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Fatigue Performance and damage mechanisms of Reinforced Polymer Composites - A Review

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Abstract - Introduction of Composite materials in engineering field, constituted new challenge for several sectors of the scientific community, researchers and academicians. Composites are now used for critical structural components and they are considered as being on the same footing as the traditionally used steel, aluminum or concrete in emerging structures. Nowadays nanoparticles, short fiber and glass and carbon fiber reinforced polymer composites have been rapidly increasing and most of the components made of these materials are subjected to cyclic loading. Therefore, their fatigue behavior and modeling have been of much interest in recent years. this development changes the common perception concerning the fatigue sensitivity of each structure. This review paper attempts to address the problems and methods of the fatigue life prediction of composites and composite structures. this paper provides an update regarding current knowledge as well as on-going research in different domains, including aeronautics, wind energy, and bridge construction.

Keywords: Fatigue, Particle – reinforced composites, Fiber – reinforced composites, Damage mechanisms, Mechanical behavior.

1. INTRODUCTION

One of the many challenges in the composites industry, which has been become the focus of the current research and development in many organizations, is to produces a new generation of polymer matrix composites materials, which are not only lighter and stronger, but also tougher and durable. These terminologies i.e. 'tough and durable' are very closely related. In practical terms, composites toughness is the ability of the structure containing a crack to resist fracture, and it is generally characterized by measuring the critical energy release rate. As for composite durability, it is the ability of the structure to be 'in – service' over a relatively long period of time.

A more scientific definition for durability is the degree to which a material retains its physical properties while subjected to stress, such as heavy use, or adverse environmental conditions [1]. In general, polymer matrix composites applications have been associated with the high end industries such as aerospace and Formula One (F1) racing cars, However, in recent years these applications have been extended to many area, some of as are the military and defence industry which uses polymer matrix composites in making Unmanned Aerial Vehicles (UAVs), sporting and leisure equipment manufactures which produce carbon fiber tennis racquets and golf club shafts, and also in dentistry where polymer matrix composites are used for denture reinforcement [2]. The fact that polymer matrix composites is a multi – purpose material can be largely attributed to ability of the reinforcement to be tailored to a specific strength requirement by manipulating the orientation of the fibers and nanoparticles incorporated in the matrix phase [3].

Polymer composite materials reinforced by nanoparticles (nanocomposites) and fibers are a prominent area throughout the science and engineering composites research. The improvement of polymeric material properties that can be obtained from relatively small quantities of nanoparticles or by fiber - reinforced has been a strong motivation for further study, leading to optimistic predictions of greatly enhanced mechanical properties across the polymer materials [4]. Spherical nanoparticles, and Vapor-Grown Carbon Nano Fibers (VGCNFs), rubber, metal, silica and more recently CNTs and graphene, Glass Fiber (GF), Carbon Fiber (CF), Kevlar Fiber are all excellent candidates for reinforcement of polymer matrices are positively influence fatigue life and fatigue crack propagation rates when dispersed in epoxy matrices.

In regards to study the strength of composite materials under simple loading conditions, several researchers have investigated the strength and durability with respect to the aforementioned parameters [5-11]. In addition, the study of the strength/durability of polymeric nanocomposites tested under fatigue conditions has been conducted by researchers [12-14].

The fatigue cases of composites including Tension–Tension (T–T), Compression–Compression (C–C), Tension–Compression (T–C), bending, thermo, and some mixed loading modes. The different loading modes induce different damage mechanisms. Recently, the fatigue damage behavior of the structural composites in the cases of several loading modes has been studied [15 – 19]. And some works involve the fatigue behavior of the composites [20- 25]. However, it is necessary to investigate and understand their fatigue-failure resistance behavior and damage mechanisms.

Unidirectional transverse specimens fail immediately upon formation of the first transverse crack, whereas for multidirectional laminates, the transverse cracks have a detrimental effect on the fatigue performance. A schematic diagram of the link between microscopic to macroscopic fatigue behavior is shown in Chart-1 [26].

In the area of structural engineering applications, the performance of damage resistance to fatigue is one of the most up-to-date issues for the composite materials. Nowadays, because the requirement of safe applications in long-term service is required, fatigue damage analyses are widely performed in the design of fatigue resistance materials and structures. However, most research works have been conducted on the fatigue damage behavior of structural composites [27–32].

2. Basic Failure Modes in Polymer

Depending upon the chemistry and the curing agent used, the failure mode of the polymer matrix could be either ductile or brittle. The ductile mode is often identified by shear yielding. An increase in brittle of the polymer is seen as a shift from shear yielding to micro – voiding followed by crazing. In case of networked polymers like epoxy highly brittle failure without crazing is common.

2.1. Shear Yielding

Shear yielding is an energy absorption mechanism associated with polymer failure. It occurs when localized plastic flow starts in response to an applied stress at approximately 450 to the applied load. Such plastic flow might spread shear bands in the whole sample absorbing a significant quantity of energy or might leads to localized yielding resulting in isolated shear bands.

2.1. Crazing

Crazing is another common failure mode that is observed in glass and amorphous thermoplastic polymer [33]. During crazing, micro cracks from under tensile load and are held together by polymer fibrils called crazes. Formation and plastic deformation of such crazes involves absorption of energy, which leads to enhanced toughness. When the applied stress is high enough to cause failure of the fibrils, the micro cracks start growing.

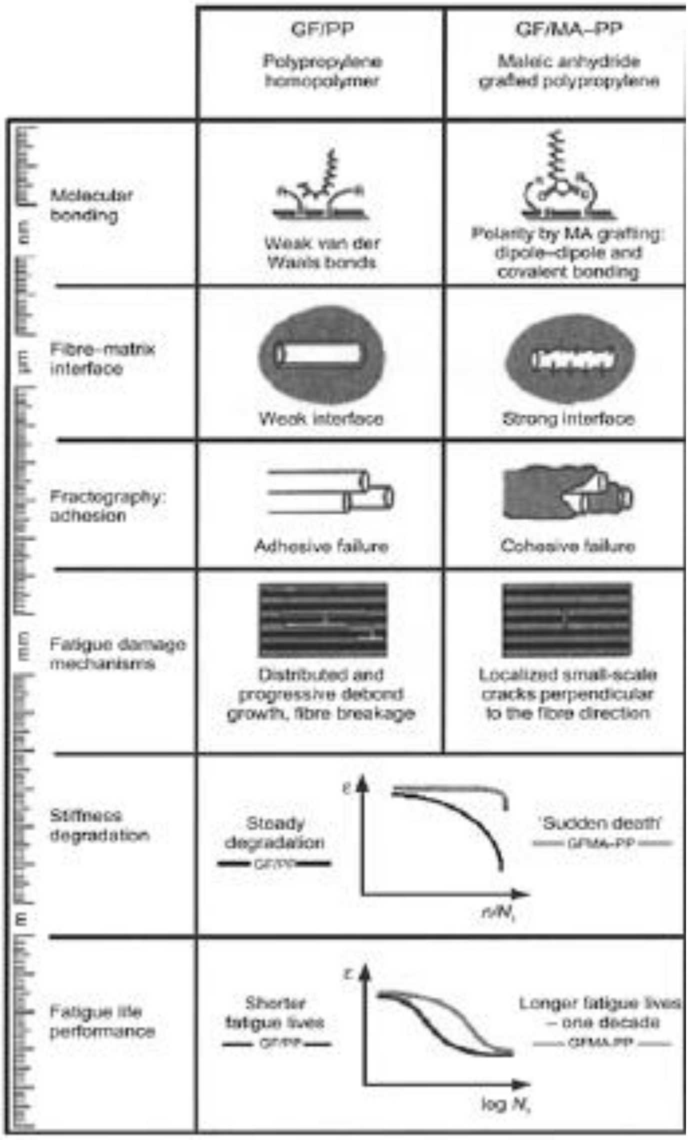

Chart -1: Microscopic to Macroscopic fatigue behavior

3. Why Fatigue Is Important

The composite materials are designated as being fatigue-insensitive, especially when compared to metallic ones; they also suffer from fatigue loads. The use of composite materials in a wide range of structural applications the researchers has to consider fatigue when investigating a composite material and engineers to realize that fatigue is an important parameter that must be considered in calculations during design processes, even for structures where fatigue was not traditionally considered an issue [34].

There is a long list of reasons why fatigue is critical for composite structures:

Composites are used for critical structural components and nowadays they participate as a material which is equal to the traditionally used steel, aluminum or concrete, in emerging structures that must bear significant fatigue loads during process, such as airplanes, wind turbine rotor blades, leisure boats, foot and vehicular bridges etc. This development changes the common perception concerning the sensitivity of each structure to fatigue. For example, whereas a concrete road bridge is normally not fatigue-sensitive since the residual loads are significantly higher than the true loads, fatigue becomes an issue for a lightweight composite bridge.

Unidirectional fiber composite materials are generally brittle in linearly load condition. Since their failure is unexpected, without any prior notice, an understanding of their fatigue behavior and prediction of their fatigue life are very importance. An understanding of composite material fatigue behavior is also valuable for the improvement of product development practices. The ability to simulate the fatigue behavior of the material, structural component and/or structure reduces the cost and allows the development of a wider range to increasing the number of fatigue life cycles.

The durability of composite structures is also an important factor. The danger of evaluating durability on the basis of static strength calculations is that the durability impact of cyclic loads is likely to be disregarded.

4. Fatigue nomenclature

Conventionally, in fatigue the following abbreviations are used:

CA: constant amplitude loading

H–L: high–low combination in a two-stage block loading pattern

L–H: low–high combination in a two-stage block loading pattern

L–H–L: multiple block loading patterns describing the load sequence

VA, irregular, spectrum, or random: refers to the loading under a variable

amplitude fatigue spectrum

σ_{max} = maximum applied cyclic stress

σ_{min} = minimum applied cyclic stress

σ_m = mean stress

σ_n = cyclic stress amplitude

Δ_σ = cyclic stress range

R-ratio: the ratio of minimum over maximum cyclic stress. This ratio defines the loading patterns that might be of:

T–T: tension–tension loading, when $0 \leq R < 1$

C–C: compression–compression loading, when $1 < R < +\infty$

T–C or C–T: combined tension–compression loading when $-\infty < R < 0$

special case: $R = -1$ when the compressive stress amplitude is the

same as the tensile stress amplitude and the mean stress equals zero. This is known as reversed loading

f: test frequency, measured in Hz, or loading cycles per second [35].

5. Fatigue Tests of polymer nanocomposites and reinforced composites

The test specimen for fatigue tests on bulk polymer nanocomposites are carried out using dog-bone ASTM D638 type IV test specimen as shown in Fig. 1. [36]. These specimens are generally cut and prepared from the bulk polymer nanocomposites fabricated after dispersion of nano filler in the liquid resin and cured. The surface preparations of specimens play a major role in fatigue life.

The specimen has been tested at room temperature at loading frequency 1Hz under constant displacement, were used for tension-tension (R = 0.1) fatigue testing of material. The elastic modulus of materials was tested the attachment of an extensometer.

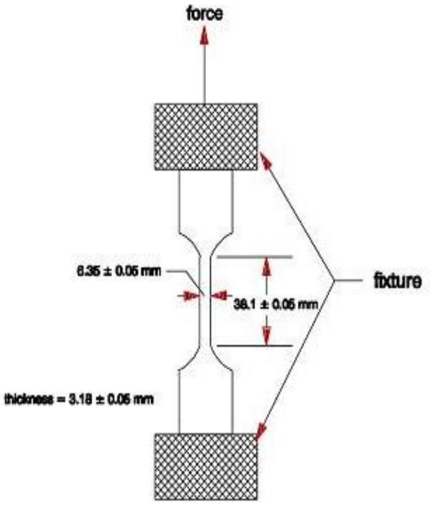

Fig -1: Dog-bone Coupon.

All fatigue tests reported here were run under load control sine waveform constant amplitude. Tests were run at different R values, defined in Chart -2 . and Equation 1.

$$R = \text{MiniumStress}/\ \mathit{MaximumStress} \qquad (1)$$

It should be noted that compressive stresses are taken as negative, so the maximum stress in Equation 1 is always the more tensile stress. In a case where the mean stress is compressive, the minimum stress may have a higher absolute value.

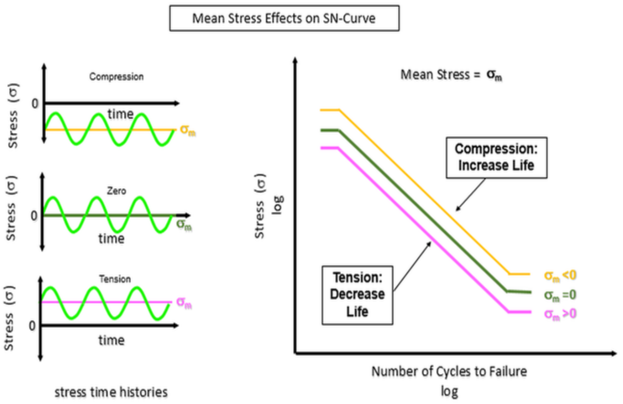

Chart -2: Waveform Definitions

6. Damage mechanisms

In order to quantify the actual accumulation of damage in a composite material due to fatigue loading, one must characterize and quantify the damage, which reduces the stiffness and toughness of the composites. Damage can be defined as the gradual degradation of composite materials and is an intrinsic material property of composite as a damage variable [37]. There have been a multitude of authors that consider damage as an intrinsic material state [38 – 45]. In terms of fatigue, damage can be considered as a strain – life approach concept in relation is more appropriate to conventional approaches such as S-N and Coffin-Manson curves. According to Coffin [46] and Manson [47], the plastic strain amplitude follows a similar power law as Eq. (2) to Nr for fatigue of metallic materials. Generalized later by Moustafa et al. [48], the same form of equation also applies to total strain amplitude on fatigue of polymer composites.

$$N_r = 2(N_f - 1) \approx 2N_f \qquad (2)$$

In fact, damage is not defined in these approaches since they provide a number of cycles to failure or fatigue life prediction, which does not truly reflect the progressive process of fatigue damage evolution due to growth and combination of micro cracks. Traditional fatigue theories do not reflect an inherent intrinsic approach, and cannot give the damage distribution of the particles in the composites material under cyclic loading [49].

In conventional materials, damage is characterized in terms of dislocation density or micro crack density used in boundary value continuum mechanics problems due to the fact that elasticity is directly correlated with damage.

This elasticity to damage correlation is confirmed because the number of atomic bonds decreases with damage [50]. Fig.2. shows the formation of damage in filler and fiber reinforced composites.

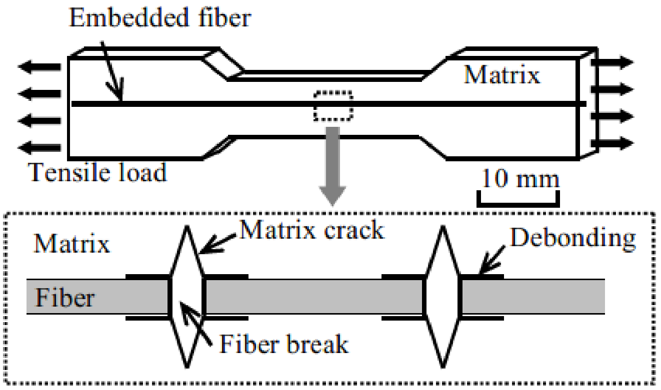

Fig-2: Damage formation in single fiber composite fragmentation test: (a) debonding when the intrinsic is weak; (b) matrix cracking when interface is strong

7. Fatigue in composite materials

Many light duty metal gears and bearings are replaced with reinforced polymer product. It is because of the economical and technical advantages of the polymer composite materials. Generally, polymer composites are light in weight and exhibit good environmental and chemically resistance. The durability and toughness of the polymer composites are higher than conventional metals. Despite durability and toughness, the polymer composite has limited application in light duty parts, due to their low strength and modulus. In recent studies, Liu et al. [51], Manjunatha et al. [52], Manjunatha et al. [53] and Wetzel et al. [54] indicate that there are ways to improve the strength and stiffness of polymer composites such as by incorporation of nanosize clay, short fibers, continuous fibers or nanoparticles into the virgin matrix. Then, nanocomposite becomes a common material after incorporation of clay, fibers or particles into the matrix. It has reinforcement size of the order of 1-100nm with the aspect ratio of 10-100.

Some interesting observations have been made regarding the physical degradation of PET, unreinforced fiber samples [55-57]. In addition, Cho et al. [58] studied the fatigue behavior of unreinforced PET fibers under various processing conditions with the same crystal structure at 10^4 - 10^6 cycles.

Other efforts to illuminate the effects of fatigue on the accumulation of damage in PET fibers have been investigated in [59], in which destructive tests were performed. In their experiments, the ultimate failure of PET fibers after 4.22E6 cycles was due to the presence of a congenital, inherent flaw hypothesized to be antimony trioxide (Sb_2O_3), which was used as a catalyst in the production of PET.

Liang et al. [60] investigated the effects of chain rigidity on the nonlinear viscoelastic behavior of several polymeric fibers, to include PET. The mechanical and fatigue behavior of poly (lactic acid) (PLA) neat films and PLA films reinforced with 5 wt% nanoclay particles has been examined using various analytical procedures. The results showed that for the films tested in this study, PLA 5 wt% nanoclay composite has good fatigue than the PLA neat [61]. Many studies have been conducted on nanocomposite samples under simple loading conditions to ascertain the effects of filler content on the mechanical properties.

Sandler et al. [62] have performed uniaxial tensile experiments on melt-spun polyamide 12 fibers employed with various reinforcing agents, to include arc-grown nanotubes (AGNT), aligned catalytically grown nanotubes (aCGNT), entangled catalytically grown nanotubes (eCGNT) and catalytically grown nanofibers (CNF). In all cases, the modulus and yield stress of the nanocomposites were shown to be higher than the unreinforced polyamide 12 fiber, and the values were shown to be linearly correlated with the filler content (increases in modulus and yield strength with increased filler content).

Breton et al [63] have also noticed significant increases in modulus with decreases in the ultimate strain and fracture strength for epoxy/MWNT composites. This clearly indicates that filling the epoxy with MWNTs led to stiffer and more brittle materials. Other evidence has been provided by Wuite and Adali [64], Chen and Tao [65], and Kim et al. [66] that indicates stiffening of the polymer matrix due to the inclusion of nano-sized reinforcing agents under simple loading conditions. What can be concluded from these studies is that nano-sized reinforcing agents increase the mechanical properties and overall mechanical behavior of the materials for engineering applications.

Grimmer and Dharan [67] suggested that the addition of CNTs to a glass fiber epoxy composite resulted in the adsorption of strain energy through the creation of nanoscale cracks in tension-tension fatigue testing. It was observed that CNTs had a marked effect in high-cycle fatigue testing corresponding to low applied stress amplitudes. Although the phenomena of crazing is not typically observed in epoxies due to its high crosslink density, Zhang et al. [68].

In another report [69], the same group suggested that geometrical considerations and quality of dispersion are directly linked to fatigue improvements in MWCNT composite epoxy. It was maintained that reducing diameter, increasing length and bettering the dispersion of MWCNTs significantly reduced the rate of fatigue crack propagation. Rotary bending fatigue tests at low stress magnitudes also suggested MWCNTs to improve fatigue life in epoxy [68]. Other reports have linked MWCNTs to significant increases in the fatigue life of thermoplastics such as PMMA [70-73]. To this regard, it was the aim of this study to test the effect of the addition of small amounts (= 1.0 wt%) of CNFs on the fracture resistance and fatigue performance of a structural polymer (epoxy) system.

8. CONCLUSION

Many research efforts have focused on investigation of the fatigue behavior of nano filers and fiber reinforced polymer composite materials. Based on the obtained literature, it is clear that the presence of silica, CNTs, and alumina nano-particles in the polymer matrix reduces the brittle nature of the polymer (epoxy) such that enhancing the maximum fatigue stress, fatigue life and roughness of the composite surface. And also, better enhancement was observed for composite reinforced by carbon and glass fiber.

The wide range of composites test was carried with low (2–5 Hz) test frequencies used have limited the fatigue data available on well characterized materials, particularly at lives greater than 106 cycles. In future, the use of higher frequencies, at low stresses, could enable progress on:

Establishing larger database at long lifetimes

(i.e. > 10^6 cycles),

Establishing, if it is present, a fatigue limit stress level,

Validating predictive methods for long lifetime data

(i.e. > 10^6 cycles).

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