Effect of stress ratio on the fatigue behaviour of glass/epoxy composite

A R A Syayuthi, M S Abdul Majid, M J M Ridzuan, K S Basaruddin, Peng, T L
School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.
sayayuthi@unimap.edu.my,

Abstract. The effect of stress ratio on the fatigue behaviour of the GFRE composite has been investigated. The glass fibre reinforced epoxy (GFRE) composite plates were fabricated using vacuum infusion method. Static tensile was performed in accordance with the ASTM D5766 standard, and the cyclic test was conducted according to ASTM D3479 with three different stress ratio, R= 0, 0.5, -1. Static tensile tests were carried out to determine the ultimate strength of this composite. Subsequently, fatigue tests loads ranging from 30% to 90% of the ultimate load were applied to each specimen. The S–N curve of different stress ratio loading of fibreglass/epoxy composites was then established. The results show that the number of cycles to failure increases as the loading is decreased. The specimens for fatigue tests loads 30% at R= 0 and -1 recorded the highest number of cycles at 2 million cycles. The results obtained from this test indicated a significant life reduction for R = -1 compared with the tension-tension loading, with the life reduction for R = - 1 being greatest. The fatigue behaviour of the GFRE composite materials is not only influenced by the percentage of fatigue tests load but with different of stress ratio.

Keywords: Glass fibre reinforced composites; tensile properties; fatigue strength; stress ratio.

1. Introduction
Glass fibre reinforced epoxy (GFRE) composites exhibit desirable physical and chemical properties that include light weight coupled with high stiffness and strength along the direction of the reinforcing fibre, dimensional stability, temperature and chemical resistance, flex performance, and relatively easy processing [1]. The stiffness and strength properties of the GFRE composite can be controlled efficiently by layering various layers of glass fibre on top of each another with oriented (stacking) in different preferred directions [2]. GFRE exhibits desirable specific mechanical and physical properties such as light weight, good in strength properties and stiffness properties, excellent with temperature and chemical resistance and relatively easy processing. Also, GFRE laminated composite is also popularly used in various applications such as aircraft manufacturing, automotive engineering, structure engineering and also sport equipments. However, composite materials exhibit complex failure mechanism under static and fatigue loading and therefore, it is a necessity to investigate the fatigue behaviour of GFRE composite.

Sureshkumar et al. [3] studied the mechanical response of glass fibre reinforced polyurethane resin composite in three different volume ratios. They found that as the fibre content increases, the strength of the composite also increases, though, at some point, it will decline due to lack of resin (Polyurethane). Moreover, Arifin et al. [4] studied the failure characterization in polymer matrix
composite for unnotched and notched (open-hole) specimens under tension condition. It was founded that unnotched samples for both types of epoxy and polyester composites had high values concerning strength and stress.

Besides that, composite materials also very well know with the fatigue resistance properties. However, the fatigue behaviour of the composite can influence the notch size or the stress concentration factors. Sonsino and Moosbrugger [5] studied the effect of notches on axial fatigue behaviour of short glass fibre reinforced polyamide-6,6. The difference stress ratio used in the test can affect the fatigue life of a specimen. Furthermore, Jason et al. [6] explored the effect of R-ratio on fatigue life and residual strength of glass-reinforced polymer composite materials. The composite materials were undergoing fatigue test with three different stress ratio (R=0.1, R=-1, and R=10). It was shown that the smaller the stress ratio, the longer the fatigue life, the lower the maximum stress.

2. Materials and Methods

2.1. Materials
Woven E-glass fibre and Epoxy Amite 100 series resin were supply by a local supplier. The woven glass fibre was prepared with dimension 600 x 600 mm per layer, and the diameter of the single fibre has been measured approximate to 12.8 μm. The Epoxy Amite 100 series resin was mixed with a hardener to a ratio of 4:1.

2.2. Composite fabrication
The GFRE composites were laminated with 14 layers; 12 layers in the 0°/90° orientation and two layers at the mid of the laminates with 45° orientation. This GFRE composite was fabricated using vacuum infusion method at room temperature (25°C). The resin was infused into the lamination plies, and the curing process took about 12 h. Finally, rectangular 600 × 600 × (2.6 ± 0.1) mm³ plates were obtained and the specimens were cut using a Dremel 4000 tool, in accordance with ASTM D5766 standard [7].

2.3 Tensile Test
The tensile specimens were prepared as illustrated in figure 1. The tensile tests were performed using a universal testing machine with a load cell of 100 kN at a crosshead speed of 1mm/min. Five specimens were tested, and the average result of the tensile strength and tensile elastic modulus were determined. From the load-displacement tensile test results, the stress and strain curves were plotted by using the formula as below:

![Figure 1. GFRE composite specimens.](image)

Eq.1 show the formula Area of specimen,

\[ A = b \times d \]  

where,

- \( b \) = width of specimen;
- \( d \) = thickness of specimen;

The stress was calculated from the ratio of force to the area of specimen shown in Eq. 2
\[ \sigma = \frac{F}{A} \]  

where, \( F \) = Force; 
\( A \) = Area of specimen;

Strain of specimen on tensile test,
\[ \varepsilon = \frac{\Delta d}{L_0} \]  

where \( \Delta d \) = elongation of the specimen from tensile test; 
\( L_0 \) = Original length of specimen;

Elastic Young’s Modulus of each specimen, \( E = \frac{\Delta \sigma}{\Delta \varepsilon} \) (slope of stress-strain curve)

**Figure 2.** Experimental set-up for the tensile test. (a) Universal Testing Machine (b) Tensile test of GFRE specimen using Universal testing machine (c) Schematic diagram of the experimental set-up

2.4 Fatigue test

The experimental set up of the fatigue tests was shown in figure 3. The fatigue tests were performed using Instron 8801 Servo hydraulic Fatigue Machine 100kN at three different stress ratio, \( R = 0, 0.5, -1 \), respectively. Fatigue load was applied in a sinusoidal waveform with a frequency of 20 Hz, and five displacement levels were obtained corresponding to 30, 45, 60, 75 and 90% of the maximum load of Tensile test.

**Figure 3:** Experimental set-up for fatigue test (a) Schematic diagram of the experimental set-up (b) Fatigue test of GFRE composite using fatigue machine
2.5 Fracture observation
The fracture side surface of the composite was observed using Optical Microscope CV-M50IR.

3. Results and Discussion

3.1 Tensile properties
Figure 4 shows a typical stress-strain curve GFRE composites obtained from the static tensile test. The figure shows the stress linearly increases with increasing strain prior reaching the maximum stress of the specimen failure. The average maximum tensile strength and Young modulus of GFRE composites were 221.79 MPa and 7.03 GPa, respectively. The fibre exhibited a brittle behaviour with a sudden load drop following a slight softening when fibre failure occurred. Figure 5 shows the sample of failure specimen of the tensile test to observed the bonding between the resin and single fibre are non-uniform.

![Figure 4. The typical stress-strain curve for none hole specimen.](image)

![Figure 5. Side view of failure specimen of fatigue test (a) for R > 0 and (b) for R < 0](image)

3.2 S-N curves with different stress ratio
Figure 6 show comparisons between the S–N relationships at different stress ratios R = 0, -1, 0.5 for representative GFRE composites respectively. These results clearly show that the number of cycles to
failure increases as the loading is decreased. The specimens 90% loading from ultimate stress at R= 0.5 recorded the lowest number of cycles, 70N respectively compared to others stress ratio. The results show at R=0.5 the number of cycles for specimen 30% (lower) loading from ultimate stress are 780000N. The fatigue strength of the GFRE composites under R=0 and 0.5 were almost similar exhibit stress loading higher than R=-1. The R ratio equal to -1 when minimum stress would be negative of the maximum stress also known as fully reversed (R=-1) testing. The compressive loads in fatigue produce a significant reduction in fatigue life when compared with results for tension tension loading. The tensile and compressive parts(R=-1) of the stress do not contribute equally to the damage[8][9]. The compressive loads in fatigue produce a significant reduction in fatigue life when compared with results for tension tension loading. For R=-1, the energy associated with the tensile loading causes damage. Overall, the fatigue behaviour of the GFRE composite materials is not only influence by the percentage of fatigue load from ultimate stress, but also of stress ratio applied.

![S-N curve under different stress ratio](image)

**Figure 6:** S-N curve under different stress ratio (R) 0, -1 and 0.5 of FGRE specimen.

Figure 7 shows the definition of the strain energy for various values of the stress ratio for negative stress ratios, R=-1 if it is assumed that only the energy associated with the tensile loading causes damage, then the damaging energy would be represented by the shaded area

4. Conclusions

In this study, the GFRE composite has been fabricated using the vacuum infusion method and the effect of stress ratio on the fatigue behaviour of an un-notched unidirectional GFRE was examined at room temperature. A phenomenological fatigue that considered the effect of stress ratio on the fatigue behaviour of composites was evaluated through observed fatigue behaviours at different stress ratios. A fatigue failure criterion for GFRE based on the input strain energy is presented. This criterion takes into account the effect of stress ratio. The number of cycles of GFRE composites is found to highly influenced by stress ratio. The results clearly show that the number of cycles to failure increases as the loading is decreased. The specimens for fatigue tests loads 30% at R= 0 and -1 recorded the highest number of cycles. The results obtained from this work that the fatigue behaviour of the GFRE composite materials are not only influence by the percentage of fatigue tests load, but with different of stress ratio. The strain energy may be used as a fatigue failure criterion for fibre-reinforced materials[10]. Since this parameter does not rely on the different failure modes obtained in
composites, it gives equally good results independent of the failure mechanism. It is shown that, in general, the tensile and compressive parts \((R=-1)\) of the stress do not contribute equally to the damage. The compressive loads in fatigue produce a significant reduction in fatigue life when compared with results for tension tension loading.

![Diagram showing strain energy and stress-strain relationship](image)

Figure 7: Definition of the strain energy for different values of the stress ratio, \(R < 0\)

5. References

[1] A. R. Syayuthi, Haftirman, K. S. Basaruddin, and M. S. Abdul Manan, “The Effect of Thicknesses on Impact Damage Advanced Composite Material for Aircraft Application,” Appl. Mech. Mater., vol. 754–755, pp. 802–806, 2015.

[2] Y. C. Keshavamurthy, N. V Nanjundaradhya, R. S. Sharma, and R. S. Kulkarni, “Investigation of Tensile Properties of Fiber Reinforced Angle Ply laminated composites,” vol. 2, no. 4, pp. 700–703, 2012.

[3] P. Sureshkumar, B. Karthick, S. Dinakaran, and R. Rajapradeepan, “Experimental Investigation of Mechanical Behavior of Glass- Fiber Reinforced Polyurethane ResinComposite in three Different ratios,” vol. 4, no. 3, pp. 36–41, 2014.

[4] A. M. T. Arifin, S. Abdullah, R. Zulkifli, and D. A. Wahab, “Failure Characterisation in Polymer Matrix Composite for Un-notched and Notched (open-hole) Specimens under Tension Condition,” vol. 15, no. 8, pp. 1729–1738, 2014.

[5] E. M. C. M. Sonsinoa, “Fatigue design of highly loaded short-glass-fibre reinforced polyamide parts in engine compartments,” Int. J. Fatigue, vol. 30, no. 7, pp. 1279–1288.

[6] J. J. Cain, N. L. Post, S. W. Case, J. J. Lesko, and J. J. Cain, “R-Ratio Effects on Glass-Reinforced Polymer Composite Life and Remaining Strength,” In 16th International Conference On Composite Materials.

[7] ASTM, “D5766/ D5766M Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates,” ASTM Stand., no. May, pp. 1–7, 2012.

[8] A. Rotem and H. G. Nelson, “Failure of a laminated composite under tension-compression fatigue loading,” Compos. Sci. Technol., vol. 36, no. 1, pp. 45–62, 1989.

[9] A. Rotem, “The fatigue behavior of composite laminates under various mean stresses,” Compos. Struct., vol. 17, no. 2, pp. 113–126, 1991.

[10] M. Kawai and K. Kato, “Effects of R-ratio on the off-axis fatigue behavior of unidirectional hybrid GFRP/Al laminates at room temperature,” Int. J. Fatigue, vol. 28, no. 10 Spec. Iss., pp. 1226–1238, 2006.