In-service Performance of Fiber Reinforced Polymer Composite in Different Environmental Conditions: A Review

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Abstract

FRP composite materials exhibit superior mechanical properties. The most promising properties include strength to density ratio, anti-corrosion property, high toughness and strength etc. During their service period they are exposed to various severe environmental conditions which include high temperature, low temperature, thermal shock, thermal spike, UV radiation, high humidity, sea water, alkaline fluids etc. The present review focuses on in-service performance of FRP composites in diversified environmental conditions as mentioned above. Subjecting the composite to high temperature may lead to significant mass loss and material shrinkage. Generation of residual stresses at low temperature accelerates delamination, debonding and matrix hardening. Thermal shock leads to sudden debonding of fibre/matrix interface due to catastrophic fluctuation in temperature. Decolourisation of composite is resulted under exposure to UV radiation. Moisture and sea water exposure cause swelling in matrix and thus modify the geometry of the composite.

Keywords: FRP composite, Thermal conditioning, UV radiation, Sea water, alkaline environment, Cryogenic exposure, Mechanical behaviour, Durability

Introduction

In the realm of science and technology of fibre reinforced polymer (FRP) composite materials, the overall properties of composites are recognised by fibre/polymer interface/interphase. Interface is a three-dimensional region between the bulk fibre and bulk matrix [1]. A region of finite thickness extending on both sides of the interface is also included along with the two-dimensional (2D) area of contact (interface) between the fibre and matrix. Atomic arrangement, molecular conformation and chemical composition influence the bonding between fibre and matrix. Further the morphological properties of the fibre and the diffusivity of elements in each constituent also have pronounced effects [2],

therefore between individual fibre/matrix systems there is unique interface. Various mechanisms which attribute fibre/matrix adhesion are adsorption, wetting, electrostatic attraction, chemical bonding, reaction bonding and exchange reaction bonding [2]. The behaviour and performance of advanced structural FRP composites accommodate influence of existing interface/interphase between fibre and matrix and also it cannot be explained in terms of specific properties [3], [4].

The use of them in various fields is assisted by mechanical properties like high strength to weight ratio, corrosion resistance, good impact resistance, better damping characteristics and improved fatigue properties. Every type of advanced structure is covered by FRP's widespread application spectrum. Variouscomponents in aircraft, helicopters, spacecraft, boats, ships, offshore platforms and also in automobiles, chemical processing equipment, sports goods, and civil infrastructure such asbuildings and bridges include their usage [5].During the service life all these components and structures are exposed to some environment. The environmental conditions can be high temperature, low temperatures, high humidity, UV light exposure, alkaline environment, freeze thaw, sea water exposure and may be more severe if there is cyclic variation oftemperature, hygrothermal environment and low earth orbit space environment.In these environments Polymer matrix composites are vulnerable to damage. The interfacial adhesion at fibre-matrix interface dominates the mechanical behaviour of FRP composites.Interface degradation can occur due to differential thermal expansion of fibre and matrix at elevated temperatureand thus leading to lower the interlaminar shear strength of the composite.The behaviour of most polymer matrix is brittle at low temperature and residual stresses or stress concentration is disallowed for relaxation. Large debonded interfaces are resulted at low temperatures by presence of residual stresses. The interfacial adhesion can be changed by the presence of moisture, hence affecting properties of FRP composites. The dissociation of molecular bonds in polymer matrix can be done by the energy associated with UV radiation and can degrade the materials.Polymer matrix composites are capable materials for mechanical supporters and electrical insulators infusion reactors for superconducting magnets [6]. They are vulnerable to keep their performance effectively even in harsh space environments despite of having a lot of positive aspects of utilizing FRP's in space structures. One of the frequent life limiting damage in laminated composites is delamination.There is significant improvement in polymeric mechanical properties by incorporating nano-sized second phase by proper load transfer at

the interface.The interfacial shear strength of nano-filler/polymer matrix will be dependent on property and structure of any interface region between bilk polymer resin and surface of reinforcement [7]. Healing capabilities of interface can be increased by the formation of reversible covalent bonds between the polymer network andthe reinforcement material hence resulting in improved lifetime of the composite [8]. During exposure of composites in sea water the degree of moisture induced degradation of the matrix and the fibre/matrix interface is highly dependent upon the composite system under consideration. The saturation moisture content is reduced by the presence of salt in conditioning bath when compared with distilled water. Present review focuses on different degradations and degree of damages under different environmental conditionings.Direct exposure to freeze thaw can lead to matrix micro-cracking in resin rich regions which frequently causes weak regional zones, Interface's role is necessary for understanding environmental conditioning of FRP composite system.

Effects of different environmental temperature events on FRP composites

High temperature

Exposure to high temperature results in problems like mass loss, shrinkageand degraded surface with surface micro-cracks and poor mechanical properties in case of polymer resins. The problem gets more complicated in case of FRP composites as cracking is further formed at the fiber/matrix interface. Thermally (or mechanically) induced intraplymicro-cracks are formed in the matrix material of composite laminates. These cracks provide further exposure to the interior of the material to external environment causing accelerated damage of the bulk material.Thermal ageing alone results in significant changes in the physical nature of the matrix, with the exception of a marked increase in the flexural properties at higher temperatures [9]Thermo Mechanical Analysis (TMA) of PMR-15 resin composites aged in nitrogen indicated a large increase in the glass transition temperature (a change of over 130°C after 24 hours ageing at 371°C) which is correlated with greatly improved mechanical properties at high temperatures.

Bowles [10] studied the effect of thermal aging on neat PMR-15 resin by exposing it to a temperature ranging between 288°C and 343°C for 3000 hours each. There is a continuous degradation at elevated temperatures due to several combined mechanisms resulting in mass loss, specimen shrinkage, formation of a distinct surface layer, development of surface micro cracks and degradation of mechanical properties. The extent of degradation is further

increased for PMR-15 composites at elevated temperatures[11]. Bowles et al. [12] reported combination of physical and chemical aging effects in a study of the effects of isothermal aging on the compression strength of PMR-15 composites. They are noticed at lower temperatures. The degradation in compression strength was attributed to physical aging effects, while at higher temperatures the loss in compression strength was shown to be directly related to the mass loss from the material. The values of compression strength with various specimen thickness again suggested that chemical change does not occur evenly throughout the entire volume of the material. However this effect could be structural, as specimen thickness is increased, change in failure mechanisms occur. Kamvouris et al. [13] found that both physical (reversible) aging effects and chemically induced (mass loss) effects occur during long term exposure at elevated temperatures and studied the feasibility of using shear stress relaxation for determining the extent of aging in PMR-15. The stress relaxation curves measured after aging at 316^{o}C for 800hrs could be shifted to form a master curve. The investigation revealed that the shift in stress relaxation curves and the extent of reversibility of aging effects can provide quantitative information about the physical and chemical aging which occured in PMR-15 at temperatures up to 316°C. Scott et al. [14]studied CFRP pultruded plate coupons that were tested at steady and transient states for temperatures range from approximately 20 to 700 °C. The tests showed that, for the temperature ranges 20–150 °C and 450–706 °C, reduction in tensile strength of the pultruded CFRP plate occurred. Between these temperature ranges, the tensile strength dropped a little while at 300 °C, the ultimate strength was approximately 50% of the room-temperature strength. In addition, the tensile strength of the plate was as low as 7% of the room-temperature tensile strength at the approximate peak temperature of 700 °C. Hanson [15] experimentally determined the strength and creep characteristics of PRD49 fiber in epoxy. In the range of temperature 20 to 477K they found the mechanical properties like tensile strength and creep. Tensile strength properties were generally retained to 450 K (350 F); however, at 477 K (400° F) the tensile strength was about 73 percent of that at 297 K (75° F). The tensile modulus showed no significant change at elevated temperatures; however, at 20 K (-423° F) the modulus increased by about 40 percent ascompared to the modulus at 297 K (75° F). In creep testing, the PRD49 fiber experienced an accelerated primary creep followed by a much lower secondary creep rate. At room temperature, the fiber exhibited a low secondary creep rate and sustained a tensile stress of about 80 percent of the ultimate tensile strength for 1000 hours without failure. Humidity caused a minor effect on creep behaviour of the fiber.

Low temperature

Some researchers have been attracted by the application of glass fibre /epoxy and carbon fibre/epoxy composite materials in low temperature i.e. cryogenic environment [16][17][18][19].Gong etal. [20]experimentally studied the behaviour of composite laminate at low temperature with the help of 2 types of specimen 1) E-glass fibre/epoxy reinforced laminate with fibre volume fraction of 0.4 and 2) carbon fibre/epoxy reinforced laminate with fibre volume fraction of 0.55 and made observations. Stress vs. strain graph shows linearity when exposed to low and room temperature and this extends up to failure. Brittleness is the failure characteristics found. As compared to the strength of laminates at 296K, the strength is higher at 77K for each tested specimen. The value for carbon fibre /epoxy is about 15-20% and it is 30-40% for glass fibre/epoxy. Hence there is an improvement in the properties of laminates at low temperature.At 77K the laminates have more damaged area around the notch tips as compared to the damaged area obtained at 296K.The micro rupture events are responsible for the damage area for example fibre rupture around notch tip, matrix cracking, fibre- matrix interface split, delamination etc. Some energy is dissipated by each micro-rupture event. Hence more the micro-rupture events, larger are the damage area and the large damage areas specifies that during tension, the dissipation of energy is high at 77K. For all the test cases the density of energy dissipation is larger at 77K than at 296K. The difference between the notch and lay up angle of laminates is dissimilar by the rate of rising. For un-notched unidirectional composites, the rate of rising of energy dissipation reaches 50% at 77K and over [20].There is a huge demand of polymeric composite material at various places like aerospace application, satellites automobile, heavy vehicles, sports goods, thermal insulation industry like hydrogen technology, cryostats etc. and sometimes used also in biomedical application like biomedicine for body implants and treatment of related issues [21][22]. Ray et al[23] used Araldite LY-556,an unmodified epoxy resin based on Bisphenol-A and hardener (Ciba-Geigy, India) HY-951 with woven E-glass fibres treated with silane based sizing system (Saint-Gobain Vetrotex) to fabricate the laminated composites and studied its effect on mechanical properties at low temperature. The conclusions were as: For all loading rates the breaking load for cryogenically treated laminate is maximum as compared to the breaking loads of untreated laminates. The reason is that at low temperature matrix phase gets cryogenically hard. There is freezing of polymer chains which leads to reduction in deformation process hence resulting in less polymer relaxation so gets hardened. The Scanning electron micrograph of matrix cracking at cryogenic condition i.e. at 77K is

shown in fig. 1.Differential thermal contraction between the fibre and the matrix during sudden cooling from room temperature to low temperature leads to the induction of residual stresses.There is increment in the breaking load with increase in cross head speed up to 50 mm/min and above it the load reduces. The high failure strain at low strain rate attributes the lower value of breaking load at low strain rates, hence with increase in speed the load increases. More time to failure is obtained by laminate at low cross head speed and thus resulting in more deterioration leading to low load bearing capacity. The curve is reverse above 50 mm/min speed of crosshead. Hence for failure to take place very less time is available hence the load behaves like force of impaction i.e. impact force. Hence there is no transfer of load from matrix to fibres leading to cracking in the matrix [23].

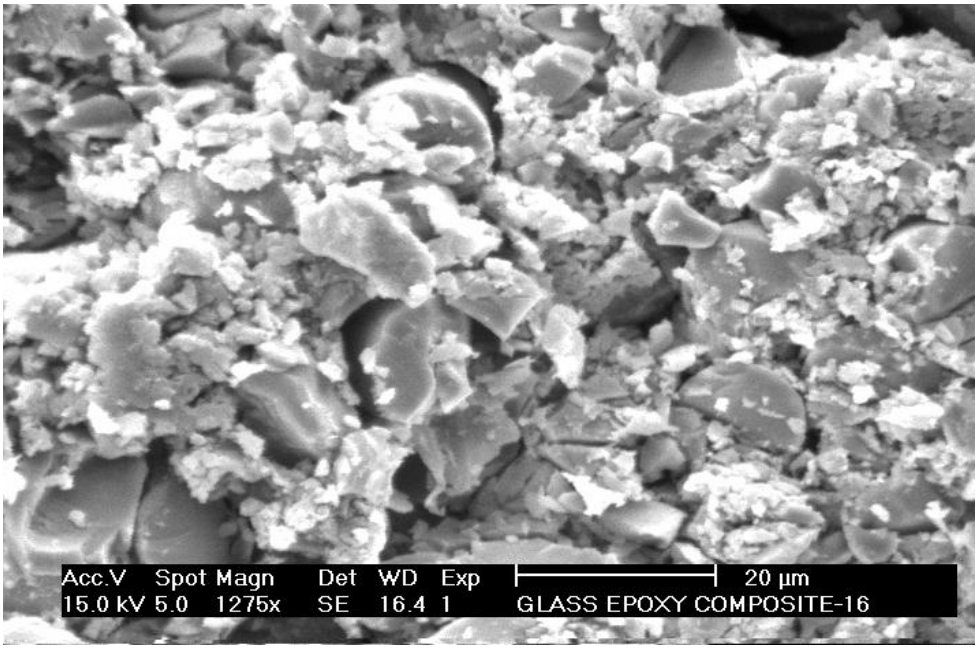

Fig.1Schematic of Matrix cracking at cryogenic temperature i.e.77K [23].

Since many researches have been done on low and high temperature exposure of hybrid composite laminate it is found that there is a considerable effect in impact behaviour [24][25][26][27]. Sayer et al. [28] studied the effect of temperature on hybrid composite laminate under impact loading and found following results: At room temperature the energy absorption capacity of hybrid laminate is higher as compared to other temperatures. Maximum values for impact characteristics are -20^{o}C or 60^{o}C and it is found that they are affected by temperature variations. The damage is concentrated at the impact contact point for low impact energies. The main failure mechanisms after this level are fibre breakage

through sample thickness and delamination expanding between the adjacent layers.Application of Polymer–matrix composites in aerospace and other applications involves the exposure of composites to temperature and humidity. There are many literatures that indicate that the physical and mechanical properties change to a considerable manner in this hygrothermal environment, hence reducing the overall composite's performance [29][30][31].Prasanth et al. [32] studied the Mode-I fracture Analysis of Thermally Aged of glass/epoxy and glass-carbon/epoxy Hybrid Composites and concluded the following: There is decrement in the energy release rate of glass epoxy aged specimen of about 10%-15% of the same material but in pristine condition and for glass carbon hybrid specimens the decrement is about 5%-10%. DCB (Double Cantilever Beam) test carried out on specimens conditioned at -20^{o}C for 500 hours shows that in case of glass epoxy composites, thedecrement in energy release rate is more as compared to the rate obtained for glass carbon hybrid composites[32].

Thermal shock

Thermal shock simply means a sudden change in temperature associated with the operative environment of any engineering and structural material. The fibre/matrix interfacial bonding is drastically damaged by the thermal shock conditioning[33][34][35][36][37]. An experimental analysis have been carried out on the effect of thermal shock on the interlaminar shear strength (ILSS) of thermally (at above and below the room temperature) conditioned woven fabric glass/epoxy and glass/polyester composites, which revealed that there is decrease in ILSS value with increase in conditioning time. But there is increment in shear strength for less conditioning time.

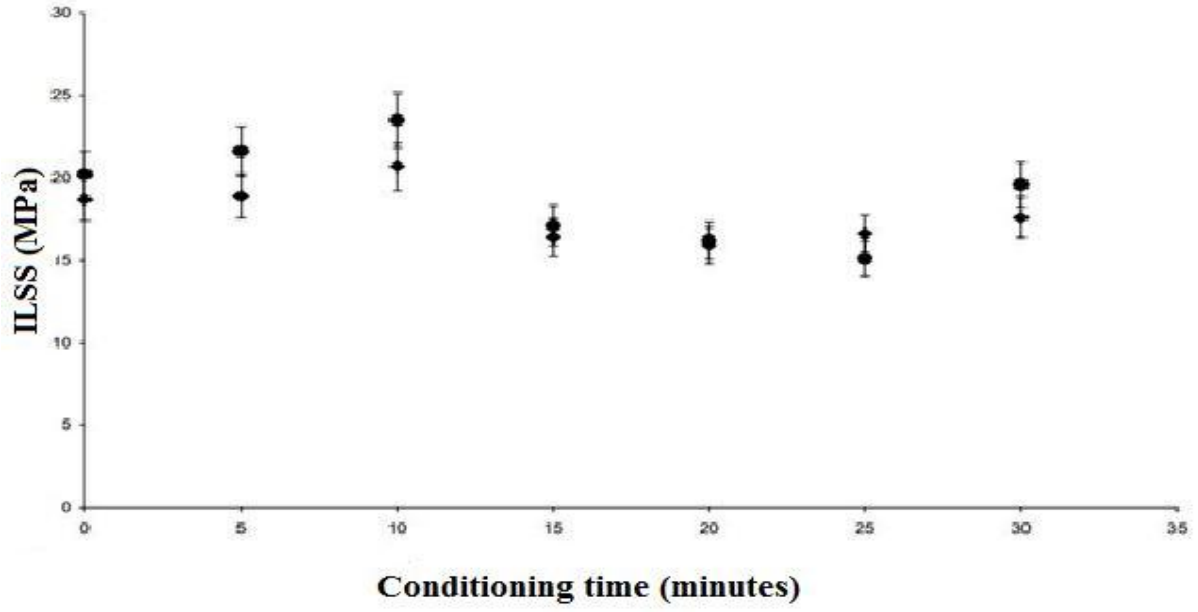

Fig.2 Effect of repeated thermal shock on ILSS value of woven fabrics glass fibre reinforced epoxy (•) and polyester (♦) matrices composites [38].

Fig. 2 reveals the effect of thermal shock cycles on ILSS value of the thermally (at above and below the room temperature) conditioned woven fabric glass/epoxy and glass/polyester composites for different conditioning times.The difference in thermal coefficients of glassand resins may lead to increase indegree of residual stress at the interface for the longer conditioning period. This probably results in better order involving debonding for the interfaces along with the decrease in ILSS values. Low energy deterioration because of the debonding device will depend on this interfacial relationship energy involving the fiber along with the matrix. Lower bonding strength may perhaps initiate a large fiber/matrix interfacial debonding. Interfacial debonding is usually expected to introduce this intralaminar crack initiation intended for composite made up of weak fiber/matrix interface bonds [38]. This indication involves advancement from the shear value for thirty minutes conditioning may perhaps be because of the increased cryogenic compressive stress due toadditional accessible time. Perhaps it will help in additional keying factor for the interface involving the fiber along with the matrix.

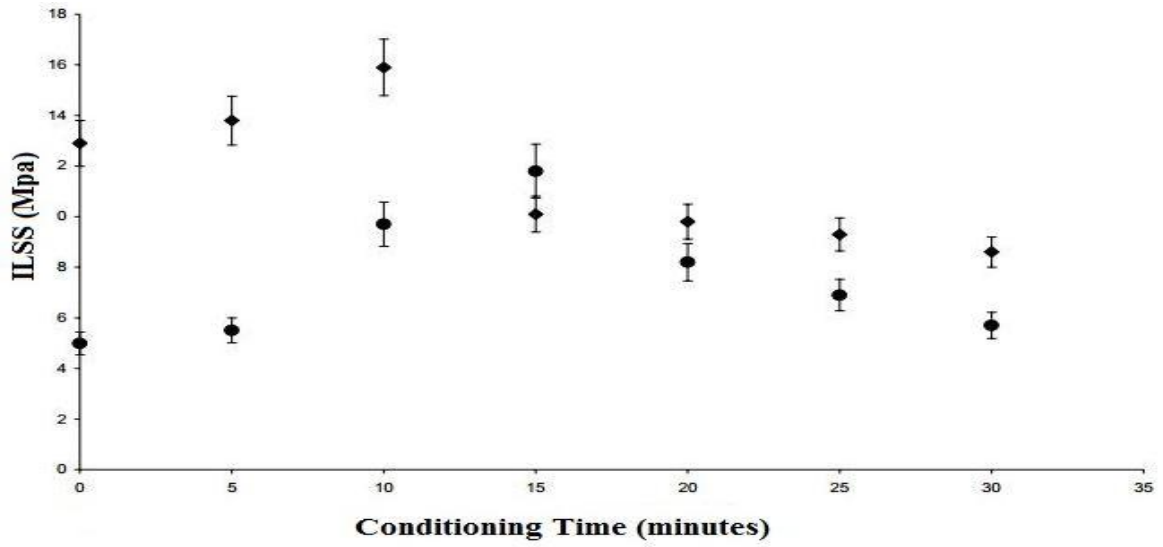

Fig.3 Effect of repeated thermal shock on ILSS value of random orientation glass fiber reinforced epoxy (•) and polyester (♦) matrices composites [38].

Fig. 3 reveals the effectof thermal shockof the ILSS valuesof the thermally conditioned specimens for the random glass fibers reinforced epoxyalong with polyester based composites. It will be noticeable that there is a rise throughout shear strength for less conditioning period. At 60°C temperaturethe conditioning may enhance fiber/matrix interfacial strength by surface area chemistry principle. This might be ruling in the de-adhesion effect associated with thermal shock for that less conditioning period. The more conditioning period might produce a larger thermal stress due to larger amountof mismatch involving the fiber along with resin. The actual debonding phenomena are more deteriorative for glass/polyester system due to the weaker interface. The idea can be related to the large curing shrinkage associated with polyester resin. The laminates having low bond strength displays significant areas of interfacial debonding that intensifies different destruction parts to advertise laminate failure. It must be famous that unmodified epoxy along with polyester resins could go through a limited magnitude associated with deformation before failure. Matrix cracking gets a macroscopic sort of destruction which may consequently lead to delamination failure. The actual interfacial connection in the epoxy laminates will be believed to be too high to be able to encourage comprehensive delamination [38]

The laminates with low bond strength exhibits large areas of interfacial debonding that intensifies other damage mechanisms to promote laminate failure. It should be noted that unmodified epoxy and polyester resins could undergo a limited extent of deformation prior to failure. Matrix cracking becomes a macroscopic form of damage that could subsequently lead

to delamination failure. The interfacial bonding in the epoxy laminates is believed to be too high to induce extensive delamination [38].

Thermal spike

Fibre reinforced polymer (FRP) composites are extensively used in aerospace structures and during flight they are usually exposed to kinetic heating. With very hot and moist conditions, FRP composite possess moisture.Existence associated with thermal shocks and thermal spikes guide to expansion associated with thermal stresses. This reputation of these stresses leads to matrix damage. In the FRP composite, this soluble fiber and the matrix have various coefficients of thermal expansions (CTE). This difference in CTE leads to debonding and finally delamination of the composite by simply interfacial failure. This shrinkagebaredby composites while in recovery leads to curing stresses. The high cross-linked networks have lower molecular mobility. The mechanical behaviour of these composites is different from the composites without any form of thermal conditioning [39]. The state on the composites will become more intricate as a result of the filling circumstances throughout their application. The bundled interactions of those elements cause destruction of mechanical attributes as well as succeeding fracture. The fracture amount of resistance of FRP composites may be described based on elongation of material. They will elongate in a stepwise manner because folded away domain names or loops are taken open. The molecular elongation is the key reason for toughness [40]. This phenomenon is actually associated with several concern with aerospace applications, through which rapid temperature variations may occur during take-off.

Freeze thaw

The effect of freeze thaw of polymeric composites at different loading rates at ambient and sub ambient temperature has been investigated in the current experimental method. The need of freeze thaw is the use of various structural components and lightweight materials in cryogenic applications. The experimental work is emphasised on the role regarding interface in freeze-thaw reaction at several rates of loading with varied percentages of constituent phases of polymer composites. It must be emphasised that the direct exposure of freeze-thaw leads to matrix microcracking in resin-rich regions that frequently causes regional zones regarding weakness. Most of these regional zones regarding weakness alters this fracture/ failure components in the loading process [41]. A final efficiency of a fiber-reinforced

composite is dependent on the fiber properties, resultant matrix properties and the character regarding fiber- polymer matrix interface [42].

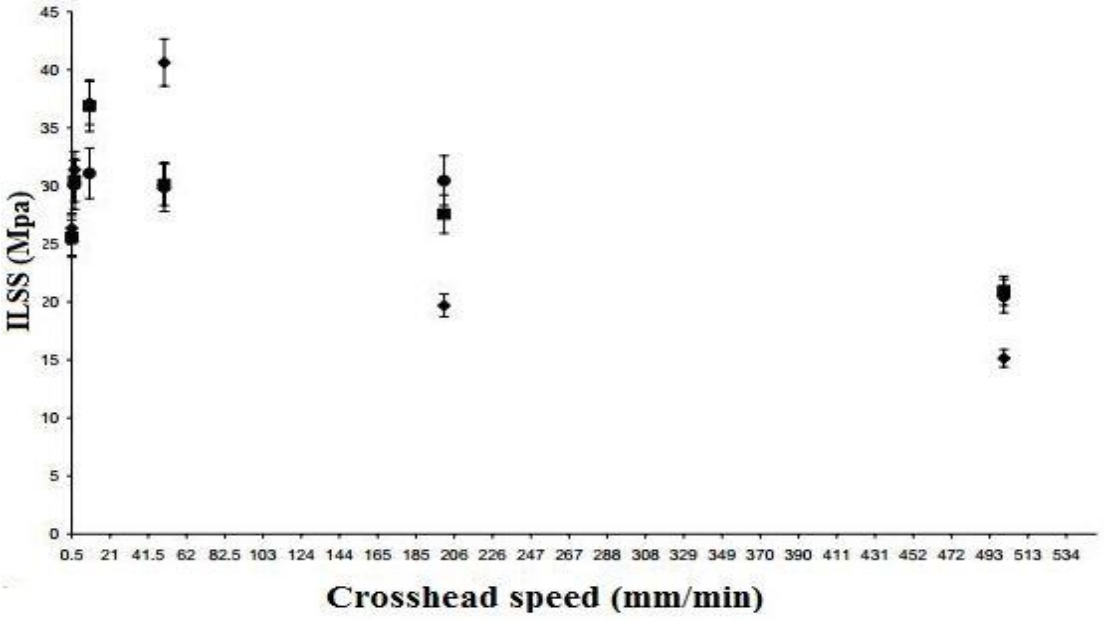

Fig.4 Variation of ILSS value with crosshead speed of ILSS of glass-polyester composites (fiber = 0.55 weight fraction) with crosshead speed at room temperature (●), thawing temperature (■), and cryogenic temperature (♦) [43].

Fig.4 reveals the effect of loading rate on ILSS value of glass/ polyester composites (0.55 fiber weight fraction) at ultra-low freezing temperature, at thawing temperature, and also at room temperature. It is clearly visible here that the nature of curves for all temperature differs from the others at over and below 50mm/min crosshead speed. The particular ILSS values generally increases at freezing along with thawing temperature in comparison with neglected trials upto concerning 50 mm/min crosshead speed. Most of these are caused by the actual cryogenic hardening connected with polymer matrix.

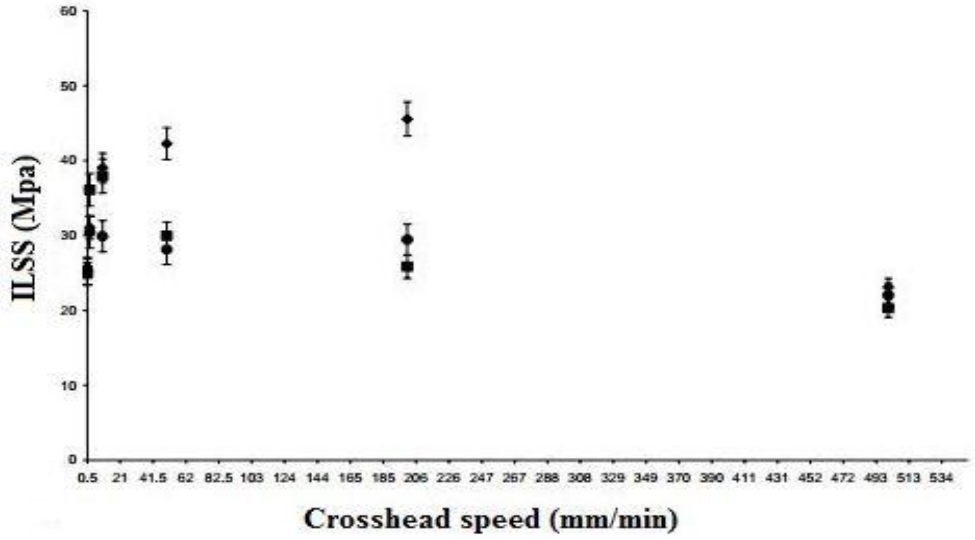

Fig.5 Variation of ILSS value with crosshead speed of glass-polyester composites (fiber = 0.60 weight fraction) with crosshead speed at room temperature (●), thawing temperature (■), and cryogenic temperature (♦)[43].

The percentage of matrix phase at this point is 45% by weight. A sharp and continuous decrease in ILSS value is observed for higher crosshead speed. Fig.5 reveals effect of loading rate on the glass/polyester composites (fiber 0.60 weight fraction). Here the variations in ILSS value for two types of situations are of different nature unlike Fig.4,the particular shear strength value at cryogenic temperature for all crosshead speedsusually increases as compared to some other conditions. The lower percentage of polymer phase in the composite is subjectedto have high percentage of damage during thawing by the effect of thermal shock. This reasonably explains the debonding of interfacial areas. The harder interfaces in composites are inclined to damage by means of thawing cycle. It is visible from fig. 5 that the ILSS values are generally low for all conditions at 500mm/min crosshead speed. The particular damage might feasibly always be faster as a result of weak fibre-polymer adhesion or improper/insufficient wetting. The effect of cryogenic micro cracking connected with matrix-fiber interface with damage mechanism is not firmly influenced at ultra-low freezing temperature. The different cross-link density connected with polymer chains can certainly develop an extremely non-homogeneous local stress field. FRP composites generally contain randomly spaced micro voids, incipient damage sites and microcracks with statistically spread styles along with information. For that reason, the local strength in the materials can vary in any arbitrary manner, therefore the failure sites do not coincide while using maximum stress location. The various damage mechanisms are time dependent processes. These

processes are reliable for the time sensitivity of the constitutive and fracture behaviour of the material [43].

Thermal Cycling

Ray [44] studied the effect of thermal and cryogenic conditionings on fiber reinforced polymer composites. The investigations were mainly concentrated on the debonding effect of different nature of thermal shock and strengthening phenomena of thermal conditionings. The study indicates that whenever specimen is exposed at down thermal shock from 40^0C to -40^0C there is slight improvement in ILSS value for less conditioning time. In case of longer conditioning time degradation effect is observed in ILSS value. The conditioning at -40^0C causes development of mechanical locking at fiber-matrix interface. For the short conditioning time, the mechanical keying factor dominates over the weakening effect of thermal shock. The cryogenic conditioning causes differential contraction and increment in the resistance to debonding by better adhesion at the interface [44]. The development of misfit strain at the fiber–resin interface occurs because of mismatch in thermal expansion coefficients of fiber and matrix [45]. Papanicolaou et al. [46] investigated the effect of thermal fatigue on the creep and recovery behaviour of polymer-matrix composites. For this investigation specimens were subjected to certain number of thermal cycles (from +50^0C to -20^0C). The results indicated that the strain response decreases as the number of cycles increases. Also the number of cycles increases, the difference in strain corresponding to successive number of cycles decreases tending to zero comparing two cycles 36 and 48 cycles.

Effect of vacuum thermal cycling

The particular carbon/epoxy composites can be employed upon structural elements for instance antennas, solar panels and also truss framework throughout aircrafts. During earth's orbit shadow areas are formed due to other planetsand any spacecraft travelling nearby experiences big change throughout its surface temperature from the range of -160°C to 120°C [47]. Since the thermal expansion coefficient associated with carbon fibres is usually less than that of the epoxy matrix, thermal stresses results from the composites under fluctuating temperature conditions, producing problem for the material like degradation in mechanical properties. Moreover, the particular carbon/epoxy composites tend to exhibit out gassing and mass loss effects under excessive vacuum (10^{-5} Pa) [48][49][50], which might result in contaminants around the external surface of spacecraft. For those previously mentioned

causes, it's associated with meaning to examine the particular behaviour in the carbon/epoxy composites under vacuum thermo-cycling for their application throughout spacecraft. The modifications throughout interlayer bonding and mass loss proportion associated with several polymer composites are researched under vacuum thermo-cycling [51][52][53][54].

The effect of vacuum thermal cycle on tensile strength at 90° (perpendicular to fibers) of the composite is revealed in Fig.6As the thermal cycle increases, the tensile strength decreases and tends to level off after 48 cycles.

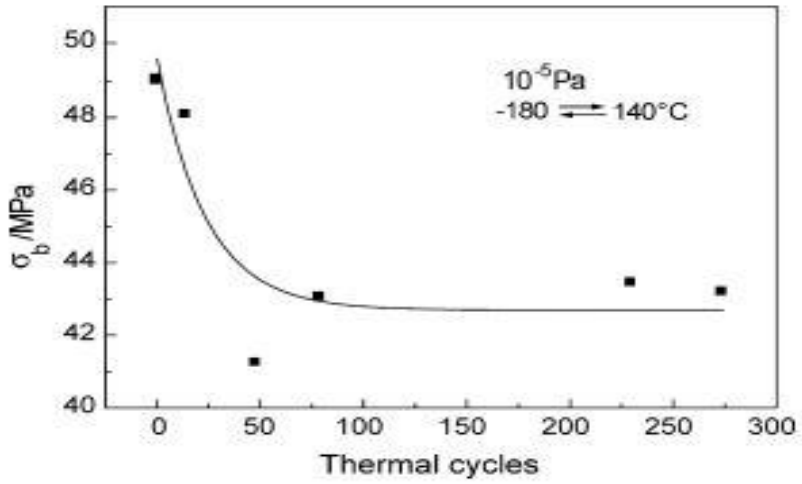

Fig. 6. The 90 ° tensile strength vs. thermal for composites [55].

Fig. 7(a) and 7(b) are SEM micrographs for 90°tensilesamples before and after vacuum thermo-cycling for 48 cyclesrespectively. The micrographs for the samples exposedto vacuum thermo-cycling for more than 48 cycles are similar to Fig. 7(b). It can be seen from Fig. 7(a) that some fibers are exposed with the epoxy resin adhesion, shown by arrow A. Also, some fibers without the adhesion can be observed, as shown by arrow B in Fig. 7(a). The typical fracture morphology of the epoxy matrix can be seen in the area shown by the arrow C. The above phenomena indicates that the fracture of pristine specimens mainly develops along the epoxy layers nearby interfaces.

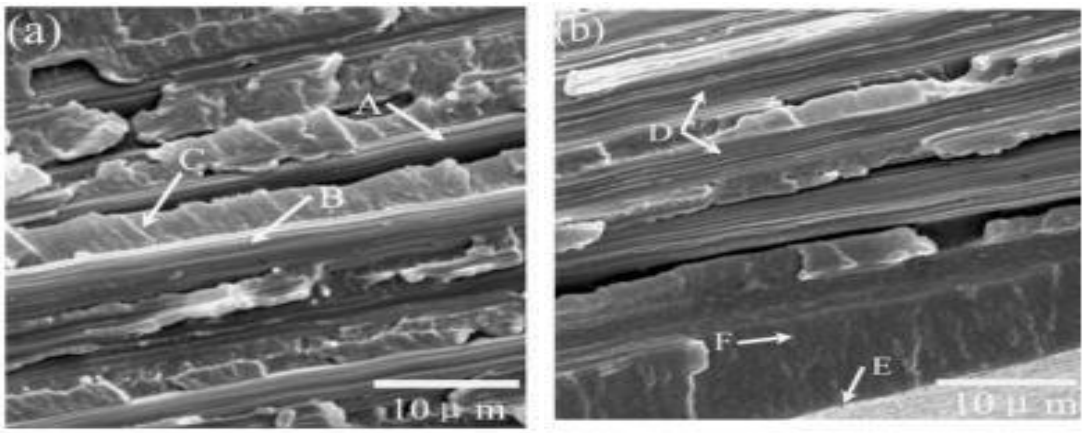

Fig.7 SEM micrographs showing the 90 ° tensile fracture for Composites before (a) and after (b) vacuum thermal-cycling for 48 cycles [54].

Fig. 7(b) shows that all the fibers are fully exposed on the fracture (as shown by the arrow D), almost without epoxy resin adhesion on them, showing an obvious characteristic of interface debonding. The fracture morphology of the epoxy matrix can be observed in the area indicated by F near the specimen surface (shown by arrow E).The extensive distinction in thermal expansion coefficients between carbon fibers and the epoxy matrix (more than a magnitude of order) will generate other thermal stresses through vacuum thermo-cycling. More often, the most extreme thermal stress exists at interfaces in between fibers and the matrix. The thermal stress including the residual stress formed by cooling after curing in the matrix could elevate to affect debonding of interfaces, prompting tensile strength with expanding thermal cycles. With further expanding the thermal cycles, the residual stress has a tendency to be reduced and the debonding region builds. Both the impacts will diminish the sensitivity of thermal mismatch at interface layers to the vacuum thermo-cycling. Also, the most maximum thermal stress at the interfaces may bring about cracks at a few deformities like debonded interfaces, impurities, pores in the epoxy matrix. Hence reducing the immediate damage to the well-bonded interfaces. Subsequently, the tensile strength has a tendency to level off after a certain thermal cycle.

Effect of Humidity

There has been a various debate made by numerous researchers in the last few years, to assemble a highly required relationship between the mechanical property of the material, and the humid environment.The main centre of attention of assessment has been concentrated to comprehend the change that takes place at the holding interface between the fiber and

matrixas it is of prime criticalness because of its connection to the stress transfer, and distribution of loading. It additionally governs mechanism of propagation and damage accumulation. Numerous procedures have been developed to get such interfacial properties. Tensile testing properties, interlaminar shear stress (ILSS) are determined by three point bending test giving a decent record of this at a mass scale.

Integrity of the composite structure is mostly selected by the adhesion attributes of the fiber and the matrix. Numerous endeavours are made to create procedures to measure the fiber-matrix bond level [55] for last few decades. The past researchers have revealedthat the degradation of mechanical properties has shown itself through the decline in strength at the fiber-matrix interface, which offers rise to the degradation of the material[56]. As demonstrated in the fig.8 (a), the minimum temperature occurs at night as compared to the normal least temperature around evening, the ascent demonstrates the day time rise in temperature, the level for the time during the whole day and bringing down the temperature during evening. Conditioning of composite structure in oceanic situation has likewise been recreated [57] which concentrates on the impact marine parameters on the structural trustworthiness of the composite. This environmentalcondition influences the dampness retention in composite structures in its own particular extraordinary way that incorporates a certain level of stress inside itself, the impact of which is to be basically considered.

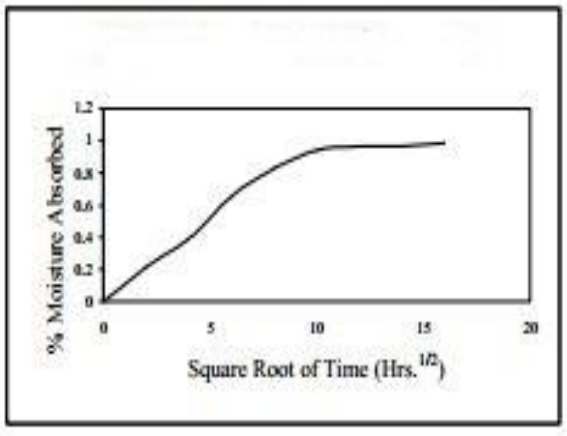

Fig. 8 (a) Effect of time on moisture absorption [57]

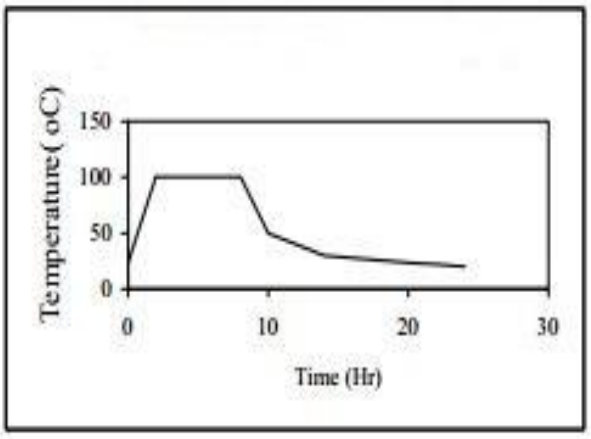

Fig.8 (b) Simulation of accelerated thermal cycling [57]

It is examined that at humid conditions thereis degradation in the mechanical properties of the composite under solidified conditions. In this way, the impact on ILSS values were recorded for both plain and frozenhumidity under same level of humidity content, and were plotted against the square foundation of the introduction time fig. 9 (a). As demonstrated in the figure, in the starting time of conditioning, the shear strength of the samples with frozen

humidity was lower than that of plain humiditysample with the same time of conditioning. This may be because of the expansion in swelling stresses due to volume expansion at the time of freezing. The starting exemption may be because the composite was not strained, as the swelling stresses were created because solidification of humidity have discharged the residual strains incorporated at the time of cooling of the composite from its curing temperature [58].

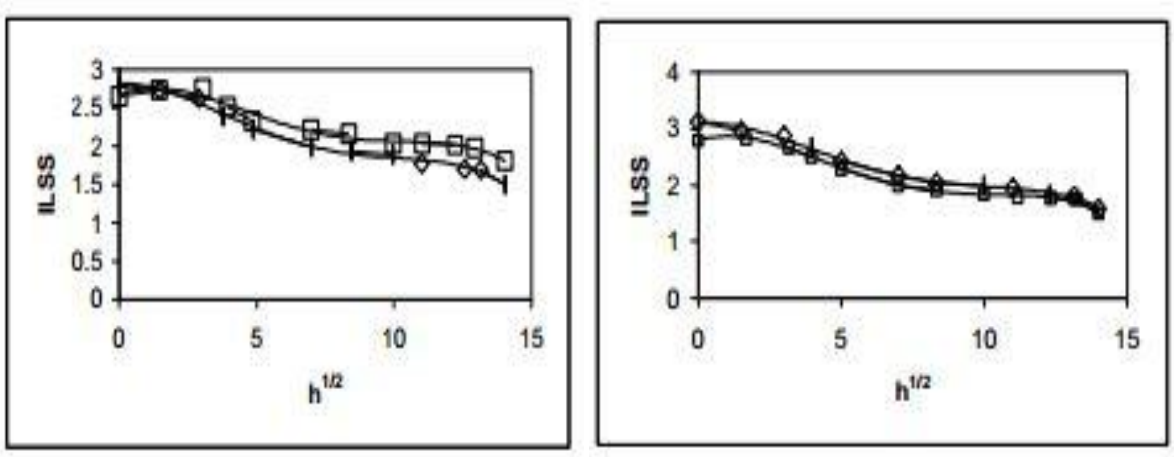

Fig.9 (a) Effect on ILSS values for composites exposed to both plain and frozen humidity [58].

Fig.9 (b) Effect of conditioning time on frozen composites for different crossheads speeds [58].

Fig.9 (b) demonstrates the impact of loading speed on the ILSS values of frozen moist composites, plotted against the square foundation of molding time. The general nature of the graph demonstrates that the ILSS values for the lower loading speed are lower than that for the higher loading speed for the same time of conditioning. The more unfavorable impact for the lower loading speed may be because of the more prominent time accessible for the retained humidity to diffuse through the debonded spaces into the stress concentrated region, hence creating additional decay of the fiber-matrix interface and/or matrix itself at the time of the testing.

Effects of Ultraviolet Exposure on Composite

Specimens were prepared of glass/epoxy composite and were cut to shape according to the ASTM standard for Compression test, tensile test and shear test as in fig. 10. All were tested for exposure to UV light for specific amount of time.Shokrieh et al. [59] studied the effects of ultraviolet radiation on composites and gave the following results:

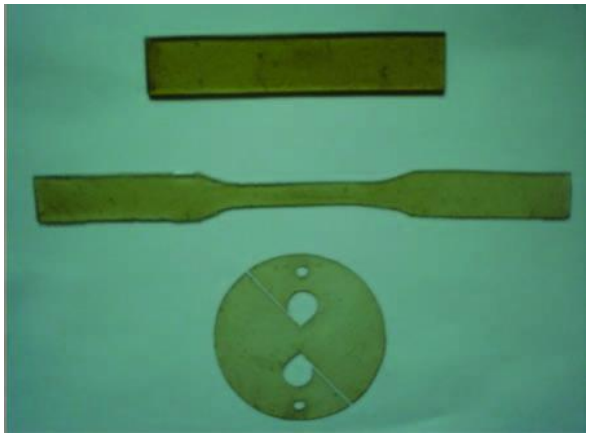

Fig.10 Schematic of compression test, tensile test and shear test specimens [59].

On carrying tensile test after 100hrs exposure of UV light on the samples, it was found that there was 34.8% drop in tensile strength, 18.9% drop in tensile modulusand 15.2% drop in failure strain. Also such high drop in failure strain confirmed that thecomposite behaved as a brittle material. The Shear Test carried out for 100hrs of exposure of UV light brought about 18.8% drop in shear strength and 25.4% drop in shear modulus. After performing the compression test, it was concluded that the exposure of UV on composite had no effect on the compressive properties and they remained the same.The above mention tests were carried out on unidirectional laminates.Glass/polyester specimens having $[0/90]_s$ fibre orientation were made and conditioned in a chamber and were exposed to Ultraviolet light under intensity of 800 W/m^2 from both sides at 30℃ and 5.66% reduction was found in E_1^0 modulus and 23.7% reduction was found in E_6^0 modulus.From the experiment it was found that for the samples which were tested for less than 40hrs, there was not much change found in mechanical properties like tensile and shear strength. A much significant change was found when the same were exposed for more than 40hrs.When unidirectional ply laminate was exposed to UV light, a change was observed in transverse modulus instead of change in longitudinal direction. The load carrying capacity of the fibre are in their loading direction. It is found that the longitudinal modulus is not affected by change in resin properties[59]**.**

The polymeric resin matrix is discoloured and hardened by the Ultraviolet radiation. Only the skin of FRP laminate is degraded as there is screening effect on thematerial although topcoat delamination may result. The degradation effect on the mechanical properties is less for a thick composite. The associated degradation can be tactically eliminated or slowed down with the help of Ultraviolet resistant coating. For polymers, the oldest form of UV protection materials are the UV screeners made from material like carbon black and titanium dioxide. Absorption of light and increase in photo stabilisation are the main role of UVprotection

materials. Light stabilizing oxidants which include hindered amine light stabilizers (HALS), are used to terminate the free radicals obtained from bond breakage due to absorption of unreleased energy. They retard thermal oxidation. UV protection effect is obtained by the combination of UVA and HALS.

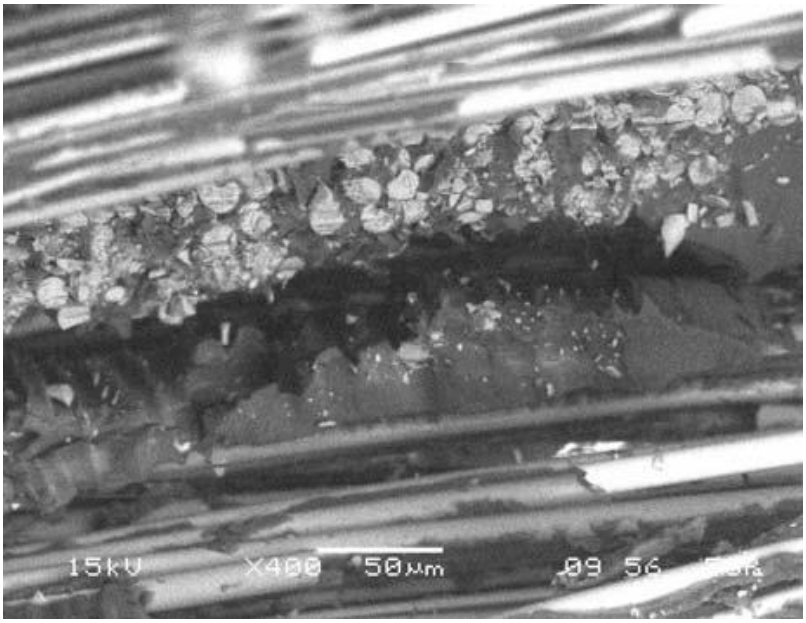

Fig.11 Scanning electron micrograph of the deformation which occurred in the matrix due to crack propagation and hence leading to matrix failure. [60].

The specimens that were subjected to UV light started decolourizing after 100hrs of exposure and finally turned yellow. There were no signs of chalking of matrix or fibres that were exposed to the surface of the composite. Scanning Electron Micrographin fig. 11 showsthe detachment of fibre matrix interface. Also micro-cracks were observed in the matrix which then propagated through it and caused matrix failure, hence caused composite failure at high exposure time [60].

Signor et al.[61] studied the effects of ultraviolet radiation exposure on vinyl ester resins & characterization of chemical, physical and mechanical damage and came to the conclusion: Below shownin fig. 12 are the Stress–strain curves for specimens which were tested at 0 hrs, 1000 hrs and 4000 hrs of exposure in UV light. Ductile behaviour, a proper yield point and a small amount of plastic deformation were obtained for the sample which was not exposed to UV light. After 1000hrs of exposure, small but notable changes were recorded in the tensile properties of the materialand the curve still indicated yielding and plastic deformation. There was a transition from ductile to brittle observed after 4000hrs of irradiation.

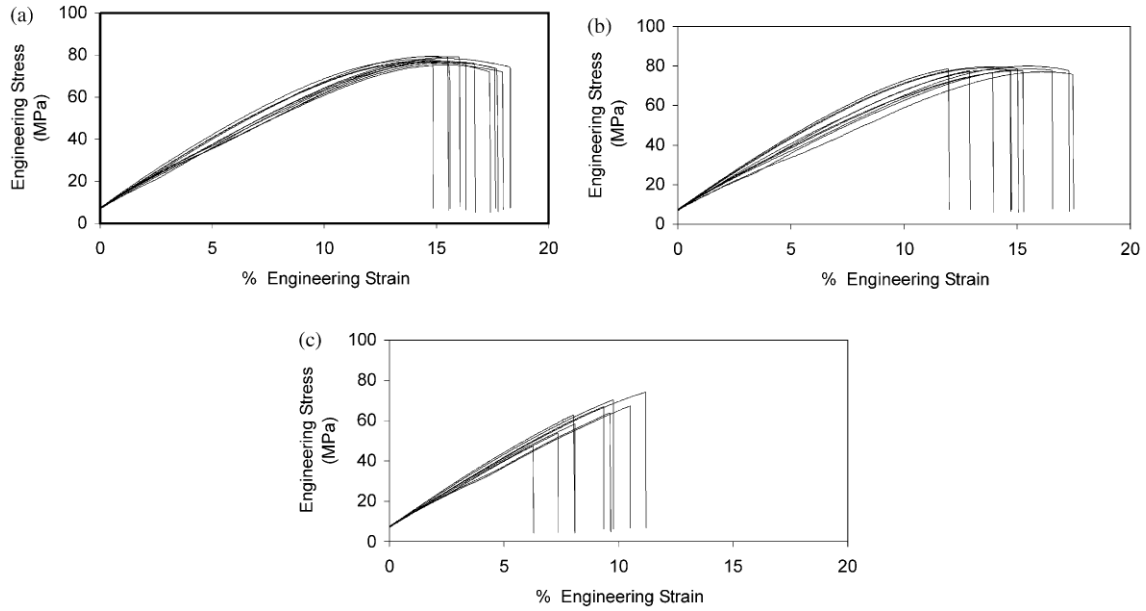

Fig.12 Stress–strain curves for vinyl ester exposed to Ultraviolet light for (1) 0 h, (2) 1000h and (3) 4000 h [61].

There was a drop in ultimate engineering strain from 16.7% to 14.9% for unexposed sample after 1000hrs of exposure and after 4000hrs it was 8.9%. Similarly a drop was also observed in average specific toughness (total energy to break/unit cross-sectional area)from 1.4 kg mm/mm^2 for the unexposed material to 1.2 kg mm/mmafter 1000 hrs of exposure and 0.56 kg mm/mm^2 after4000 hrs. Thus, after 4000 hrs of exposure, the strain tofailure decreased to approximately 40% of the originalvalue and the specific toughness decreased to approximately60% of the original value. As aresult of increased UV exposure changes in tensile properties suggest that there is transition from ductile to brittle.In Ultraviolet induced degradation,specific toughness andultimate strain were found to be much subtle. The energyrequired for nucleating a crack and making it propagate through the material were noticeably reduced by generation of defects on thin surfacelayer. Thus, this change in the bulk properties is responsible for changing the mechanical properties of ultraviolet treated surface layer which has degraded. Many researchers have noted that any simply formed surface crack found in UV degraded polymer is ultimately decreasing the polymer's mechanical properties [61]**.**

Combined exposure of UV and humidity

Fiber-reinforced thermoplastic composites in open air applications experience encompassing moisture and ultraviolet (UV) radiation in accumulation of stress and temperature, which influences mechanical properties. In polymer matrix composites, these variables cause damages and influence their long-term quality. The degree of susceptibility shifts with every polymer, depending upon its principal functional group. But in some cases, moisture absorption and UV radiation are gainful like moisture absorption in polyamides expands their impact strength, and ultraviolet exposure may expand the strength if local crystallinity accumulates [62].

Numerous analysts have analysed the effect of moisture absorption in fiber-reinforced polymeric composites. Past studies report fiber matrix detachment [63] and micro-cracking[64] that eventually cause a decrease in elastic modulus and tensile strength. Conversely, different studies report hygrothermal introduction to relax the processing-induced residual strains [64]. On the other hand, some studies have shown decrease in Tg (Glass transition temperature) for thermoplastics [65] .

Effect of Alkaline environment

Some researchers have studied the environmental and chemical degradation of Fibre/epoxy based composites which were made to be used as lap joints.The exposure environment is mainly of water, saline water, jet fuels, anti-icing agents, alkaline water, organic fuel etc.[56][66].The lap joint was prepared with 120 mm gauge length, 25.4 overlay areaas recommended by ASTM D5868-01. Hysol EA 9360 was used as adhesive. The specimens were soaked for 243hrs in humidity of 100% RH environment in (a) fresh water, or (b) jet fuel, (c) Skydrol500B hydraulic fluid, and (d) anti-icing fueladditive. Sugita et al. studied the Environmental and chemical degradation of carbon/epoxy lap jointsfor aerospace applications and their mechanical performance. The study concluded that the adhesive is damaged by the hydraulic fluid and fuel additives. The damage caused to the adhesive at temperature greater than room temperature has a sudden effect on its tensile strength and hardness.The flammability potential is affected by this exposure. On performing gravimetric test on the specimens, changes were observed in mechanical properties, colour, microscopic features, mass etc. The anti-icing additives affect the carbon/epoxy weave at a less rate.

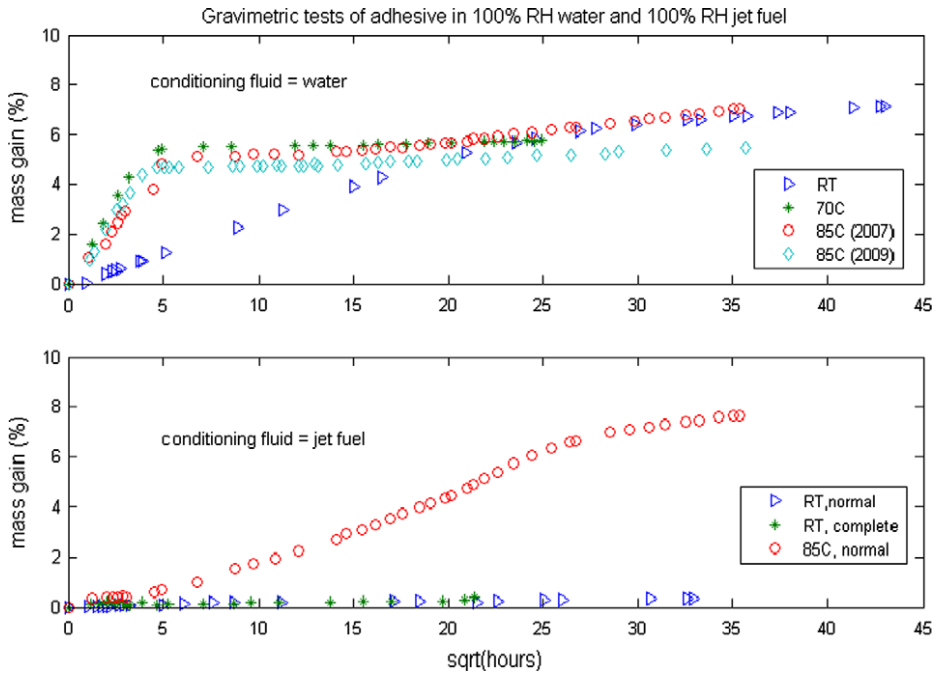

Fig.13 Median mass gain Vs. Square root (hours) for adhesive specimens conditioned with water (above) and jet fuel (below) [67].

Above curve shown in fig. 13 explains that water or jet fuel immersed specimen shows 10% gain in mass over 77 days of exposure.

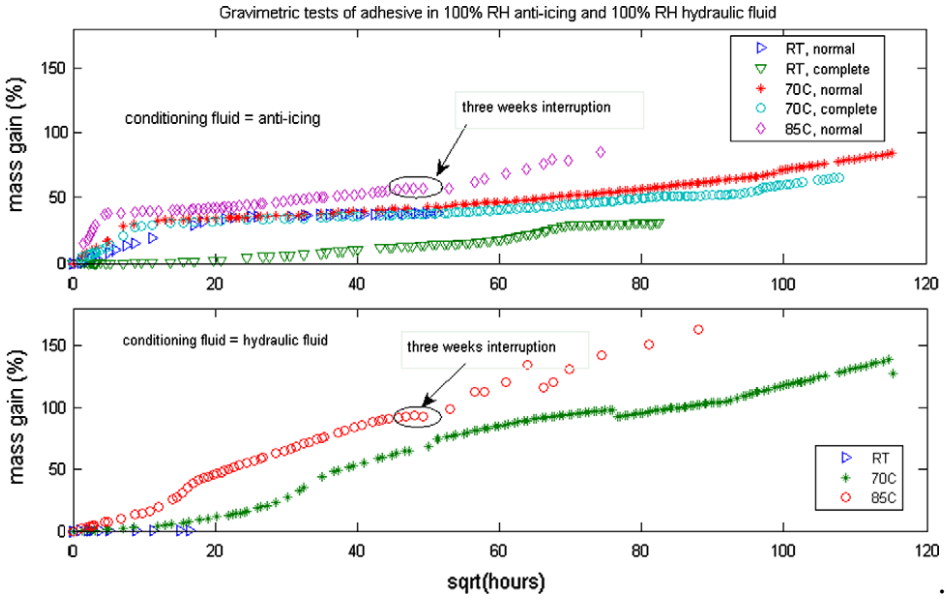

Fig.14 Median mass gain Vs. Square root hours for adhesive specimens conditioned with anti-icing additive (top) and hydraulic fluid (bottom) [67].

This curve shown in fig. 14 explains that there is increment in mass of specimens by 90% and 180% for exposure in anti-icing additive and hydraulic fluid respectively over 555 days [67].

Exposure to Sea water

The oil industry is presently investigating the possibility of drilling out oil from ocean at depths of 2000m and more. To recover oil economically from such depths, several new technologies are developed. A drawback of using composites in offshore applications is the lack of information concerning the long term effects of seawater on composites. There have been a few studies in which specimens were aged under similar condition to that of ocean environment, and even some long term effects of such exposure.An experimental investigation has been carried out to interpret the failure behaviour and to know the effects of sea water on polymeric composites. A review of the literature reveals several factors which should be taken into consideration when investigating the effect of long term seawater immersion on hybrid composites. These factors are as follows:

a) Moisture absorption in E-glass/carbon/epoxy hybrid composites can be designed according to model of Fickian [68], [69].

b) Moisture does not cause irreversible damage at ambient temperatures in glass-fiber composites and carbon-fiber composites [70][71].

c) the degree of moisture induced degradation of the matrix and the fiber/matrix interface is highly dependent upon the composite system under consideration [70][72].

d) the presence of salt in the conditioning bath reduces the saturation moisture content compared with distilled water [72][73].

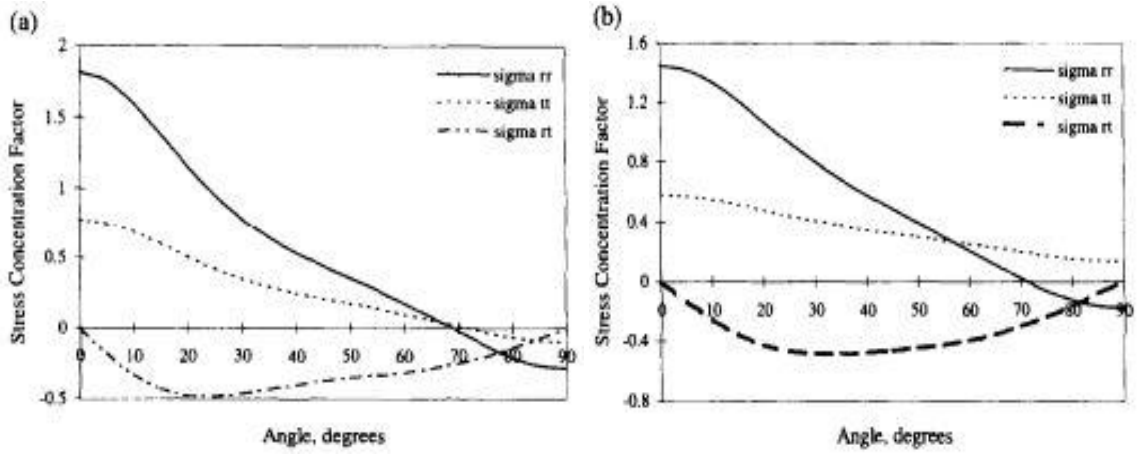

Fig.15Stress Concentration factors for (a) a glass/epoxy lamina and (b) a carbon/epoxy lamina with fibers arranged in a square array [74].

The magnitude of the stress concentration factor with view to stress at a desired angle is not more to cause matrix failure and the magnitude of thestress concentration factor with view to radial stress at an angleis more to overcome the interfacial shear strength that causes

debonding. The stress concentration factor with view to radial stress is the most important because when a transverse load is applied, the radial stresses at the fiber/matrix interface cause interfacial debonding. The stress concentration factor values depend upon the arrangement of fibers i.e. either hexagonal or diamond arrangement. Hence contributing different results [74].

Conclusion and Remarks

The study of in-service performance of fiber reinforced polymer composite is important with respect to environmental conditioning. During the service period the fiber reinforced polymer composite is susceptible to detrimental environmental conditions that cause failure of the composite. Continuous evaluation of interface/interphase is essential because it reflects the strength and stiffness of the composite material during the in-service application. At high temperature, interfacial damage and degradation of the composite occurs because of the mismatch in coefficient of thermal expansion between the fiber and the matrix phase. At low temperature, usually the polymer matrix shows brittleness i.e. it hardens due to the residual stresses. By the implication of thermal shock the initiation of crack growth and debonding of the interfaces takes place resulting in weak interfacial bonding between fibre and matrix. When polymeric composite is exposed to thermal spike, it introduces thermal stresses that lead to debonding and delamination of the composite. The effect of freeze thaw in fibre reinforced polymeric composite induces matrix microcracks in resin rich region. At fibre-resin interface because of the difference in coefficient of thermal expansion there is development of strain misfit. Due to thermal cycling in vacuum, debonding in the interface region starts building up and the overall residual stress reduces in the material. Cracks are initiated at few deformities in the interface region due to high thermal stress, which include debonded interfaces, pores, impurities in the epoxy matrixand damage to the strongly bonded interface. Tensile strength drops on increasing the number of thermal cycles. The effect of humidity on FRP composites is generating swelling stress in the interface area causing volume expansion of the composite. When UV radiation is exposed on composite there is decolourisation and deformation in the matrix because of formed microcracks. Combined action of UV and humidity on fiber-matrix interface causes separation of fibres from matrix and formation of microcracks which lead to drop in tensile strength and elastic modulus of the composite. Moisture absorption causes degradation in fiber-matrix interface region when composite is exposed to sea water. Interface is the most critical part in deciding the overall performance of the FRP composite materials especially in structural applications. Hence

proper engineering and designing of the interface is the key factor to achieve long term reliability, durability and integrity for better utilization in the respective field of application.

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