fire

Article

Reliability Assessment Approach for Fire Resistance Performance of Prestressed Steel–Concrete Box Girder Bridges

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Abstract: This paper employs probability methods to evaluate the fire safety performance of prestressed steel–concrete beam bridges based on simulation experimental research. Firstly, fire simulation experimental sample analysis was conducted on actual small box girder bridges to assess the structural response of prestressed steel–concrete structures to fire, as is in line with engineering practice. Next, we constructed a reliability analysis model to investigate the fire resistance performance of prestressed steel–concrete beam bridges. Combining reliability theory with the finite element method, we established a reliability analysis method for the fire resistance performance of prestressed steel–concrete beam bridges. Subsequently, we proposed a safety factor evaluation model for the fire resistance performance of prestressed steel–concrete beam bridges and then established a safety factor evaluation method for the fire resistance performance of prestressed steel–concrete beam bridges based on reliability back analysis. Finally, based on the analysis of the post-fire structural response in the specific case of a steel–concrete continuous beam bridge project moving from conditions of being simply supported to continuously prestressed, a structural resistance sample of the prestressed steel–concrete beam bridge was generated via the uniform design method, and statistical analysis was conducted. Subsequently, probability methods were used to evaluate the safety of the prestressed steel–concrete beam bridge after a fire. Through analysis, we concluded that the duration of the fire had a significant impact on the structural performance of prestressed steel–concrete beam bridges and that the randomness of parameters had a significant impact on the safety reserve of prestressed steel–concrete beam bridges following the fire. Going forward, it is necessary to pay attention to this factor in specific engineering practices and strengthen the monitoring and statistical analysis of structural random characteristics.

Keywords: prestressed steel–concrete; girder bridges; fire resistance performance; reliability index; safety factor

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1. Introduction

Civil engineering structures are affected by different environmental factors, and the study of the safety performance of structures under external actions is very important [1–6]. Bridge fires are rare but serious accidents. Strict standards and safety measures must be followed during the construction and maintenance process of civil engineering structures, especially bridges, to ensure their fire resistance performance [7–12]. However, some factors may lead to bridge fires, such as electrical failures, extreme temperatures, and human factors [13,14]. In the event of a fire, bridges are typically severely damaged, potentially leading to traffic paralysis and significant casualties. Therefore, preventing bridge fires is extremely important.

As determined via the investigation and analysis of actual bridge fires, there are two main types of bridge fires: deck fires and under-bridge fires. Irrespective of the form of fire, the conflagration will not only pose a threat to personal and property-related safety but will also inflict more or less damage to some or all of the bridge structure [15–22]. Bridge fires occur sporadically, and it is difficult to collect data and information concerning fire scenes, which poses significant limitations to the development of related research. Therefore, the current academic community's attention to and research on bridge fires is far less focused than on other natural disasters. In addition, the issue of fire resistance is rarely considered in the process of bridge design. Ultimately, this is because there is currently relatively little research on it. Therefore, conducting research on the fire resistance performance of bridge structures is of great significance. This practice will provide technical support for the future development and revision of bridge fire protection design specifications and constitute a basis for the evaluation and reinforcement of bridge fire protection performance.

Research into the fire resistance performance of prestressed concrete structures is currently mainly focused on the following aspects. The first area of focus is the research on fire resistance design methods, such as how to establish accurate and convenient practical methods. The second dimension of research involves post-disaster assessment methods, such as how to scientifically and accurately evaluate the degree of damage to overheated prestressed concrete bridge structures and, based on this, how to develop plans for repairing and strengthening damaged structures [23–32]. The latter subject has been extensively studied by domestic and foreign experts and scholars, while there is relatively little research on the fire protection design of prestressed concrete bridge structures [33–37]. Although there are building fire protection design codes in various countries, they mainly rely on experience and structural measures to solve the problem, and no mature analysis method currently exists for bridge structure fire protection design [38–44]. Therefore, it is necessary and urgent to conduct research on the fire resistance evaluation of prestressed concrete bridge structures.

This paper aims to provide a theoretical basis for the reasonable evaluation of the fire resistance reliability of bridge structures, focusing on the key uncertainty factors of fire and the structure itself and proposing a set of fire resistance reliability evaluation methods for prestressed concrete bridges. The innovative points and implementation methods of this article are as follows: (1) we evaluate the fire safety performance of prestressed concrete beam bridges from a probabilistic perspective, considering the impact of parameter randomness on structural safety. (2) We adopt a uniform design method for the sample collection of fire resistance performance indicators, greatly reducing the time cost in the probability analysis process and ensuring accuracy. (3) We determine that using the goodness-of-fit test method can analyze the most statistical characteristics of structural fire resistance to ensure the accuracy of probability analysis. (4) By analyzing the impact of different parameters on the fire resistance safety of prestressed steel–concrete structures through time-varying characteristics, the main influencing parameters on the fire resistance performance are accurately identified. Our aim in conducting this research is to improve the capacity of science to accurately and reasonably evaluate the reliability of the fire resistance performance of prestressed steel–concrete box bridges and to provide technical support to ensure the fire safety of prestressed concrete beam bridges. The purpose of reliability analysis of the fire resistance performance of prestressed steel–concrete beams is to evaluate whether a structure achieves the expected quality and safety goals set out in research and development, design, and manufacturing in the event of a fire. This is performed by observing the changes in the fire resistance performance of the structure over time in a fire environment in order to evaluate the overall structure and determine the fire resistance safety reliability life of the structure.

2. Principles of Prestressed Concrete Fire

The material properties of prestressed steel–concrete structures change when facing fire environments. The thermodynamic properties of concrete and steel are functions of temperature. The higher the temperature, the more significant the decrease in the thermodynamic parameters of the material, which can have a significant impact on the structure. The analysis of structures in fire scenarios, performed using finite element analysis, is the theoretical basis of reliability performance evaluation, which is mainly reflected in the structural response and gradient values of structures under fire action.

2.1. Thermal Performance of Materials

2.1.1. Concrete

(1) Thermal conductivity

The thermal conductivity coefficient of concrete in the analysis of the temperature field of the box girder section fire is taken as per Table 1.

Table 1. Value of thermal conductivity of concrete (unit: [W/(m·°C]).

Temperature/°C	20	100	200	300	400	500	600	800	1000	1200
Thermal conductivity	1.62	1.53	1.43	1.34	1.22	1.11	1.02	0.86	0.72	0.64

(2) Specific heat capacity

Specific heat capacity refers to the amount of heat (J) absorbed by a unit mass (tank) object with a temperature rise of one degree (°C or K). This represents the heat storage capacity of the object, expressed in units of J/(kg·K) or J/(kg·°C). The principal factors affecting the specific heat capacity of concrete include temperature, mix ratio, aggregate type, and moisture content.

On account of the small variation in the specific heat of concrete with temperature, this is taken approximately as a constant during the calculation process, with a constant value of 920 [J/(kg·°C)]. In the analysis of the temperature field of box girder section fires, the specific heat capacity of concrete is taken as a constant value of c = 920 [J/(kg·°C].

(3) Thermal expansion coefficient

The coefficient of thermal expansion is the elongation per unit length of an object for every 1 °C increase in temperature, expressed in m/(m·°C). The values of the thermal expansion coefficient of concrete in the analysis of the temperature field of box girder section fire are shown in Table 2.

Table 2. The value of thermal expansion coefficient of concrete (unit: [m/(m·°C)]).

Temperature/°C	20	100	200	300	400	500	600	800	1000	1200
Thermal expansion coefficient	5.6	6.5	7.7	8.9	10.1	11.3	12.5	14.9	17.3	19.7

2.1.2. Thermal Performance of Prestressed Steel Bars

(1) Thermal conductivity

The values of the thermal conductivity coefficient of the steel bars in the analysis of the temperature field of the box girder section fire are shown in Table 3.

Table 3. Value of thermal conductivity of steel bar (unit: [W/(m·°C)]).

Temperature/°C	20	100	200	300	400	500	600	800	1000	1200
Thermal conductivity	49	47	45	43	41	38	35	29	22	19

(2) Specific heat capacity and density

The specific heat capacity of steel bars in the temperature field analysis of the box girder section fire is shown in Table 4. Mass density refers to the mass per unit volume of an object. The mass density of steel does not vary significantly with temperature, and the constant is generally taken as ρ = 7850 kg/m^3.

Table 4. Specific heat capacity of steel bar (unit: [J/(kg·°C)]).

Temperature/°C	20	100	200	300	400	500	600	800	1000	1200
Thermal conductivity	520	527	541	561	586	618	656	748	865	1005

(3) Thermal expansion coefficient

The values of the thermal expansion coefficient of steel bars in the analysis of the fire temperature field of the box girder section are shown in Table 5.

Table 5. The value of thermal expansion coefficient of prestressed steel bar (unit: [m/(m·°C)]).

Temperature/°C	20	100	200	300	400	500	600	800	1000	1200
Thermal expansion coefficient	11.4	12.0	12.8	13.6	14.4	15.2	15.3	16.1	17.0	17.8

2.2. Temperature Transient Analysis

The International Organization for Standardization (ISO) developed the ISO-834 standard heating function, as shown in Equation (1):

$$T = T_0 + 345 \times \log(8t + 1), \tag{1}$$

where T is the fire temperature, T_0 is the starting point temperature, and T is the duration of the fire.

According to the analysis conducted using Equation (1), ISO-834 defines a monotonic heating function, and the temperature does not decay over time during the cooling process. However, the unified application of this standard can provide a unified standard for fire resistance research, increase the comparability of fire resistance performance of different structures, and improve the safety of structures produced using the fire resistance design method. If it is necessary to consider the difference in temperature rise of the actual structure, equivalent detonation time and equivalence (which refers to the time when the structure reaches a certain temperature and is on the standard temperature curve under conditions of actual fire) can be used.

Fire Temperature Field of Box Girder Section

When convection and radiation occur simultaneously on the fire-exposed surface, it is generally necessary to consider the effects of both convection and radiation in order to comprehensively express the heat transfer coefficient. The effect of thermal radiation must be included in defining the emissivity on non-fire surfaces. The comprehensive heat transfer coefficient in the temperature field analysis of the box girder section is shown in Table 6.

Table 6. The value of comprehensive heat transfer coefficient (unit: [kcal/(m·h·°C)]).

Flame temperature/°C	60–200	400	500	600	800	1000	1200
Thermal expansion coefficient	10	15	20	30	55	90	150

2.3. ANSYS Finite Element Temperature Field Analysis

The thermal performance of materials, heat flux, boundary conditions, system temperature, and internal energy are among the parameters that vary over time during the transient heat transfer process. The transient heat balance, determined based on energy conservation, can be expressed as:

$$[C]\left\{\dot{T}\right\} + [K]\{T\} = \{Q\}, \tag{2}$$

where C is the specific heat matrix, considering the increase in internal energy of the system; $\dot{T}$ is the derivative of temperature over time; K is the heat conduction matrix, including thermal conductivity, convection coefficient, emissivity, and shape coefficient; T is the node temperature vector; Q is the node heat flux vector.

The temperature field analysis of prestressed concrete small box girder fires primarily includes the following steps:

(1) Define the model: Determine the geometric dimensions, physical properties, and boundary conditions in the model, such as the size of the small box girder model and the position and quantity of prestressed steel bars. The three-dimensional thermal solid SOLID70 element can be used to simulate concrete in ANSYS temperature field analysis, with eight nodes and temperature degrees of freedom assigned to each node.

(2) Develop mathematical models and assumptions for the model: Determine the mathematical model required to calculate the temperature field of the small box girder model using physical equations, taking into consideration heat transfer mechanisms such as radiation, conduction, and convection. Simplify the model using assumptions, such as assuming that the physical property constant of the small box girder is constant.

(3) Determine boundary conditions: Determine boundary conditions, including initial temperature, fire conditions, material properties, and environmental conditions. The initial temperature is 20 °C according to the international standard organization IS0834 heating function.

(4) Choose a numerical method to solve the mathematical model: Usually, the finite element method is employed to numerically calculate the temperature field of the small box girder model.

(5) Calculation: Based on the mathematical model and boundary conditions, perform numerical calculations to calculate the temperature field of the small box girder model.

3. Reliability Theory

Due to the numerous random factors affecting prestressed steel–concrete structures, the structural response is an implicit function of random variables. Since functional function expression is not displayed, it is appropriate to use the probabilistic finite element method for reliability theory.

The failure criterion of a structure is often represented by the load effect S, while the statistical information of the structure is represented by the basic random vector X. The relationship between $\boldsymbol{S}$ and $\boldsymbol{X}$ can be expressed as follows:

$$\boldsymbol{S} = \boldsymbol{S}(\boldsymbol{X}). \tag{3}$$

Equation (3) is commonly referred to as "mechanical transformation". In practical engineering, due to the implicit form of mechanical transformations, numerical algorithms such as the finite element method can only be used to solve problems.

For the finite element first-order reliability method, the limit state function is

$$g[\mathrm{s}(x), x] = \mathrm{G(u)}, \tag{4}$$

$$d_i = \frac{\nabla_{u_i} G^T u_i - G(u_i)}{\|\nabla_{u_i} G\|^2} \nabla_{u_i} G - u_i. \tag{5}$$

The limit state function value $G(u_i)$ in Equation (5) can be obtained via finite element analysis, rendering the calculation of gradients $\nabla_{u_i} G$ crucial. Working according to the chain differentiation rule, the relationship of $\nabla_{u_i} G$ with the gradient $\nabla_x g$ of the limit state function $\boldsymbol{g}$ (s, x) is obtained as follows:

$$\nabla_{u_i} G = (J_{u,x}^{-1})^T \cdot \nabla_x g, \tag{6}$$

$$\nabla_x g = \nabla_s g \cdot J_{s,x}, \tag{7}$$

$$\nabla_{u_i} G = (J_{u,x}^{-1})^T \cdot \nabla_x g \cdot J_{s,x}, \tag{8}$$

where $\nabla_s g$ is the gradient of limit state function g ($\boldsymbol{s},\boldsymbol{x}$) to $\mathbf{s}$; $\nabla_x g$ is the gradient of limit state function g ($\boldsymbol{s},\boldsymbol{x}$) to $\boldsymbol{x}$; $J_{u,x}$ is the Jacobian matrix for probability transformation; $J_{s,x}$ is the Jacobian matrix for mechanical transformation.

This paper uses the central difference method to calculate the gradient of the limit state function, with a basic format of:

$$K(x)U(x) = F(x), \tag{9}$$

$$K(x + \Delta x)U(x + \Delta x) = F(x + \Delta x), \tag{10}$$

$$\frac{dU}{dx} = \frac{U(x + \Delta x) - U(x - \Delta x)}{2 \cdot \Delta x}, \tag{11}$$

$$\frac{dg}{dx} = \frac{\partial g}{\partial x} + [\frac{\partial g}{\partial U}]^T \frac{dU}{dx}. \tag{12}$$

Finite element reliability analysis is a structural reliability analysis method based on two components, namely, the finite element method and reliability theory. When calculating the reliability of the fire resistance performance of prestressed concrete beam bridges, a reliability program developed using MATLAB language is utilized to perform reliability analysis, and the application program interfaces of ANSYS and MATLAB software are used to achieve mutual calls between the two. The specific steps are as follows:

(1) Establishment of structural finite element model: First, it is necessary to establish a finite element model of the structure based on the geometric model and material characteristics of the actual structure, including nodes, elements, constraint conditions, loads, etc.
(2) Analysis of parameter uncertainty: Second, the researcher must describe the probability distribution of structural design parameters, such as mean and standard deviation, as well as analyze the sources of uncertainty, including measurement errors, manufacturing errors, changes in material parameters, etc.
(3) Selection of reliability indicators: Third, it is necessary to determine the reliability indicators of the structure based on engineering requirements and design specifications, such as reliability indicators, failure efficiency indicators, safety factors, etc.
(4) Reliability calculation: Then, the scholar must apply reliability theory and finite element method to conduct structural reliability analysis, calculate the reliability indicators of the structure, and the probability distribution of other parameters in the reliability analysis.
(5) Sensitivity analysis: Fifth, it is necessary to analyze the sensitivity of parameter uncertainty in relation to reliability indicators and determine the parameters that have the greatest impact on structural reliability.
(6) Optimization design: Based on the sensitivity analysis results, researchers should optimize the design scheme of the structure to improve its reliability indicators.
(7) Result evaluation: Evaluate the analysis results to determine whether the reliability indicators meet the design requirements. If not, it is necessary to perform repeated calculations and optimization.

4. Finite Element Reliability Fire Resistance Analysis

When using probabilistic finite element theory, it is necessary to construct a reliability model for the fire resistance performance of prestressed steel–concrete structures. This model is composed of the fire resistance bearing capacity of the structure and its resilience against external effects. The latter factor makes the model an implicit function of random variables. The establishment of fire resistance limit state equations for prestressed concrete beam bridges requires the consideration of factors such as the structural characteristics, material properties, and fire scenarios of the bridge. The establishment of the bridge fire resistance limit state equation primarily includes the following steps:

(1) Determine the design load and fire scenario: Based on the design load and environment of the bridge, determine the fire scenario of the bridge during a fire and assess the size of the fire, thermal radiation intensity, temperature changes, etc.
(2) Determine material properties: Based on the design drawings and component material information of the bridge, determine the basic mechanical properties and fire resistance parameters of materials such as concrete and steel bars, as well as the changes in material mechanical properties under fire conditions.
(3) Establish a mechanical model: Based on the structural and mechanical characteristics of the bridge, establish a mechanical model of the bridge under fire conditions, taking into account factors such as temperature changes and nonlinear behavior of the structure, including load displacement and stress–strain relationships.
(4) Establish limit state equation: Based on the design load and mechanical model under fire scenarios, establish the limit state equation for bridge fire resistance, including strength limit state and deformation limit state.
(5) Verification and optimization: Verify the established bridge fire resistance limit state equation through numerical simulation, experimental verification, and other methods, and optimize and adjust parameters as required.

Assuming that the bearing capacity of the component without fire damage is R_i, the strength loss after fire damage is ΔR_i, and $S_{i\Delta} = \Delta R_i$, the functional function of the reinforced concrete structure is as follows:

$$Z_i = G(R_c, c, \rho, b) = R_i - S_{i\Delta} - S_{iG} - S_{iQ}, \quad (13)$$

where R_i refers to the bearing capacity of the structure when it is not under conditions of fire, i.e., the structural resistance; $S_{i\Delta}$ is the loss of structural strength after being subjected to a fire, i.e., the fire load effect; S_{iG} is the dead load effect of the structure after fire; S_{iQ} is the variable load effect after a fire on the structure.

5. Application

This section uses an example from engineering to illustrate the adaptability and accuracy of the method proposed in this article. First, the finite element method is used to establish a fire model for prestressed steel–concrete structures. Based on this, the uniform design method is used to extract structural fire resistance performance samples and identify the optimal probability model via overall goodness-of-fit testing. Then, the probability method is deployed to analyze the structural fire resistance reliability performance and perform parameter sensitivity analysis.

5.1. Project Overview

This project involves a prestressed reinforced concrete upper beam bridge in a certain area, analyzing a continuous beam bridge of 30 m + 30 m + 30 m. The construction method varies from simple to continuous support, and the main beam of the upper structure of the bridge is a small box beam. The beam has a width of b = 500 mm and a height of h = 1200 mm. The primary beam comprises C50 concrete, with limestone used as the aggregate. The axial compressive strength is fc = 32.4 MPa, and the axial tensile strength is fs = 1.89 MPa. The reinforcement used is HRB335 with a known strength grade, and the main reinforcement in the beam comprises 1860 MPa steel strands. The thickness of the protective layer on the concrete is 50 mm.

5.2. Finite Element Model

The finite element model size of prestressed steel–concrete beams is modeled in a 1:1 ratio according to the experimental dimensions. It is necessary to select the experimentally measured heating curve during simulation. The constitutive relationships between thermal parameters and the thermal coupling of siliceous concrete under high-temperature conditions are shown in Tables 1 and 2, with density taken as ρ = 2400 kg/m^3. Meanwhile, the constitutive relationships of thermal parameters and thermal coupling constitutive for steel under high-temperature conditions are shown in Tables 3–5, with density taken as ρ = 7850 kg/m^3. The temperature field model uses SOLID70 elements for concrete and LINK33 elements for steel bars and steel strands. The fire resistance calculation model uses SOLID65 elements for concrete and LINK8 elements for steel bars and steel strands. The grid size is set to 10 mm.

5.3. Structural Response of Prestressed Concrete Beam Bridges after Fire

Using nonlinear finite element technology to analyze the structural response of prestressed concrete beam bridges after a fire, the equivalent load method is used to analyze prestressed concrete structures. This method simulates the action of prestressed steel bars by applying loads to the line, surface, and body, i.e., applying prestressing force to the structure in the form of loads. Thermal stress analysis was conducted on the performance of prestressed concrete beam bridges after a fire. The structural response clouds after the fire times of t = 15 min, t = 30 min, and t = 60 min are shown in Figures 1–3.

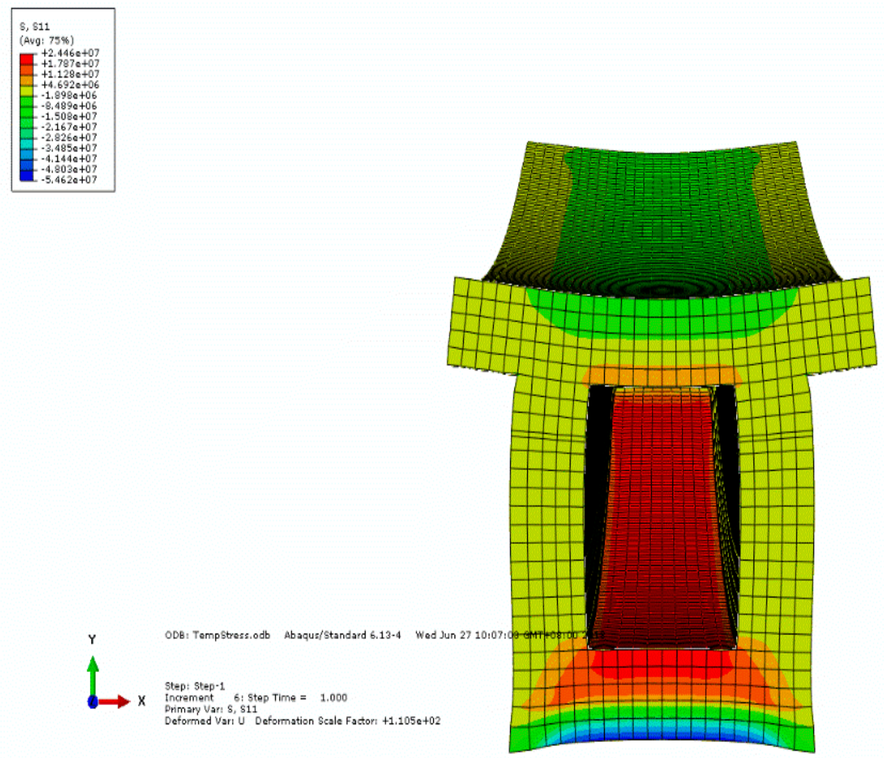

Figure 1. Structural response of prestressed concrete box girder under fire for 15 min.

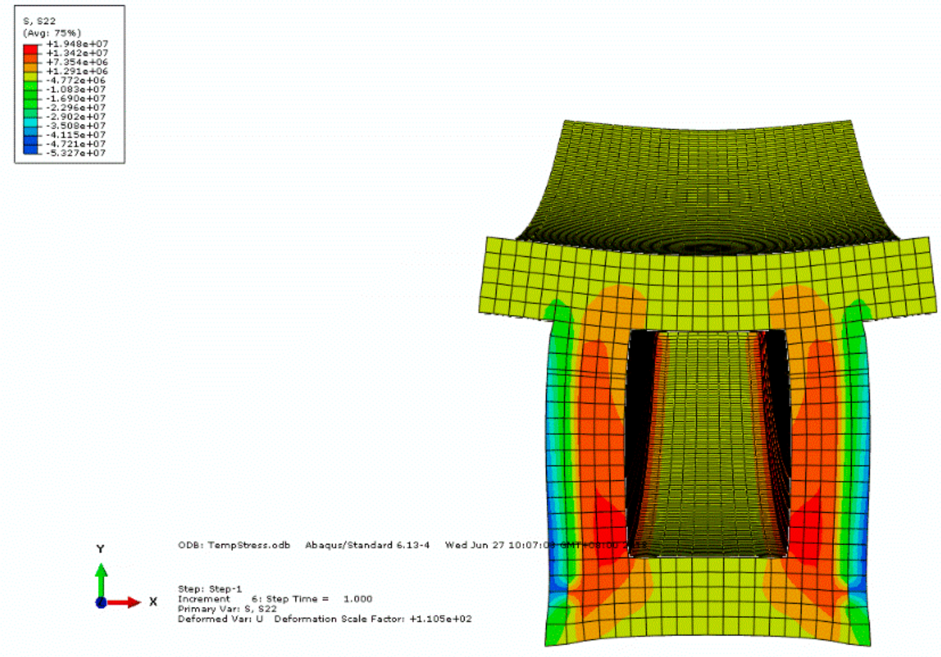

Figure 2. Structural response of prestressed concrete box girder under fire for 30 min.

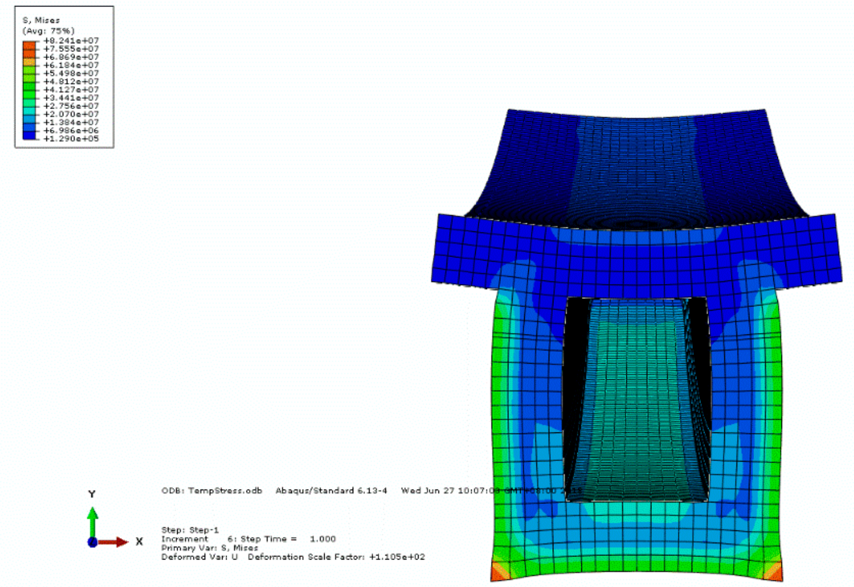

Figure 3. Structural response of prestressed concrete box girder under fire for 60 min.

5.4. Statistical Analysis of Structural Resistance of Prestressed Concrete Beam Bridges after Fire

The statistical parameters of various calculated random variables affecting the structural performance of prestressed concrete beam bridges after a fire are shown in Table 7.

Table 7. Statistical parameters for structural resistance calculation of prestressed concrete beam bridge.

Random Variables	Distribution Type	Mean Value	Standard Deviation	Coefficient of Variation
Section width	Normal distribution	1.00	0.01	0.01
Section height	Normal distribution	1.01	0.02	0.02

Table 7. *Cont.*

Random Variables	Distribution Type	Mean Value	Standard Deviation	Coefficient of Variation
Concrete strength	Normal distribution	1.39	0.19	0.14
Calculation mode	Normal distribution	1.10	0.08	0.07
Area of prestressed steel bars	Normal distribution	1.00	0.01	0.01
Strength of prestressed steel bars	Normal distribution	1.08	0.13	0.12
Dead load effect	Normal distribution	1.00	0.04	0.04
Live load	Gumbel distribution	1.00	0.18	0.18

For the purpose of analyzing the statistical characteristics of the resistance of prestressed concrete beam bridges after a fire, a uniform design method was used to randomly generate sample points based on the determination of the statistical characteristics of the principal parameters affecting the structure's fire resistance performance. Then, statistical analysis was conducted on the structure of prestressed concrete beam bridges post-fire via goodness-of-fit testing. All told, just six factors affect the prestressed concrete beam bridge following a fire, and 30 samples were randomly generated within a range of three times the standard deviation of each factor. The uniform design table is shown in Table 8.

Table 8. Uniform design of prestressed concrete beam bridge samples after fire.

1	8	2	17	16	19
2	12	21	8	4	7
3	21	20	27	20	26
4	24	15	5	27	10
5	3	29	21	11	17
6	15	11	20	24	2
7	18	7	2	7	24
8	27	24	24	6	14
9	4	5	11	21	8
10	29	13	13	12	30
11	14	26	14	30	12
12	22	9	28	10	6
13	6	23	6	18	29
14	10	16	29	1	20
15	28	6	22	29	22
16	19	30	12	15	1
17	2	12	4	5	15
18	1	18	16	25	23
19	25	4	15	2	4
20	26	28	3	23	18
21	13	3	25	14	18
22	7	25	26	26	5
23	20	1	7	19	13
24	16	27	18	3	27
25	9	17	1	13	3

Table 8. *Cont.*

26	30	19	19	17	9
27	11	10	9	28	25
28	5	8	23	8	11
29	23	22	10	9	21
30	17	14	30	22	16

After conducting finite element random analysis, we assessed the bending bearing capacity samples of the maximum prestressed concrete beam bridge after 15 min, 30 min, and 60 min of fire exposure.

(1) Sample of prestressed concrete after 15 min of fire

The flexural capacities (KN·m) of samples were as follows: 102,130, 106,127, 98,723, 103,120, 110,203, 104,298, 105,267, 108,272, 109,172, 104,152, 108,279, 103,728, 110,289, 109,821, 106,672, 106,827, 104,263, 105,527, 104,263, 107,723, 109,283, 105,637, 102,891, 106,374, 108,273, 105,273, 108,374, 106,627, 107,263, and 108,273.

The statistical characteristics of the flexural bearing capacity of prestressed concrete beams following 15 min of exposure to fire were analyzed using goodness-of-fit testing (see Table 9). Flexural bearing capacity followed a logarithmic normal distribution, with statistical characteristics, including a mean of 106,237 KN·m, a standard deviation of 2558 KN·m, and a coefficient of variation of 0.024.

Table 9. Sample statistics of prestressed concrete after 15 min fire.

α = 0.05	**Normal Distribution**	**Log-Normal Distribution**	**Gumbel Distribution**
D_n	0.1503	0.1366	0.2063
D_n^α	0.242	0.242	0.163
Accept/reject	Accept	Accept	Reject
k_i	0.6217	0.5591	-

(2) Sample of prestressed concrete after 30 min of fire

The flexural capacities of samples (KN·m) were as follows: 99,283, 95,637, 92,891, 96,374, 98,273, 95,273, 9837, 96,627, 97,263, 98,273, 92,130, 96,127, 98,723, 93,120, 100,203, 94,298, 95,267, 98,272, 99,172, 94,152, 98,279, 93,728, 100,289, 99,821, 96,672, 96,827, 104,263, 95,527, 94,263, and 97,723.

Following 15 min of fire treatment, we analyzed the statistical characteristics of the flexural bearing capacity of prestressed concrete beams using goodness-of-fit testing (see Table 10). It can be seen that the flexural bearing capacity followed a logarithmic normal distribution, and the statistical characteristics were a mean of 96,904 KN·m, a standard deviation of 2608 KN·m, and coefficient of variation of 0.027.

Table 10. Sample statistics of prestressed concrete after 30 min fire.

α = 0.05	**Normal Distribution**	**Log-Normal Distribution**	**Gumbel Distribution**
D_n	0.1321	0.1105	0.1899
D_n^α	0.242	0.242	0.163
Accept/reject	Accept	Accept	Reject
k_i	0.5869	0.4921	-

(3) Sample of prestressed concrete after 60 min of fire

The flexural capacities of the samples (KN·m) were as follows: 83,728, 90,289, 89,821, 86,672, 86,827, 84,263, 85,527, 84,263, 87,723, 89,283, 85,637, 82,130, 86,127, 78,723, 83,120, 90,203, 84,298, 85,267, 86,627, 87,263, 88,273, 88,272, 89,172, 84,152, 88,279, 82,891, 86,374, 88,273, 85,273, and 88,374.

The statistical characteristics of the flexural bearing capacity of prestressed concrete beams after 15 min of fire exposure were analyzed using goodness-of-fittesting (see Table 11). The flexural bearing capacity followed a logarithmic normal distribution, with statistical characteristics of a mean of 86,238 KN·m, a standard deviation of 2628 KN·m, and a coefficient of variation of 0.030.

Table 11. Sample statistics of prestressed concrete after 60 min fire.

α = 0.05	Normal Distribution	Log-Normal Distribution	Gumbel Distribution
D_n	0.1321	0.0988	0.1799
D_n^{α}	0.242	0.242	0.163
Accept/reject	Accept	Accept	Reject
k_i	0.6314	0.5736	-

5.5. Reliability Evaluation of Prestressed Concrete Beam Bridges after Fire

Operating on the premise of the need to clarify the factors that affect the fire resistance performance of prestressed concrete beam bridges, the finite element reliability principle was used to evaluate the probabilities for prestressed concrete beam bridges after a fire. The calculated reliability index and the probability safety coefficient when the existing target reliability index was 4.2 are shown in Table 12.

Table 12. Probabilistic assessment results of prestressed concrete beam bridge after fire.

Parameter	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	5.2772	5.1031	4.9917	4.4732
Deterministic safety factor	4.2901	3.9982	3.8871	3.6728
Probabilistic safety factor	3.9827	3.7872	3.6279	3.4821

According to the analysis in Table 12, there are significant changes in the structural performance of prestressed concrete beam bridges before and after a fire, and the overall fire resistance performance of the structure decreases with the increase in fire duration. In this specific instance, the reliability index of the prestressed concrete beam bridge before the fire was 5.2772. The reliability index of the structure dropped to 5.1031 at 15 min post-fire, 4.9917 at 30 min, and 4.4732 after 60 min. The safety factor that characterizes the safety of the structure also decreased from 4.2901 before the fire to 3.9982 15 min after the fire, 3.8871 at 30 min, and 3.6728 after 60 min. Taking the randomness of parameters into consideration, the probability safety factor of the structure decreased from 3.9827 before the fire to 3.7872 at 15 min after the fire, 3.6279 at 30 min, and 4821 after 60 min. From the perspective of probability analysis, it can be seen that the probability safety factor was reduced to a certain degree compared to the deterministic safety factor. This occurred because the randomness of the parameters reduced the safety reserve of the structure.

5.6. Parameter Sensitivity Analysis

The principal factors that affect the reliability index and probability safety coefficient of the structural performance of prestressed concrete beam bridges following a fire are the following: (1) the mean value of variables, (2) the coefficient of variation of variables, and (3) target reliability indicators.

(1) The Influence of Random Variable Mean on Reliability Index and Probability Safety Factor

The control variable method is adopted in order to study the influence of the mean value of random variables on the reliability indicators and probability safety factors of prestressed concrete beam bridges following fire. Each analysis only alters the mean value of a certain variable. The change plan involves taking 0.9, 1.0, and 1.1 times the original value, respectively, with the mean values of other random variables taken as the original value. The specific calculation results of the influence of the mean of each random variable on the reliability index and probability safety coefficient of the performance of prestressed concrete beam bridges after fire are shown in Tables 13–20.

Table 13. Effect of average section width on reliability index and probabilistic safety factor.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	5.1928	5.0018	4.7829	4.0192
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.3817	5.2938	5.1029	4.8372
Probabilistic safety factor	0.9	3.7182	3.6728	3.5782	3.3928
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	4.1029	3.8172	3.7292	3.6172

Table 14. Impact of average section height on reliability index and probabilistic safety factor.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	5.1928	5.0018	4.8982	4.3827
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.2932	5.1827	5.1019	4.5627
Probabilistic safety factor	0.9	3.8272	3.6729	3.5827	3.3928
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	4.1029	3.8472	3.7182	3.5728

Table 15. Effect of average concrete strength on reliability index and probabilistic safety factor.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	4.9182	4.8271	4.8271	4.1029
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.4982	5.3919	5.2109	4.9828
Probabilistic safety factor	0.9	3.8271	3.6279	3.5826	3.2647
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	4.1029	3.8271	3.7463	3.6274

Table 16. Effect of the mean uncertainty of the calculation mode on reliability indicators and probabilistic safety factors.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	5.1716	5.0187	4.8721	4.2761
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.3928	5.1982	5.2817	4.5261
Probabilistic safety factor	0.9	3.7261	3.6251	3.5627	3.2817
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	4.2817	3.8172	5.7162	3.6581

Table 17. Effect of mean area of prestressed reinforcement on reliability index and probabilistic safety factor.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	5.1722	5.0018	4.8271	4.1029
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.3627	5.2171	5.0271	4.7182
Probabilistic safety factor	0.9	3.8172	3.6273	3.5182	3.2019
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	4.1029	3.7298	3.7182	3.6271

Table 18. Effect of average strength of prestressed steel bars on reliability indicators and probabilistic safety factors.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	4.9182	4.8172	4.6172	4.2018
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.4817	5.4716	5.3716	4.7162
Probabilistic safety factor	0.9	3.7162	3.6172	3.5827	3.3928
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	4.1028	3.8172	3.7162	3.5102

Table 19. Effect of average dead load on reliability index and probabilistic safety factor.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	5.3817	5.2817	5.1829	4.8172
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.1928	5.0182	4.8271	4.0192
Probabilistic safety factor	0.9	4.1029	3.9182	3.7172	3.6571
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	3.7162	3.6721	3.5817	3.2492

Table 20. Impact of average live load on reliability index and probabilistic safety factor.

Parameter	Mean Value	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.9	5.4271	5.3281	5.1082	4.7168
	1.0	5.2772	5.1031	4.9917	4.4732
	1.1	5.2091	4.9281	4.7821	4.2918
Probabilistic safety factor	0.9	4.1029	3.8719	3.7162	3.6152
	1.0	3.9827	3.7872	3.6279	3.4821
	1.1	3.8721	3.6271	3.5721	3.2481

By analyzing the contents of Tables 13–20, it can be concluded that the reliability index of prestressed concrete beam bridges following a fire increases with the increase in the main beam width, main beam height, concrete strength, calculation mode uncertainty, prestressed steel area, and the average of prestressed steel strength while decreasing with the increase in the average of dead and live loads. The reliability index is a functional relationship between the mean and variability of random variables. As such, an increase in the mean of random variables that helps to improve resistance will enhance the reliability index, while an increase in the mean load will decrease the reliability index. Among the random variables that affect resistance, the influence of section height is more significant than that of section width, and the influence of steel reinforcement is greater than that of concrete.

The results in Tables 13–20 show that the probability safety factor of prestressed concrete beam bridges after a fire increases with the increase in the main beam width, main beam height, concrete strength, calculation mode uncertainty, prestressed steel bar area, and the mean value of prestressed steel bar strength, decreasing with the increase in the mean value of dead and live loads. The probability safety factor has a similar functional relationship to that of the reliability index, meaning that an increase in the mean value of the random variable that helps to improve resistance will increase the safety factor, whereas an increase in the mean value of the load will decrease the safety factor. Among the random variables related to safety factors, the influence of section height is more significant than that of section width, and the influence of steel reinforcement is more significant than that of concrete.

Overall, the mean of random variables exerts a significant impact on the reliability index and probability safety factor of prestressed concrete beam bridges after exposure to fire. In specific engineering practice, attention should be paid to monitoring and the use of statistics to reduce structural safety risks and ensure the normal operation of prestressed concrete beam bridges after a fire. Special attention should be paid to the impact of fire on the thickness of concrete protective layers and steel reinforcement. These are important factors affecting the fire resistance performance of prestressed steel-reinforced concrete. Corresponding risk sources should be strictly controlled in structural design and construction processes.

(2) The Influence of Random Variable Variation Coefficient on Reliability Index and Probabilistic Safety Factor

The control variable method is adopted to study the influence of the coefficient of variation of random variables on the reliability indicators and probability safety factors of prestressed concrete beam bridges after exposure to fire. Each analysis only alters the coefficient of variation of a certain variable. The change plan involves taking values 0.5, 1.0, and 2.0 times the original value, respectively, while also ensuring that the coefficient of variation remains unaltered for other variables. The specific calculation results of the influence of the coefficient of variation of each random variable on the reliability index and probability safety coefficient of the structural performance of prestressed concrete beam bridges after exposure to fire are shown in Tables 21–28.

Table 21. Effect of section width variation coefficient on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.5	5.3726	5.2918	5.1928	4.6872
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.1827	5.0182	4.8271	4.2817
Probabilistic safety factor	0.5	4.1028	3.8232	3.8172	3.6716
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.8271	3.6251	3.4726	3.2817

Table 22. Impact of section height variation coefficient on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.5	5.3716	5.1726	5.1029	4.7162
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.0192	4.9181	4.8172	4.3716
Probabilistic safety factor	0.5	4.1028	3.8172	3.7164	3.7162
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.7172	3.6527	3.5627	3.1726

Table 23. Effect of concrete strength variation coefficient on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.5	5.3918	5.1928	5.0182	4.5263
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.1928	5.0819	4.7182	4.3617
Probabilistic safety factor	0.5	4.1827	3.6172	3.7179	3.7162
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.7162	3.6521	3.5728	3.1928

Table 24. Effect of calculation mode uncertainty variation coefficient on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.5	5.3198	5.2183	5.1029	4.7162
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.1827	5.2771	4.8172	4.5162
Probabilistic safety factor	0.5	4.1928	3.8172	3.7861	3.6172
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.8172	3.6173	3.5617	3.1874

Table 25. Effect of area variation coefficient of prestressed steel bars on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire 60 min
Reliability index	0.5	5.3817	5.2615	5.1823	4.6257
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.1726	4.9182	4.7456	4.2736
Probabilistic safety factor	0.5	4.2716	3.9182	3.7584	3.6474
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.6172	3.6153	3.8745	3.3162

Table 26. Effect of strength variation coefficient of prestressed steel bars on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire 60 min
Reliability index	0.5	5.4827	5.2737	5.2183	4.6517
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.2617	4.9827	4.7264	4.4726
Probabilistic safety factor	0.5	4.1725	3.9183	3.7261	3.6253
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.7163	3.5726	3.4516	3.2617

Table 27. Effect of constant load variation coefficient on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.5	5.3716	5.2716	5.2172	4.7263
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.1827	5.0182	4.6735	4.3627
Probabilistic safety factor	0.5	4.2182	3.9271	3.8721	3.3627
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.8271	3.5262	3.5287	3.2617

Table 28. Effect of live load variation coefficient on reliability index and probabilistic safety factor.

Parameter	Coefficient of Variation	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Reliability index	0.5	5.4638	5.2716	5.1028	4.6274
	1.0	5.2772	5.1031	4.9917	4.4732
	2.0	5.0281	4.8927	4.8109	4.2817
Probabilistic safety factor	0.5	4.1726	3.8172	3.7263	3.5162
	1.0	3.9827	3.7872	3.6279	3.4821
	2.0	3.7162	3.6573	3.5267	3.3627

By analyzing the contents of Tables 21–28, it can be concluded that after a fire, the reliability indicators of prestressed concrete beam bridges decrease with the increase in the main beam width, main beam height, concrete strength, calculation mode uncertainty, prestressed steel bar area, prestressed steel bar strength, constant, and live load variation coefficients. The variability of random variables has a significant impact on structural reliability indicators, as an increase in parameters related to variability can lead to an increase in the discreteness of the structure, resulting in a decrease in reliability. Among all relevant random parameters, the variability of concrete section height, steel reinforcement area, and live load exert the most significant impact.

As with the results in Tables 21–28, it can be shown that the probability safety factor of prestressed concrete beam bridges after a fire decreases with the increase in main beam width, main beam height, concrete strength, calculation mode uncertainty, prestressed steel bar area, prestressed steel bar strength, and variation coefficients of dead and live loads. Similarly, the safety factor is closely related to the discreteness of structural parameters, and an increase in variability-related parameters will lead to an increase in the discreteness of the structure, resulting in a decrease in the safety factor. Among the random parameters that affect structural safety, the variability of concrete section height, steel reinforcement area, and live load exerts the most significant impacts.

Overall, the coefficient of variation of random variables has a significant impact on the reliability index and probability safety factor of prestressed concrete beam bridges after a fire. In specific engineering practice, attention should be paid to the discreteness of monitoring and statistical parameters in order to reduce structural safety risks and ensure the normal operation of prestressed concrete beam bridges following a fire. Therefore, during the construction process of prestressed steel–concrete structures, it is necessary to strictly monitor the relevant indicators of the structure to prevent the dispersion of structural parameters from increasing and improve the reliability and safety of the structure. Special attention should be paid to the control of the thickness of the protective layer, the area of the steel reinforcement, and the live load, as these parameters possess the most obvious discreteness.

(3) The Influence of the Target Reliability Index on the Probability Safety Factor

In order to study the impact of target reliability indicators on the probability safety factor of performance of prestressed concrete beam bridges after exposure to a fire, the target reliability indicators were modified each time; that is, the changed target reliability indicators were 3.2, 3.7, 4.2, 4.7, and 5.2. The specific calculation results of the impact of target reliability indicators on the probability safety coefficient of performance of prestressed concrete beam bridges after a fire are shown in Table 29.

Table 29. Impact of target reliability index on probability safety factor.

Parameter	Target Reliability Index	Before Fire	After Fire: 15 min	After Fire: 30 min	After Fire: 60 min
Probabilistic safety factor	3.2	4.3627	3.9827	3.8172	3.6172
	3.7	4.1827	3.8172	3.7162	3.5162
	4.2	3.9827	3.7872	3.6279	3.4821
	4.7	3.7182	3.6172	3.5263	3.3617
	5.2	3.5162	3.5018	3.4561	3.2817

According to the analysis in Table 29, as the target reliability index increases, the probability safety coefficient of prestressed concrete beam bridges shows a decreasing trend after fire exposure. This indicates that, with the increase in the target reliability index, the probability safety coefficient of prestressed concrete beam bridges after fire gradually decreases, the actual required safety performance of prestressed concrete beam bridges after fire gradually increases, and the safety reserve of prestressed concrete beam bridges after fire gradually decreases. The probability safety coefficients, calculated based on the reliability back analysis method under each target reliability index, are all smaller than the safety coefficients calculated based on the deterministic model, indicating that parameter uncertainty has a significant impact on the probability safety coefficient of prestressed concrete beam bridges after fires. Ignoring parameter uncertainty will lead to the overestimation of the safety coefficient of prestressed concrete beam bridges after fires.

6. Conclusions

This paper takes prestressed steel–concrete beam bridges as the research object and conducts research on the fire response analysis of prestressed concrete beam bridges, using reliability analysis methods to assess the fire resistance performance of prestressed concrete beam bridges and safety factor evaluation methods to evaluate the fire resistance performance of prestressed concrete beam bridges. In summary, the primary achievements and conclusions of this article are as follows:

(1) We conducted a study into the fire response of prestressed concrete beam bridges. Based on the nonlinear finite element analysis of the temperature field of the box girder section during a fire and the high-temperature mechanical performance analysis of prestressed steel–concrete box girder bridges, a method for analyzing the fire resistance performance of prestressed concrete beam bridges was established, laying the foundation for the subsequent reliability evaluation of the fire resistance performance of prestressed steel–concrete beam bridges.

(2) A fire resistance reliability model for prestressed concrete continuous beam bridges was established. The main influencing factors on the fire resistance performance of prestressed concrete beam bridges were summarized through statistical research, including the high-temperature characteristics of reinforced concrete components, the strength reduction of steel and concrete after fire, the bonding strength of steel and concrete after high-temperature exposure, and the resistance performance of prestressed concrete beams.

(3) A reliability analysis method was proposed to assess the fire resistance performance of prestressed concrete beam bridges. On the basis of clarifying the factors that affect the fire resistance performance of prestressed concrete beam bridges, a reliability model for evaluating the fire resistance performance of prestressed concrete beam bridges after a fire was constructed. By combining reliability theory with the finite element method, a reliability analysis method for the fire resistance performance of prestressed concrete beam bridges was proposed.

(4) Based on the analysis of the structural response after a fire in a specific engineering case of a simply supported to continuous prestressed concrete continuous beam bridge, a uniform design method was used to generate structural resistance samples of the prestressed concrete beam bridge and statistical analysis was conducted. Subsequently, probability methods were used to evaluate the safety of the prestressed concrete beam bridge after a fire.

(5) Using parameter sensitivity analysis of the reliability index and probabilistic safety factors of mean value and coefficient of variation, we concluded that the randomness of parameters exerts a significant impact on the safety reserve of prestressed concrete beam bridges after exposure to fire. In particular, the section height and steel bar parameters affect the fire resistance performance of the structure. The related discreteness of these two parameters exerts a very significant impact on the reliability and safety of the structure.

(6) By analyzing the time-varying characteristics of fire resistance, it was determined that the fire duration exerts a significant impact on the structural performance of prestressed concrete beam bridges. It is necessary to pay attention to this factor in specific engineering practices and strengthen the monitoring and statistics of structural random characteristics. The variability of parameters related to target reliability

indicators has a significant impact on structural safety assessment, especially the thickness of concrete cover and the statistical characteristics of steel reinforcement. Both of these should be strictly controlled during the design and construction process.

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