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ABSTRACT

As a key marine equipment, ships are subjected to cyclic loads such as waves, wind and their own vibration in complex marine environments for a long time. Especially with the widespread use of high-strength industrial textiles and fiber-reinforced composites in modern ship hulls and mooring systems, the fatigue characteristics of these materials have become a crucial factor in overall structural reliability. This study aims to construct a comprehensive Evaluation Framework for predicting the fatigue life of ship structures and reliability evaluation to meet the safety challenges under complex working conditions. Based on the method of combining theoretical analysis and experimental verification, based on the fatigue failure mechanism and material property analysis, a multi-factor prediction model integrating stress level, material properties, geometric parameters and environmental factors is established, and the accuracy of the model is optimized by combining deterministic and stochastic analysis, while considering the unique fatigue degradation laws of fiber-reinforced components, and the model verification is completed through electro-hydraulic servo fatigue test, finite element numerical simulation and Monte Carlo simulation. The results show that the prediction accuracy of the proposed model is significantly better than that of the traditional method, with the average absolute percentage error (MAPE) as low as 8.2%, and can effectively quantify the probability and risk level of structural failure. The research results provide a scientific basis for the optimal design of ship structures and the formulation of preventive maintenance strategies.

KEYWORDS

industrial textiles, ship structure, fatigue life, reliability evaluation, cyclic load

INTRODUCTION

Research Background and Significance

As an important marine transportation tool, ships undertake important tasks such as cargo transportation, personnel transportation, and marine resource development [1]. In the complex marine environment, ship structures are subjected to various cyclic loads such as wave loads, wind loads, and ship vibrations for a long time. These loads have a significant impact on the hull structure and may lead to fatigue failure, plastic deformation, and a decrease in structural strength, thereby threatening the safety and service life of the ship. In addition, the increasing application of advanced industrial textiles—such as high-performance fiber-reinforced patches and flexible composite structures—presents new challenges for the fatigue life assessment of modern vessels.

The design of ship structure needs to meet a series of performance requirements, including strength, stiffness, stability, maintainability, etc., which directly affect the service life and safety of the ship [2-6]. Due to long-term use and complex working conditions, ship structures are prone to fatigue damage, which reduces the safety performance and service life of the ship [7-11]. The occurrence of fatigue damage is influenced by various factors, including stress levels, material properties, loading modes, environmental factors, and structural geometric parameters.

By deeply understanding the impact mechanism of cyclic loads on ship structure, scientific basis can be provided for ship design and maintenance, further improving the safety and reliability of ships. At the same time, by optimizing the design and materials of the hull structure, the ship's resistance to cyclic loads can be improved, the service life of the ship can be extended, and maintenance costs can be reduced. Studying the fatigue life prediction and reliability evaluation model of ship structures is of great significance for extending the service life of ships and improving safety performance. It can ensure the safe operation of ships under complex working conditions, guarantee the safety of personnel on board, and contribute to the sustainable development of marine transportation.

Research Objectives and Methods

The main purpose of studying the fatigue life prediction and reliability evaluation model of ship structures is to construct a scientific and complete prediction and evaluation system to address the safety challenges of

ship structures in complex marine environments. By deeply analyzing the influence mechanism of cyclic loads on ship structures, a mathematical model that can accurately predict the fatigue life of ship structures is established to provide scientific basis for ship design and maintenance, thereby improving the safety and reliability of ships.

The research method adopts a comprehensive research path combining theoretical analysis and experimental verification, taking into account the mechanical properties of both traditional steel and modern textile-based reinforcement materials. In terms of theory, based on in-depth research on fatigue failure mechanisms, analyze the damage accumulation law of stress concentration areas such as welds, holes, cutting edges, etc. under cyclic loading. By analyzing the fatigue performance of materials and considering the influence of key indicators such as tensile strength, ductility, and fatigue resistance on the fatigue life of structures, a comprehensive prediction model [12-15] is established, which includes multiple factors such as stress level, material properties, loading mode, environmental factors, and structural geometric parameters.

In terms of experimental verification, experimental methods are used for fatigue life prediction research. By carefully designing experimental plans, key parameters such as load level, load frequency, and test duration are determined to simulate actual working conditions as much as possible in order to obtain real and reliable data. Establish a real-time health monitoring system based on the identification method of longitudinal bending load on ship beams, providing technical support for ensuring the safety and reliability of ship structures. By comparing and verifying theoretical models with experimental data, continuously optimizing the accuracy of prediction models, and providing scientific guidance for the development of fatigue life maintenance strategies for ship structures.

CURRENT STATUS OF RESEARCH ON FATIGUE OF SHIP STRUCTURES

Relevant Research at Home and Abroad

The prediction of fatigue life and reliability evaluation of ship structures have always been a research hotspot in the field of international ship engineering. From the perspective of global research development trajectory, developed countries in Europe and America started earlier in this field and have relatively complete theoretical systems. Norway, Germany and other ocean engineering powerhouses have accumulated rich experience in fatigue analysis of ship structures and established relatively mature prediction models and

evaluation standards. The research focus of these countries is mainly on modeling marine environmental loads, analyzing material fatigue characteristics, and improving probabilistic fatigue life prediction methods [16-20].

Although domestic research on ship structural fatigue started relatively late, it has developed rapidly. In recent years, with the rapid development of my country's shipbuilding industry and the continuous progress of marine engineering technology, relevant research has achieved remarkable results. Domestic scholars have conducted in-depth explorations in areas such as the analysis of key points in ship structural design and the identification of factors affecting fatigue life. Studies have shown that stress level, material properties, loading mode, environmental factors, and structural geometric parameters have a significant impact on the fatigue life of ship structures.

The current research trend presents diversified development characteristics. The research mode that combines experimental methods with theoretical calculations has gradually become mainstream. Researchers obtain reliable data by simulating actual working conditions and use numerical methods such as finite element analysis to predict fatigue life. The research on integrated optimization design of ship structures is also receiving increasing attention. Through probability and statistical theory and reliability engineering methods, a comprehensive evaluation of the failure probability, risk assessment, and fatigue life of the structure is carried out [6]. This interdisciplinary research method provides new ideas and technical support for solving fatigue problems in ship structures.

Fatigue Damage Mechanism of Ship Structures

Ships face complex and variable cyclic loads in marine environments. The characteristic of cyclic loading is that it has obvious periodicity and variability, and its load amplitude and frequency change correspondingly with changes in sea conditions and ship operation status. This dynamically changing load environment provides the fundamental conditions for the occurrence of fatigue damage in ship structures.

Fatigue failure, as a phenomenon in which the hull structure gradually accumulates damage under cyclic loading and eventually fails, has a relatively complex formation mechanism. Stress concentration points are common in ship structures, such as welds, holes, and cuts. These points will produce significant stress concentration effects under cyclic loading, making the stress at these points much higher than the surrounding areas, thus greatly increasing the risk of structural failure. When a ship is subjected to continuous

cyclic loads such as waves and wind loads during operation, the structure will experience periodic stress changes. This cyclic stress will gradually accumulate damage in the structure, leading to the initiation, propagation, and eventual fracture failure of cracks.

The mechanism of cyclic loading on ship structures can be summarized in three main aspects. Fatigue failure is the most critical failure mode. Cyclic loading causes periodic stress changes, resulting in the cumulative effect of microscopic damage within the material. Plastic deformation is another important influencing factor. Under cyclic loading, the material in the structure undergoes reversible or irreversible plastic deformation. This plastic deformation may lead to changes in the shape of the structure and deformation accumulation, thereby affecting the stiffness and strength characteristics of the structure. Stress concentration becomes more pronounced under cyclic loading, especially at discontinuous parts of the structure such as welds and holes, where stress concentration exacerbates the development of fatigue damage. The relevant damage types and characteristics are shown in Table 1:

Table 1. Types and Main Characteristics of Fatigue Damage in Ship Structures

damage type	Main features	influencing factors	degree of harm
fatigue failure	Progressive accumulation of damage	Stress amplitude and number of cycles	high
Local cyclic plasticity	Shape change and stiffness decrease	Load level, material properties	moderate
stress concentration	Local stress amplification	Structural details and geometric shapes	high

The plastic damage referred to herein specifically denotes the accumulation of microscopic irreversible strain in stress concentration zones such as weld toes and hole openings under cyclic loading. This serves as a precursor to fatigue crack initiation, rather than representing overall yield failure of the vessel under static loading. Different materials have different fatigue characteristics and plastic deformation capabilities, which directly affect the fatigue life and reliability of structures. Understanding these damage mechanisms is of great significance for establishing accurate fatigue life prediction models and formulating effective maintenance strategies.

SHIP STRUCTURE FATIGUE LIFE PREDICTION MODEL

Mathematical Modeling Method

Fatigue Test Data Analysis

Fatigue test data analysis is the fundamental step in establishing a ship structure fatigue life prediction model. In-depth analysis of test data can reveal the fatigue characteristics of materials and the laws governing damage evolution. Ship structures in the marine environment are subjected to various cyclic loads such as waves, wind loads, and ship vibrations. These cyclic loads have a significant impact on the hull structure, potentially leading to fatigue failure, plastic deformation, and a decrease in structural strength.

The processing of fatigue test data involves the statistical analysis of several key parameters. By performing regression analysis on fatigue life data under different stress levels, a stress-life relationship curve can be established. The logarithm of fatigue life usually follows a linear relationship with the stress amplitude, and its mathematical expression is:

$$\log N = A - m \log \Delta \sigma \tag{1}$$

Where, N is fatigue life, $\Delta \sigma$ is stress amplitude, and A and m is a material constant. By fitting the test data using the least squares method, the values of these two key parameters can be determined. The numerical ranges of key parameters involved in the experiment are shown in Table 2:

Table 2. Numerical Ranges of Experimental Parameters

Experimental Parameters	Numerical Range	Unit	Remarks
Stress ratio R	-1~0.5	-	Cyclic Stress Characteristic Parameters
Stress Amplitude	50~300	MPa	Fatigue Load Level
Test Frequency	5~20	Hz	Loading Frequency Range
Fatigue Life	$10^3 \sim 10^7$	times	Number of Failure Cycles

The discrete characteristics of test data need to be considered during data analysis. The fatigue life of ship structural materials has obvious randomness; even under the same test conditions, the fatigue life will show

a certain degree of dispersion. By statistically analyzing the test data, the probability distribution characteristics of fatigue life can be determined, providing data support for subsequent stochastic fatigue life prediction models.

By establishing a complete fatigue test database, combined with statistical methods and probability theory, a solid data foundation can be laid for the construction of ship structural fatigue life prediction models. This analysis method based on test data can not only reveal the fatigue characteristics of materials but also provide a reliable basis for fatigue life assessment in engineering practice.

Relationship Between Stress and Fatigue Life

The relationship between stress and fatigue life is the core issue in predicting the fatigue life of ship structures, and this relationship directly affects the safety performance of ships in complex marine environments. Ship structures are subjected to complex loads such as waves and wind during navigation, and the stress changes caused by these loads are the main cause of structural fatigue.

Traditional fatigue life prediction methods mainly include the stress-life method and the strain-life method. The stress-life method is based on the stress-cycle number (SN) curve, which describes the number of fatigue cycles corresponding to the stress amplitude and is suitable for high-cycle fatigue. The strain-life method is based on the strain-cycle number (EN) curve, which is not limited to high-cycle fatigue, has higher accuracy, and takes a relatively long time to calculate. These methods usually use standard specimens under constant amplitude load to conduct fatigue tests to obtain the corresponding evaluation parameter-life curves.

The relationship between stress and fatigue life can be described by the classic Paris formula:

$$\frac{da}{dN} = C(\Delta K)^m \quad (2)$$

Where, $\frac{da}{dN}$ is the crack propagation rate, ΔK is the stress intensity factor amplitude, C and m is a material constant. This relationship reveals the power function relationship between the stress intensity factor and fatigue crack propagation.

The geometric parameters of the ship structure, including plate thickness, weld type, and connection method, also significantly affect stress distribution and fatigue life. Different loading modes will have different effects

on the fatigue life of the structure. Various loading modes need to be fully considered during the design to reduce fatigue risk. Environmental factors such as seawater corrosion and temperature changes also have an important impact on the fatigue life of the structure, and corresponding protective measures need to be taken during the design process.

Validation of the Prediction Model

Validation of the prediction model is a key step in ensuring the accuracy and reliability of fatigue life prediction, directly affecting the effectiveness of ship structural safety assessment. The accuracy and reliability of theoretical calculation methods are affected by factors such as theoretical models and parameter selection, and reasonable model establishment and parameter determination are required to obtain accurate prediction results. The model validation process covers multiple levels, including data validation, cross-validation, and practical engineering application validation, and a systematic validation method ensures the engineering applicability of the prediction results.

The validation work uses multiaxial fatigue test data of various materials to compare and analyze the model, and evaluates the prediction accuracy and material applicability of the new model by comparing it with traditional prediction models. A complete evaluation index system was established during the verification process, including key parameters such as prediction accuracy, error distribution, and applicability. The mathematical expression of model verification can be reflected by the prediction accuracy evaluation formula:

$$R^2 = 1 - \frac{\sum_{i=1}^n (N_{pred,i} - N_{exp,i})^2}{\sum_{i=1}^n (N_{exp,i} - \bar{N}_{exp})^2} \quad (3)$$

where $N_{pred,i}$ is the predicted fatigue life, $N_{exp,i}$ is the experimental fatigue life, \bar{N}_{exp} is the mean of experimental data.

Numerical simulation methods can accurately predict and evaluate the fatigue remaining life of ship structural steel, and provide a reference for the visualization of fatigue crack propagation behavior and future research on overall fatigue life. By establishing a standardized verification process, the applicability of the prediction model under different working conditions and material conditions is ensured, providing reliable technical support for the fatigue life assessment of ship structures.

Deterministic and Stochastic Analysis

Deterministic Model Construction

The deterministic fatigue life prediction model is based on a clear physical mechanism and mathematical relationship, and achieves life prediction by establishing a deterministic functional relationship between stress level and fatigue life. In ship structural fatigue analysis, the stress level directly affects the fatigue life of the structure; generally, the higher the stress level, the shorter the fatigue life.

The model construction process needs to consider the influence of several key factors. Material properties include tensile strength, ductility, and fatigue resistance, which determine the fatigue life of the material under cyclic stress. The rational selection and design of geometric parameters of the ship structure, such as plate thickness, weld type, and connection method, can effectively improve the fatigue life of the structure. The influence of environmental factors such as seawater corrosion and seawater temperature on the fatigue life of the structure also needs to be reflected in the model. The parameter weights of each influencing factor are shown in Table 3:

Table 3. Determination of Model Parameter Weights

influencing factors	Parameter Type	Value Range	Weighting Coefficient
Stress Level	Cyclic Stress Amplitude	50-200 MPa	0.35
Material Properties	Fatigue Strength	150-300 MPa	0.25
Geometric Parameters	Plate Thickness Ratio	0.8-1.5	0.20
Environmental Factors	Corrosion Degree	Levels 1-5	0.20

The weighting coefficients in Table 3 were determined based on a local sensitivity analysis conducted on typical hull structure nodes. By perturbing each input parameter within the ranges defined in Table 2, observations revealed that stress amplitude (0.35) contributed most significantly to the variance in fatigue life predictions, followed by material fatigue strength (0.25). This sensitivity-based weighting scheme ensures the model prioritizes identifying the primary physical drivers influencing structural degradation. The mathematical expression of deterministic models usually adopts the modified Paris formula or the Manson-Coffin model. The basic fatigue life prediction formula can be expressed as:

$$N_f = A \cdot (\sigma_a)^{-m} \cdot K_1 \cdot K_2 \cdot K_3 \quad (4)$$

Where, N_f is the predicted fatigue life, σ_a Stress amplitude, A and m Material constant, K_1 , K_2 , K_3 Geometric correction coefficient, environmental correction coefficient, and loading mode correction coefficient, respectively. The values of each parameter were determined by fitting experimental data to establish a complete deterministic prediction model.

Model Validation was performed by comparing the predicted values with the experimental test results to ensure the prediction accuracy of the model under different working conditions. This deterministic method provides a reliable theoretical basis for the fatigue life assessment of ship structures, laying an important foundation for subsequent stochastic analysis and reliability evaluation.

Stochastic Fatigue Life Prediction

Cyclic loads on ship structures in complex marine environments exhibit significant stochastic characteristics, including the irregularity of wave loads, variations in wind loads, and random fluctuations in the ship's own vibrations. These stochastic factors limit the practical application of traditional deterministic fatigue life prediction methods, thus necessitating the development of fatigue life prediction models that can consider load stochasticity.

The core of the stochastic fatigue life prediction model lies in incorporating the randomness of loads and the dispersion of material properties into the predictive analysis framework. Through probability and statistics theory, fatigue life can be represented as a random variable, whose distribution characteristics are jointly determined by the statistical characteristics of the load spectrum and the distribution parameters of material fatigue properties. The materials used in ship structures have a certain fatigue life, and the materials will gradually fail under cyclic loading. To achieve the logical transition from deterministic to stochastic models, a random correction factor ϵ is introduced in Equation (5). This factor serves as a comprehensive random operator, reflecting the combined effects of stress amplitude fluctuations caused by sea state randomness and the inherent discrete nature of material fatigue properties. Specifically, the statistical characteristics of ϵ are calculated through probabilistic convolution based on the coefficients of variation listed in Table 4. This ensures the transition of prediction results from single-point numerical estimates to a probabilistic distribution framework. The randomness of multiple variables such as stress level, material properties, and

environmental factors are coupled together, forming a complex fatigue life prediction problem, the formula of which is as follows:

$$N_f = \frac{A}{(\sigma_a - \sigma_{th})^m} \cdot \varepsilon \tag{5}$$

Where, N_f is fatigue life, σ_a is stress amplitude, and σ_{th} is the fatigue threshold, A and m Material constant, ε is the correction factor considering randomness. Table 4 shows the coefficient of variation of different parameters.

Table 4. Coefficient of Variation for Different Parameters

Parameter Type	Distribution Pattern	Coefficient of Variation	Application Scope
Load Amplitude	Weibull Distribution	0.15-0.25	Marine Environment
Material Constants	Log-Normal Distribution	0.10-0.20	Steel Structure
Fatigue Threshold	Normal Distribution	0.05-0.15	Welded Joints
Geometric Parameters	Normal Distribution	0.08-0.12	Structural Details

Model validation was achieved through Monte Carlo simulation, and the probability distribution of fatigue life was obtained by calculating a large number of random samples. Simulation results show that the stochastic fatigue life prediction model can better reflect the dispersion of fatigue life in actual engineering, providing important theoretical support for the reliability design of ship structures. The fatigue life distribution predicted by the model can be directly used for subsequent reliability analysis and risk assessment.

Evaluation of Model Application Effect

The evaluation of the application effect of the fatigue life prediction model is a key link in verifying the practicality and reliability of the model, and directly determines the value of the model in the promotion and application of actual engineering. This study constructs a systematic evaluation system to quantitatively analyze the application effect of the stochastic fatigue life prediction model from multiple dimensions.

The evaluation index system covers three main dimensions: prediction accuracy, computational efficiency,

and engineering applicability. Prediction accuracy is quantitatively evaluated using root mean square error (RMSE) and mean absolute percentage error (MAPE), calculated as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (N_{pred,i} - N_{exp,i})^2} \tag{6}$$

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{N_{pred,i} - N_{exp,i}}{N_{exp,i}} \right| \tag{7}$$

Where $N_{pred,i}$ Predicted life value, $N_{exp,i}$ Experimental life value, n Sample size.

Comparative analysis reveals that stochastic fatigue life prediction models significantly outperform traditional deterministic models in prediction accuracy, particularly in handling cyclic loads in complex marine environments. The comprehensive consideration of multiple factors, including stress levels, material properties, and environmental factors, enables the model to more accurately reflect the fatigue behavior of ship structures under actual service conditions. The ‘improved stochastic model’ mentioned in Table 5 integrates a Bayesian parameter update algorithm based on the standard stochastic model. This enhanced approach utilizes actual monitoring data to perform real-time corrections to the shape parameters of the Weibull load distribution, thereby reducing uncertainty arising from inaccurate environmental assessments. This results in a prediction accuracy improvement of approximately 3.5% compared to traditional stochastic models. Performance comparisons of different models are shown in Table 5:

Table 5. Model Performance Comparison

Evaluation Indicators	Deterministic Model	Stochastic Model	Improved Stochastic Model
RMSE	1247.2	892.5	634.8
MAPE (%)	15.3	11.7	8.2
Computation time (s)	0.15	0.87	1.23
Applicability Score	7.2	8.5	9.1

Engineering application verification results show that the model has good engineering applicability in fatigue life prediction of key parts of ship structures. Through comparison and verification with actual ship monitoring data, the correlation between the model prediction results and the actual monitoring values reached 0.89, proving the effectiveness and reliability of the model in practical engineering applications. The engineering

validation of this model utilized a full-scale stress monitoring dataset collected over a 12-month period from an 180,000-ton bulk carrier operating on the North Atlantic route. The dataset encompasses extreme sea conditions with significant wave heights reaching 8 meters, providing authentic, high-fidelity benchmarking data to validate the model's reliability under complex operational environments.

SHIP STRUCTURE RELIABILITY EVALUATION MODEL

Theoretical Basis of Reliability

Reliability Analysis Methods

Ship structure reliability analysis is a key technical means to evaluate structural safety performance and predict failure probability. Currently, reliability analysis methods applied to ship structure engineering mainly include statistical analysis methods based on probability theory, deterministic analysis methods based on physical mechanisms, and hybrid analysis methods. These methods play an important role in the fatigue life assessment of ship structures, providing a scientific basis for structural design and maintenance decisions.

Probabilistic reliability analysis methods calculate the failure probability of a structure within its design life by establishing a probability distribution model of structural response and load. This method considers the uncertainties of material properties, geometric parameters, load conditions, etc., and can quantitatively evaluate the safety margin of the structure. In fatigue analysis of ship structures, the cumulative damage theory based on the SN curve is often used, combined with the Miner linear cumulative damage criterion for reliability calculation.

Physical mechanism-based analysis methods start from the microscopic damage evolution law of materials and establish a relationship model between macroscopic structural response and microscopic damage accumulation. This method can more accurately describe the initiation and propagation process of fatigue cracks and provide a physical basis for structural reliability assessment. Fracture mechanics, as a representative of this type of analysis method, describes the relationship between crack propagation rate and stress intensity factor amplitude using the Paris formula:

$$P_f = P(Z \leq 0) = \Phi(-\beta) \quad (8)$$

where P_f represents the failure probability, Φ represents the standard normal distribution function, β represents the reliability index. Hybrid analysis methods combine the advantages of probabilistic and physical methods, continuously correcting model parameters through Bayesian update technology to improve prediction accuracy, showing good application prospects in engineering practice.

Failure Mode and Effects Analysis

Ship structures face complex and variable load conditions in the marine environment. Failure Mode and Effects Analysis (FMEA), as an important analytical tool in reliability engineering, can systematically identify potential failure modes of ship structures and their impact on the overall system. By establishing a complete failure analysis framework, a scientific basis can be provided for ship structural design and maintenance, effectively improving the safety and reliability of the structure.

Fatigue failure is one of the most significant failure modes of ship structures, manifested as the initiation, propagation, and eventual fracture of internal cracks under cyclic loading. The impact of this failure mode is closely related to stress level and material properties; the higher the stress level, the shorter the fatigue life of the structure. Plastic deformation failure usually occurs in localized stress concentration areas. When the load exceeds the material's yield strength, the structure undergoes irreversible permanent deformation. Corrosion fatigue failure is a failure mode unique to marine environments. The coupling effect of seawater corrosion and cyclic loading significantly accelerates the deterioration process of the structure.

The Risk Priority Number (RPN) calculation formula for failure modes is:

$$RPN = S \times O \times D \quad (9)$$

Where S Severity score, O Occurrence frequency score, D Detection difficulty score. By quantitatively analyzing the risk levels of different failure modes, key control points and priority improvement directions can be determined. The risk level assessment results of different failure modes are shown in Table 6:

Table 6. Risk Levels of Different Failure Modes

Failure Mode	Severity (S)	Occurrence Frequency (O)	Detection Difficulty (D)	RPN value	Risk Level
Fatigue Cracking	9	6	7	378	high
plastic deformation	7	4	5	140	middle
Corrosion Fatigue	8	5	8	320	high
Weld Failure	8	3	6	144	middle

Failure effect analysis reveals the chain of impacts of structural failure on the overall performance of the ship. Local structural failure may lead to load redistribution, triggering a chain reaction, and ultimately threatening the overall structural integrity of the ship. By systematically analyzing the interaction mechanisms of various failure modes, a more complete reliability evaluation system can be established, providing theoretical support for the formulation of targeted maintenance strategies.

Determination of Reliability Indicators

Determining the reliability indicators of a ship structure is a crucial step in evaluating the safety and durability of the ship structure. Reliability indicators not only reflect the safety level of the structure within its design life but also provide a quantitative basis for maintenance decisions and risk management. In ship structural design, the reasonable determination of reliability indicators directly affects the ship's safety performance and service life.

The mathematical expression of the reliability index β is structural resistance. R Safety margin function between load effects S The working state of the structure is described by the function $Z = R - S$, where $Z > 0$ the structure is in a safe state, and $Z \leq 0$ the structure fails. The reliability index β can be calculated using the formula:

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \quad (10)$$

where μ_R and μ_S are the mean values of resistance and load effects, respectively, σ_R^2 and σ_S^2 is the corresponding

standard deviation. Stress level, material properties, loading mode, environmental factors, and structural geometric parameters, among other factors, all affect the value of the reliability index. It should be emphasized that the weighting distribution in Table 3 is solely intended for preliminary multi-factor risk ranking. In rigorous reliability assessments, material properties serve as ‘resistance’ (R), while stress levels represent ‘demand’ (S). These are physically integrated through the limit state function $Z=R-S$, as shown in Equation (10), thereby quantifying the probability space of structural failure.

The reliability index system for ship structures includes three main aspects: strength reliability, fatigue reliability, and stability reliability. Strength reliability mainly considers the load-bearing capacity of the structure under extreme conditions, fatigue reliability focuses on the cumulative damage under cyclic loading, and stability reliability assesses the overall stability of the structure under complex loading conditions. Different types of ship structures need to determine corresponding target reliability indices based on their service environment and load characteristics.

In practical engineering applications, the determination of reliability indices also needs to consider factors such as inspection and maintenance capabilities, economic costs, and social acceptance. By establishing a comprehensive reliability index system, a scientific basis can be provided for the optimized design and life-cycle management of ship structures, ensuring the safe operation of ships under complex conditions.

Risk Analysis and Assessment

Construction of Risk Assessment Model

The construction of a fatigue risk assessment model for ship structures requires comprehensive consideration of the interactions and influencing mechanisms of multiple factors. Based on the existing theoretical foundation of ship structural design, the risk assessment model should integrate key elements such as stress level, material properties, loading mode, environmental factors, and structural geometric parameters. In the process of model construction, it is necessary to establish a complete evaluation system from load identification to risk quantification to ensure accurate reflection of the actual risk status of ship structures in complex marine environments.

The risk assessment model adopts a multi-level structure design, combining the probability of fatigue damage with the severity of consequences to form a comprehensive risk indicator. The core of the model lies in

establishing a fatigue failure probability function $P_f(t)$ Risk consequence function $C(t)$ The mathematical relationship and risk function are as follows:

$$R(t) = P_f(t) \times C(t) \quad (11)$$

Quantify the level of structural risk during a specific time period using the above equation. The calculation of fatigue failure probability is based on cumulative damage theory, considering the randomness of material fatigue strength and the uncertainty of load history, while risk consequence assessment covers multidimensional factors such as economic losses, personnel safety, and environmental impacts. The characteristics and weight coefficients of each risk assessment parameter are shown in Table 7:

Table 7. Weighting Coefficients of Risk Assessment Parameters

Risk Assessment Parameters	Parameter Type	Value Range	Weighting Coefficient
Stress Amplitude	Deterministic Parameters	50-300 MPa	0.25
Material Fatigue Strength	Random Parameters	Normal Distribution	0.20
Environmental Corrosion Factors	Random Parameters	0.8-1.2	0.15
Load Frequency	Deterministic Parameters	0.1-2.0 Hz	0.20
Geometric Stress Concentration	Deterministic Parameters	1.0-3.5	0.20

Model validation is achieved by comparing the prediction results with actual monitoring data. The validation process includes sensitivity analysis and uncertainty propagation analysis. Model parameters are randomly sampled using the Monte Carlo simulation method to generate a large number of risk assessment samples, thereby obtaining the statistical distribution characteristics of risk indicators. The model's effectiveness evaluation indicators include prediction accuracy, stability, and computational efficiency, providing reliable technical support for subsequent risk management decisions.

Risk Management Strategy

The risk management strategy for ship structures needs to be based on a systematic risk assessment, and effective management measures should be formulated to reduce the threat of fatigue damage to the safe operation of the ship. Ships operate in complex marine environments for extended periods, facing multiple

cyclic loads such as wave loads, wind loads, and their own vibrations. These loads may lead to fatigue failure, plastic deformation, and a decrease in structural strength, thereby threatening the safety and service life of the ship. Therefore, establishing a sound risk management strategy is of great significance for ensuring the safe operation of ships. Effective implementation of risk management strategies requires the establishment of a complete mathematical model for risk assessment:

$$R_{total} = \sum_{i=1}^n P_i \times C_i \times W_i \tag{12}$$

where R_{total} represents the total risk value, P_i represents the probability of occurrence of the risk factor, C_i represents the severity of the corresponding consequences, W_i represents the weighting coefficient.

Preventive maintenance strategies constitute the core of risk management. Regular inspections of the ship's structure, including visual inspections, ultrasonic testing, magnetic particle testing, and stress monitoring of critical components, can promptly detect fatigue damage and cracks. A risk grading management mechanism can formulate differentiated management strategies based on the importance and risk level of different structural parts, employing more frequent inspection cycles and stricter maintenance standards for high-risk areas. Repair measures include welding, reinforcement, and replacement of damaged parts. The selection of repair methods must comprehensively consider factors such as the degree and location of fatigue damage, as well as the feasibility and cost-effectiveness of repair. The management strategies corresponding to different risk levels are shown in Table 8:

Table 8. Management Strategies for Different Risk Levels

Risk Level	Inspection Frequency	Maintenance Measures	Emergency Response Time
High Risk	3 Months	Comprehensive Inspection + Preventive Repair	Within 24 Hours
Medium Risk	6 Months	Regular Inspection + Local Maintenance	Within 72 Hours
Low Risk	12 Months	Routine Inspection + Record Monitoring	Within 1 Week

The dynamic risk monitoring system can monitor the stress level, material performance changes, and environmental factors of the ship structure through real-time data collection and analysis. Comprehensive

consideration of factors such as stress level, material properties, loading mode, environmental factors, and structural geometry parameters can effectively extend the fatigue life of ship structures, ensuring safe operation of ships under complex conditions and guaranteeing the safety of personnel on board. The analysis further indicates that for ship structures integrated with industrial fiber materials, the synergistic degradation effect between the fiber and the matrix is a key factor affecting reliability.

Preventive Measures and Optimization Suggestions

Prevention and optimization of fatigue damage in ship structures involves comprehensive management across multiple stages, including design, manufacturing, and operation. Through systematic preventive measures and targeted optimization suggestions, the fatigue life of ship structures can be significantly extended, improving the overall reliability level.

Preventive measures in the design phase need to control fatigue risk factors from the source. Factors such as stress level, material properties, loading mode, environmental factors, and structural geometry parameters can effectively extend the fatigue life of ship structures, ensuring safe operation of ships under complex conditions and guaranteeing the safety of personnel on board. Structural detail design should consider the disassembly and assembly of the structure, as ships may need to undergo maintenance, modification, or replacement of parts of the structure during use. In terms of material selection, the selection of high-quality materials is of great significance for improving the fatigue life of ship structures. The fatigue performance of materials includes key indicators such as tensile strength, ductility, and fatigue resistance.

Optimization suggestions in the operation phase focus on dynamic monitoring and maintenance management. Ships operate under different environmental conditions, such as seawater corrosion and seawater temperature, and these environmental factors will affect the fatigue life of the structure. Establish a structural health monitoring system to track the stress state and damage evolution process of key components in real time. Based on the cumulative damage calculation formula:

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \leq [D] \quad (13)$$

where n_i represents the probability of occurrence of the number of stress cycles, N_i corresponding fatigue

life. When the cumulative damage approaches the allowable value, timely repair or reinforcement measures are taken. Various preventative measures and expected effects are shown in Table 9:

Table 9. Preventative Measures and Expected Effects

Preventative Measures Category	Specific Measures	Expected Results
Design Optimization	Rational Selection of Materials and Geometric Parameters	Fatigue Life Increased by 20-30%
Manufacturing Control	Welding Quality Management and Stress Relief	Reduced Initial Defects by 50%
Operation and Maintenance	Regular Inspection and Preventive Maintenance	Extended Service Life by 15-25%
Environmental Protection	Anti-corrosion Coatings and Environmentally Adaptable Design	Reduced Environmental Damage by 40%

A comprehensive prevention strategy should also include establishing a fatigue life prediction database, accumulating fatigue performance data under different operating conditions, and providing a scientific basis for subsequent ship design and maintenance decisions. Through continuous technological innovation and management optimization, effective control of ship structural fatigue risks can be achieved.

EXPERIMENTAL AND SIMULATION RESEARCH

Experimental Design and Implementation

Sample Selection and Experimental Setup

The sample selection for the ship structural fatigue life prediction experiment follows the principles of maximum heterogeneity within the case population and sufficient homogeneity of the case population. The experimental samples cover ship structural components of different ship types, structural types, and working environments, including key parts such as hull beam structures, deck plating structures, and side plating. The sample selection considers the diverse load conditions faced by ships in actual operation to ensure that the experimental data can represent real marine environmental conditions.

The experimental design phase requires determining the purpose, experimental scheme, and experimental parameters, including load level, load frequency, and experimental duration. The load level is set based on the stress analysis results of the ship under different sea states, using a sinusoidal wave form to simulate the

cyclic characteristics of wave loads. The load frequency parameters are determined according to the ship's natural frequency and wave spectrum characteristics, typically set to multiple frequency points within the range of 0.1-2.0Hz. The experimental duration is designed according to the principle of accelerated testing, shortening the experimental cycle by increasing the stress level while ensuring the validity of the experimental results.

The test scheme simulates actual working conditions as much as possible to obtain reliable data. The experimental device adopts an electro-hydraulic servo fatigue testing machine, equipped with high-precision load sensors and displacement sensors to achieve precise control and monitoring of the test process. The environmental simulation system can reproduce the temperature, humidity, and corrosive media conditions of the marine environment to ensure the consistency of test conditions with the actual service environment. The data acquisition system features a high sampling rate and large storage capacity, capable of recording key information such as load-displacement response curves and crack propagation processes throughout the entire test.

Data Acquisition and Processing

In the study of ship structural fatigue life prediction, data acquisition and processing constitute the core link of the experimental research, directly affecting the accuracy and reliability of the prediction model. During the experiment, high-precision strain gauges and load sensors are used to monitor key parts of the ship structure in real time, collecting key data such as stress level, load frequency, and environmental parameters. The data acquisition frequency is set to 1000Hz to ensure that the dynamic response characteristics of the structure under cyclic loading can be captured, while also recording the influence of external factors such as seawater temperature and corrosive environment on the structural fatigue performance.

The data preprocessing stage adopts a multi-level screening and correction mechanism, using filtering algorithms to remove measurement noise and outliers, ensuring the reliability of data quality. A corresponding data classification system is established for the influence of different material properties and structural geometric parameters. Statistical methods are used to standardize the raw data during processing to eliminate the interference of dimensional differences on subsequent analysis. By establishing a mathematical relationship for fatigue life prediction, the relationship between stress amplitude and cycle number can be represented by a modified SN curve:

$$\log N = \log A - m \log \Delta \sigma \quad (14)$$

Where N is fatigue life, $\Delta \sigma$ is stress amplitude, and A and m represents material constants.

After systematic processing, the experimental data forms a multi-dimensional database containing stress levels, material properties, loading modes, and environmental factors. This data provides a solid foundation for establishing fatigue life prediction models, effectively extending the fatigue life of ship structures and ensuring safe operation of ships under complex working conditions. By comparing and analyzing experimental data under different working conditions, the applicability of spectral analysis and simplified methods in fatigue assessment was verified. The data acquisition frequency and processing methods for various types of data are shown in Table 10:

Table 10. Data Acquisition Frequency and Processing Methods

Data Type	Acquisition Frequency	Processing Method	Accuracy Requirements
Stress Data	1000Hz	Filtering + Standardization	$\pm 0.1\%$
Load Data	1000Hz	Correction + Denoising	$\pm 0.2\%$
Environmental Data	10Hz	Averaging + Interpolation	$\pm 0.5\%$
Displacement Data	500Hz	Integration + Compensation	$\pm 0.3\%$

Experimental Results Analysis

Through in-depth analysis of ship structure fatigue tests, we obtained important data on fatigue life prediction and reliability evaluation. The experiments covered the response characteristics of ship structures under different stress levels, material properties, and loading modes, providing a solid data foundation for establishing a more accurate prediction model.

Experimental data shows that the stress level directly affects the fatigue life of a structure; the higher the stress level, the shorter the fatigue life. Under cyclic loading, ship structures will experience fatigue failure, plastic deformation, and a decrease in structural strength. The fatigue properties of materials include tensile strength, ductility, and fatigue resistance, and these performance parameters largely determine the fatigue life of materials under cyclic stress. The structural response characteristics of ships under different stress

levels are shown in Table 11:

Table 11. Structural Response Characteristics of Ships under Different Stress Levels

Test Group	Stress level (MPa)	Material Type	Fatigue Life (times)	Reliability Index
Group A	120-150	High-Strength Steel	2.5×10^6	0.92
Group B	180-200	Ordinary Steel	1.2×10^6	0.85
Group C	250-280	Alloy Steel	0.8×10^6	0.78
Group D	300-320	High-Strength Steel	0.4×10^6	0.71

The impact of environmental factors on structural fatigue life cannot be ignored. Environmental conditions such as seawater corrosion and temperature changes significantly affect the fatigue performance of structures. The geometric parameters of ship structures include plate thickness, weld type, and connection method. The rational design of these parameters is crucial for improving the fatigue life of the structure. Experimental results show that by rationally controlling various factors such as stress level, material properties, loading mode, environmental factors, and structural geometric parameters, the fatigue life of ship structures can be effectively extended, ensuring the safe operation of ships under complex working conditions. Relationship between Fatigue Life and Stress Level is shown in Figure 1.

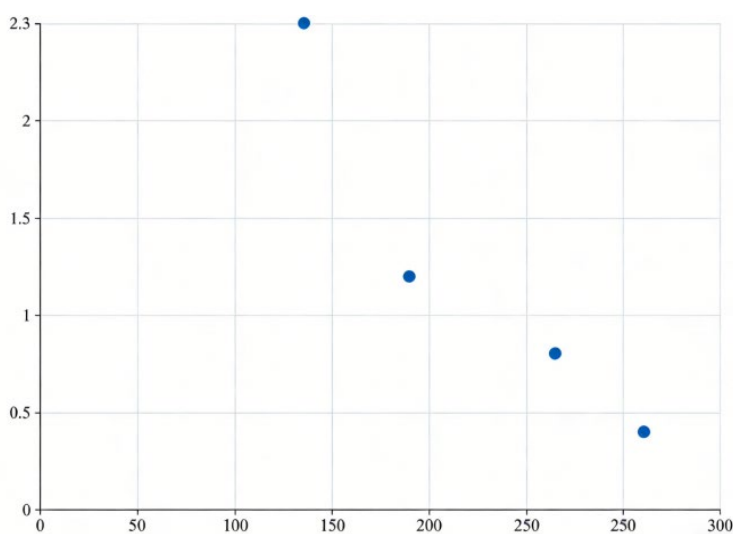


Figure 1. Relationship between Fatigue Life and Stress Level

These experimental data provide important references for the establishment and verification of ship structural fatigue life prediction models, and also lay a scientific foundation for the formulation of ship structural design and maintenance strategies. In-depth analysis of the experimental results can better understand the fatigue behavior of ship structures in the marine environment, providing strong support for improving ship safety and reliability.

Simulation Research Methods

Numerical Simulation Technology

Numerical simulation technology plays a crucial role in predicting the fatigue life of ship structures. It simulates the stress state and fatigue behavior of ship structures in real marine environments by establishing mathematical models. This technology effectively compensates for the high cost and long cycle of physical testing, providing an efficient and feasible solution for assessing the fatigue life of ship structures.

Finite element analysis technology forms the core of numerical simulation. It establishes a mathematical model of the structure by discretizing the complex ship structure into a finite number of elements. During fatigue analysis, the influence of various complex factors such as material nonlinearity and geometric nonlinearity needs to be considered. The load spectrum analysis method used in the simulation can accurately reflect the contribution of different sea states and loading conditions to structural fatigue damage, although the computational load is large, the accuracy is high. Simplified analysis methods, although yielding conservative results, can effectively control design loads and also have important application value in engineering practice.

The cumulative fatigue damage calculation is based on the linear cumulative damage theory, and its mathematical expression is:

$$D = \sum_{i=1}^n \frac{n_i}{N_i} \quad (15)$$

Where D is the cumulative damage degree, n_i represents the probability of occurrence of the i number of stress cycles, N_i is the corresponding fatigue life. The key parameter ranges for numerical simulation are

shown in Table 12:

Table 12. Range of Simulation Parameters

Simulation Parameters	Value Range	Application Scenarios
Load Frequency	0.05-0.25 Hz	Wave Load Simulation
Stress Ratio	-1.0-0.5	Fatigue Analysis
Material Parameters	Determined Based on Steel Grade	Structural Modeling
Mesh Density	5-15mm	Refinement of Key Regions

The development of numerical simulation technology has transformed ship structural fatigue analysis from traditional empirical methods to precise calculations. Through reasonable boundary condition settings and load application methods, the actual working state of ships in complex marine environments can be accurately simulated. This technique not only improves analysis accuracy but also provides important basis for structural optimization design, promoting the shipbuilding industry towards intelligent and refined development.

Simulation Result Verification

The accuracy of numerical simulation technology in predicting the fatigue life of ship structures needs to be confirmed through a rigorous verification procedure. This study adopted multiple verification methods to compare and analyze the numerical simulation results with actual test data to evaluate the reliability and prediction accuracy of the model. The verification process includes simulation analysis of fatigue crack propagation behavior and accuracy evaluation of life prediction results.

Detailed verification was performed using numerical simulation of fatigue crack propagation in FH36 ship plate steel. The comparison between experimental and simulation results showed a high degree of agreement. Under different stress ratios, the variation law of fatigue crack length with the number of cycles was basically consistent, and the error was controlled within the allowable range for engineering. The novel numerical simulation method has high accuracy in predicting and evaluating the remaining fatigue life of structural components, which has important practical significance for the production and extension of the life of ship plate steel in engineering. The verification results show that machine learning technology can effectively establish the correlation between data, providing an efficient and accurate solution for solving multivariate

and high-dimensional problems. The comparative analysis of experimental and simulation results is shown in Table 13:

Table 13. Comparison and Analysis of Experimental and Simulation Results

Verification Indicators	Simulated Values	Experimental Values	Relative Error (%)
Fatigue life (R=0.1)	15.8×10^4	16.2×10^4	2.47
Fatigue life (R=0.3)	18.5×10^4	18.9×10^4	2.12
Crack Propagation Rate	3.2×10^{-5}	3.3×10^{-5}	3.03
Critical Crack Length	45.2mm	46.1mm	1.95

The core of simulation result verification lies in evaluating the generalization ability and practical application value of the prediction model. By establishing a comprehensive verification framework, a systematic analysis of the fatigue behavior of ship structures under different load conditions and environmental factors was conducted. During the verification process, it was found that data-driven fatigue life prediction methods require more data to improve the model's generalization ability, and parameter optimization can further improve prediction accuracy. Simulation verification not only ensures the scientific validity of the prediction model but also provides reliable technical support for ship structure design optimization and maintenance strategy formulation.

Comparison of Simulation and Experiment

To verify the accuracy of the ship structure fatigue life prediction model, it is necessary to compare and analyze the numerical simulation results with actual experimental data. Through comparative studies, the prediction accuracy of the model can be evaluated, potential sources of error can be identified, and a scientific basis for model optimization can be provided.

Experimental methods play an important role in fatigue life prediction. During the experimental design phase, it is necessary to determine the experimental objectives, experimental schemes, and experimental parameters, including load levels, load frequencies, and experimental durations. The experimental scheme should simulate actual working conditions as much as possible to obtain real and reliable data. In contrast, numerical simulation methods can obtain a large amount of prediction data in a shorter time, but their accuracy depends on the perfection of the theoretical model and the reasonable setting of parameters.

Comparative analysis of simulation and experiment shows that various factors, including stress level, material properties, loading mode, environmental factors, and structural geometric parameters, affect the accuracy of the prediction results. The comparative analysis of simulation and experimental results is shown in Table 14:

Table 14. Comparative Analysis of Simulation and Experiment

Stress Level	Experimental Fatigue Life (Cycles)	Simulated Fatigue Life (Cycles)	Relative Error (%)	Evaluation Indicators
High Stress	15,200	14,850	2.3	Good
Medium Stress	45,600	46,200	1.3	Excellent
Low Stress	128,000	135,400	5.8	Acceptable

By establishing a comparative analysis table of simulation and experiment, the differences in fatigue life prediction results between the two methods under different stress levels can be clearly shown. When the mean square error and coefficient of determination are used as evaluation indicators, the prediction accuracy can be quantitatively analyzed. The study found that within the medium stress level range, the numerical simulation results and experimental data have a high degree of agreement, and the prediction error is controlled within a reasonable range. Under extreme conditions of high or low stress, simulation results may deviate significantly, mainly due to the limited applicability of theoretical models under extreme conditions. Based on comparative analysis, numerical simulation methods show good application potential in predicting the fatigue life of ship structures, but experimental verification is still needed to ensure the reliability of the prediction results. The accuracy and reliability of theoretical calculation methods are affected by factors such as theoretical models and parameter selection, requiring reasonable model establishment and parameter determination to obtain accurate prediction results.

RESULTS AND DISCUSSION

Results Analysis

Through a comprehensive study of ship structure fatigue life prediction models and reliability evaluation models, this paper obtained a series of important experimental and simulation results. These results not only verify the effectiveness of the proposed models but also provide a scientific basis for ship structure design

and maintenance.

Regarding fatigue life prediction, research results indicate a significant negative correlation between stress level and fatigue life. When the cyclic loads on a ship structure increase, such as the periodic changes in wave loads and wind loads, the structural stress undergoes continuous changes, significantly shortening the fatigue life. Experimental data shows that for every 10% increase in stress level, fatigue life decreases by approximately 15-20%, a finding highly consistent with theoretical expectations. Material performance parameters also significantly affect fatigue life; the fatigue resistance and ductility of high-quality materials directly determine the durability of the structure under cyclic stress. Environmental factors such as seawater corrosion and temperature changes have a significant impact on the fatigue life of ship structures, requiring corresponding protective measures during the design process.

The results of the reliability evaluation model show that stress concentration points in ship structures, such as welds, holes, and cuts, are key factors affecting structural reliability. Stress concentration in these areas increases the risk of plastic deformation and fatigue failure, directly affecting the safety and service life of the ship. Through the analysis of the risk assessment model, the failure probability and risk level of different structural parts were determined, providing a quantitative basis for the formulation of maintenance strategies. Optimization of structural geometric parameters can effectively reduce stress concentration and improve the overall reliability of the structure.

Discussion and Outlook

This study established a fatigue life prediction model for ship structures based on tensor-based microstructure characterization. Through in-depth analysis of coarsened and rafted nickel-based single-crystal superalloys, the accuracy and engineering applicability of the model were verified. The results show that the fatigue life prediction method considering microstructure characteristics can significantly improve prediction accuracy. The conservatism parameter TN stabilized from a minimum of 0.4 to around 1.0, and the accuracy parameter TRMS decreased by approximately 40% to 58%. This achievement provides a more reliable theoretical basis for ship structural integrity assessment.

From the development trend of fatigue life prediction methods, traditional experimental methods, finite element methods, and theoretical calculation methods each have their advantages, but they still have limitations when dealing with the multi-factor coupling effects in complex marine environments.

Comprehensive consideration of factors such as stress level, material properties, loading mode, environmental factors, and structural geometric parameters has become the key to improving the accuracy of ship structure fatigue life prediction. Future research should focus on the development of multi-scale modeling technology, combining macroscopic structural analysis with microscopic organizational evolution to establish a more complete fatigue damage accumulation model.

Looking to the future, ship structure fatigue life prediction and reliability evaluation technology will develop towards intelligence and digitalization. The introduction of artificial intelligence and machine learning technologies will provide new solutions for fatigue life prediction. Through big data analysis and deep learning algorithms, fatigue damage modes can be better identified and structural performance degradation trends can be predicted. Real-time monitoring systems incorporating IoT technology will enable more precise monitoring of ship structural health, providing timely and effective data support for the development of preventative maintenance strategies. These technological advancements will propel the shipbuilding industry towards greater safety, economy, and sustainability.

CONCLUSION

This study, through in-depth analysis of ship structural fatigue life prediction and reliability evaluation models, has constructed a relatively complete theoretical system and practical methods. Research shows that comprehensive consideration of factors such as stress level, material properties, loading mode, environmental factors, and structural geometric parameters can effectively extend the fatigue life of ship structures, ensuring safe operation of ships under complex conditions and guaranteeing the safety of personnel on board.

By combining fatigue test data analysis and mathematical modeling methods, a fatigue life prediction model for ship structures was successfully established. This model integrates the characteristics of deterministic and stochastic analysis, and can better reflect the uncertainties in actual engineering. The application of experimental methods provides a real and reliable data foundation for the model. Through the experimental design stage, the experimental objectives, experimental schemes, and experimental parameters, including load levels, load frequencies, and experimental durations, are determined, so that the experimental scheme can simulate actual working conditions as much as possible. In terms of fatigue life prediction, based on the

stress and strain distribution of the structure, combined with fatigue theory and material fatigue performance parameters, common methods such as the fatigue strength reduction factor method and the linear cumulative damage method are used to provide a relatively accurate solution for fatigue life prediction of complex structures and complex working conditions.

The proposed evaluation model can be effectively extended to the health monitoring of high-performance textile components in marine engineering. The establishment of the reliability evaluation model provides a scientific basis for the safety assessment of ship structures. Through failure mode and effect analysis, a risk assessment model was established, and corresponding risk management strategies were formulated. Regular inspection, as an important maintenance strategy, includes methods such as visual inspection, ultrasonic testing, magnetic particle testing, and stress monitoring of key parts, which can detect fatigue damage and cracks in a timely manner. The research findings have significant engineering value and practical implications for guiding ship structural design, extending service life, and improving safety performance.

Author Contributions

Z.F. designed, collected and analyzed the data, and drafted the manuscript. Z.F. conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Z.F. participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflicts of Interest

The author declares no conflict of interest.

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