ISSN: 2096-3246
Volume 54, Issue 02, December, 2022

Special Issue

COMPARISON OF FATIGUE BEHAVIOUR OF UNI-DIRECTIONAL AND BI-DIRECTIONAL GLASS FIBRE COMPOSITES

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Abstract— Glass Fiber composites are considered to have potential use as a reinforcing material in epoxy polymer based composites because of their good strength, stiffness etc., in present study, mechanical properties for glass fiber composites were evaluated. Here, Glass fiber is the fiber reinforcement and epoxy polymer resin as a matrix material. Composites were prepared with longitudinal (Unidirectional) and cross (Bidirectional) glass fiber reinforced with epoxy based polymer. Mechanical test i.e. compression and tensile test were performed on UTM and the results are reported. The result showed compressive and tensile strength of unidirectional and bidirectional glass fiber reinforced epoxy polymer composites and presented the conclusion

Keywords— unidirectional, bidirectional, epoxy, compressive-compressive, tensile-tensile.

Introduction

In general, a composite material can be defined as a material that consists of two or more distinct components. The composite materials used to manufacture structures or other components have usually comprised continuous or discontinuous fibers embedded in a matrix. The fibers provide the strength and the stiffness and the matrix holds the fibers together. Considerable weight savings can be achieved by using composite materials in aircraft because of their higher specific strength and specific stiffness compared to aluminum alloys.[1] Even though the composite material has replaced the conventional material in automobile, aircraft, and wind turbine industries, the generation of crack and delamination will not be eliminated. Fatigue failure is one of the main failure mechanisms associated with composites [2]. The big advantage of fiber-reinforced polymer is their extraordinary fatigue performance. Even though the validation of fatigue behavior models is rarely available yet. But during the last few years, these fiber-reinforced polymers are introduced more in fatigue loaded parts. More models are available since the 1980s the breakthrough is not yet achieved [3].

The increased use of composite materials has the fact that their fatigue behavior is more complex than metals fatigue behavior. The fatigue damage of metals is appearing as crack initiation, crack propagation, and failure. But in composite materials, the fatigue damage will be in the form of matrix cracking, fiber failure, delamination, fiber-matrix debonding, and void growth [4]. These are the various factors which affects the fatigue life of composites. In this paper crack is consider to predict the fatigue life of composites. The above damage modes will cause changes in the mechanical properties of composite laminates [5]. In fiber-reinforced composite materials, fatigue life and damage propagation highly depend on a few parameters. The parameters are the orientation of fiber, stress ratio, frequency of fatigue loading, maximum stress applied, volume fraction, stacking sequence [6]. Depending on the desired depth of representation of damage, the result and available fatigue models are categorized as general models, phenomenological, and progressive damage model [7]. Many models are developed for fatigue behavior of fiber-reinforced composites and they are classified into three types. They are fatigue life models based on the S-N curve and fatigue failure criteria, residual stiffness- strength model, and progressive fatigue damage model.

In all these three models S-N curve is the basement of fatigue life assessment [8]. One of the simple equations used to describe the fatigue behavior of many composite materials. There are many manufacturing methods are available for making composite materials. They are Resin transfer molding (RTM), Resin infusion process, Compression molding, Injection molding and Hand layup method [9]. From these hands layups are the simplest and most widely used method and also called a wet layout method. In the hand layup method, the laminates are placed manually on the mold and the resin will be applied on the laminate in every layer. The fiber-reinforced plastic specimen is made stronger with a volume fraction of 50 percent. Their tensile properties are more important for the experimental fatigue test.

The traditional method used to determine the tensile property is by using a universal testing machine. A flat rectangular specimen with standard ASTM3039 is used for the tensile test. For the gripping purpose, tapping will be provided on both the ends of the test specimen by using the same GFRP material [10]. Basic fatigue testing involves the preparation of samples without any damage which is cycled to failure at various values of constant amplitude at alternating stress level. The data drawn as a graph into alternating stress and number of cycles to failure are generally referred to as materials S-N curve [11]. A multi-axial fatigue testing machine is used for testing GFRP composite material with ASTM606 standard. By varying the frequency and stress ratio the specimen will be tested. The fatigue strength will be reduced by increasing stress ratio, so the fatigue behavior of composites will be depending on stress ratio. The multi-axial fatigue loading of approximately 36 percent of materials ultimate tensile strength which will be outside to the materials endurance limit [12].

For the determination of fatigue characteristics of structural material, there are three types of load. They are tensile-tensile, tensile-compressive, and compressive-compressive. With the values of applied stress and the number of cycles to failure, the S-N curve will provide a regression line with approximately 50% probability [13]. In this work, GFRP composite material is fabricated by using the hand layup method, and the specimen is made according to the ASTM standard for the test purpose, and experiments are conducted for developing the S-N curve and regression equation.

Problem definition and objectives

The use of composites is growing in structural applications in many industries including aerospace, automobile, wind turbine, marine and civil engineering. There will be a chance of a generation of cracks and delamination due to the load conditions. Due to this, there are uncertainties about the long-term performance of these composites and how they will perform under cyclic loading. Fatigue life prediction of composites and composite structures provides a detailed review of fatigue damage and how they can be used in practice. So, by developing the regression equation it is easy to predict the fatigue of the composite and accordingly, the maintenance and replacement of the component can be planned.

This work is to predict the fatigue life of the unidirectional and bidirectional glass fibre composites specimen and comparing the fatigue behavior of both.
The objective is to fabricate the GFRP composite specimen by hand layup method and the fatigue test need to be carried out on that fabricated specimens to develop an S-N curve. Finally, fatigue behavior will be compared.

Methodology

[Fig. 1 to be included here]

Purchase of raw material

From the list of the fabrication method, the hand layup method is chosen in the present work. By using this method unidirectional four-layer GFRP composite is fabricated with and without delamination. Components used are woven roving GFRP sheet, epoxy LY 556, hardener HY 956, brush, steel roller, teflon tape and plastic sheet.

Woven roving GFRP sheet

This is a heavy durable fabric shown in Fig. 2. available in various widths, thicknesses, and weights. Woven roving costs less than conventional woven fabric and is used to provide high strength in large structural components such as tanks and boat hulls. Woven roving is used primarily in hand lay-up processing.

[Fig. 2 to be included here]

Epoxy resin and hardener

Epoxy is either any of the basic components or the cured end products of epoxy resins, as well as a colloquial name for the epoxide functional group. Epoxy resins, also known as polyoxides, are a class of reactive pre-polymers and polymers which contain epoxide groups. Epoxy resins may be reacted (cross-linked) either with themselves through catalytic homo-polymerization, or with a wide range of co-reactants including polyfunctional amines, acids, phenols, alcohols and thiols (usually called mercaptans). These co-reactants are often referred to as hardeners or curatives, and the cross-linking reaction is commonly referred to as curing.

Calculation of weight and volume fraction

Fiber volume ratio, or fiber volume fraction, is the percentage of fiber volume in the entire volume of fiber-reinforced composite material. When manufacturing polymer composites, fibers are impregnated with resin. The amount of resin to fiber ratio is calculated by the geometric organization of the fibers, which affects the amount of resin that can enter the composite. The fraction of fiber reinforcement is very important in determining the overall mechanical properties of a composite. A higher fiber volume fraction typically results in better mechanical properties of the composite.

Importance of fiber volume fraction

Adding too little fiber reinforcement in the composite will actually deteriorate the properties of the material. Too much fiber volume may also decrease the strength of the composite due to the lack of space for the matrix to fully surround and bond with the fibers. Therefore, there is an optimal space between fibers that will fully exploit the uniform load transfer between fibers.

Weight fraction

While the fiber weight ratio is easily determined by simple weighing, the fiber volume ratio is quite difficult to determine. The fiber weight is based on the areal weight and a known or measured planar area. After processing, the composite laminate weight is measured. The resin weight is the difference between the composite and fiber weights

$$W_{Composite} = W_{matrix} + W_{fibre} \quad (1)$$

The weight fraction of the composite material selected is 50% of fiber and 50% of the matrix. The bidirectional woven roving glass fiber is cut into 8 pieces of size 300mmX300mm and its weight is measured with a weighing machine.

The measured weight of fiber is w_f = 300 grams

The weight of matrix is w_m= 300 grams

Weight of matrix = weight of Epoxy + weight of hardener (2)

In the mixture of matrix, 10% of hardener should be added with the epoxy resin.

Weight of Epoxy = 270 grams

Weight of hardener = 30 grams

$$Weight\ fraction = \frac{W_{fiber}}{W_{fiber}+W_{matrix}} \quad (3)$$

$$= \frac{300}{300+300}$$

Therefore, weight fraction = 50%.

Volume fraction

Fiber volume fraction, FVF = $\frac{\mathbf{1}}{[\,\mathbf{1}+\frac{\rho_f}{\rho_m}\left(\frac{1}{FWF}-\mathbf{1}\right)]}$ (4)

Fiber weight fraction, FWF = 0.5

Density of fiber, $\rho_f = \frac{mass}{volume}$ (5)

Weight of fiber, w_f = 300 grams

Volume of fiber, v_f = 30x30x0.2

Volume of fiber, v_f = 180 cm^3

Therefore,

Density of fiber, $\rho_f = \frac{300}{180}$

ρ_f = 1.66 $g/_{cm^3}$

Density of matrix, ρ_m= 1.2 $g/_{cm^3}$

Therefore,

Fiber volume fraction = $\frac{\mathbf{1}}{[\,\mathbf{1}+\frac{\mathbf{1.66}}{\mathbf{1.2}}\left(\frac{\mathbf{1}}{\mathbf{0.5}}-\mathbf{1}\right)]}$

Fiber volume fraction = 0.419

Fiber volume fraction = 42%

Volume fraction of composite = volume fraction of fiber + volume fraction of matrix

Volume fraction of matrix = 1- 0.42

Therefore,

Volume fraction of matrix = 58%

Fabrication of Composites

The surface is treated by release anti-adhesive agent to avoid the sticking of polymer to the surface. Then, a thin plastic sheet is applied at the top of the surface to get a smooth surface of the product. The layers of woven reinforcement are cut to required shapes as shown in Fig. 3 and placed on the surface of the mold. Thus, as previously mentioned, the resin mixed with other ingredients and infused onto the surface of reinforcement already positioned on the surface using a helping brush to uniformly spread the resin on fiber material. And then the other mats are placed on the preceding polymer layer and pressured using a roller as shown in Fig. 4 to remove any trapped air bubbles and the excess of the polymer as well. After curing at room temperature, the weight is removed and the woven composite is removed from the mold surface.

[Fig. 3 to be included here]

Preparation of specimen

After the fabrication is completed it is allowed to cure for three days at room temperature. After three days the weight is removed from the composite and it is ready for the preparation of the specimen.

ASTM 3039 is a tensile specimen standard and its dimensions are 250mm X 25mm X 3mm as shown in Fig. 4. So, by using a water jet cutting machine the required shape is prepared.

ASTM E606 specimen of size 125mm x 25mm x3mm is used for fatigue test and crack of 1 mm depth at the middle of the specimen is developed by using hacksaw blade and the width and depth of the crack is measured using electron microscope.

[Fig. 4 to be included here]

Preparation of tabs

A composite material is tabbed prior to testing, typically for one of two reasons to protect the material from damage from applied loads during the test or to increase the area of the loading region and, thus, reduce local stress concentrations. The same GFRP material is used as a tab material. The dimension for tabbing is 50mm length on both sides and the thickness is same as the specimen thickness as shown in Fig. 5.

[Fig. 5 to be included here]

Design of Experiments

Design of Experiments (DOE) is a powerful statistical technique introduced by R. A. Fisher in England in the 1920's to study the effect of multiple variables simultaneously. In his early applications, Fisher wanted to find out how much rain, water, fertilizer, sunshine, etc. are needed to produce the best crop. Since that time, much development of the technique has taken place in the academic environment, but did help generate many applications in the production floor.

The main concept in creating design of experiment includes blocking, randomization, and replication. Blocking will restrict randomization by carrying all the trials with one setting and all other with other setting. Randomization is the order in which the experiments are conducted. Randomized sequence will help in eliminating the effect of unknown variables. Repetition of a complete experiment including the setup.

The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations.

Using the factors and levels determined in the brainstorming session, the experiments now can be designed and the method of carrying them out established. They are select the appropriate orthogonal array, assign factor and interaction to columns, describe each trial condition, and decide order and repetition trials.

Factors and levels

The factors are, design parameters that influence the performance, input that can be controlled, included in the study to determine their influence and control upon the most desirable performance. The levels are, values that a factor assumes when used in the experiment.

Taguchi method

It includes 2-level designs, 3-level designs, 4-level designs, 5-level designs, and Mixed-level designs. Choose the appropriate design based on the requirements of the experiment. Choose the design from the Stat > DOE menu, also open the appropriate toolbar by choosing Tools > Toolbars. After choosing the design and its features, Minitab creates the design and stores it in the worksheet. Mixed-level design is selected for the experiment, the two factors are load and crack depth in the specimen. The level is 2 for crack factor and 4 for load factor. So, for this mixed-level design, Minitab creates the orthogonal array.

Available orthogonal array

The following Standard Orthogonal Arrays are commonly used to design experiments. They are 2-Level Arrays: L-4 L-8 L-12 L-16 L-32 L-64, 3-Level Arrays: L-9 L-18 L-27 (L-18 has one 2- level column), and 4-Level Arrays: L-16 & L-32 Modified.
From the design calculation by Minitab it creates the array as L18 is shown in Table I.
[Table I to be included here]

Result and Discussion

A fatigue test is also used for the determination of the maximum load that a sample can withstand for a specified number of cycles. All of these characteristics are extremely important in any industry where a material is subject to fluctuating instead of constant forces.

Multi axial fatigue testing machine is used to conduct the fatigue test. ASTM E606 specimen of size 125mm x 25mm x3mm is used for fatigue test. The test specimen is loaded in the machine as shown in Fig. 6 and in multi axis dynamic software the setup for loading need to be done. In this case tensile-compressive load is fixed and the stress value of 60% of yield stress is applied.
Yield stress of the composite = 170 MPa

[Fig. 6 to be included here]

Load type: Unidirectional – Tensile - Compressive load
[Table II to be included here]

Load type: Bidirectional - Tensile – Compressive load
[Table III to be included here]

Conclusion

In this paper, polymer matrix composite material (GFRP and epoxy resin) is fabricated by using hand layup method with fiber volume fraction of 42% and matrix volume fraction of 58%. Then the tensile test is conducted on this specimen to get the tensile properties. With the help of this tensile properties the experimental fatigue test is performed for 50%, 60%, and 70% of yield strength of the composite material. In all the testing of properties of material as compression and tension on samples of uni and bi-directional glass fiber reinforced epoxy resin-based polymer composites, following points have been concluded. Unidirectional oriented glass fiber epoxy composites have large value of all the properties such as Ultimate force, yield force, Compressive strength, Tensile strength, elongation etc. in tensile as well as compression test. It means unidirectional oriented glass fiber composites strength

Acknowledgment

I would like to express my sincere gratitude to the faculty of Department of Mechanical Engineering, for providing continuous encouragement throughout the project work made it possible to complete this dissertation work well in advance.

References

M. Senthilkumar, T. G. Sreekanth, and S. Manikanta Reddy, "Nondestructive health monitoring techniques for composite materials: A review." Polymers and Polymer Composites, pp. 1- 13, 2020.

S.M. Abhilash, P.K. Sahoo, and B. Raghuvir Pai, "Fatigue analysis of CFRP composite laminates with circular cutouts," International Journal of Electrical, Electronics and Computer Systems, vol. 2, pp. 2347-2820, 2014.

P. Romanowicz and A. Muc, "Estimation of Notched Composite Plates Fatigue Life Using Residual Strength Model Calibrated by Step-Wise Tests," Materials, pp. 2180-3390, 2018.

R. J. Huston, "Fatigue life prediction in composites," International Journal of Pressure vessel and piping, pp. 131-14, 1994.

S. Mouleeswaran and V. Sabapathy , "Analytical and Experimental Studies on Fatigue Life Prediction of Steel and Composite Multi-leaf Spring for Light Passenger Vehicles Using Life Data Analysis," Journal of Material science, pp. 2352-3421, 2007.

D.K. Adarsh, R. Andrews, M. Banuchandar, and R. Manikandan, "Numerical Analysis on Fatigue Strength of Composite Materials," Journal of Basic and Applied Engineering Research, pp. 2350-0077, 2014.

A.Bhanage and K. Padmanabhan, "Design for fatigue and simulation of glass fibre/epoxy composite automobile leaf spring," Journal of Engineering and Applied Sciences, pp. 1819-6608, 2014.

W.Zhang, H. Liu, Q.Wang, and J. He, "A Fatigue Life Prediction Method Based on Strain Intensity Factor," Journal of Material science, pp. 689-3390, 2017.

D.K. Rajak, D.D.Pagar, P.L.Menezes, E. Linul, "Fiber-reinforced polymer composites: Manufacturing, properties, and applications". Polymers. 2019 Oct;11(10):1667.

J. C. Newman, "Fatigue-Life Prediction Methodology Using a Crack-Closure model," Journal of Engineering Materials and Technology, pp. 117-433, 1995.

R.C. Kennedy and S.B Leen, "A preliminary design methodology for fatigue life prediction of polymer composites for tidal turbine blades," International Journal of Materials: Design and Applications, vol. 39, pp. 4497-3265, 2012.

S.Zhoua and X. Wua, "Fatigue life prediction of composites laminates by fatigue master curves," Journal of Material research and Technology, pp. 1016-10003, 2019.

F. Micelli, and A. Nanni, "Tensile characterization of FRP rods for reinforced concrete structures" Mechanics of Composite Materials, vol. 5, pp. 0191-5665, 2003.

D.R. Shankara and P. Kiran kumar , "Review paper fatigue behavior of fiber reinforced polymer composites- A Review," Journal of Material science, pp. 2347-2820, 2017.

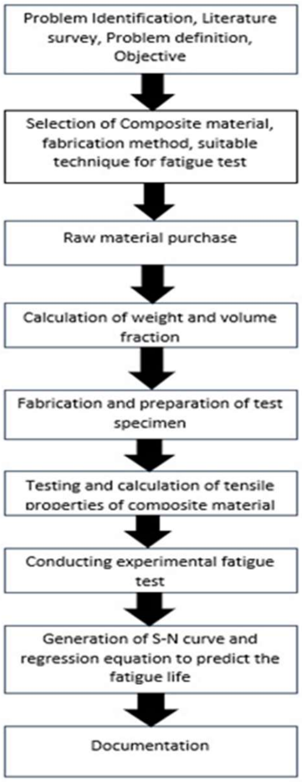

Fig. 1. Methodology

Fig. 2. Bidirectional glass fiber

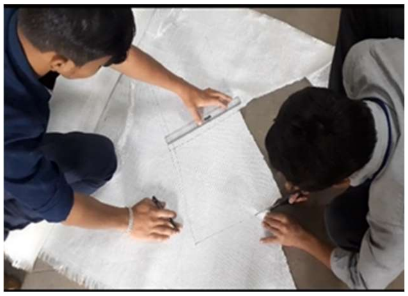

Fig. 3. Fabrication of composite

Fig. 4. Composite tensile specimen

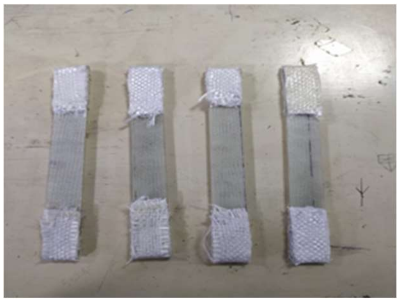

Fig. 5. Specimen with tabs

Fig. 6. Multi axial fatigue testing machine

TABLE I. Minitab results

Type of load	Crack Depth(mm)	Load
T-T	0	50%
T-C	0	50%
C-C	0	50%
T-T	1	50%
T-C	1	50%

C-C	1	50%
T-T	0	60%
T-C	0	60%
C-C	0	60%
T-T	1	60%
T-C	1	60%
C-C	1	60%
T-T	0	70%
T-C	0	70%
C-C	0	70%
T-T	1	70%
T-C	1	70%
C-C	1	70%

TABLE II. Unidirectional – Tensile-Compressive load

Load (Mpa)	**No. of cycles to failure**
85	17500
102	16000
119	1550

TABLE III. Bidirectional – Tensile - Compressive

Load (Mpa)	**No. of cycles to failure**
85	18000
102	16200
119	1650