Effect of Mean Stress on Fatigue Behavior of Glass Fiber-Reinforced with Epoxy Composites

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Abstract. In this study, fatigue tests have been conducted on the glass fiber reinforced with epoxy (GFRE) composites under completely reversed loading. Test specimens were prepared for fiber orientation of [±45°]². Further, experimental fatigue data obtained from the S-N curve at stress ratio, R = -1 are analyzed using the Goodman approach for different mean stress levels. It was noted that stress ratios such as 0.5, 2, and 10 had a detrimental effect on the fatigue life of GFRE composites. Whereas, stress ratios such as -1, -2, and -0.5 had beneficial effect on increasing the fatigue life of GFRE composites under cyclic loading.

Keywords: Fatigue Test, Glass Fiber, S-N Curve, Mean Stress

1. Introduction
Composite materials refer to a combination of two or more different materials that are combined at various proportions to attain the relative advantages of their constituents while retaining their individual distinctiveness. Major constituents of composites are particles, fibers, laminae, fillers, flakes, and matrix materials. Composites are usually given bulk form by the matrix materials. The reinforcements are embedded within the matrix and are protected against environmental effects/damages. The structure of the composites is determined by the type of fibers, laminae, fillers, flakes used. Fiber-reinforced polymer (FRP) matrix-based composites are progressively being employed in making structural members such as ship hulls, wind turbines, airframes and in electric/solar vehicles due to its high strength to weight ratio and stiffness properties. In addition to this, these materials also possess good damage tolerance characteristics [1]. Failure of composite materials can be viewed from macroscopic and microscopic levels. Macroscopic damage in composites is due to manufacturing inaccuracies associated with the fabrication process/methods. These defects are present in composites before the application of loads. Microscopic level damage usually starts with the application of external loads. With the continuous application of the external loads, these microscopic defects grow at the macroscopic level and result in the failure of engineering structures. Fatigue life prediction of fiber-reinforced polymeric composites under repeated loads has gained considerable importance in recent years due to their wide range of applications in spacecraft, automobile, aerospace, and aircraft industries. For FRP composites, cyclic strength is relatively greater in tension, in contrast to metallic materials such as steel or aluminum alloys. For ferrous materials like steel, a definite endurance limit will exist. Whereas for non-ferrous and anisotropic materials like aluminum alloys, copper, brass and composites, a definite endurance limit does not exist. Therefore special care has to be taken by the designers while designing the structural machine components using these materials to avoid unpredictable failures.
1.1. Literature Review
Several studies in the literature have addressed the modelling and characterization of fatigue behaviour for composite materials. Agarwal and James [2] examined the influence of stress ratio on the fatigue behavior of GFRP composites under low cycle fatigue. It was revealed by the authors that the fatigue life of GFRP composites was negatively affected by stress ratio and matrix failure was observed prior to the final failure of the composites. Abd-Allah et al. [3] studied the effect of fiber volume fraction on the fatigue life of composites, and they concluded that the fatigue strength was proportional to the fiber volume fraction. Mandell et al. [4] conducted a fatigue study on the effect of fiber and matrix and fiber, and they determined that structural integrity and strength were largely dependent on a stable matrix system for wind turbine blades. Piggott [5] stated that the temperature rise in fiber composites was insensitive at test frequencies below 30 Hz. Also, several other researchers in the literature have evaluated the fatigue strength of fiber-reinforced epoxy composites for different stacking sequences, fiber orientation, stress ratios, and test frequencies using glass fibers and epoxy matrix [6-11]. From these studies, it has been observed that the fatigue strength of the fiber composites is largely influenced by the type and orientation of fibers. Composites with fiber orientation in off-axis directions were found to be weaker than unidirectional laminates. Stiffness degradation was witnessed at high-stress levels leading to catastrophic failure of fibers. Matrix degradation was observed owing to large plastic deformation at high-stress levels and test frequencies. In this study, the tension-compression bending fatigue behavior of glass fiber reinforced with an epoxy matrix is characterized. Then, the S–N curve and modified Goodman diagram are drawn to show the effect of mean stress on the fatigue life of the developed composite specimens under cyclic loading.

2. Materials and Method
Glass fibers and epoxy matrix (GFRE) were used as reinforcement and matrix to prepare the test specimens. The properties of the constituent materials are given in Table 1. Test specimens were prepared for the dimensions as follows:
   a) External diameter = 13mm;
   b) Thickness = 2.5 mm and
   c) Gauge Length = 60mm.

| Properties            | Glass Fibre       | Epoxy   |
|-----------------------|-------------------|---------|
| Tensile Strength [N/mm²] | 2700-3500        | 300-320 |
| Elastic Modulus [N/mm²]  | 70000-75000       | 300-4000|
| Elongation (%)         | 4 to 5            | 5 to 7  |
| Density (kg/m³)        | 2570              | 1100    |
| Thermal Expansion coefficient (* 10⁴/°C) | 4.9 to 5.4 | 45-65   |

Fatigue tests were carried out at room temperature for zero mean stress at a frequency of 10 Hz using a rotating bending fatigue tester [12]. Five stress levels were selected based on the tensile strength of the GFRE composites. The selected stress levels fall in the range of 40-80% of the static tensile strength of GFRE composites as shown in Table 4.

3. Results and Discussion
3.1. Density of GFRE composites
The theoretical density of the GFRE composite specimens is determined by burning off the epoxy matrix. The volume fraction rate of the epoxy matrix from the GFRE composites was calculated based on the mass of glass fiber and epoxy matrix to determine the density of GFRE composite specimens using the rule of mixture. The obtained density of the GFRE specimens is tabulated in Table 2.
3.2. Tensile results of GFRE composites
The tensile test was carried out by applying load in a uniaxial direction. The strain rate chosen for this study is 0.03mm/sec. Figure 1 shows the stress-strain plot of GFRE Composites. The tensile properties like elastic modulus, tensile strength, proof stress, and strain at failure are tabulated in Table 3.

![Stress strain curve of GFRE Composite](image)

**Figure 1.** Stress-strain curve of GFRE Composite

3.3. Fatigue results of GFRE composites
Constant amplitude type fatigue testing was carried out for developed composites specimens R. R Moore type fatigue tester. During the test, as the specimens were rotated fully, it underwent through a complete

### Table 2. Density of composites

| Sl. No | Composite Code | Volume Rate | Density (kg/m³) |
|--------|----------------|-------------|-----------------|
|        |                | V_Epoxy Matrix | V_Glass Fibres  |                  |
| 1      | GFRE Composites [±45°]_2 | 0.47         | 0.53            | 1791             |

### Table 3. Tensile properties of GFRE composites

| Sl. No | Properties             | Particulars |
|--------|------------------------|-------------|
| 1      | Elastic Modulus (N/mm²)| 152         |
| 2      | Proof Stress, (N/mm²)  | 9           |
| 3      | Tensile Strength, (N/mm²) | 14         |
| 4      | Fracture Strain        | 0.12        |

\[ y = 152x - 1.8726 \]
\[ R^2 = 0.9915 \]
reversed type of tension and compression loading cycles. Figure 2 shows the S-N curve for GFRE composites. The required bending stress was calculated by using equation (1).

\[ \sigma = \frac{M_b}{Z} \text{ N/mm}^2 \]  

where \( M_b \) = Applied Bending Moment; \( Z \) = Section Modulus

### Table 4. Fatigue Stress Levels and Cycles to Failure

| Sl.No. | Selected Stress Level | Number of cycles to failure a |
|--------|-----------------------|-------------------------------|
| 1      | \(0.4\sigma_{ult}\)   | 293464                        |
| 2      | \(0.5\sigma_{ult}\)   | 122858                        |
| 3      | \(0.6\sigma_{ult}\)   | 53748                         |
| 4      | \(0.7\sigma_{ult}\)   | 360                           |
| 5      | \(0.8\sigma_{ult}\)   | 65                            |

a = average of five specimens

3.4. Effect of Mean Stress
The magnitude of mean stress is the average value of the maximum and minimum stress cycles acting on the machine component. Hence an attempt is made in this work, to assess the fatigue behavior of the developed GFRE composite specimens for a wide range of alternating and mean stress using the simplest method called the “Goodman approach”. This method helps us to understand the mean stress effects and material properties collectively on estimating the fatigue life cycle of the machine components under consideration. “R-Ratio” is mathematically given as follows.

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]  

![Figure 2. S-N Curve for Developed GFRE Composites](image)
For stress cycles with the mean stress $\sigma_m$ and stress amplitude value $\sigma_a$, the corresponding equivalent stress value $\sigma_{eq}$ at $R = -1$ is stated as follows:

$$\sigma_{eq} = \frac{\sigma_a \times UTS}{UTS - \sigma_m} \quad \text{for} \quad \sigma_m > 0,$$

(3)

$$\sigma_{eq} = \frac{\sigma_a \times UCS}{UCS - \sigma_m} \quad \text{for} \quad \sigma_m > 0,$$

(4)

The above-described model was applied to the available experimental data attained from the fatigue tests. The value of mean stress $\sigma_m$ and alternating stress $\sigma_a$ were estimated using equations (3) and (4). The obtained results are presented in Figure 3.

The corresponding equivalent value of stress $\sigma_{eq}$ after stress amplitude can be found by using the relations given in equations (3) and (4). This will give us the value of several cycles to failure from the selected S-N curve at desired stress ratio $R$. The different stress ratios $R$ considered are 2, 10, -2, -1, -0.5, and 0.5 as shown in Figure 3. The obtained results are depicted in the form of an S-N curve as shown in Figure 4. It was observed that, for the developed GFRE composite specimens, stress ratios such as 0.5, 2, and 10 have detrimental effects under fatigue loading leading to shorter fatigue lives. Whereas stress ratios such as -1, -2, and -0.5 will not affect the fatigue life of the machine component significantly.
4. CONCLUSION
In this work, an experimental and analytical method was adopted to illustrate the effect of mean stress on the fatigue life of GFRE composites. Non-linear behaviour was observed from tensile test results due to the orientation of fibers in off-axis directions. The S–N curve was drawn for completely reversed loading (R = -1) with a coefficient of determination (R^2) being greater than 0.9. It was observed that, for the developed GFRE composite specimens, stress ratios such as 0.5, 2, and 10 have detrimental effects under fatigue loading leading to shorter fatigue lives. Whereas, stress ratios such as -1, -2, and -0.5 have beneficial effects under cyclic loading. Hence, for the proposed GFRE composites, the stress ratios should be around -1 for the conservative design of machine components under fatigue loading.

Reference
[1] Hemanth Kumar C, Swamy R P. 2015 "Analysis of Metallic and Composite Tail Rotor Drive Shaft for Ballistic Impact," International Journal of Mechanical Engineering and Robotics Research, 4(1) 455–462.
[2] Agarwal, B.D. and James, W.D. (1975). Prediction of Low-cycle Fatigue Behavior of GFRP: An Experimental Approach, Journal of Materials Science, 10(2): 193–199.
[3] Abd-Allah, M.H., Abdin, E.M., Selmy, A.I. and Khashaba, U.A. (1996). Effect of Fiber Volume Fraction on the Fatigue Behavior of GFRP Pultruded Rod Composites, Composites Science and Technology, 56(1): 23–29.
[4] Mandell, J.F., Samborsky, D.D. and Scott, M.E. (2003). DOE-MSU Wind Turbine Blade Composite Material Fatigue Database, Department of Chemical Engineering, Montana State University at Bozman, Montana, USA.
[5] Piggott, M.R. (1980). Load-Bearing Fiber Composites, Pergamon Press, New York, NY.
[6] G. Belingardi, M.P. Cavatorta. 2006 “Bending fatigue stiffness and strength degradation in carbon–glass/epoxy hybrid laminates: Cross-ply vs. angle-ply specimen”. International Journal of Fatigue 28 815–825.
[7] A. Bernasconi, P. Davoli, A. Basile, A. Filippi. 2007 “Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6”. International Journal of Fatigue. 29 199–208.

[8] N.K. Kar, Y. Hu, E. Barjasteh, S.R. Nutt. 2012 “Tension–tension fatigue of hybrid composite rods” Composites: Part B 43 2115–2124.

[9] P.K. Mallick, Yuanxin Zhou. 2004 “Effect of mean stress on the stress-controlled fatigue of a short E-glass fiber reinforced polyamide-6, 6” International Journal of Fatigue 26 941–946.

[10] S. Mortazavian and A. Fatemi 2015 “Effects of mean stress and stress concentration on fatigue behavior of short fiber reinforced polymer composites”. Wiley Publishing Ltd. Fatigue Fract. Engg. Mater. Struct. 001–18.

[11] Bernasconi Robb M. Kulin. 2015 “Effect of frequency upon fatigue strength of a short glass fiber reinforced polyamide 6” © Wiley Publishing Ltd. Fatigue Fract. Engg. Mater. Struct. 154–161.

[12] Hemanth Kumar C & R.P. Swamy. “Experimental Investigation on the Fatigue Behavior of Glass Fiber-Reinforced Epoxy Composites Under Rotating Bending Loads”. J Fail. Anal. and Preven. https://doi.org/10.1007/s11668-020-01105-3

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