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Failure and Fractography Studies of FRP Composites: Effects of Loading speed and Environments

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Abstract

Advanced fibrous polymeric composites are one of the most successful composite material systems due to their wide range of advantages such as high specific strength and stiffness, fatigue properties and corrosion resistance. Composite structures undergo different loading conditions i.e. from static to dynamic during their service life. The polymer matrix is more susceptible to the environmental changes than the fiber and thus dominates the mechanical behavior of FRP composites. Polymers are characterized as visco-elastic materials that their mechanical properties are strain rate dependent or they are called as sensitive to the rate at which loaded. At higher crosshead speed due to shorter load assisted relaxation time, there is reduction in ILSS. The polymer gets more time for relaxation at lower crosshead speeds; as a result there is enhancement of ILSS values. Fracture processes at the crack tip are controlled by thermal relaxation time and mechanical relaxation. (At higher strain rates the heat generation was much faster than heat removal due to quasi-adiabatic heating which increases the fracture strain. In both the systems the locus of failure will shift from fiber polymer interface to the matrix itself that means instead of adhesion failure the predominating failure may be cohesive failure and that too shear cusp formation.) Implications of thermal conditioning most often lead an improved adhesion of the interface and/or increased crack density. These changes might lead further complications in accessing the failure mechanisms of FRP Composites.

Introduction

Advanced composite materials are superior to conventional materials in specific strength and stiffness, fatigue and corrosion properties.Composite structures undergo different loading conditions during their service life, e.g. sports equipment at higher loading rates to pressure vessels at lower loading rates [1]. The effects of varying loading rate on the mechanical properties of FRP composites are investigated and observed a variety of contradictory conclusions [2]. From the past researches the data describing that influence of strain rate on the mechanical properties are sparse the studied composite materials are glass/epoxy and carbon/epoxy systems [3]. Because of the presence of the two different constituents (fiber and matrix) and the fiber/matrix interface several complicating factors arises. The factors that depend on the loading rate are the individual constituents, fiber/matrix interface, the reinforcement configuration and the direction of loading [4]. In the light of these factors, it has been observed that for a full characterization of the mechanical behavior at different loading rate it needs more experimentation. The fiber/matrix interfacial bond greatly influences the mechanical behavior of composite materials [5]. Both GFRP and CFRP have been found to be rate sensitive, information available in the open literature was not extensive to draw any concrete conclusion. Woven and unidirectional GFRP and CFRP are rate dependent, both the modulus and strength increase as the test rate are increased, strain to failure decrease with increasing strain rate [6-8]. Thermal degradation of epoxy resin involves chemical reaction and physical changes. Chemical reaction is represented by oxidation, further cross-linking and further reaction of un-reacted monomers, while physical change is the visco-elastic behavior [9]. At quasi-static strain rate, micro and macro level defectsin the materials play a major role to initiate and propagate the damage utilizing most of the applied energy. At higher strain rates, the polymer not gets enough time to realize the material internal defects during loading [10]. Effects of thermal conditioning on FRP composites result in post-curing strengthening effect [11]. The present investigation has been focused on the loading rate and temperature dependence of glass/epoxy and carbon/epoxy composites [12]. It was explained that the increase in failure strength was due to change in failure modes with strain rate.Brittle thermo-set epoxy resin can undergo a limited extent of deformation prior to failure [13]. The ductility of a matrix resin may become a limiting factor at a high strain rate for the composite strength. It is more ductile than it’s composite at a lower strain rate [14].

Materials and Methods

Materials

Resin LY-556 is an unmodified liquid epoxy resin based on Bisphenol A along with Hardener HY 951(aliphatic primary amine), it provides a low viscosity, solvent free room temperature curing laminating system. Silane treated woven roving E-glass fibers with 60 weight percentages were used for glass/epoxy composite fabrication. Woven carbon fibers of epoxy compatible sizing (PAN based high strength) with 60 weight percentages were used for fabrication of carbon/epoxy composites.

Methods

Glass/epoxy composite laminates were fabricated by hand lay-up method, Silane treated E-glass fiber of required dimensions was laid over a releasing sheet and then catalyzed epoxy resin was poured absorbed over the reinforcement. The layered structure was allowed to harden on cure. It was cured at room temperature for 48 hours. After curing, the laminate was cut into the required size for 3-point bend (Short-Beam Shear) test by diamond cutter. Then stability test was done for the composite laminates, here the laminates were weighed and then heated in an oven at 50˚C. The weight is intermittently checked till we get a stable weight, so that with further heating of the composites there is no change in the weight. The same procedure was again repeated for the fabrication of carbon/epoxy laminates.

Thermal conditioning

Above ambient temperature: One batch of sample was put in a baking oven at +50˚C for 2 and 5 hours for thermal conditioning at above ambient temperature.
Below ambient temperature: Similarly another batch of sample was put in an ultra low chamber at -50˚C for 2 and 5 hours conditioning time.

Short beam shear test

The state of interaction between the fiber and matrix was reflected in inter-laminar shear strength (ILSS) values measured by short beam shear test with an Instron tensile testing machine with five increasing cross head speeds ranging from 1, 10, 100, 200 and 500 mm/min at the conditioning temperatures.
The ILSS was measured as follows:

$$ILSS = 0.75\ Pb\ /BD$$

wherePb load at yield, B is the width and D is the thickness of the specimen

Results and Discussion

Glass/epoxy composites

The variation of ILSS values for both the conditioned specimens are plotted against the cross head speeds for glass/epoxy composites in fig. 1. It is a three-point flexural test, which generally promotes failure by inter-laminar shear, and the results of the test are useful for assessment of interfacial de-bonding and composite quality [11]. Fig. 1(a) depicts the ILSS value increases at each point of testing with increasing temperature and time.Due to thermal conditioning at above ambient temperature, there is further polymerization in terms of epoxy embrittlement and along with the development of penetrating and/or semi-penetrating network at the fiber/matrix interface. At lower cross head speed the polymer gets more time for relaxation, less gross plastic deformation, enhancement of ILSS. With increasing cross head speed up to 100mm/min crack density increases due to structural integrity losses, this deteriorates ILSS values. At higher cross head speed there is shorter load assisted relaxation time, the polymer unable to transfer the load properly, reduction in ILSS. Here the load is like an impact due to this several damage mechanisms such as fiber fracture, fiber pull out, matrix cracking and de-lamination occur. These micro-failure processes allow a composite laminate to exhibit a more gradual deterioration rather than a catastrophic failure [4]. Fracture processes at the crack tip of polymers are controlled by mechanical and thermal relaxation time. At low strain rate loading time greater than mechanical relaxation time and at high strain rate loading time greater than thermal relaxation time. Fig. 1(b) prevails that at lower stain rate the polymer becomes brittle, less plastic deformation which results higher strain at yield values and at higher strain rate the strain at yield increases due to adiabatic heating i.e. here heat generation was faster than heat removal at the time of testing. Thermal conditioning at above ambient temperature might possibly improve adhesion level at the interfaces. Adhesion chemistry at the interface may be influenced by post-curing phenomena and this effect is supposed to increase with more conditioning time limited by some optimum value. Fig.1(a) shows that at higher crosshead speed i.e.at 500 mm/min the strain at yield is higher for 2 hours conditioning time. SEM micrographs of different failure mechanism of glass/epoxy composites are shown in fig.2(a) and (b), it reveals the presence of less fiber/matrix de-bonded areas which indicates an enhanced adhesion by thermal conditioning.

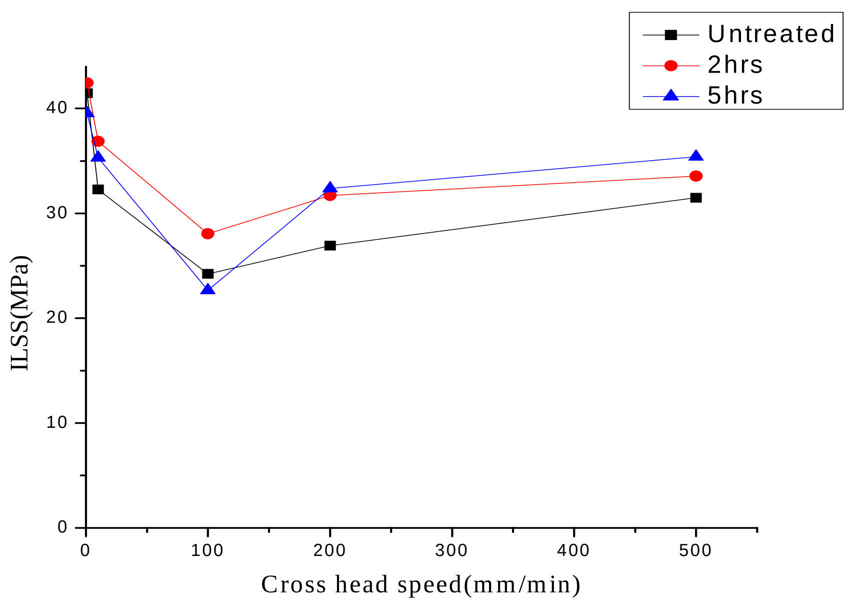

Fig.1 (a) Crosshead speed Vs ILSS for carbon/epoxy composites above ambient temperature at + 50˚C for 2 and 5 hours conditioning time.

Low strain

Medium strain

Very high strain

High strain

Fig.1(b) Strain at yield Vs Crosshead speed at ambient temperature for glass/epoxy composite.

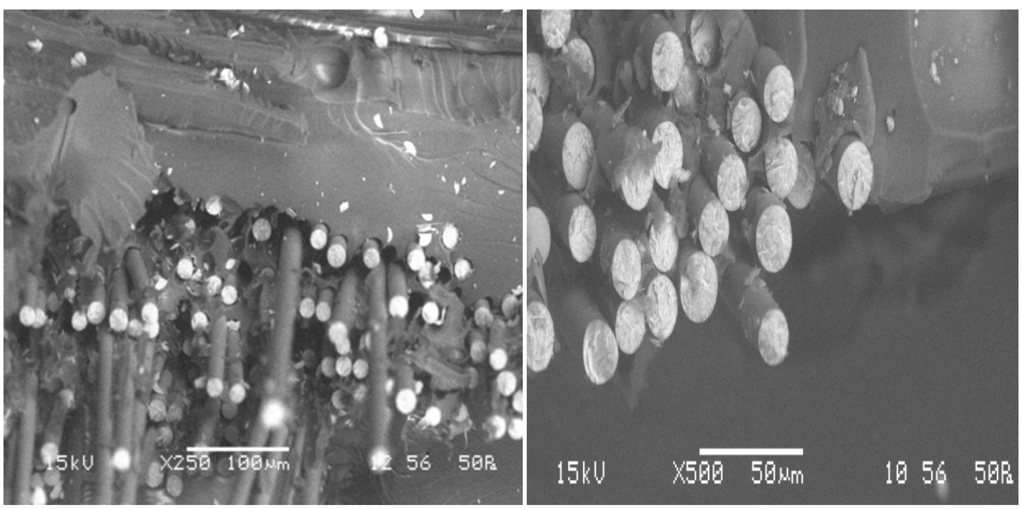

Fig.2(a) Showing extensive fiber/matrix de-bonding and fiber pullout in glass/epoxy composite at higher cross head speed and fig. 2(b) depicts increase fiber/matrix adhesion due to thermal conditioning.

Carbon/epoxy Composites

The effect of cross head speeds on ILSS for carbon/epoxy composites at above ambient showing fig.3(a), there is increase in ILSS values with more thermal conditioning time; it may be due to post curing. Strain at yield Vs cross head speed for carbon/epoxy systems at above ambient fig 3(b) are vary in a similar fashion as glass/epoxy systems. At the above ambient temperature due to further polymerization, interfacial strength increases.For carbon/epoxy systems at high strain rate it is stiffer than at the lower strain rates. The maximum stress increases with strain rate, but the increase is not significant [15]. De-bonding occurs as a result of failure initiated at a point in the fiber/matrix interface which then propagates through the entire length of the interface. There was a greater density of resin debris and fiber fracture of the specimens tested at high strain rate [16]. The locus of failure will shift from fiber polymer interface to the matrix itself that means instead of adhesion failure the predominating failure may be cohesive failure and that too shear cusp formation.CFRP are sensitive to temperature variations as a result of the development of the thermal stresses between the fibers and matrix due to their distinct thermal expansion coefficients. The induced thermal stresses may be relieved by crack formation in the matrix and in extreme cases, by fiber failure. Both matrix cracking and fiber failure degrade the mechanical properties of the composite. Fig.4(a) reveals that adhesion level increase and less de-bonded areas with thermal conditioning for carbon/epoxy systems. Fig.4.(b) depicts signs of few hackle markings for carbon/epoxy due to thermal conditioning at above ambient temperatures.

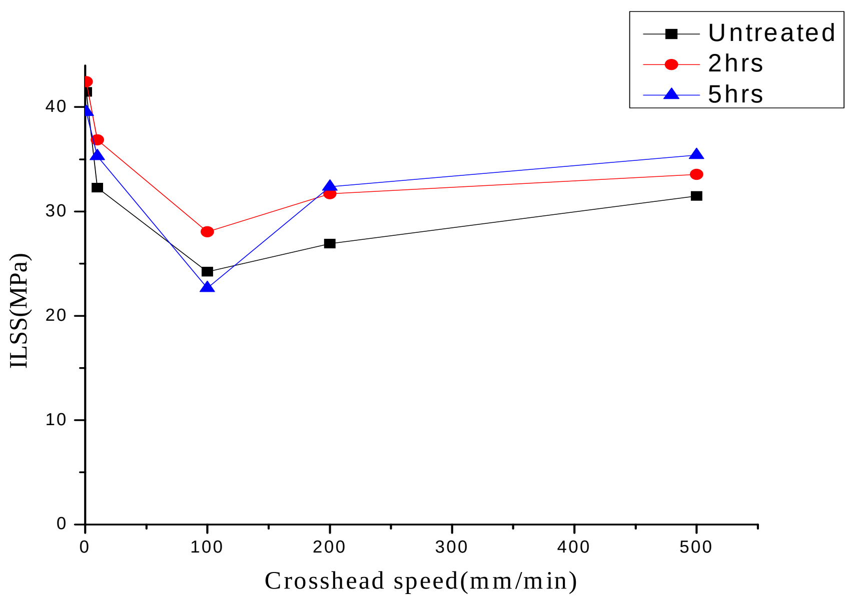

Fig.3 (a) Crosshead speed Vs ILSS for carbon/epoxy composites above ambient temperature at + 50˚C for 2 and 5 hours conditioning time

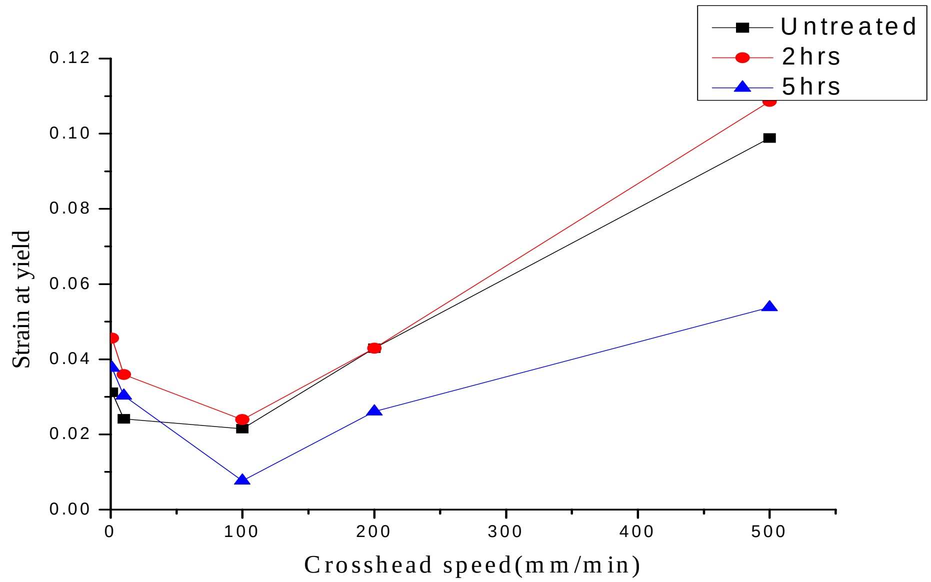

Fig.3(b) Strain at yield Vs Crosshead speeds of carbon/epoxy composites above ambient temperatures at + 50˚C for 2 and 5 hours conditioning time

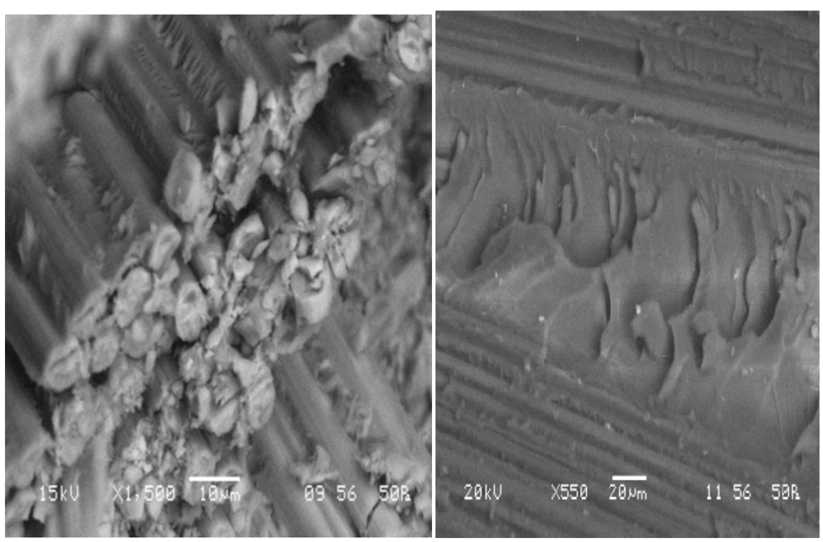

Fig.4. (a) Showing matrix cracking, fiber/matrix de-bonding, fiber fracture and fiber pullout at higher cross head speed and fig4.(b) depicts developments of cusp due to shear stress in CFRP.

Conclusion

The SBS test results show that the mechanical properties of epoxy matrix composites depend on the conditions of the tests i.e. the crosshead speed and temperature. The variations of ILSS with crosshead speed are found to be unusual and may be unreported on the open literature. ILSS values increases at above ambient temperature and it may be increased with more conditioning time limited by some optimum value due to post curing. Glass/epoxy systems are loading rate sensitive up-to 200 mm/min after that they are seemingly less sensitive to loading rate. Whereas carbon/epoxy systems are less sensitive or insensitive to loading rate as compared to glass/epoxy systems. Different failure mechanisms occur at higher crosshead speed due to less relaxation time thus the chances of uniform and gross deformation is reduced. With changing in loading rate from static to dynamic, the failure mechanisms are also changing from fiber fracture to matrix cracking.

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