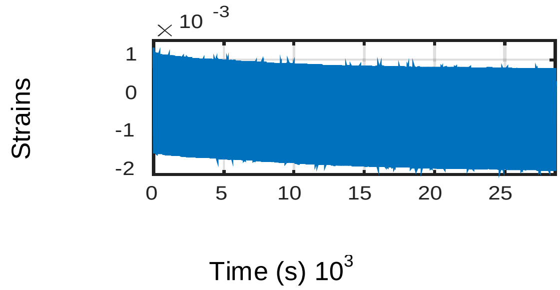


Figure 6: Strain variation as a function of time at 25% UFS load

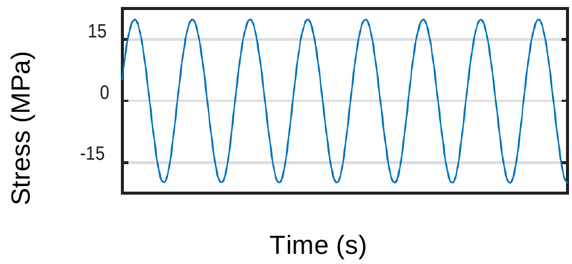


Figure 7: Sample of applied stress signal.

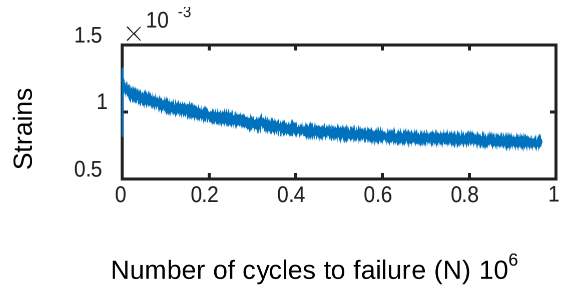


Figure 8: Maximum strains against number of cycles at 25% UFS load.

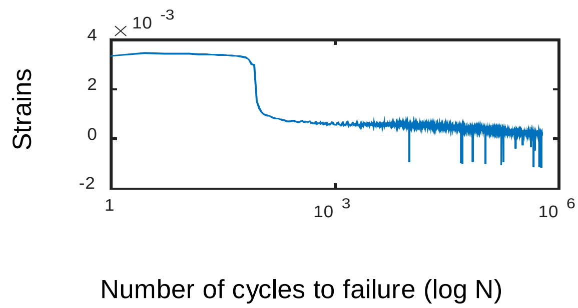


Figure 9: Maxima strains against number of cycles at 50% load.

5 DISCUSSION

Figure 3 clearly shows that the general shape of the load displacement response is consistent among all the specimens which implies that material production and material composition are soundly consistent. The stress-strain curves can be interpreted by dividing them into two linear regions which are indicated as 1 and 2 in Figure 3. The linear regions have different tensile moduli which are 0.828 GPa and 0.129 GPa respectively, showing a bilinear response. This drop in modulus indicates development of damage in the material. The curves are linear to final fracture; there is no indication of large-scale plastic deformation. This is consistent with fiber-matrix interface failure. This is the major reason why the prominent failure mode observed during the tensile testing phase was fiber pull-out as shown in Figure 4(a).

Figure 5 shows the stress-strain response of the material under 3 point bending load. The response under a flexural load has a higher modulus compared to the response under a tensile load. This indicates a significant contribution of the viscoelastic resin. Hence, the resin contributes more under a flexural load which is also supported by the difference in the ultimate tensile strength (UTS) and the ultimate flexural strength (UFS) which are 157.23 MPa and 221.1 MPa respectively.

The response of the material under cyclic loading is indicated in Figure 8 which shows a plot of the variation of maximum strains. At a load level of 25% of UFS, there is a small drop in the strains which is indicative of a change in component stiffness or stress relaxation. A linear fit to the maxima gives a gradient of 0.0000067 strains/number of cycles. This suggests that, for 25% load level, the damage development is gradual and this is as expected since general damage in composites has been reported to be gradual at low load levels [1].

However, there is dramatic damage observed at 50% load level compared to 25% load level. Figure 9 shows a log plot of the strain variation against the number of cycles. Damage occurs early in the fatigue life, within the first 1000 cycles. This is indicated by the sudden drop in the recorded strain. The damage becomes gradual beyond 800 cycles. This indicates the second stage of damage development which is gradual. This stage is observed up to the cut-off point which is one million cycles. The specimen does not reach stage three suggested in literature [1, 7].

6 CONCLUSION

Biaxial carbon fiber/epoxy composites were successfully prepared tested under cantilever bending cyclic loading at a stress ratio of R = -1. Damage was continuously monitored by measuring the strain response of the material at a specific location on the specimen. Based on the results obtained the following conclusions can be made:

- Bending strength is higher than the tensile strength. This shows the anisotropic nature of the composite material. Flexural strength and tensile strength would have been the same if the material was homogeneous.
- Biaxial composites exhibit a bilinear response under a tensile load, which means that they have a secondary tensile modulus. Final failure under a tensile load is fiber pull-out.
- A 25% UFS cyclic loading level does not cause considerable damage to the specimen. However, it exhibits gradual damage development.
- Stage one and stage two damage are observed at a load of 50% of UFS exhibited by a sudden change in stiffness. Stage three damage is not observed.

The results presented are useful in design of composite structural components. Further work needs to be done to get more information for other load levels and continued loading to ultimate failure. Similar work is also recommended for other types of composites.

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8 BIOGRAPHY

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