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Assessment of Cyclic Load Induced Energy Dissipation and Damping on GFRP Composite Laminate

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Abstract: Polymeric composites exhibit load sensitive stiffness unlike the case of homogeneous metallic material. Composites are widely used in dynamic loading environment and hence it is necessary to study their response in terms of structural properties. Behavioural changes of glass epoxy composite laminate on exposure to cyclic loading has been assessed in terms of energy dissipation (E_d) and Damping factor (DF) by hysteresis loop. GFRP composite specimens (UD-0, 0/30/60/0, 0/45/0/-45, 0/90/90/0, and 0/90/0/90) are exposed to low velocity constant amplitude cyclic loading using a laboratory arrangement (by an eccentric disc) at 4.6 Hz and 8.6 Hz frequencies. In fibre-reinforced composites apart from the fibre volume fraction, the fibre interaction angle significantly influences their dynamic properties on loading. Unidirectional (UD-0) laminate exhibits low damping/energy dissipation, while 0/90/0/90 laminate with large fibre interaction angle shows highest damping/energy dissipation. Whereas, symmetric cross ply (0/90/90/0) laminate acts as a performance demarcation among the chosen laminates. Thus, optimum E_d/DF properties of GFRP laminate in dynamic environment is attributed to symmetric lay-up, smaller fibre orientation interaction angle in the lay-up sequence and 0 fibre layer at the boundary.

Keywords: Cyclic loading, Energy dissipation, Damping, GFRP

Introduction

High performance, high energy absorbing and lightweight materials find significant application in the present scenario of dynamic structures. In this context, composite materials are mostly chosen owing to their high specific strength and inherent properties such as energy dissipation and damping to sustain/safeguard the structure from undesirable damage. The investigation of composite material applied to wind mill, leaf spring, turbine blades and sports equipment involve cyclic loading. The formation of micro cracks in brittle epoxy matrices of the composites contributes to energy dissipation, which tends to improve the fatigue response due to energy balance between the imposed loads and dissipation. The behaviour of GFRP laminate on cyclic loading [1,2] can be expressed in terms of damage accumulation and the change in the modulus is due to changes in the energy interaction between polymer chains of the matrix material. The fatigue of non-homogeneous materials has heterogeneous damage sequence, which has been measured by hysteresis to highlight the damage in terms of stiffness-degradation, creep and damping [3,4]. The fibre movement in the viscoelastic matrix imparts damping variants associated with fibre matrix compatibility along with fibre matrix interface area and fibre orientation [5-8] as observed in longitudinal and transverse mode. The fatigue failure [9] of the composite is classified as fibre mode (with a fibre angle between 0° and 10°) and matrix mode (with a fibre angle between 10° and 90°).

The energy consideration in composites involves processing, fabrication, retention/residual and dissipation energy as in other materials like metals. Unlike the homogeneous materials, the design of energy absorbing composite materials is relatively challenging, owing to various damage mechanisms involved during loading such as matrix and fibre cracking, disturbance to the orientation, delamination, dislocations [10,11] and thermal effects acting simultaneously at varying magnitudes [12]. Upon cyclic loading, the imposed energy is transferred into the material that may be either dissipated in the form of heat affecting possibly the molecular chain of the matrix or consumed as stored energy. The stored energy in composite tends to disintegrate the resin/fibre system, inflicting matrix interface debonding and resulting in non-linear response. Hysteresis loop is one of the methods suitable to study non- linear response of the composite materials in terms of energy dissipation and damping of the material through load/unload displacement plots. Hysteresis energy increases in the beginning, exhibiting a steady/progressive rise, followed by a pointy/rapid rise at the final failure [13]. In contrast to homogeneous materials, composite materials have features for mitigating damage by transferring the applied energy into opening/creating crack surfaces, spreading the damage zone (weak zone) associated with plastic deformation, buckling and other dynamic instabilities that characterize the material response in terms of damping [14,15]. Thus, energy method is considered to be more relevant to investigate the response of cyclic loaded composite laminate [3,4] than the stiffness measurement.

The present work investigates the response of the GFRP composite laminate to the applied cyclic load in terms of energy dissipation [16] and damping. With the intention to find the sustainability of the laminate-structure exposed to

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cyclic loading, energy method has been considered and extended to obtain the damping factor. GFRP laminate of specific lay-ups are individually subjected to cyclic loading with varying frequency is assessed in terms of energy dissipation (E_d) and damping factor (DF) [17].

Experimental

Specimen Preparation and Experiment

GFRP composite laminate plates (300×300 mm^2) of 4 layers with the stacking sequence of UD-0, 0/30/60/0, 0/45/0/-45, 0/90/90/0 and 0/90/0/90 has been prepared by hand lay-up technique [18,19] using glass fibre roving of 1100 gsm and epoxy LY556 and hardener HY995 (mix ratio 10:1) with 32 % fibre volume fraction. The test specimen of size 150 mm×10 mm×4 mm has been cut from the laminate and used for the experiment. The specimens were exposed to low velocity, constant amplitude cyclic loading [24] using an eccentric disc with an eccentricity of 1.5 mm as shown in the Figure 1 at two different spindle speeds of 275 rpm (4.6 Hz) and 516 rpm (8.6 Hz). The cyclic loading was imposed sequentially up to around 60×10^3 cycles on the specimen, which is kept as cantilever beam. The imposed load produces flexural bending on the specimen with load at the free end and combining the effect of tensile and compressive deformation. Further, to substantiate the influence of fibre orientation in the lay-up sequence in damage pattern, Fractography [24] study was done on the specimens using SEM images.

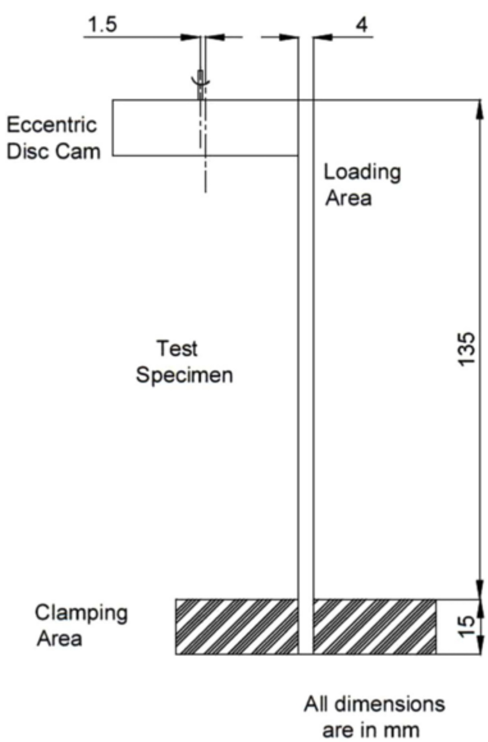

Figure 1. Cyclic loading set up.

Energy Dissipation and Damping Factor

The energy changes in the composite on loading is found to be reflected in the form of a matrix crazing/cracking, fibre matrix debonding and fibre breakage. The energy method utilizes the hysteresis plot (Figure 2) from loading/unloading (Figure 3) of both virgin and post-loaded specimen. The area enclosed by the loop is the dissipated energy (E_d) and the area under the loading curve is the stored energy (E_p). The magnitude of the E_d indicates the extent of structural alteration and related damping in the composite laminate. The damping factor [DF (η)] is the ratio of energy dissipated E_d and the stored energy E_p. The computation of E_d, E_p (by trapezoidal summation) and DF are by the following formulae given below [20,21].

$$E_p = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1}-d_i)[f(d_{i+1})+f(d_i)] \quad (1)$$

$$E_d = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1}-d_i)\{[f(d_{i+1})+f(d_i)]-[g(d_{i+1})+g(d_i)]\} \quad (2)$$

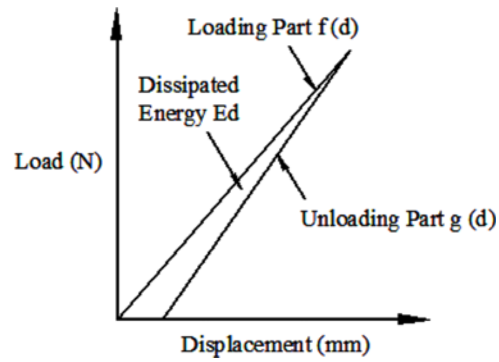

Figure 2. Hysteresis loop.

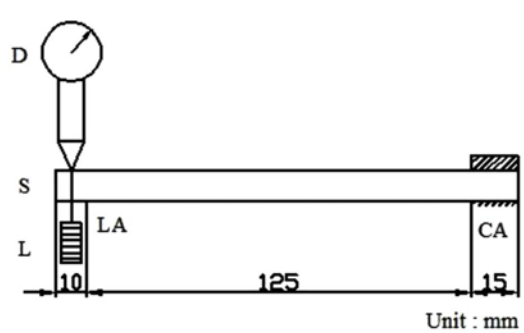

Figure 3. Load-deflection setup.

$$DF = \eta = \frac{E_d}{2 \Pi E_p} \quad (3)$$

d_i: displacement during ith stage
d_{i+1}: displacement during i+1th stage
$f(d_i, d_{i+1})$: load on loading path during ith and i+1th stage
$g(d_i, d_{i+1})$: load on unloading path during ith and i+1th stage

Results and Discussion

The energy dissipation and damping factor of the prepared specimens were assessed in two variants as Virgin (without exposing to any load) and Cyclic Loaded (exposed to specific number of load cycles). The outcomes of the tests are presented below.

Assessment of Energy Dissipation and Damping Factor

Pre-Loading (Virgin Specimen) Assessment

The obtained E_d and DF of virgin specimens are given in the Table 1. It is observed that, E_d and DF are proportional to one another in the virgin state. Among the chosen laminate configurations, UD-0 and 0/90/0/90 are the extremities in terms of E_d/DF. The load bearing fibre in the UD-0 ply laminate enhances the energy storage with reduced E_d attributed to the efficient load transfer between the lay-up. The increasing fibre interaction angles between the plies in 0/30/60/0 and 0/45/0/-45 [7] induces higher E_d. In symmetric (0/90/90/0) and non-symmetric cross ply (0/90/0/90) configuration, the presence of orthogonal interaction in the lay-up rises E_d/DF.

Post-Loading (Cyclic Loaded Specimen) Assessment

The response of the specimen in terms of E_d and DF to the imposed cyclic load are discussed in the following sections.

Unidirectional Laminate (UD-0 ply)

The variation in energy dissipation (E_d) and damping (DF) of unidirectional (UD 0-ply) laminate for both the loading frequencies is given in the Figure 4. Both the E_d and DF reached the minimum value at 33×10^3 cycles with 4.6 Hz loading frequency and the variation of E_d and DF with respect to virgin specimen is 0.74 % and 1.80 %.

The homogeneous structural arrangement of UD-0 ply ensures effective transfer of imposed load as stored energy

Table 1. E_d and DF of virgin specimen

Lay-up	V_f (%)	Energy dissipation (E_d) (J/m^3)	Damping factor (DF) (%)
UD-0		18.8	0.44
0/30/60/0		22.3	0.56
0/90/90/0	32	36.3	0.64
0/45/0/-45		41.8	0.84
0/90/0/90		47.0	0.93

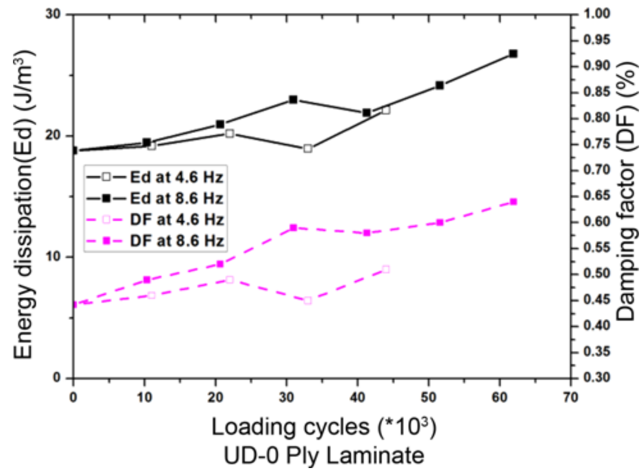

Figure 4. E_d and DF of UD-0 ply laminate.

with minimum energy dissipation as oberseved by Jean *et al.* and Hong *et al.* [28,29]. On subsequent loading, the stored energy in composite tends to disintegrate the resin/fibre system, inflicting matrix interface debonding and resulting in non-linear response. Thus, presenting a rise in the E_d and DF value exhibiting the onset of failure. At a higher loading frequency (8.6 Hz), the imposed load increases the damage within the composite system, shown by the rise in E_d/DF above the virgin. The minimum E_d/DF variation of post loaded specimen from the virgin indicates the possibility of improvement in response [11] with the lower loading frequency. Increasing frequency can aid in creating new surfaces in the craze region contributing to rise in DF.

Angle Ply (0/30/60/0, 0/45/0/-45) Laminate

Figure 5 and 6, illustrates the E_d and DF variation from the virgin of angle ply laminates. The E_d of 0/30/60/0 laminate at higher frequency (8.6 Hz), rises followed by a marginal drop on loading. Further, it reaches minimum at 41×10^3

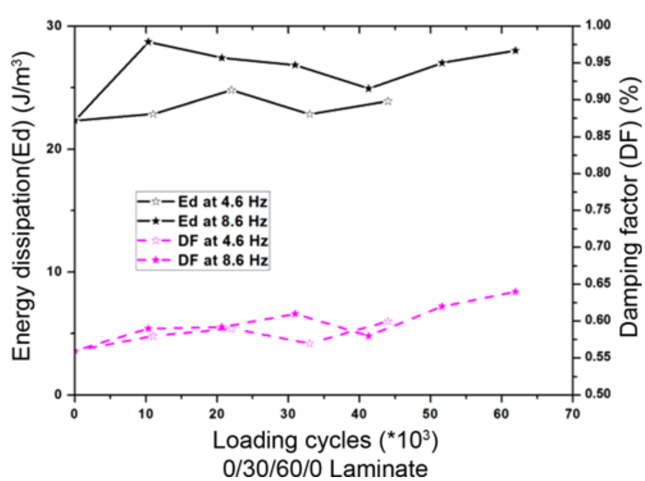

Figure 5. E_d and DF of 0/30/60/0 laminate.

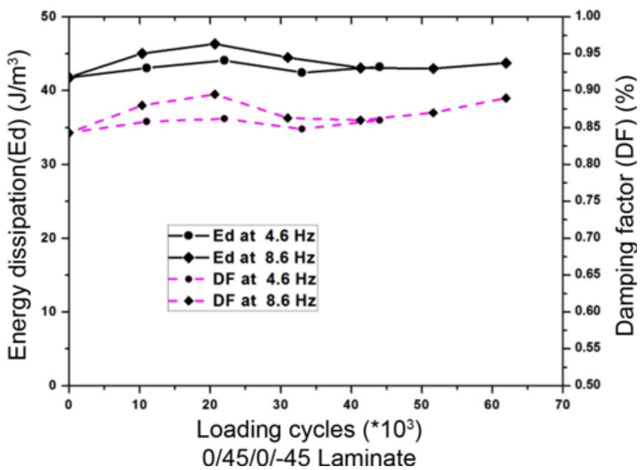

Figure 6. E_d and DF of 0/45/0/-45 laminate.

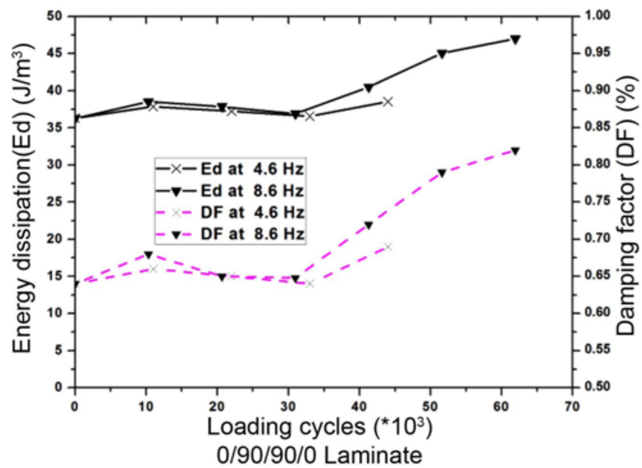

Figure 7. E_d and DF of 0/90/90/0 laminate.

cycles with a variation of 11.59 % from virgin. Later, E_d rises with the load cycles. At lower (4.6 Hz) frequency, the same trend is observed with a minimum E_d value at 33×10^3 cycles with 2.32 % variation from the virgin.

The steady damping up to 21×10^3 loading cycles [1] proves the concept of energy balance between applied load and dissipated energy. After that, DF increases at a higher loading frequency and drops at 41×10^3 cycles with 3.57 % variation from virgin, followed by a drastic rise. At lower frequency, the DF has minimum variation of 1.78 % with virgin at 33×10^3 cycles. The smaller fibre interaction angle in the lay-up favours resistance to damage transfer with minimum DF at 33×10^3 cycles for 4.6 Hz and at 41×10^3 cycles for 8.6 Hz and the corresponding loading cycle could be considered as a critical loading cycle. Loading beyond the critical cycle, influences the loss in structural integrity and the DF rises for both the loading frequencies.

The E_d and DF response pattern of 0/45/0/-45 laminate resembles one another. The minimum variation of E_d and DF at 8.6 Hz and 4.6 Hz are 2.87 % and 1.55 %, 2.01 % and 0.59 %, respectively. It is observed that, both the loading frequencies produced similar changes in the E_d and DF values up to 40×10^3 cycles. The larger fibre interaction angle between the adjacent layers in the lay-up reduces the resistance to damage transfer in the laminate, leading to a rise in E_d and DF, exhibiting similarity to that of Mode I DF of angle ply laminate [29].

Cross Ply (0/90/90/0 and 0/90/0/90) Composite Laminate

Typically monitored response of the cyclic loaded symmetric and non-symmetric cross ply laminates are illustrated in the Figure 7 and 8. The trend of E_d/DF of the 0/90/90/0 symmetric cross ply laminate is the same up to 30×10^3 cycles for both the loading frequencies and presents a change after that. Beyond 30×10^3 cycles, a steep rise in both DF and E_d is noticed. The minimum variation of E_d and DF at 8.6 Hz is obtained at 31×10^3 cycles with 1.65 % and 1.25 % and for

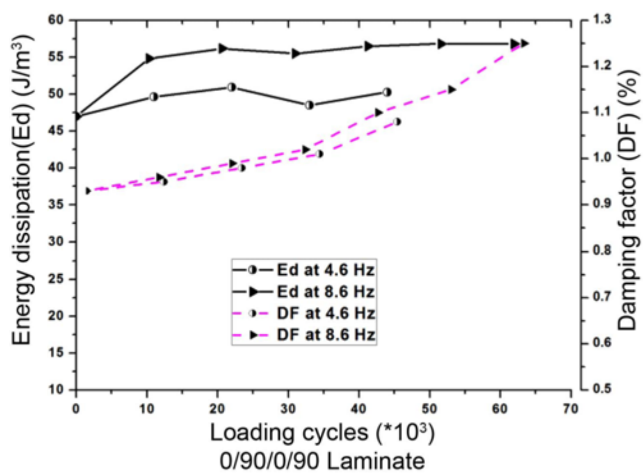

Figure 8. E_d and DF of 0/90/90/0 laminate.

4.6 Hz, it is at 33×10^3 cycles by 0.74 % and 0.78 % respectively. Thus, exhibiting performance enhancement at low frequency loading for long duration and vice versa.

The E_d of non-symmetric cross ply laminate remains stable after a marginal rise on load cycles at 8.6 Hz. It records minimum E_d with 3.19 % variation from the virgin around 33×10^3 cycles at 4.6 Hz loading frequency. Whereas, DF rises steadily with both the loading frequencies. The presence of 90^o transverse layer at the extremity and the coupling of bending - extension term (due to non-symmetric lay-up) accounts for the increased dissipation/damping. On comparing the performances of Symmetric and non-symmetric cross ply laminate, the boundary 0 fibre layer in symmetric performs better in terms of E_d and DF than later resembling the response of cross ply as presented by Hong *et al.* [29].

Relative E_d and DF of Cyclic Loaded Laminate

Figure 9(a) and (b) illustrate the relative effect of DF with

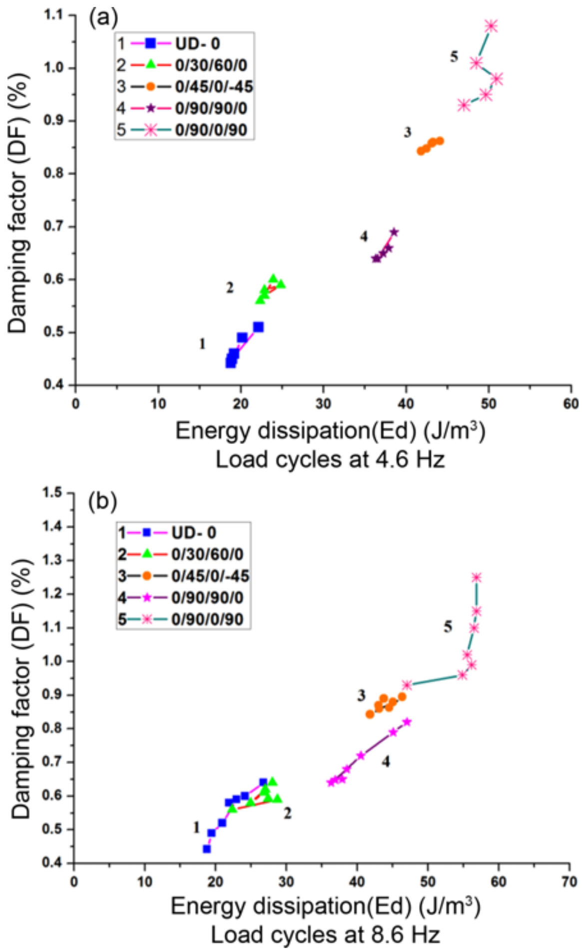

Figure 9. DF and E_d of cyclic loaded laminates; (a) 4.6 Hz and (b) 8.6 Hz.

respect to E_d after cyclic loading at 4.6 Hz and 8.6 Hz. The fibre interaction angle in the lay-up sequence influences the variation of DF and E_d. Of all, UD-0 Ply (1) exhibits minimum value and the non-symmetric cross ply (5) exhibits the maximum value. The small fibre orientation interaction angle in the 0/30/60/0 (2) reduces E_d/ DF value, whereas the large fibre interaction angle within 0/45/0/-45 (3) increases E_d/DF value due to the presence of -45 layer at the boundary. Damping and dissipated energy are directly proportional in 0/90/90/0 (4). Whereas in case of 8.6 Hz of loading, there exists an overlap among the laminate response in terms of E_d/DF.

Fractography of Test Specimen

The energy dissipation and damping factor results of the cyclic loaded GFRP laminate specimen exhibits the influence of lay-up sequence within the laminate. The quantified factors in the previous sections are supported by the observed damage pattern in the SEM images (Figures 10-12) of the laminate specimen when subjected to 3 point bend test

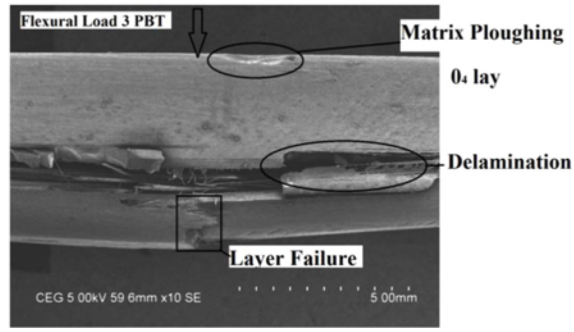

Figure 10. UD-0 ply laminate.

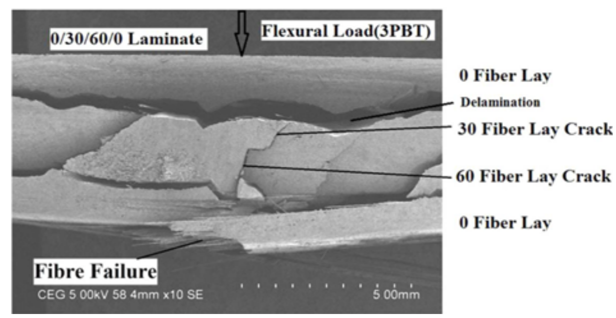

Figure 11. 0/30/60/0 laminate.

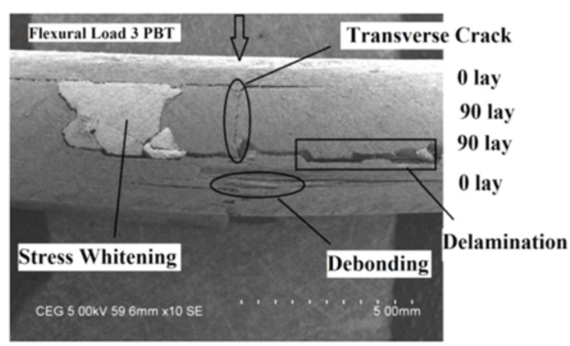

Figure 12. 0/90/90/0 laminate.

(PBT). In 3 PBT, the damage initiated from the bottom and propagates to the top. Here, one specimen under each category (UD - 0 ply, angle ply - 0/30/60/0 and cross ply - 0/ 90/90/0) is considered for the discussion.

In UD-0 ply laminate, boundary lay failure and delamination (Figure 10) are predominant favoring less energy dissipation attributed to the homogeneous fibre orientation in the lay-up sequence. Whereas in 0/30/60/0 angle ply laminate, fibre oriented lay cracks are observed along with boundary layer failure and delamination (Figure 11). In the case of cross ply laminate (0/90/90/0), the damage pattern comprises of transverse crack attributed to the middle 90 ° layer along with delamination and debonding (Figure 12).

It is observed that, the increasing fibre orientation angle in the lay-up sequence enhances the damage pattern and consecutive energy dissipation and damping.

Conclusion

The energy dissipation and damping of GFRP composite laminate exposed to cyclic load in a cantilever model has been carried out in the present work and the following conclusions are drawn with respect to the loading frequency and fibre interaction angle in the laminate lay-up.

1. The homogeneous structural lay-up in the UD-0 ply laminate reduces the energy dissipation with less damping at low loading frequency than at high frequency [28,29].
2. The heterogeneous lay-up in 0/30/60/0 and 0/45/0/-45 laminate, with large fibre interaction angle [7] records higher E_d and DF values on cyclic loading for both the loading frequencies than UD-0 ply.
3. Operational behavior changes are encountered in UD-0 ply, 0/30/60/0 and 0/90/90/0 owing to 0 fibre layers at the boundary [29].
4. The fibre orientation in 0/90/0/90 causes a structural fluctuation on loading attributed to boundary 90^o ply resulting in higher structural damage facilitating better damping.
5. 0/90/90/0 laminate acts as performance demarcation among the chosen laminates in terms of damping and energy dissipation on exposure to cyclic loading.
6. The minimum E_d/DF value due to cyclic loading is limited to critical cumulative strain at 33×10^3 (4.6 Hz) and 40×10^3 (8.6 Hz) cycles. This can be attributed to the possible crack arresting reinforcement, matrix interface [7,8] and fibre interaction.
7. Amongst the selected lay-up, the 0/90/0/90 shows the high damping and UD-0 shows the least, attributed to the weak transverse fibre 90 layer and strong longitudinal fibre 0 layer at the tensile region.
8. The optimum E_d/DF performance of GFRP laminate for dynamic environment is attributed to symmetric lay-up with smaller fibre orientation interaction angle in the lay-up sequence and 0 fibre layers at the boundary under critical loading condition.

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