Indian Journal of Science and Technology, *Vol 8(15), 59383, July 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Investigation on Flexural Response of GFRP Composite Laminate Subjected to Low Velocity Cyclic Loading

T. G. Loganathan*, **R. Krishna Murthy and K. Chandrasekaran**

Department of Mechanical Engineering, RMK College of Engineering and Technology, RSM Nagar, Gummidipondi Taluk, Tiruvallur District, 601206, Tamil Nadu, India; dhanushaudi@gmail.com

Abstract

The suspension systems in automobiles are to provide adequate flexure modulus and damping in response to the road tyre interaction. This will ensure adequate driving comfort. In this context, as a weight reduction measure and to provide sufficient response to the vehicle dynamics leaf springs made of composite materials and can be a replacement for traditional metal leaf springs. Hence the present study on the GFRP composite laminate is to experimentally simulate the loading environment in the vehicle and the response of spring leaf made of composite material. GFRP composite laminate specimen of configurations such as Unidirectional Laminate (UD-0), angle ply laminate (0/30/60/0 and 0/45/0/-45) and symmetric and non-symmetric cross ply laminates (0/90/90/0 and 0/90/0/90) are prepared by hand lay-up technique. The laminates are exposed to low cycle (4.6 Hz and 8.6 Hz), constant amplitude cyclic loading in the laboratory setup. The flexural modulus of the virgin and pre-cyclic loaded specimen is measured by three point bend test using digital UTM as per ASTM D 790. The flexural modulus of the pre-cyclic loaded laminate specimen presents a positive improvement up to certain loading cycles at low frequency (4.6Hz). At high frequency (8.6 Hz) loading cycles there exist degradation in the flexural modulus of the pre-cyclic loaded specimen. The enhancement and degradation of flexural modulus on exposure to cyclic loading signify the influence of loading cycle frequency and laminate configuration. Any variation in the specimen configuration apart from UD-0 ply, record a drop in the flexural modulus. The optimum flexural responses characteristics in composite material are attributed to the selection of lay-up configuration and loading condition.

Keywords: Cyclic Load, Fibre Orientation, Flexural Modulus, GFRP, Loading Frequency

1. Introduction

The GFRP laminates are widely used in lightweight applications due to their high specific mechanical and directional properties. Some of the applications involve static, and other dynamic load condition. In the dynamic loading, the resistance of the structure to cyclic load is considered to be important along with the structural integrity. Cyclic load may be repeated or reversed along the axis or transverse to it. GFRP composite laminate offers better operating performance attributed to the combination of matrix and reinforcement in comparison with homogeneous metallic counterpart. However, the transverse modulus of the GFRP laminate is comparatively low in comparison with the resistance to longitudinal loading. Fatigue damages are dispersed throughout the specimen and are not limited to a single point of failure as in the case of metals. This is attributed to the fact that the load distribution is predominantly through the matrix material. The type of damage depends upon the constituent

**Author for correspondence*

material used, fibre orientation, stacking sequence and the type of loading[1]. The failure mode includes matrix crazing, interfacial debonding, delamination, fibre breakage and laminate failure. It has been reported[2] that the damage analysis is more complicated, and in the first 20 percent of fatigue life, matrix crack would occur following a damage plateau and sudden rise in damage up to failure. In composite materials, the fibre reinforcement not only contributes significantly to the load capacity, but also serves as crack arrester. The resistance enhancement offered by the matrix to the loading, accounting for the observed damage plateau in the early phase of fatigue loading. The damage growth phenomenon is generally analyzed as stiffness degradation leading to reduction of compression, bending and buckling strength. A lot of studies have been carried out to understand the fatigue behaviour and response of the composite structures[3,4]. The critical number of impact cycles[5] would produce significant changes in the composite behaviour in terms of tensile strength degradation and fatigue life cycles. The flexural strength[6] found to vary after the impact induced damage and variation was assessed by Weibull distribution. The effect of fibre orientation in the plies in the lay-up dictates the delamination damage intensity of composite laminates under transverse static /low velocity impact loading[7]. The effect of lay-up and fibre orientation angles between the plies influences on crack formation and propagation between the plies[8]. The process effect on flexural fatigue of UDGFRP over its life has been analysed[9] along with the influence of interface shear strength and toughness of the matrix. Fatigue life of GFRP composite laminate increases with increase in fibre matrix interface shear strength and matrix toughening. The effect of interaction angle of the fibre orientation θ with the 0^0ply has been instrumental in the composite performance[10]. The fibre matrix interface bonding and debonding during loading produce notable changes for various values of θ. The modulus[11] reduction from 90^0 ply transverse cracks extending in the width direction. Composite material is anisotropic and transverse crack reduces the stiffness, but not the structural integrity.The fatigue life[12] of composite laminate could be predicted by considering the different modes of failure for various load angles and stress ratio. The relation between fibre angle and type of failure to identify the matrix failure mode (with fibre orientation between 10^0 and 90^0) or fibre failure mode (with fibre orientation between 0^0 and 10^0)[12].

The growing demand of the material for light weight structure for specific application involves the need of understanding the flexural behaviour when subjected to cyclic loading at various frequencies and for different cycle time, as in the case of automobile leafspring[13], turbine blades, aero-foil structures and modern sports equipment. In this work, a leaf of automobile leaf spring has been experimentally simulated by considering one half (symmetric) of the leaf as a cantilever beam fixed at one end and exposed tocyclic load of constant amplitude (considering the road-tyre interaction) at the free end. Usually loading produces visible damage on the laminate as in drop weight method to measure the impact strength of the laminate. But, this paper considers the flexural modulus variation to investigate the influence of stacking sequence[14,15], loading frequency and loading cycles on unidirectional ply, angle ply, symmetric and non-symmetric cross ply GFRP laminate exposed to dynamic application as in automobile leaf spring.

2. Material and Specimen Preparation

The materials used for laminate preparation are glass fibre roving of 1100 gsm aerial density and epoxy resin LY 556 with hardener HY995. The resin and hardener are taken in the ratio of 10:1 with the glass fibre roving accounting for fibre volume fraction of 32 percent. Normally, for mere load capacity at the relative service requirement, mostly 20 percent volume fraction is adopted. This will not only ensure adequate load capacity enhancement, but also contain the hardness of the composite. Mostly for impact application, including ballistic conditions a higher volume fraction is used. To investigate the flexural modulus response under cyclic load, laminate configuration like unidirectional, angle ply and cross ply laminate has been identified for testing and comparison. Thus, the specimen was prepared using four layers with ply orientation 0,0/30/60/0, 0/45/0/-45, 0/90/90/0, 0/90/0/90, by hand lay-up technique to a size of 300x300 mm^2. The laminate preparation is carried out between two glass plates and laminate is cured for a period of 24 hours with a small surface pressure of 1 kN/m^2 by keeping dead weight on the laminate after the initial set of the matrix considering the gel time. The test specimens are then cut from the laminate plate to a size 150mmx10mmx4mm Figure 1&2, by diamond wheel cutter. The cut specimens are finished using fine emery paper to reduce the edge effects during loading.

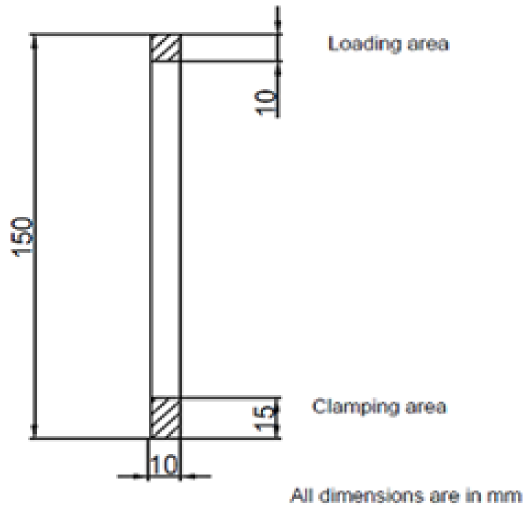

Figure 1. Specimen dimension.

Figure 2. Cut specimen.

3. Experimental Work

The flexural response of GFRP laminate in this paper is twofold: finding the flexural modulus of virgin specimen and, then the flexural modulus after specific cycle of low velocity constant amplitude cyclic load (denoted as pre-loaded laminate). The flexural modulus of the specimen is obtained by a three point bend test using digital UTM as per ASTM D 790, with a span of 100mm between supports as shown in Figure 3, and crosshead speed of 1mm/min. Unlike the case of the brittle ceramic and several other materials, the relatively tougher polymeric composite can be exposed to three point bend loading. An average of five test results has been utilized for the analysis and discussion. The maximum flexural deflection of the virgin specimens has been utilized to fix the amplitude of loading to be within safe limits.

3.1 Cyclic Load

Low velocity constant amplitude cyclic load is imposed on the virgin specimen (to simulate the effect of load on the leaf spring of automobile) with laboratory setup as shown in Figure 4 and 5. Cyclic load is applied using an eccentric disc with an eccentricity of 3mm (safe deflection for all test specimens obtained from flexural deflection of the virgin specimen) on a radial drilling machine with eight speed steps, of which two speeds viz. 516 rpm and 275 rpm (to yield the loading frequency of 8.6Hz and 4.6 Hz) are selected for the conduct of the experiment. The specimen is clamped at one end and loaded at the other end to resemble the symmetric half of a leaf spring between the shackle and the loading point in an automobile.The clamping area was limited to 10 percent of the length of

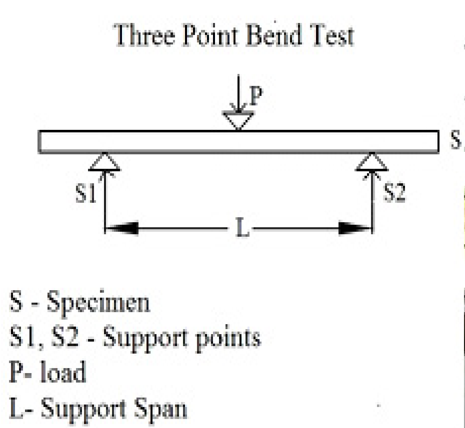

Figure 3. Three point bend test.

the specimen so as to have the maximum effect of loading on the specimen which would be useful in analysing its behaviour. The flexural modulus of the virgin and pre-cyclic loaded specimen is obtained by three point bend test using the formula,

$E = mL^3/4bd^3$

E= Flexural Modulus (kN/mm^2)
b= Specimen width=10mm,
m=Slope of load deflection curve of 3PB test

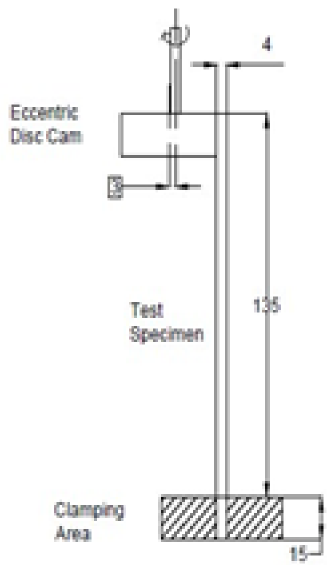

Figure 4. Cyclic loading.

Figure 5. Cyclic loading setup.

d= Specimen thickness=4 mm.
L= Span length of the specimen =100mm

The imposed load deflects the specimen like a cantilever beam with load at the free end. The layer which receives the load experiences tensile deformation and the layer behind loading side experiences compressive deformation. Each load cycle combines the effect of both tensile and compressive deformation.

4. Result and Discussion

4.1 Flexural Behaviour

The flexural moduli of the virgin specimen are determined by the digital UTM machine. An average of five trials is presented in Table 1 and Figure 6. The flexural modulus of the specimens shows variation in its value. The flexural test by three point bend test induces tensile stress at the bottom and compressive stress at the top. Most often the test specimens fail by failure on the tension side rather compressive.

Table 1. Flexural modulus of virgin specimen

Sl. No.	Ply Orientation	V_f	Flexural Modulus kN/mm^2
1	UD-0_4	32%	44.50
2	0/30/60/0		42.30
3	0/90/90/0		36.30
4	0/45/0/-45		27.08
5	0/90/0/90		22.75

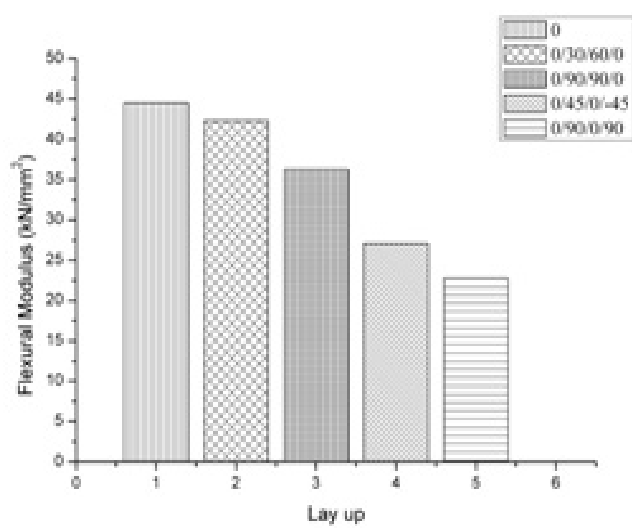

Figure 6. Flexural modulus of virgin specimen.

1. The UD-0^0 ply laminate results the maximum flexural modulus of all.
2. The fibre orientation in each ply and the interaction between the adjacent ply to transfer the load, produced a difference in the modulus value among the angle ply laminates 0/30/60/0 and 0/45/0/-45. The literature revealed that the varying fibre interaction angle in the laminate with respect to load yields a poor load carrying[8,10]. This due the presence of immediate load as well as damage transfer mechanism. However, with the 0/45/0/-45 orientation laminate, the large fibre interaction angle yields poor modulus in flexural test. The reason would be the early failure of the extreme -45 ply, inducing interfacial debonding between -45 and 0 ply. This is continued further and attributed to the poor modulus value. In the 0/30/60/0 laminate, even though the interaction angle is less which yields better, because of the presence of 0 ply at the extremities.
3. In case of the symmetric and non-symmetric cross ply laminates, the coupling of extension and twisting effect is minimal (value of B matrix is zero) in the former compared with later[16], which produces a significant change in its modulus. The initiation of transverse crack in the 90^0 ply of 0/90/0/90 laminate resembling mode 1 crack[8] at the bottom surface shows early matrix cracking and reduces the load carrying capacity in three point bending with fibre matrix debonding and consequent poor flexural modulus. Normally, 90^0 orientation normal to the load direction always exhibit lower order resistance to loading.

4.2 Significance of Pre-flexural Cyclic Load on Flexural Modulus of Composites

The test specimens of composite laminate are preloaded by exposing to low velocity, constant amplitude cyclic load at 8.6Hz and 4.6 Hz using an eccentric disc. The flexural moduli of the pre-loaded specimens are obtained after a specific number of loading cycles and the values of the flexural modulus of the loaded specimens are presented in the Figure 7-11.The loading on the composite material produces an observable degradation in the stiffness in stages due to the formation of the initial matrix crazing, fibre matrix debonding,followed by delamination, and fibre breakage. The effect of cyclic loading frequency shows notable variation in the flexural modulus of the laminate under study. The cyclic loading on GFRP specimen exhibits changes in the modulus value depending on the frequency of loading after every specific number of cycles. The ply orientation, stacking sequence[14,15] and loading frequencies produced visible changes in the flexural modulus of the loaded specimens. In most of the cases there exists a rise in the modulus values between $30x10^3$ to $40x10^3$ cycles of loading at both the frequency. This gives the limiting number of cycles of loading beyond which the modulus decreases. It should be noted that the modulus shows an initial drop and then a marginal improvement followed by drastic drop. The significance of the pre-flexural cyclic loading on the chosen laminate has been discussed in the following part.

4.2.1 *Unidirectional Laminate-0^0Ply*

Typical monitored variation of flexural modulus of UD-0 ply orientation influenced by the pre flexural cyclic loading is shown in Figure 7. It is seen that, the specimen with UD-0 ply orientation exhibits relative higher order flexural resistance with lower frequency of pre- flexural cyclic loading. This laminate exhibits a drop in the flexural modulus with early phase of loading followed by a rise. The flexural modulus tends to rise around $30x10^3$ cycles of loading, followed by a drop. Also, with lower frequency (4.6 Hz) of cyclic load, the specimen exhibits a flexural modulus greater than that of virgin specimen. Unidirectional orientation over the entire thickness of

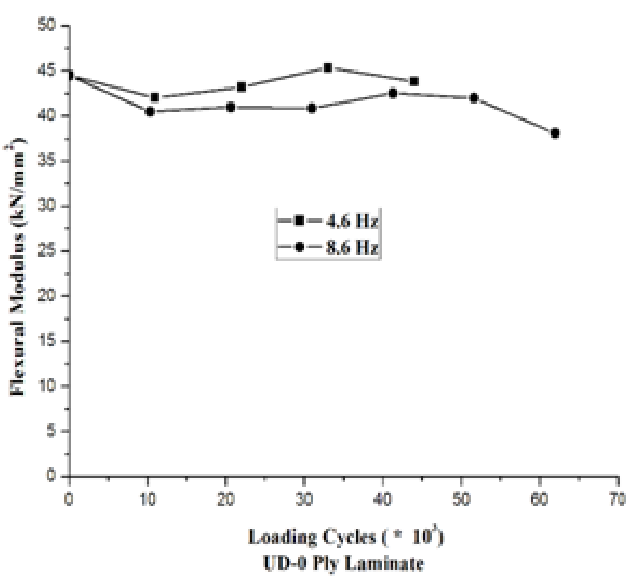

Figure 7. Flexural modulus variations UD-0 ply laminate.

the composite ensures better structural homogeneity and enhanced flexural resistance. But, the cyclic load at frequency 8.6 Hz shows a stable value of flexural modulus less than the virgin specimen up to 51.6x10^3 loading cycles and decreases from then. The loading at 8.6 Hz may not contribute too much to the rise in the flexural modulus of the pre-loaded specimen, thus presenting the onset failure of the laminate.

4.2.2 Angle Ply Laminate- 0/30/60/0 and 0/45/0/-45

Figure 8 and 9 show the variation of flexural modulus of angle ply laminate 0/30/60/0 and 0/45/0/-45 respectively.

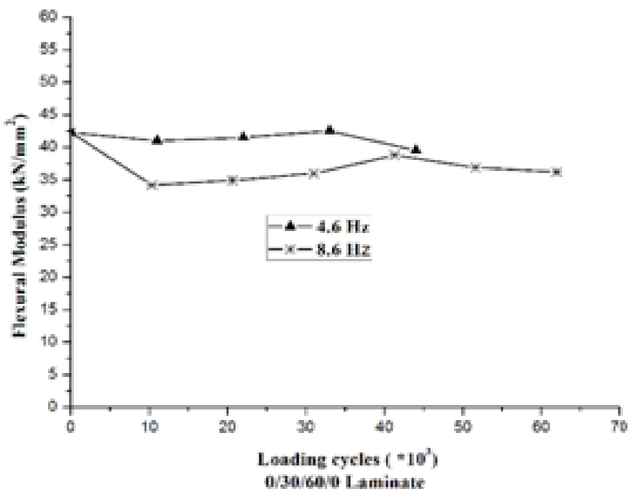

Figure 8. Flexural modulus variation of 0/30/60/0 laminate.

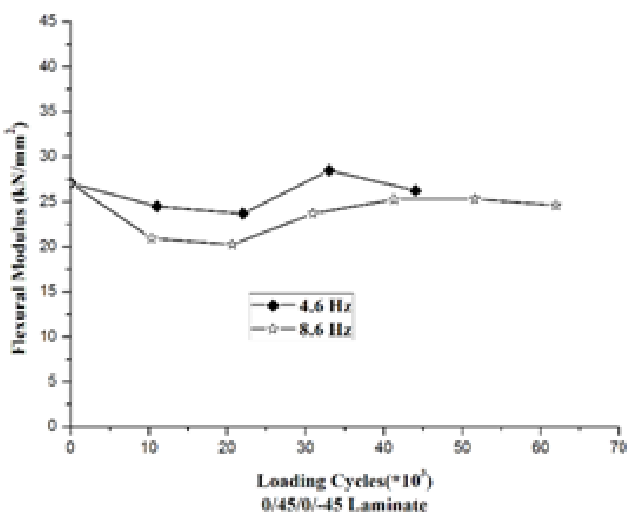

Figure 9. Flexural Modulus Variation of 0/45/0/-45 laminate.

The presence of angle ply between 0 ply reduced the flexural modulus in comparison with the UD-0 ply laminate. The interaction angles between the fibre orientations in angle ply composite significantly produced the changes in the modulus[8]. The fibre interaction angle between lay-up is larger in 0/45/0/-45 and smaller in 0/30/60/0. The effect of interaction angle is visualised in the flexural modulus variation band of pre-loaded specimen. The modulus value of 0/30/60/0 laminate shows considerable variation on two loading frequency unlike the case of 0/45/0/-45 orientation. Also, it is noted that the rise in flexural modulus of pre-loaded angle ply laminate specimensare obtained close to the virgin specimen at 4.6 Hz loading frequency around 31x10^3 cycles. The influence of fibre interaction angle in the angle ply laminate is well pronounced by the variation of modulus.

4.2.3 Cross Ply Laminate- 0/90/90/0 and 0/90/0/90

The responses of cross ply laminates on exposure to cyclic loading are shown in Figure 10 and 11. The flexural modulus of the pre-loaded symmetric cross ply laminate specimen degrades initially and rises to the virgin value around 30x10^3 loading cycles for the loading frequency. Thereafter, a drastic drop in the modulus at high loading frequency (8.6 Hz) and steady decay at low loading frequency (4.6 Hz). The presence of 90^0 ply at the bottom of the 0/90/0/90 lay-up, develop early transverse cracks that degrade the stiffness of the laminate and

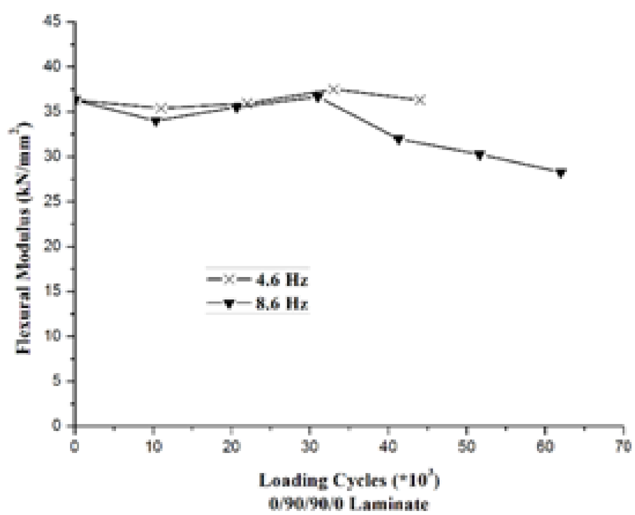

Figure 10. Flexural Modulus Variation of 0/90/90/0 laminate.

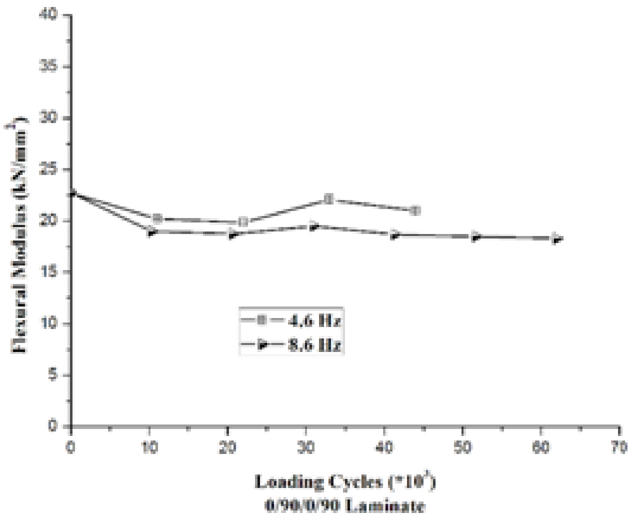

Figure 11. Flexural Modulus Variation of 0/90/0/90 laminate.

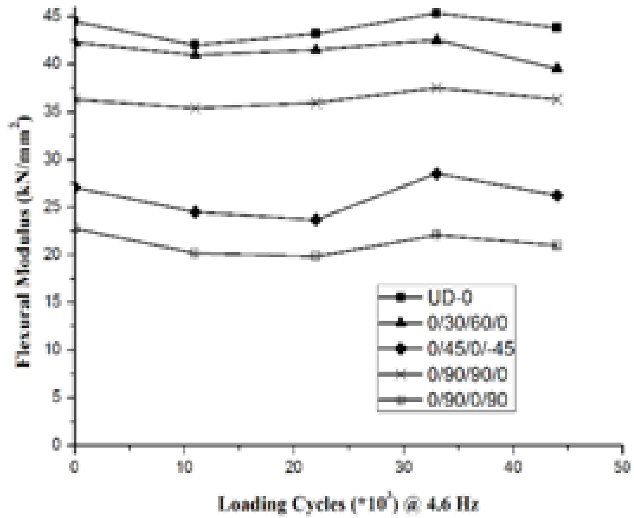

Figure 12. Relative Modulus after loading at 4.6 Hz.

developed on further loading results in poor modulus than symmetric 0/90/90/0 lay-up. The effect of loading frequency on modulus value becomes more distinct only after 30x10^3 cycles in both the laminates. This shows the effect of transverse crack initiated damage at increased loading cycles. Also, beyond 33x10^3 cycles, the material exhibit degradation as indicated by a visible drop in flexural modulus. With low frequency load, a marginal rise in flexural modulus with loading cycle can be seen. Though, the 0/90/90/0 laminate has 0 orientations on top and bottom surface, the presence of 90 lay in the middle portion weakens the structure considerably.

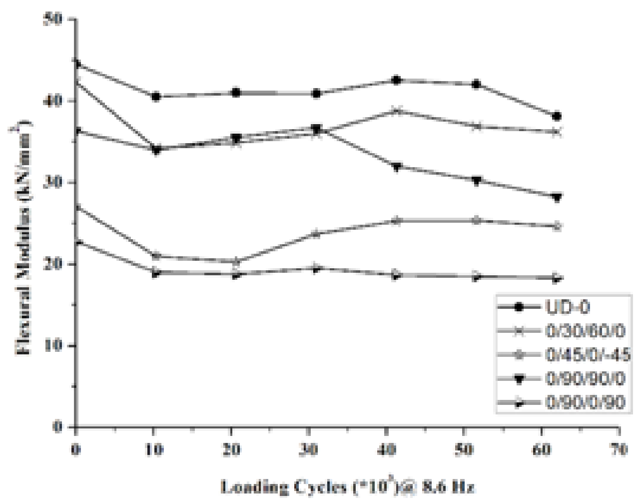

Figure 13. Relative Modulus after loading at 8.6 Hz.

4.2.4 Relative Flexural Modulus of GFRP Laminate

Figure 12 and 13 illustrates relative flexural response of specimen under investigation. All the specimens show early signs of a drop in flexural modulus up to 10x10^3 cycles and a marginal rise around 33x10^3 cycles at 4.6 Hz of loading frequency irrespective of the fibre orientation in the lay and drop in the modulus after 33x10^3 loading cycles. This similarity in the behaviour in the entire chosen ply is attributed by the constituent matrix material rather the reinforcement fibre. At a high loading frequency (8.6 Hz), the drop in the modulus is retained for loading cycles between 10x10^3 to 30x10^3 and changes thereafter. Especially in UD-0, 0/30/60/0 and 0/45/0/-45 orientation shows marginal rise, but the degradation of the laminate is noticed in symmetric and non-symmetric lay-up due to the presence of weak transverse 90^0 ply.

The responses of the polymeric composite exhibits rise in flexural modulus with progressive cyclic loading. The enhanced stiffness during the early phase of cyclic loading ceases to retard which is attributable to the flow stresses. This effect is seen mostly with relatively higher loading frequency. Also, unlike the case of relative homogeneous metallic structure, the composite material with relatively heterogeneous structure, exhibit hysteresis absorption up to certain cycles. This can also contribute to the arrangement of the lay-up, however this depends on the frequency and amplitude of loading as reflected in the illustrations in Figure 12 and 13.

5. Conclusion

The flexural response of the GFRP composite of lay-ups like UD-0, 0/30/60/0, 0/90/90/0, 0/45/0/-45 and 0/90/0/90 on pre-flexuralcyclic loading has been investigated experimentally simulating a half of automobile leaf of a leaf spring and the following observations are made to identify the suitability of GFRP laminate in the selected application.

1. The UD-0 ply laminateis observed to have higher flexural modulus compared to the other angle-ply laminates and it offers an enhanced flexural resistance. Other orientations, exhibit a discernable modulus reduction compared to the UD-0.
2. A marginal reduction in flexural modulus of 0/30/60/0 compared with UD-0 ply composite is seen with loading cycle. Composite with orientation 0/30/60/0 exhibits more structural heterogeneity as noticed in wide differences in flexural modulus of composite exposed to cyclic loading at different frequencies.
3. Despite better overall structural reinforcement in the central region of 0/45/0/-45 orientation, the composite exhibits a reduced flexural response compared to 0/90/90/0 composite. The difference is attributed to the not so good orientation of -45 compared to 0 orientation in 0/90/90/0 composite.
4. 0/90/90/0 composite exhibits relatively lower order flexural modulus compared to UD-0 and 0/30/60/0 laminates.
5. Non-Symmetric cross ply composite laminate exhibit the least flexural response. This is attributed to the weak reinforcement (90^0) at the bottom surface. Also, composite exhibits a flexural response model which is mostly in variation with frequency of cyclic loading.
6. For both the loading frequencies, the relative flexural modulus displays an undulating variation with respect to loading cycles. In general it is seen that any departure from the UD-0 ply laminate tends to bring in a drop in flexural resistance of pre-cyclic loaded specimen.
7. 4.6 Hz of loading frequency ensures better performance thanat 8.6 Hz and loading cycle up to around $33x10^3$ at 4.6 Hz presenting a marginal rise in the flexural response considered as limiting cycle of loading.
8. The flexural performance of GFRP laminate simulating the automobile leaf spring is found to improve on cyclic loading with low loading frequency (4.6Hz), fibre interaction angle between 0 to 60 and 0 ply layers at the boundary.

6. References

1. Muc A. Design of composite structures under cyclic loads. Computer and Structures. 2000; 76:211–4.
2. Tarleja R. Fatigue of composite materials. Lancaster Techonomic Publishing; 1990. p. 78–97.
3. Gagel A, Dirk L, Schulte K. On the relation between crack densities, stiffness degradation and surface temperature distribution of tensile fatigue loaded glass-fiber non-crimp fabric reinforced epoxy. Composites: Part A. 2006; 37: 222–8.
4. Vallons K, Zong M, Lomov SV, Verpoes I. Carbon composite based on multi-ply stitched preforms-Part 6. Fatigue behavior at low loads: Stiffness degradation and damage development. Composites: Part A. 2007; 38:1633–45.
5. Yuanjian T, Isaac DH. Combined impact and fatigue of glass reinforced composites. Composites: Part B. 2008; 39(3):505–12.
6. Kang K-W, Koh S-K, Kim D-K, Kim K-J. Assessment of the statistical distribution of flexural strength of woven fabric laminates with impact-induced damage. Composite Structure. 2009; 90:60–6.
7. Wang J, Karihaloo BL. Matrix crack-induced delamination in the composite laminate under transverse loading. Composite Structure. 2005; 38:661–6.
8. Yokozeki T, Aoki T, Ogasawara T, Ishikawa T. Effect of layup angle and ply thickness on matrix crack interaction in contiguous plies of composite laminates. Composites: Part A. 2005; 36:1229–35.
9. Salvia M, Fiore L, Fournier P, Vincent L. Flexural fatigue behavior of UDGFRP experimental approach. International Journal of Fatigue. 1997; 19:253–62.
10. Morioka K, Tomita Y. Effect of lay-up sequences on mechanical properties and fracture behavior of CFRP laminate composite. Material Characterization. 2000; 45:125–36.
11. Pradhan B, Venukumar BN, Rao NS. Stiffness degradation resulting from 900 ply cracking in angle ply composite laminate. Composite Science and Technology. 1999; 59:1543–52.
12. Shokrieh MM, Taheri F-B. A unified fatigue life model based on energy method. Composite Structure. 2006; 75:444–50.

13. Abu Talib AR, Ali Aidy, Goudah G, Che Lah NA, Golestaneh AF. Developing a composite based elliptic spring for automotive applications. Materials and Design. 2010; 31:475–84.
14. Haj Mohammad MH, Salari M, Hashemi SA, Hemmat Esfe M. Optimization of stacking sequence of composite laminates for optimizing buckling load by neural network and genetic algorithm. Indian Journal of Science and Technology. 2013; 6:5070–7.
15. Mlyniec A, Korta J, Kudelski R, Uhl T. The influence of the laminate thickness, stacking sequence and thermal aging on the static and dynamic behaviour carbon/epoxy composites. Composite Structures. 2014; 118:208–16.
16. Zhang D, Ye J, Lam D. Ply cracking and stiffness degradation in cross ply laminate under biaxial extension, bending and thermal loading. Composite Structure. 2006; 75:121–31.