A Review on Mechanical Behavior of FRP Composites at Different Loading Speeds

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Abstract

Fibre reinforced polymer (FRP) composites are increasingly becoming suitable and durable materials in the repair and replacement of traditional metallic materials. The built-in promise of performance assurance and retention of structural integrity in harsh and hostile environments of these materials certainly offer an alternative and attractive avenue for a wider range application to explore its potential to the zenith. The toughest challenge faced by material scientists is to assess and ascertain its behavioural log in a range of loading rates. The heterogeneity and responses of multiple distinct phases to varying loading conditions are most often complex and far away from comprehensive conclusion. Furthermore, composites with common structural polymer matrices quite often absorb moisture during service period. Then, FRPs become a much more complex system to comprehend its sensitivity to experimental variation. The present review has emphasized the need of understanding this perpetual problem of FRPs which might pose a threat to its prospects.

Keywords: Fibres Polymer-matrix composites (PMCs), Environmental Degradation, Mechanical properties, Durability, Loading Rate

Contents

1. Introduction

Widespread engineering and high performance structural applications have made FRP composite materials ubiquitous in the present century. These materials possess attractive mechanical properties for designers and manufacturers. Especially thanks to, light weight, high specific strength and specific modulus, corrosion resistant, good fatigue properties and the ability to tailor the properties in required direction as per the application. During service life these materials are exposed to various environmental and loading conditions ranging from quasi-static to dynamic loading. In many structural applications FRP's are subjected to high energy and high velocity dynamic loadings that can produce multi-axial dynamic states of stress. Composites are anisotropic materials, so the damages due to these stresses are complex phenomenon involving many failure mechanisms (frequently interactive) in micro scale. Several methods have been proposed and discussed, including fracture mechanics, nonlinear viscoplastic constitutive modelling, damage mechanics, and macroscopic (global) failure criteria. For quasi-static loading conditions the latter are the commonly followed method in design and analysis of composite structures. Under certain biaxial states of stress and under dynamic loading conditions available failure criteria and design guidelines are still not promising and fully reliable. These loadings are typically highly transient and the material and structural response occurs over very short (dynamic) time scales (of the order of milliseconds or microseconds). A servo hydraulic testing machine can be used to obtain quasi-static and low strain rates up to approximately 10 s^{-1}. A drop tower apparatus can generate strain rates between 10 s^{-1} and approximately 200 $s^{-1}$and higher rates up to and exceeding 1000 s^{-1} can be produced by means of a split Hopkinson pressure bar (or Kolsky bar) [1-3]. The absorbed energy with increasing strain rate also increases up to 62.4% .This increase in energy absorption is beneficial in applications of composite structures under dynamic loading conditions. The design and analysis of glass/epoxy composite structures based on the mechanical properties obtained at lower cross-head stroke rates leads to a conservative design. [4]. In dynamic loading, toughness and mechanical properties of composites are known to change and this places limitations on their performance. Translaminar fracture could occur when there is through-thickness damage in GRP laminated composites [5]. Some researchers have given explicit empirical relations for the rate dependence of these mechanical properties [2,6-7]. High strain rate studies by Daniel et al. [8] and Gilat et al. [3] through uniaxial tensile test methods have shown considerable increases in stiffness and strength of FRP composites with increased strain rate.

2. Tension behaviour at different strain rates

2.1 Glass fibre reinforced composites

Davies and Magee [9-10] investigated the effect of strain rates from $10^{-3}$to $10^{3}s^{-1}$ on the ultimate tensile strength of glass fibre/polyester composites. They reported the glass fibre/polyester composites to be rate sensitive with 55% increase in magnitude ofthe ultimate tensile strength over the given strain rate change. Rotem and Lifshitz [11] studied the tensile behavior of unidirectional glass fibre/epoxy composites over a wide range of strain rates from $10^{-6}$to 30 $s^{-1}$and reported that the dynamic modulus is 50% higher than the static modulus and the dynamic strength is three times higher than the static strength. However, for angle ply glass/epoxy laminates, Lifshitz [12] found that the elastic modulus and failure strain were insensitive to the strain rate and the failure stress in dynamic loading was only 20–30% higher than the failure stress in static loading. Okoli and Smith [13-14] investigated the effects of strain rate on the tensile, shear, and flexural properties of glass/epoxy laminate in the range of speeds from 0.008 mm/s to 4 mm/s. Their results were in agreement with the results of the studies conducted by Armenakas and Sciamarella [15] at various strain rates (0.0265–30,000 min^{-1}), that reported a linear variation of the tensile modulus of elasticity of unidirectional glass fibre/epoxy composites with the log of strain rate. However, with the increase in strain rate the ultimate tensile stress and strain of the composite decreased. An increase in tensile, flexural, and shear energy of 17%, 8.5%, and5.9%, respectively, per decade of increase inthe log of strain rate was reported [8]. Their study also indicated thatthere is a change in failure modes as the strain rate changes from quasi static to dynamic. Staab and Gilat [16-17] did a systematic study of the strain rate effects on the mechanical behavior of glass/epoxy angle ply laminated composites using a servo hydraulic testing machine for the quasi-static tests (approximately $10^{-5}s^{-1}$) and a direction tension split Hopkinson barapparatus for the high strain rate tests (approximately $10^{3}s^{-1}$). The tensile tests results at higher strain rates showed a marked increase in the maximum normal train and stress when compared to the values obtained in the quasi-static tests. Although both matrix and fibers are strain rate sensitive but they suggested that the fibers may influence laminate's rate sensitivity more than the matrix. Harding and Welsh [18-19] validated a dynamic tensile technique by performing tests (over therange 10^{-4} to 1000 s^{-1}) on glass/epoxy composites. The dynamic strength and modulus for the glass/epoxy composite were observed about twice the static value. Hayes and Adams [20] constructed a specialized pendulum impactor to study the strain rate sensitivity on the tensile properties of unidirectional glass/epoxy composites. The strength and modulus of the glass/epoxy composites were observed to be rate insensitive at impact speeds in the range of 2.7–4.9 m/s. Daniel and Liber [21-22] investigated the effect of strain rate (in the strain range $10^{-4}$to 27 s^{-1}) on the mechanical properties of unidirectional S-glass/epoxy composites and found that the tensile modulus and failure strength of the composites were rate insensitive. Kawata et al. [23-24] studied glass/polyester, and glass/epoxy composite materials under tension loading between the strain rate $10^{-3}$to 2000 s^{-1} and for both the composite systems they observed an increase in strength with increased strain rate. The effects of strain rate from 0.1 to 10s^{-1} on the tensile properties of glass/phenolic resin, and glass/polyester resin composites were studied by Barre et al. [25], and they also reported the increase in elastic modulus and strength with increased strain rate. Peterson et al. [26] investigated the tensile response of chopped glass fiber-reinforced styrene/maleic anhydride (S/MA) composite materials in the range of 10^{-3} to10 s^{-1} and observed a 50–70% increase in the strength and elastic modulus with increase in strain rate. The behavior of unidirectional glass/epoxy composite materials at quasi-static (approximately 0.001 s^{-1}) and dynamic strain rates (from 1 to 100 s^{-1}) were investigated by Shokrieh et al. [27] using a servo-hydraulic testing apparatus. The experimental results show increase in tensile modulus, strength, strain to failure and absorbed failure energy of 12%, 52%, 10%and 53%, respectively. For an increase in loading rate from static condition (0.0216 mm/s) up to a dynamic loading (1270 mm/s), the dynamic strength of glass/epoxy composites increases 1.5times with respect to the static strength.

2.2 Carbon fibre reinforced composites

Melin and Asp [28] investigated the strain rate dependence of the transverse tensile properties of a high performance carbon fiber/epoxy composite loaded in transverse tension. The specimens were tested under quasi-static and dynamic loading conditions (10^{-3} to $10^{3}s^{-1}$). The initial transverse modulus was found to decrease slightly with increased strain rate while the average transverse modulus was observed to be independent of strain rate**.** With increased strain rate the stress and strain at failure were found to increase slightly. Thus, it was concluded that when the carbon/epoxy composite is loaded in the transverse direction it can exhibited a weak dependence on strain rate. Harding and Welsh [18-19] studied strain rate sensitivity (over therange 10^{-4} to 1000 s^{-1}) on carbon/epoxy composites by tensile tests. The failure stress, modulus, and failure mode of the carbon/epoxy composite were observed to be strain rate insensitive. Daniel et al. [29] studied the dynamic tension response of unidirectional carbon/epoxy composites at high strain rates (up to $500s^{-1}$) using an internal pressure pulse generated explosively through a liquid medium. Tension test in longitudinal direction revealed that the modulus increased moderately with strain rate (up to 20% over the static value) but the ultimate strain and strength did not vary significantly. The strength and modulus increased sharply over static values in the transverse direction and the slight increase in the ultimate strain were noticed. There was a 30% increase in the in-plane shear modulus and strength. Hayes and Adams [20] also investigated the strain rate sensitivity on the tensile properties of unidirectional carbon/epoxy composites and reported that the strength and modulus of the graphite/epoxy composites decreased with increasing impact speeds. For unidirectional carbon/epoxy Daniel and Liber [21-22] found the tensile modulus and failure strength to be rate insensitive (in the strain range $10^{-4}$to 27 s^{-1}). Chamis and Smith

[30] and Daniel et al. [31] studied the mechanical behavior of unidirectional carbon/epoxy laminates at strain rates up to 500 s^{-1}. The tensile strength in the fiber direction was the same in static and dynamic loading conditions, confirming the results of Daniel and Liber [21-22]. The results also indicated an increase in the transverse tensile properties and shear properties with increasing loading rate. Chiem and Liu [32] studied the dynamic behavior of woven carbon/epoxy composites under shear and tensile impact loadings in the orthogonal direction using the torsional and tensile split Hopkinson bars at various strain rates, ranging from 500 to 3000 s^{-1}.The experimental results reported an increase in both the shear and the tensile strengths with increasing strain rate. Gilat et al. [33] investigated the tensile behavior of carbon/epoxy composites, using a hydraulic testing machine for the quasi-static and intermediate tests and a tension split Hopkinson bar apparatus for the high strain rate tests. Tensile tests were performed for fiber orientations of 90°, 10°, 45° and $[\pm 45°]_s$ at strain rates ranging from 10^{-5} to 650 s^{-1}. A significant increase in the stiffness was reported with increased strain rate in all of the configurations tested. For 45° and $[\pm 45°]_s$ layup configuration significant effect of the strain rate on the maximum stress was found while for 90° and 10° layup configuration a slight increase in the maximum stress with increased strain rate was reported. Further, the maximum strain at all strain rates in the tests with the $[\pm 45°]_s$ layups is much larger than in all the other types of test configurations. Daniel at al. [8] conducted Multi-axial experiments on a unidirectional carbon/epoxy material at three strain rates, quasi-static, intermediate and high, 10^{-4}, 1 and 180–400 s^{-1}, respectively. A Hopkinson bar apparatus is used and off-axis specimens loaded (to produce stress states combining transverse normal and in-plane shear stresses) [8]. The basic matrix dominated mechanical properties of the composite, including the initial transverse and in-plane shear moduli, E_2 and G_{12} , the transverse tensile and compressive strengths, F_{2t} and F_{2c} ,and the in-plane shear

strength, F_6 , were derived from the transverse (90°) and off-axis stress–strain curves are shown in table.[8]

Table1: Matrix dominated properties of carbon/epoxy material (AS4/3501-6).

Properties	Strain rate 0.0001 S^{-1}	Strain rate 1 S^{-1}	Strain rate 400 S^{-1}
Transverse modulus, E_2 (GPa)	11.2	12.9	14.5
Shear Modulus, G_{12} (GPa)	7.0	8.0	9.0
Modulus ratio, $\alpha = (E_2/G_{12})$	1.60	1.57	1.61
Transverse tensile strength, F_{2t} (MPa)	65	[80]	[90]
Transverse compressive strength, F_{2c}(MPa)	285	345	390
Shear strength, F_6 (MPa)	80	[95]	[110]
Strength ratio, F_{2c}/F_6	3.56	3.63	3.55

Note: Numbers in brackets denote extrapolated values.

Danial et al. [34] proposed strain rate dependent engineering failure criteria which can be easily implemented in design of composite structures undergoing small nearly elastic dynamic deformations.

Compression dominated failure:

$$\left(\frac{\sigma_2^*}{F_{2c}}\right)^2 + \alpha^2\left(\frac{\tau_6^*}{F_{2c}}\right)^2 = 1$$

Shear dominated failure:

$$\left(\frac{\tau_6^*}{F_6}\right)^2 + \frac{2}{\alpha}\left(\frac{\sigma_2^*}{F_6}\right) = 1$$

Tension dominated failure:

$$\frac{\sigma_2^*}{F_{2t}} + \frac{\alpha^2}{4}\left(\frac{\tau_6^*}{F_{2t}}\right)^2 = 1$$

where $\alpha = E_2 / G_{12}$ and

$$\sigma_i^* = \sigma_i \left(m_f \log \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} + 1 \right)^{-1}, \quad \sigma_i = \sigma_2, \tau_6$$

And symbols

M_f = 0.057, τ_6 = Shear stress, σ_2 = uniaxial stress normal to the fiber direction, $\acute{\varepsilon}_0$ = Reference strain (10^{-4} for quasi-static loading), $\acute{\varepsilon}$ = strain rate.

The measured strengths were evaluated based on classical failure criteria, (maximum stress, maximum strain, Tsai–Hill, Tsai–Wu, and failure mode based and partially interactive criteria (Hashin–Rotem, Sun, and Daniel) [34-37].

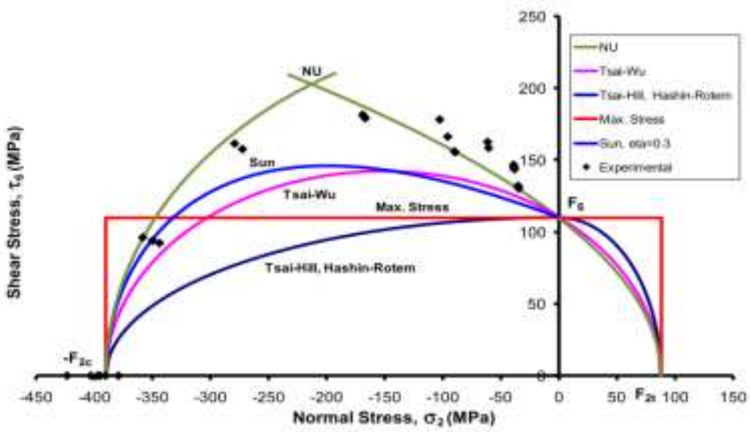


Fig.1. Comparison of theoretical failure envelopes and experimental results for AS4/3501-6 carbon/epoxy composite under high rate transverse normal and shear stress. [As per ref.8]

2.3 Kevlar fibre reinforced composites

Investigations of Daniel and Liber [21-22] on unidirectional kevlar/epoxy composites in the strain range $10^{-4}$to 27 s^{-1} showed a 20% increase in tensile modulus and failure strength in the fiber direction with increasing tensile strain further during transverse and shear (off-axis) loadings the increase in modulus and failure strength of the composite was 40% and 60%, respectively.

3. Compression behaviour at different strain rates

3.1 Glass fibre reinforced composites

Amijima and Fujii [38] investigated the effects of strain rate (from10^{-3} to $10^{3}s^{-1}$) on the compressive strength of unidirectional glass/polyester and woven glass/polyester composites and found that the compressive strength of both composites increased with strain rate. The increase in strength was also reported to be higher for the woven composites than for the unidirectional ones. Kumar et al. [39] investigated the dynamic compressive response of unidirectional and transversely isotropic glass–epoxy composites, using the Kolsky pressure bar technique for fibre orientations of 0°, 10°, 30°, 45°, 60° and 90° at an average strain rate of $265s^{-1}$. The compressive behavior of glass fibre/epoxy composites was found to be strain rate sensitive for all fiber orientations. Compared to quasi-static ($2\times10^{-4}s^{-1}$), the dynamic ultimate strength increased almost 100% for 0°, 80% for 10° fiber orientations and about 45%for all other orientations. Composite specimens of 0°orientation fractured along the fibers by tensile splitting, this can be attributed to the formation of transverse tensile strainsbecause of Poisson's effect under compressive loading. Specimens of 10°,30° and 45° fibre orientation fractured along the fiber mainly by interlaminar shear, although cracks resulted by a degree of tensile splitting were also observed on the surface of some of the specimens. They also noticed that the dynamic stress–strain curves are linear up to fracture for fibre orientation of 0° and 10°, and nonlinear for orientations greater than 10°. El-Habak [40] studied the compressive behavior of woven glass–fiber reinforced composites at strain rates ranging from 100 to $10^{3}s^{-1}$. The results indicated a slight increase in the compressive strength for all composite variables such as fiber volume fraction and fiber orientation. Their work was concentrated on the comparison of selected polymer matrix systems, namely polyester, vinyl ester, and epoxy. The highest strength was resulted from the composite based on vinyl ester matrix. An investigation into the effect of strain rate (in the strain range, 5×10^{-4} s^{-1} to 2500 s^{-1}) on pure epoxy resin and cross-woven glass–fiber reinforced epoxy under compressive loading was studied by Tay et al. [41]. The experimental results on the response of pure epoxy and GFRP revealed that both are strain rate sensitive, mainly in the low strain rate. A marked increase in the dynamic modulus was reported with increasing strain rate. It was observed that the stress-strain response under dynamic loading is a function of strain state and strain rate. Lowe [42] studied strain rate effects on transverse mechanical properties of T300/914 Carbon/Epoxy unidirectional composites at various strain rates in transverse compression tests. The experimental results indicated an increase in both transverse modulus and compressive strength with increasing strain rate. Vural and Ravichandran [43] studied the transverse failure behavior of thick unidirectional S2-glass fibre/epoxy composites at strain rates from $10^{-4}$to 10^{4} s^{-1}. Their experimental results indicated that the compressive strength increased with the increment of the strain rate. Tsai and Kuo [44] studied the effect of strain rate from $10^{-4}$to 500 s^{-1}on the transverse compressive strength of glass fibre/epoxy and carbon fibre/epoxy composites using a hydraulic MTS machine and a split Hopkinson pressure bar. For both composite systems, the transverse compressive strength was found to increase with increasing strain rates. Inspection of the compression failed specimens using the scanning electron microscope (SEM) revealed that for the glass fibre/epoxy composites, the main failure mode was due to the matrix shear failure, however, for the carbon fibre/epoxy composites, it was the fibre/matrix interfacial debonding, which might dramatically reduce the transverse compressive strength of the composites. Dynamic transverse lamina properties of unidirectional glass fibre/epoxy composites are extracted from tensile and compressive test results, using a high-speed servo-hydraulic machine by Shokrieh et al. [45]. For both the tensile and compressive loading cases, the obtained transverse lamina strength and modulus response show a clear strain rate dependency. For an increase in the strain rate from 0.001$s^{-1}$to 84 s^{-1}; there is an increase of 41.36% in tensile strength and 13.78% in tensile modulus. The corresponding values for compressive strength and modulus are about 31.37% and 23.36%, respectively. The transverse tensile failure strain shows an increase of 16% as the strain rate changes from quasi static to dynamic, while the transverse compressive failure strain decreases with increased strain rate. Khan et al. [46] investigated the effects of strain rate on mechanical behaviour of glass fibre/polyester and glass fibre/vinyl ester composites. Their results indicated that the in-plane strength and elastic modulus first increased with strain rate and then decreased significantly at higher strain rates. Delamination (progressive cracking between plies) resulted in low strength values and corresponding high values of strain at maximum stress. When the woven GRP composite specimens were loaded compressively in through thickness direction the strength increased by approximately 20% between strain rates of 0.1/s and up to 11.0/s, however, the strain at maximum stress and the modulus were found almost insensitive to strain rate. The translaminar fracture toughness of the woven glass fibre reinforced composite was found to increase linearly with loading rate, and was also found to be a function of the specimen thickness. At any given loading rate the thick specimens indicated higher value of fracture toughness than in thin specimens. For the given loading range, increasing the loading rate caused a 50% increase in fracture toughness in thick specimens, while, for thin specimens the increase was 38% [46].

3.2 Carbon fibre reinforced composites

Daniel and LaBedz [47] developed a test method to obtain compressive properties at strain rates upto 500 s^{-1}, utilizing a thin graphite/epoxy ring (6–8 plies thick) composite specimen. The 90° properties were observed much higher than static modulus and strength while some increase in initial modulus over the static values and no change in strength were observed for 0° properties. In all cases the dynamic ultimate strains were lower than the static values by 33%. Investigation of the effect of strain rate (over the range 10^{-3}–600 s^{-1}) on the compressive strength of unidirectional graphite/epoxy composite specimens by Cazeneuve and Maile [48] reported a 30% increase in the transverse strength and a 50% increase in the longitudinal strength. Montiel and Williams [49] determined compressive mechanical properties of AS4 graphite/PEEK cross-plied composite laminates for strain rates upto $8s^{-1}$. The results indicated that at strain rates of the order of $8s^{-1}$, the strength and strain to failure increased by 42%, 25%, respectively over the static values. But, only small strain rate sensitivity on the initial modulus was observed. Daniel et al. [50] studied the dynamic compression response of unidirectional carbon fibre/epoxy composites at high strain rates using an internal pressure pulse generated explosively through a liquid medium under longitudinal and transverse loading. In longitudinal loading up to a strain rate of 90 s^{-1}, they observed that the longitudinal modulus is 30% higher over the static value but the ultimate strain and strength were equal to or a little lower than the static values. In transverse loading the dynamic strength and modulus at 210 s^{-1} increased sharply over static values while the ultimate strain was lower than the static one. Woldesenbet and Vinson [51] studied the effect of specimen geometry with respect to the material properties at varying strain rates of between $4\times10^{2}$and $1.3\times10^{3}s^{-1}$ for unidirectional IM7/8551-7 graphite/epoxy composite. They investigated the effect of varying the length to diameter (L/D or aspect ratio) of the specimen, as well as the effect of changing from the more typical cylindrical to rectangular /square specimen geometry. The results indicated no statistically significant effect of either L/D or geometry for carbon/epoxy laminates tested at varying strain rates. Similar high strain rate properties for both types of specimen shapes were observed. Compressive failure properties of unidirectional glass/epoxy composites are studied at various strain rates from 0.001 to 100 $s^{-1}$by Shokrieh et al. [4]. The obtained longitudinal lamina modulus and strength properties showed an increase of approximately 53.4% and 66.9% in comparison with the measured quasi-static value, respectively. The absorbed energy with increasing strain rate also increases up to 62.4%. No significant change in the strain to failure were observed for the given strain rate range. Cazeneuve and Maile [52] studied of the effect of strain rate from $10^{-3}$to 600 s^{-1} on the compressive strength of unidirectional carbon/epoxy composite specimens and reported a

30% increase in the transverse strength and a 50% increase in the longitudinal strength. Hall and Guden [53] studied strain rate sensitivity of unidirectional graphite/epoxy composites using a split Hopkinson pressure bar at various strain rates up to 2000 s^{-1}. The results of their study indicated that in the transverse direction, as the strain rate changes from quasi-static to dynamic, the failure strength increased noticeably from 215 MPa to an approximately constant value of 360 MPa. The failure strain was almost constant at 5 ± 0.3%, and for the given strain rate range no significant change was noted in Young's modulus. Hosur et al. [54] studied the dynamic response of unidirectional carbon/epoxy composites under transverse loading using a modified split Hopkinson pressure bar set-up at three different strain rates of 82, 164 and 817s^{-1}. Their experimental results reported a 25–50% increase in the modulus and a 0.6–25% increase in transverse strength under dynamic loading as compared to static values.

4. In-plane shear behaviour at different strain rates

4.1 Glass fibre reinforced composites

The results of the researches by Harding and Welsh [18] on the -45° glass/epoxy composite and Staab and Gilat's [16] onthe ±45° glass/epoxy composite specimens indicated sensible increase of laminate strength with strain rate of the order of 1000 s^{-1}. The increase in laminate strength reflects to a large increase in the shear strength. Al-Salehi et al. [55] obtained the lamina in-plane shear properties at various rates of strain on glass/epoxy and Kevlar/epoxy filament wound tubes with winding angles ±55° and ±65°, for both, under internal hoop loading. The results obtained from±55° specimens indicated that with increasing strain rate from 0 to 400s^{-1}, the shear strength is increased by 70% for glass/epoxy, and 115% for Kevlar/epoxy materials. The results extracted from ±65° specimens were lower than the ±55° specimens. Tsai and Sun [56-57] studied the strain rate effect (up to700 s^{-1}) on the in-plane shear strength of unidirectional off-axis S2/8552 glass fibre/epoxy laminate composites using split Hopkinson pressure bar. The specimens were tested at fibre orientations of 15°, 30°, 45°, and 60°. They modelled stress–strain curves based on a viscoplasticity model established at the lower strain rate data. Further, this model is extended to high strain rates up to 700 s^{-1}[56]. The shear strain rate was also extracted from the axial strain rate by relating the effective plastic strain rate to the plastic shear strain rate on the basis of a viscoplasticity model [57]. The experimental results showed that, in all cases, the shear strength of the glass fibre/epoxy composite was quite sensitive to strain rate and the shear strength increased as strain rate increases.

In-plane shear failure properties of unidirectional glass/epoxy composites are studied at various stroke rates from 0.0216 to 1270 mm/s with high-speed servo-hydraulic tester by Shokrieh et al. [58]. The dynamic shear strength response showed an increase ofapproximately 37% over the measured quasi-static value. The shear modulus and shear strain to failure of the composite decreased with the increase in strain rate.

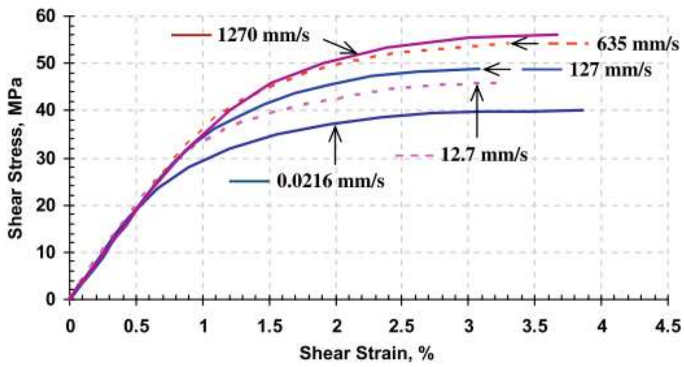


Fig.2. Typical in-plane shear stress–strain response of glass/epoxy composites under various stroke rates. (As per ref.58)

4.2 Carbon fibre reinforced composites

Daniel et al. [59] investigated the strain rate sensitivity on in-plane shear properties of carbon/epoxy composites upto 500 s^{-1}strain rates. The results indicated that the in-plane dynamic shear strength and shear modulus increased approximately 30% over static values. While, the dynamic ultimate shear strainwas lower than the static one. Hsiao et al. [2] studied the in-plane shear behavior of 45° off-axis unidirectional carbon/epoxy specimens using a split Hopkinson pressure barat strain rate upto 1200 s^{-1} and found that the dynamic shear strength increased sharply with strain rate by up to 80%. The initial modulus also followed a similar response with an increase up to 18%. Raju et al. [60] studied experimentally the in-plane shear responses of carbon fabric/epoxy and glass fibre/epoxy composites using a servo-hydraulic testing machine at nominal crosshead velocities ranging between $2.5\times10^{-5}$and 12.7 m/s. TheV-notch rail shear specimen configuration was used for characterizing the in-plane shear properties of the composite systems. During the tests, a maximum estimated shear strain rate of 500 $s^{-1}$was achieved up to shear strain levelsof 0.08 radians. The experimental results reported that at the highest strain rate, the shear strengths increased by a factor of three relative to that of the quasi-static rate, and were independent of the reinforcement type.

5. Epoxy

It is known that the tensile stress and yield stress of polymers are time dependent [61] and the fracture properties of epoxy resin are also expected to be time dependent. Low and Mai [62] studied the failure mechanisms of several epoxy polymers (including pure, rubber and particulate modified, as well as rubber/particulate hybrid epoxies) over a wide range of strain rates (10^{-6}–$10^{2}s^{-1}$) and temperatures (-80 to 60 °C). They found that the plastic induced crack blunting mechanisms resulted in the decrease of critical strain energy release rate with increasing strain rate. Morgan and O’Neal [63] investigated the relationship between the structure, the microscopic flow, and failure processes of diethylenetriamine-cured bisphenal-A-diglycidyl ether epoxies. The epoxy films deformed and failed by a crazing process, i.e.mirror-like fracture topography with fine fibrils for well-developed crazes, and coarse fracture topography with coarse fibrils for poorly developed crazes. D’Almeida and Monteiro [64] studied the topographic marks left at the fracture surfaces of epoxy resins with various resin/hardener ratios. For amine-rich (hardener-rich) compositions an unexpected deformation capacity was observed, and the development of a tear zone and striations were present on their fracture surface, while featureless fracture surfaces were observed for the epoxy rich compositions. Kanchanomaia et al. [65] studied the effects of loading rate on fracture behavior and mechanism of thermoset epoxy resin and found that the displacement to fracture continuously decreasedwith increasing loading rate and became stable after a rate of 100mm/min. The formation of a stretched zone, shear lips, crazing and crack blunting, i.e. localized plastic deformation processes, were prime damage mechanisms and resulted in the plane stress-dominated condition for specimens tested under quasi static loading rates, while brittle fracture and the condition of plane strain were dominating damage mechanisms for specimens tested under loading rate of10 mm/min or higher [65].

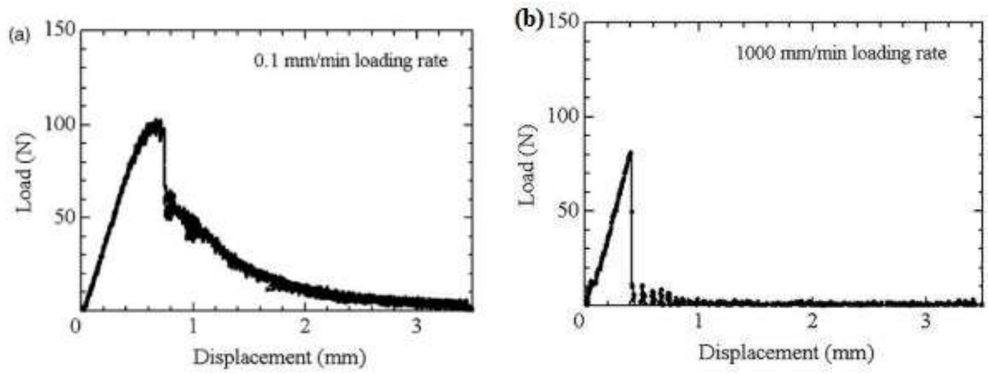


Fig. 3. Relationships between load and displacement of epoxy resin tested under (a) 10^{-1} mm/min loading rate, and (b) 10^{3}mm/min loading rate. [As per ref.65]

Under quasi static loading, it is observed that the matrixcracking growth rate depends upon the loading rate at temperatures of 110 °C [66] and 120 °C [67] or even at room temperature [68-69].

6. Interlaminar fracture behaviour at different strain rates

A number of studies [70-72] have reported that impact energies as low as two or three Joules are capable of generating extensive matrix cracking and delamination in brittle polymer matrix composites. Post-failure analyses of the fracture surfaces of many of these composite systems have highlighted the presence of extensive plastic flow within the polymer matrix material at quasi-static rates of loading [73-76]. Some researchers have investigated the effect of high loading rates on the interlaminar fracture properties of tough FRP composites [77-79]. Daniel et al. [77] conducted DCB and width-tapered DCB tests on a tough carbon reinforced elastomer-modified epoxy resin system. They observed that the mode 1 critical strain energy release rate decreased by roughly 20% over three decades of crack velocity. Gillespie et al. [78] studied AS4 carbon fibre reinforced polyetheretherketone (PEEK) over a range of crosshead displacement rates. At low loading rates, linear elastic behavior and stable crack propagation was observed. At higher loading rates, some non-linearity was observed in the load-displacement curves and crack propagation observed in an unstable stick-slip mode. In the process zone that develops in the crack tip region, effects of strain rates result in the stick-slip phenomenon. Friedrich et al. [79] presented a simple model to describe the translation of matrix properties to the interlaminar fracture toughness of a composite. They were highlighted a number of energy absorbing mechanisms, including matrix microcracking, localized plastic deformation, and crack bridging by fibres or fibre bundles. A number of studies have reported the influence of high loading rates on the mode II interlaminar fracture properties of fibre reinforced composite materials [73, 80-85]. Matsumoto et al. [73] utilized the curvature driven delamination (CDD) test to analyse loading rate effects in a glass fibre reinforced composite based on a polywbonate matrix. Their experimental results indicated that the values of G_{IIc} increased by approximately 22% over roughly three decades of loading rate. However, no explanation was offered to explain these effects. Smiley and Pipes [81] investigated a carbon fibre/PEEK composite over a wide range of loading rates and reported that the value of G_{IIf} decreased by approximately 85% at high loading rates. A subsequent fractographic analysis suggested that this significant reduction in toughness can be attributed to decreased plastic flow within the thermoplastic polymer. Maikuma et al. [82] observed pronounced rate effects on an AS4/PEEK composite during ENF tests. They found the values of G_I, increased steadily for crosshead displacement rates between 0.01 and 100 mm/min. Mode II interlaminar fracture tests on AS4 carbon fibre reinforced PEEK composite [86] have indicated that the mode II interlaminar fracture toughness of this composite systemincreases with increasing crosshead displacement rateand decreases with increasing temperature. Double end notch flexure geometry has been used to identify crack tip failure processesand shear yielding has been identified. For a cross-ply carbon epoxy (T300/914) laminate, Hallettet al. [87] observed some evidence for a small increase in both interlaminar shear strength and failure strain with increased strainrate and a small decrease in the through-thickness shearmodulus.

7. Loading rate sensitivity of environmentally conditioned FRP composites

Loading rate sensitivity of hygrothermally conditioned E-glass/epoxy and E-glass/unsaturated polyester composites were assessed by Ray [88]. For both the systems the interlaminar shear strengths (determined by short beam shear test) were higher at higher loading rate (i.e. 50mm/min).

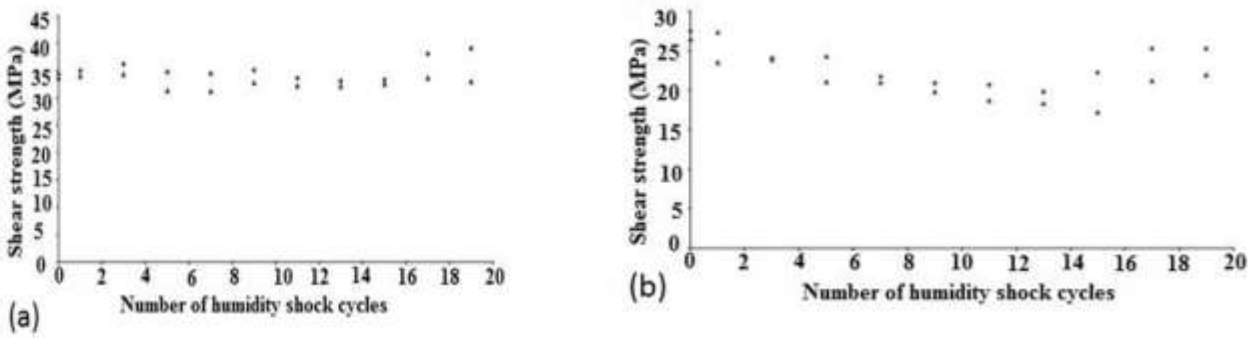


Fig.4. Variation of ILSS with number of humidity shock (at constant temperature) cycle at 2mm/min (▲) and 50mm/min (♦) crosshead speeds for (a) glass fibre reinforced epoxy (b) glass fibre reinforced polyester composites.

Loading rate sensitivity of ultra-low temperature conditioned (−40°C, −60°C, and −80°C temperatures) E-glass fibres/epoxy composites with 55, 60 and 65 weight percentages were studied by Ray [89]. They reported that the loading rate sensitivity of the polymer composites was appeared to be inconsistent and contradictory at some points of conditioning time and as well as at a temperature of conditioning. Phenomena may be attributed by low-temperature hardening, matrix cracking, and misfit strains. Loading rate sensitivity of reeze thaw conditioned glass fibre/polyester composite is also investigated [90]. Loading rate sensitivity is strongly evident at lower range of crosshead speed (0.5 to 50 mm/min) and Interlaminar shear strength (ILSS) values are found to increase in all situations with more loading speed in the range. Thereafter, the fall in ILSS value is observed with higher crosshead speed. ILSS of thermal shock conditioned glass fibre/epoxy composites has also indicated loading rate sensitivity when tested in short beam shear test at two different loading rates; viz 2mm/min and 10mm/min [91]. The ILSS values were higher at 10mm/min. The investigation on hygrothermally conditioned glass fibre/epoxy and glass fibre/polyester composite systems revealed that the ILSS of both the composite systems is strain-rate sensitive [92-93]. The strain rate sensitivity is less pronounced at higher conditioning times [92]. Freezing of absorbed moisture inside the composite leads to further damaging effect. These degradative effects of further freezing treatment are more evident at lower loading speed.The state of fibre/matrix interface after hygrothermal ageing may introduce more complications in evaluating the loading rate sensitivity of fibre reinforced composites.The effect of changing seawater temperature during immersion ageing of glass/epoxy and glass/polyester composites on ILSS has been shown by short beam shear test at two crosshead velocities;viz 2mm/min and 50mm/min [94]. The shear strength values obtained were higher at all points of the cyclic environment at higher crosshead speeds.

8. The effects of strain rate on damage mechanisms in FRP composites

On a macroscopic scale, fibre reinforced polymer composites are generally heterogeneous. Thus, unlike their metallic counterpart materials, composites have no single, similar self-propagating crack. Various internal material failure mechanisms may be observed separately or jointly in the damage zone, and may result in component failure [95] such as: matrix microcracking, Fibre breakage, fibre separation (debonding), and delamination. In composites, generally, the microscopic material response changes well before the macroscopic failure. Furthermore, it has been observed that the mechanical behaviour of composites not only depends on the constituents (fibre and matrix) properties, but also on the fibre/matrix interface/interphase. The interface transfers the load from the matrix to the fibres, which contribute the greater portion of the composite strength. Friedrich et al. [79] studied the strain rate dependent energy absorption mechanisms during interlaminar fracture of unidirectional carbon fiber reinforced epoxy and PEEK composites. The study has been carried out on double cantilever beam (mode I) and end notched flexure (mode II) specimens. The observed rate dependence is attributed to the rate dependent toughness of the viscoelastic polymer matrix and the size of the process zone around the crack tip. For different lay-up configuration in E-glass fibres/epoxy composites Tarfaoui et al. [96] have been described various damage modes at high strain rates (ranges from 200 s^{-1} to 2000 s^{-1}) as shown in fig 5.

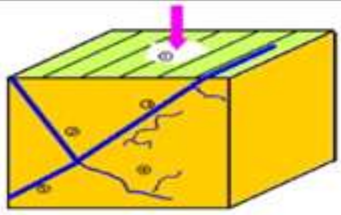
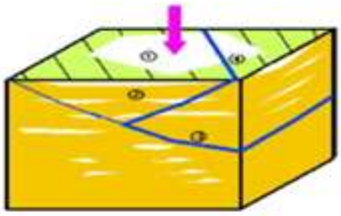
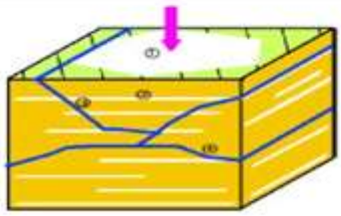
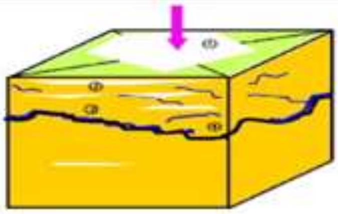
$[0/90]_{40}$		① : Crushing of the resin in contact with the incidental bar ② : Formation of damaged zone (V shape) ③ : "Macro"-cracks ④ : "Micro"-cracks ⑤ : Propagation of ② and ③ → Failure
$[\pm20/\pm70]_{20}$		① : Crushing of the resin in contact with the incidental bar ② : Layers crushing with plasticity (important crushing in the direction of the incidental bar - matrix cracks) ③ : Shearing through the layers – Macrocracks ④ : Cracks in the external layers → Failure
$[\pm30/\pm60]_{20}$		① : Crushing of the resin in contact with the incidental bar ② : Layers crushing with plasticity (important crushing in the direction of the incidental bar - matrix cracks) ③ : Shearing through the layers – Macrocracks ④ : Cracks in the external layers → Failure
$[\pm45/\pm45]_{20}$		① : Layers crushing with plasticity ② : Microcracks ③ : Macrocracks ④ : Propagation of ③ → Failure

Fig.5: Damaging modes for Out of Plane tests [96].

For short glass fiber reinforced poly(vinyl chloride) composites and neat resin, during the irreversible deformation of un-notched specimens Yuan et al. and Koenczoel et al. [97-98] have been shown that interfacial debonding is a time dependent process in this composite system, and the failure process is linked to the deformation rate through the viscoelastic response of the polymer matrix and interface. Kander et al. [99] has been shown that the "apparent" fiber-matrix interface properties of the glass/PP composite changed as a function of strain rate. These properties were closely related to the balance between the time scale of fiber pull-out and the characteristic time scale of matrix deformation.

The effect of loading rate on failure mechanisms was investigated by Okoli et al. [100] for woven glass/epoxy Tufnol 10G/40* composite laminate (fibre volume fraction 70%) and Warwick Manufacturing Group (WMG) random continuous glass/epoxy laminates with different fibre volume fractions (15.5, 20.7, 26.9, 38.0 and 41.2%). They reported that as the loading rate changes from quasi-static to high the failure mode in woven glass/epoxy composite changes from fibre brittle failure with fibre pull out, to brittle failure with considerable matrix damage preceding final fracture. Furthermore, the results of effect of volume faction of fibre on failure mechanism of random continuous (WMG) laminates shown that increasing the fibre volume fraction increased the likelihood of a matrix dominated failure mode as shown in fig.6 and fig.7. The laminate having lowest fibre content (15.5%) failed solely in a fibre dominated mode.

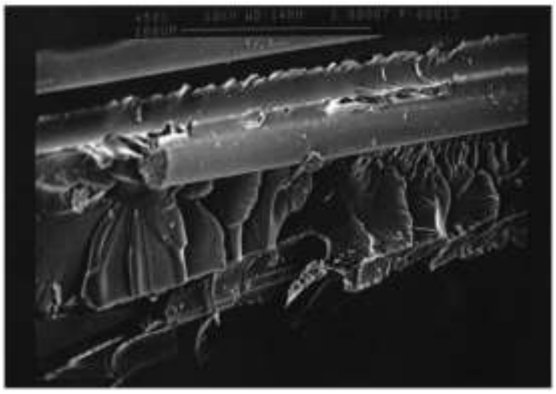


Figure 6: WMG Random Continuous Glass/Epoxy Laminates with 15.5% fibre volume fraction showing fibre pull-out with ‘smooth’ fibres, indicating fibre-matrix debonding. [100]

Figure 7: WMG Random Continuous Glass/Epoxy Laminates with 41.2% fibre volume fraction showing crack running through debonded matrix. [100]

To get an in-sight of various damage mechanisms inside the fibre reinforced composites some micrographs are provided which have been obtained by the authors during experimental investigations of synergetic effects of temperature and crosshead speed on the mechanical performance of woven fabric glass/epoxy, carbon/epoxy and, Kevlar/epoxy composite systems [unpublished work by B.C.Ray]. Fig. 8 represents the fracture morphology of glass fibre/epoxy composites, subjected to +50 °C temperature and tested with a 3-point loading fixture. For the specimen tested at 1 mm/min, extensive matrix crackings are evident from the micrographs (fig.8 (a)). For the specimen tested at 700 mm/min fibre imprints on the polymer matrix represents the interfacial debonding and separation of fibre from the polymer matrix (fig.8 (b)).

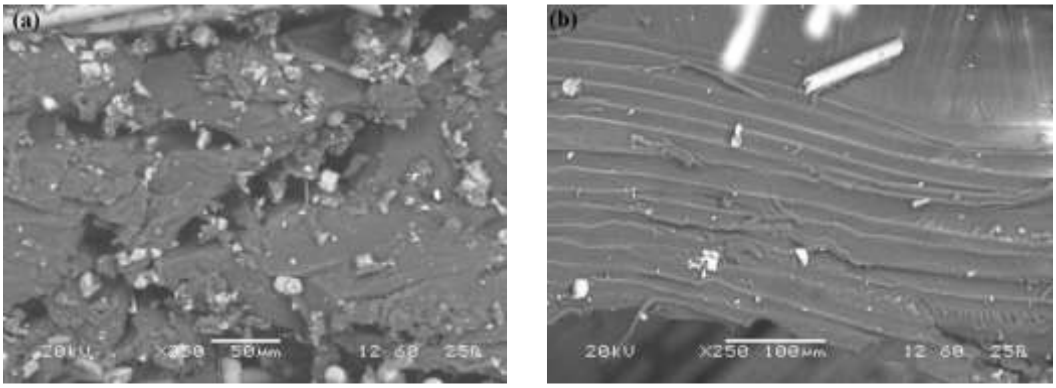


Figure 8: Glass fibre/epoxy composites in-situ tested at +50 °C temperature with a 3-point loading fixture (a) 1mm/min, and (b) 700 mm/min crosshead speed.

At low temperature (i.e. -50 °C) glass fibre/epoxy composite undergone fibre pull-out with significant shear yielding of matrix as revealed by the rows of shear cusps in the micrograph (fig. 9(a)) and extensive fibre pull-out for the specimen at 200mm/min (fig.9 (b)).

For carbon fibre/epoxy composite system the micrographs revealed the formation of voids and/or matrix microcracks at 1 mm/min (fig.10 (a)) and extensive damage in matrix at 700 mm/min (fig.10 (b))

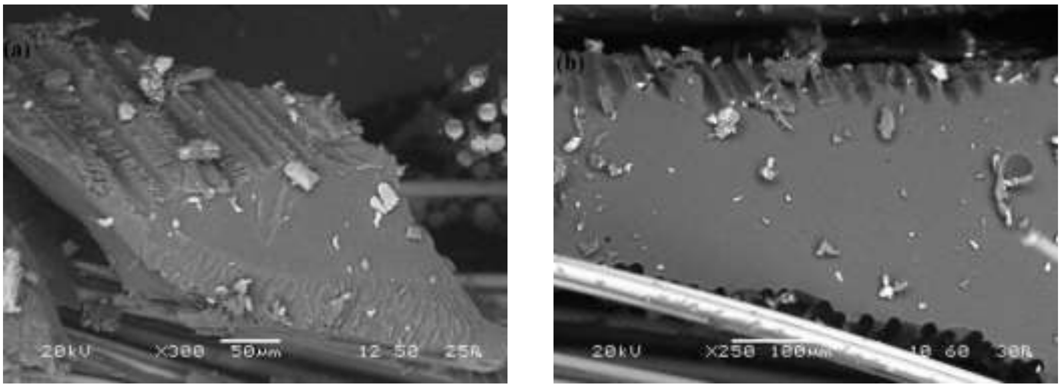


Figure 9: Glass fibre/epoxy composites in-situ tested at -50 °C temperature with a 3-point loading fixture (a) 100mm/min, and (b) 200 mm/min crosshead speed.

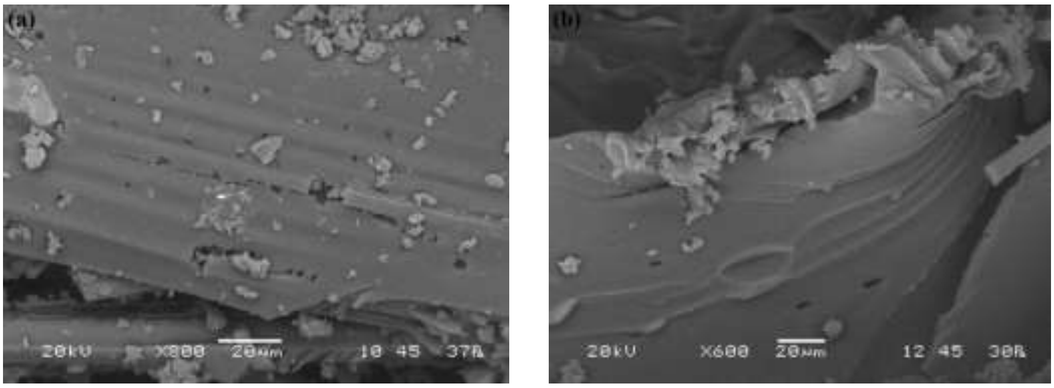


Figure 10: Carbon fibre/epoxy composites in-situ tested at +50 °C temperature with a 3-point loading fixture (a) 1 mm/min, and (b) 700 mm/min crosshead speed.

For Kevlar fibre/epoxy composite system generally the interfacial adhesion strength is lower as compared to glass fibre/epoxy and carbon fibre/epoxy composites. The micrographs for Kevlar fibre/epoxy composites are revealing mainly the matrix dominating failure modes in terms of matrix cracks (fig.11 (a) and fig.11 (b)).

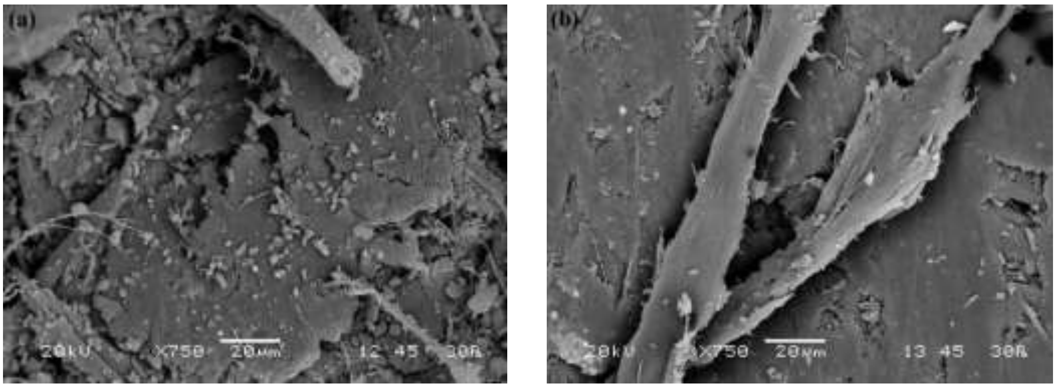


Figure 11: Kevlar fibre/epoxy composites in-situ tested at -50 °C temperature with a 3-point loading fixture (a) 1 mm/min and (b) 700 mm/min crosshead speed.

9. Damage resistance and damage tolerances

Damage-tolerant design criteria complies the use of FRP composites with greater safety and reliability. Damage resistance is the ability of the structure to resist damage initiation and/or growth under specific mechanical loading conditions and damage tolerance is the ability of the structure to resist catastrophic failure in the presence of cracks, or other damage, without being repaired, during their service life. Low velocity or low energy impact can result in invisible damage beneath the upper surface layer of FRP composite. These damages may act as a precursor for the growth of other damages that may result from mechanical loading or environmental variation. Designs which take damage-tolerance into consideration sometimes inevitably result in economical overload and hinder the full potential of FRP composite. Damage tolerance can be improved by using optimum laminate design, through thickness reinforcement, control of fiber/polymer adhesion, and insertion of interlaminar “interleave” layers. Under the exposure of different environments like high temperature, low temperature, hygrothermal, the common damages observed are surface oxidation, delamination and surface swelling. Delamination is one of the most frequent lives limiting damage mode observed in laminated composites because they can cause serious reductions in compression strength and are difficult to detect. During service, delaminations may develop due to the presence of excessive interlaminar shear stresses or through-the-thickness tensile stresses at:

free edges, holes, regions of section changes, and bonded joints [101-103]. However, the most important source whose probability of occurrence is high is "impact" for instance from stones thrown up from the runway or from dropped tools [104]. Impact event can cause a significant amount of delamination, but the indication of the damage is a very small surface indentation; thus damage of this type is often referred to as 'barely visible impact damage' (BVID) [104]. The problem of BVID is of particular concern because the damage cannot be discovered unless the region is subjected to non-destructive inspection (NDI), generally using ultrasonic procedures. In order to assess the impact resistant concepts in composites, the understanding of the processes by which the damage initiates and forms during the impact process is key a stage. The critical material parameters which govern the impact tolerance of aerospace skin-stringer composite panels are Mode I toughness (G_{IC}), Mode II toughness (G_{IIC}), Bending (D_{II}) and shear (G_{12}) moduli, Compressive and flexural strength (σ_c and σ_f). These parameters can be tailored novel material and processing concepts: Tougher matrix systems, Planar woven laminates, Unidirectional or non-crimp fabrics (NCF), Mixed-woven fabric laminates, Selective interlayers and hybrids, Three dimensional architecture, Stitching, Z-pinning, Protective layers [105].

10. Environmental instability of fiber/polymer interfaces

The fiber/polymer interfaces in composite materials play an important role to sustain the structural stability and integrity of the system. Thereby, under loading, its function is critical and decissive in stress transmissibility. The reliability and durability of the composite systems in the service life is linked to the health of interphase/interface. From the past few decades rapidly growing applications of FRPs have drawn significant attention of research communities over the world in tailoring well bonded and durable interfaces [106]. Many research activities have been concentrated in characterizing the molecular structure of the interphase rgion and its relation to mechanical and chemical stabilty [106]. It is reasonably assumed that the molecular structure in interphase region is dynamic in nature and, different from the bulk polymer matrix. Existence of chemical inhomogeneity in the interphase region provides an easy path of the system for becoming more susceptible to thermal, chemical, mechanochemical and thermochemical degradtions. Sometimes attraction and or migration of polar adherents of low molecular weight impurities from the bulk polymers onto adherents manifests a weak boundary layer having high crosslink density. This microstructural gradient in the interphse region might promote failure intiation or crack propagation through this weak layer of manifested boundary [107]. The degradation of fibre/polymer interface has been found to be the most detrimental on the properties and performances of FRPs. The precise mode of failure is a function of the status of environmentally conditioned interfaces and time of exposure, thus complicating the prediction of performances and behavior of polymeric composites. The interface is the most highly stressed region of composite materials. The various service environments may include high and low temperatures, high humidity, UV light exposure, alkaline environment and may be more severe if there is cyclic variation of temperature, hygrothermal environment and low earth orbit space environment. These environments are having deleterious and deterimental effects on the character and chemistry of the interface/interphase. At elevated temperature, differential thermal expansion of fiber and matrix can degrade the interface which leads to the lower interlaminar shear strength of the composite while embrittlement of polymer matrix at low temperature do not allow the relaxation of residual stresses or stress concentration and sometimes may results in larger debonded interfaces. Excursion to thermal fatigue may induce gross matrix cracking because of large misfit strain and the subsequent damage could usually be weaker interface and/or delamination. The failure mechanisms commonly attributed to fatigue are matrix crackings, fibre/matrix debonding and delamination Accumulation of moisture at the interface can modify the interfacial adhesion thereby affecting the mechanical performance of the FRP composites. Furthermore, swelling and plasticization of polymer matrix are amongst the worst consequences of moisture induced degradations. Prior cryogenic exposure might introduce interfacial debonding and/or matrix cracking which may result in greater percentage of absorbed water in a shorter time. The physical properties of polymeric materials depend severely on frequencies of excitation. Exposure to UV radiation may also leads to the degradation of the materials. The energy associated with the UV radiation is capable to dissociate the molecule bonds in polymer matrix. FRPs are promising materials for electrical insulators and mechanical supporters in the construction of superconducting magnets for fusion reactors. Exposure to such kind of applications the neutron and γ-ray irradiation may modify the structure and microstructure of polymer matrix. Most forms of high-energy radiation are deleterious to polymers because of the relatively low energies required to cause chemical damage. Molecular chain scission often causes a lowering of the polymer viscosity and softening temperature and reduction of mechanical strength, and in some cases, it may also lead, to an increase in the degree of crystallinity. The long-term effects of irradiation are almost always serious embrittlement of the polymer. Internal stresses are also developed which, in the presence of external loading and an aggressive environment, may result in rapid disintegration of the constituent materials [106].

11. Reasons and Remarks

The less substantial durability data related to the loading rate sensitivity of FRPs in conjunction with environmental exposures has created more confusion in using high factors of safety, and thus led to increased cost and weight of the composites. Further, dynamic characterization of FRP composites as a transversely isotropic material is cumbersome, expensive and needs special apparatuses. Thus, there is also an urgent need to develop precise micromechanics methods to predict the dynamic mechanical properties of composites. The endurance on durability and tailorability is most often underrated. Continuous crack growth usually occurs at low temperature and high strain rates, which promotes the brittle failure of the polymeric composite materials. Fracture energy (strain) can be significantly increased by yielding or other inelastic deformation at the vicinity of ambient temperature and above-ambient temperature. The precise mode of failure is a function of the status of environmentally conditioned interfaces and time of exposure, thus complicating the prediction of its performances and behavior. The interface is the most highly stressed region of composite materials. It's function is critical and decissive in stress transmissibility under loading. Many years of investigation have been concentrated in characterizing the molecular structure of the interface rgion and its relation to mechanical and chemical stabilty. The interface degradtion has been found to be the most detrimental on the properties and performances of FRPs. The micro changes in the interfacial region may manifest a substantial variation in mechanical response of FRPs under different loading rates. It is reasonably assumed, the molecular structure here is dynamic in nature at the interfacial area, which is different from the bulk polymer matrix [106]. The changes occuring at the interface are highly sensitive and susceptible to degradations under different environmental conditionings. The mode of failure depends on the strain rate, and the failure of composite appears at high strain rates primarily an interface-failure dominant mode while at low strain rates seemingly a matrix-failure dominant one. The perpetual growth of FRPs in its uses necessitates a pressing understanding of the theories and mechanisms involved in explaining the unpredictive variation of mechanical behavior with loading speed in wet and humid environments. The attributing factors in such non-linear behavioural pattern are so diversified and it is a challenging job to convolute all in making a reasonable and reproducible conclusions.

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