Chapter 17
Fatigue Analysis of FRP Laminate Composites

Nitin Johri and Bhaskar Chandra Kandpal

Abstract Fiber reinforced polymer (FRP) laminate composites display anisotropic behaviour on account of alternating phases of fiber and matrix in suitable weight fractions. Recent research has focussed on structural analysis of these composites pertaining to various strengths like tensile, compressive, flexural etc. This paper attempts to estimate fatigue life of these laminated composites on account of fatigue damage calculation using "Miner's Rule". Modelling of laminated composites is done in Ansys® Workbench (ACP) as per required weight/volume fraction. The structural response of modelled laminate is done by "Random Vibration Analysis" which utilises the standard deviation (1σ) of a stress, force or displacement to determine fatigue life of the laminated structure. The effect of fiber orientation and thickness of lamina is analyzed on fatigue life of epoxy E-glass laminated composite.

Keywords Fatigue · Standard deviation · FRP · Fiber orientation · Miner's rule

17.1 Introduction

Degradation of a material's mechanical properties or a mechanical component subjected to cyclic/intermittent loading is known as fatigue. Analyzing fatigue behaviour of laminated composites is of vital importance. Application of composite materials for commercial means may involve situations involving cyclic load widely, e.g., parts utilized in automobile, mass transit, and heavy vehicles. Comprehending the fatigue behaviour of laminated composites as compared to the determination of elastic stiffness or strength is rather difficult as the application of conventional fatigue approaches, like linear elastic fracture mechanics approach or stress versus cycles curve for laminated composites is not as straightforward. Presence of inherent heterogeneity and anisotropic nature in composites, being the primary reason for this

---

N. Johri (✉)
ME Department, Graphic Era (Deemed to be) University, Dehradun 248002, India

B. C. Kandpal
ME Department, Inderprastha Engineering College, Ghaziabad 201010, India

R. Pratap Singh et al. (eds.), *Proceedings of the International Conference on Industrial and Manufacturing Systems (CIMS-2020)*, Lecture Notes on Multidisciplinary Industrial Engineering, https://doi.org/10.1007/978-3-030-73495-4_17

complexity. This result in different damage in composites on account of fatigue as compared to conventional materials.

Different damage modes characterizing fracture behaviour of composites with an early onset in fatigue life are fiber fracture, interfacial debonding and delamination, brittle matrix cracking, polymeric matrix crazing, matrix plasticity, multidirectional cracking and void growth. This leads to gradual stiffness loss during fatigue deterioration of a composite laminate. Varying zones of damage [1] formed in a fiber reinforced composite which behaves as anisotropic material and a conventional isotropic material on comparison are shown in Figs. 17.1 and 17.2, respectively.

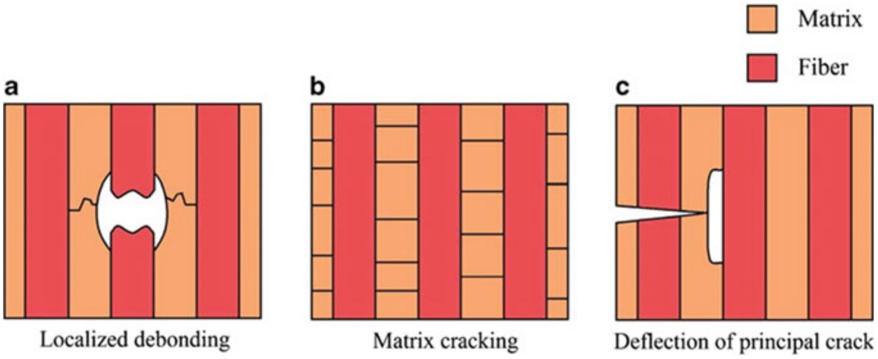
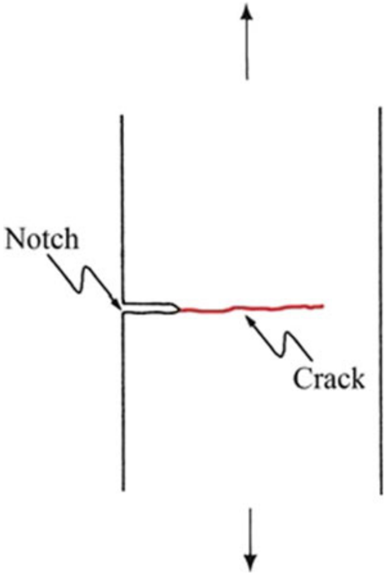


Fig. 17.1 Laminated FRP composite material damage zone: **a** fiber breakage and localized debonding; **b** matrix crack formation; **c** principal crack deflection along a weak fiber/matrix interface [1]

Fig. 17.2 Conventional (isotropic) material damage zone [1]



In case of the isotropic material, the cyclic loading results in initiation of a single crack propagating in a direction transverse to the axis of cyclic loading (mode I) whereas in the fiber reinforced composite (FRP) laminates, various damage mechanisms being subcritical (as shown) leads to a damage zone which is highly diffuse.

Various composite failure modes like delamination, fiber fracture, longitudinal and transverse matrix on account of being subjected to cyclic loading are visible in Fig. 17.3 on account of loading in a longitudinal and cross-ply laminated composite. The fracture of fiber and matrix accompanied by shear crack growth are seen in Fig. 17.4.

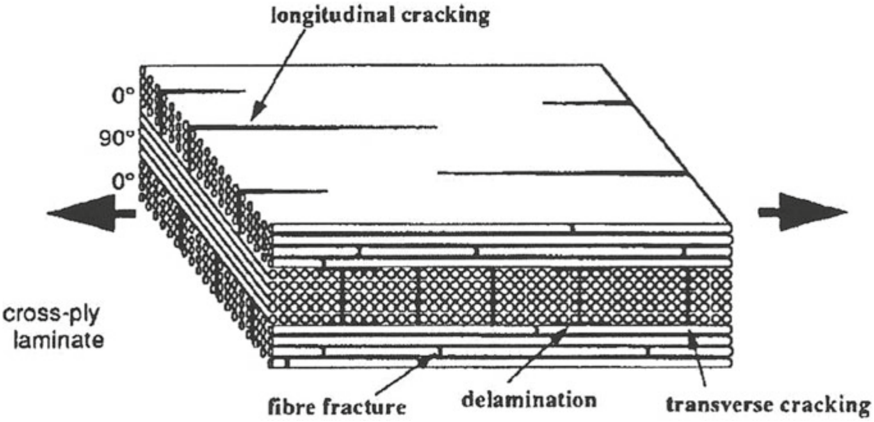
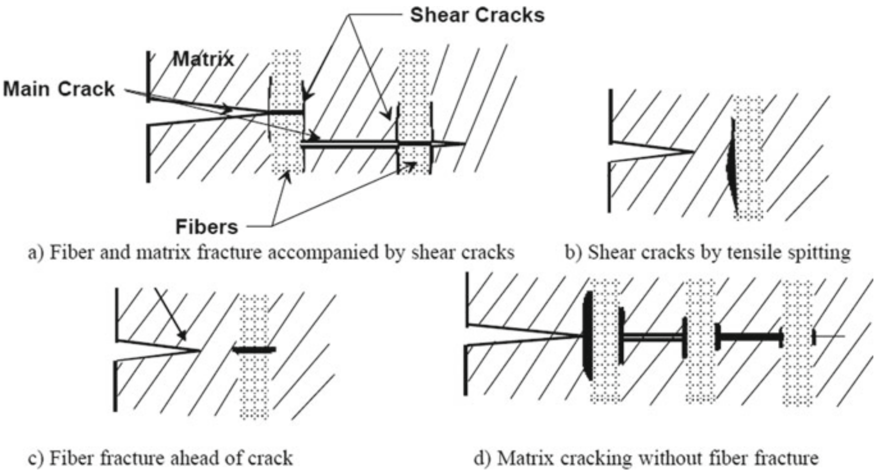


Fig. 17.3 Composite behaviour under cyclic loading [2]



a) Fiber and matrix fracture accompanied by shear cracks
b) Shear cracks by tensile spitting
c) Fiber fracture ahead of crack
d) Matrix cracking without fiber fracture

Fig. 17.4 Crack growth in composites subjected to fatigue loads [3]

A relative comparison of various composite failure modes like fiber fracture, delamination, matrix cracking and debonding in terms of stress amplitude versus cycle curve is seen in Fig. 17.5. This implies the fiber fracture being least affected, whereas fiber-matrix debonding being highly affected by fatigue loads.

Fiber orientation effect on fatigue failure in cross-ply roving and woven roving polymer composites is seen in Fig. 17.6. This emphasizes on highest fatigue resistance by longitudinal (0°) fibers in comparison to other fibers. Figure 17.7, illustrates a relative comparison of fiber volume fraction effect on fatigue damage in

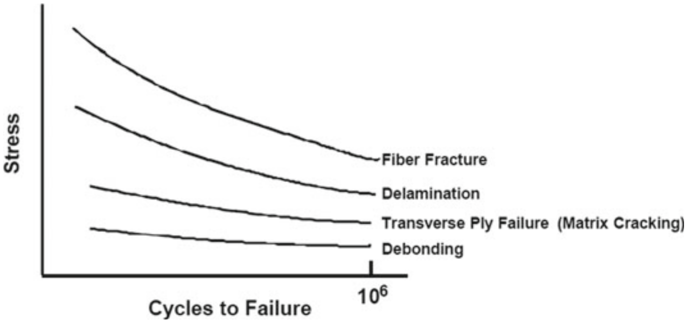


Fig. 17.5 Relative stress amplitude vs cycles curve for fatigue damage modes [3]

Fig. 17.6 Effect of fiber orientation on fatigue damage in polymer composites [3]

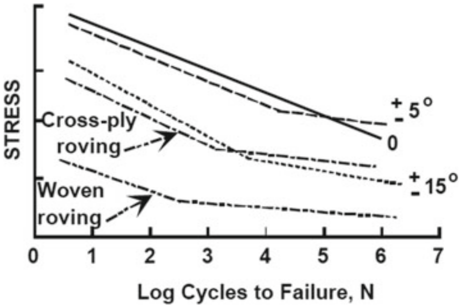
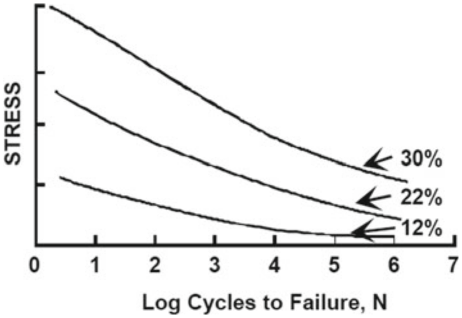


Fig. 17.7 Effect of fiber volume fraction on fatigue damage in polymer composites [3]



polymer composites, emphasizing reduced fatigue damage on account of increased fiber content. Various failure mechanisms like matrix cracking, interfacial debonding, delamination and fiber fracture in terms of percentage of fatigue life are shown in Fig. 17.8. Reduction in fatigue limit strain with increase in fiber orientation from 0° to 90° is shown in Fig. 17.9.

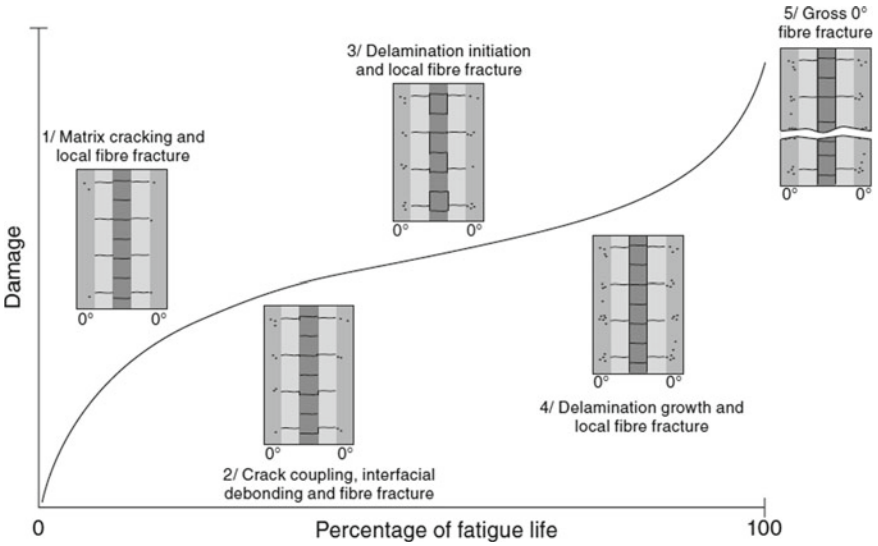


Fig. 17.8 Fatigue damage growth in a composite laminate under translaminar loading [4]

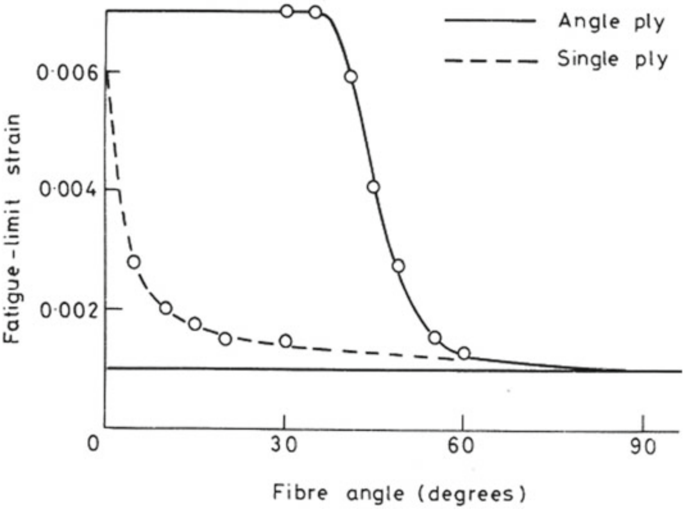


Fig. 17.9 Fiber orientation effect on fatigue limit strain [2]

17.2 Research Background

Ansari et al. [5], explored the effects of various parameters like fiber volume fraction, fiber orientation, fiber type etc. on the fatigue response of fiber-reinforced composites. In composite materials, the various types of fatigue damages are initiated on account of initiation of multiple micro-cracks in the initial stages of the fatigue growth. Fatigue strength is seen to increase with increasing fiber volume fraction till a certain level and then starts decreasing due to insufficient resin to grip the fibers. Fatigue behaviour of laminated composites is based on various factors, e.g., constituent materials, manufacturing process, fiber orientation, and type of loading. Degrieck and Van Paepegem [6], reviewed major fatigue patterns and methodology for life expectancy for fiber-reinforced polymer (FRP) composites subject to fatigue loads is presented. Samples are classified into three main categories: fatigue life models using SN curves and Goodman-type diagrams that take into account the actual attenuation mechanism, with the onset of some fatigue failure criteria, using one or more loss variables. Making progressive damage models related to measurable standards and damage—phenomenological model using transverse matrix cracks, contamination magnitude, etc. and finally residual hardness/strength. Kumar [7], calculated fatigue life of the components exposed to the sinusoidal periodic vibration using random vibration analysis, so that the damage content is analyzed by multiplying the stress amplitude of each cycle in the harmonic analysis by the actual number of cycles components experience in service. The miner’s rule is seen to provide a very good assessment considering the complex evaluation of fatigue life in the random process. Irvine [8], utilized band pass filtering method to perform the power spectral density calculation in terms of (G^2/Hz) for the calculation of power spectral density functions, which can be used appropriately in random vibration analysis.

Belmonte et al. [9], investigated the effect of volume fraction of fiber on the fatigue deterioration mechanism in a small glass fiber reinforced polyamide composite. Tests for uniaxial fatigue were performed with different fiber content on the notched specimens. Field emission scanning electron microscopy has been performed for damage investigation. Mortazavian and Fatemi [10], assessed the mean stress effect on fatigue behaviour of two small glass fibers reinforced thermoplastic composites and stress concentration effect on the fatigue behaviour of an unreinforced and small glass fiber reinforced thermoplastics by experimental study. Several mean pressure parameters have been used to evaluate the ability to interact with average pressure data, including the revised Goodman, Walker, and Smith-Watson-Topper evaluation. Significance of effect of stress concentration was seen to be high with or without application of pressure in longitudinal as well as transverse directions. Vasiukov et al. [11], developed a method involving direct computation of life estimation for fiber reinforced polymers (FRP). This follows simplified direct method (SDM) approach, which allows estimation of life from a stabilized damage condition. Experimental verification of the method with different load ratios on standard fiberglass, angle ply and cross ply laminate plates with fatigue loads was done. The effects of tension and compression load types and applied mean stress and quasi-static stress in testing of fatigue on damage mechanisms and mechanical behaviour in unidirectional carbon/epoxy laminates were studied in Brunbauer and Pinter [12], in addition with effect of fiber volume content.

Effect of fiber volume fraction on fatigue behaviour of carbon/epoxy laminate is investigated in Brunbauer et al. [13]. Unidirectional carbon/epoxy fiber and epoxy resin samples with varying fiber volume fractions were tested under tension-tension and quasi-static tensile fatigue loads. The results confirm the increase in strength and stiffness with increasing fiber content. The fatigue life of glass-fiber reinforced plastic (GFRP) used in wind turbine rotor blades is estimated by considering the fiber orientations in Huh et al. [14]. Fatigue limits were estimated and predicted for composites with linear Goodman and Gerber diagrams. The fatigue behaviour of GFRP alloys produced by the vacuum bagging process is evaluated by changing the fiber volume fraction by Mini et al. [15]. The constant-amplitude flexural fatigue tests were performed at zero mean stress, by variation in the frequency of the test machine.

The fatigue behaviour of various fiber reinforced polymer composites comprising fibers such as carbon, glass and basalt fibers, including hybrid such as carbon/glass and carbon/basalt is studied in Wu et al. [16]. Results suggest that progressive damage propagation can lead to fatigue failure of composites and that hybrid alloys of carbon/basalt significantly improve fatigue resistance compared to homogeneous basalt composites. Suppressed matrix cracking and a low crack propagation rate were observed in the hybrid-epoxy matrix, resulting on account of various toughening micro mechanisms induced by both rubber micro particles and silica nano particles. These factors are thought to contribute to a better fatigue life using the GFRP composite hybrid-epoxy matrix in Manjunatha et al. [17].

Fiber orientation distribution effect on the thickness of the specimen in determining the fatigue resistance of small glass fiber reinforced polyamide composites was investigated in Bernasconi et al. [18]. Stinchcomb and Bakis [19], presented the mechanics of stress redistribution on account of structural damage in the context of experimental evidence. The fatigue behaviour of many composite material systems in terms of strength, stiffness and life of composite laminates, both notched and without notch under different loading modes, are discussed.

The literature reviewed has largely focussed on damage assessment due to fatigue failure resulting due to cyclic repetitive loads. The vibrations caused due to lack of straightforward cyclic repetition can also lead to these types of failure and requires further research.

17.3 Research Methods

Fatigue analysis of a laminated composite Epoxy E-Glass with unidirectional fibers with a fiber volume fraction of around 50% is attempted with E-Glass fibers as reinforcement and Resin Epoxy as matrix of Fiber reinforced polymer (FRP) composite. The methodology comprises of: creating composite tensile specimens with different ply thickness and ply orientation configurations (as per Table 17.1) in Ansys Workbench®, importing Composite model into modal analysis, finding mode shapes, applying boundary conditions and finally determining the fatigue behaviour of composite tensile specimen.

Modelling of a tensile test specimen as shown in (Fig. 17.10), is done using design modeller of Ansys Workbench®. Meshing of specimen is done taking 'Quadrilateral Elements' with an element size of 2 mm (Fig. 17.11). In setup mode of Ansys Composite Prepost (ACP) module, for a laminate for a constant thickness of 3 mm, the fabric for lamina is defined as "Epoxy E-Glass UD" with ply thickness as stipulated in (Table 17.1). Solid model (Fig. 17.12) of laminate is made by proper configuration of laminates as per the specified ply thickness and orientation. Fatigue Analysis

Table 17.1 Fatigue analysis of fiber reinforced polymer composite laminate

Ply orientation (all plies)	Ply thickness = 0.1 mm (30 plies)	Ply thickness = 0.3 mm (10 plies)	Ply thickness = 0.5 mm (6 plies)
	Fatigue life (days)	Fatigue life (days)	Fatigue life (days)
0	6.84	6.85	6.86
30	0	0	0
0/30	0.01	0.01	0.01
30/0	0.01	0.01	0.01
45	0	0	0
0/45	2.4	2.76	3.13
45/0	2.4	2.76	3.13
60	0.12	0.12	0.12
0/60	2.1	2.43	2.78
60/0	2.1	2.43	2.78
90	191.6	191.09	190.1
0/90	2.07	2.4	2.76
90/0	2.07	2.4	2.76

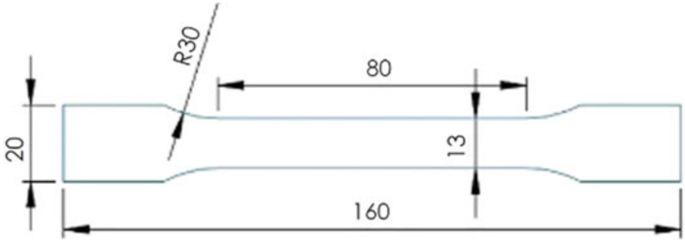


Fig. 17.10 Tensile test specimen

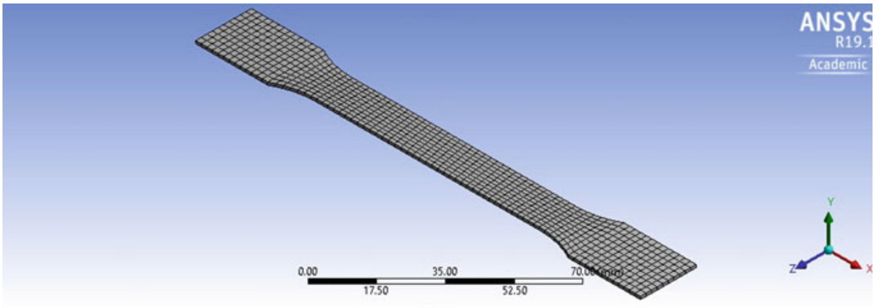


Fig. 17.11 Face meshed quadrilateral elements

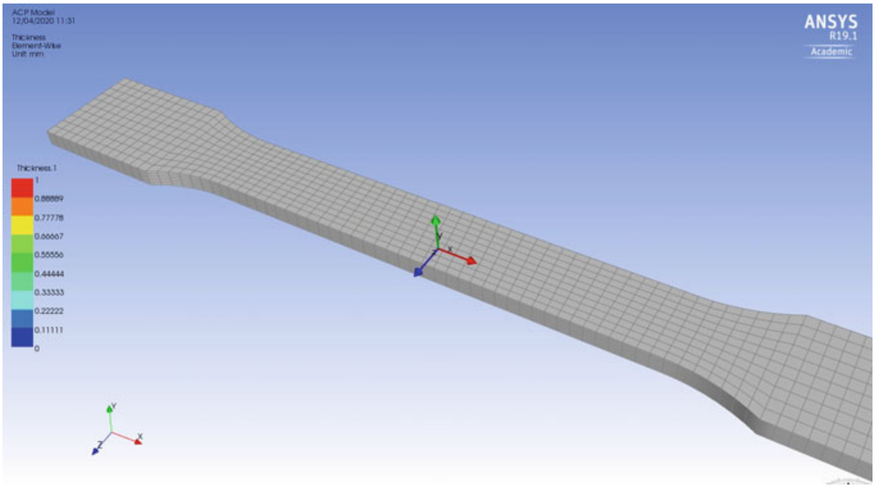


Fig. 17.12 Solid model of FRP composite laminate

of laminates on basis of ply thickness and ply orientation is done and analyzed using Miner's fatigue damage criteria. Modal Analysis followed by random vibration analysis in Ansys Workbench® [7, 8] is employed for determining and comparing the fatigue life of the various FRP Composite laminates configurations.

17.3.1 Miner's Fatigue Damage Criteria:

The stress amplitude (σ) versus cycles to failure (N) are shown on a logarithmic S-N curve, where these are related as:

$$\log \sigma = A \log N + B \tag{17.1}$$

Here ‘A’ refers to slope of the log—log S-N Curve and ‘B’ is the coefficient which refers to value of stress amplitude σ at N = 1 cycle.

As per Miner’s fatigue damage criteria, the damage due to cyclic stresses resulting in fatigue failure in a mechanical component is given by:

$$D = \left(\frac{n_{1\sigma}}{N_{1\sigma}} + \frac{n_{2\sigma}}{N_{2\sigma}} + \frac{n_{3\sigma}}{N_{3\sigma}}\right) \tag{17.2}$$

Here

$n_{1\sigma}$ actual no. of cycles at or below the 1σ level
$n_{2\sigma}$ actual no. of cycles between 1σ and 2σ level
$n_{3\sigma}$ actual no. of cycles between 2σ and 3σ level.

And $N_{1\sigma}$, $N_{2\sigma}$, $N_{3\sigma}$ = allowable number of cycles (from fatigue curve) at 1σ, 2σ, 3σ stress levels.

The values of $n_{1\sigma}$, $n_{2\sigma}$ and $n_{3\sigma}$ are obtained for 1σ, 2σ and 3σ levels respectively as:

$$\frac{1\left(Direction\ velocity\ in\ maximum\ node\left(\frac{\mathrm{mm}}{\mathrm{s}}\right)\right)}{2\pi\,(Directional\ deformation\ in\ maximum\ node(\mathrm{mm}))} \tag{17.3}$$

In statistics the band of equivalent stress amplitude on account of modal analysis can be considered spread about mean value as 1σ, 2σ and 3σ (σ-Standard deviation) corresponding to the occurrence level as 68.3%, 27.2% and 4% respectively. Random vibration analysis is a spectral method which using results from modal analysis can determine some statistical properties of a structural response like standard deviation (1σ) of a displacement, force or stress. In this analysis standard deviation (1σ) is used to determine the fatigue life of structure.

17.4 Result Discussion

A comparative analysis of various laminate configurations of Epoxy-E Glass unidirectional laminate for fatigue life is done on basis of ply orientation, ply thickness and number of plies (Fig. 17.13). Following points can be inferred from the graph:

- The fiber orientation which can sustain fatigue for the longest duration is [90]° with a fatigue life of around 191 days.
- The fatigue life is increased hugely while changing the fiber orientation from [60]° to [90]° with variation being 0.12 days to 191 days.
- The fiber orientations which cannot sustain cyclic/intermittent loads leading to fatigue failure are [30]° and [45]° with a fatigue life of 0 days.
- Plies with fiber orientations of [60]°, [0/30]° and [30/0]° are also having very weak response to fatigue with fatigue life of 0.12, and 0.01 days respectively.

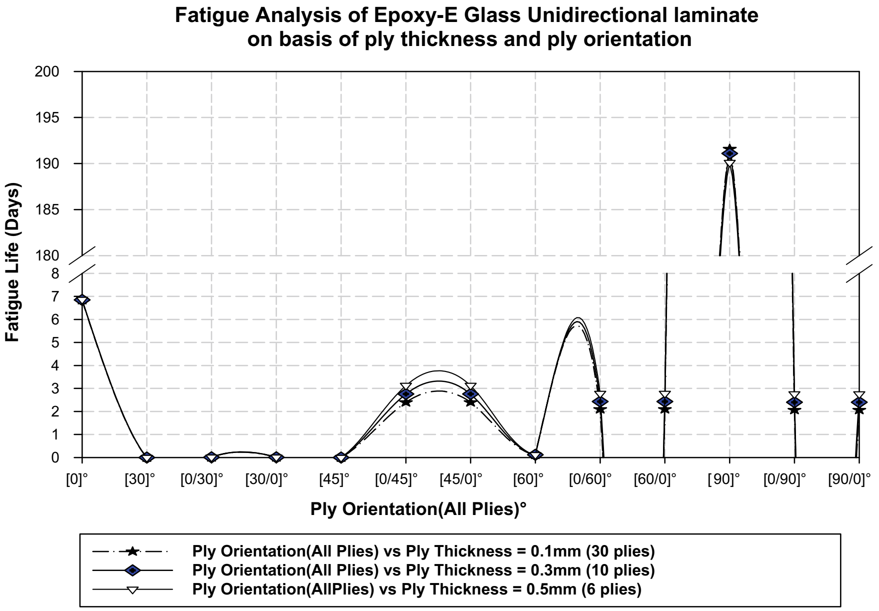


Fig. 17.13 Fatigue analysis of Epoxy-E Glass unidirectional laminate on basis of ply thickness and ply orientation

- Fatigue life is not affected by reversing the ply orientations in consecutive plies for e.g. [0/45]° to [45/0]°
- For cross-ply laminate [90]° configuration, the increased number of plies seems to have a favourable effect on fatigue life.
- For ply configurations—[0/45]°, [0/60]° and [0/90]° the reduced number of plies will have a favourable response to fatigue loads.
- For other ply configurations—[0]°, [0/30]°, [45]° and [60]° the response to fatigue failure seems not to be affected by increasing/decreasing number of plies/lamina.

17.5 Conclusion

Fatigue loads are responsible for unexpected failure of a wide variety of materials, which can fail at stresses well below the yield stress owing to cyclic/intermittent nature of these loads. Composite materials owing to their anisotropic nature responds to fatigue in a different way as compared to structures made from normal materials like steel, aluminium, copper etc. which behave in a isotropic manner. A modelling and simulation of a type of FRP composite laminate is suggested in Ansys Workbench® using Miner's fatigue damage criteria for prediction of fatigue life.

Fatigue analysis of FRP composite laminate subjected to cyclic loads is attempted with some important conclusions emphasizing the effect of fiber orientation in ply on fatigue life. As per the simulation results the longitudinal plies with fiber orientation of 0° though good for static tensile or compressive loading are having extremely low fatigue resistance as compared to cross ply laminates with a ply fiber orientation of 90°. Also, the fatigue life is not affected by reversing the fiber orientation in a stackup for e.g. changing the fiber orientation of plies from [0/30]° to [30/0]° and vice versa.

Acknowledgements The authors acknowledge the support of the Coordination Committee of Scientific Research Projects of Mechanical Engineering Department, "Graphic Era (Deemed to be) University", Dehradun, and "Inderprastha Engineering College", Ghaziabad, India.

References

1. Chawla, K.K.: Composite Materials: Science and Engineering, 3rd edn (2012)
2. Bucinell, R.B.: Composite Materials: Fatigue and Fracture, vol. 7 (1998)
3. Salkind, M.: Fatigue of Composites (2009)
4. Hiley, M.: Fatigue Failures of Polymer Composites (2009)
5. Ansari, M.T.A., Singh, K.K., Azam, M.S.: Fatigue damage analysis of fiber-reinforced polymer composites—a review. J. Reinf. Plast. Compos. **37**, 636–654 (2018)
6. Degrieck, J., Van Paepegem, W.: Fatigue damage modeling of fiber-reinforced composite materials: review. Appl. Mech. Rev. **54**, 279–300 (2001)
7. Kumar, S.M.: Analyzing random vibration fatigue. ANSYS Adv. **II**, 39–42 (2008)
8. Irvine, T.: Power Spectral Density Units: [G^2/Hz] Vibrationdata.com [Online] (2007). Available: https://vibrationdata.com/tutorials2/psd.pdf
9. Belmonte, E., De Monte, M., Hoffmann, C.J., Quaresimin, M.: Damage initiation and evolution in short fiber reinforced polyamide under fatigue loading: influence of fiber volume fraction. Compos. Part B Eng. **113**, 331–341 (2017)
10. Mortazavian, S., Fatemi, A.: Effects of mean stress and stress concentration on fatigue behavior of short fiber reinforced polymer composites. Fatigue Fract. Eng. Mater. Struct. **39**, 149–166 (2016)
11. Vasiukov, D., Panier, S., Hachemi, A.: Direct method for life prediction of fiber reinforced polymer composites based on kinematic of damage potential. Int. J. Fatigue **70**, 289–296 (2015)
12. Brunbauer, J., Pinter, G.: Effects of mean stress and fiber volume content on the fatigue-induced damage mechanisms in CFRP. Int. J. Fatigue **75**, 28–38 (2015)
13. Brunbauer, J., Stadler, H., Pinter, G.: Mechanical properties, fatigue damage and microstructure of carbon/epoxy laminates depending on fiber volume content. Int. J. Fatigue **70**, 85–92 (2015)
14. Huh, Y.H., Lee, J.H., Kim, D.J., Lee, Y.S.: Effect of stress ratio on fatigue life of GFRP composites for WT blade. J. Mech. Sci. Technol. **26**, 2117–2120 (2012)
15. Mini, K.M., Lakshmanan, M., Mathew, L., Mukundan, M.: Effect of fiber volume fraction on fatigue behaviour of glass fiber reinforced composite. Fatigue Fract. Eng. Mater. Struct. **35**, 1160–1166 (2012)
16. Wu, Z., Wang, X., Iwashita, K., Sasaki, T., Hamaguchi, Y.: Tensile fatigue behaviour of FRP and hybrid FRP sheets. Compos. Part B Eng. **41**, 396–402 (2010)
17. Manjunatha, C.M., Sprenger, S., Taylor, A.C., Kinloch, A.J.: The tensile fatigue behavior of a glass-fiber reinforced plastic composite using a hybrid-toughened epoxy matrix. J. Compos. Mater. **44**, 2095–2109 (2010)
18. Bernasconi, A., Davoli, P., Basile, A., Filippi, A.: Effect of fiber orientation on the fatigue behaviour of a short glass fiber reinforced polyamide-6. Int. J. Fatigue **29**, 199–208 (2007)
19. Stinchcomb, W.W., Bakis, C.E.: Fatigue Behavior of Composite Laminates, vol. 4 (1991)