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ORIGINAL ARTICLE

Composite Failure Modes at High Cyclic Fatigue Life Evaluation

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ABSTRACT – Fibre reinforced polymer composite have been utilised in applications that require high strength-to-weight ratio and durability like automotive and spacecraft components. The literatures has indicated that there is a gap of knowledge in fatigue failure mechanism, and reliable prediction of fatigue life for glass and carbon fibre laminates. This study is to address experimentally the stress level dominated the composite failure mode and how to avoid stress concentration in fatigue design. In addition, it contributes to the scientific knowledge and to further increase the understanding the fatigue behaviour of composite materials structures. To accomplish this investigation goals, three types of materials were fabricated and tested; glass/epoxy, carbon/epoxy, and chopped glass/epoxy. Traditional hand layup technique for composite processing was used to fabricate the composite specimens. It involves manually positioning the reinforcement woven roving in an open mould and pouring, brushing, the resin onto the composites. This study details the experimental results of the ultimate tensile strength and high cycle fatigue, with a stress ratio of 0.1, using ASTM. Results showed that carbon fibre composite had the highest ultimate tensile strength. The power curves conducted from this paper were used to estimate the number of cycles which the material can endure.

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Fatigue properties;
Fibre reinforced

INTRODUCTION

A composite material is a combination of two or more different materials. The combination of these materials ultimately leads to a material that is enhanced compared to the individual initial materials in terms of mechanical and chemical properties. The properties of the new composite materials can be designed for structural applications, where both strength-to-weight and stiffness-to-weight ratios are critical. The classification of composite materials is divided into two categories, macroscale and micro-scale materials [1] [2]. In general, composite materials have excellent fatigue resistance. This resistance greatly facilitates their applications in the aerospace industry and for high-end industrial equipment. These applications require high-life expectancy versus fatigue progression, both of which are innate to composite materials [3] [4]. Liang et al. [5] investigated the fatigue life of flax/epoxy composites. They concluded that stable fatigue performance decreases stiffness by only about 15–20%. Other testing included, Cioffi et al. [6] used the American Society for Testing and Materials (ASTM 3039 D, ASTM D 3479) to carry out experimental tensile and fatigue tests for composite materials. It was stated that fatigue behaviour is a complex stress loading condition, that might occur in components during cyclic loads. Moreover, Cioffi et al. utilised statistical analysis to study the possibility of failure under cyclic loads, and they detected that composites have excellent fatigue properties. Another tension–tension fatigue investigation on woven fabric composites was carried out by Yasuhide et al. [7]. Their experiments were carried out in the range of 4-10 Hz with a fatigue ratio of 0.1. Baere et al. [8] examined the mechanical properties and fatigue behaviour of carbon/epoxy composites based on ASTM D3039/D3479. From their experimental results, and it was observed that specimens under a load of 400-450 MPa stress with a 5 Hz frequency, they resist failing and the test was stopped at 1,268,688 cycles. The first failure of the specimens occurred at the stress of 550 MPa, after 1.2 million cycles (high cyclic loading). Their findings suggested that all specimens fail in the machine tab section, which is suggestive of the fact that the specimens need to be upgraded. A more comprehensive and detailed investigation of the progressive damage that occurs with composite materials was done by [9] [10] [11]. Additionally, Nikishkov et al. [10] used finite element techniques to predict the damage that might occur on carbon/epoxy laminate composites under fatigue loading as an attempt to simulate fatigue failures. The process was constructed by modifying materials' strengths according to the S–N curves and getting rid of its reliance on specific amplitudes. The mechanical properties are based on an eight layers coupon with a 0.1 load ratio. Furthermore, the work of [12] [13] [14] [15] examined the behaviour of advanced composite material experimentally to fill in the pre-existing gap regarding this subject.

The review of literature has indicated that there is a knowledge gap in fatigue failure mechanism, their design factors and reliable prediction of fatigue life for glass and carbon fibre laminates. Yet, questions are remaining on how the stress level dominated the composite failure mode and how to avoid stress concentration in fatigue design. The innovation of this study is to address these questions experimentally to contribute to the scientific knowledge and to increase further the understanding of the fatigue behaviour of composite materials structures. To accomplish this goal, three types of

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materials were tested: glass/epoxy, carbon/epoxy, and chopped glass/epoxy. The ultimate tensile strength, failure modes, and fatigue properties of the materials were determined experimentally. Specimens were fabricated using the hand lay-up technique. This is a traditional composite processing technique [16] [17] that involves manually positioning the reinforcement mat or woven roving in an open mould and pouring, brushing, or spraying the resin onto the composites. The samples were tested at various stress levels low to high as per ASTM, to understand the fatigue behaviour. The outcome of this experiment is essential to understand the property and failure behaviour implementation of composite materials subjected to fatigue loading and designing structures under moving loads.

EXPERIMENTAL PROCEDURE

The used materials were woven fibre, due to its superior characteristics, such as excellent stiffness-to-weight ratio and corrosion resistance. Woven roving fibres were determined to be the finest materials in the context of the hand lay-up method [16]. Moreover, the intertwining fibre structural design prevents fibre failure modes, such as micro buckling and gross delamination [17] [18]. The fibre reinforcement materials modelled in this work were E-glass woven fabric (EWF400-1000), carbon woven fabric (EC3K) and chopped glass fibre (CHOPPED STRAND 3075). The pattern design of the composite reinforcement was 2/2 twill plain weave. The selected matrix was the epoxy resin (EP-A215C1) and hardener (EP-B215); which are commonly used for hand lay-ups at room temperatures. The low viscosity allows easy handling and provides good wetting of the reinforcements and substrates. They were mixed at the volume ratio of 100:20.

The woven roving fibre was manually positioned onto a plate of glass, and the epoxy resin was brushed over into the woven roving fibres. The preparation of the specimens involved using two glass plates and a few layers of thin, flexible plastic tarps. This was used to protect the glass plate from being in direct contact with the epoxy resin. The fibre volume fraction of the specimens was between 50-56 %. The process starts by fixing the fibre onto the glass plate and simultaneously preparing the solution mix of epoxy resin and hardener. The ratio used in this case was a 100-unit volume of epoxy resin mixed with a 20-unit volume of hardener. The mixing needed to be fast and accurate to avoid the hardening of the mixture before its fabrication. This mixture was then brushed onto the fibre and distributed evenly over the entire dimension of the fibre. The hardener already has a direct correlation with the composite's strength. Next, a second glass plate was added onto the specimen. The specimens were then covered with fibre-epoxy composites. The composite was left to dry for at least eight hours then exposed to the atmosphere for an additional two hours to ensure that it was totally dry. Once the epoxy hardened, the specimens were removed for the final process of cutting. Finally, the specimens were cut into identical dimensions for testing.

Static Test

The monotonic tension test is regarded as a basic mechanical experiment for materials. The tensile test is performed to obtain the fatigue strength and Young's modulus, which provides a comprehensive knowledge of the properties of composite materials. The data of the stress-strain curve was acquired from the INSTRON machine and was then used to determine the mechanical properties, carry out post-analysis, and document the tensile test. The tensile test speed is set at a constant value of 1 mm/min, up to the fracture stage, according to ASTM recommendations. Five specimens were fabricated for each type of material: (glass fibre, carbon fibre and chopped glass fibre) based on ASTM (D3039) [19]. Each test specimen made up of eight layers of fabric lamina. This was done to provide a symmetrically balanced angle-ply laminate, as recommended in the standard with the stack sequence of the ply 0/90°. Resins and hardeners form the matrix of the composite material, and both regarded as being the most suitable [3]. The experimental work consisted of materials used, specimen preparation, finishing process and finally testing. The dimensions of a typical tensile ASTM specimen are 10-30 mm wide, having a length of 200-250 mm, with a maximum thickness of 10 mm [3]. It should be noted that the tensile tests were carried out at a room temperature of 20 °C.

Fatigue Test

Fatigue is one of the most common failures experienced by materials, with the most common factor being cyclic loading. This makes the calculation of the fatigue life of the proposed composite vital, especially in the context of lightweight industrial applications such as carbon/epoxy, glass/epoxy and chopped glass/epoxy. The fatigue tests were carried out under a dynamic servo-hydraulic INSTRON testing machine. The specimens' dimensions for tension-tension fatigue are similar to the static tensile specimens and mostly based on the ASTM D3039 / D3479. The stress ratio (R) of +0.1 was engaged in this study and kept fixed for all the specimens. The fatigue tests were performed under constant amplitude loading with a sinusoidal waveform and continued until the specimens ultimately failed (i.e. 10^6 cycles). Seven different stress levels (from 35% to 80% of the fatigue strength of the composite) were used to plot the fatigue stress life diagram. It should also be pointed out that the fatigue strength of the materials was determined from the tensile test results. At each stress level, three specimens were tested. Special software was then used to monitor the amplitude stress and number of fatigue life cycles.

RESULTS AND DISCUSSION

Monotonic Mechanical Properties and Failure Modes

In this section, the properties of the proposed composite material, such as Young's modulus, ultimate tensile strength, and its respective failure modes, are presented. The effective Young's modulus of the materials in the multi-axial directions were calculated from the experimental results. The stress levels in both directions were similar. The stress level for the glass/epoxy was 315 MPa, 894 MPa for the carbon/epoxy, and 124 MPa for the chopped glass/epoxy. It was observed from Table 1 that the results agreed with the other researchers [7] [9] [20] [21] utilising similar standard. The macroscopic failure modes are shown in Figure 7(a) and 7(b) of Appendix A. The failure modes were analysed and classified according to the recommendations set out by the ASTM D3039 [19]. The ASTM classification, type and location of the damages that occurred to the specimens are illustrated in Table 2.

Table 1. Comparison between the current work properties and literature review

Composite	Property	Ultimate strength (MPa)	Young's modulus (GPa)
Carbon/epoxy	Current work	894	67
	Alexander [9]	900	57.4
	Jane [21]	810.0	67.8
Glass/epoxy	Current work	314	26.8
	Yasuhide [7]	294	26.4
	Edson [20]	570	26.7
Chopped glass/epoxy	Current work	124.98	16.5

Table 2. ASTM failure mode code classification, type, area, and location [19].

Failure Type	Code	Failure Area	Code	Failure Location	Code
Angled	A	Inside grip/tab	I	Bottom	B
Edge delamination	D	At grip/tab	A	Top	T
Grip/tap	G	<1W from grip/tab	W	Left	L
Lateral	L	Gage	G	Right	R
Multi-mode	M (xyz)	Multiple Area	M	Middle	M

The average ultimate tensile strength and type of specimens' failure are reported in Table 3. It is obvious that most of the specimens failed within the gauge length either at the middle, top, or on the bottom. These failures are regarded as good failures, due to the fact that it is indicative of a well-manufactured specimen. However, the applied concentrated pressure of the machine grip on the specimens, the grip area turns out to be weak. As a result, certain specimens failed in the grip area (not within grip) of the specimen gauge. Furthermore, localised compression at the end of the grips can cause stress concentrations that stimulate failure at the grip/tap area such failure can occur in metal as well.

Table 3. Average fatigue strength and selected coupons failure mode

Composite	Tensile strength (MPa)	Failure mode
Glass/epoxy	315 ±10	EGT (1 specimens)
		DGT (1 specimens)
		LGM (3 specimens)
		LIT (3 specimens)
		LGT (6 specimens)
Carbon/epoxy	894±15	MGT (1 specimens)
		MGB (2 specimens)
		LGM (7 specimens)
		LIT (2 specimens)
		LGT (2 specimens)
Chopped glass	124.98±15	LGM (4 specimens)
		LIT (4 specimens)
		LGT (6 specimens)

Fatigue Life

This section addresses the fatigue life test results of the proposed composite materials. As discussed previously, fatigue (caused by cyclic loading) is considered to be one of the central failures in most materials. This results in the degradation of the mechanical properties of the material, resulting in failure after several cycles. Consequently, fatigue life prediction is an important parameter that needs to be evaluated for the innovative composite materials being proposed. The S-N curves are plotted without including the fatigue strength of the materials because it is measured from a quasi-static test and not a fatigue test. In addition, the quasi-static test setup is different from the fatigue test rates. The fatigue results for chop/epoxy, glass/epoxy and carbon/epoxy composite are presented in Figure 1, Figure 2, and Figure 3, respectively. All of the fatigue data were plotted as absolute maximum stress vs log cycles to complete separation (specimen failure).

Figure 1 shows the plot of the Wohler stress–life (S–N) curve for the chopped glass epoxy composite. The vertical axis in Figure 1 represents the ultimate tensile strength for the chopped glass epoxy, while the horizontal axis represents the log of cycles when the specimen fails. The black curve shown in the figure represents the power regression equation law, determined for each type of material. It was observed that the chopped glass epoxy has a lower ultimate tensile strength of 125 MPa compared to the other composite materials used. In addition, it can be seen that the endurance limit of chopped glass epoxy is very low, with a value of 26 MPa, and fails at 935,533 cycles.

The glass/epoxy specimens fatigue strength is 315 MPa as in Figure 2. Furthermore, a remark should be made regarding the fatigue test of glass fibre composite specimens with a maximum stress level of 117 MPa. In the experimental tests of this level, one specimen managed to withstand one million cycles, while the other two specimens failed within the range of 914,350 cycles. However, these two specimens failed prior to one million cycles due to tab failure, which means that these samples failed ahead of time. It is because the compression under the grips causes the local cross-sectional area to be smaller than the tensile section; as a result, failure took place at the grip area.

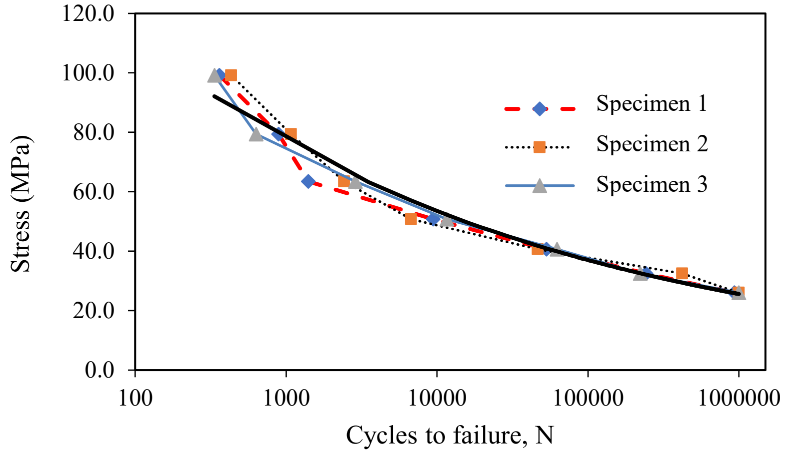

Figure 1. Experimental fatigue S-N curve of chopped glass/epoxy composite under tension-tension fatigue test with R=0.1.

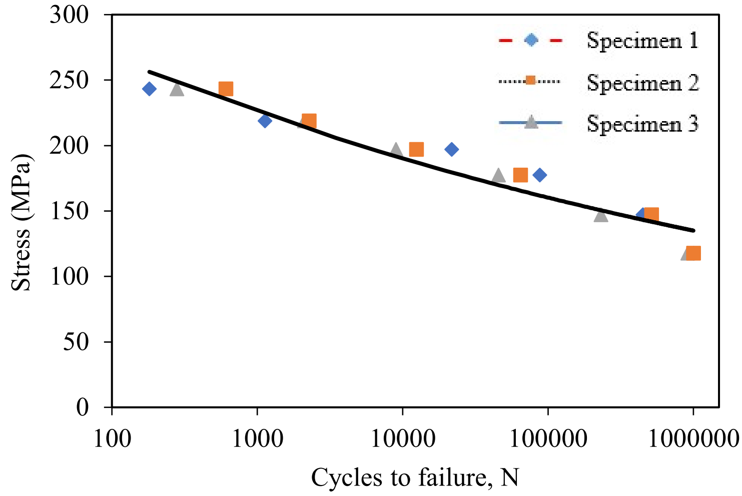

Figure 2. Experimental fatigue S-N curve of glass/epoxy composite under tension-tension fatigue test with R=0.1.

Carbon/epoxy specimen showed the highest fatigue strength compared to the other composite materials. It is perceived from Figure 3 that 267 MPa is the endurance limit for the carbon/epoxy and the arrowhead at 10^6 indicates a 'run out tests', which means that the specimens did not fail. A particular visual matrix crack on the specimen's surface was detected, which is not regarded as a major failure, but nonetheless, the endurance load was reduced by a further 10 % just to guarantee that no failure occurs in the future. It is noted that there were no visible damages on the carbon/epoxy specimen, and the test was automatically stopped after one million cycles.

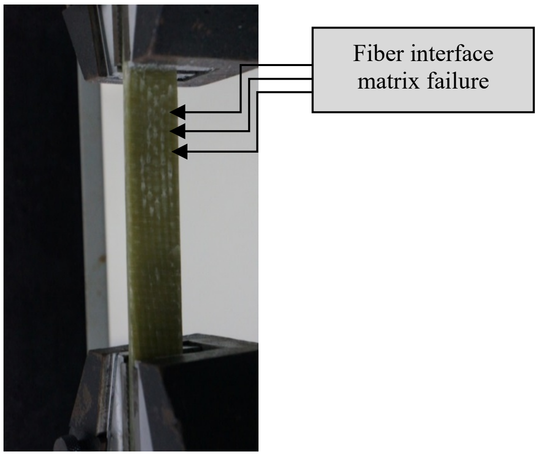

Figure 3. Fatigue common failure mode on a Glass/epoxy specimen under low loads.

Additionally, it should be noted that the glass fibres were more sensitive to maximum loads and the first failure that occurred in the specimen's surface was a random fibre interface matrix failure along with the matrix, as shown in Figure 4. This kind of failures directly affects the elastic properties of the materials during the primary stage, particularly in the fatigue test.

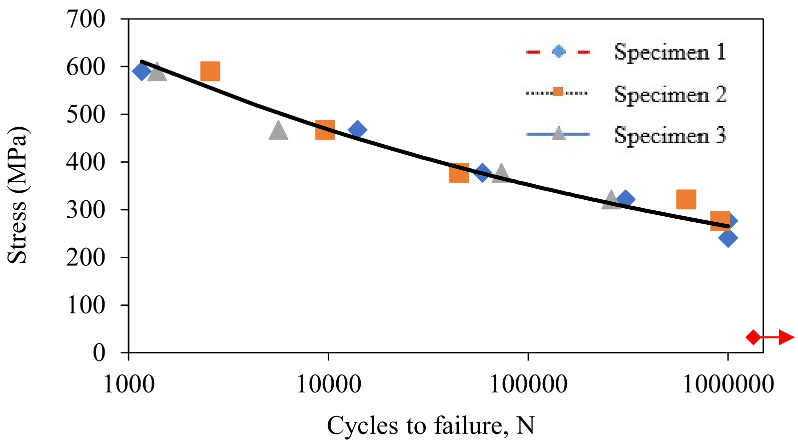

Figure 4. Experimental fatigue S-N curve of carbon/epoxy composite under tension-tension fatigue test with R=0.1

In the carbon fibre/epoxy specimens, the main failure occurred was matrix cracks at low load levels in its early lifetime, as clearly illustrated in Figure 5. To be more specific, the matrix failed audibly and visibly after the load exceeded 20 kN. If the failure was framed in the context of time, the matrix would fail, first; followed by fibre breakage, and finally, the specimen undergoes a permanent, irreversible failure. The specimens exhibited brittle behaviours, where its failure was sudden without any prior indication of failure initiation.

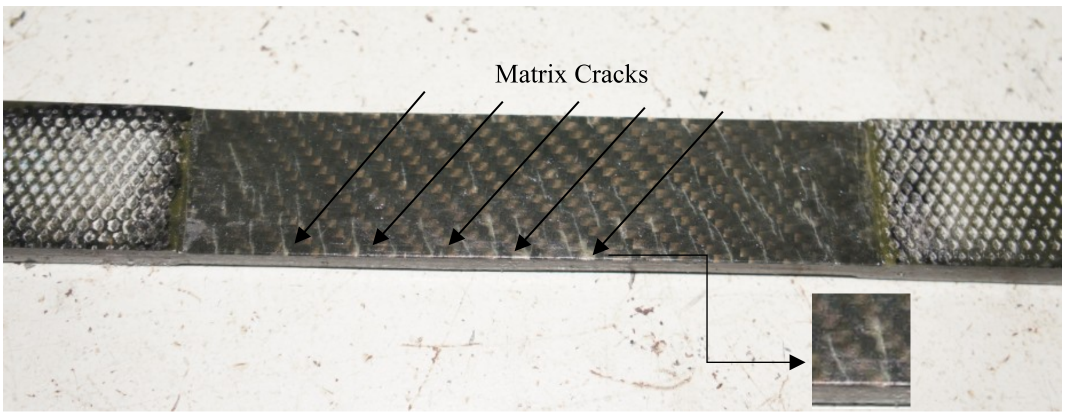

Figure 5. Illustration of matrix cracks on carbon/epoxy composite specimen in high cyclic fatigue region.

Different Materials Comparison

From the S-N data, it is important to note that the carbon/epoxy possess significantly stronger fatigue properties than the glass/epoxy and chopped glass for all loading conditions. It is also confirmed from the fatigue test that the chopped glass exhibited the lowest values compared to the aligned fibre. However, it should also be pointed out that the glass/epoxy has higher fatigue strength than chopped glass in terms of static and fatigue properties. This is depicted in Figure 1 and Figure 2. Therefore, it was surprising that the failures and damage accumulation on the glass/epoxy specimens exceeded the chopped glass composite. One possible explanation is that the fibre and matrix interface of the glass/epoxy was very feeble due to poor adhesion between the sticking layers. This might have been the result of the rough surface of the fibres. Other explanations are that the complex directional nature of composite materials induces these types of unique failures or that the chopped glass maintains its strength over the fatigue life cycle at low failure modes. Overall, the fatigue failure modes of the fabricated composite specimens were similar to static failure modes. The Wöhler curve, shown in Figure 6, compares the composite and stainless-steel materials (Type 316L) [21]. In summary, the specimens failed at 1000 cycles. This is a very short life, and the failure modes are still similar to the high cycle fatigue because the material reaction at the microstructural level is similar to the one million-cycle failure under lesser stresses.

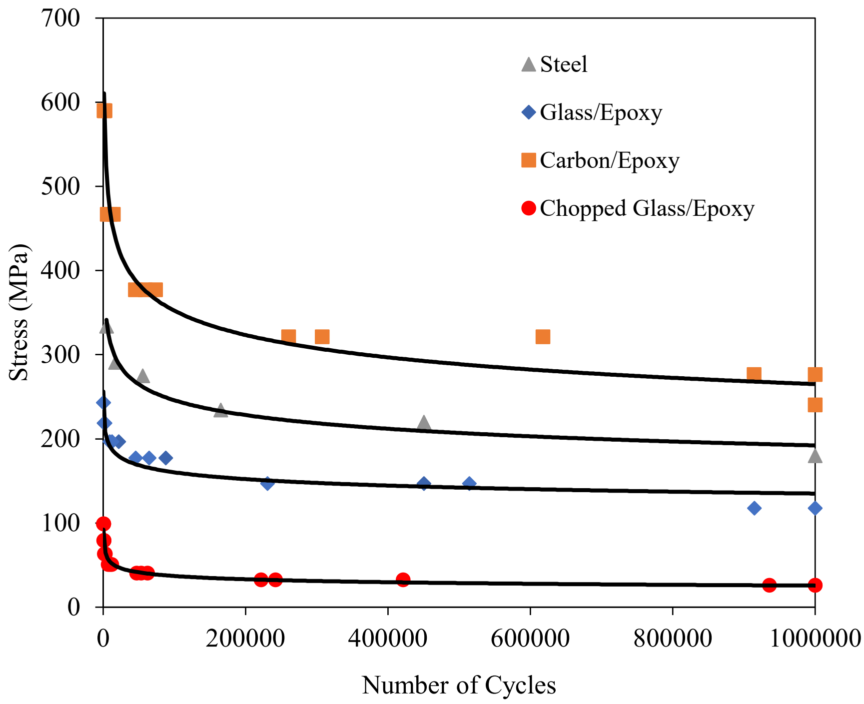

Figure 6. Number of cycles with applied stress comparison between steel and composite materials.

CONCLUSION

The presented work investigated the mechanical properties of three types of composite materials, namely, glass/epoxy, carbon/epoxy, and copped glass/epoxy. The specimens' dimensions and failure modes were classified according to ASTM D3039. S-N curves were plotted from the experimental stage to evaluate the composite materials high cyclic fatigue life as shown in Figure 1, Figure 2 and Figure 4. The results showed that carbon fibres have higher fatigue properties comparing to stainless steel, as shown in Figure 6. The endurance limits of carbon epoxy were 267 MPa under high cyclic fatigue test. At the same time, chopped glass/epoxy exhibited the lowest fatigue life endurance limit with a value of 26 MPa. Based on the test outcomes, the chopped glass fibre epoxy did not have true endurance life limit, as it failed all trails when tested under several cycles. The results enhanced knowledge depth into the potential uses and suitability of various types of composite materials in a variety of fields such as the aerospace or automotive industries. The study provides new data evaluations fatigue failure mechanism and reliable prediction of fatigue life for glass and carbon fibre laminates used in this instance. In conclusion, all the composites utilised in this investigation fit to the power-law curve, nevertheless using different types of resin are recommended for future research.

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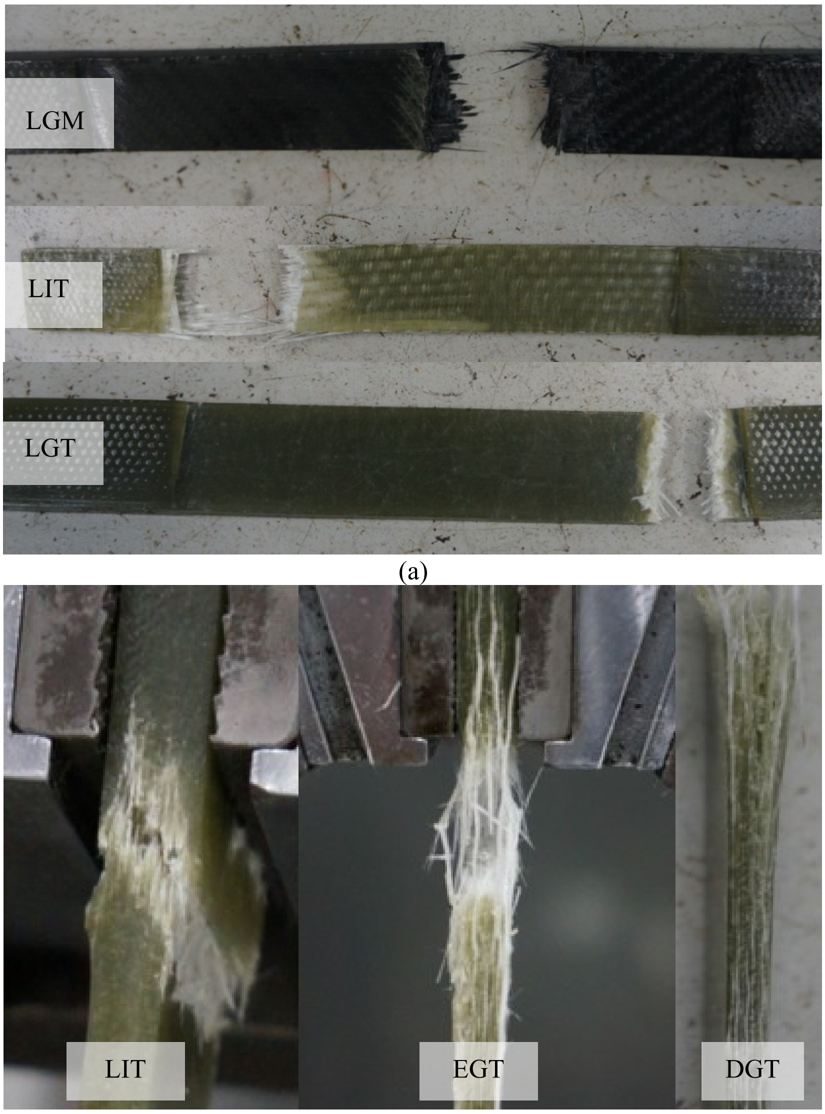
APPENDIX A



(b)

Figure 7. (a) Composite failure modes and, (b) failure mode type.