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EXAMINING FATIGUE OF FIBER REINFORCED POLYMER: A COMPREHENSIVE REVIEW

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Abstract: *Since their introduction in the 1950s, composite materials have been extensively studied for their fatigue performance across various engineering fields. Numerous publications have documented experimental investigations into how these materials perform under different loading and environmental conditions. Fiber-reinforced polymer (FRP) composites are increasingly replacing metals due to their high strength and stiffness. These composites face various static and fatigue loads in service, necessitating fatigue tests to assess cyclic behavior. Unlike metals, where a single crack propagates to failure, composites exhibit complex fatigue damage with multiple micro-cracks forming early in the process. FRP composites serve as pivotal structural materials across diverse industries. Yet, before their incorporation into structures, meticulous testing of both test coupons and structurally representative samples is essential to evaluate their physical attributes, particularly their fatigue properties. Regrettably, the considerable expense entailed in fabricating coupons for these evaluations poses a notable hindrance to the extensive integration of fibre-reinforced polymer(FRP) into end products. The objective of this study is to forecast and simulate the fatigue lifespan of FRP composites. Extensive research in this domain will be outlined within this paper, encompassing diverse prediction methodologies employed to ascertain the fatigue endurance of these materials.*

Keywords: *Fatigue life, fiber-reinforced polymer, (FRP), fatigue test, carbon fiber*

1. INTRODUCTION

The rapid development in industries has created a need for materials with enhanced strength, hardness, and density, while also reducing costs and improving sustainability. Composite materials have emerged as a solution that meets these requirements and are widely used in various applications. These materials consist of a combination of two or more components, with one serving as a matrix and the other in the form of particles or fibers as reinforcement. Research studies have shown that composite materials can effectively replace many traditional materials, offering significant improvements in structural, mechanical, and frictional properties, particularly when reinforced with fibers[1],[2],[3]. FRP are composite materials typically consisting of fibers embedded in a matrix material. Due to their outstanding properties such as low weight, high specific strength, rigidity, and excellent resistance to corrosion and fatigue[4],[5]. FRP composites are extensively employed in the construction of automotive structures, and aerospace, marine and aircraft applications [6]. In military defence systems, reinforced polymers are widely used to manufacture components such as helmets, body armour, and ballistic protection panels for light vehicles, boats, and helicopters. These materials are characterized by excellent mechanical properties, such as high strength, stiffness, and a great capacity for energy absorption. They also contribute to reducing weight compared to traditional materials, which improves vehicle mobility and fuel efficiency while maintaining a high level of protection[7]. FRP composites face cyclic loading in various applications, leading to fatigue failure, a common issue. Understanding and addressing this failure mode is crucial for ensuring the reliability and longevity of FRP structures[4],[8]. Carbon fiber reinforced polymers (CFRPC) are considered one of the best and most famous types of reinforced polymers. These composites are witnessing increased usage across various advanced technology industries, including aerospace, defence, marine, and sporting goods. This trend is attributed to the unique combination of high specific strength and stiffness[9]. These materials excel in enduring both constant and cyclic loads, serving as effective alternatives to traditional metal alloys. CFRP exhibit robust fatigue resistance along the fiber direction due to their exceptional stiffness, preventing local damage initiation. However, their anisotropic nature and varying stiffness coupling can induce notable strains perpendicular to the fibers or at the fiber/resin interface, potentially leading to fatigue damage due to mismatches in elastic properties [10]. the replacement of metallic components with CFRP-based alternatives leads to significant weight savings [11]. despite extensive studies, understanding the fatigue behavior of fiber-reinforced composites remains complex due to differences from metal fatigue. Composites experience multiple simultaneous cracks, complicating

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fatigue assessment. Damage mechanisms like fiber breakage, matrix cracking, delamination, and debonding degrade mechanical properties such as strength and stiffness. Therefore, research often focuses on the degradation of residual strength and stiffness during fatigue[12]. This study aims to explore modern methods for predicting material fatigue life, particularly focusing on reinforced composites. It provides an overview of their significance across engineering fields, emphasizing their unique fatigue behavior compared to metals. Previous research on fatigue life determination in composites is reviewed, highlighting both progress and gaps. The study also examines fatigue behavior and failure patterns, including micro-crack initiation and propagation. Strategies for improving composite fatigue performance are summarized, with practical implications and future research recommendations provided.

2. FATIGUE FAILURE

Fatigue has long been a major industrial concern. The increased use of composite materials highlights their complex fatigue behavior compared to metals. Unlike metals, where fatigue damage typically appears as a single crack, composites exhibit various forms of damage such as delamination, matrix cracking, fiber failure, debonding, and void growth, influenced by testing conditions and material composition[13]. In composites, failure criteria like the hashing criterion have been adapted from static to fatigue conditions by replacing static strength with fatigue or residual strength. This adaptation is supported by the presence of Characteristic Damage States (CDS) in composites under fatigue loading. Fatigue induces cracks parallel to the fiber direction in multidirectional laminates, creating a degraded but integrated material state. Each fatigue cycle is akin to a quasi-static loading process, enabling failure prediction with each cycle[14]

3. Composites of Fiber Reinforced Polymer (FRP)

Today, composite materials are gaining an edge over conventional materials due to their superior specific strength, and excellent stiffness and fatigue properties, although they have lower fire resistance. In recent decades, polymer composites have been widely adopted as alternatives to traditional materials across various applications. Their ability to fulfill diverse design requirements, coupled with their robust mechanical and physical properties, makes them ideal for meeting specific application demands[15]. Composite materials can be tailored to specific service conditions, much like natural composites such as wood and bone, which have evolved to meet specific mechanical needs. This adaptability makes them attractive for industrial applications[16]. Composite materials are categorized by their components: the base material (matrix or binder) and the filler material. The matrix holds the filler, which can be sheets, particles, fibers, or whiskers from natural or synthetic sources as reinforcement. As shown in Figure 1, composites are classified into three main categories based on their structure[1].

(FRP) composites, known for their heterogeneous and anisotropic properties and lack of plastic deformation, are widely used in many applications. (CFRP) and glass fiber-reinforced polymers are preferred over traditional materials due to their excellent strength-to-weight ratios, customizable strength, high fatigue resistance, toughness, and resilience to high temperatures and oxidation, making them ideal for various engineering applications [17].

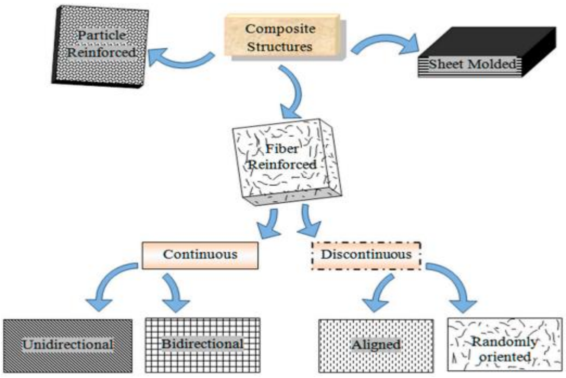

Figure 1. Types of Composite Materials.

3.1. Carbon fiber reinforced polymer (CFRP)

Carbon, a vital element for life, forms the basis of numerous compounds, totalling approximately 1.7 million. Derived from sources like coal, oil, and diamonds, carbon fibers possess exceptional properties including high strength, stiffness, and resistance to heat, moisture, and chemicals. When combined with polymer matrices to create CFRP composites, they offer advantages such as high strength-to-weight ratios and fatigue resistance. Despite drawbacks like high costs and low impact resistance, CFRP find extensive use in aerospace, automotive, electronics, medical, and sports equipment industries due to their superior strength and lightweight properties compared to steel and aluminium [18]. Table 1 provides a summary of the most important properties of carbon fibres [19].

Table 1: properties of carbon fibres.

Property	Young's modulus (GPa)	Ultimate tensile strength (MPa)	Percent of elongation	Density (g/cm^2)	Specific strength (Mpa/g. cm^3)
value	220-350	2300-3700	0.7-1.7	1.8-2	1300-1900

4. FATIGUE OF CFRP

In their investigation into the fatigue life of CFRP composites. Lu Ke and colleagues examined the fatigue performance of steel plates that have been reinforced with CFRP for enhanced strength and durability emphasizing the role of adhesive properties. They tested 20 various specimens to evaluate fatigue life, analyze failure modes, and observe crack propagation patterns. The study revealed that epoxy resin-based structural adhesives, notably Araldite 420 and J133C, provided superior bonding with CFRP. This significantly improved the fatigue life of the CFRP-reinforced steel plates[20]. Selim Mrzljak et al. studied the effect of oriented carbon nanofibers on the mechanical properties of bidirectional polymer-reinforced carbon fibers was studied. They produced carbon nanofiber-reinforced polymer with and without orientation using a press hot. Their results showed that the orientation of carbon nanofibers has a significant effect on the mechanical and fatigue properties with guidance, it was observed that it increases the force, reduces the resulting damage, and slows it down[21]. J.-D. Wacker and his team investigated the computational prediction of fatigue life for CFRP adherents in hybrid adhesive joints. They examined two fatigue life models based on multiaxial stress and strain energy density related to various failure modes. Using finite shell and volume elements for stress analysis, they predicted the fatigue lifespan of hybrid steel-CFRP single-lap joints, considering geometric nonlinearity. The models showed reasonable accuracy compared to experimental data until initial ply failure, but further refinement is needed to improve predictive precision[22]. Jianxiong Gaoa et al. studied how stiffness degradation affects the fatigue life and reliability of FRP composites. They developed a probability model accounting for the randomness in initial and critical stiffness, finding that stiffness degradation follows a distinct pattern: rapid decline, slower phase, and then another rapid decline before failure. Their model accurately fit experimental data and outperformed existing models, enhancing the understanding and prediction of stiffness degradation to improve the reliability and longevity of FRP composites[4]. Slavko Mijatov and his team developed a novel composite material for rocket propulsion liner insulation, using hydroxyl-terminated polybutadiene (HTPB) with carbon fibers (CF) and inorganic filler powders (IFPs). They introduced an elastomeric adhesive to enhance mechanical properties and heat resistance. Various formulations with different CF and IFP loadings and NCO/OH ratios were rigorously tested for viscosity, rheological and mechanical properties, and geometric compatibility. Dynamic mechanical analysis (DMA) and small-scale ablation tests confirmed that these new materials provide excellent thermal insulation and ablation characteristics, making them ideal for rocket propulsion applications [23]. Li Bowen et al. they studied utilized molecular dynamics (MD) simulations to investigate the mechanical behavior of epoxy resin reinforced with multilayer graphene during fatigue. They examined the degradation of performance under axial and transversal fatigue, respectively. Despite significant differences in loading rates between atomic and macroscopic scales, the MD method proved feasible, as evidenced by a noticeable drop in mean stress during simulation. Performance degradation was observed to be most rapid in the initial cycles, with degradation occurring faster in the transversal direction compared to the axial[24]. Mithil Kamble and colleagues conducted research aimed at enhancing the fatigue resistance of CFRP by incorporating nano-silica, thereby producing nano-modified carbon fibers. Their study showcased a significant enhancement in fatigue life, with the addition of nano-silica resulting in fatigue life improvements of 6-7 times under high cycle fatigue conditions. Through their investigation, they elucidated the mechanism behind this performance enhancement, attributing it to the ability of nano-silica to interrupt and prolong the initial crack propagation phase. This, in turn, delays the ultimate failure of the carbon fiber-reinforced polymer, leading to an augmentation in fatigue life[25]. Md Sarower Tareq et al. investigated the flexural stress behavior and fracture toughness of CFRP composites enhanced with graphene nanosheets. Through bending stress tests, they analyzed the primary mode of plate fracture. Employing the Employing the two-parameter Weibull distribution function, they made estimations regarding both the likelihood of failure and the fracture toughness. The results highlighted a significant enhancement upon incorporating graphene nanosheets, with an average fatigue life increase ranging from 155% to 190%, along with improved fracture toughness. In essence, these composite materials exhibited prolonged fatigue life and delayed crack formation within the matrix attributed to the presence of nanoparticles[9]. Xiang-FaWu et al. They experimentally studied the fatigue residual tensile strength and its probability distribution on PMC sheets made of unidirectional CF. The statistical analysis of the experimental data revealed that the residual tensile strength of the samples conformed to the two-parameter Weibull model with a reliability of 95.2%. As the cycles increased, the value of the residual fatigue strength decreased, while its deflection increased. They emphasized that the experimental study they used is valuable for understanding fatigue strength in addition to reliable design and prediction of the performance of composite structures[26]. Aida Cameselle-Molares and her team investigated the delamination behavior of GFRP/balsa sandwich panels featuring circular disbands subjected to out-of-plane fatigue loading. Two configurations of face sheets were examined: SPA (comprising solely woven plies) and SPB (consisting of woven plies combined with continuous filament mat). The study revealed that 2D crack propagation led to stable advancement and slower crack growth rates under load control conditions. The SPB configuration exhibited inferior performance under fatigue with an R ratio of 0.1, yet displayed a prolonged lifespan and arrested crack propagation at higher R ratios. Furthermore, they noted an elevation in cyclic stiffness attributed to the in-plane stretching stresses in the debonded face sheets[27]. They investigated the augmentation of fatigue strength in sugarcane fiber-reinforced epoxy composites (SFRPC) through a novel treatment method. This treatment resulted in a significant improvement in cyclic fatigue strength CF and extended fatigue life by up to 40%. Evaluation of fatigue performance involved bending cyclic fatigue tests, and comparing treated and untreated SFRPCs with CFRPC. Finite element models and statistical analysis were utilized to assess the treatment's impact and load ratios. Enhanced fatigue behavior was observed, supported by SEM imaging. The stress-strain-life relationship suggested that the increased CFS in treated SFRPCs stemmed from shear yielding due to the fracture of the glass layer on the fibers[28]. Hemanth Kumar and colleagues delved into the fatigue behavior of glass fiber-reinforced epoxy composites subjected to cyclic bending loads, employing neural networks for predictive analysis. Through rotating bending stress tests with reversed load cycles, they observed a decrease in the fatigue life of the glass fiber composites with rising stress levels. The efficacy of neural networks was validated by juxtaposing their predictions with experimental outcomes. Notable observations encompassed matrix cracking and fiber interfacial debonding. Furthermore, the utilization of backpropagation algorithms enabled neural networks to proficiently classify failure modes[6]. mitigates the impact of weak interfaces on the structural reliability of FRP laminates, S.S.R. Koloor and colleagues devised a cyclic cohesive zone model (CCZM). This model aptly characterizes interlaminar fatigue failure by incorporating fatigue-induced degradation of strength, stiffness, and critical energy release rate. Utilizing experimental data and finite element analysis, they applied the model to unidirectional CFRP specimens. At key interfaces, shear stress exhibited variation (τmax = 30 MPa, R= 0.1), revealing a sigmoidal damage pattern. Crack initiation occurred after 301,750 cycles, exhibiting a consistent crack front progression.[29]. Xin Wang et al. examined how salt solution exposure affects the fatigue behavior of basalt fiber-reinforced polymer (BFRP) composites at stress ratios of R = 0.1 and 0.8. They found that while static strength was stable, fatigue strength decreased due to saltwater. SEM revealed early interface debonding and deterioration over time in aged samples, leading to varied fatigue lives and degradation. The study concluded that saltwater significantly impacts BFRP's fatigue strength, crucial for long-term performance[30]. Shoutan Song et al. delved into the fatigue characteristics of CFRP. Their study employed an innovative wedge-type anchorage system during fatigue testing of CFRP tendons. The adoption of this novel fixation system demonstrated exceptional fatigue resistance, as evidenced by the absence of tendon slippage or failure upon fixation. Predictions generated using Whitney’s method provided a confidence level of 95%[31]. Ayoub Yari Boroujeni et al. investigated a novel technology, Graphitic Structure by Design (GSD), aimed at growing uniform, multi-walled carbon nanotubes. They explored two different configurations: one with a uniform patterned covering and the other with a checkerboard-like coating on woven carbon fiber. Tensile tests were conducted on the carbon fiber to determine properties such as modulus of elasticity, failure stress, and tensile strength. Additionally, fatigue life was tested at three stress levels. Their findings revealed a significant 150% improvement in the fatigue life of carbon fibers with both uniform and patterned multi-walled carbon nanotubes. Fractography analysis highlighted the role of MWCNTs in shielding the fiber yarn from matrix cracks, leading to substantial enhancements in fatigue life[10]. Priscilla Rocha Vieira et al. They studied focused on the fatigue behavior of pultruded Glass-fiber Reinforced Polymer composites. Static tests measured the material's strength and elasticity. Fatigue tests (R=0.1, 4Hz) were performed to establish the S-N curve and analyze damage progression and failure modes. Typically, fatigue damage started with matrix cracks, potentially leading to delamination, fiber failure, and ultimately, specimen rupture. Tomography revealed misaligned fiber layers and numerous voids, contributing to material heterogeneity and variability in experimental results[32]. Mondher Haggui and his team investigated the mechanical characteristics and damage mechanisms of flax fiber-reinforced thermoplastic composites under both static and fatigue loading conditions. Static tensile tests were conducted to discern mechanical properties and elucidate damage mechanisms, whereas fatigue tests were employed to assess material stiffness. The findings unveiled four distinct acoustic event categories during failure: matrix cracking, fiber debonding, fiber pull-out, and fiber breakage. It was noted that the composite structure played a pivotal role in influencing damage density and behavior under both static and cyclic loading. [33]. Moustafa Mahmoud and his team explored the effects of incorporating cellulose nanocrystals into polymers to develop nanocomposites with continuous glass fibers, thereby merging the advantages of both traditional and nanomaterials. They produced four types of samples: Unreinforced polyester (UR), Glass fiber-reinforced polyester, Nano polyester composites (NP), and Nano glass fiber-reinforced composites (NGFRP). Their innovative material combinations revealed that NGFRP can significantly enhance the fatigue life of composite structures while also lowering manufacturing costs. This material design shows great potential for applications in the biomedical, energy, and electronics industries[34]. Pritam V. Kulkarni and his team conducted a study utilizing a conditional test aimed at extending the fatigue life of carbon fiber reinforced plastic sheets. They fabricated composite sheets with carbon fibers oriented in multiple directions. The study demonstrated that the proposed test is an effective, non-destructive method for estimating the fatigue life of composite plates. From the experimental results, they derived empirical equations that establish a relationship between fatigue life and natural repeatability[12]. CFRP is highly valued by gas turbine engine manufacturers for its exceptional properties and lightweight nature. M. Nikhamkin et al. developed a fatigue testing method for CFRP that reduces the number of samples needed to determine fatigue properties. Using the "Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials," their approach reduced test specimen use by 83.3% and structural specimens by 62.5%. This method effectively determined the acceptable fatigue limit, showing potential for significant sample reduction[35]. S. Backe et al. conducted a study with the goal of saving time and materials in the analysis of the fatigue behavior of carbon fiber reinforced polymer composites. They developed a novel, short-time procedure for calculating the fatigue life of these composites, focusing on a series of tests to increase the cyclic load for all plates. The advanced overload test was performed at a frequency of 5 Hz with a stress ratio of R=0.1. This method proved effective in calculating fatigue life. Utilizing accumulated irreversible deformation energy as a metric for estimating fatigue life represents a completely new approach, offering significant potential for efficient and accurate fatigue life estimation[11]. K. Tanaka et al. conducted an in-depth study on how fiber orientation affects crack propagation behavior, using single-edge specimens taken from an injection-molded sheet. By employing Fracture Mechanics parameters determined through Finite Element Method (FEM) based on anisotropic elasticity, they established correlations between the crack propagation rate and various factors. The key findings are as follows: fiber reinforcement significantly enhanced crack propagation resistance, particularly when examining the relationship between crack propagation rate and stress range. Fatigue cracks were found to propagate under mixed mode loading conditions, and the crack propagation rate data correlated with the range of the total energy release rate[36]. Fabio Baschnagel et al. studied the fatigue behavior of CFRP tapes loaded with pins under tensile stress. These tapes are used in various applications, such as sailing yacht rigging systems, crane suspension cables, and bridge suspenders. They conducted extensive tensile and fatigue tests on the tapes, subjecting them to millions of loading cycles. The tests revealed that the pin-reinforced CFRP tapes have a significant stress limit, approximately half of their ultimate tensile strength, and identified a fatigue limit when the tape withstands a substantial number of load cycles. Their findings were used to develop an S-N curve for the material[37].

6. CONCLUSION

For the past seven and a half decades, the scientific and engineering communities have been deeply engrossed in unravelling the mysteries surrounding the fatigue behavior of composite materials, with a particular focus on FRP composites. These materials have garnered widespread interest since their inception in various industrial applications. As researchers delved deeper into their fatigue characteristics, it became increasingly evident that the fundamental principles governing fatigue phenomena are applicable across a broad spectrum of materials and structural configurations. The complex interplay of continuous and cyclic loading, coupled with fluctuations in temperature, stress concentrations, and environmental factors, plays a pivotal role in dictating the degradation and eventual failure of composite materials[5]. These multifaceted factors contribute to the intricate fatigue behavior observed in FRP composites and other similar materials. While significant strides have been made in understanding and predicting the fatigue life of FRP composites, the field remains vast and ripe for further exploration. Specialized research papers have documented substantial advancements in fatigue life prediction techniques. However, the quest for a comprehensive understanding of fatigue behavior continues unabated. The objective of this research was to delve into sophisticated methodologies, state-of-the-art forecasting techniques, and empirically validated strategies to delve into the complexities of fatigue behavior in composite materials. Despite considerable progress, the pursuit of a comprehensive grasp of fatigue life in composites persists, highlighting an ongoing commitment to innovation and enhancement in the critical realm

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