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

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Abstract: This paper uses probability method 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 obtain the structural response of prestressed steel-concrete structures under fire, which is in line with engineering practice. Next, construct a reliability analysis model for the fire resistance performance of prestressed steel-concrete beam bridges; Combining reliability theory with finite element method, establish a reliability analysis method for the fire resistance performance of prestressed steel-concrete beam bridges. Subsequently, a safety factor evaluation model for the fire resistance performance of prestressed steel-concrete beam bridges was proposed, and a safety factor evaluation method for the fire resistance performance of prestressed steel-concrete beam bridges based on reliability back analysis was established. Finally, based on the analysis of the structural response after a fire in a specific case of a simply supported to continuous prestressed steel-concrete continuous beam bridge project, a structural resistance sample of the prestressed steel-concrete beam bridge is generated through uniform design method, and statistical analysis is conducted. Subsequently, probability methods are used to evaluate the safety of the prestressed steel-concrete beam bridge after a fire. Through analysis, it can be concluded that the time of fire has a significant impact on the structural performance of prestressed steel-concrete beam bridges, and the randomness of parameters has a significant impact on the safety reserve of prestressed steel-concrete beam bridges after fire. It is necessary to pay attention to it in specific engineering practice and strengthen the monitoring and statistics of structural random characteristics.

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

1. Introduction

Bridge fires are a rare but serious accident. Strict standards and safety measures must be followed during the construction and maintenance process of bridges to ensure their fire resistance performance [1–6]. However, some factors may lead to bridge fires, such as electrical failures, extreme temperatures, and human factors [7,8]. In the event of a fire, bridges are usually severely damaged, which may lead to traffic paralysis and significant casualties. Therefore, preventing bridge fires is extremely important.

Based on the investigation and analysis of actual bridge fires, there are two main types of bridge fires: deck fires and under bridge fires. No matter what form of fire, while posing a threat to personal and property safety, it will cause more or less damage to the entire or partial bridge structure [9–16]. Bridge fires occur sporadically, and it is difficult to collect data and information about the fire scene, which poses significant limitations to the development of related research. Therefore, the current academic community's attention and research on bridge fires are far less focused on other natural disasters. In addition, the issue of fire resistance is rarely considered in the process of bridge design. Ultimately, it is because there is currently relatively little research on it. Therefore, conducting

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research on the fire resistance performance of bridge structures is of great significance. This will provide technical support for the future development and revision of bridge fire protection design specifications, and provide a basis for the evaluation and reinforcement of bridge fire protection performance.

The research on the fire resistance performance of prestressed concrete structures is currently mainly focused on the following aspects: Firstly, the research on fire resistance design methods, such as how to establish accurate and convenient practical methods; The second is the research on post disaster assessment methods, such as how to scientifically and accurately evaluate the degree of damage to prestressed concrete bridge structures that have been overheated, and based on this, develop plans for repairing and strengthening damaged structures [17–26]. The latter 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 [27–31]. Although there are building fire protection design codes in various countries, they mainly rely on experience and structural measures to solve the problem, and there is currently no mature analysis method for bridge structure fire protection design [32–36]. 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 such 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. To improve people's accurate and reasonable evaluation ability of the reliability of the fire resistance performance of prestressed concrete bridges, and to provide technical support to ensure the fire safety of prestressed concrete beam bridges.

2. Principles of prestressed concrete fire

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 at a temperature rise of one degree (°C or K). It represents the heat storage capacity of the object, expressed in units of J/(kg.K) or J/(kg.°C). The main factors affecting the specific heat capacity of concrete include temperature, mix ratio, aggregate type, and moisture content.

Due to the small variation of concrete specific heat with temperature, it is approximately taken 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.

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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 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= 7850kg/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) has developed the ISO-834 standard heating function, as shown in Equation (1).

$$T = T_0 + 345 \times \log(8t + 1) \quad (1)$$

where T was fire temperature, T0 was starting point temperature, T was duration of the fire.

According to equation (1) analysis, ISO-834 defines a monotonic heating function, and the temperature does not decay over time during the cooling process. But 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 make the fire resistance design method of structures safer. 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 actual fire) can be used.

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2.2.2. Fire temperature field of box girder section

When convection and radiation occur simultaneously on the fire surface, it is generally necessary to consider the effects of both convection and radiation to comprehensively express the heat transfer coefficient; The effect of thermal radiation needs to 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 · ℃)]).

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 some parameters that vary over time during the transient heat transfer process. The transient heat balance based on energy conservation can be expressed as:

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

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 mainly 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 8 nodes and temperature degrees of freedom assigned to each node.

(2) Develop mathematical models and assumptions for the model: Determine the mathematical model for calculating the temperature field of the small box girder model through physical equations, considering 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. 20 °C is set as the initial temperature 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 used 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

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 S and X can be expressed as

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

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.

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

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

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

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

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

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

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

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

This paper uses the central difference method to calculate the gradient of the limit state function, and its basic format is:

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

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

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

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

Finite element reliability analysis is a structural reliability analysis method based on 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 used for reliability analysis, and the application program interfaces of ANSYS and MATLAB software are used to achieve mutual call between the two. The specific steps are as follows:

(1) Establishment of structural finite element model: Firstly, 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: 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: 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: 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 reliability analysis.

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(5) Sensitivity analysis: Analyze the sensitivity of parameter uncertainty to reliability indicators and determine the parameters that have the greatest impact on structural reliability.
(6) Optimization design: Based on the sensitivity analysis results, 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, perform repeated calculations and optimization.

4. Finite element reliability fire resistance analysis

The establishment of the fire resistance limit state equation for prestressed concrete beam bridges requires 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 mainly 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, including 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 temperature.
(3) Establishing a mechanical model: Based on the structural and mechanical characteristics of the bridge, establish a mechanical model of the bridge under fire, 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 needed.

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

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

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

5. Application

5.1. Project overview

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

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5.2. 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 for the analysis of prestressed concrete structures. This method simulates the action of prestressed steel bars by applying loads on the line, surface, and body, that is, 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 time of t=15min, t=30min, and t=60min are shown in Figure 1 to Figure 3.

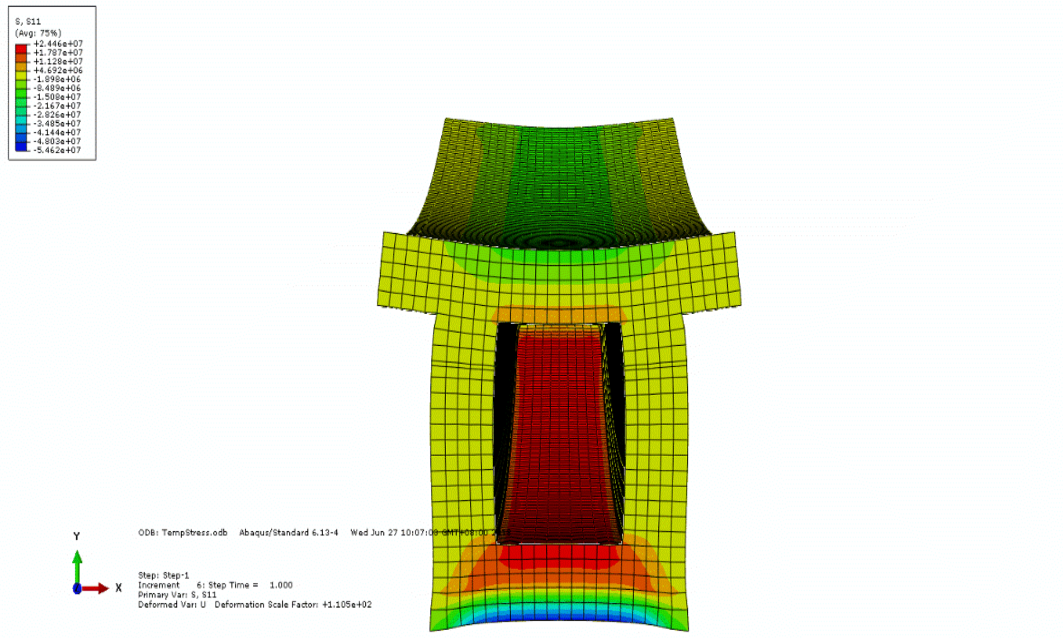

Figure 1. structural response of prestressed concrete box girder under fire for 15min.

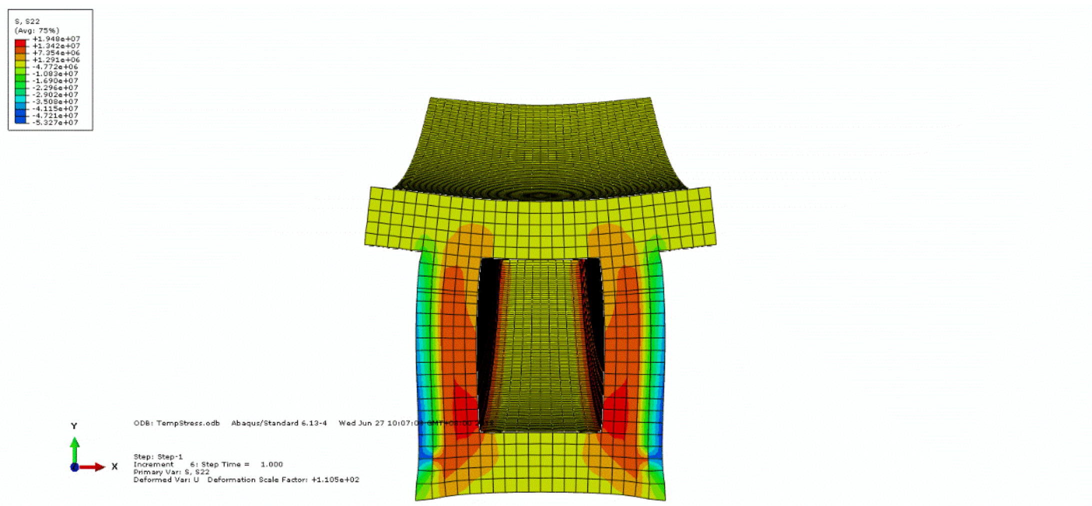

Figure 2. structural response of prestressed concrete box girder under fire for 30min.

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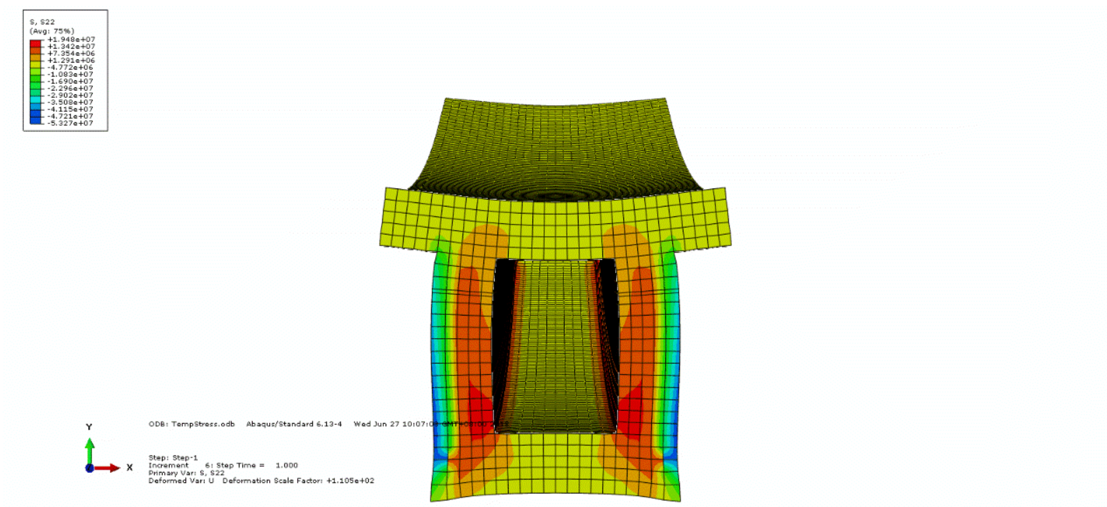

Figure 3. structural response of prestressed concrete box girder under fire for 60min.

5.3. Statistical analysis of structural resistance of prestressed concrete beam bridges after fire

The statistical parameters of various calculated random variables that affect 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
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

In order to analyze 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 main parameters that affect the fire resistance performance of the structure. Then, statistical analysis was conducted on the structure of prestressed concrete beam bridges after a fire through goodness of fit testing. There are 6 main factors that affect the prestressed concrete beam bridge after a fire, and 30 samples are randomly generated within a range of 3 times the standard deviation for each factor. The uniform design table is shown in Table 8.

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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
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 finite element random analysis, the bending bearing capacity samples of the maximum prestressed concrete beam bridge after 15 minutes, 30 minutes, and 60 minutes of fire are as follows:

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

Samples of Flexural capacity（KN.m） were as follows：102130、106127、98723、103120、110203、104298、105267、108272、109172、104152、108279、103728、110289、109821、106672、106827、104263、105527、104263、107723、109283、105637、102891、106374、108273、105273、108374、106627、107263、108273。

The statistical characteristics of the flexural bearing capacity of prestressed concrete beams after 15 minutes of fire were analyzed using goodness fit test (see Table 9). The flexural bearing capacity follows a logarithmic normal distribution, with statistical characteristics of a mean of 106237 KN. m, a standard deviation of 2558 KN. m, and a coefficient of variation of 0.024.

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Table 9. Sample Statistics of Prestressed Concrete after 15min Fire.

$\alpha = 0.05$	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 minutes of fire

Samples of Flexural capacity（KN.m） were as follows：99283、95637、92891、96374、98273、95273、98374、96627、97263、98273、92130、96127、98723、93120、100203、94298、95267、98272、99172、94152、98279、93728、100289、99821、96672、96827、104263、95527、94263、97723。

The statistical characteristics of the flexural bearing capacity of prestressed concrete beams after 15 minutes of fire were analyzed using goodness fit test (see Table 10). It can be seen that the flexural bearing capacity follows a logarithmic normal distribution, and the statistical characteristics are: mean 96904 KN. m, standard deviation 2608 KN. m, and coefficient of variation 0.027.

Table 10. Sample Statistics of Prestressed Concrete after 30min Fire.

$\alpha = 0.05$	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 minutes of fire

Samples of Flexural capacity（KN.m） were as follows：83728、90289、89821、86672、86827、84263、85527、84263、87723、89283、85637、82130、86127、78723、83120、90203、84298、85267、86627、87263、88273、88272、89172、84152、88279、82891、86374、88273、85273、88374。

The statistical characteristics of the flexural bearing capacity of prestressed concrete beams after 15 minutes of fire were analyzed using goodness fit test (see Table 11). The flexural bearing capacity follows a logarithmic normal distribution, with statistical characteristics of a mean of 86238 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.

$\alpha = 0.05$	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	-

5.4. Reliability evaluation of prestressed concrete beam bridges after fire

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

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

Parameter	Before fire	After fire 15min	After fire 30min	After fire 60min
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 of fire time. Specifically, the reliability index of the prestressed concrete beam bridge before the fire is 5.2772. The reliability index of the structure drops to 5.1031 at 15 minutes after the fire, 4.9917 at 30 minutes, and 4.4732 after 60 minutes. The safety factor that characterizes the safety of the structure has also decreased from 4.2901 before the fire to 3.9982 at 15 minutes after the fire, 3.8871 at 30 minutes, and 3.6728 after 60 minutes. Considering the randomness of parameters, the probability safety factor of the structure decreases from 3.9827 before the fire to 3.7872 at 15 minutes after the fire, 3.6279 at 30 minutes, and 4821 after 60 minutes. From the perspective of probability analysis, it can be seen that the probability safety factor has a certain degree of reduction compared to the deterministic safety factor, because the randomness of parameters will reduce the safety reserve of the structure.

5.5. Parameter sensitivity analysis

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

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

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 after fire, the control variable method is adopted. Each analysis only changes the mean value of a certain variable, and the change plan is to take 0.9, 1.0, and 1.1 times the original value respectively, while the mean values of other random variables are 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 Table 13 to Table 20.

Table 13. Effect of Average Section Width on Reliability Index and Probabilistic Safety Factor.

Parameter	Mean value	Before fire	After fire 15min	After fire 30min	After fire 60min
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

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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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 Table 13 to Table 20, it can be concluded that the reliability index of prestressed concrete beam bridges after a fire increases with the increase of the main beam width, main beam height, concrete strength, calculation mode uncertainty, prestressed steel area, and the average of prestressed steel strength, while decreases with the increase of the average of dead and live loads; The probability safety factor of prestressed concrete beam bridges after a fire increases with the increase of 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, while

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decreases with the increase of the mean value of dead and live loads. Overall, the mean 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 monitoring and statistics to reduce structural safety risks and ensure the normal operation of prestressed concrete beam bridges after a fire.

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

In order 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 fire, the control variable method is adopted. Each analysis only changes the coefficient of variation of a certain variable, and the change plan is to take 0.5, 1.0, and 2.0 times the original value respectively, while ensuring that the coefficient of variation of other variables remains unchanged. 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 fire are shown in Table 21 to Table 28.

Table 21. Effect of Section Width Variation Coefficient on Reliability Index and Probabilistic Safety Factor.

parameter	coefficient of variation	Before fire	After fire 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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

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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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 15min	After fire 30min	After fire 60min
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 Table 21 to Table 28, it can be concluded that the reliability indicators of prestressed concrete beam bridges after a fire decrease with the increase of 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 probability safety factor of prestressed concrete beam bridges after a fire decreases with the increase of 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. 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 to reduce structural safety risks and ensure the normal operation of prestressed concrete beam bridges after a fire.

(3) The Influence of Target Reliability Index on 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 fire, the target reliability indicators were modified each time, that is, the changed target reliability indicators were taken as 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 15min	After fire 30min	After fire 60min
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 after fire shows a decreasing trend. This indicates that with the increase of 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 overestimate the safety coefficient of prestressed concrete beam bridges after fires.

6. Conclusion

This paper takes prestressed concrete beam bridges as the research object, and conducts research on fire response analysis of prestressed concrete beam bridges, reliability analysis methods for fire resistance performance of prestressed concrete beam bridges, and safety factor evaluation methods for fire resistance performance of prestressed concrete beam bridges. In summary, the main work and conclusions of this article are as follows:

(1) A study was conducted on 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 fire and the high-temperature mechanical performance analysis of prestressed concrete box girder bridges, a method for analyzing the fire resistance performance of prestressed concrete beam bridges has been established, laying the foundation for the subsequent reliability evaluation of the fire resistance performance of prestressed concrete beam bridges.

(2) A fire resistance reliability model for prestressed concrete continuous beam bridges has been 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, and the resistance performance of prestressed concrete beams.

(3) A reliability analysis method for the fire resistance performance of prestressed concrete beam bridges has been proposed. 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 is constructed. By combining reliability theory with finite element method, a reliability analysis method for the fire resistance performance of prestressed concrete beam bridges is 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 is used to generate structural resistance samples of the prestressed concrete beam bridge, and statistical analysis is conducted. Subsequently, probability methods are used to evaluate the safety of the prestressed concrete beam bridge after a fire. Through analysis, it can be concluded that the time of fire has a significant impact on the structural performance of

prestressed concrete beam bridges, and the randomness of parameters has a significant impact on the safety reserve of prestressed concrete beam bridges after fire. It is necessary to pay attention to it in specific engineering practice and strengthen the monitoring and statistics of structural random characteristics.

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