Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 13, No. 2, 2024

Research Progress on Fatigue of Carbon Fiber Composite Materials and Their Bolted Connection Structures

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Abstract: This paper primarily investigates the fatigue performance of carbon fiber composites and their bolted joint structures. Carbon fiber composites have gained increasing attention due to their high strength, lightweight properties, and corrosion resistance. However, technical challenges remain regarding the fatigue characteristics of carbon fiber composites and the durability of their joint structures in practical applications. This paper reviews the research progress on fatigue performance testing of carbon fiber composites at home and abroad, focusing on failure mechanisms under cyclic loading, fatigue life prediction methods, and key influencing factors. Additionally, the paper discusses the current research status of bolted joint structures in carbon fiber composites, analyzing the impact of different joint methods on structural fatigue performance, as well as existing experimental and simulation research methods.

Keywords: Composite materials, Carbon fiber, Bolted connections.

1. Introduction

The rapid development of technology has gradually brought composite materials with outstanding mechanical properties into the public eye. Carbon Fiber Reinforced Polymer (CFRP) is an advanced material with high specific strength, high modulus, high temperature resistance, corrosion resistance, fatigue resistance, and strong designability. It is widely used in aerospace, automotive transportation, chemical and wind power industries. The extensive use of composite materials has led researchers to have higher standards for material properties, including requirements for fatigue performance [1]. During the service of composite materials, cracks caused by fatigue can degrade the material's strength and reduce its load-bearing capacity, leading to safety accidents. Among them, the connection of composite material structures is an unavoidable challenge in use, and the most striking data is that about 60% to 80% of structural damage occurs at mechanical connections. This not only threatens the safety of the components, but also shortens their service life, revealing that the connection structure is a weak link in applications. Although bolted connections have excellent maintainability, high load-bearing capacity, and reliability in composite material connection methods, they are easily affected by factors such as vibration, impact, alternating loads, or long-term work during actual operation, leading to loosening or even damage. More importantly, fatigue characteristics play a crucial role in the safety of structures. According to statistics, parts that fail due to fatigue account for about 70% of the total number of mechanical equipment failures. Therefore, the fatigue problem of composite bolt connections has attracted the attention of many scholars.

2. Current Status of Fatigue Testing Research on Carbon Fiber Composite Materials

As an advanced high-performance material, carbon fiber composite primarily consists of two components: carbon fiber, which acts as the reinforcement material, and a matrix material, which can be resin, ceramic, or metal. Combining the high strength of carbon fiber with the formability of the matrix material gives carbon fiber composites excellent mechanical properties and broad application prospects. However, the fatigue behavior of composites is highly complex, often resulting from multiple interacting mechanisms. Common failure mechanisms include fiber breakage, fiber-matrix debonding, matrix cracking, fiber-matrix crack propagation, and delamination damage. The fatigue performance of composites is influenced not only by the intrinsic properties of the material but also by external factors, including the properties of the fiber and matrix, material layering [2,3], manufacturing defects, fatigue loading, and the service environment of the composite [4].

Wang Ying et al. conducted fatigue performance tests on T300/6511 composite materials ([±45°]), observed and analyzed the fracture morphology and internal damage of the samples, and studied the damage accumulation and fracture process of the laminated board under fatigue load. Huang Xi conducted fatigue tests on T300/BMP-316 new composite laminates (without holes and openings). Wang Yu-qian et al. conducted tensile-tensile fatigue tests on T700 composite materials at high stress levels, and the results showed that there was no clear pattern between stress levels and fatigue life, and the fatigue life was highly dispersed at different stress levels. Song Guang-qi conducted experiments on unidirectional plates and measured the degradation law and stress life relationship in their main direction. Based on the theory of simple laminated plates, a fatigue life prediction method for mixed laminated plates composed of different materials was developed. Mo Mingzhi conducted a study on the fatigue life and fatigue damage analysis of [0°/90°] laminates, and found that the main damage forms and processes of the material varied with the increase of cycle times, showing an overall three-stage trend of change. Kulkarni et al. [5] predicted the fatigue life of carbon fiber composite laminates with different fiber orientations

[0°/90°/45°].

Most fatigue research on composites involves conducting a series of tests on the material, then summarizing and analyzing the results to develop a fatigue life model for predicting untested materials. In previous studies, numerous scholars have conducted extensive fatigue testing, resulting in a relatively comprehensive fatigue database. However, due to the complexity of composite working environments, variations in layering, and differing loads, this database still has certain limitations. A new approach in current research should involve combining testing and simulation to study the fatigue performance of composites, enabling predictions of fatigue life and failure modes.

3. Research Status of Composite Bolt Connections

Composite material joining technology is a critical aspect of the engineering application of composites. By designing appropriate joining methods, different working conditions can be accommodated to fully leverage the material's performance, thereby enabling efficient replacement of traditional metal materials. Composite forming and processing are more complex than traditional materials, and the joining method impacts load transfer and overall structural performance. The design of the joint area will significantly affect the structure's strength and service life. Properly designing composite joints not only maximizes material performance but also effectively reduces assembly costs and improves assembly efficiency. Mechanical joining, adhesive bonding, and hybrid joining are the three most commonly used composite joining methods. Bolt joining, a type of mechanical connection, has become one of the primary methods for composite joining due to its ease of assembly, disassembly, and maintenance, along with its strong environmental fatigue resistance.

Many scholars have used modeling methods, finite element methods, and experimental methods to study the strength and failure modes of composite material connection structures under different loads. Yang Xiao et al. established a numerical analysis model for the failure of composite laminates under tensile load based on finite element method, and explored the failure modes and bearing capacity of bolt connections under tensile load by combining experimental and numerical analysis results. Liu Feng-rui et al. designed connectors with different layers and geometric dimensions, and used a method based on progressive loss of composite materials to obtain the failure load and failure mode of the connectors through experiments and simulations. Qin Zheng-qi conducted research on the fatigue damage characteristics of countersunk inclined surfaces and the fatigue wear behavior around holes in low-temperature environments using countersunk bolts as the research object. Joseph et al. [6] combined the Schapery theory for modeling microcracks in the matrix and the crack band theory for modeling macroscopic failures in laminates, and analyzed three failure modes of composite materials, including cracks, macroscopic and local compression, in the matrix. Jiang et al. [7] studied the fatigue performance of two types of laminates, [±45°] and [0°/90°], under various cyclic loads. Micro X-ray computed tomography was used for non-destructive testing to explore the fatigue failure mechanism of composite materials. Guo et al. [8] used a finite element model and stiffness degradation method to simulate the damage evolution process of bolted composite laminates. They numerically calculated the connection strength and failure mode of bolted composite laminates and obtained the influence of bolt quantity and arrangement on the tensile properties of bolted composite laminates.

Due to their anisotropy and brittleness, composite materials often have weak points at the opening of the structure. The bolt holes cut off the fibers, resulting in a complex and concentrated stress distribution around the holes. Unlike the plastic behavior of metallic materials, bolted connections in metals can achieve uniform stress distribution in each bolt hole through load redistribution, while composite materials exhibit linear behavior near failure, without local yielding or stress redistribution, resulting in uneven stress distribution in bolt holes. If the connection design of composite materials is improper, it may lead to serious structural damage and affect its reliability and durability. Therefore, it is necessary to continuously conduct in-depth research on composite material connection technology, analyze the influence of different materials, geometric parameters, and connection methods on strength and failure modes, in order to optimize the design of connectors.

4. Conclusion

This study examined the fatigue performance of carbon fiber composites and the current development of their bolted joint structures. With high strength, light weight, and excellent corrosion resistance, carbon fiber composites show tremendous application potential in fields such as aerospace and automotive manufacturing. However, predicting and optimizing their fatigue performance remains challenging due to the multiple factors affecting the fatigue behavior of composites. Through a review of relevant studies, this research identified the main failure mechanisms of carbon fiber composites under cyclic loading and analyzed the advantages and limitations of existing fatigue life prediction methods. Meanwhile, bolted joints, as the most commonly used mechanical joining method for composites, offer high assembly efficiency and ease of disassembly, yet the damage characteristics and fatigue performance of their joint areas require further study. Future research should combine experimental studies with advanced numerical simulation techniques to establish more accurate fatigue models and explore more efficient joint design methods.

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