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Analysis of Fatigue Behavior of Carbon Fiber Sucker Rods

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ABSTRACT

This study modeled a carbon-fiber sucker rod using a three-layer concentric finite-element design comprising a carbon fiber core, a glass fiber interlayer, and a high-modulus glass fiber outer layer to simulate axial fatigue behavior in ANSYS under bonded reverse cyclic axial loading. The rod's midsection demonstrated exceptional fatigue performance, reaching 6.53×10^7 cycles and a damage index of ten, highlighting carbon fiber's lightweight nature and high reliability. At the load application end, severe stress concentration caused a significant reduction in fatigue life, making that region especially vulnerable to failure. Along the rod's radius, the central zone experienced the lowest fatigue life of about 2.15×10^6 cycles and the highest damage peak around 465.9, due to complex load paths combined with concentrated stress. Conversely, the outer edge region, where carbon fiber directly bore the load, exhibited fatigue life and damage characteristics similar to those of the midsection. The study identified material anisotropy and uneven stress distribution as primary factors contributing to increased fatigue risk at both the rod ends and the central core. These findings offer essential guidance for optimizing end-connection design and laminate lay-up, supporting reliable and lightweight applications of composite sucker rods in deep-well environments.

KEYWORDS

Carbon Fiber Sucker Rod; Fatigue Life Analysis; Finite Element Analysis.

1. INTRODUCTION

Carbon fiber is a high-performance new material made from petroleum, containing over 90% carbon and characterized by high strength and high modulus. It combines the soft processability of textile fibers with notable advantages such as low density, high strength, corrosion resistance, and fatigue resistance [1, 2]. Continuous sucker rods made primarily from carbon fiber have demonstrated excellent results in oil extraction. The development of carbon fiber composite continuous sucker rods originated from the practical needs of oilfields. Traditional steel sucker rods often fail due to drawbacks like high density, comparatively limited strength, and poor corrosion resistance, especially in deep, ultra-deep, and corrosive oil wells. These issues have long been a weak point in pumping systems. To address these problems, Western countries led research and development efforts to create flexible continuous sucker rods, resulting in carbon fiber continuous sucker rods. Technological development of these rods can be traced back to the United States: in the early 1980s, the U.S. initiated research on carbon fiber sucker rods. In the early 1990s, Henlan Company in the U.S[3]. successfully developed a non-metallic ribbon sucker rod utilizing advanced graphite composite technology from the aerospace sector. To test its performance, field trials were conducted in 1981 and 1983 in oil wells measuring 1219.2 meters and 1524 meters, respectively, yielding positive results. These efforts marked the beginning of research, development, and application of carbon fiber continuous sucker rods. Currently, the analysis of their fatigue characteristics remains limited, so this paper investigates this aspect.

2. FATIGUE LIFE SIMULATION OF CARBON FIBER SUCKER RODS

2.1. Calculation Parameters

(1) Assumptions for the Finite Element Model of Carbon Fiber Composite Sucker Rods

To significantly simplify the model and reduce the computational cost of composite sucker rods in ANSYS finite element analysis, and to focus on how the material properties of the core and winding layers influence the overall mechanical response under dominant axial loads, the following key assumptions are adopted in this simulation.

Firstly, the effects of the non-circular cross-section caused by the actual fiber winding process and the influence of winding angles on performance are overlooked. The three-layer structure, which might originally have a complex cross-section, is simplified as a coaxial concentric circular ring cross-section with clear thickness measurements—that is, the carbon fiber core, the glass fiber intermediate layer, and the high-modulus glass fiber outer layer are tightly nested in perfect circular rings in sequence.

Second, without considering the actual adhesive properties between layers, potential interfacial slip, or debonding failure mechanisms, perfect displacement coordination and force transfer between the carbon fiber core and the glass fiber layer, as well as between the glass fiber layer and high-modulus glass fiber layer, are achieved through "tied contact," which is equivalent to no relative movement between layers.

Third, ignoring the subtle regulatory effect of curing agent characteristics on the overall macroscopic mechanical behavior of the winding layers, each layer of material is considered as a macroscopically uniform and equivalent continuous medium—the carbon fiber core provides its overall mechanical properties, the intermediate glass fiber layer offers its homogeneous material properties based on the cured state of its specific glass fibers, and the outermost high-modulus glass fiber layer supplies its own homogeneous material properties based on the cured state of its specific high-modulus glass fibers. These equivalent properties must be determined through experimental characterization or micromechanical methods.

The main goal of these simplification measures is to isolate and evaluate the role of the core material and key properties, such as modulus and strength of each layer, in the axial performance of the sucker rod. This relates mainly to load conditions involving axial tension and compression.

(2) Determination of mechanical property parameters of materials

The table displays the modeling parameters of carbon fiber pumping rods.

Table 1 Structural parameters of composite sucking rod

parameters	Free bar length /mm	Diameter D/mm	Core diameter d/mm	Wrap layer thickness /mm	Fiberglass layer thickness /mm
Composite sucking rod	200	22	12	0.7	4.3

2.2. Geometric Modeling and Simulation Conditions

The service environment of sucker rods in oilfields in China is mostly at well depths of one to two thousand meters. When studying the oil well lifting process, establishing a finite element solid model for the sucker rod string can produce analysis results closer to actual test data. However, solid elements are complex, resulting in high computational load for large engineering problems and demanding hardware requirements. This poses challenges for subsequent numerical simulations of the rod string lifting motion. Therefore, this paper uses an equivalent model approach. To reduce computational complexity, a simulation mesh with a resolution of 7 is selected instead.

Figure 1 Grid division of composite sucking rod section

2.3. Fatigue Analysis

2.3.1. Fatigue Life and Damage Analysis

Amid the trend of lightweight upgrades in oil and gas extraction equipment, carbon fiber sucker rods have become a major alternative to traditional metal sucker rods due to their high specific strength and low density. In this study, fatigue life and damage simulations were conducted on a 200mm-long, 22mm-diameter carbon fiber sucker rod using Ansys2023R1 simulation software. Mechanical response patterns were analyzed across axial and cross-sectional dimensions, establishing a solid theoretical foundation for engineering applications and optimal design. Key findings are summarized as follows:

(1) Axial dimension: "End sensitivity" characteristics of fatigue life and damage

1) Fatigue life distribution pattern:

As shown in the axial life contour plot (Figure 2), the main body of the sucker rod displays a uniformly dark blue region, indicating high-magnitude life values with a maximum of 6.5259×10^7 cycles. This confirms that carbon fiber materials offer excellent baseline fatigue resistance to the rod—under typical cyclic loading, the primary structure maintains a stable load-bearing capacity with minimal risk of fatigue damage initiation, fully demonstrating the benefits of lightweight design and high reliability in carbon fiber composites. In contrast, the end region shows notable differences: the maximum and minimum life values are relatively close to each other. Since the end is where tensile force is applied, stress concentration effects overlap, making it a sensitive area for fatigue life.

2) Distribution law of fatigue damage:

In the axial damage nephogram (Figure 3), the main area is predominantly yellow, indicating low damage values, with the minimum damage value being 10. This suggests that the primary structure faces minimal damage risk under simulated working conditions, allowing the mechanical properties of the carbon fiber material to be effectively utilized. In contrast, the color in the local end region gradually changes, and the damage value increases significantly, reaching a maximum of 465.86. This confirms the "end sensitivity" identified in the life analysis and further indicates that the end region may have potential fatigue failure risks due to stress concentration effects.

(2) Cross-Sectional Dimension: Life Gradient and "Circular Layer Characteristics" of Damage

1) Fatigue Life Gradient Distribution

The cross-sectional life contour map (Figure 4) reveals a clear "center-edge" life gradient: the central area, marked by yellow and red (low-life zone), has a minimum life value of just 2.1466×10^6 cycles, while the edge area, shown in dark blue (high-life zone), aligns with the axial life values of the main body. Due to complex load transfer paths and overlapping stress concentration effects, the central area is likely a high-risk zone for fatigue damage. In contrast, the edge area demonstrates better fatigue resistance, thanks to the direct load-bearing capacity of carbon fiber reinforcements and a more even stress distribution.

2) Fatigue Damage in Circular Layer Distribution

In the cross-sectional damage contour map (Figure 5), damage values form a circular pattern with "higher central values and lower edge values": the damage in the central area approaches the peak axial damage at the end, reaching a maximum of 465.86, while the damage at the edges decreases to match the axial damage level of the main body, showing strong consistency with the life gradient distribution.

Figure 2 Axial life cloud diagram

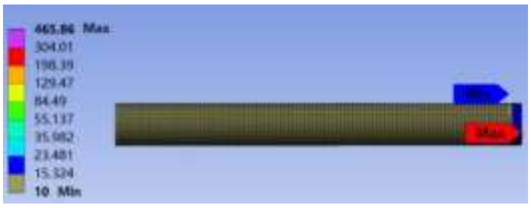

Figure 3 Axial damage cloud diagram

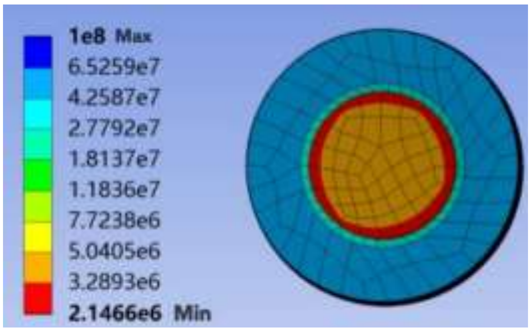

Figure 4 Cross-sectional life cloud diagram

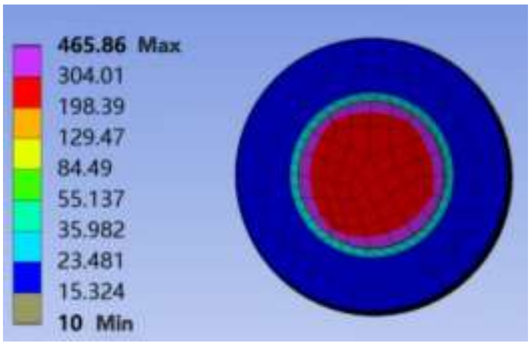

Figure 5 Cross-sectional damage cloud map

In conclusion, based on simulation analysis with Ansys, the fatigue performance characteristics of carbon fiber sucker rods are revealed from multiple perspectives. This research establishes a vital link for structural optimization design and engineering application promotion, supporting the combined advancement of "lightweight" and "high reliability" for carbon fiber composite materials in the oil and gas extraction industry.

3. SUMMARY

To examine the fatigue performance of carbon fiber sucker rods in lightweight applications, this paper develops a simplified three-layer concentric circle model using Ansys 2023 R1. This model comprises a carbon fiber core, a glass fiber intermediate layer, and a high-modulus glass fiber outer layer. Assuming bonded contact and neglecting interlayer slip and interface failure, the focus is on how material properties influence axial mechanical responses. Fatigue simulations were performed on a 200 mm-long and 22 mm-diameter sucker rod, leading to the following key conclusions:

In the axial direction, the main rod body exhibits excellent fatigue resistance, with a lifespan of up to 6.53×10^7 cycles and a damage value of just 10, clearly showing the benefits of carbon fiber in lightweight design and high reliability. However, the end becomes a fatigue-prone area due to stress concentration, leading to a significant reduction in service life and an increase in damage value to 465.86. Structural optimization is urgently needed through chamfer transitions or flexible connections.

In the cross-sectional view, fatigue properties exhibit a clear gradient from the center to the edge. The central area, with complex load transfer paths and stress concentration, has the shortest service life of just 2.15×10^6 cycles and a peak damage value of 465.86, similar to the failure risk at the edges. Conversely, the edge area, where carbon fiber reinforcements directly carry the load, maintains a service life comparable to the main body and has a lower damage value of 10. This characteristic results from the material's anisotropy and uneven stress distribution, indicating that the center of the cross-section is a potential high-risk zone for fatigue damage.

This study explains the fatigue failure mechanism of carbon fiber sucker rods from multiple angles, providing an essential foundation for engineering improvements: Changing lay-up configurations, such as adjusting angles or gradient layering, can distribute load transfer paths more evenly across the cross-section; at the same time, enhancing the design of the end connection structure improves overall fatigue performance. This allows carbon fiber composites to make significant advances in lightweight design and high reliability for oil and gas extraction applications.

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