International Journal of Heat and Technology
Vol. 42, No. 5, October, 2024, pp. 1541-1550
Journal homepage: http://iieta.org/journals/ijht

Effects of High-Temperature Environments on the Thermodynamic Performance of Reinforced Concrete Bridge Structures

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https://doi.org/10.18280/ijht.420507

Received: 6 April 2024
Revised: 23 August 2024
Accepted: 19 September 2024
Available online: 31 October 2024

Keywords:
high-temperature environment, reinforced concrete bridge, thermodynamic performance, linear rotational boundary, bilinear rotational boundary

ABSTRACT

With global climate change and the increasing occurrence of extreme high-temperature weather, the safety and durability of infrastructure such as bridges face significant challenges. The thermodynamic performance of reinforced concrete bridge structures in high-temperature environments becomes particularly critical, as thermal expansion and contraction, along with reduced material strength, can lead to structural damage, potentially affecting the service life and stability of bridges. Although previous research has explored the thermodynamic behavior of reinforced concrete structures under high temperatures, most studies have only considered simple boundary conditions, neglecting the effects of complex rotational boundary conditions on the thermodynamic performance of these structures. Current models also lack sufficient accuracy to fully explain the complex changes that occur in reinforced concrete bridge structures under high-temperature effects. To address these issues, this paper first investigates the thermodynamic theory of reinforced concrete bridge structures in high-temperature environments. It then analyzes the high-temperature effects under linear rotational boundary conditions. Finally, the impact of bilinear rotational boundary conditions on the thermodynamic performance of these structures is explored. The results of this study provide a reliable theoretical foundation and engineering guidance for bridge design and maintenance.

1. INTRODUCTION

With global climate change and the frequent occurrence of extreme high-temperature weather, critical infrastructure such as bridges is facing severe challenges [1-4]. As an indispensable part of modern engineering, the degradation of the performance of reinforced concrete bridge structures when exposed to high-temperature environments for long periods cannot be ignored [5-7]. High temperatures significantly affect the thermodynamic performance of reinforced concrete, potentially leading to thermal expansion and contraction, a decrease in material strength, and structural damage. These changes not only affect the safety and service life of bridges but also directly threaten the stable operation of transportation systems [8, 9]. Therefore, studying the impact of high-temperature environments on the thermodynamic performance of reinforced concrete structures is of great practical significance.

Currently, research on the impact of high-temperature environments on reinforced concrete structures has made some progress, but there are still many gaps and shortcomings [10-13]. The complexity of high-temperature effects and the influence of different boundary conditions on the structural response have not yet been fully revealed. Particularly in bridge engineering, accurate analysis of thermodynamic effects is crucial for preventing structural failure and optimizing design. Therefore, a systematic and in-depth investigation of the thermodynamic behavior of reinforced concrete bridge structures under high-temperature environments holds great value for both engineering applications and theoretical research [14, 15].

Most existing studies focus on thermodynamic analysis of structures under static conditions or only consider simple boundary conditions, neglecting the complex influence of linear or bilinear rotational boundary conditions in high-temperature effects [16-19]. Some studies lack precision in their thermodynamic models, making it difficult to effectively explain the thermodynamic changes in reinforced concrete bridge structures under complex boundary conditions [20-23]. For the design and maintenance of bridges in high-temperature environments, current methods have not yet fully guided protective measures in practical engineering, which remains a pressing issue that needs to be addressed in current research.

This paper aims to systematically analyze the thermodynamic performance of reinforced concrete bridge structures in high-temperature environments and to explore the high-temperature effects under different boundary conditions. First, the thermodynamic theory of reinforced concrete structures in high-temperature environments is studied. Next, the high-temperature effects considering linear rotational boundary conditions are analyzed. Finally, the influence of bilinear rotational boundary conditions on the thermodynamic performance of the structure is discussed. The research in this paper fills the gaps in existing studies and provide more reliable theoretical basis and engineering references for bridge design and maintenance under high-temperature environments.

2. THERMODYNAMIC THEORY OF REINFORCED CONCRETE BRIDGE STRUCTURES IN HIGH-TEMPERATURE ENVIRONMENTS

In high-temperature environments, the thermodynamic performance of reinforced concrete bridge structures is influenced by multiple factors, primarily including heat conduction, heat radiation, and heat convection. For reinforced concrete bridges, the heat transfer characteristics of concrete and reinforcement differ when exposed to temperature changes. Concrete, as a heterogeneous material, has a relatively low thermal conductivity, whereas reinforcement has higher thermal conductivity. Therefore, in high-temperature environments, there is a difference in heat transfer rates between concrete and reinforcement, leading to the formation of localized stress concentrations and temperature gradients. This stress concentration may induce cracks and structural damage, especially in areas with large temperature differences. When bridges are exposed to high-temperature scenarios such as solar radiation or fire, the surface of the concrete continuously absorbs and releases energy through heat radiation. Due to the differing surface characteristics of concrete and reinforcement, the efficiency of absorbing and radiating heat also varies. As the exposure time increases, the temperature of the concrete surface gradually rises, which accelerates thermal damage to the structure, resulting in surface spalling, crack propagation, and other issues. Therefore, the heat radiation effect on reinforced concrete bridge structures in high-temperature environments not only affects the external temperature but also changes the internal temperature distribution, which in turn affects the overall performance of the structure. In high-temperature environments, the surrounding air movement intensifies the rate of heat exchange on the surface of the bridge, especially under strong sunlight or during a fire, where air movement accelerates heat dissipation from the bridge surface. However, the intensification of heat convection in high temperatures may increase the temperature gradient, resulting in greater stress and deformation within the structure. If certain parts of the bridge are exposed to strong winds or rapidly changing airflows, the heat convection effect will further exacerbate the concentration of thermal stress in these areas. Therefore, studying the temperature changes of reinforced concrete bridge structures under different convection conditions can help better predict the structural response and damage in high-temperature environments. Figure 1 illustrates the various forms of heat exchange between reinforced concrete bridge structures and the external environment.

In high-temperature environments, the thermodynamic performance of reinforced concrete bridge structures is affected by various parameters, including cross-sectional area, elastic modulus, thermal expansion coefficient, structural length, and boundary conditions. The cross-sectional area of reinforced concrete bridge structures directly influences the heat dissipation performance and heat accumulation of the structure. A larger cross-sectional area can absorb more heat in high-temperature environments, but it can also lead to uneven heat dissipation due to the larger volume, forming internal temperature gradients that induce thermal stress. If the cross-sectional area is smaller, although less heat accumulates, the faster conduction speed under high temperatures may cause local overheating and the formation of cracks. In high-temperature environments, the elastic modulus of reinforced concrete decreases significantly as the temperature rises, leading to a reduction in the stiffness of the structure. The extent of this decrease depends on the composition of the material and the duration of high-temperature exposure. A lower elastic modulus makes reinforced concrete bridge structures more prone to deformation and buckling under high temperatures, especially when heat distribution is uneven. In such cases, the intensification of local deformation may lead to more severe structural damage. Therefore, considering the change in elastic modulus is crucial for predicting the response of bridges under high temperatures.

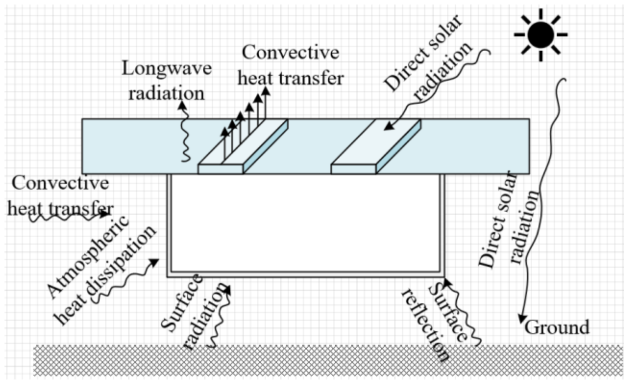


Figure 1. Various forms of heat exchange between reinforced concrete bridge structures and the external environment

The thermal expansion coefficients of reinforcement and concrete differ. In high-temperature environments, the difference in expansion rates between concrete and reinforcement leads to internal stress concentrations. Particularly during abrupt temperature changes, the thermal expansion effect further amplifies stress concentration phenomena. The thermal expansion coefficient of materials under high temperatures directly affects the overall stability of the structure. If the structural design does not adequately account for the effects of thermal expansion, the bridge may develop cracks, spalling, and other issues. Thus, reasonably evaluating the impact of the thermal expansion coefficient on reinforced concrete structures in high-temperature environments is essential. The length of reinforced concrete bridge structures determines the distribution of thermal stress in high-temperature environments. Longer structures tend to develop significant temperature gradients under high temperatures, especially when there are large temperature differences at both ends, resulting in a more pronounced accumulation of thermal stress within the structure. In longer bridges, the linear expansion effect caused by high temperatures becomes more evident, which may lead to overall deformation or local warping of the structure. Conversely, shorter structures may have a more uniform temperature distribution, but local damage may still occur due to thermal expansion. Therefore, considering the effect of structural length on thermal expansion and thermal stress is a factor that cannot be overlooked in design. Figure 2 shows the dimensions of the reinforcement in a reinforced concrete bridge structure specimen. Figure 3 shows the reinforcement details in the cross-section of a reinforced concrete bridge structure specimen.

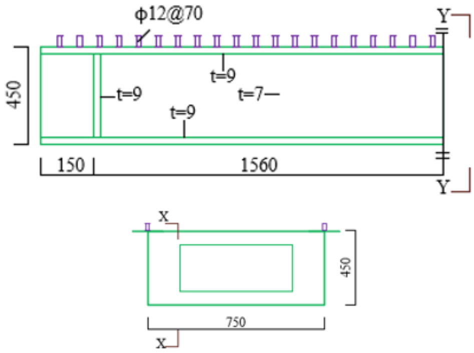


Figure 2. Reinforcement dimensions of reinforced concrete bridge structure specimen

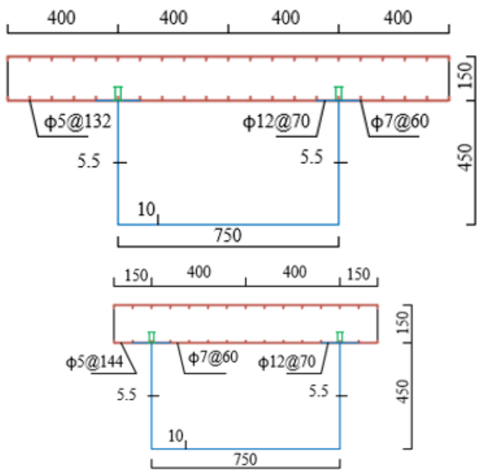


Figure 3. Reinforcement diagram of cross-section of reinforced concrete bridge structure specimen

Boundary conditions play a crucial role in the thermodynamic response of reinforced concrete bridge structures in high-temperature environments. Different boundary conditions, such as fixed, simply supported, linear rotational boundary, or bilinear rotational boundary conditions, significantly affect the distribution of thermal stress and deformation patterns of the structure. For instance, linear or bilinear rotational boundary conditions can alter the degrees of freedom of the structure, changing the way stress is relieved under high-temperature conditions, thus influencing the overall thermodynamic response.

3. ANALYSIS OF HIGH-TEMPERATURE EFFECTS ON REINFORCED CONCRETE BRIDGE STRUCTURES CONSIDERING LINEAR ROTATIONAL BOUNDARY CONDITIONS

In practical engineering, the boundary conditions of reinforced concrete bridge structures are often complex, especially in high-temperature environments, where fixed and simply supported structures cannot fully reflect the actual stress state. Linear rotational boundary conditions allow for a certain degree of rotational freedom at the support points, which better approximates the actual behavior of bridges under thermal stress caused by temperature changes. In high-temperature environments, due to thermal expansion and stress concentration, slight rotations may occur at the support points of the structure. Introducing linear rotational boundary conditions can more accurately simulate the deformation and stress characteristics of bridges, thereby improving the accuracy of the analysis. Moreover, reinforced concrete bridge structures in high-temperature environments generate internal stress due to thermal expansion effects, particularly at the support points where the constraints of fixed supports may prevent effective stress relief, exacerbating stress concentration. By introducing linear rotational boundary conditions, the structure can release part of the thermal stress through a certain degree of rotation at the support points, thus preventing structural damage caused by stress concentration. This boundary condition effectively alleviates the thermal stress caused by temperature gradients, enhancing the thermal resistance and long-term stability of the structure. This paper first analyzes the high-temperature effects on reinforced concrete bridge structures under linear rotational boundary conditions.

First, the temperature distribution of reinforced concrete bridge structures in high-temperature environments is analyzed, particularly considering linear gradient temperature conditions. Typically, under the influence of factors such as solar radiation and ambient temperature changes, the reinforced concrete bridge structure shows a linear temperature gradient distribution along its longitudinal direction. This gradient temperature can be determined through formulas or experimental data to describe the temperature difference across the structure from one end to the other.

Once the temperature field distribution is determined, the next step is to analyze the rotational displacement ϕ_S of reinforced concrete bridge structures without rotational constraints. In this case, the left end of the beam is a simply supported support, and the right end is a sliding support, where the boundary conditions allow free rotation of the beam under high-temperature effects. Under the linear temperature gradient, the temperature difference between the left and right ends of the beam causes non-uniform expansion of the material, leading to bending deformation of the beam due to the temperature difference. This part of the analysis can be calculated using the thermal expansion effect formula, in combination with the material's thermal expansion coefficient, the length of the beam, cross-sectional dimensions, and other parameters, to determine the rotational displacement ϕ_S in the absence of rotational constraints.

In practical bridge design, rotational constraint boundary conditions are often introduced to control the thermal deformation of the structure. For structures with rotational constraints, the rotational displacement will not be entirely equal to the free rotational displacement in the absence of constraints but will be limited by the boundary conditions. In this case, the rotational constraint at the left end of the beam will result in a constrained rotational displacement ϕ_E, and the actual rotational displacement ϕ_I will be smaller than the displacement without rotational constraints. According to the description, the actual rotational displacement is the sum of the free rotational displacement ϕ_S and the constrained rotational displacement ϕ_E, that is, ϕ_I=ϕ_S -ϕ_E. The key here is to clarify the impact of rotational constraints on the thermal deformation of the structure and calculate the rotational displacement of the structure under actual constraint conditions. Assuming the thermal expansion coefficient is represented by β, the temperature at the top of the beam is represented by S_1, the temperature at the bottom of the beam is represented by S_2, the length of the reinforced concrete bridge structure is represented by M, and the height of the reinforced concrete bridge structure is represented by g, the relationship can be expressed as follows:

$$\phi_S = \phi_E + \phi_I \tag{1}$$

For the reinforced concrete bridge structure with non-rotational constraint boundary conditions, the rotational displacement ϕ_S under the effect of the temperature gradient is fundamental to the thermal effect analysis of the bridge. This rotational displacement is closely related to the temperature gradient distribution along the beam, its geometric dimensions, and the material properties. In high-temperature environments, the temperature gradient causes thermal expansion, and the temperature differences at different locations lead to bending and deformation of the beam. Based on the geometric deformation relationship of the beam and the thermal expansion effect, the rotational displacement ϕ_S can be derived through the following formula:

$$\phi_S = -\frac{\beta(S_1 - S_2)M}{2g} \tag{2}$$

Under non-rotational constraint conditions, both the left and right ends of the beam will experience free rotational displacement due to the temperature gradient, and ϕ_S is the integral result of the temperature field and the geometric parameters of the beam. This expression provides the specific value of free rotational displacement ϕ_S, which reflects the direct influence of the temperature gradient on the reinforced concrete bridge structure and provides a basis for subsequent moment analysis.

In high-temperature environments, a linear rotational constraint is applied to the left end of the reinforced concrete bridge structure. According to the constraint conditions, the rotational displacement is not entirely free but partially restricted. This constrained rotational displacement is defined as ϕ_E. Due to the presence of rotational constraints, the bending caused by the thermal expansion of the beam is hindered, generating a moment at the beam's end. To address this issue, the specific expression for the end moment L_T needs to be derived through mechanical equations. Eqs. (2) and (3) respectively express the geometric and mechanical relationships of the reinforced concrete bridge structure. Assuming the modulus of elasticity is represented by R, the moment of inertia of the cross-section is represented by U, and the rotational boundary stiffness parameter is represented by j_e, these two equations can be substituted into the structural moment Eq. (4), leading to the specific expression of the end moment L_T as shown in Eq. (5).

$$\phi_E = \frac{L_T M}{3RU} \tag{3}$$

$$L_T = j_e \phi_I = j_e(\phi_S - \phi_E) \tag{4}$$

$$L_T = -\frac{j_e \beta(S_1 - S_2)}{2g\left(1 + \frac{j_e M}{3RU}\right)} \tag{5}$$

According to the equations above, the rotational displacement ϕ_I is the key deformation quantity of the reinforced concrete bridge structure with rotational boundary conditions under the action of a temperature gradient. Deriving this rotational displacement helps in understanding the force and deformation behavior of the structure under different boundary conditions. Based on Eq. (4), the moment *Ms* expression includes the related quantities of rotational displacement. Combining the boundary condition constraints, the rotational displacement ϕ_I depends not only on the free rotational displacement ϕ_S under non-constraint conditions but also on the constrained rotational displacement ϕ_E due to the rotational constraint. Through the relationship between the moment and the rotational displacement, these variables can be related, leading to the expression of the rotational displacement ϕ_I.

$$\phi_I = -\frac{\beta(S_1 - S_2)}{2g\left(1 + \frac{j_e M}{3RU}\right)} \tag{6}$$

Once the rotational displacement θU is determined, the next step is to analyze the stress and strain response of the structure under rotational constraint conditions. According to Eqs. (6) and (7), the stress and strain relationship for the reinforced concrete bridge structure can be derived. Here, the stress mainly arises from internal thermal stress within the structure, as the temperature gradient causes uneven expansion in different parts of the structure, generating internal stress. When the reinforced concrete bridge structure is subjected to external forces, the thermal stress caused by the temperature gradient significantly affects the force state of the structure. In this paper, using the relationship between these factors, the strain γ_E for the structure with rotational constraints is derived. Assuming the distance from the neutral axis is represented by b, we have:

$$\delta = R\gamma = \frac{L_T}{U} b \tag{7}$$

$$\gamma_E = -\frac{j_e \beta(S_1 - S_2)b}{2gRU\left(1 + \frac{j_e M}{3RU}\right)} \tag{8}$$

Through the above analysis, it is found that the temperature gradient, strain, and rotational displacement in reinforced concrete bridge structures under high-temperature environments exhibit a linear relationship. This is because, under the influence of the temperature gradient, the uneven thermal expansion at different positions in the reinforced concrete bridge structure leads to bending and deformation. Specifically, when the temperature difference increases, the bending deformation and internal stress of the beam increase accordingly. The greater the temperature difference, the more pronounced the thermal expansion difference between the top and bottom of the beam, resulting in a stronger strain and rotational displacement response in the structure.

Rotational boundary conditions have a significant impact on the high-temperature response of reinforced concrete bridge structures. When the value of the rotational boundary condition parameter is 0, the reinforced concrete bridge structure is equivalent to being in a free rotational state. In this case, the beam ends can rotate freely, meaning they are not subjected to any rotational constraint. This implies that the rotational displacement of the reinforced concrete bridge structure under the temperature gradient reaches its maximum value, and since there is no additional constraint, the strain at the beam end is 0. At this time, the temperature difference between the top and bottom of the beam only leads to the free rotation and deformation of the beam, without generating internal stress or additional strain. When the value of the rotational boundary condition parameter tends to infinity, the beam ends are effectively in a fixed state. In this situation, the beam ends cannot rotate freely, so the rotational displacement under the temperature gradient approaches 0. As the beam ends are fixed, the thermal expansion caused by the temperature difference generates significant stress and strain within the beam, and the high-temperature response of the structure mainly manifests as stress concentration and strain accumulation. Under fixed boundary conditions, the high-temperature deformation of the beam is significantly constrained, but this also increases the risk of stress concentration, imposing higher safety requirements on the structure.

4. ANALYSIS OF HIGH-TEMPERATURE EFFECTS ON REINFORCED CONCRETE BRIDGE STRUCTURES CONSIDERING BILINEAR ROTATIONAL BOUNDARY CONDITIONS

In high-temperature environments, the material properties of reinforced concrete bridge structures undergo significant changes. As the main load-bearing materials of bridges, steel reinforcement and concrete experience thermal expansion, strength reduction, and changes in elastic modulus under the influence of high temperatures. These changes in thermodynamic properties will directly affect the overall force state of the reinforced concrete bridge structure, potentially leading to deformation, cracking, or even failure. Additionally, reinforced concrete bridge structures often operate in complex high-temperature environments, such as during hot summers or when exposed to fire, where noticeable temperature gradients can form between the top and bottom of the structure due to uneven heating. The inconsistent thermal expansion caused by the temperature difference can induce bending deformation and the accumulation of thermal stress in the reinforced concrete bridge structure. Therefore, this study further considers bilinear rotational boundary conditions to better simulate the deformation characteristics of reinforced concrete bridge structures in high-temperature environments, providing a more detailed analysis of the structural response under different temperature gradients, including changes in rotational displacement and strain. Bilinear rotational boundary conditions allow the beam ends to rotate freely to a certain extent while being constrained, which aligns with common support conditions in actual engineering. This approach can also more accurately reflect the real force and deformation behavior of bridges under high temperatures. Bilinear rotational boundary conditions allow the structure to rotate freely within certain limits while providing appropriate constraints to prevent excessive deformation. This enables the model to simulate the deformation characteristics of actual reinforced concrete bridge structures, leading to more accurate mechanical response results. Figures 4 and 5 present the arrangement of temperature and strain measurement points for the reinforced concrete bridge structure specimens.

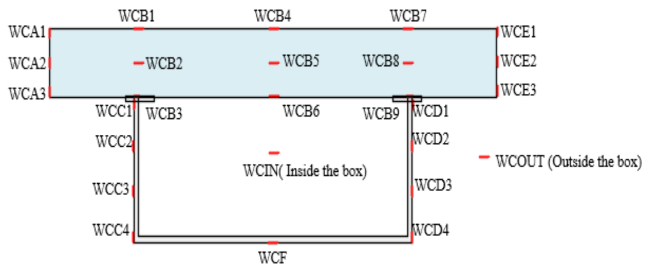


Figure 4. Arrangement of temperature measurement points in the reinforced concrete structure specimen

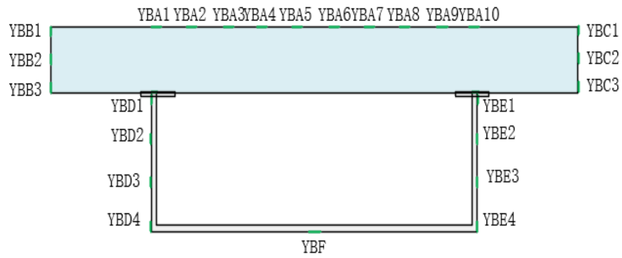


Figure 5. Arrangement of strain measurement points in the reinforced concrete structure specimen

In complex high-temperature environments, reinforced concrete bridge structures are often subjected to significant temperature gradients. This section first analyzes the impact of high temperatures on the material properties of reinforced concrete bridge structures, especially when temperature differences occur between the top and bottom of the beam. Such gradients can result in uneven thermal expansion coefficients, leading to non-uniform thermal stresses and deformations. As a result, the mechanical response of reinforced concrete bridge structures is not only influenced by external loads but also directly affected by temperature changes. In the initial analysis, it is assumed that the material properties of the reinforced concrete structure of the bridge change in a high-temperature environment, such as a decrease in the strength of the concrete and an increase in the thermal expansion coefficient of the steel. Subsequently, the study further examines the stress and deformation of the structure through the introduction of bilinear rotational boundary conditions.

When establishing bilinear rotational boundary conditions, this study assumes that there is a bilinear relationship between the rotational displacement of the reinforced concrete bridge structure and the stiffness of its boundary conditions. Specifically, when the rotational displacement $|\phi_l|$ of the structure is less than or equal to a certain threshold value ϕ_y, the boundary stiffness remains constant, represented as j_{e1}. However, when the rotational displacement exceeds ϕ_y, the boundary stiffness decreases from j_{e1} to j_{e2} (where $j_{e2} < j_{e1}$). This simulates the rotational constraints of actual bridge structures, where smaller rotational displacements experience higher boundary constraints, while larger displacements lead to reduced stiffness, allowing for greater rotational freedom. When the rotational displacement exceeds a certain threshold ϕ_y, the stiffness of the boundary conditions decreases, allowing the reinforced concrete structure of the bridge to undergo larger rotations. It is assumed that the temperature difference between the top and bottom of the beam when the rotational boundary conditions of the reinforced concrete structure enter the bilinear phase is represented by S_{ey}, the stiffness value after the reinforced concrete structure enters the bilinear phase is represented by j_{e2}, and the moment required for the rotational boundary conditions to enter the bilinear phase is represented by L_y. Specifically, the rotational displacement and strain of the reinforced concrete structure of the bridge when $|\phi_I|\leq\phi_y$ can be calculated using the following formula:

$$\phi_I = -\frac{\beta(S_1 - S_2)}{2g\left(1+\frac{j_{e1}M}{3RU}\right)} \tag{9}$$

$$\gamma_E = -\frac{j_{e1}\beta(S_1 - S_2)b}{2gRU\left(1+\frac{j_{e1}M}{3EU}\right)} \tag{10}$$

When $|\phi_I|>\phi_y$, the rotational displacement and strain of the reinforced concrete bridge structure can be calculated as follows:

$$\phi_I = -\phi_y - \frac{\beta(S_1 - S_2 - S_{ey})}{2g\left(1+\frac{j_{e2}M}{3RU}\right)} \tag{11}$$

$$\gamma_E = -\frac{L_y b}{RU} - \frac{j_{e2}\beta(S_1 - S_2 - S_{ey})b}{2gRU\left(1+\frac{j_{e2}S}{3RU}\right)} \tag{12}$$

where, in ϕ_y can be determined by the following expressions:

$$\phi_y = \frac{\beta S_{ey}}{2g\left(1+\frac{j_{e1}M}{3RU}\right)} \tag{13}$$

$$\phi_y = \frac{L_y}{j_{e1}} \tag{14}$$

Under a temperature gradient, when $|\phi_I|\leq\phi_y$, the thermal expansion and deformation caused by the temperature gradient are effectively controlled by the boundary stiffness j_{e1}. In this case, the rotational displacement is small, and the internal stress and strain are limited. The thermal stresses are primarily concentrated as bending stresses caused by the thermal expansion difference between the top and bottom of the beam. The boundary condition plays a constraining role, preventing excessive deformation of the structure. However, when the temperature gradient increases, causing the rotational displacement to exceed ϕyϕyϕy, the boundary stiffness decreases from j_{e1} to j_{e2}, reducing the rotational constraints on the beam. At this stage, the reinforced concrete bridge structure undergoes larger rotational displacements, and the internal stress and strain increase accordingly. The effect of thermal expansion becomes more pronounced, and the reduced stiffness of the boundary allows for further accumulation of thermal stresses, which increases the risk of significant structural deformation.

In the case of bilinear rotational boundary conditions, the mathematical expressions for rotational displacement and strain were further derived. Initially, when $|\phi_I|\leq\phi_y$, the rotational displacement and strain of the reinforced concrete bridge structure can be obtained through classical mechanical analysis. The stress-strain relationship in this case is related to the material's thermal expansion coefficient and the boundary stiffness j_{e1}, resulting in relatively small displacements and strains. However, when $|\phi_I|>\phi_y$, the boundary stiffness j_{e2} comes into play, and the rotational displacement and strain must be recalculated. At this point, the strain increases more significantly, and the deformation of the beam exhibits non-linear characteristics. The expressions for rotational displacement and strain for $|\phi_I|>\phi_y$ are as follows:

$$\phi_I = -\frac{L_y}{j_{e1}} - \frac{\beta(S_1 - S_2)}{2g\left(1+\frac{j_{e2}M}{3RU}\right)} + \frac{\frac{L_y}{j_{e1}}\left(1+\frac{j_{e1}M}{3RU}\right)}{\left(1+\frac{j_{e2}M}{3RU}\right)} \tag{15}$$

$$\gamma_E = -\frac{L_y b}{RU} - \frac{j_{e2}\beta(S_1 - S_2)b}{2gRU\left(1+\frac{j_{e2}M}{3RU}\right)} + \frac{j_{e2}\frac{L_y b}{j_{e1}}\left(1+\frac{j_{e1}M}{3RU}\right)b}{RU\left(1+\frac{j_{e2}M}{3RU}\right)} \tag{16}$$

Through the research, it can be found that the bilinear rotational boundary condition significantly affects the mechanical response of beam structures under high-temperature environments. When the rotational displacement of the beam structure $|\phi_I|\leq\phi_y$, the temperature difference between the top and bottom of the beam and the strain and rotational displacement of the structure show a linear relationship. In this stage, the boundary condition parameters of the beam structure remain unchanged, and the stiffness value is j_{e1}. At this time, the thermal stress and deformation caused by temperature changes are mainly constrained by j_{e1}, the deformation of the beam structure is small, and the stress distribution is relatively uniform. However, when the rotational displacement of the beam structure $|\phi_I|>\phi_y$, the structure enters the bilinear stage, and the boundary condition stiffness decreases from j_{e1} to j_{e2} ($j_{e2} = 0.3 \times j_{e1}$). At this point, the rotational constraint of the beam structure is significantly weakened, and the influence of the temperature difference on the beam structure is further aggravated. The temperature difference between the top and bottom of the beam and the strain and rotational displacement of the beam structure show a bilinear relationship. It can be seen that the introduction of bilinear rotational boundary conditions effectively simulates the nonlinear response of beam structures in actual engineering under high-temperature environments.

In a high-temperature environment, the temperature difference between the top and bottom of the beam has a particularly significant effect on the structure. When the temperature difference reaches 15℃, the rotational displacement of the beam structure exceeds the critical value ϕ_y, and the boundary condition stiffness decreases from j_{e1} to j_{e2}, and the structure enters the bilinear response stage. By analyzing the relationship between rotational displacement and strain under different temperature differences, we reached the following conclusions:

(1) When the temperature difference < 15℃: The rotational displacement and strain of the beam structure are linearly related to the temperature difference. At this time, the deformation is constrained by j_{e1}, the stress and deformation of the structure are small, showing good stiffness and stability.

(2) When the temperature difference ≥ 15℃: The rotational displacement and strain of the beam structure enter the bilinear stage, and the boundary condition stiffness decreases to j_{e2}. At this time, the increase in temperature difference causes a significant increase in rotational displacement and strain, and the stiffness and stability of the structure decrease, showing obvious nonlinear characteristics.

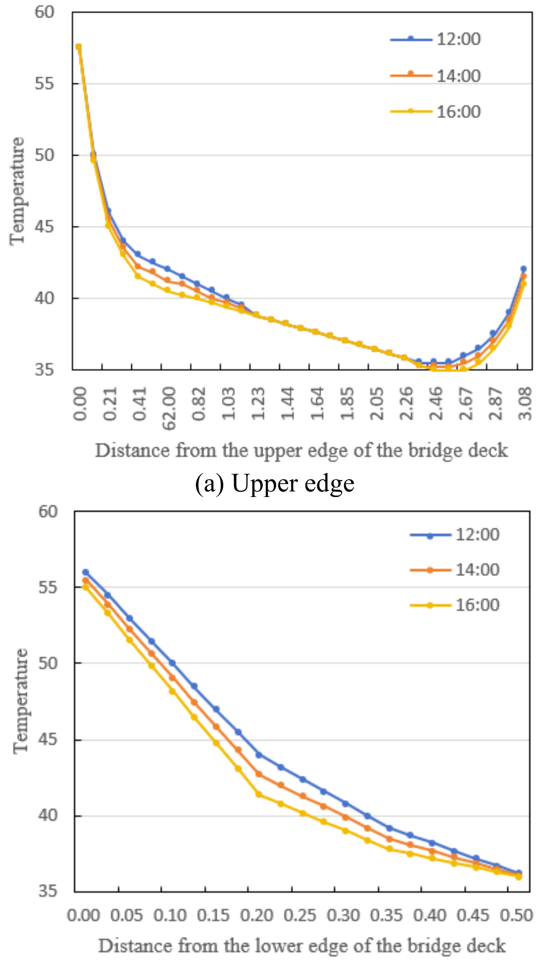
In a high-temperature environment, the temperature gradient has a direct impact on the thermal stress distribution of the beam structure. Due to the uneven thermal expansion caused by the temperature difference, different thermal stresses are generated between the top and bottom of the beam. Through the analysis of the bilinear rotational boundary condition, it can be found that:

(1) Linear stage: When the temperature difference is small, the thermal stress is mainly concentrated in the bending stress between the top and bottom of the beam. The boundary condition j_{e1} effectively constrains the thermal deformation of the structure, and the thermal stress distribution is relatively uniform.

(2) Bilinear stage: When the temperature difference is large, the rotational constraint of the beam is weakened, and the reduction of j_{e2} further concentrates the thermal stress. The thermal stress distribution of the beam structure becomes more complicated, and local stress concentration is likely to occur, increasing the risk of structural failure.

5. EXPERIMENTAL RESULTS AND ANALYSIS

From the data in Figure 6, it can be seen that the temperature difference distribution of the bridge concrete structure in a high-temperature environment shows significant time and position variations. At 12:00, the temperature at the upper edge of the bridge section decreases as the distance from the bridge deck increases, with the highest temperature being 57.5℃ and the lowest temperature being 35.5℃. A similar phenomenon is observed at the lower edge, where the highest temperature is 56℃, and the lowest is 36.2℃. As time progresses, by 14:00, the temperature at the upper edge decreases, with the highest temperature being 57.5℃ and the lowest being 35.25℃, while the lower edge temperature decreases from 55.5℃ to 36.1℃. By 16:00, the overall temperature further decreases, especially with the lowest temperature at the upper edge dropping to 35℃, and the lowest temperature at the lower edge being 36℃. It can be seen that the temperature shows a significant gradual decline trend throughout the day. Based on data analysis, the thermodynamic performance of the bridge concrete structure is significantly affected by high temperatures, and the temperature difference at different height positions reflects the dynamic changes of the high-temperature effect over time. The temperature variations at different positions of the section indicate that the heat conduction mechanism within the structure is limited by the thermal conductivity of the material, and boundary conditions, such as bilinear rotation, have a certain influence on the temperature distribution. Furthermore, as time progresses, the temperature gradually decreases, indicating that the external environmental temperature changes and the thermal inertia of the bridge structure result in a significant temperature gradient at a certain height. This temperature difference can have a potential impact on the thermal stress and deformation of the structure, which necessitates the consideration of reasonable thermal insulation and cooling measures in actual engineering applications.

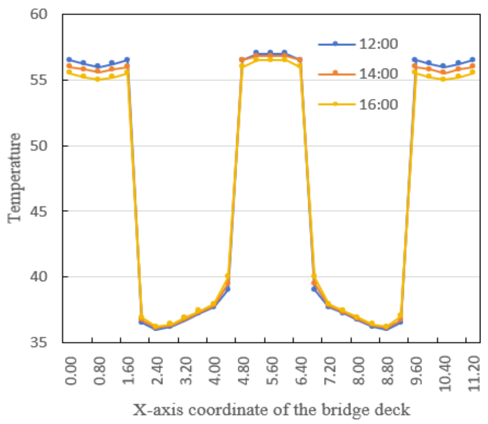


(a) Upper edge

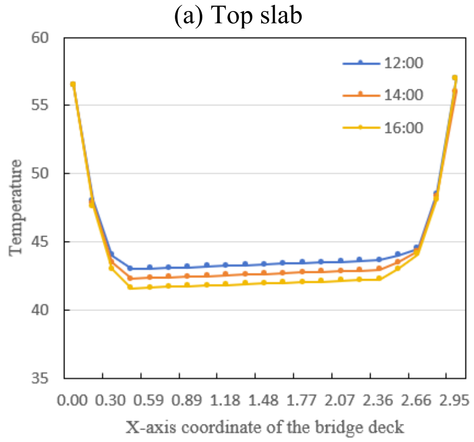
(b) Lower edge

Figure 6. Vertical temperature difference diagram at typical moments on the central line section of the bridge concrete structure

From Figure 7, it can be seen that the lateral temperature difference of the bridge concrete structure base shows a certain regularity with the changes in the X-axis coordinates and time. At 12:00, the highest temperature of the bottom slab occurs at the X-axis position of 0.00, reaching 56.5℃. As the X-axis coordinate increases, the temperature gradually decreases, dropping to 43.35℃ at 2.95 meters. With the passage of time, the overall temperature decreases at 14:00, maintaining a maximum temperature of 56.5℃, while the minimum temperature at 2.95 meters drops to 42.65℃. By 16:00, the temperature further decreases, with the temperature at X-axis 0.00 remaining at 56.5℃ and dropping to 41.95℃ at X-axis 2.95 meters. It can be observed that as time progresses, the temperature of the bottom slab structure shows a significant declining trend, especially with a more substantial temperature drop in areas farther from the center. Analyzing the changes in lateral temperature difference of the bridge bottom slab indicates that high temperatures have a significant impact on the thermal conduction of the concrete structure. The temperature distribution at different positions along the X-axis reveals that the temperature at the center region (X-axis 0.00) maintains a higher heat level, while the temperature gradually decreases as the X-axis coordinate increases, indicating a gradual weakening of heat transfer efficiency within the concrete structure. This temperature difference is mainly limited by the thermal conductivity and thermal diffusion capacity of the materials, and the impact of boundary conditions further exacerbates the formation of the temperature gradient, especially under the bilinear rotational boundary condition, resulting in uneven temperature distribution. This phenomenon suggests that the temperature difference may lead to thermal stress concentration in different areas of the bottom slab, resulting in structural deformation or damage. Therefore, effective thermal treatment and temperature control measures need to be implemented to mitigate the damage to the bridge caused by the high-temperature environment.



(a) Top slab



(b) Bottom slab

Figure 7. Lateral temperature difference diagram of the bridge concrete structure base at typical moments

From the Z-direction normal stress data in Table 1, it can be observed that the stress distribution of the bridge concrete structure under high-temperature conditions undergoes significant changes with time and the positions of key points. For the left-side key points of the YBD series, the negative stress at YBD4 gradually decreases from -7.85 MPa at 12:00 to -6.37 MPa at 18:00, while the stress at YBD3 increases from -0.28 MPa to -1.12 MPa, indicating a trend of increased compressive stress. YBD2 consistently maintains positive stress, with stress values rising from 1.02 MPa to 1.34 MPa, suggesting an increase in tensile stress. YBD1 changes from a positive stress of 0.01 MPa at 12:00 to a negative stress of -0.48 MPa at 18:00. For the YBB series, the positive stress gradually increases over time, with YBB1's stress rising from 1.40 MPa to 1.77 MPa, reflecting a significant change in tensile stress. The experimental results indicate that the Z-direction stress at the left-side key points of the bridge concrete structure exhibits complex time-varying behavior under high-temperature conditions, with significant differences in stress states at different positions. For the YBD series, the negative pressure stress at YBD4 gradually decreases, while YBD2 and YBD1 show varying degrees of tensile stress changes under high temperatures, indicating a significant impact of the high-temperature environment on the tensile-compressive balance of the structure. The YBB series key points display a consistent increasing trend in positive stress, particularly with YBB1 experiencing a gradual increase in tensile stress, suggesting that this area may be under considerable tensile conditions. Overall, the thermodynamic performance of the bridge is significantly influenced by different boundary conditions, with high temperatures leading to uneven internal stress distribution, potentially causing localized stress concentrations, thereby increasing the risk of structural failure. Therefore, it is essential to enhance considerations of stress changes in high-temperature environments during design and construction.

Table 1. Z-direction normal stress table at key points on the left side of the bridge concrete structure (Unit: MPa)

Key Point	Typical Time			
	12:00	14:00	16:00	1:00
*YBD*4	-7.85	-7.86	-7.34	-6.37
*YBD*3	-0.28	-0.55	-0.85	-1.12
*YBD*2	1.02	1.22	1.32	1.34
*YBD*1	0.01	-0.22	-0.37	-0.48
*YBB*3	1.12	1.23	1.21	1.14
*YBB*2	1.32	1.45	1.44	1.62
*YBB*1	1.40	1.55	1.65	1.77

Table 2. Z-direction normal stress table at key points on the right side of the bridge concrete structure (Unit: MPa)

Key Point	Typical Time			
	12:00	14:00	16:00	18:00
*YBE*4	-8.02	-7.89	-7.23	-6.28
*YBE*3	-0.47	-0.65	-0.92	-1.23
*YBE*2	0.03	-0.04	-0.25	-0.62
*YBE*1	1.12	1.23	1.23	1.13
*YBC*3	0.71	0.95	1.14	1.14
*YBC*2	1.03	1.26	1.35	1.36
*YBC*1	1.08	1.38	1.56	1.68

From the Z-direction normal stress data at key points on the right side of the bridge concrete structure in Table 2, it can be observed that as time progresses, there are significant changes in the stress distribution at each key point. The negative stress at the YBE series key points gradually decreases; for instance, the stress at YBE4 drops from -8.02 MPa at 12:00 to -6.28 MPa at 18:00, and the negative pressure stress at YBE3 also gradually increases from -0.47 MPa to -1.23 MPa, while YBE2 transitions from positive stress of 0.03 MPa to negative stress, ultimately reaching -0.62 MPa at 18:00. YBE1 consistently maintains positive stress and reaches a maximum value of 1.23 MPa at 14:00. The YBC series shows an upward trend in positive stress over time, particularly for YBC1, where positive stress rises from 1.08 MPa at 12:00 to 1.68 MPa at 18:00, reflecting a gradual increase in tensile stress. Analysis shows that the Z-direction stress at the right-side bridge concrete structure exhibits significant time-varying characteristics due to the high-temperature effects. Among the YBE series key points, the negative pressure stress at YBE4 to YBE2 gradually decreases over time, especially YBE2, which undergoes a transition from positive to negative stress, indicating that the structure in these areas is gradually subjected to greater compressive stress under high temperatures. Conversely, all key points in the YBC series are in a tensile state, with stress continually increasing over time, particularly with a notable rise in positive stress at YBC1, indicating that this area is experiencing an increase in tensile stress, which may lead to localized tensile stress concentrations. Overall, the impact of high temperatures on structural stress is reflected not only in the changes in stress at different key points but also in the disruption of the balance between tensile and compressive forces within the structure. Therefore, effective temperature control measures should be implemented to reduce the uneven stress distribution caused by high temperatures, thereby enhancing the safety and durability of the structure.

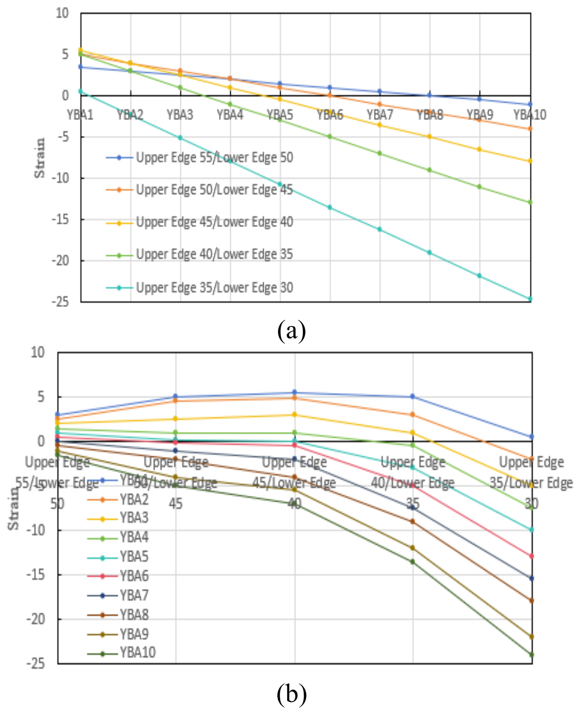


Figure 8. Strain of bridge reinforced concrete structure under high temperature load

From the strain data of the bridge reinforced concrete structure shown in Figure 8, it can be observed that the strain values at different measurement points (YBA1 to YBA10) exhibit regular variations under high temperature loads, depending on the measurement point position (from upper edge 55/lower edge 50 to upper edge 35/lower edge 30). The strain value at upper edge 55/lower edge 50 is 3.5 at YBA1 and decreases to -1 at YBA10. As the position lowers, the strain values gradually increase; for instance, at upper edge 50/lower edge 45, the strain value is 5 at YBA1, dropping to -4 at YBA10. Particularly at the layer of upper edge 35/lower edge 30, the change in strain value is significant, dropping rapidly from 0.5 at YBA1 to -24.7 at YBA10. This trend indicates that the lower the measurement point, the greater the strain value, leading to increased compressive or tensile deformation, with the lower region showing the most dramatic strain changes. The experimental results indicate that under high temperature conditions, the strain distribution of the bridge reinforced concrete structure shows significant stratification and spatial differences. The higher positions (e.g., upper edge 55/lower edge 50 and upper edge 50/lower edge 45) have relatively small strain values, maintaining a certain degree of positive strain characteristics, suggesting that these areas mainly experience tensile strain. However, as the height decreases, particularly from upper edge 45/lower edge 40 to upper edge 35/lower edge 30, there is a gradual increase in negative strain, with significant strain amplitudes, indicating that these areas are experiencing greater compressive strain, potentially leading to a cumulative deformation effect. In summary, the bottom regions of the structure experience the highest compressive strain under high temperature loads, demonstrating the thermal imbalance within the concrete structure due to thermal loads, which causes deformation and stress concentration in the lower areas. It is essential to enhance temperature control and stress management in the lower regions during design and construction to ensure the overall stability of the structure.

6. CONCLUSION

This paper systematically analyzes the thermodynamic performance of bridge reinforced concrete structures under high temperature environments, focusing on the thermal effects of the structure under different boundary conditions and their impacts on stress and strain. The experimental results indicate that under high temperature loads, the temperature difference, stress, and strain distribution of the bridge reinforced concrete structure exhibit significant spatial and temporal variations. The analysis of vertical and lateral temperature differences reveals the phenomenon of temperature gradients in the structure under high temperatures, further exacerbating the unevenness of internal stresses within the concrete structure. The Z-direction normal stress data from the left and right key points suggest complex stress changes in the tensile and compressive regions of the structure, particularly showing significant differences in stress states at different positions, with noticeable localized stress concentrations. Strain analysis further confirms the deformation characteristics of the structure under high temperature conditions, with a sharp increase in compressive strain in the lower regions, indicating a particularly significant impact of high temperature loads on these areas, potentially leading to localized instability.

The value of this research lies in revealing the thermodynamic response laws of bridge reinforced concrete structures in high temperature environments, filling a research gap regarding the impact of boundary conditions on stress and strain distribution under high temperature conditions. However, there are limitations, such as the boundary condition settings in the experiments and simplifications of the thermal models, which may not fully reflect the complex temperature loads and mechanical boundary conditions in actual engineering. Future research should further explore the structural performance under complex boundary conditions and prolonged high temperature exposure, particularly through more numerical simulations and validations in real engineering scenarios to improve structural design theory for high temperature conditions, providing stronger theoretical support for enhancing the durability and safety of bridge reinforced concrete structures.

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