Accepted for publication in Journal of Reinforced Plastics and Composites (2006) This is Author's Post-print version

Archived in http://dspace.nitrkl.ac.in/dspace

Effect of hygrothermal shock cycles on interlaminar shear strength of hybrid composites

P. K. Ray, S. Mula, U.K. Mohanty and B. C. Ray*

Department of Metallurgical & Materials Engineering

National Institute of Technology, Rourkela 769008, India

* Author for correspondence:

E-mail: bcray@nitrkl.ac.in, Phone: +91-661-2462559

ABSTRACT

The present work aims to assess the interlaminar shear strength (ILSS) of interply woven fabric glass/carbon hybrid composites under the influence of a fluctuating humid environment. The ILSS values have been used for quantification of mechanical degradation. The effects of fluctuating environment on moisture sorption as well as the degradation kinetics have been assessed. It is seen that the ILSS shows a gradual degradation over a period of time. It is has been observed that the ILSS scales inversely with crosshead velocities. This is attributed to the presence of alternating strong and weak interfaces and the differences in their moisture sorption tendencies.

KEY WORDS: Fluctuating environment; ILSS; Degradation kinetics, Interfacial behaviour; Delamination

INTRODUCTION

Hybridization provides materials designers with an added degree of freedom in tailoring composites to achieve a better balance of stiffness and strength, increased failure strain, better damage tolerances, improved ability to absorb impact energy, and possibly a significant reduction in cost [1]. Hence, the behavior of fiber reinforced plastic (FRP) hybrid composites under possible service conditions is a matter of significant practical interest. The mechanical behavior of FRP composites are dominated by the interfacial adhesion at the fiber-matrix interface. The presence of moisture at the interface can modify the interfacial adhesion thereby affecting the mechanical performance of the FRP composites. Moisture absorption in the composites introduces dilatational stresses. During moisture absorption, the outside ply of a composite laminate is in compression [2]. This results from the outer ply trying to swell, but being restrained by the dry inner plies. Similarly, on desorption, the outer plies try to shrink, but are restrained by the wet swollen inner plies. This results in tensile stresses in the outer plies. Consequently the mechanical properties and long term durability show a marked deterioration. Hence an environment comprising of high humidity fluctuations, whereby moisture absorption occurs in the high humidity regime and desorption occurs in the low humidity regime, can have highly deleterious effects on the mechanical behavior and long term durability of the composites.

The present study has been carried out to assess the effect of a fluctuating Hygrothermal environment on the mechanical behavior of interply woven fabric glass-carbon fibers/epoxy hybrid composites. The rapid fluctuations, in essence, constitute a hygrothermal shock. A variety of structural components may experience such an active environment during their service life. Unfortunately, there is a paucity of data in this area. The effect of fluctuating environment on the degradation kinetics has been assessed here. The interlaminar shear strength (ILSS) values have been used for quantification of mechanical degradation.

EXPERIMENTAL

Woven fabric carbon fibers (T-300, PAN based high strength carbon fiber) along with E-glass fiber woven roving having a density of 0.36 kg/m^2 were used as fiber reinforcement. Epoxy adhesive (Ciba-Geigy LY-556 araldite, HY-951 hardener) was used as the matrix material. The composite specimens were prepared using the hand lay-up method. The composite specimens were initially subjected to an environment characterized by 95% relative humidity (RH) and 50^{o}C temperature for a period of one hour. Then they were exposed to a second environment characterized by 55% RH and 50^{o}C temperature for another one hour interval. Thus nineteen humidity cycles were carried out with a time period of two hours. The ILSS values were evaluated from the short beam shear test according to the following relation:

$$ILSS = \frac{0.75P_b}{bd}$$

where P_b = breaking load, b and d are width and thickness of the specimen respectively.

RESULTS AND DISCUSSIONS

The composite specimen, when subjected to a fluctuating humid environment, exhibits a marked tendency for moisture absorption. Figure 1 depicts the moisture absorption behavior of the composite specimen under experimental conditions. The plot can be divided into four regimes. The initial region displays sluggish kinetics, with the absorption rate being quite low. The second region displays accelerated moisture transport into the composite. The third region displays a relatively slower transport process whereas the last region is one tending towards saturation. The flux of moisture into or out of the specimen is primarily dependent on the pressure differential, or in other words, the thermodynamic potentials of the composite and the environment [3]. When exposed to a humid environment, the positive concentration gradient between the environment and the specimen, as well as the higher pressure outside the specimen favors moisture absorption. When the same specimen is exposed to a relatively dry environment, the conditions get reversed resulting in moisture desorption. The relative rates of absorption and desorption controls the net moisture pickup by the specimen. Additionally, the presence of cracks also has a significant bearing on the net moisture pickup.

During the initial cycles, the extent of damage caused by the environment is less, due to lower exposure times. Hence the specimen is relatively fault free. Consequently, the moisture pickup is largely governed by the balance of absorption and desorption during humid and dry cycles. The desorption cycle, therefore, serves to reduce the moisture absorption rate in the initial regime than it would otherwise be for composite specimens aged in a constant high-humidity environment. The results obtained in the present set of experiments are in agreement with the results of a recent study, where the hygrothermal response of glass fiber reinforced epoxy composites where studied under constant humidity conditions [4]. It has been shown [2] that during absorption the outer plies of the composite tries to swell, but are resisted by the inner plies. This results in compressive stresses during moisture absorption. On the other hand, when the specimen looses moisture, the reverse case occurs, with a tensile stress being set up at the interface. The effect of the hygrothermal shock is to introduce a sudden tensile stress in the material leading to debonding at the fiber-matrix interface. The cracks which open up in this manner are a prime channel for moisture transport during hygrothermal exposure. The initiation of interface damage looks all the more plausible due to the enhanced moisture pickup kinetics in the second regime, as well as a fall in the interlaminar shear strength at this juncture. The third region of the plot shows a relatively slow kinetics, suggesting the approach of saturation of the voids and interface cracks through which moisture transport takes place. This is further validated by the observation that at the later stages, the curve almost saturates.

Figures 2 and 3 show the variation of ILSS as a measure of degradation kinetics due to the fluctuating environment. The ILSS is seen to deteriorate over a period of time. In the initial stages, the ILSS values are seen to plummet downwards. Amount of moisture absorbed by the epoxy matrix is significantly greater than fibers which absorb little or no moisture [5]. This results in significant mismatch in moisture induced volumetric expansion between matrix and fibers leading to evolution of localized stress and strain fields in the composite at the interfacial region. The stress field existing in a hygrothermally conditioned composites adversely affect the interfacial bond thereby resulting in deadhesion. With increased moisture uptake, the nature of stresses during absorption and desorption have a more significant impact leading to a slow, but steady fall in the ILSS values. As the moisture transport kinetics saturate, the stresses at the interface, being governed of moisture pickup, also stop fluctuating. This is reflected by the gradual leveling of the ILSS values at higher conditioning times.

Figure 4 shows a comparative study of the moisture uptake, degradation kinetics and the effect of varying the crosshead velocity. It is noted that the ILSS assessed at higher crosshead velocity have lower values as compared to those for lower crosshead velocity. This anamolous dependence of ILSS on the crosshead velocity may be attributed to the presence of two different types of interfaces in the composite. The epoxy matrix absorbs moisture amounting to 4% of its weight prior to saturation, whereas the glass-epoxy interfaces and carbon-epoxy interfaces can absorb 2% and 1% moisture respectively. As a compressive force is applied on the material, the moisture at the interfacial regions has a tendency to get rejected in the adjacent matrix. Since, the carbon-epoxy interfaces have lesser porous zones to accommodate the moisture, it is expected that this interface will reject a greater amount of moisture at a faster rate. The overall direction of moisture transport in such a situation would be towards the glass-epoxy interface. The net effect, then, would be the accumulation of moisture in the matrix immediately adjacent to the glass-epoxy interface, even as the regions adjacent to carbon-epoxy interfaces remain relatively moisture free. At a higher crosshead velocity, the moisture transport has a greater impetus to move towards the glass-epoxy interface. Hence the probability of additional moisture trapping at the glass-epoxy interface would be greater in such a case. Moisture absorption results in significant mismatch in moisture induced volumetric expansion between matrix and fibers leading to evolution of localized stress and strain fields in the composite. Additionally moisture absorption leads to changes in thermophysical, mechanical and chemical characteristics of the epoxy matrix by plasticization and hydrolysis [6]. These changes decrease the glass transition temperature (T_g) and elastic modulus. At the same time, the moisture wicking along the fiber-matrix interface degrades their bond. Consequently, the interfacial adhesion degrades and the ILSS decreases even as the weak interface becomes weaker. This effect is more pronounced at higher crosshead velocities because of accelerated moisture movement through the resin. Consequently the ILSS values obtained at lower crosshead velocities are higher.

Initially, at lower conditioning times, there exists a marked difference between the ILSS values obtained at different crosshead velocities. The stresses developed during a humidity shock cycle are similar to that developed in case thermal shocks. Hence, humidity shocks cause additional interface cracking in a manner analogous to thermal shocks [7]. At higher conditioning times, the difference in the ILSS obtained from testing at different crosshead velocities narrow down gradually. This may be attributed to the fact that at higher levels of absorbed moisture, the degradation in the epoxy matrix and the interfaces are colossal. Such damage is likely to preclude the sensitivity to the crosshead velocities. Hence, the effect of crosshead velocities should become less significant over prolonged exposure periods [8].

CONCLUSIONS

In retrospection, one may conclude that the effect of fluctuating environment may have a reasonably deleterious effect on the mechanical behavior of hybrid composites. Following a very short sluggish period at the start of conditioning, the moisture absorption rate increases. The enhanced moisture pickup is responsible for breaking of bonds at the fiber-matrix interface and this result in a fall in the ILSS values. After the initial accelerated moisture transport and matrix damage, the kinetics of the process gets stalled due to the presence of an interpenetrating network at the interface. The presence of alternating weak and strong interfaces governs the material response when the loading rate is changed. The differences in percentage of elongation of the constituents in a hybrid composite at fracture could modify the nucleating stress required for delamination.

REFERENCES

1. B. Z. Jang, “Advanced Polymer Composites: Principles and Applications” (ASM International, Materials Park, OH 1994) p. 112.
2. S. S. Tompkins, D. R. Tenney, J. Unnam, Composite Materials: Testing & Design (Fifth Conference), ASTM STP 674 (1979) p. 368.
3. S. C. George and S. Thomas, “Transport Phenomena through Polymeric Systems”, Prog. Polym. Sci. **26** (2001) 985.
4. P.K. Ray, T. Bera, S. Mula, B.C. Ray, **“**Prior Thermal Spikes and Thermal Shocks on Mechanical Behavior of Glass Fiber-Epoxy Composites”, J. Reinf. Plast. & Compos., published online on 16th August
5. B. C. Ray, “Study of the influence of thermal shock on interfacial damage in thermosetting matrix aramid fiber composites”, J. Mater. Sci. Lett. 22 (2003) 201-202.
6. G. Sala, Composites **B 31** (2000) 357.
7. B. C. Ray, Thermal shock on interfacial adhesion of thermally conditioned glass/epoxy composites, Mater. Lett. 58(16) **2004**, 2175-2177.
8. B. C. Ray, “Effects of crosshead velocity and sub-zero temperature on mechanical behaviour of hygrothermally conditioned glass fibre reinforced epoxy composites”, Mater. Sci. & Engg. A 379 (2004) 39-44.

Figure Captions

Figure 1 Moisture absorption plot over a number of cycles

Figure 2 Degradation kinetics at a crosshead velocity of 2 mm/min

Figure 3 Degradation kinetics at a crosshead velocity of 50 mm/min

Figure 4 A comparative study of moisture pickup kinetics and degradation kinetics

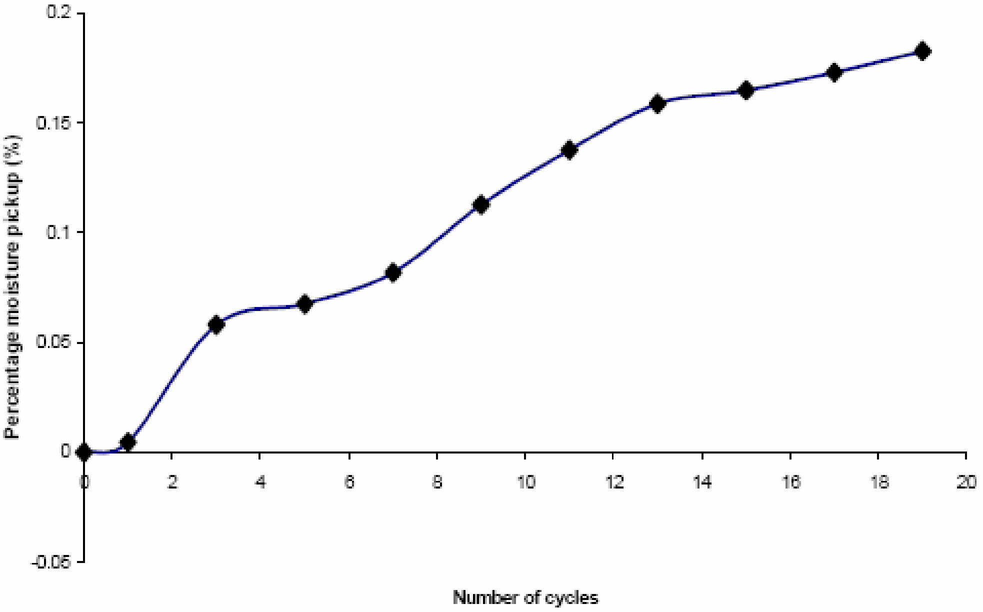

Figure 1 Moisture absorption plot over a number of cycles

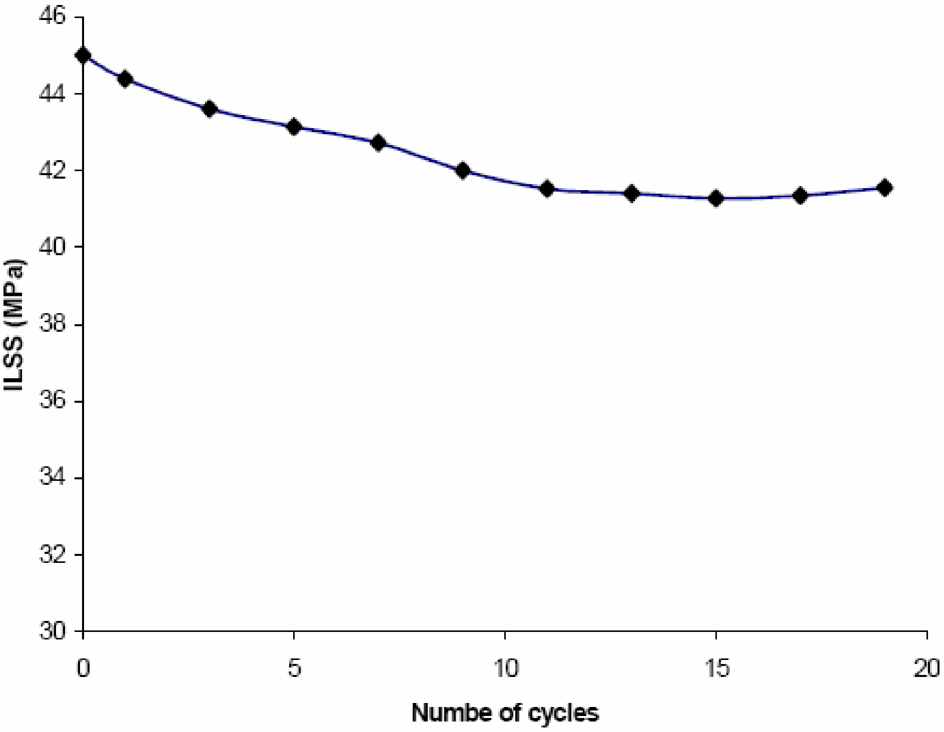

Figure 2 Degradation kinetics at a crosshead velocity of 2 mm/min

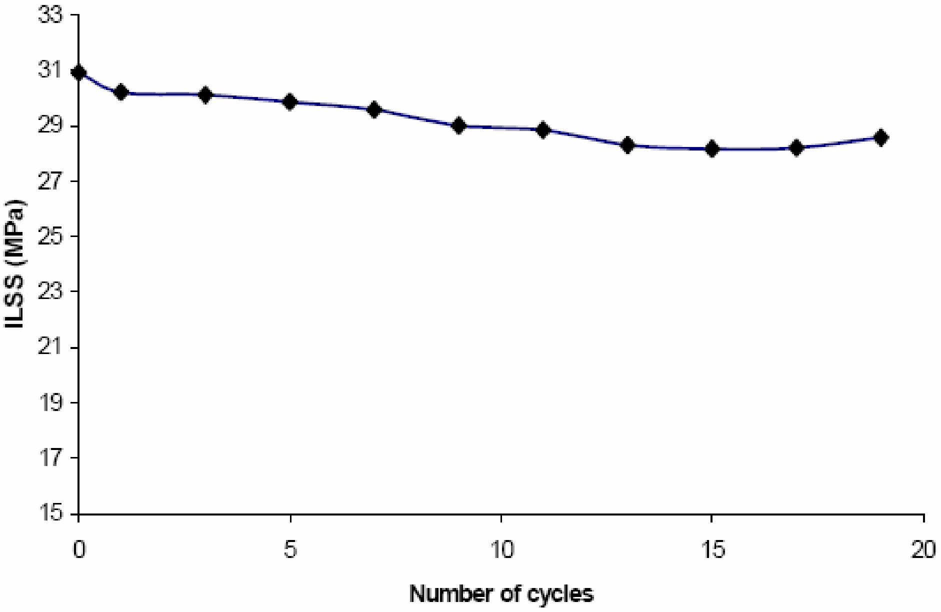

Figure 3 Degradation kinetics at a crosshead velocity of 50 mm/min

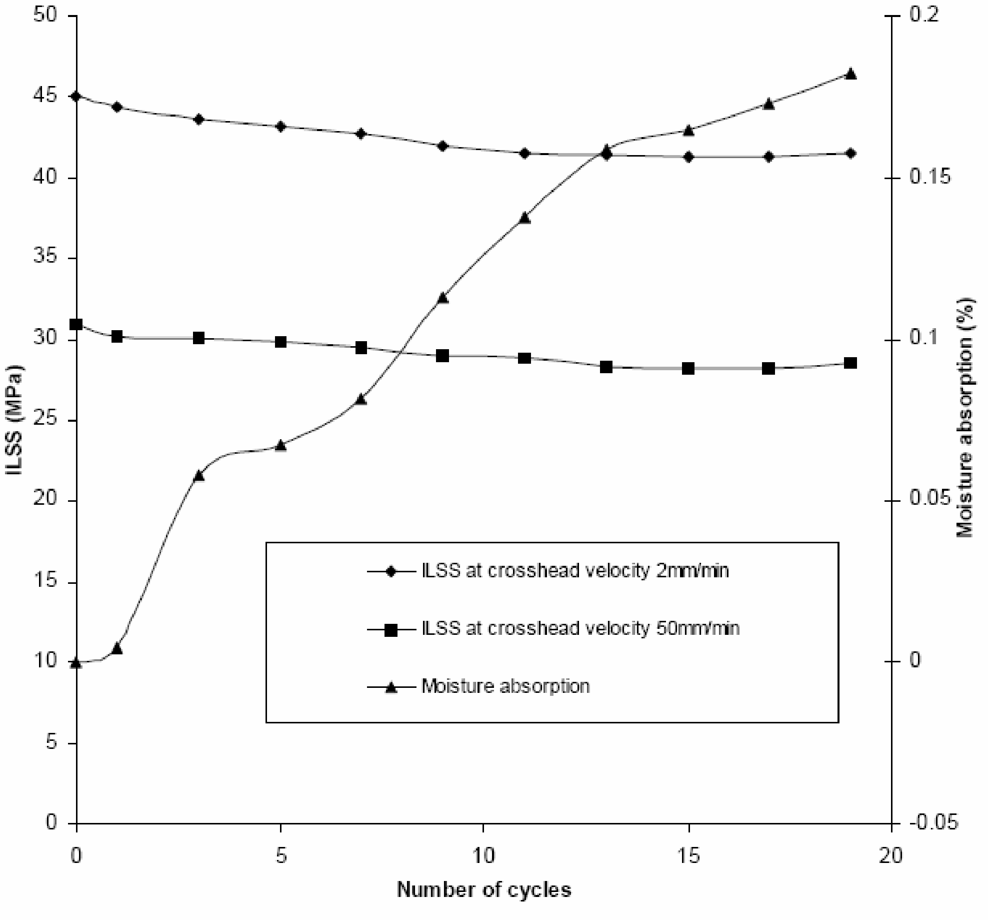

Figure 4 A comparative study of moisture pickup kinetics and degradation kinetics.