FATIGUE LIFE BEHAVIOUR OF FIBERGLASS-REINFORCED COMPOSITES SUBJECTED TO UNDERLOADING

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ABSTRACT: Each Fiberglass-reinforced composites (FGRC) can be used as replacement of most metal in manufacturing vehicle parts due to their excellent mechanical properties, low cost and corrosion resistance. Fatigue failure occurs in FGRC upon subjected to constant amplitude loading (CAL). However, studies on the behaviour of FGRC are still in lacking of tools for predictive engineering and analysis mainly due to inadequate understanding of these materials behaviour including it's integrity when subjected to variable amplitude loadings (VAL). Therefore, this study aim to investigate the effect of underload towards the fatigue life behaviour of FGRC with different laminate orientations. The Reinforcement materials use is unidirectional fiberglass with [0/90]° and [±45]° orientations and chopped strand mat is choose to study the effect of periodic underload in cycles. Meanwhile polyester resin is use as the matrix material. The FGRC composite is fabricated using a hand lay-up technique according to ASTM D3039 for tensile test and ASTM D3479 for fatigue test. Results showed that underload effect deteriorate the fatigue life behaviour of FGRC from 1.4% to 18% decrement from the actual value when being compared to result in CAL.

KEYWORDS: *Fatigue Life; Fiberglass Reinforced Composite; Fiber Orientation; Underload*

1.0 INTRODUCTION

Fiber reinforced plastics have been widely used for manufacturing aircraft and vehicles structural parts because of their particular mechanical and physical properties such as high specific strength and lower cost compare to metal and alloy [1-2]. Fiber reinforced composites are demanded in the industry due to their fast fabrication processes and high environmental resistance allowed this composites material to replace the current metallic material in industries [3-4]. Previous researchers have focused on composite materials especially the fiberglass to determine the fatigue strength and failure mechanisms of the material.

However, there still lack information on the fatigue behaviour of the material when subjected to VAL. The known effects towards the fatigue strength of fiberglass such as the loading rate, mean stress, load frequency, thickness, fiber volume and fiber orientation of the composite lamina still inadequate to understand the fatigue behaviour in VAL condition especially subjected to underload (UL) [5-9]. The effect of VAL in fatigue life is more complex because it involves the loading history effect and loading sequence [10-11]. Since the 1960s, the effects of UL on fatigue behaviour of most metal have been studied extensively but very rare for fiber reinforced plastic especially for fiberglass. This sort of loading condition will generate acceleration of the fatigue crack propagation and lead to reduction in fatigue life [12].

The presence of UL in the sequence produces a different behaviour of the material fatigue crack growth (FCG) rates. Zitonis and Irving [13] applied a single underload at certain stress ratios in a sequence on a specimen made of aluminium alloys AA8090-T852 and AA7010-T76351. Their results indicate that the FCG rates under a loading sequence containing tensile under load accelerates the FCG rates compared with those of CAL.

A study done by Rotem and Nelson [14] on the fatigue behaviour of graphite/epoxy laminates and showed that VAL tension–compression fatigue load have more effect toward the reduction of fatigue life. Reis et al. [15] study on the fatigue life evaluation for carbon/epoxy laminate composites under variable block loading and they found that the carbon fiber reinforced plastic (CFRP) produced a non-linear behaviour due to progressive fiber buckling in compression fatigue test that lead to a drastic decay of fatigue strength. Therefore will reduce the fatigue life of the composite laminates. According to El-

Kadi and Ellyin [16], the tensile and compressive stresses, in general, do not contribute equally to the damage. The compressive loads produce a significant reduction in fatigue life when compared with results for tension–tension loading [14].

Even though a previous study was done on the effect of variable amplitude loading, recent study in this subject for composite materials is still lacking. This motivates the current work to investigated the UL effect on fatigue life behaviour of FGRC with different types of fiberglass, namely, unidirectional fiberglass and chopped strand mat (CSM) using a hand lay-up technique. The final result shows that fatigue life reduction of the composite when subjected to UL in the loading cycle.

2.0 METHODOLOGY

For composite preparations, the fabrication of sample is using a hand lay-up technique and polyester resin as the matrix. A Unidirectional glass fiber of with 33% fiber volume content with orientation of [0/90]°, [±45]° and CSM is chosen to study fatigue life behaviour subjected to underload. The specimens were cut out into size 30cm x 30cm with four pieces for each composite to achieve the required thickness of 3.0 mm. Polyester resin and hardener are mixed, then the mixture is applied to mat using a roller to eliminate air bubbles as well as to distribute the matrix evenly on each ply surface. The laminates were fabricated by placing the glass fiber one over the other with a matrix in between the layers. The same procedure is carried out for all four mats for each composite. Finally, the laminates were cured in room temperature for 2 days to ensure the matrix is completely dry.

After fabrication, experiment is carried out for the specimens subjected to both CAL and UL fatigue test. The specimens were cut to meet the standard of ASTM D3479 for fatigue test using a sine wave at 10 Hz frequency and stress ratio, R= 0.1 for CAL while for UL the setting of parameter is using a Wave Matrix software as shown in Figure 1. The fiber orientation selected for the tensile test were [0/90]°, [±45]° and CSM. The experiment is conducted using a Universal Testing Machine, Instron 8872.

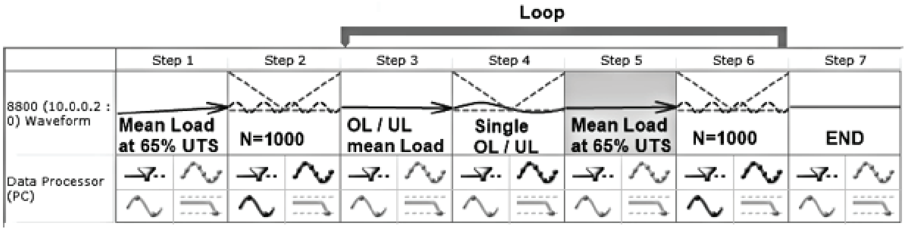


Figure 1: Step by step parameter setting for VAL fatigue test

The CAL fatigue test was carried out first to obtain the data at 65% ultimate tensile strength (UTS) value which is chosen as a reason of medium fatigue load to save time consumption running the experiment. Data from that value are used to study the UL effect towards the FGRC fatigue behaviour. The UL experiment is conducted by selecting six loading amplitude ranging from 5% UL to 30% UL. A single UL cycle is introduced periodically every 1000 cycle until the composite samples break. The result is presented in the form of load percentage versus number of cycle to failure (Nf).

3.0 RESULTS AND DISCUSSION

3.1 Mechanical Properties of FGRC

Tensile test is one of the fundamental mechanical test which is required to obtain the mechanical strength of any material, where a carefully prepared specimen is subjected to tensile load that was operated at constant head-speed tests of 5 min/mm. The information from tensile test is important to determine the load amplitude in fatigue test when subjected to CAL. Table 1 shows the mechanical properties of CSM and [0/90]° and [±45]° orientations. The results are obviously affected by the fiber orientation.

Table 1: Mechanical properties of fiberglass polyester composite

Mechanical Properties			
Orientation	UTS (MPa)	εult (mm/mm)	E (MPa)
CSM	71.6	0.11	995.2
[0/90]°	166.2	0.21	1947.7
[±45]°	40.7	0.18	713.9

The above results show that [0/90]°present a higher mechanical strength compare to CSM and [±45]°. The UTS value which mean the capacity of the composite to withstand load before fracture, showed that [0/90]° is the highest with 166.2 MPa. Meanwhile, CSM and [±45]° orientation, respectively showed the UTS value of 71.6 MPa and 40.7 MPa. Table 1 showed that [0/90]° have the highest value of Strain, εult compare to CSM and [±45]°, this indicated that the sample can elongate more before reach the plastic region. The [0/90]° orientation showed a value of 0.21 while CSM and [±45]° orientation respectively showed a value of 0.11 and 0.18.

The same trend also observed for the Young's modulus, E; the highest value is at [0/90°] with 1947.7 MPa. This indicated that [0/90°] orientation is more elastic compared to CSM and [±45°]. Meanwhile, CSM and [±45]° orientation respectively showed the Modulus Elasticity, E value of 995.2 MPa and 713.9 MPa. The results obtained in this research are having the same trend with other research findings. A study done by Mortazavian and Fatemi [17] on the effect of fiber orientation using two type of glass fiber which are Polybutylene Terephthalate (PBT) with 30 wt% glass fiber and Polyamide-6 (PA6) with 35 wt% glass fiber. The findings indicated that fiber orientation of [0/90°] showed a higher UTS value compare to [±45°]. The reason behind this is due to the longitudinal samples much of the resistance against loading occurs in shell layers, due to load enduring capability of oriented fibers. According to Mortazavian and Fatemi [17], shell layers compromise a greater percentage of the cross section than the core layer, tensile properties in the longitudinal direction is greater, as compared with in the transverse direction.

The best mechanical properties can generally be obtained for composites when the fibre is aligned parallel to the direction of the applied load. For the case of CSM which is higher than the [±45°] orientation is because in this research a higher fiber content of CSM is used. This is because the main findings is to compare the aligned long fiber with the random discontinuous fiber arrangement. Although a higher fiber volume content is selected for CSM, the finding still indictates that [0/90]° is stronger. Another reason is because of the production sources and manufacturing processes that involved attributed to the variations of result in fiber strength. The [±45°] orientation is arranged in transverse direction in which transverse tensile loads may also be present. So Under these circumstances, premature failure may result in extremely low transverse strength, which sometimes lies below the tensile strength of the matrix [17-18].

3.2 Fatigue Life Behaviour of FGRC Subjected to CAL

The UTS result from tensile test is use to determine the life cycle of FGRC through fatigue test subjected to CAL. The life cycle of the composite is presented in form of S-N curve in Figure 2 showed a semi-log plot of stress amplitude versus number of cycle fatigue life for composite with orientation of [0/90°], [±45°] and CSM.

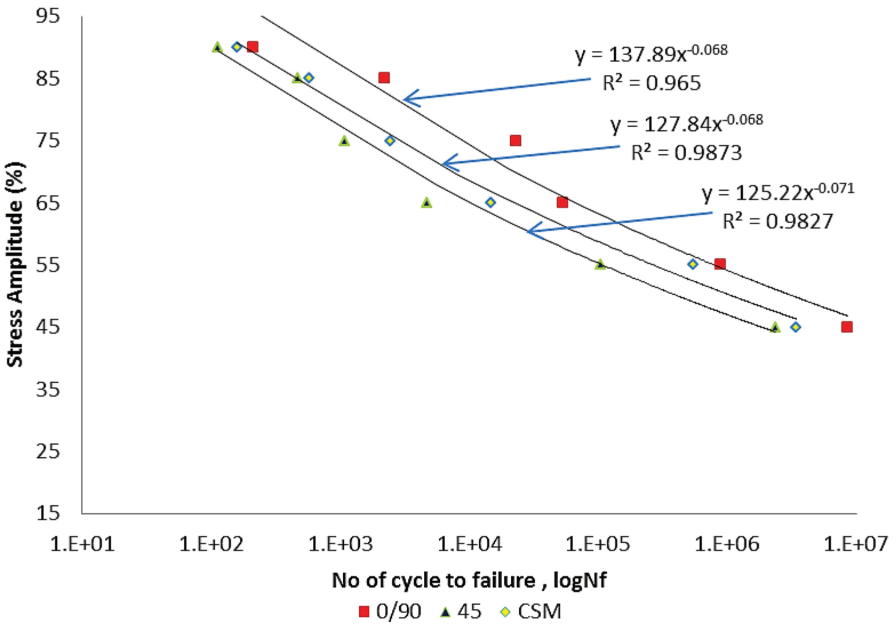


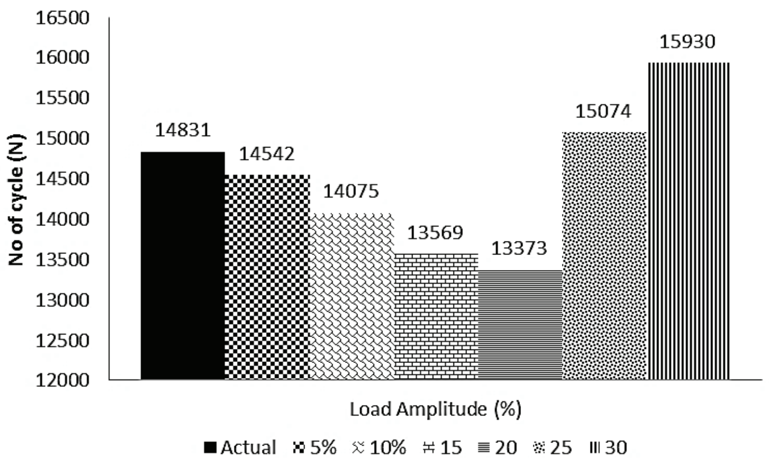
Figure 2: S-N curves showed the comparison of the number of cycles to failure for the different FGRC orientations subjected to CAL

The S-N curve shows a general trend, where the number of cycles of fatigue life increases with decreasing stress amplitude, as normally occurred in fatigue life of composite laminate when subjected to constant amplitude.

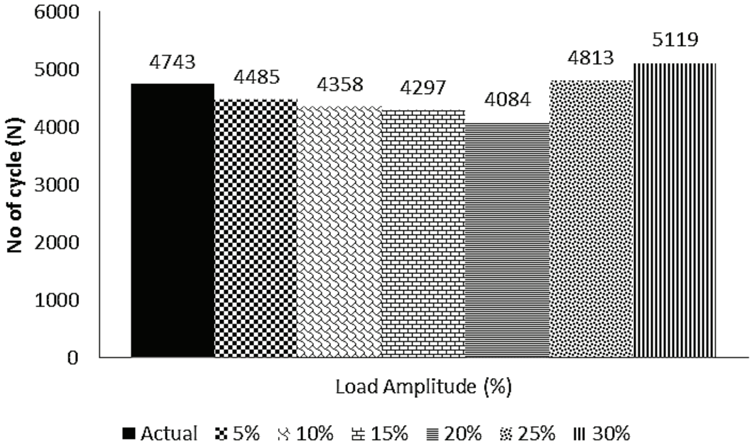
It is obviously noticed that the number of cycle to failures is greater in [0/90]° orientation compared to CSM and [±45]° orientation. By looking at 3 points of stress amplitude (%), the trend of fatigue behaviour can be understood. At 90% UTS (high load), the S-N curve showed that [0/90]° orientation has the highest number of cycle with 212 cycles before failure, followed by CSM with 160 cycles before failure and the lowest number of cycle before failure is shown by [±45]° orientation with 113 cycles. At 65% UTS, the S-N curve showed that [0/90]° orientation has the highest number of cycles with 54021 cycles before failure, followed by CSM with 14831 cycles before failure and the lowest is [±45]° orientation with 4743 cycles before failure. At 45% UTS (low load), the S-N curve showed that [0/90]° orientation has the highest highest number of cycles with 8 548264 cycles before failure, followed by CSM with 4 429129 cycles before failure and the lowest is [±45]° orientation with 2 383652 cycles before failure. Fatigue life was found to be the longest in [0/90]° orientation, whereas the shortest was observed in [±45]° orientation. The results of the fatigue tests seem to have an agreement with the fiber orientation effect. According to previous study done by Ferreira et al. [18] the fatigue strength of [0/90°] orientation is much higher due to the normal stress is predominantly absorbed by longitudinal direction. Normally the failure is due to the fiber breakage. Whereas for [±45°] orientation the failure is in the transverse planes where predominant fatigue mechanism is the debonding between the fiber and matrix caused by normal stresses that resulted matrix failure in the direction of fiber.

3.3 Fatigue Life Behaviour of FGRC Subjected to UL

The Fatigue life behaviour of the fiber orientations and CSM shows that the number of cycle of each composite sample decreases from 5% UL to 20% UL. The trend seems to have a slightly increment at 25% UL to 30% UL for each composite sample. Overall, the histogram chart shows that every point of UL obviously affects the number of cycle (*N*) of each composite. The comparison between the actual value and the value after each UL is presented in Figure 3.



(a)



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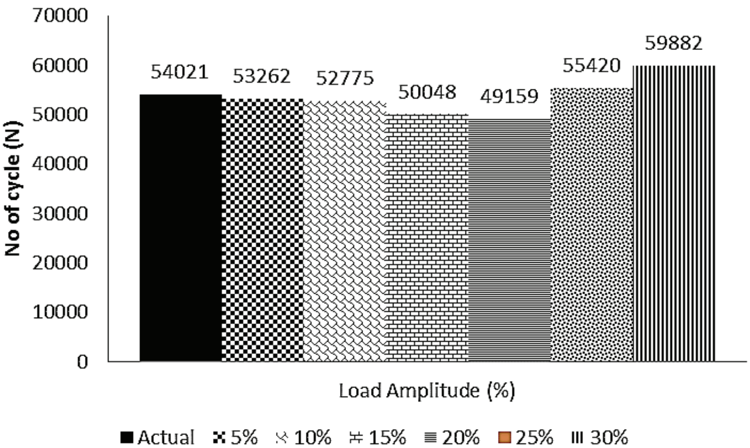

(c)

Figure 3: Comparison of actual number of cycle at 65% UTS with number of cycle after each UL: (a) CSM, (b) [±45]° and (c) [0/90]°

From the histogram chart of CSM, UL seems to reduce the number of cycle from 5% to 20%. At 5% UL, the number of cycle decreases about 7% from actual value. The lowest value of the chart is at 20% UL, which contributes to the 9.8% decrement from actual value. The trend line started to slightly increases at 25% UL, which is at a value of 1.6% increment from actual value. The trend continues to increase until 30% UL, which is at a value of 7.4% increment.

The same trend is found in the histogram chart of [±45]° orientation. A total of 1.4% decrement to the number of cycle from the actual value when the composites are subjected to 5% UL. The lowest value of the chart is at 20% UL, which contributes to 14% decrement from actual value. However, at 25% and 30% UL, the number of cycle climb to 1.5% and 7% increment from actual value.

Histogram chart for [0/90]° orientation showed the same trend as CSM and [±45]° orientation. At 5% UL, the number of cycle showed a decrement of 1.4% from the actual value. The lowest peak is at 20% UL showed a 49159 cycle which is 9% below the actual. The same effect of UL is noticed at 25% UL and 30% UL; the trend line slightly increasing from actual number of cycles at 65% UTS.

From the comparison in Figure 3, the number of cycle of each composites sample decreases within 5% UL to 20% UL. This finding is explained by the single periodic UL introduced every 1000 cycle that causes the reduction in fatigue life of the composite followed by the acceleration effect that took place in the fatigue crack propagation as a load interaction effect [19]. This phenomenon is explained by some theory for metal and alloy which stated that UL effect induces tensile residual stresses ahead of the crack tip. Another research finding stated that when UL is introduced, the effect will reduces the height of plastically deformed material in the area behind the crack by compressive yielding [20-21]. These previous finding by Carlson and Kardomateas [22] mentioned that the fatigue crack growth rate under periodic ULs goes significantly faster than the results obtained from a CAL test; this come to an agreement in this study that UL effect reduce the fatigue life of FGRC.

For the case of 25% UL and 30% UL, the fatigue life seems to be slightly increase from the actual value at 65% UTS; which is a contradiction to the effect of UL in this study. The two points of load may have too low to contribute the acceleration of crack growth; hence less damage during the fatigue cycle that lead to a higher fatigue life of the composite.

4.0 CONCLUSION

The effect of UL on fatigue behaviour of FGRC was investigated. The results indicated that the FGRC [0/90]° orientation has the highest mechanical strength and fatigue strength under CAL compared to [±45°] orientation and CSM. The application of UL in the cycle will reduce the fatigue life of FGRC from 1.4% to 18% reduction. This result indicates that the composites have lower number of cycles before failure when subjected to UL in comparison with CAL. In conclusion, fatigue life behaviour of FGRC is significantly affected by the UL ratio for all the composite fiber orientation, which is explained by the loading condition generate acceleration of the fatigue crack propagation and lead to reduction in fatigue life during the UL cycle.

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