Research Article

Optimal Design Method for Vessel-Bridge Collision Based on Life-Cycle Theory

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As structures crossing waterways, bridges are obstacles to vessels. Vessel-bridge collisions are inevitable. They not only involve the safety of vessel passage but also seriously affect the safe operation of bridges. Vessel-bridge collisions cause not only huge economic losses and casualties but also severe political and environmental losses. Vessel collision safety of existing and new bridges is one of the key technical problems that engineers and bridge managers must solve. Comprehensive consideration of vessel-bridge collision risk loss and structural performance in the design stage to achieve optimal cost over the life cycle is an important aspect of bridge design. Based on the current life-cycle design theory of engineering structures, this paper proposes a theoretical framework for vessel-bridge collision optimization design based on the life cycle, which includes three parts: vessel-bridge collision probability analysis, vessel-bridge collision vulnerability analysis, and vessel-bridge collision hazard. Taking the minimum cost of the bridge structure in the design service life period as the objective function, the optimization design model and design process of vessel-bridge collision based on whole life are established, and the key problems to be solved in each part are expounded.

1. Introduction

In recent years, with economic growth, more bridges have been built around the world, bigger vessels are being built, and vessel-bridge collisions occur frequently [1, 2]. Bridges, as structures spanning waterways, are undoubtedly an obstacle to vessels. Of course, it is impossible to completely prevent the occurrence of vessel-bridge collisions. At the same time, the completion of the bridge will change the water environment of the bridge area, such as flow velocity, bend, scouring, siltation, and tidal level. The tonnage, scale, and speed of vessels are increasing continuously. Therefore, the occurrence of vessel-bridge collisions is inevitable, which not only involves the safety of vessel passage but also seriously affects the safe operation of bridges. Vessel-bridge collision is different from a general traffic accident. Once it occurs, it usually has serious consequences, which not only cause huge economic losses and casualties but also have negative political effects and cause serious environmental losses. So, the vessel collision safety of existing and new bridges is one of the key technical problems that engineers and bridge managers need to solve.

Life-cycle design concepts and methods are the mainstream development direction of the civil engineering structure design theory [3]. At present, in the design theory of vessel-bridge collision, the design theory in American AASHTO specification and European specification is the most comprehensive. In 1991, the American Society of Road Engineers compiled the Guidelines for Vessel Collision Design of Highway Bridges [4], which specifically proposed the vessel collision design standards and design methods based on risk thinking for inland bridges in the United States, covering the determination of design of vessels, collision probability analysis, vessel collision failure.
probability calculation, vessel collision force calculation, vessel damage length calculation, and collision protection system design. Since 1994, the core provisions of the guide have been incorporated into the American Code for Design of Highway Bridges [5]. In 2009, the United States revised and updated its Guidelines for Design of Highway Vessel-Bridge Collision [6]. This specification introduced the idea of risk assessment into the design for vessel-bridge collisions and clearly stipulated the risk criteria for bridges with varying importance. In 1997, European Harmonized Norms Volume I (Eurocode 1) Volume 2.7 was published to guide vessel-bridge collision design [7]. The European code provides two analysis methods for vessel collision forces in bridge design as follows: deterministic analysis and probabilistic risk analysis. The risk probability analysis method mainly includes the calculation of vessel-bridge collision frequency and bridge collapse frequency. The determination of the design vessel collision force needs to ensure the annual collapse frequency of bridges caused by vessel collision is lower than the acceptable annual collapse frequency.

Geng et al. [8] analyzed the load characteristics of a trunk highway and its influence on the life-cycle cost of a highway bridge structure and compared the life-cycle cost of bridges before and after improving the bridge load level. Gu et al. [9] systematically expounded on the research status of bridge design based on life-cycle cost analysis, introducing the research background, basic concepts, and principles of life-cycle cost analysis, and provided the necessary research background for bridge life-cycle design and maintenance based on life-cycle cost. Jin and Niu [10] elaborated the research scope and research status of the durability and life-cycle theory of engineering structures, proposed the development direction of life-cycle design theory, and predicted the development trend. Frangopol [11] proposed that the decision-making over civil infrastructure systems should be supported by a comprehensive reliability life-cycle multiobjective optimization framework and considered the possibility of successful performance in the whole life cycle and the cumulative total expected cost and other factors. Jin and Zhong [12] took the structural life cycle as the research time domain, used the new concept of structural life-cycle design to construct the research framework of engineering structure life-cycle design theory, and analyzed the connotations and relationships of structural performance, cost and service life in design. Eamon et al. [13] used carbon fiber reinforced polymer (CFRP) bars and strands to carry out life-cycle cost analysis (LCCA) on the superstructure of prestressed concrete bridges. Safi et al. [14] described the basic LCC analysis tools and other useful technologies, indicating an integrated LCC implementation scheme. Ma et al. [15] proposed that bridge life-cycle design can be summarized as the design of six processes, including service life design, and proposed an overall framework of bridge life-cycle design, including three design stages and six design processes. Lin et al. [16], based on the concept of equal durability design and life-cycle design, proposed the method of life-cycle equal durability design, pointed out its core research contents, and studied the basic ideas, theoretical framework, and design process of the design method. Dong [17] briefly introduced the development of a general framework for evaluating bridge life-cycle performance and cost, focusing on analysis, prediction, optimization, and decision-making under uncertainty. Jin and Wang [18] constructed the green index system of life-cycle design of engineering structures and constructed the green index system framework of life-cycle design for the structural form, use, and environment of coastal expressway bridges. Li et al. [19] discussed the research status of time-varying models of material and component degradation caused by environmental action in the whole life cycle of the structure, which provided a direction for the analysis of the individual life performance of high-performance structures under multiple disasters. Wang et al. [20] determined the life-cycle design idea based on structural dynamic performance and established the life-cycle design system, solved the problems of fuzzy concept and repeated index in existing life-cycle design theory, and improved the connotation of life-cycle cost. In Sajedi and Huang [21], reliability-based life-cycle cost analysis (LCCA) was used to compare the long-term cost-effectiveness of six commonly used materials in the design and repair of reinforced concrete structures. Wang and Li [22] proposed the bridge life-cycle design method based on reliability and divided the bridge life-cycle design into two parts: life-cycle reliability design and life-cycle economic design, which directly reflected the unity of opposites between structural performance and cost input. Xu [23] introduced the concept of life-cycle management into an actual project of cost-benefit management, summarized the life-cycle theory, and introduced the related theoretical basis of life-cycle cost-benefit. Yao [24] ran durability design throughout the whole life cycle of the structure from the perspective of the whole life of the structure, which provided a basis for establishing the life-cycle design method of steel structures considering the corrosion environment. Wang [25] summarized the importance of the combination of the life cycle and green design and the current situation of practical engineering application, analyzed some problems that still exist, and proposed corresponding solutions.

Hitoshi Furuta et al. [26] discussed the LCC design concepts and methods with emphasis on bridges and road networks. The relationships among several performance measures were discussed. An attempt was made to provide rational balances of these measures by using a multiobjective genetic algorithm. A stochastic model of structural response under earthquake effects was proposed. Then, the probability of failure of an individual bridge due to the earthquake excitation was calculated based on the reliability theory. Tatiana García-Segura et al. [27] presented a lifetime reliability-based approach for the optimization of posttensioned concrete box-girder bridges under corrosion attack. This method determined the optimal life-cycle cost and CO₂ emissions of several initial designs of posttensioned box-girder bridges. The results showed that a durability-conscious initial design is particularly beneficial for life-cycle performance. Shekhar et al. [28] investigated the influence of uniform vs. pitting corrosion assumption on seismic life-cycle costs for varied chloride exposure conditions. The constructive suggestions were put forward for timely repair.
of aging bridges under different exposure conditions, so as to facilitate bridge engineers to balance the calculation cost and the accuracy of the results. Hassani et al. [29] presented an integrated methodology for calculating life-cycle cost (LCC) of moment-resisting concrete frames. An optimal design scheme was proposed to increase the seismic safety of structures and reduce human casualties. Shen et al. [30] presented a probabilistic framework to estimate the life-cycle cost associated with bridge decks constructed with different reinforcement alternatives. From a life-cycle cost perspective, the optimum deck reinforcement selection was proposed based on bridge attributes and life-cycle cost.

2. Theoretical Framework of Vessel-Bridge Collision Optimization Design Based on Life Cycle

The key to vessel-bridge collision life-cycle design is to introduce time parameter—useful life. In the design stage, the time domain considered by decision-making is extended to the whole life cycle of the bridge structure, and the cost analysis decision-making method is used for vessel-bridge collision design and scientific decision-making. The life-cycle reliability design theory for bridge structures can be described as, in the whole life cycle, the multiobjective performance requirements of design, construction, detection, maintenance, and demolition stages are comprehensively considered to seek the optimal solution to ensure the safety of vessel-bridge collision. The life-cycle reliability design theory of bridge structures under vessel collision includes three aspects: vessel-bridge collision probability analysis, vessel-bridge collision vulnerability analysis, and vessel-bridge collision hazard analysis. The theoretical framework of vessel-bridge collision optimization design based on life cycle is shown in Figure 1.

3. Vessel-Bridge Collision Optimization Design Model Based on Life Cycle

The concept of vessel-bridge collision life-cycle cost analysis (LCC) requires a risk (cost) and income comparison. In many bridge design schemes, the optimization scheme should make LCC a minimum. The full-life cost of vessel-bridge collision can be expressed as formula (1).

In formula (1), \( E[C_T(X|T)] \) is the expected life-cycle cost of vessel-bridge collision, and it is a function of design variable \( X \) and lifetime \( T \); \( C_I \) is the initial cost; \( E[C_{Mj}(X|t)] \) is the expected maintenance cost for item \( j \); \( E[C_{Fk}(X|t)] \) is the expected loss for the \( k \)th limit state; and \( r \) is the discount rate.

The structural life-cycle optimization design can be mathematically expressed as formula (2).

In formula (2), \( g_j(X) \) is the \( j \)th design constraint; \( P_{Fk}(X) \) is the failure probability of the \( k \)th limit state; \( P_{\text{allow}}^{k} \) is the allowable failure probability of the \( k \)th limit state; \( X_L \) and \( X_U \) are lower and upper bounds of design variables, respectively.

The multiobjective optimization design of vessel-bridge collision life needs to consider the initial cost of the structure and the failure probability and failure economic loss expectation under different performance levels. Therefore, the objective function of vessel-bridge collision life optimization can be written as formula (3).

In formula (3), \( X \) is the design variable of the structural design scheme, such as the span of the bridge structure and the foundation size; \( C_I(X) \) is the initial cost of the structure, and it is the function of structural design variable \( X \); \( C_M(X) \) is maintenance cost; \( P_{f_i}(X) \) is the structural failure probability of design variable \( X \) corresponding to performance level \( i \); \( C_{f_i}(X) \) is the expected value of failure economic loss corresponding to performance level \( i \) of design variable \( X \); \( n \) is the total number of structural performance levels; \( g_j(X) \) is...
the $j$th design constraint condition; $X^L$ and $X^U$ are lower and upper bounds of design variables, respectively.

### 3.1. Vessel-Bridge Collision Life-Cycle Optimization Design Process

According to the key issues involved in the life-cycle design method of vessel-bridge collision, the life-cycle optimization design process of vessel-bridge collision is shown in Figure 2.

\[
\begin{align*}
\min & \quad E[C_T(X|T)] = C_f(X) \\
& + \sum_{j=1}^{n} \left[ \sum_{i=1}^{r} \int E[C_{Mj}(X|t)] + \sum_{k=1}^{K} E[C_{FK}(X|t)] \right] (1 + r)^t \\
\end{align*}
\]

\[\text{Minimize } E[C_T(X|T) | g_j(X) \leq 0; p_{FK}(X) \leq p_{allow}; X^L \leq X \leq X^U],\]

\[X^L \leq X \leq X^U \]

\[g_j(X) \leq 0.\]

### 3.2. Vessel-Bridge Collision Probability Analysis

Probabilistic vessel collision risk analysis is a probability method to determine that the vessel collision of a bridge exceeds a given value in a certain design reference period in the future. Firstly, it is necessary to classify the influencing factors of vessel collision probability and establish the logical relationship between the influencing factors of vessel-bridge collision. The scene of a vessel-bridge collision is classified. According to the characteristics of each scene, the influencing factors that need to be considered in each scene of a vessel-bridge collision are analyzed, including general water flow field distribution, meteorological conditions, seasonal

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**Figure 2:** Vessel-bridge collision life-cycle cost design process.
variation of water depth, vessel draft depth, navigation management, and navigation vessel characteristics.

According to the bridge location and bridge design scheme, certain water area in upstream and downstream of the bridge location is selected, and the whole water area is divided based on the analysis of the characteristics of each subdomain.

Based on the division of the water area, the scene of a vessel-bridge collision in each subdomain is classified. The specific division of the collision scene is as follows:

1. Vessels that misnavigate due to human error
2. Vessels whose mechanical power fails
3. Drag of anchor, a nonpowered drifting vessel under the action of water and wind

The probability of vessel collision is $P_1$, $P_2$, and $P_3$, respectively, in three scenarios of human error, mechanical power failure, and anchor event, and then the total probability $P$ of the event that the vessel may collide with bridges is $P = P_1 + P_2 + P_3$. The process of bridge-vehicle collision probabilistic risk analysis for bridge structures is shown in Figure 3.

4. Vessel-Bridge Collision Vulnerability Analysis

Vessel collision fragility of bridge structure refers to the probability of various damage states of bridge structures under the impact of different vessel tonnages. It quantitatively describes the antivessel collision performance of engineering structures in the sense of probability and describes the relationship between vessel tonnage and structural damage degree from a macroperspective.

All the uncertain factors affecting the vessel impact vulnerability of a bridge structure are represented by the basic random vector $X$, and the failure state $a$ of the structure is described by the limit state function $G_i(X)$. Then, the problem of vessel impact vulnerability of a bridge structure can be expressed as the problem of structural reliability:

$$F(a,j) = P[G_i(X)|DWT = a_j] = \int_{\{G_i(X)|DWT = a_j\leq 0\}} f(X)dX,$$

$$F(a) = \Phi^{-1}(\beta_i|DWT = a_j).$$

In the formula, when $P[G_i(X)|DWT = a_j]$ represents vessel tonnage $DWT = a_j$, probability of structure reaching limit state $G_i(X), G_i(X)|DWT = a_j \leq 0$ denotes $DWT = a_j$ when the structure reaches or exceeds state $i$. $f(X)$ represents the joint probability density function of the basic random vector $X$. $\Phi^{-1}$ is the inverse function of the standard normal distribution function, and $\beta_i$ is the reliability index of the $i$th limit state corresponding to the structure.

The basic steps of vessel collision vulnerability analysis are as follows:

1. According to the vessel tonnage, considering the randomness of impact angle and impact velocity, the time-history curve of random vessel impact force is generated
2. Establish a reasonable bridge, nonlinear mechanical model
3. The nonlinear time-history analysis of vessel collision with bridge structure is carried out, and the vessel collision response of the bridge structure is calculated

Figure 3: Flow chart of vessel-bridge collision probability analysis.
(4) The boundary value of the performance index under different performance levels of the bridge structure is calculated.

(5) According to the structural reliability theory, the probability of structural response exceeding a certain failure state under different vessel tonnages is calculated.

Through the above vulnerability analysis method, the exceedance probability of damage to a bridge structure under each vessel tonnage can be obtained. Through the analysis of vessel collision vulnerability of the bridge structure, the exceedance probability of damage in different damage degrees of a bridge structure under full probability condition can be obtained. Through the elaboration of the analysis method of vessel collision vulnerability, it can be seen that the core issue of vessel-bridge collision vulnerability analysis is the reliability analysis of the vessel-bridge collision.

In order to analyze the reliability of vessel-bridge collision, it is necessary to collect the vessel track data of typical waterway bridges, conduct statistical analysis of the data, determine the transverse distribution of vessel tracking, yaw angle distribution, and typical vessel speed distribution, and obtain the probability model and parameters of the...
corresponding random variables. According to the typical failure mode of vessel-bridge collision, the failure criterion of a bridge structure and the reliability calculation model of a bridge structure are established. The function of time-varying reliability of vessel-bridge collision is proposed, and the reliability of vessel-bridge collision is analyzed. The reliability analysis process for vessel-bridge collision is shown in Figure 4.

4.1. Component Limit State Function

4.1.1. Pier Failure Mode

(1) Shear Failure Mode. According to the strength failure criterion, to ensure that the pier does not suffer shear brittle failure, the shear response $V_{S,\text{column}}$ of the pier under vessel impact and the shear strength $V_{R,\text{column}}$ of the pier must meet the following:

$$V_{S,\text{column}} < V_{R,\text{column}}.$$  

At this time, the corresponding limit state function is as follows:

$$G_i(X) = V_{R,\text{column}} - V_{S,\text{column}}.$$  

Among them, $V_{S,\text{column}}$ is related to the impact angle, impact velocity, and vessel impact tonnage, and is the function of the above three factors. Therefore, equation (7) can be further expressed as follows:

$$G_i(X) = V_{R,\text{column}} - V_{S,\text{column}}(V, DWT, \theta).$$  

In the formula, $V$ represents the speed of vessel impact, DWT represents the tonnage of the vessel, and $\theta$ represents the angle of vessel impact.

(2) Bending Failure Mode. According to the deformation failure criterion, to ensure that the component does not have bending failure, the component rotation angle $\theta_{S,\text{column}}$ under vessel impact and the component rotation angle limit value $\theta_{R,\text{column}}$ under different performance levels should meet

$$\theta_{S,\text{column}} < \theta_{R,\text{column}}.$$  

At this time, the corresponding limit state function under different performance levels is as follows:

$$G_i(X) = \theta_{R,\text{column}} - \theta_{S,\text{column}}.$$  

Among them, $\theta_{S,\text{column}}$ is related to the impact angle, impact velocity, and ship tonnage, which is the function of the above three factors. Therefore, equation (10) can be further expressed as follows:

$$G_i(X) = \theta_{R,\text{column}} - \theta_{S,\text{column}}(V, DWT, \theta).$$  

4.1.2. Failure Mode of Pile Group Foundation. The destruction of the pile group foundation generally occurs at the front row side pile. Therefore, for the pile group foundation, attention should be paid to the damage and failure of the most unfavorable single pile in the pile group system. For the pile group foundation, according to the deformation failure criterion, in order to ensure that the pile group foundation is not damaged, the most unfavorable single pile group foundation under vessel impact angle $\theta_{S,\text{pile}}$ and different performance levels of angle limit bar $\theta_{R,\text{pile}}$ must meet as follows:

$$\theta_{S,\text{pile}} < \theta_{R,\text{pile}}.$$  

At this time, the corresponding limit state function under different performance levels is as follows:

$$G_i(X) = \theta_{R,\text{pile}} - \theta_{S,\text{pile}}.$$  

Among them, $\theta_{S,\text{pile}}$ is related to the impact angle, impact velocity, and ship tonnage, which is the function of the above three factors. Therefore, equation (13) can be further expressed as follows:

$$G_i(X) = \theta_{R,\text{pile}} - \theta_{S,\text{pile}}(V, DWT, \theta).$$  

4.2. Limit State Function of Bridge Structure System. According to the definition of vessel collision failure mode of a single pier, for a single pile-column pier system composed of pile groups, caps, and piers, the ship of any part will lead to the failure of the entire pier system, so the entire pier system constitutes a series system, as shown in Figure 5.

The limit state function of a single pile-column pier under various performance levels under vessel collision can be expressed as formula (15).

The failure of each performance level of the bridge structure system under vessel impact is defined as that any pier reaches the corresponding performance level state, that
is, the whole bridge structure system reaches the corresponding performance level state.

According to the above definition of bridge structure failure, each pier is regarded as a component in the reliability calculation series system. According to the weakest link criterion, when a pier fails, the entire bridge structure system is considered invalid. Therefore, the whole bridge structure can be regarded as a series system, so the calculation of vessel-bridge collision failure probability can be simplified as the calculation of failure probability of a series structure system.

Assuming that a bridge system has $K$ piers, the failure probability of the whole bridge system under ship collision force can be expressed as formula (16).

Therefore, the limit state function of the whole bridge structure system under vessel collision force can be expressed as the minimum value of the all-pier function, as shown in formula (17).

Through the functional function of the bridge structure system established above, the reliability of the vessel collision system of the bridge structure under vessel impact can be solved by using the method of reliability theory.

$$G_i(X) = \min \left\{ \theta_{R,pile} - \theta_{S,pile}, \min \left\{ V_{R,column} - V_{S,column}, \theta_{R,column} - \theta_{S,column} \right\} \right\}, \quad (14)$$

$$P_F = \text{Prob}[\min \{g_1, g_2 \ldots g_k\} > 0], \quad (15)$$

$$G(X) = \min \{g_1, g_2 \ldots g_k\}. \quad (16)$$

5. Hazard Analysis of Vessel-Bridge Collision

The life-cycle cost of vessel-bridge collision can be divided into three categories as follows: initial construction cost, maintenance cost, and vessel collision loss. The harm of vessel-bridge collision is mainly reflected in the economic losses.

The assessment method of vessel-bridge collision economic loss includes the following steps.

5.1. Classification of Economic Losses Caused by Vessel-Bridge Collision. Vessel-bridge collision accidents may result in various losses, which are classified according to certain principles, which is not only beneficial for statistics and comprehensively grasping the economic losses but also to estimate and analyze losses according to different types.

5.2. Establishing the Mathematical Model of Vessel-Bridge Collision Loss Assessment. An estimation model that can comprehensively estimate and analyze the size or severity of economic losses caused by vessel-bridge collisions is established. For each loss in the model, according to its category, the corresponding calculation expression or solution method is established to estimate the loss.

5.3. Unified Consequence Indicators and Comprehensive Evaluation of Economic Losses. The evaluation methods and measurement methods of different types of economic losses are different. The losses in the loss estimation model must be expressed in accordance with the unified measurement method, so as to integrate them into the estimation model for comprehensive estimation and obtain the total economic losses.

Vessel-bridge collisions often cause losses in various aspects, including bridge losses, bridge user losses, vessel owner losses, indirect consequences for industry, trade and society, and environmental damage. In order to facilitate analysis and calculation, the consequences of vessel-bridge collisions can be divided into direct economic losses and indirect economic losses, and the specific classification is shown in Figure 6.

The economic loss estimation model of vessel-bridge collisions should be established on the basis of scientific and reasonable theories and methods and strive to correctly and effectively evaluate the various economic losses contained, be simple and clear, should not be too cumbersome, and have certain feasibility, as far as possible to quantify the indicators or results to reflect the size and severity of the vessel-bridge collision consequences. According to the division of vessel-bridge collision economic losses, this paper...
establishes the overall model of vessel-bridge collision economic loss evaluation as follows:

\[
C_{\text{Loss}} = C_{L,\text{dir}} + C_{L,\text{indir}},
\]

\[
C_{L,\text{dir}} = C_{L,B} + C_{L,V} + C_{L,L} + C_{L,G},
\]

\[
C_{L,\text{indir}} = C_{L,S} + C_{L,E}.
\]

In the formula, \(C_{\text{Loss}}\) is the sum of vessel-bridge collision losses; \(C_{L,\text{dir}}\) is direct economic loss; \(C_{L,\text{indir}}\) is indirect economic loss; \(C_{L,B}\) is the bridge structure loss; \(C_{L,V}\) is the loss of vessels and vehicles; \(C_{L,L}\) is the loss of casualties; \(C_{L,G}\) is the loss of goods; \(C_{L,S}\) is the economic loss of bridge interruption; and \(C_{L,E}\) is the loss of environmental pollution.

6. Conclusion

The development direction of the new generation bridge structure design theory is "life-cycle reliability design." The life-cycle reliability optimization design for vessel-bridge collision involves the vessel-bridge collision probability analysis, vessel-bridge collision vulnerability analysis, and vessel-bridge collision hazard analysis.

(1) The time parameter is introduced in the design of vessel-bridge collision. In the design stage, the time domain considered in the decision is extended to the life cycle of the bridge structure, and the cost analysis decision method is used to optimize the design of vessel-bridge collision.

(2) According to the characteristics of various influencing factors affecting vessel collision probability, the scene of a vessel collision pier is classified into three parts, such as human error, mechanical power failure, and dragging anchor events. The analysis process of vessel-bridge collision probability is proposed.

(3) The basic flow of vessel-bridge collision vulnerability analysis is established. According to the typical pier form of the bridge structure, the limit state function for calculating the failure probability of bridge structure is advanced.

(4) The life-cycle cost of vessel-bridge collision is analyzed, and the overall model and steps of vessel-bridge collision economic loss assessment are proposed.

(5) For the new bridge structure, the life-cycle reliability design concept is introduced into the current vessel-bridge collision design, which can ensure the rationality of vessel-bridge collision design. The life-cycle reliability analysis of the existing bridge structure can detect potential risks in time and aid to make maintenance decisions to avoid the occurrence. It is used to avoid vessel collision accidents in major bridge engineering and provide theoretical basis for vessel collision design.

Data Availability

The underlying data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this study.

Authors’ Contributions

Tao Fu conceptualized and supervised the study and acquired funding. Kai Wang wrote the original draft and took part in formal analysis. Ye Zhou investigated and reviewed the study. Xiaoqian Ren took part in formal analysis. Zhixin Zhu was responsible for data curation. Yan Li investigated the study. Yue Sun reviewed the study. Lingxiao Meng edited the manuscript.

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