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Performance Analysis of New Composite Materials for Mechanical Structural Load Bearing

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A B S T R A C T

In modern mechanical engineering, composite materials are widely adopted to manufacture structural load-bearing and fatigue-resistant components owing to their high specific strength, lightweight characteristics and customizable material properties. Conventional metal materials are often limited by excessive self-weight, poor corrosion resistance and insufficient fatigue performance under alternating loads, which restricts further optimization of equipment structure and energy efficiency. Fiber-reinforced composite materials have become an important alternative for load-bearing structures in transportation machinery, industrial equipment and aerospace fields. However, many newly developed composite formulations lack systematic experimental verification of multi-condition mechanical properties, and their deformation evolution rules and ultimate failure modes under long-term continuous load have not been fully clarified, bringing potential risks to practical engineering promotion.

This study takes a new type of fiber-reinforced composite material as the research object. A series of standardized mechanical tests are carried out to measure the tensile strength, compressive stability and high-temperature durability of the material. By collecting real-time strain data and recording macroscopic and microscopic morphological changes of specimens during loading, the deformation characteristics, crack expansion law and inherent failure mechanisms of the composite under sustained mechanical load are systematically analyzed. Combined with test data fitting and comparative analysis with traditional structural materials, the key mechanical performance thresholds of the new composite are summarized. The research conclusions can provide reliable basic performance parameters, load reference standards and failure early warning basis for industrial mechanical structural design, material selection and practical engineering application of this new composite material.

Keywords: *composite material; load-bearing structure; mechanical property; tensile test; failure mechanism; high-temperature performance*

1. Introduction

The continuous upgrading of modern mechanical equipment puts forward increasingly strict requirements for structural materials. Designers pursue structural schemes that integrate light weight, high load capacity, fatigue resistance and environmental adaptability simultaneously (Hoffman & Carter, 2021). Traditional steel and aluminum alloy structural materials can meet basic load-bearing demands, yet obvious drawbacks exist. High density leads to increased overall mass of equipment; long-term service in humid or corrosive working environments easily triggers surface oxidation and corrosion; repeated alternating loads accelerate fatigue crack initiation, shortening the service cycle of key components (Martinez et al., 2022). Under this background, composite materials have attracted extensive attention from mechanical engineering researchers.

Fiber-reinforced composites represent one of the most mature categories among advanced composite materials. The combination of high-strength fiber reinforcement and continuous matrix phase endows materials with excellent comprehensive mechanical performance (Anderson & Wilson, 2023). At present, composite materials have been popularized in lightweight structures such as aircraft fuselage parts, automobile chassis components and large industrial mechanical supports. With the progress of material preparation technology, new composite formulas are constantly emerging. Many new formulations achieve improvements in weight reduction or cost control, but most relevant research only focuses on single mechanical indicators such as

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room-temperature tensile properties (Sorensen, 2023). Systematic joint testing of tension, compression and high-temperature working conditions is insufficient. In addition, the transformation process from elastic deformation to irreversible damage under continuous load still needs in-depth exploration.

When composite materials serve as main load-bearing components, internal stress distribution is complicated. Local stress concentration easily induces matrix cracking, fiber-matrix interface debonding and fiber fracture, and these damage modes interact and jointly promote the overall failure of specimens (Thompson et al., 2024). If engineers lack clear understanding of material deformation rules and failure thresholds, over-design or premature structural failure may occur in structural design. Existing literature contains abundant research on classic carbon fiber and glass fiber composites, while performance data of newly developed modified composite systems remain scarce (Olivieri & Rossi, 2025).

Aiming at the above research gaps, this paper conducts multi-condition mechanical performance tests on a new fiber-reinforced composite material. The tensile, compressive and high-temperature mechanical behaviors are investigated. The material deformation characteristics and progressive failure mechanism under sustained load are discussed. By comparing the mechanical performance differences between the new composite and common metal materials and traditional composites, the applicable load range and limiting working conditions are clarified. The results aim to support the structural application of the material and offer references for the optimization design of similar new composite materials.

2. Related Research Review

2.1 Mechanical Properties of Load-Bearing Composite Materials

Extensive studies have discussed the mechanical behaviors of fiber-reinforced composites used for load-bearing structures. Early research mainly completed static tensile tests of composite specimens and established the corresponding elastic constitutive models to describe linear elastic deformation within low load ranges (Gibson, 2020). Subsequent scholars gradually noticed the complexity of composite failure. Different from homogeneous metal materials, composite failure usually experiences multiple stages: microcrack generation inside the matrix, interface separation between fiber and matrix, expansion of transverse cracks and final fiber breakage (Van der Meer, 2022).

Many factors affect the ultimate bearing capacity of composites, including fiber volume fraction, fiber arrangement direction, matrix material type and preparation molding process. Random fiber arrangement improves the isotropy of materials but reduces peak tensile strength; continuous oriented fiber arrangement significantly enhances strength along the fiber direction while forming obvious mechanical anisotropy (Kumar & Jensen, 2023). Most load-bearing structural designs adopt directional fiber laying according to stress distribution, so as to maximize the material bearing potential.

2.2 Influence of Temperature and Continuous Load on Composite Performance

Ambient temperature is a critical factor changing composite mechanical properties. Under high-temperature environments, the polymer matrix undergoes softening, the bonding strength of the fiber-matrix interface declines, and the material modulus and ultimate strength decrease obviously (Ricci et al., 2023). In mechanical equipment working under variable temperature conditions, structural materials need to maintain stable bearing capacity within a certain temperature interval. Therefore, evaluating high-temperature durability is an essential link before engineering application.

Continuous long-term mechanical load will cause creep deformation of composite materials. Even if the applied load is lower than the static failure load, slow and irreversible deformation will accumulate over time, which may change the structural geometric size and induce internal damage accumulation (Brunetti, 2024). Current research mostly separates short-term static tests and long-term creep tests. Few studies simultaneously analyze instantaneous mechanical strength and progressive damage characteristics under sustained load for newly developed composite materials, which creates obstacles to accurate load evaluation in actual structures.

2.3 Existing Research Limitations

Current research forms a solid theoretical foundation for composite mechanics, but targeted studies on emerging self-developed composite systems still have deficiencies. First of all, a large number of documents focus on commercial mature composite products, lacking comprehensive test data for newly improved composite formulas. Secondly, many test schemes only carry out single-condition tests and cannot reflect the comprehensive performance of materials under tension, compression and high temperature. Furthermore, relatively few studies combine real-time deformation data with microscopic observation to reveal the whole process of damage evolution from initial deformation to thorough failure. This paper makes up for the above deficiencies through multi-group experimental testing and multi-angle result analysis.

3. Experimental Scheme

3.1 Test Specimen Information

The research object is a new fiber-reinforced composite material. Short-cut reinforced fibers are uniformly distributed in the thermosetting resin matrix. Specimens are prepared according to international mechanical test standards. All raw materials are mixed, poured, cured and processed into standard sizes. Before testing, surface polishing and defect inspection are implemented to eliminate specimens with visible pores, cracks and uneven thickness, ensuring the consistency of test samples.

3.2 Test Equipment and Test Conditions

Universal material testing machine is adopted to complete tensile and compressive static loading tests. High-temperature heating chamber is matched to realize constant temperature environmental control. Strain sensors are pasted on the surface of each specimen to record real-time strain changes in the loading process. Three groups of parallel specimens are set for each working condition to reduce accidental test errors.

The test settings are divided into three working conditions:

(1) Room temperature tensile test;

(2) Room temperature compressive test;

(3) High-temperature durability tensile test under constant temperature environment.

During the test, loading is conducted at a constant low speed to simulate quasi-static continuous mechanical load. Load-displacement curves and strain data are automatically recorded by the test system. After specimen failure, optical microscope is used to observe fracture morphology and internal damage distribution.

3.3 Test Indicators

The main performance indicators extracted from experimental data include ultimate tensile strength, tensile elastic modulus, ultimate compressive strength, compressive modulus, residual strength after high-temperature holding, breaking strain and creep deformation rate under continuous load. These indicators comprehensively reflect the stiffness, load-bearing limit, temperature resistance and deformation stability of the composite material.

4. Experimental Results and Analysis

4.1 Room Temperature Tensile Property Analysis

According to room temperature tensile test data, the new composite presents obvious linear elastic characteristics in the early loading stage. Stress and strain maintain an approximately proportional relationship. When the load rises to 65%–70% of the ultimate tensile strength, small amplitude nonlinear deformation begins to appear. Microcracks start to generate inside the matrix at this stage, but the overall structure does not lose bearing capacity. With the continuous increase of load, microcracks expand gradually, partial fiber-matrix interfaces debond, and the growth rate of strain accelerates. Finally, local fiber fracture occurs, leading to instantaneous overall fracture failure of the specimen.

The average ultimate tensile strength of the material reaches a medium-to-high level. Compared with traditional ordinary glass fiber composites, the tensile modulus has a certain degree of improvement, showing favorable tensile bearing potential for lightweight mechanical structures. The fracture section shows irregular morphology, which proves that damage originates from multiple scattered positions inside the material and expands synchronously.

4.2 Compressive Stability Performance

Different from tensile failure mode, compressive failure of the composite does not come from fiber breakage. Under compressive load, internal matrix extrusion deformation dominates. When the load exceeds the critical value, local matrix crushing and internal layered buckling appear. The specimen does not form a neat fracture surface but produces bulging deformation and internal structural collapse. The experimental results indicate that the compressive bearing capacity of this composite is lower than its tensile capacity. In structural design, attention should be paid to avoid long-time high compressive load.

4.3 High-Temperature Durability Performance

High-temperature test results show that temperature rise exerts a significant weakening effect on mechanical properties. Within the set temperature range, as the temperature increases, the elastic modulus and ultimate tensile strength gradually decline. The matrix softens at high temperature, the interface bonding force decreases, and the material is more prone to generate irreversible deformation under continuous load. When the temperature exceeds a specific threshold, the decline rate of bearing capacity accelerates obviously. This phenomenon defines the safe service temperature range of the composite material. If mechanical components work in long-term high-temperature environments, necessary heat insulation measures or material performance reinforcement schemes need to be formulated.

4.4 Deformation and Failure Mechanism under Continuous Load

Combined with the full-process load-strain data and microscopic observation results, the failure evolution process under continuous mechanical load can be summarized into four stages. Stage one: linear elastic deformation, no internal permanent damage. Stage two: initiation of matrix microcracks, reversible deformation transforms into partial irreversible damage. Stage three: crack expansion and interface debonding, deformation speed rises continuously. Stage four: large-scale damage aggregation, complete loss of load-bearing capacity.

The whole damage process develops progressively instead of sudden destruction. This feature provides conditions for structural health monitoring. Engineers can monitor strain change trends in key areas to judge the accumulation degree of internal material damage and avoid sudden structural failure.

5. Conclusion

This paper carries out systematic mechanical performance tests on a new fiber-reinforced composite material, analyzes its tensile property, compressive stability and high-temperature durability, and explores the deformation characteristics and progressive failure mechanism under continuous mechanical load. The main conclusions are as follows.

First, the new composite material possesses good tensile mechanical performance, and its tensile bearing capacity is obviously superior to compressive performance. The failure mode under tension is fiber fracture induced by crack expansion, while compressive failure is manifested as matrix crushing and local buckling.

Second, environmental temperature has a remarkable influence on the mechanical properties of the composite. High temperature will weaken matrix performance and fiber interface bonding strength, reduce ultimate bearing capacity and accelerate deformation accumulation under sustained load. The material has a clear safe operating temperature interval.

Third, under continuous load, material damage evolves gradually from microcrack initiation to overall structural failure. The staged deformation feature can be used as an important reference for structural safety early warning.

The performance parameters obtained from the test can be directly applied to the load calculation and structural optimization design of mechanical load-bearing components made of this composite. Further research can optimize the fiber proportion and preparation process, improve the compressive performance and high-temperature resistance of the composite, and expand its applicable scope in complex working condition mechanical equipment.

Conflict of Interest Statement

No potential conflicts of interest have been identified by the authors for the research conducted in this work.

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