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Strain-Based Fatigue Damage Modeling of Plain Woven Glass/Epoxy Fabric Composites

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Abstract

Strain-Based Fatigue Damage Modeling of Plain Woven Glass/Epoxy fabric Composites is well developed by utilizing Helmholtz Free Energy Model, S-N Model and Strain-Life Model. Due to repeated cyclic loading at a defined number of cycles to the failure, Glass Fiber experienced disturbance in their intermolecular bonding structures and finally development of microcracks, macrocracks, cracks and fatigue fracture at final stage. For, validation of Model, Strain Based constant amplitude of fatigue loading is achieved through Fatigue Testing which was performed by adopting the positive load method for evaluation of any potential crack propagation, fiber fractures, de-laminations, etc. With the application of continuous stressing in the material, evaluation of life cycle capabilities of glass fiber composites are essential for Research Development, Structural Design, Quality assurance, Modeling and finally the preparation of Specifications for the product of said Material. By using an epoxy resin system with glass fiber at a mandrel diameters 140 mm and the winding angle of 15° and 90° were selected in four lay-up i.e. 15°, 90°, 15°, 90° had fabricated according to filament winding process. The Specimen is cut into 20 pieces each of width 50 mm, thickness 3.3 mm was fixed in 809 MTS Axial/Torsional Test Machine with constant frequency 1 HZ and the test result was recorded in the Computer connected to that Machine. From the fatigue test, it is observed that final reading at the time of fracture i.e. in terms of running time, axial force, axial displacement, and axial integral count cycle was recorded as 72801.390625 Sec, 0.121522857666016 KN, 4.7763674519961 mm and 72737.50 Cycles. The maximum number of cycle to failure obtained from the fatigue testing is N_f=72737.50 interfere cycles at 1.00 fatigue damage factor, initial strain at 0.00 cycle at 63.57617 sec time was recorded as 0.0244, final strain at 72735.50 cycle at 72801.40 sec was recorded as 0.0659. Initial, at middle and final stress was recorded as 0.329183 GPA initial, varying to 0.58809 GPA at middle point and 0.002202 GPA to 0.00 at failure state. Minimum and Maximum Strain Measurement corresponding to 0001 Cycle were -0.00045313 and 0.0075, at 30000 Cycle -0.00050313 and 0.00995, at 50000 Cycle -0.00075 and 0.0115, at 70000 Cycle (Final Cycle for fracture) was -0.010234375 and 0.515625 which validates the required Strain-based fatigue model achieved through theoretically.

Keywords: Strain-based; Glass/epoxy woven fabric composites; Fatigue damage; Filament winding; Layup angle; Epoxy; Hardener

Introduction

The well-defined composition of two or more materials or phases or matrix having distinct physical and mechanical properties and characteristic, whose dimensions are larger than molecular dimensions and considered homogeneous at macroscopic level and heterogeneous at microscopic level, having same properties at every points is termed as composites. It is generally classified as (a) Natural Composites i.e. wood, bamboo, bone, tissues etc. (b) Micro-composite i.e. Metallic alloys, rubber toughened thermoplastic, fiber and particle reinforce polymer etc. (c) Macro Composites i.e. steel reinforced concrete, galvanized steel, skis and other laminated structures etc. (d) Nano composites such as (almost any materials) and designed by modification on Nano level. Furthermore, Micro Composites are further classified as (i) Continuous fibers such as aligned, random (ii) Short fibers such as aligned, random (iii) Particulates such as sphere, plates, sheets, irregular (iv) Lamellar structures (v) Multi-component. For introducing polymer composite one can say that composites based on polymer matrices such as epoxies and polyesters, as well as thermoplastic matrices such as polypropylene and polyamides. The composition of the composites are of polymer reinforced with glass, aramid and carbon fibers which plays a vital role in the large industries and product of automotive, boats and aerospace constructions.

Composite materials properties and constitutive relations combined with laminate theory enables a practical and efficient framework for composite engineering and design of components and structures such as Fibers and matrix: micro-scale and micromechanics in which dimensions are in μm, Anisotropic materials (Hooke's law) in which dimensions are in "mm", Laminates and laminate theory in which dimensions are in "cm" and finally structures in which dimensions are in "m". The anisotropic nature of composite materials implies that there are many material constants involved, and need to consider material orientation. Furthermore, composites are often found as layered structures (laminates). These laminates may have a high number of layers. Consequently, any realistic, or efficient, numerical study on composites and laminates requires numerical tools to handle the evaluations of a large number of expressions, particularly linear algebra and matrix operations. Composite materials which are foundational in composite materials in engineering are generally being created simultaneously with the fabrication of the composite parts and structures.

In order to of estimate strength and stiffness, structural materials are subjected to mechanical testing. Tests aimed at evaluating the mechanical characteristics of fibrous polymeric composites are the very foundation of technical specification of materials and for design

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purposes. Composite materials in the context of high performance materials for structural applications have been used increasingly since the early 1960s; although materials such as glass fiber reinforced polymers were already being studied 20 years earlier. Initially conventional test methods originally developed for determining the physical and mechanical properties of metals and other homogenous and isotropic construction materials were used. It was soon recognized however that these new materials which are non-homogenous and anisotropic (orthotropic) require special consideration for determining physical and mechanical properties. The uses of composite structures have proliferated recently to include a large number of new applications. Once only used for specialized parts or secondary members, composites are now considered to be competitive with other materials in many applications. The fact that composites in general can be custom tailored to suit individual requirements have desirable properties in corrosive environment; provide higher strength at a lower weight and have lower life-cycle costs has aided in their evolution. Also it provides a good combination in mechanical property, thermal and insulating protection.

Because of the high specific strength, light weight and good stiffness in characteristics the Fiber-reinforced glass composites are increasingly used in especially aerospace, automotive and almost in construction industries. Woven glass fabric epoxy composites are widely used in different purpose of civil engineering because of superior balanced physical properties in fabric reinforce plane such as balanced damage tolerance, impact resistance, light in weight, high specific strength, dimensional stability, impact resistance and superior performance during uniaxial, biaxial, triaxial, torsional fatigue loading state as compared to other conventional lamina which reflects its beauty also.

The S-N approach and E-N approach for fatigue behaviour of woven glass composite has been the very essential and active research in these modern ages. Widespread study, from many literature of previous research on fatigue loading have been concluded that almost 90% of the failure of the woven fabric glass composites are due to fatigue failure [1]. So many experiments, investigations and researches on fatigue damage of fabric glass composites have been done in past. Isotropic material with homogeneous monolithic materials have occurred fatigue failure by creating a single crack which propagates in specified directions perpendicular to the axis of cyclic loading. For composite materials, experiments observed by Rim Ben Toumi [2] by multiple models of damage such as fiber-matrix alterations, debounding in fiber breakage and matrix cracking etc. Hansen [3] was observed the multitude of cleavage types of multiple distributed cracks which are highly in unidirectional. According to the theory of Continuum Damage Mechanics, Kachanov 1958 has discovered the progressive distributed damage which is very much useful for the damage analysis of composite fatigue and has been addressed by many researchers [3-8]. The strain based approach is being very advantageous tools for numerical simulation and for complete stress-strain behavior [9-11].

The philosophy of changing in the material stiffness i.e. E which plays an important role in internal molecular change, change in dissipation and growth of crack has been addresses in past literatures [2-4,11-13]. Hansen [3] was used one of such process in his fatigue damage model formulation for woven fabric composite.

For glass-reinforced woven fabric composites in both static and fatigue environment, experiments had done by Hansen [3]. Depending upon the penetration of Damage, it had classified as undamaged, barely visible impact damaged (BVID) and penetrated damage. For detecting the damage initiation and growth Infrared thermography related to non-destructive inspection technic was used and observed mechanism of fatigue procedure that changed continuously non-uniform field of stress due to stress redistribution and stress raiser effects.

In his damage detection, property of material was degraded sharply caused by "knee-effect", whereas glass-epoxy debounding and failure was inspected in transverse fiber bundles caused by microcracks. Phase I was ended by saturation of cracks and starting of phase II. Friction between fibers and some delimitations caused microcracks progressively distributed was observed in phase II. Fatigue life in phase I and phase II estimated which was almost 92%. Fiber breakage localized of damage and failure of specimen was inspected in phase III. Using Continuum Damage Mechanics approach Hansen [3] has developed constitutive fatigue model for the fatigue damage regarding phase I and II. Internal variable evolving with damage was considered as material compliance tensor. The developed fatigue model was multi axial but could not address any anisotropic effects of cracking and was unable to detect permanent deformation due to fatigue loading.

For glass-epoxy woven composites during tension-tension fatigue totally based on Damage Mechanics theory was developed by Chao [6] for inelastic and anisotropic fatigue damage model in fulfillment of multitude of interfacial debounding and matrix cracking which is capable of capturing the permanent deformation and elastic degradation due to anisotropic damage. After that it was compared to the Hansen's experimental works. The model formulation was totally on stress based which was not ability to capture the static stress-strain behaviour and cyclic stress-strain behavior has also not been able to satisfy the developed S-N Curve. Inelastic Strain accumulation with number of cycle has not been discussed in his literature. Further, unified bounding surface approach guided by isotropic hardening/softening theories of plasticity and theory of Damage Mechanics for detection of fatigue behavior was developed by Chao [7] for woven composites under biaxial loadings in stress based formulation.

Damage model for structural concrete in strain space within the continuum thermodynamics framework has developed by Thapa and Yazdani [9] with equivalency of the stress and the strain space formulation. Rate independent behavior, infinitesimal deformations and isothermal conditions were assumed and Helmholtz Free Energy (HFE) was utilized as an energy potential to develop damage surface. Anisotropy caused by induced cracking was captured by developing and using kinetic relations which was developed by adopting additive decomposition of the stiffness tensor. The prepared damage model was capable of capturing the general mechanical behavior of concrete in both tension and compression. The model lacks addressing the material non linearity under large confining pressure which actually can be captured using a plasticity type approach. It was concluded that strain based formulation involves iterative procedure which actually reduces processing time and also optimizes the data storage.

This paper aims to perform Strain-Based Fatigue Damage Modeling of Plain Woven Glass/Epoxy fabric Composites is well developed by utilizing Helmholtz Free Energy Model, S-N Model and Strain-Life Model and validated by the result of fatigue testing from the Experiment.

Model Formulation

Model regarding Helmholtz free energy

For brittle materials, validity of assumption for small deformations in inelastic damaging process at low frequency fatigue, ignoring thermal effects, the constitutive relation between stress and strain tensor can be deducted from Thapa and Yazdani [9] by utilizing fourth order material stiffness tensor as:

$$\boldsymbol{\sigma} = \frac{\partial A}{\partial \boldsymbol{\varepsilon}} = \boldsymbol{E}(k) : \boldsymbol{\varepsilon} - \boldsymbol{\sigma}^i(k) \quad (1)$$

Where, $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are the stress and strain tensors, A is the Helmholtz Free Energy, $\boldsymbol{E}$ is the material stiffness tensor depending upon the rates of micro cracks and k denotes cumulative scalar fatigue damage parameter. Here, the tensor contraction operation is designated by **":"** and the stress tensor for inelastic damage is given by $\boldsymbol{\sigma}^i$. Suppose "N" is the fatigue loading unloading cycle number, differentiating Eq. (1) with respect to "N":

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{E}(k) : \dot{\boldsymbol{\varepsilon}} + \dot{\boldsymbol{E}}(k) : \dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\sigma}}^i(k) \quad (2)$$

$$= \dot{\boldsymbol{\sigma}}^e + \dot{\boldsymbol{\sigma}}^D - \dot{\boldsymbol{\sigma}}^i(k)$$

Where, $\dot{\boldsymbol{\sigma}}^e$ denotes incremental stress, $\dot{\boldsymbol{\sigma}}^D$ is the rate of stress relaxation due to elastic damage and $\dot{\boldsymbol{\sigma}}^i(k)$ denotes for the stress tensor rate. It is further assumed that, damage during fatigue loading degrades elastic properties and affects the stiffness tensor. The damage is recorded by **E** in the fourth order material stiffness tensor**.** To introduce material anisotropy, the essential additive decomposition of **E** is adopted:

$$\boldsymbol{E}(k) = \boldsymbol{E}^o + \boldsymbol{E}^D(k) \quad (3)$$

Where, $\boldsymbol{E}^o$, $\boldsymbol{E}^D(k)$, $\dot{\boldsymbol{E}}(k)$, $\dot{\boldsymbol{\sigma}}^i$ is the initial stiffness tensor of untracked material, overall stiffness degradation while application of fatigue loadings, the rates of stiffness tensor and inelastic stress tensor respectively which are expressed as fluxes regarding the theory of thermodynamics state sense and written in terms of evolutionary equations which are,

$$\dot{\boldsymbol{E}}^D = -\dot{k}\boldsymbol{L} \text{ and } \dot{\boldsymbol{\sigma}}^i = \dot{k}\boldsymbol{M} \quad (4)$$

Where, **L** and **M** are the response tensors regarding fourth and second order for determination of the direction of the inelastic and elastic damage processes.

For the further extension of specific forms of response tensor **L** and **M** must be specified. Since the damage is anisotropy, hence response tensor should be achieved as anisotropic by decomposing strain tensor into positive and negative cone which holds good positive and negative eigen values such that $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^+ + \boldsymbol{\varepsilon}^-$. Experimental results for glass/epoxy woven fabric composite materials in tension-tension fatigue loading by Hansen [3], maximum strain take place in the direction of applied strain (anisotropic) in tension regimes as Figure 1, and no coupling between cleavage type cracks in orthogonal direction is assumed, the proposed form of response tensors are.

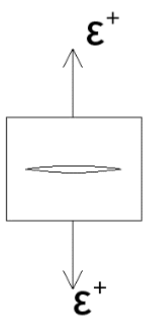

Figure 1: Cleavage mode of cracking.

$$\boldsymbol{L} = \frac{\boldsymbol{\varepsilon}^+ \otimes \boldsymbol{\varepsilon}^+}{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+} \quad (5)$$

$$\boldsymbol{M} = \frac{\alpha \boldsymbol{\varepsilon}^+}{(\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+)^{1/2}} \quad (6)$$

Where, the symbol "⊗" denotes the operation of tensor product. The material used in Hansen's experimental work was assumed to be quasi-isotropic laminate in nature, with the lay-up sequence of $[(+45^0\#-45^0)/(90^0\#0^0)]_s$, made up of plain woven glass/epoxy fabrics. So, the strength values are considering equal in different directions.

A new damage evolution law regarding second invariant of positive cones of strain tensors has proposed in this paper on the base that the damage at each cycle are dependent on E, N and second invariant of the positive cone of the strain tensor

$$k = E\int_0^N A\left(\frac{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}{\varepsilon_O^{\ 2}}\right)^m N^B dN \quad (7)$$

Where, A, B and m indicates material constants, N indicates the number of cycles and ε_0 indicates reference strain level. Differentiating above equation with respect to N, the increment damage per one cycle is written as,

$$\dot{k} = EA\left(\frac{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}{\varepsilon_O^{\ 2}}\right)^m N^B \quad (8)$$

Adopting Eqs. (5), (6) and (8) into Eq. (4), the equation yields

$$\dot{\boldsymbol{E}}^D = -EA\left(\frac{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}{\varepsilon_O^{\ 2}}\right)^m N^B \frac{\boldsymbol{\varepsilon}^+ \otimes \boldsymbol{\varepsilon}^+}{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+} \quad (9)$$

$$\dot{\boldsymbol{\sigma}}^i = EA\left(\frac{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}{\varepsilon_O^{\ 2}}\right)^m N^B \frac{\alpha \boldsymbol{\varepsilon}^+}{(\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+)^{1/2}} \quad (10)$$

Adopting Eqs. (3) and (4) into Eq. (2), finally we get:

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{E} : \dot{\boldsymbol{\varepsilon}} + \left[-EA\left(\frac{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}{\varepsilon_O^{\ 2}}\right)^m N^B \frac{\boldsymbol{\varepsilon}^+ \otimes \boldsymbol{\varepsilon}^+}{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}\right] : \boldsymbol{\varepsilon} - EA\left(\frac{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}{\varepsilon_O^{\ 2}}\right)^m N^B \frac{\alpha \boldsymbol{\varepsilon}^+}{(\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+)^{1/2}} \quad (11)$$

S-N Curve models

To develop the model regarding S-N Curve from Basquin Model subjected to constant loading and fixed stress ratio (R) can be written as

$$\sigma_{max} = \alpha\,(N_f)\,\beta \quad (12)$$

Where, σ_{max}=applied peak stress

α and β=curve fittings parameters and

N_f = loading frequency

For, log log equation, equation (1) can be also written as

$$\sigma_{max} = \alpha\,(\log N_f) + \beta \quad (13)$$

According to investigation done by Subramanian, Mandelland, Bond and Farrow, Tamuzsetal had formed the fatigue equation for composites as

$$\sigma_{max} = \alpha\left[N_f\right]^\beta + \sigma_\infty \quad (14)$$

Where,

σ_∞=fatigue limit, which is the additional parameter for calculation of ultimate fatigue stress

Weibull had given the equation for fatigue stress which is emphasized by E. Epremian such that

$$\frac{\sigma_{max}-\sigma_{\infty}}{\sigma_{uT}-\sigma_{\infty}}=1-\alpha\left[N_f\right]^{\beta}+\sigma_{\infty} \quad (15)$$

The assumption made by Henry and Dayton is assumed as

$$\sigma_{max}=\frac{\alpha}{N_f}+\beta \quad (16)$$

At $N_f=1$, $\sigma_{max}=\sigma_{uT}$

The Proposed model of Sendeckyj

$$\sigma_{max}=\frac{\sigma_{UT}}{\left(1-\alpha+\alpha N_f\right)^{\beta}} \quad (17)$$

$$N_f=\frac{\left(\frac{\sigma_{uT}}{\sigma_{max}}\right)^{1/\beta}-1+\alpha}{\alpha} \quad (18)$$

Where, σ_{uT} stands for Ultimate Tensile Strength and σ_{max} stands for Applied Peak Stress

α and β are the fittings Parameters and N_f is the Number of Cycles to the failure

The Model formulated by Hwang and Han by introducing "fatigue Modulus" and a "fatigue strain failure" are given as:

$$N_f=\alpha\left(1-\frac{\sigma_{max}}{\sigma_{uT}}\right)^{1/\beta} \quad (19)$$

$$\sigma_{max}=\sigma_{uT}\left(1-\frac{N_f^{\beta}}{\alpha}\right) \quad (20)$$

The basic design of S-N Curve is given as

$$logN=log\dot{a}-mlog\Delta\sigma \quad (21)$$

N=predicted number of cycles to failure for stress range Δσ

Δσ =stress range=σ_{max} - σ_{min}

M=negative inverse slope of S-N curve

$log\dot{a}=intercept\ of\ \log N-axis\ by\ S-N\ curve$

$log\dot{a}=loga-2s$

Where,

a=constant relating to mean S-N curve

s=standard deviation of log N

Strain-life model

According to Coffin-Manson relation, the general equations for Strain Life Curve are as following:

$$\frac{\Delta\varepsilon_p}{2}=\varepsilon_f^{'}\left(2N\right)^{c} \quad (22)$$

Where, N=No. of Failure Cycle, $\varepsilon_f^{'}=Coefficient\ of\ Fatigue\ ductility$, c=Fatigue ductility exponent.

The value of $\varepsilon_f^{'}$ and c can be calculated from the linear fittings of $\log(\frac{\Delta\varepsilon_p}{2})$vs $\text{Log}(2\text{N})$.

Curve regarding Elastic strain fatigue life:

The relationship between elastic strain and fatigue life in the high cycle fatigue can be calculated from Basquin's reformulated equations which are as follows:

$$\sigma_a=\frac{\Delta\varepsilon_p}{2}E=\sigma_f^{'}\left(2N\right)^{b} \quad (23)$$

Where, $\sigma_f^{'}$ and b are the fatigue strength coefficient and Fatigue strength exponent.

Miner's Rule for fatigue damage calculation:

The fatigue damage produced by n cycles at one strain level can be defined as

$$D=\frac{n}{N} \quad (24)$$

Where,

n=Number of applied cycles at strain range level $\Delta\varepsilon_a$

N=Total Number of cycles to the failure at strain range level $\Delta\varepsilon_a$

For variable amplitude loading condition which contains more than one strain range level within the spectrum then the formula can be derived as

$$\sum D_i=\sum D_i\frac{n_i}{N_i} \quad (25)$$

Failure is occurs at the level where, $\Sigma D_i \geq 1$

The general formula for obtaining the Fatigue stress from old derivation is

$$\sigma = E_0\,(1 - D).\varepsilon \quad (26)$$

The Modulus of elasticity can be obtained from

$$E_s=\frac{\sigma_{max}}{\varepsilon_{max}} \quad (27)$$

$$E_{cyclic\ tensile\ tests}=\frac{(\sigma_{0.003}-\sigma_{0.001})}{(0.003-0.001)} \quad (28)$$

For example,

$$E_{cyclic\ tensile\ tests}=\frac{(\sigma_{0.003}-\sigma_{0.001})}{(0.003-0.001)} \quad (29)$$

Residual Strength Based Models

Broutman and Sahu was developed the Residual Strength based Models which is die to progressive loss of strength during fatigue are expressed as:

$$\sigma_R=\sigma_0+\frac{\left(\sigma_i-\sigma_0\right)}{N}n \quad (30)$$

Where, σ_R represents the residual strength, σ_i represents maximum applied stress level, σ_0 represents the static strength of the specimen, N is the Number of constant amplitude cycle to the failure, n is the number of cycles experienced at sress level.

According to DNVGL-ST-C501, Edition August 2017, for Composite Components

Time to failure for fiber dominated property

$$\log[\varepsilon(N)] = 0.063 - 0.101\log N \quad (31)$$

For Stress rupture under permanent static loads,

$$\text{Log}\sigma = \text{Log}\sigma_{0\,stress\,rupture} - \beta\text{Logt} \quad (32)$$

Where, t=time to failure under a permanent stress, i.e. σ.

The Cycles to failure under cycic fatigue loads,

$$R = \frac{\text{Minimum Stress}}{\text{Maximum Stress}} \quad (33)$$

Threrefore,

$$\text{log}\sigma = \text{Log}\sigma_{0\,fatigue} - \alpha\text{LogN} \quad (34)$$

$$\text{log}\varepsilon = \text{Log}\varepsilon_{0\,fatigue} - \alpha\text{LogN} \quad (35)$$

Reduction of Strength with time can be described by one of the following equations,

$$\log[\sigma(t)] = \log[\sigma(1)] - \beta\log(t) \quad (36)$$

OR,

$$[\sigma(t)] = [\sigma(1)] - \beta\log(t)$$

$$\log[\varepsilon(t)] = \log[\varepsilon(1)] - \beta\log(t)$$

$$[\varepsilon(t)] = [\varepsilon(1)] - \beta\log(t)$$

Where, $\sigma(t)$, $\varepsilon(t)$=time dependent stress or strain to the failure

$\sigma(1)$, $\varepsilon(1)$=scalar depending on material failure mechanism and on the environmental conditions at time (1)

Units of time must be consistent in this equation.

β=Slope depending on materials, failure mechanism and on the environmental conditions.

Log is the logarithmic to the base (10).

General Strain-life Model

The general strain-life model is now being widely used to describe strain controlled small specimen fatigue behaviour over a wide range of strain. Consider elastic strain and plastic strain life seperately. The two are added to obtain the total strain-life curve.

$$\varepsilon_a = \frac{\sigma_f^{'}}{E}\left(2\text{N}\right)^b + \varepsilon_f^{'}\left(2\text{N}\right)^c \quad (37)$$

ε_a =Strain amplitude

E = Modulus of elasticity

$\sigma_f^{'}$ = fatigue strength coefficient

$\varepsilon_f^{'}$ = fatigue ductility coefficient

C= fatigue ductility exponent.

Low cycle fatigue:

Low Cycle Fatigue (LCF) (high Strain) is concened about fatigue failure at relatively high stress and low numbers of cycles to failure. LCF data is normally presented as a plot of strain range $\Delta\varepsilon_p$ against N. On the log scale, this relation can be described by

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'}\left(2\text{N}\right)^c \quad (38)$$

Where, $\frac{\Delta\varepsilon_p}{2}$ = plastic strain amplitude

= Plastic ductility coefficient

2N=Number of Strain reversals to failure

C=fatigue ductility exponent varies between -0.50 to -0.70.

Strain-life equation

For the high-cycle (low strain) fatigue (HCF) regime, where the nominal strains are elastic, Basquin's equation can be reformulated to describe,

$$\sigma_a = \frac{\Delta\varepsilon_e}{2}\text{ E} = \sigma_f^{'}\left(2\text{N}\right)^b \quad (39)$$

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} \quad (40)$$

$$\frac{\Delta\varepsilon}{} = \frac{}{}\left(2\text{N}\right)^b + \quad \left(2\text{N}\right)^c \quad (41)$$

Where,

σ_a = alternate stress amplitude

$\frac{\Delta\varepsilon_e}{2}$ = elastic strain amplitude

E=Young's modulus

$\sigma_f^{'}$ =fatigue strength coefficient defined by the stress intercept at 2N=1

2N=number of load reversals to failure (N= number of cycles to failure)

B= fatigue strength exponent, which varies between -0.05 and -0.12

The typical specific properties of woven glass/epoxy composites are 1.6, 1443.0, 89.90 as density (g/cc), Tensile specific strength (MPa/g/cc) and Tensile specific modulus (Gpa/g/cc).

Numerical simulation:

From the Figure 2, it is clearly shown that the force is reduced and tends to zero after 72500 cycle; i.e. the damage of the Woven glass/epoxy fabric composites after that cycles and complete failure occurred at N_f=72737.50 Cycles.

From the Figure 3, Damage Factor=0.00 indicates the state of virgin of the material and Damage Factor=1.00 indicates the complete failure state of the materials). In Figure 3, the initial Fatigue stress is 0.329182672 GPA for the linear Fatigue Strain ranges from 0.023 to 0.043. This is due to initial loading condition. Initially, when loaded to the material, then the intermolecular structure of the material is activated for capturing the effect of the fatigue load, so the strain ranges formulation at that time. After activation of the all the active molecule in the material then variation of the strain should be very small like as constant (Figures 4 and 5). When the capacity of molecules of the material is tired i.e. formulation of the weak zone then the stress decreases and strain should be increased and fatigue fracture takes place. Suddenly decreased in the stress magnitude is the prime symbol of fatigue fracture of the Material. In Figure 6, after the fatigue stress ranges from 0.065548192 is suddenly changed and there is much more increment of linear strain which causes fracture as the symbol of damage.

Test Experiment

Fabrication of composite test specimen

Filament winding: Filament winding is one of the best processes for manufacturing of special high strength structural composite

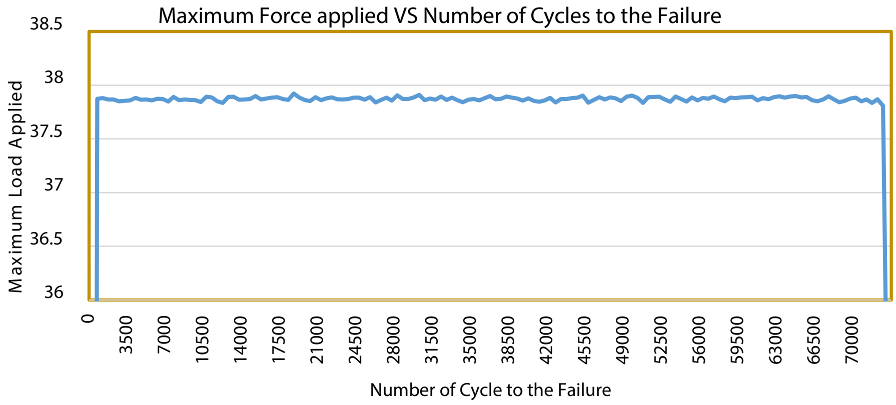

Figure 2: Model prediction curve regarding Maximum force applied verses Number of Cycle to the failure (From the above figure, it is clearly shown that the force is reduced and tends to zero after 72500 cycle; i.e. the damage of the Woven glass/epoxy fabric composites after that cycles and complete failure occurred at N_f = 72737.50 Cycles.

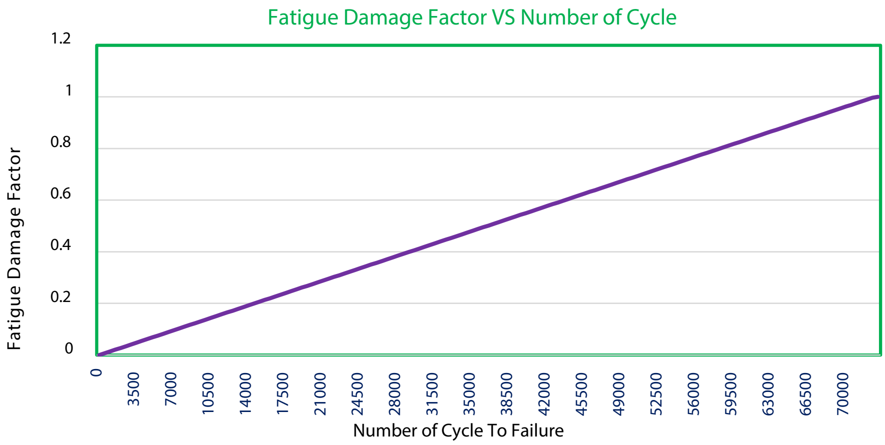

Figure 3: Model prediction curve regarding Fatigue Damage Factor verses Number of Cycle to the failure (From the above figure, Damage Factor=0.00 indicates the state of virgin of the material and Damage Factor=1.00 indicates the complete failure state of the materials).

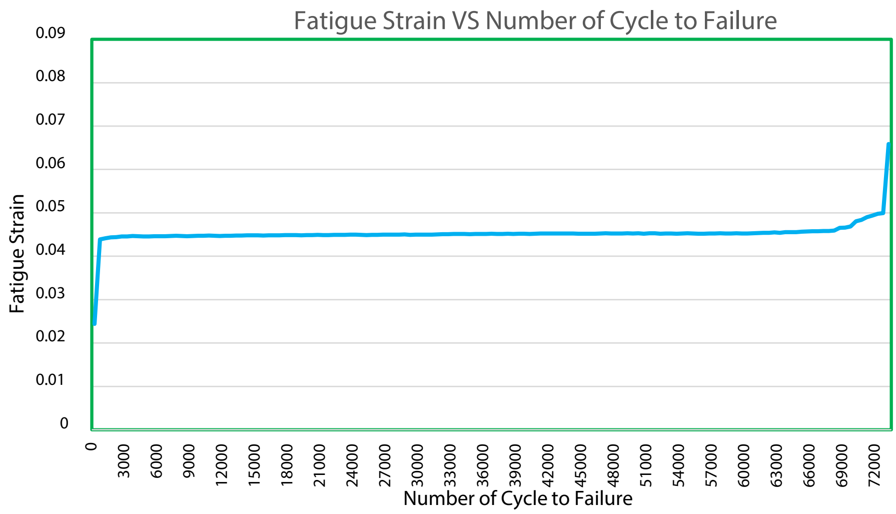

Figure 4: Model prediction curve regarding Fatigue Strain VS Number of Cycle to Failure. In this figure, it is clearly shown that after the 67500 cycle number there is huge changes in fatigue strain as a symbolic cause of fracture.

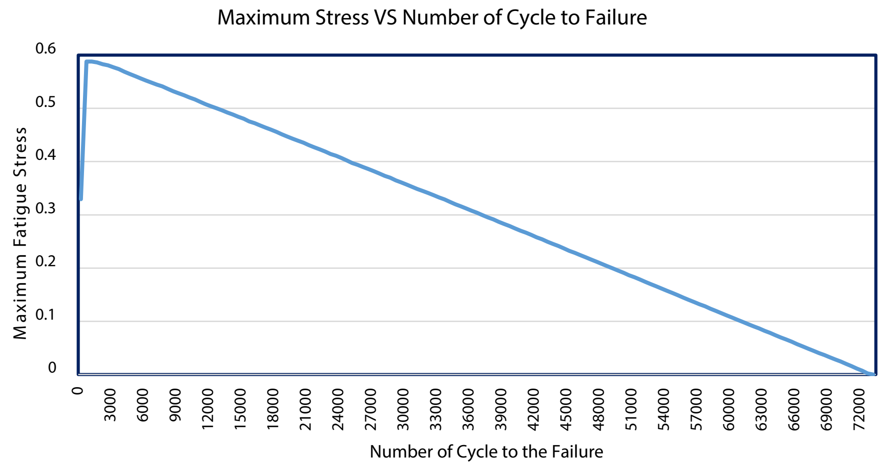

Figure 5: Model prediction curve regarding Maximum Stress VS Number of Cycle to Failure.

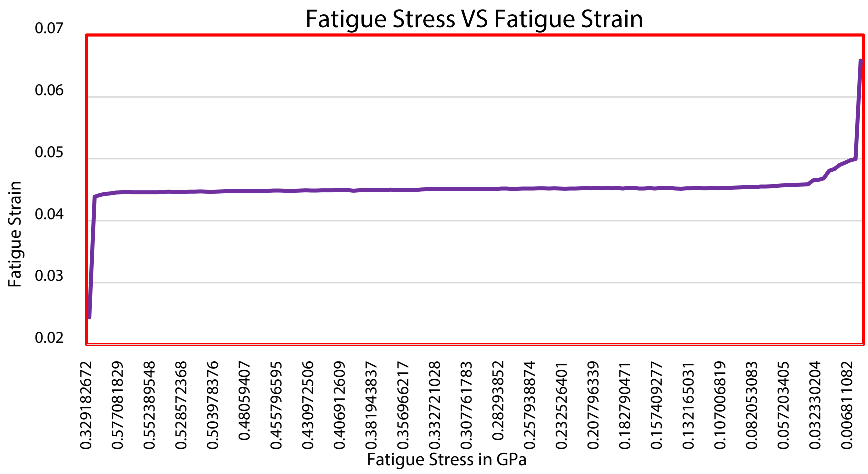

Figure 6: Model prediction curve regarding Fatigue Stress VS Fatigue Strain of woven Glass/Epoxy Composites.

component by creating the winding of resigning impregnated fiber around the Mandrel after that hardening them to form wound reinforcement in the form of the mandrel. The reinforcement fibers are placed firstly on the rotating mandrel by the help of the horizontal carrier. The fiber position is controlled by controlling the speed of the horizontal carrier. After that hardening is done at an appropriate temperature and time. After hardening is completed then the wound composite is removed from the mandrel.

Winding material: According to Farhan Manasiya et al., filament winding material type, properties, and process technology are as follows:

Fiber: According to chemical compositions, Fibers are classified into groups mainly C-glass, S-glass and E-glass fibers which were found for excellent fiber forming capacity and nowadays it is used as the reinforcing phase in the material known as glass fiber.

Epoxy resin: For keeping the composite together, resin plays as a role of glue which has good mechanical properties, good adhesive properties, good toughness properties, and good environmental properties.

(c) Process of filament winding

The Process of filament winding for Glass epoxy composites is shown below.

The tubes were manufactured by using an epoxy resin system with glass fiber at a mandrel diameters 140 mm and the winding angle of 15° and 90° were selected in four layers i.e. 15°, 90°, 15°, 90°. The mandrel is supported horizontally between a head and a tail stroke. The tail stroke is driven by the required angle and speed using a computer program. As the mandrel rotates, a carriage moves along the mandrel and give a fiber with a given position and tension. Carriage motion is controlled by the computer. Figure 7 represents the process of manufacturing composite tubes using the filament winding process.

Fiber passed through a resin bath and get wet before winding operation. The amount of resin was reduced with a blade which was attached to the resin bath. Once the composite tubes are manufactured, a blanket and Teflon were wrapped on the tubes and tighten it with the plastic tape in order to absorb the excess resin. Manufactured tubes were kept in room temperature for 48 hours and then placed in the furnace for curing. The curing operation was carried out at 60°C for 15 hours (Figures 8 and 9).

Test procedure

Computer controlled 809 MTS Axial/Torsional Test Machine as per Figure 5 was used for Tension Fatigue test with a load capacity of 50 KN. The test rate was adjusted to 0.1 mm/s, putting frequency to 1 HZ. The tests were conducted in room temperature. Composite tubes were tensed between two parallel grips. While the upper grip was moving the lower one was stationary. The fixed grip was fitted with a load cell from which the load signal, crosshead displacement and time were stored in the computer. In each test, the load was assigned as the Y-axis and the crosshead displacement as X-axis. For all composites Tension tests, progressive crushing occurred.

Summarized Procedure are:

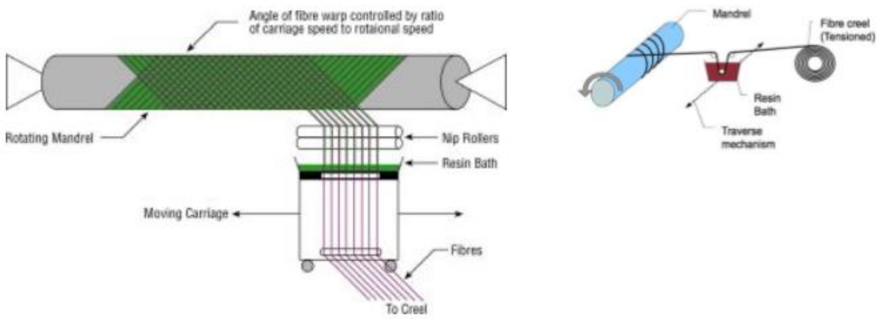

Figure 7: Process of filament winding according to Farhan Manasiya et al.

Figure 8: Winding of Glass Fiber at 15° at left and 90° right side.

Figure 9: Winding of Glass Fiber at 90° left side and Cutting of Test Sample for fatigue testing after hardening at the right side.

Install the Grips

Install the Specimen

Load to "0" KN

Start

Fatigue Tension tests were carried out on each cylindrical composite tube. The load-displacement response, running time and number of the cycle was recorded. The effects of using different fibers sample were studied. The energy absorbed during progressive crushing of composite tube is the area under the load-displacement curve. Energy absorption of glass/epoxy composite tubes was calculated from load-displacement curves with the graphical method. High Macroscopic Camera was used to taking the photos of Samples at the end of 0001, 30000, 50000 and 70,000.00 Cycles (Figure 10).

Results and Discussion

Figure 2 illustrates the maximum fatigue load i.e. 38 KN and number of fatigue cycles to the failure is 72737.50 integer cycles. Figure 3 gives the idea of damage mechanism factor initial zero at the virgin state of material and one at the failure state of the materials. Regarding Figure 4, it is the representation of idea of fatigue strain behaviour at different cycles of loading, whereas Figure 5 gives the idea of maximum capacity of materials at different cycle of fatigue loading. The relationship of fatigue stress and fatigue strain of woven glass fabric composite is described in Figure 6. Analysis of Fatigue Strain recorded during tensile fatigue test is described in Table 1. Figures 11-13 are the state behaviour and Fatigue Strain recorded at the time of testing and tabulated as (2).

Figures 14-23 is the interpretation of the result obtained from fatigue testing of Glass Fiber Composites in terms of Fatigue load, deformations, fatigue stress, maximum and minimum fatigue load, and strain at different fatigue cycle including plotting of S-N Curve. The maximum number of cycle to failure obtained from the fatigue testing is N_f=72737.50 interfere cycles at 1.00 fatigue damage factor, initial strain at 0.00 cycle at 63.57617 sec time was recorded as 0.0244, final strain at 72735.50 cycle at 72801.40 sec was recorded as 0.0659. Initial, at middle and final stress was recorded as 0.329183 GPA initial, varying to 0.58809 GPA at middle point and 0.002202 GPA to 0.00 at failure state. Damage factor was calculated according to Minor's

Figure 10: Initial Position, Test Sample loaded, Imaging and taking the reading in Fatigue Testing.

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	Min Time, Sec	Diff. in time	Max. Axial Force, KN	Min. Axial Force, KN	Max. Axial Displacement, mm	Min. Axial Displacement, mm	Difference in Displacement	Axial Integer Count, cycles	Damage Factor, D=N/Nf	Strain=ε	$\sigma=E_0x(1-D)x\varepsilon$
63.9082	63.57617	0.332	17.8634	4.094	1.2192	0.5677313	0.651464	0	0	0.0244	0.329183
563.908	563.4395	0.4688	37.873	4.4	2.19319	0.7440537	1.449132	500	0.00687	0.0439	0.58809
1063.91	1063.439	0.4688	37.8795	4.408	2.20778	0.7593036	1.448473	1000	0.01375	0.0442	0.587905
1563.91	1563.439	0.4688	37.8681	4.402	2.21665	0.764659	1.45199	1500	0.02062	0.0443	0.586153
2063.91	2063.439	0.4688	37.8669	4.406	222087	0.7649213	1.455951	2000	0.0275	0.0444	0.583148
2563.91	2563.439	0.4688	37.8505	431	2.22766	0.7706136	1.457048	2500	0.03437	0.0446	0.580796
3063.91	3063.439	0.4688	37.8534	4.358	2.22929	0.7686734	1.460612	3000	0.04124	0.0446	0.577082
3563.91	3563.439	0.4688	37.8593	436	2.23285	0.7703692	1.46248	3500	0.04812	0.0447	0.57386
4063.91	4063.439	0.4688	37.8816	4.352	2.23029	0.7700652	1.460221	4000	0.05499	0.0446	0.569062
4563.91	4563.439	0.4688	37.8661	4341	2.22878	0.7670939	1.461688	4500	0.06187	0.0446	0.564542
5063.91	5063.439	0.4688	37.8671	4.371	2.22889	0.7681876	1.460698	5000	0.06874	0.0446	0.560431
5563.91	5563.439	0.4688	37.8578	4361	2.2297	0.7668257	1.462877	5500	0.07561	0.0446	0.556498
6063.91	6063.439	0.4688	37.8746	4364	2.22982	0.7691652	1.460656	6000	0.08249	0.0446	0.55239
6563.91	6563.439	0.4688	37.8709	4348	2.23034	0.7667601	1.463583	6500	0.08936	0.0446	0.548379
7063.91	7063.439	0.4688	37.848	4.352	2.23283	0.7709503	1.461878	7000	0.09624	0.0447	0.544846
7563.91	7563.439	0.4688	37.8916	4.356	2.23485	0.7715911	1.463255	7500	0.10311	0.0447	0.541191
8063.91	8063.439	0.4688	37.8608	4.37	2.23323	0.770694	1.462534	8000	1.10998	0.0447	0.536654
8563.89	8563.439	0.4492	37.8673	4.9	2.23126	0.8052319	1.426032	8500	0.11686	0.0446	0.532041

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	**Min Time, Sec**	**Diff. in time**	**Max. Axial Force, KN**	**Min. Axial Force, KN**	**Max. Axial Displacement, mm**	**Min. Axial Displacement, mm**	**Difference in Displacement**	**Axial Integer Count, cycles**	**Damage Factor, D=N/Nf**	**Strain=ε**	**σ=E_0x(1-D)xε**
9063.91	9063.439	0.4688	37.8638	4.361	2.23411	0.7726491	1.461458	9000	0.12373	0.0447	0.528572
9563.91	9563.439	0.4688	37.8602	4.351	2.23501	0.7737816	1.461226	9500	0.13061	0.0447	0.524637
10063.9	10063.44	0.4688	37.8438	4.358	2.23585	0.7732868	1.462561	10000	0.13748	0.0447	0.520685
10563.9	10563.44	0.4688	37.8929	4.348	2.2377	0.773704	1.464	10500	0.14435	0.0448	0.516964
11063.9	11063.44	0.4688	37.8873	4.315	2.23566	0.7745087	1.461151	11000	0.15123	0.0447	0.512342
11563.9	11563.44	0.4688	37.8507	4.355	2.23305	0.7735103	1.459539	11500	0.1581	0.0447	0.501599
12063.9	12063.44	0.4688	37.8352	4.361	2.23537	0.7759809	1.45939	12000	0.16498	0.0447	0.503978
12563.9	12563.44	0.4688	37.8912	4.355	2.23713	0.7740021	1.463124	12500	0.17185	0.0447	0.500222
13063.9	13063.44	0.4688	37.8922	4.354	2.23804	0.7762968	1.461741	13000	0.17872	0.0448	0.496272
13563.9	13563.44	0.4688	37.8658	4.334	2.23783	0.7763326	1.4615	13500	0.1856	0.0448	0.492073
14063.9	14063.44	0.4688	37.8682	4.361	2.24106	0.7790715	1.461989	14000	0.19247	0.0448	0.488624
14563.9	14563.44	0.4688	37.871	4.337	2.24056	0.7801413	1.460418	14500	0.19935	0.0448	0.484356
15063.9	15063.44	0.4688	37.1!997	4.312	2.24241	0.7807672	1.461643	15000	0.20622	0.0448	0.480594
15563.9	15563.44	0.4688	37.8677	4.341	2.23907	0.7779747	1.461098	15500	0.2131	0.0448	0.475723
16063.9	16063.44	0.4688	37.8759	4.31	2.24196	0.7808328	1.46113	16000	0.21997	0.0448	0.472176
16563.9	16563.44	0.4688	37.8836	4.348	2.24206	0.7813066	1.460758	16500	0.22684	0.0448	0.468036
17063.9	17063.44	0.4688	37.8883	4.371	2.24174	0.7817865	1.459956	17000	0.23372	0.0448	0.463808
17563.9	17563.44	0.4688	37.8713	4.361	2.24373	0.7826149	1.461116	17500	0.24059	0.0449	0.460055

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	**Min Time, Sec**	**Diff. in time**	**Max. Axial Force, KN**	**Min. Axial Force, KN**	**Max. Axial Displacement, mm**	**Min. Axial Displacement, mm**	**Difference in Displacement**	**Axial Integer Count, cycles**	**Damage Factor, D=N/Nf**	**Strain=ε**	**σ=E_0x(1-D)xε**
18063.9	18063.44	0.4688	37.8629	4.352	2.24327	0.7814497	1.461816	18000	0.24747	0.0449	0.455797
18563.9	18563.44	0.4688	37.9233	4.366	2.24253	0.7821262	1.460403	18500	0.25434	0.0449	0.451485
19063.9	19063.44	0.4688	31.8855	4.373	2.24212	0.7845849	1.457539	19000	0.26121	0.0448	0.447242
19563.9	19563.44	0.4688	37.8638	4.359	2.24308	0.7838338	1.45925	19500	0.26809	0.0449	0.44327
20063.9	20063.44	0.4688	37.853	4.371	2.24321	0.7854402	1.457772	20000	0.27496	0.0449	0.439132
20563.9	20563.44	0.4688	37.8879	4341	2.24585	0.1838156	1.461974	20500	0.28184	0.0449	0.43548
21063.9	21063.44	0.4688	37.8618	4.372	2.24408	0.7841408	1.459941	21000	0.28871	0.0449	0.430973
21563.9	21563.44	0.4688	37.877	4.376	2.24415	0.7847488	1.459405	21500	0.29558	0.0449	0.426821
22063.9	22063.44	0.4688	37.8856	4.376	2.24633	0.7845491	1.461786	22000	0.30246	0.0449	0.423067
22563.9	22563.44	0.4688	37.8686	4.362	2.24569	0.7873029	1.458383	22500	0.30933	0.0449	0.418777
23063.9	23063.44	0.4688	37.8675	4.351	2.24523	0.7834285	1.461801	23000	0.31621	0.0449	0.414524
23563.9	23563.44	0.4688	37.8711	4.355	2.24773	0.7861227	1.46161	23500	0.32308	0.045	0.410815
24063.9	24063.44	0.4688	37.8835	4.346	2.24922	0.7865221	1.462701	24000	0.32995	0.045	0.406913
24563.9	24563.44	0.4688	37.8841	4.352	2.2469	0.7852108	1.461691	24500	0.33683	0.0449	0.402322
25063.9	25063.44	0.4688	37.8648	4.352	2.24269	0.7846266	1.458061	25000	0.3437	0.0449	0.397405
25563.9	25563.44	0.4688	37.8894	4.361	2.24608	0.78502	1.461059	25500	0.35058	0.0449	0.393838
26063.9	26063.44	0.4688	37.8401	4.364	2.24673	0.7886469	1.458088	26000	0.35145	0.0449	0.389783
26563.9	26563.44	0.4688	37.8628	4.365	2.24868	0.7876307	1.461053	26500	0.36432	0.045	0.385947

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	**Min Time, Sec**	**Diff. in time**	**Max. Axial Force, KN**	**Min. Axial Force, KN**	**Max. Axial Displacement, mm**	**Min. Axial Displacement, mm**	**Difference in Displacement**	**Axial Integer Count, cycles**	**Damage Factor, D=N/Nf**	**Strain=ε**	**$\sigma=E_0x(1-D)x\varepsilon$**
27063.9	27063.44	0.4688	4.352	4.352	2.24968	0.7901579	1.459527	27000	0.3712	0.045	0.381944
27563.9	27563.44	0.4688	37.8566	4.362	2.24837	0.7893264	1.459044	27500	0.37807	0.045	0.377548
28063.9	28063.44	0.4688	37.9051	4.368	2.24799	0.791049	1.45694	28000	0.38495	0.045	0.373311
28563.9	28563.44	0.4688	37.8707	4.371	2.25079	0.7916272	1.459163	28500	0.39182	0.045	0.369599
29063.9	29063.44	0.4688	37.8723	4.371	2.24704	0.7880271	1.459014	29000	0.39869	0.0449	0.364813
29563.9	29563.44	0.4688	37.8862	4.357	2.24896	0.7913083	1.457656	29500	0.40551	0.045	0.360951
30063.9	30063.44	0.4688	37.9107	4.356	2.25016	0.7924706	1.457685	30000	0.41244	0.045	0.356966
30563.9	30563.44	0.4688	37.8601	4.368	2.24941	0.7912666	1.458147	30500	0.41932	0.045	0.352614
31063.9	31063.44	0.4688	31.8755	4.359	2.24906	0.7919312	1.457125	31000	0.42619	0.045	0.348443
31563.9	31563.44	0.4688	37.8655	4.381	2.2525	0.79225	1.460248	31500	0.43306	0.045	0.344796
32063.9	32063.44	0.4688	37.8943	4.371	2.25473	0.7943332	1.4604	32000	0.43994	0.0451	0.340953
32563.9	32563.44	0.4688	37.8637	4.339	2.25436	0.1926255	1.461739	32500	0.44681	0.0451	0.336713
33063.9	33063.44	0.4688	37.8853	4.37	2.25566	0.7941484	1.461515	33000	0.45369	0.0451	0.332721
33563.9	33563.44	0.4688	37.8605	4.364	2.25747	0.7970899	1.460382	33500	0.46056	0.0451	0.328798
34063.9	34063.44	0.4688	37.8418	4.372	2.25553	0.7964969	1.459035	34000	0.46743	0.0451	0.324329
34563.9	34563.44	0.4688	37.865	4.351	2.25438	0.7952452	1.45914	34500	0.47431	0.0451	0.31998
35063.9	35063.44	0.4688	37.8723	4.368	2.25673	0.7964402	1.460293	35000	0.48118	0.0451	0.316125
35563.9	35563.44	0.4688	37.8596	4.373	2.25125	0.79723	1.460025	35500	0.48806	0.0451	0.312009

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	**Min Time, Sec**	**Diff. in time**	**Max. Axial Force, KN**	**Min. Axial Force, KN**	**Max. Axial Displacement, mm**	**Min. Axial Displacement, mm**	**Difference in Displacement**	**Axial Integer Count, cycles**	**Damage Factor, D=N/Nf**	**Strain=ε**	**$\sigma=E_0x(1-D)x\varepsilon$**
36063.9	36063.44	0.4688	37.8801	4.383	2.25683	0.7977545	1.45908	36000	0.49493	0.0451	0.307762
36563.9	36563.44	0.4688	37.9001	4.374	2.25877	0.7968575	1.461914	36500	0.5018	0.0452	0.303834
37063.9	37063.44	0.4688	37.8695	4.378	2.2563	0.7982105	1.458094	37000	0.50868	0.0451	0.299314
37563.9	37563.44	0.4688	37.8729	4.351	2.25706	0.7970035	1.460055	37500	0.51555	0.0451	0.295225
38063.9	38063.44	0.4688	37.895	4.368	2.25904	0.7975996	1.461443	38000	0.52243	0.0452	0.291292
38563.9	38563.44	0.4688	37.8846	4.357	2.25684	0.7970392	1.459804	38500	0.5293	0.0451	0.28682
39063.9	39063.44	0.4688	37.8748	4.364	2.2593	0.8010298	1.45827	39000	0.53617	0.0452	0.282939
39563.9	39563.44	0.4688	37.8573	4.365	2.26049	0.8001119	1.46038	39500	0.54305	0.0452	0.278892
40063.9	40063.44	0.4688	37.8784	4.357	2.25745	0.7972241	1.460224	40000	0.54992	0.0451	0.274327
40563.9	40563.44	0.4688	37.8545	4.381	2.25908	0.8024901	1.456586	40500	0.5568	0.0452	0.270332
41063.9	41063.44	0.4688	37.8762	4.35	2.26078	0.8019805	1.458797	41000	0.56367	0.0452	0.26634
41563.9	41563.44	0.4688	37.858	4.352	2.26074	0.801298	1.459447	41500	0.57054	0.0452	0.26214
42063.9	42063.44	0.4688	37.8821	4.373	2.2607	0.8016854	1.459014	42000	0.57742	0.0452	0.257939
42563.9	42563.44	0.4688	37.8396	4.369	2.26123	0.8026004	1.468633	42500	0.58429	0.0452	0.253803
43063.9	43063.44	0.4688	37.8718	4.379	2.2612	0.803715	1.457483	43000	0.59117	0.0452	0.249602
43563.9	43563.44	0.4688	37.8723	4.38	2.26076	0.8072585	1.453501	43500	0.59804	0.0452	0.245358
44063.9	44063.44	0.4688	37.879	4.35	2.26198	0.8046001	1.457378	44000	0.60491	0.0452	0.241292
44563.9	44563.44	0.4688	37.8838	4.362	2.25987	0.804767	1.455098	44500	0.61179	0.0452	0.236872

Citation: Yadav IN, Thapa KB (2019) Strain-Based Fatigue Damage Modeling of Plain Woven Glass/Epoxy Fabric Composites. J Material Sci Eng 8: 526.

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	**Min Time, Sec**	**Diff. in time**	**Max. Axial Force, KN**	**Min. Axial Force, KN**	**Max. Axial Displacement, mm**	**Min. Axial Displacement, mm**	**Difference in Displacement**	**Axial Integer Count, cycles**	**Damage Factor, D=N/Nf**	**Strain=ε**	**$\sigma=E_0x(1-D)x\varepsilon$**
45563.9	45563.44	0.4688	37.8368	4.371	2.25959	0.8048296	1.454765	45500	0.62554	0.0452	0.228456
46063.9	46063.44	0.4688	37.862	4.372	2.25928	0.8047521	1.454526	46000	0.63241	0.0452	0.224231
46563.9	46563.44	0.4688	37.8876	4.353	2.26133	0.8046895	1.456645	46500	0.63929	0.0452	0.220238
47063.9	47063.44	0.4688	37.8665	4.361	2.26353	0.8049637	1.458568	47000	0.64616	0.0453	0.216251
47563.9	47563.44	0.4688	37.8855	4.397	2.26152	0.8083672	1.453155	41500	0.65303	0.0452	0.211862
48063.9	48063.44	0.4688	37.8773	4.357	2.26296	0.8064866	1-456472	48000	0.65991	0.0453	0.207796
48563.9	48563.44	0.4688	37.8525	4.362	2.26283	0.8061171	1.456711	48500	0.66678	0.0453	0.203585
49063.9	49063.44	0.4688	37.8918	4.37	2.26337	0.8075059	1.455864	49000	0.67366	0.0453	0.199432
49563.9	49563.44	0.4688	37.9039	4316	2.2622	0.8086383	1.453567	49500	0.68053	0.0452	0.195131
50063.9	50063.44	0.4688	37.8826	4.367	2.26402	0.8094549	1.454565	50000	0.6874	0.0453	0.191086
50563.9	50563.44	0.4688	37.8358	4.362	2.26056	0.8080929	1.452464	50500	0.69428	0.0452	0.186598
51063.9	51063.44	0.4688	37.8884	4.381	2.26537	0.8112162	1.454151	51000	0.70115	0.0453	0.18279
51563.9	51563.44	0.4688	37.8913	4.365	2.26501	0.8112967	1.453716	51500	0.70803	0.0453	0.178558
52063.9	52063.44	0.4688	37.893	4.356	2.26035	0.80809	1.452255	52000	0.7149	0.0452	0.173995
52563.9	52563.44	0.4688	37.8672	4.38	2.26071	0.8082777	1.452434	52500	0.72177	0.0452	0.169827
53063.9	53063.44	0.4688	37.8451	4.382	2.26313	0.8115381	1.451591	53000	0.72865	0.0453	0.165809
53563.9	53563.44	0.4688	37.8943	4.372	2.26004	0.8118629	1.448178	53500	0.73552	0.0452	0.161388
54063.9	54063.44	0.4688	37.8716	4.358	2.26315	0.8122533	1.450896	54000	0.7424	0.0453	0.157409
54563.9	54563.44	0.4688	37.8474	4.364	2.26339	0.8107841	1.45261	54500	0.74927	0.0453	0.153225

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	**Min Time, Sec**	**Diff. in time**	**Max. Axial Force, KN**	**Min. Axial Force, KN**	**Max. Axial Displacement, mm**	**Min. Axial Displacement, mm**	**Difference in Displacement**	**Axial Integer Count, cycles**	**Damage Factor, D=N/Nf**	**Strain=ε**	**$\sigma=E_0x(1-D)x\varepsilon$**
55063.9	55063.44	0.4688	37.886	4.371	2.2629	0.8130491	1.449853	55000	0.75614	0.0453	0.148992
55563.9	55563.42	0.4844	37.8593	4.382	2.2596	0.8123278	1.44727	55500	0.76302	0.0452	0.144581
56063.9	56063.44	0.4688	37.8829	4.379	2.25857	0.8118927	1.446676	56000	0.76989	0.0452	0.140323
56563.9	56563.44	0.4688	37.8738	4.384	2.26162	0.813365	1.448256	56500	0.77677	0.0452	0.136315
57063.9	57063.44	0.4688	37.8941	4.349	2.26243	0.8129299	1.449502	51000	0.78364	0.0452	0.132165
51563.9	57563.44	0.4688	37.87	4.37	2.26378	0.8143455	1.449439	51500	0.79051	0.0453	0.128043
58063.9	58063.44	0.4688	37.8498	4.369	2.26237	0.8145869	1.447785	58000	0.79739	0.0452	0.123764
58563.9	58563.44	0.4688	37.8848	4.374	2.26204	0.8160591	1.445979	58500	0.80426	0.0452	0.119547
59063.9	59063.44	0.4688	37.8804	4.386	2.26415	0.8172423	1.446906	59000	0.81114	0.0453	0.115456
59563.9	59563.44	0.4688	37.8871	4.378	2.26283	0.8159966	1.446834	59500	0.81801	0.0453	0.111189
60063.9	60063.44	0.4688	37.8878	4.367	2.26319	0.8149564	1.448238	60000	0.82488	0.0453	0.107007
60563.9	60563.44	0.4688	37.8935	4.349	2.26508	0.816533	1.448545	60500	0.83176	0.0453	0.102892
61063.9	61063.44	0.4688	37.8579	4.385	2.26686	0.8159101	1.45095	61000	0.83863	0.0453	0.098766
61563.9	61563.44	0.4688	37.8809	4.404	2.26854	0.8183002	1.450241	61500	0.84551	0.0454	0.094628
62063.9	62063.44	0.4688	37.8693	4.392	2.27091	0.8212596	1.449654	62000	0.85238	0.0454	0.090513
62563.9	62563.44	0.4688	37.8892	4.393	2.27377	0.8213848	1.452389	62500	0.85925	0.0455	0.086407
63063.9	63063.44	0.4688	37.8976	4.395	2.27008	0.8191586	1.450926	63000	0.86613	0.0454	0.082053
63563.9	63563.44	0.4688	37.8851	4.367	2.27643	0.8191615	1.457265	63500	0.873	0.0455	0.078057
64063.9	64063.44	0.4688	37.8945	4.368	2.27667	0.820902	1.455766	64000	0.87988	0.0455	0.07384

Analysis of Fatigue Strain Recorded during Tensile Fatigue Testing through 809 MTS Axial/Torsional Test Machine											
Max Time, Sec	Min Time, Sec	Diff. in time	Max. Axial Force, KN	Min. Axial Force, KN	Max. Axial Displacement, mm	Min. Axial Displacement, mm	Difference in Displacement	Axial Integer Count, cycles	Damage Factor, D=N/Nf	Strain=ε	$\sigma=E_0 x(1-D) x\varepsilon$
64563.9	64563.44	0.4688	37.8986	4.381	2.2781	0.8222997	1.455802	64500	0.88675	0.0456	0.069658
65063.9	65063.44	0.4688	37.8862	4.384	2.28221	0.823155	1.45905	65000	0.89362	0.0456	0.065548
65563.9	65563.44	0.4688	37.8908	4.382	2.28456	0.8230627	1.4615	65500	0.9005	0.0457	0.061376
66063.9	66063.44	0.4688	37.8598	4.383	2.28727	0.8241117	1.46316	66000	0.90737	0.0457	0.057203
66563.9	66563.44	0.4688	37.8493	4.384	2.2892	0.8231461	1.466057	66500	0.91425	0.0458	0.053003
67063.9	67063.44	0.4688	37.8664	4.381	2.28994	0.8232355	1.466709	67000	0.92112	0.0458	0.04877
67563.9	67563.44	0.4688	37.898	4.384	2.2919	0.8254409	1.466456	67500	0.92799	0.0458	0.044558
68063.9	68063.44	0.4688	37.8665	4.385	2.29484	0.826782	1.468056	68000	0.93487	0.0459	0.040356
68563.9	68563.44	0.4688	37.8412	4.378	2.32651	0.8330315	1.493481	68500	0.94174	0.0465	0.036595
69063.9	69063.44	0.4688	37.8547	4.389	2.33035	0.8341491	1.496205	69000	0.94862	0.0466	0.03233
69563.9	69563.44	0.4688	37.8753	4.389	2.3425	0.8380711	1.50443	69500	0.95549	0.0469	0.0281 51
70063.9	70063.44	0.4688	37.8834	4.414	2.40411	0.8555204	1.548591	70000	0.96236	0.0481	0.024429
70563.9	70563.44	0.4688	37.8506	4.418	2.41796	0.8609385	1.557022	70500	0.96924	0.0484	0.020082
71063.9	71063.44	0.4688	37.8675	4.435	2.45034	0.8711219	1.579222	71000	0.97611	0.049	0.015804
71563.9	71563.44	0.4688	37.8348	4.418	2.46806	0.8787393	1.589316	71500	0.98299	0.0494	0.011337
72063.9	72063.44	0.4688	37.8684	4.426	2.48799	0.8869052	1.601085	72000	0.98986	0.0498	0.006811
72563.9	72563.44	0.4688	37.8072	4.435	2.49828	0.8944332	1.603848	72500	0.99673	0.05	0.002202
72801.4	72801.35	0.0391	33.8826	0.122	3.29422	4.7763675	-1.48214	72738	1	0.0659	0

Table 1: Analysis of Fatigue Strain Recorded during Tensile Fatigue Test through 809 MTS Axial/Torsional Test Machine.

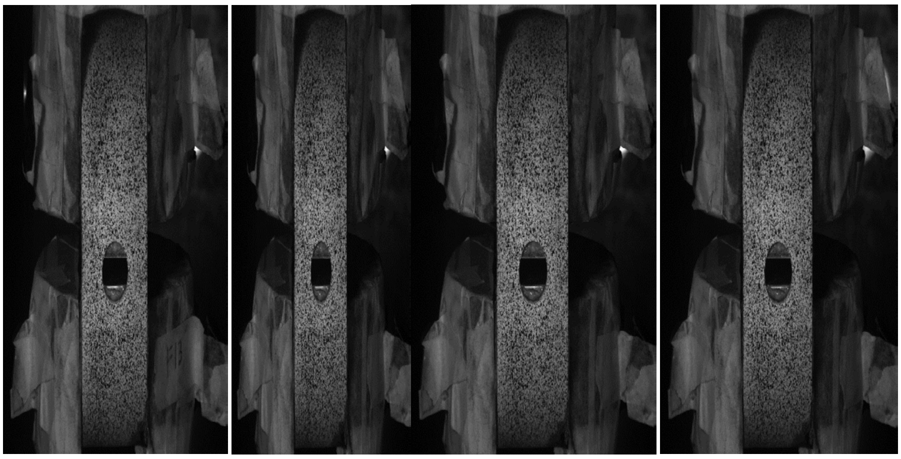

Figure 11: 0001_Cycle.tif, 30000_Cycle.tif, 50000_Cycle.tif, 70000_Cycle.tif.

Rule. All the relevant analysis and results are interpreted in Table 1. The fatigue result is well described. The fatigue fracture of the test of woven glass fiber composites was recorded at Minimum load 3.8 KN, Maximum load 38 KN and Number of Cycle at the failure was 72737.50 with constant frequency 1 HZ, in 809 MTS Axial/Torsional Test Machine. The layup of the winding of the glass fiber was made at four layers of angle 15°, 90°, 15°, 90°. The initial minimum running time, axial force, axial displacement, axial integral count cycle was recorded as 0.041015625 Sec, -0.0166537246702102 KN, 0.000736117385713442 mm and 0.00 cycle whereas initial maximum running time, axial force, axial displacement, axial integral count cycle was recorded as 63.380859375 Sec, 20.88044921875 KN, 1.30315427668393 mm and 0.00 cycles. The final (at the stage of fracture i.e. failure of composite) minimum running time, axial force, axial displacement, axial integral count cycle was recorded as 72800.9609375 Sec, 4.2207705078125 KN, 1.24663708265871 mm, and 72737.5 Cycle whereas final maximum running time with maximum axial force, axial displacement, axial integral count cycle was recorded as 72801.3515625 Sec, 33.88255078125 KN, 3.29422345384955 mm and 72737.5 Cycle. The ultimately final reading after post fracture i.e. Running time, axial force, axial displacement, and axial integral count cycle was recorded as 72801.390625 Sec, 0.121522857666016 KN, 4.7763674519961 mm and 72737.50 Cycles. Minus indicates in the initial reading was due to the activeness of intermolecular activity. From the (Table 1) Minimum

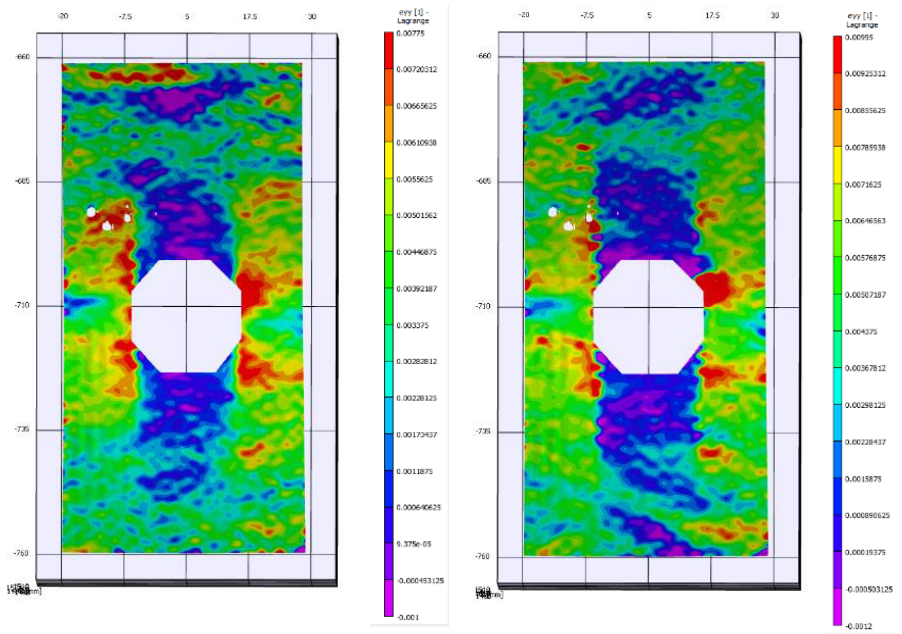

Figure 12: Fatigue Strain at 0001_Cycle and 30000_Cycle. F15. PNG.

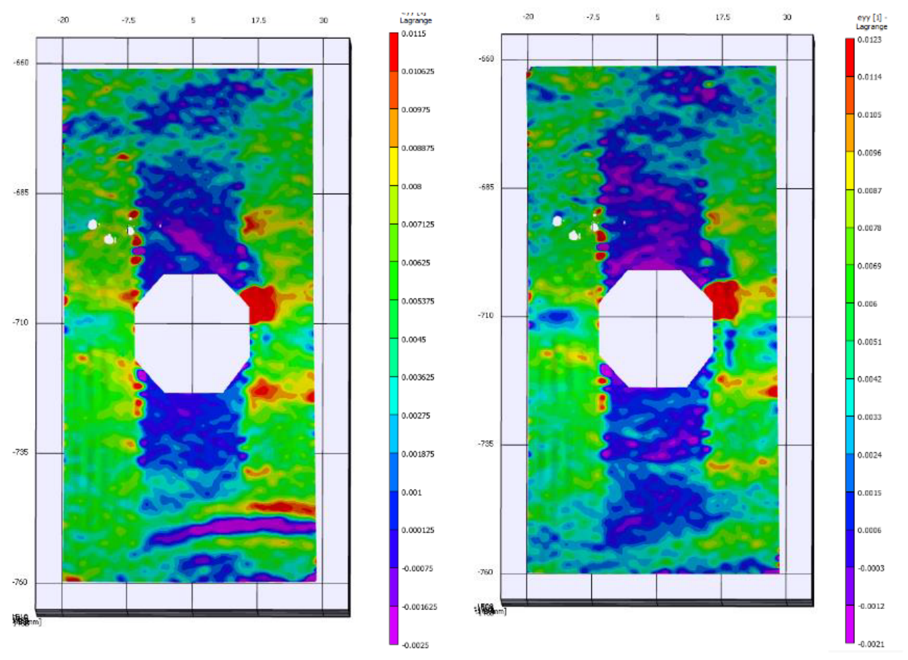

Figure 13: Fatigue Strain at 50000_Cycle and 70000_Cycle. F15.PNG.

and Maximum Strain Measurement corresponding to 0001 Cycle were -0.00045313 and 0.0075, at 30000 Cycle -0.00050313 and 0.00995, at 50000 Cycle -0.00075 and 0.0115, at 70000 Cycle (Final Cycle for fracture) was -0.010234375 and 0.515625.

Conclusions

Strain-Based Fatigue Damage Modeling of Plain Woven Glass/ Epoxy Fiber Composites is established by utilizing the Helmholtz Free Energy (HFE) Model, S-N Model and Fatigue Strain based model. The weakening of the materials due to formulation of microcracks, cracks and finally fracture is due to complete failure of bonding power of the molecules in the material structure. For the Model Validation, one experiment regarding Glass Fiber Composite was done and results are co-related to each other for model validation. The fatigue result is well described. The fatigue fracture of the test of woven glass fiber composites was recorded at Minimum load 3.8 KN, Maximum load

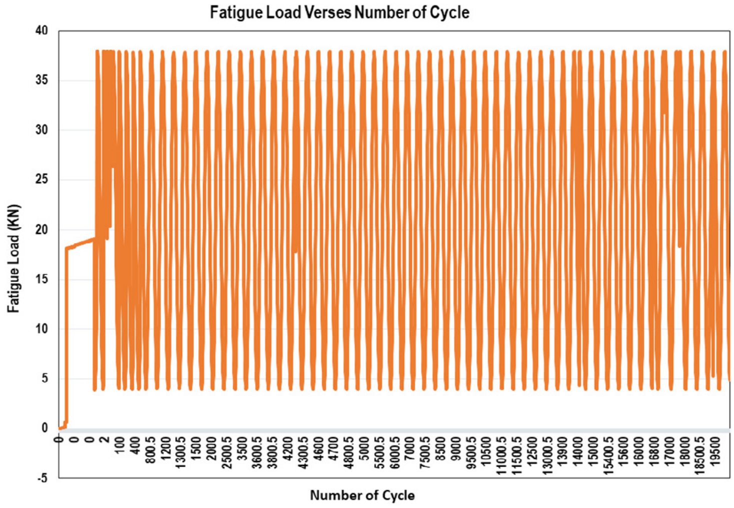

Figure 14: Curve Regarding fatigue load versus Number of Cycle to failure up to 20000 Cycle.

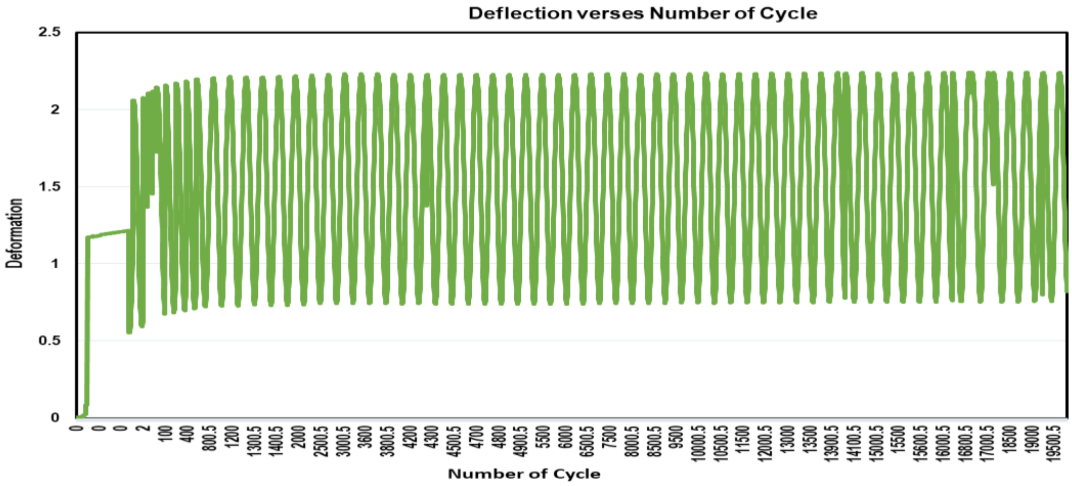

Figure 15: Curve regarding Deformation Verses Number of Cycle up to 20000 Cycle.

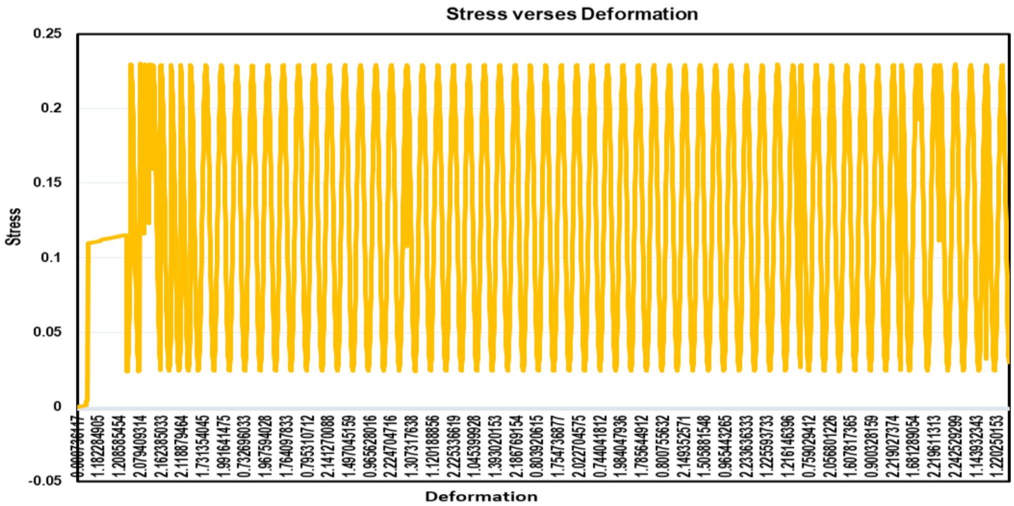

Figure 16: Curve Regarding Stress Verses Deformation up to 20000 Cycle.

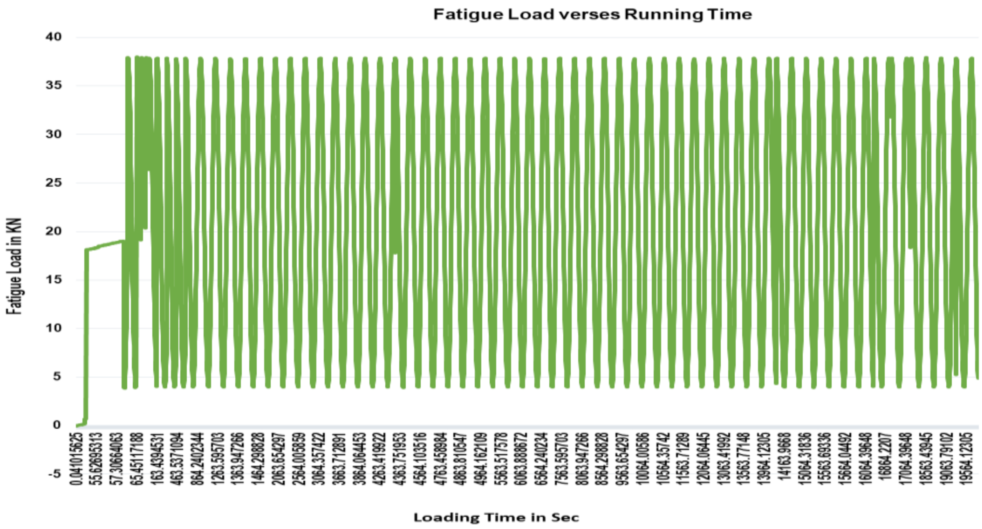

Figure 17: Curve regarding Fatigue Load Verses Loading Time Up to 20000 Cycle.

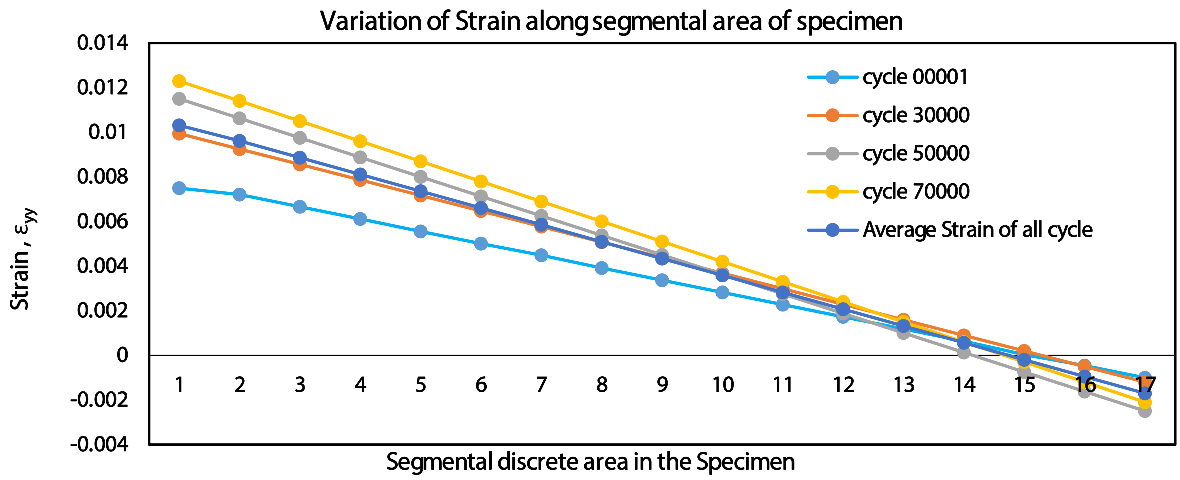

Figure 18: Curve regarding Fatigue Strain along Segmental discrete area Up to 20000 Cycle.

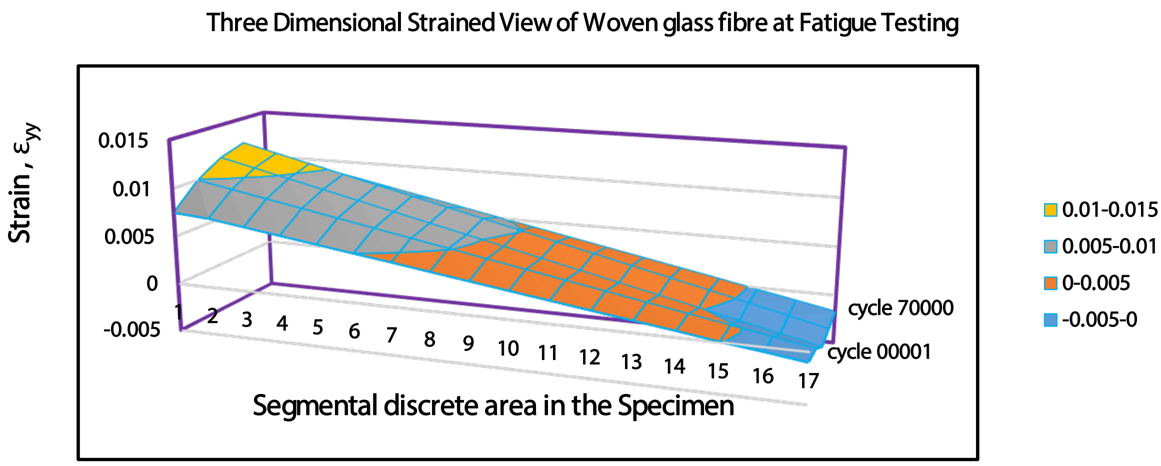

Figure 19: Three Dimensional Curve regarding Fatigue Strain Verses Segmental Area of the Test Specimen Up to 20000 Cycle.

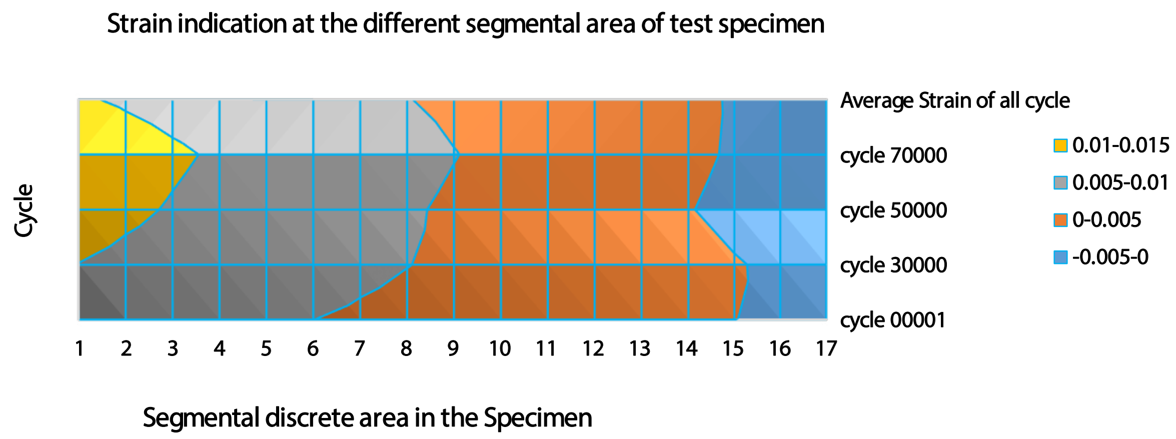

Figure 20: Strain indication at the different segmental area of the test Specimen Up to 20000 Cycle.

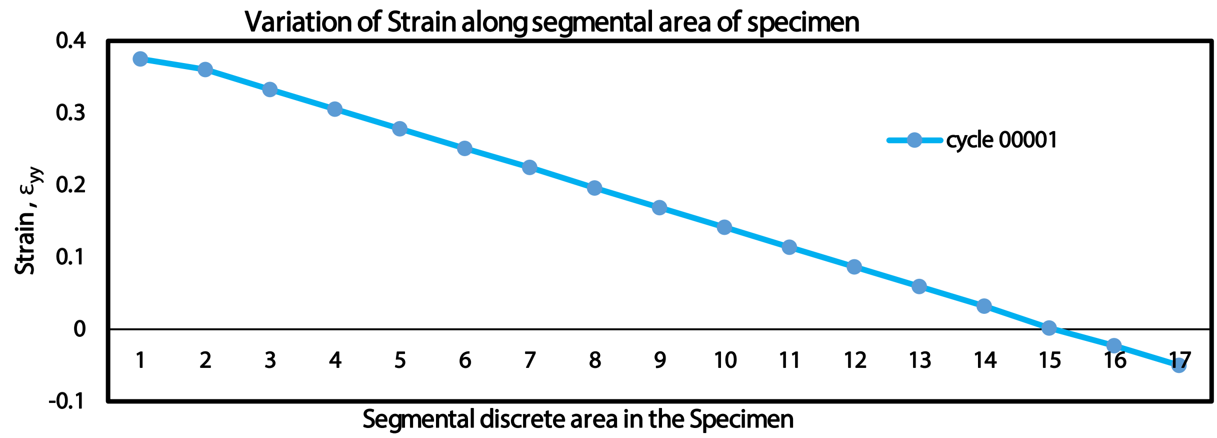

Figure 21: Variation of Strain along the segmental area of the Specimen.

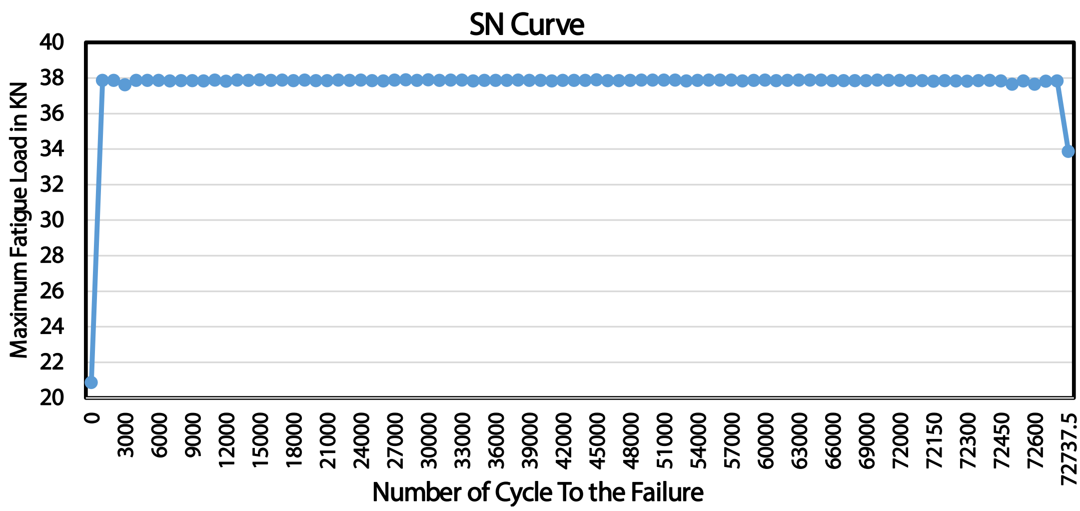

Figure 22: S-N Curve of the Tested Specimen.

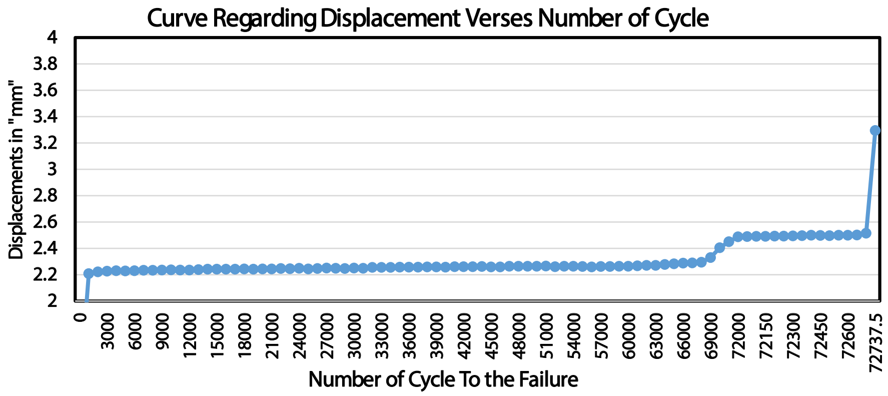

Figure 23: Curve regarding Displacement *Versus* Number of Cycle.

38 KN and Number of Cycle at the failure was 72735 with constant frequency 1 HZ, in 809 MTS Axial/Torsional Test Machine. The layup of the winding of the glass fiber was made at four layers of angle 15°, 90°, 15°, 90°. The initial minimum running time, axial force, axial displacement, axial integral count cycle was recorded as 0.041015625 Sec, -0.0166537246702102 KN, 0.000736117385713442 mm and 0.00 cycle whereas initial maximum running time, axial force, axial displacement, axial integral count cycle was recorded as 63.380859375 Sec, 20.88044921875 KN, 1.30315427668393 mm and 0.00 cycles. The final (at the stage of fracture i.e. failure of composite) minimum running time, axial force, axial displacement, axial integral count cycle was recorded as 72800.9609375 Sec, 4.2207705078125 KN, 1.24663708265871 mm, and 72737.5 Cycle whereas final maximum running time with maximum axial force, axial displacement, axial integral count cycle was recorded as 72801.3515625 Sec, 33.88255078125 KN, 3.29422345384955 mm and 72737.5 Cycle. The ultimately final reading after post fracture i.e. Running time, axial force, axial displacement, and axial integral count cycle was recorded as 72801.390625 Sec, 0.121522857666016 KN, 4.7763674519961 mm and 72737.50 Cycles. Minus indicates in the initial reading was due to the activeness of intermolecular activity. From the Table 1 Minimum and Maximum Strain Measurement corresponding to 0001 Cycle were -0.00045313 and 0.0075, at 30000 Cycle -0.00050313 and 0.00995, at 50000 Cycle -0.00075 and 0.0115, at 70000 Cycle (Final Cycle for fracture) was -0.010234375 and 0.515625. The maximum number of cycle to failure obtained from the fatigue testing is N_f =72737.50 interfere cycles at 1.00 fatigue damage factor, initial strain at 0.00 cycle at 63.57617 sec time was recorded as 0.0244, final strain at 72735.50 cycle at 72801.40 sec was recorded as 0.0659. Initial, at middle and final stress was recorded as 0.329183 GPA initial, varying to 0.58809 GPA at middle point and 0.002202 GPA to 0.00 at failure state.

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