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Enhancing Bridge Structural Stability: A Comprehensive Analysis of Thermodynamic Properties and Thermal Stress Performance

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ABSTRACT

Bridges, integral elements of transportation networks, necessitate high levels of structural stability for secure and seamless operation. Current methodologies predominantly concentrate on the influence of individual factors on bridge infrastructure, often overlooking potential interplays between environmental aspects, such as the symbiosis between thermal stress and load. Additionally, a scarcity of test data for verification and rectification restricts a comprehensive understanding of concrete bridge behavior under complex environmental conditions. To address these limitations, this study focuses on concrete bridges, investigating their thermodynamic properties and thermal stress performance. Initially, an in-depth analysis of the thermodynamic properties of concrete bridges is undertaken. Subsequently, employing a thermal stress-load coupling test, the performance of concrete bridges in intricate environments is scrutinized, and the stress test results are rectified. This study aims to introduce a novel method for evaluating bridge structural stability more accurately and comprehensively, enabling effective responses to varied environmental challenges. The findings from this research possess both theoretical and practical implications for bridge design, construction, and maintenance, contributing towards averting potential structural failures.

1. INTRODUCTION

Bridges, key components of transportation networks, are crucial in facilitating modern societal economic development and ensuring routine human activities [1-4]. Subjected to multifarious physical and mechanical influences in a complex natural environment, the stability of these structures, particularly concrete bridges, is profoundly affected by environmental factors such as temperature variations [5-11]. Changes in ambient temperature can induce material expansion or contraction, generating thermal stress that potentially compromises the structural integrity of the bridge [12-14].

Understanding the thermodynamic properties and thermal stress performance of concrete bridges is conducive to comprehending their behavior and performance amidst various temperature fluctuations [15-18]. Such an understanding can provide predictive insights into bridge stability, furnishing scientific evidence for bridge maintenance, repair strategies, and preventative measures [19-21]. As such, this research is of significant import to bridge design, construction, operation, maintenance, and the prevention of potential structural failures.

Despite these considerations, current research methodologies predominantly concentrate on the influence of single factors on bridge infrastructure, often overlooking the potential coupling effects between different environmental elements, such as thermal stress and load [22, 23]. Moreover, existing methods largely rely on theoretical calculations and model predictions, leading to a scarcity of test data for verification and rectification. These limitations hinder a comprehensive understanding of bridge behavior in complex environments [24, 25].

The objectives of this research include a detailed exploration of the thermal stress performance of bridges in complex environments, facilitated by an analysis of the thermodynamic properties of concrete bridges and a thermal stress-load coupling test. Furthermore, this research aims to rectify strain test results. Through this investigation, it is anticipated that a more comprehensive and accurate method for evaluating the structural stability of concrete bridges across varied environments will be identified. This study can provide valuable theoretical and practical insights for bridge design, construction, and maintenance, thereby ensuring the safety and stability of the overall transportation system.

2. THERMODYNAMIC PROPERTIES OF CONCRETE BRIDGES

The structural stability of concrete bridges significantly impacts the safety and efficiency of the transportation system. Bridges, exposed to the natural environment, invariably encounter alterations in temperature conditions, necessitating a thorough analysis of their thermodynamic properties. These properties critically influence the structural stability of bridges as temperature fluctuations can induce the expansion or contraction of the concrete, thereby generating thermal stress. Structural damage may ensue if this thermal stress surpasses the concrete's capacity. An exhaustive analysis of concrete bridge performance under varying temperature conditions aids in accurately defining the thermal stress threshold in bridge design, thereby averting structural damage resultant from excessive thermal stress. Concurrently, it aids in the efficient mitigation of thermal stress issues during bridge maintenance and repair. The research route of this study is elucidated in Figure 1.

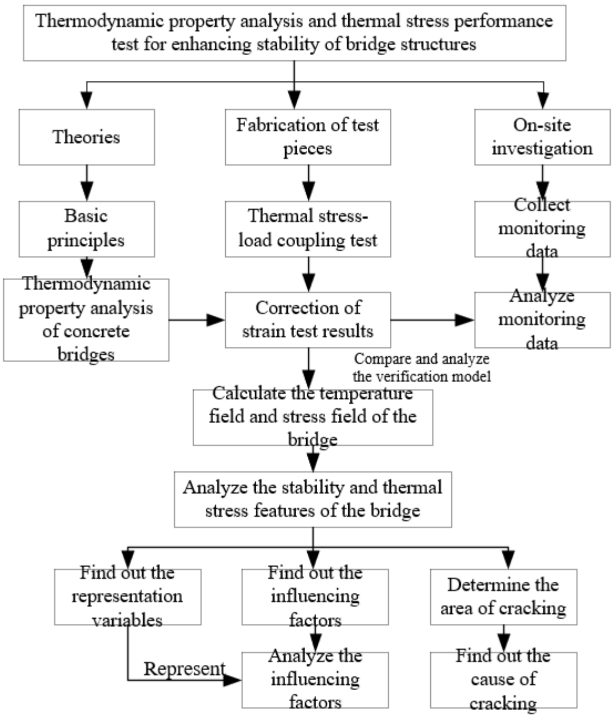


Figure 1. Diagram of the research route

In real-world conditions, concrete bridges typically function under the influence of multiple environmental factors, such as high temperatures and load. As a unified definition of thermal stress is yet to be determined, direct measurement of thermal strain proves elusive. Hence, this study utilizes fundamental mechanics linking stress and strain to analyze and calculate transient thermal stress. This approach is beneficial in examining the capacity and potential failure modes within the bridge structure under fire. Despite a deviation existing between the calculated values and the strict definition of thermal stress, the internal stress of concrete members under high-temperature conditions can be discerned. As this method incorporates other significant factors such as load, a more comprehensive analysis of the impact on thermal stress is facilitated.

Thermo solid coupling analysis scrutinizes the deformation behavior of solids under the influence of a thermal field and the reciprocal action of the movement or deformation of the solid on the thermal field. As thermal and mechanical effects are closely intertwined and influential to each other in many practical scenarios, they cannot be considered separately. Within the context of this study, concrete bridges endure various environmental factors, such as temperature changes and load. Their thermodynamic feature is not solely the result of thermal or mechanical effect but an outcome of thermo solid coupling. Therefore, employing thermo solid coupling analysis to study the thermodynamic characteristics of concrete bridges proves advantageous. This approach effectively reflects the actual scenario of concrete bridges in working environments, considering both thermal and mechanical effects and their interactions.

Assuming: W represents the amount of heat, Q represents the amount of work, ΔI represents the internal energy of the system, ΔJR represents the kinetic energy of the system, ΔOR represents the potential energy of the system. The law of conservation of energy can be applied in the thermodynamic study of concrete bridges at high temperatures, and the following formula should be met:

$$W - Q = \Delta I + \Delta JR + \Delta OR \tag{1}$$

At high temperatures, the heat transfer in concrete bridges is affected by three basic mechanisms: heat conduction, heat radiation, and heat convection, wherein heat conduction is the process that microscopic particles inside the substance vibrate, move, and transfer their energy to their neighbor particles. At high temperatures, the increase in thermal energy of particles inside concrete will accelerate the movement of particles, and they will transfer the heat to their neighbors through collision and vibration, thereby realizing heat conduction. The heat conduction properties of concrete are affected by the material's properties, temperature gradient and density. Assuming: w'' represents the density of heat flow, j represents the heat conduction coefficient, "-" represents that the heat flow runs towards the low temperature direction, then the heat conduction formula of concrete bridges is:

$$w'' = -j\frac{dY}{dz} \tag{2}$$

Heat radiation is the process of transferring heat through electromagnetic wave propagation, it can be carried out in vacuum without the help of material medium. When the temperature of concrete bridge is higher than the ambient temperature, the concrete surface will radiate heat energy outward in the form of electromagnetic waves. Since the effect of heat radiation increases with the fourth power of temperature, it can not be ignored at high temperatures. Assuming: R_n represents the radiation capacity of black body, γ represents blackness of the object, V_0 represents the heat radiation coefficient of black body, Y represents the surface temperature of the bridge, then the heat radiation formula of concrete bridges is:

$$R = \gamma R_n = \gamma V_0\left(\frac{Y}{100}\right)^4 \tag{3}$$

Heat convection is the process of heat transfer caused by internal temperature difference of liquid or gas as it flows. In a high temperature environment, if there is air or other fluid medium flowing near the concrete bridge, due to the existence of temperature difference, the heat of the concrete bridge will be carried away by the fluid, forming the thermal convection. The effect of heat convection is determined by factors such as the flow rate and properties of the fluid and the temperature difference between the concrete and the fluid. Assuming: W represents the amount of heat exchange of heat convection, y_q represents the wall surface temperature, y_d represents the temperature of the fluid, D represents the heat exchange area of heat convection, β represents the heat convection coefficient, then the heat convection formula of concrete bridges is:

$$W = \beta(y_q - y_d)D \tag{4}$$

At high temperatures, these three ways of heat transfer often co-exist, interact with each other, and jointly determine the thermal performance of concrete bridges. By investigating these heat transfer mechanisms, the distribution and change of thermal stress in concrete bridges at high temperatures can be better understood and predicted, thereby giving accurate evaluations of the thermal stability and thermal damage risks of bridges.

To gain more knowledge about how heat is propagated and distributed inside concrete bridges so as to judge the possible thermal stress distribution of bridges at high temperatures and evaluate the possible thermal fatigue and thermal damage risks, this study constructed a differential equation of the heat transfer of concrete bridges at high temperatures based on an orthogonal coordinate system. Assuming: dI represents the amount of heat absorbed by the micro-cells within per unit time, then a heat balance equation can be built as follows:

$$dI = dW_{\eta} + dW_{c} \tag{5}$$

$$dI = \vartheta v \frac{\partial Y}{\partial y} dzdtdx \tag{6}$$

Assuming: dW_{η} represents the net heat flow received by micro-cells within per unit time, then there is:

$$dW_{\eta} = \left[\frac{\partial\left(\eta \frac{\partial Y}{\partial z}\right)}{\partial z} + \frac{\partial\left(\eta \frac{\partial Y}{\partial t}\right)}{\partial t} + \frac{\partial\left(\eta \frac{\partial Y}{\partial z} x\right)}{\partial x} \right] dzdtdz \tag{7}$$

Assuming: dW_c represents net heat flow absorbed by micro-cells within per unit time, then there is:

$$dW_{c} = Wdzdtdx \tag{8}$$

Assuming: ϑ represents the density of the concrete bridge, v represents the specific heat capacity, η represents the heat conduction coefficient, in the selected orthogonal coordinate system, the heat conduction equation was converted to the corresponding form of differential equation, which requires the knowledge related to differential equation and coordinate transformation. Then, combining with above formula, the differential equation describing the heat conduction of concrete bridges can be attained as follows:

$$\vartheta v \frac{\partial Y}{\partial y} = \left[\frac{\partial\left(\eta \frac{\partial Y}{\partial z}\right)}{\partial z} + \frac{\partial\left(\eta \frac{\partial Y}{\partial t}\right)}{\partial t} + \frac{\partial\left(\eta \frac{\partial Y}{\partial x}\right)}{\partial x} \right] + W \tag{9}$$

During the heat transfer process of concrete bridges, the heat exchange of heat flow is driven by the temperature difference between the heat energy inside the concrete material and the surrounding environment. However, under some certain conditions, the amount of heat exchanged by heat flow in concrete bridges may be close to zero or non-existent. For example, under steady-state conditions, the heat distribution within a concrete bridge reaches the steady state and the change in temperature over time becomes very small or negligible. At this point, heat exchange no longer exists there is no additional heat energy that needs to be transferred from the interior of the concrete to its exterior, or in the opposite direction, Besides, when the temperature of a concrete bridge is equal to the ambient temperature, since there is no temperature difference, there is no heat exchange as well, and this is because the transfer of heat energy is driven by temperature difference. Thus, it can be concluded that, when there is no temperature difference, there is no heat transfer. Assuming: $\beta=\eta/\vartheta v$ represents the heat diffusion coefficient, then under the above said conditions, the above formula can be simplified to:

$$\frac{\partial Y}{\partial y} = \partial \left[\frac{\partial\left(\eta \frac{\partial Y}{\partial z}\right)}{\partial z} + \frac{\partial\left(\eta \frac{\partial Y}{\partial t}\right)}{\partial t} + \frac{\beta\left(\eta \frac{\partial Y}{\partial x}\right)}{\partial x} \right] \tag{10}$$

In actual problems, the initial and boundary conditions must be introduced into thermal analysis to get the unique solution of the heat conduction equation, otherwise there will be innumerable solutions that can not reflect the actual physical phenomena. Basic steps for solving the heat conduction equation are:

1. Initial conditions: Initial conditions usually define the state at starting time state. For heat conduction problems, initial conditions are usually the initial temperature distribution that can be set according to the actual situation of the problem.
2. Boundary conditions: Boundary conditions describe the physical properties on the boundary of a concrete bridge. In heat conduction problems, they can be a definite temperature, a definite heat flow density or a combination of the two. They should be set according to the actual situation of the problem as well.
3. Equation solving: After initial and boundary conditions have been set, the equation should be solved, since the heat conduction equation is a partial differential equation, numerical methods such as finite difference method or finite element method are usually adopted to solve the equation.
4. Interpretation and verification of the solution: After solution was attained, its actual physical meaning should be interpreted and verified. If experimental data can not be explained well, the modelling or setting of the initial or boundary conditions may need reconsideration or adjustment.

3. STRAIN CORRECTION OF THERMAL STRESS-LOAD COUPLING TEST

A bridge is a complex structural system whose stability is affected by various internal and external factors, including environmental conditions (temperature, humidity, etc.), material properties, and load. In applications, bridges are often subjected to a variety of forces at the same time, so simply considering the impact of various forces on the stability is not enough, the coupling effect between the forces needs to be considered as well. Thermal stress and load are the two main forces whose impact on bridge stability is related not only to their sizes, but also to the coupling relationship. First, under high temperature conditions, the physical and mechanical properties of the materials of the bridge would undergo changes, causing thermal stress that can affect the structural stability of the bridge, and the stress produced by load on the bridge can interact with thermal stress, which may cause overloading or damages to the bridge. Therefore, the coupling effect between thermal stress and load has an important impact on the structural stability of bridges. Second, since the experimental conditions are somehow different from the actual operating conditions, there are certain deviations between the strain results attained in experiment and the situation in actual cases. So, the correction of the strain results is necessary, through which experimental results that are closer to the actual working conditions could be attained, then the structural stability of bridges under actual operating conditions can be evaluated more accurately. Thus, the strain correction of the thermal stress-load coupling test is very meaningful for the accurate evaluation and maintenance of the structural stability of bridges.

Using vibrating string-style strain gauges to measure the strain of bridge structures is a common method used in thermal stress-load coupling tests, but the measurement results of a vibrating string strain gauge may be affected by many factors such as temperature changes, equipment errors, and manual operation errors, etc., so the results must be corrected to improve measurement accuracy. The corrected strain measurement results will be closer to the actual strain value, and this is very important for understanding and evaluating the thermal stress-load coupling effect and its impact on the structural stability of bridges. Figure 2 gives the arrangement positions of strain gauges.

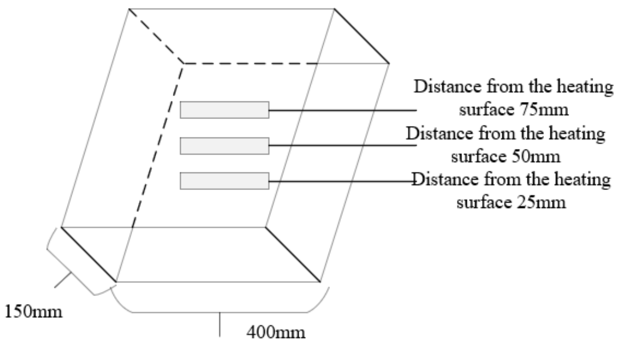


Figure 2. Arrangement positions of strain gauges

Both the concrete and strain gauges would undergo thermal expansion or contraction when subjected to temperature changes, which will cause changes in the length of the vibrating string, thereby affecting its natural frequency, and this needs to be considered in accurate measurement although it could be ignored to some extent. Moreover, temperature changes can also affect the material properties of strain gauges, such as the modulus of elasticity or density, and these changes can also cause variations in the natural frequency of the vibrating string, thereby affecting the measurement results. Specifically speaking, the test data can be corrected by modelling the temperature-strain relationship, and the part related to the thermal expansion of the concrete and strain gauges can be removed to get measurement results that can reflect the actual strain of the object being tested.

Assuming: M represents the length of the string, Y represents the tension of the string, ϑ represents the linear density of the string, then the formula for calculating the natural frequency of the vibrating string inside the strain gauges is:

$$d = \frac{1}{2M}\sqrt{\frac{Y}{\vartheta}} \tag{11}$$

The natural frequency of the vibrating string under temperature influence can be calculated as:

$$d = \frac{1}{2\left(M + \Delta M\right)}\sqrt{\frac{Y + \Delta Y}{\vartheta}} \tag{12}$$

Because $(M+\Delta M)/M=1+\Delta\gamma\approx 1$, there is:

$$d = \frac{1}{2M}\sqrt{\frac{Y + \Delta Y}{\vartheta}} \tag{13}$$

Assuming: β represents the thermal expansion coefficient of the vibrating string strain gauge, ϑ represents the thermal expansion coefficient of the concrete, Δy represents the temperature change of the sensor buried in concrete and the wrapping concrete, γ represents the test value of thermal strain, γ' represents the corrected value of thermal strain, then based on above principle, following corrections can be made:

$$\gamma' = \gamma + \left(\beta - \alpha\right)\Delta y \tag{14}$$

Besides, concrete would undergo thermal expansion or contraction when subjected to temperature changes, the extent of which is determined by the coefficient of differential thermal expansion of the concrete. The differential thermal expansion coefficient is a physical quantity that describes the volume change of a material under per unit temperature change, and its value directly affects the distribution of thermal stress and the structural stability of concrete bridges under high temperature conditions. Therefore, the influence of the differential thermal expansion coefficient of concrete needs to be considered when correcting the strain test results of the thermal stress-load coupling test, in this way, more accurate results reflecting the thermal stress and strain states of concrete bridges under high temperature conditions could be attained.

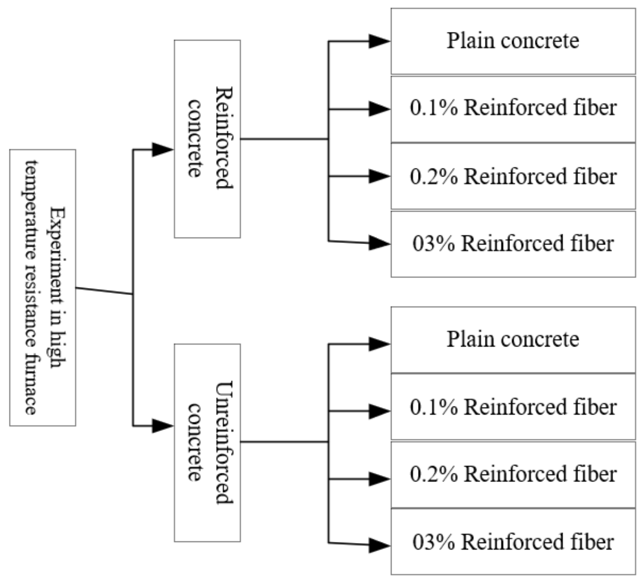


Figure 3. Test pieces of concrete bridge

Based on test data, the thermal expansion of concrete bridge was measured, and the following formula was used to calculate the differential thermal expansion coefficient. Figure 3 lists the fabrication of concrete bridge test pieces. Assuming: β_u represents the differential thermal expansion coefficient of test pieces of concrete bridge at a temperature of Y_u; M_1, M_2, M_u, $M_{u\text{-}1}$, M_{u+1} represent the length of test pieces at a temperature of Y_1, Y_2, Y_u, $Y_{u\text{-}1}$, Y_{u+1}, then there are:

$$\beta_u = \frac{1}{M_u}\lim_{Y_2 \to Y_1}\frac{M_2 - M_1}{Y_2 - Y_1}, Y_1 < Y_u < Y_2 \tag{15}$$

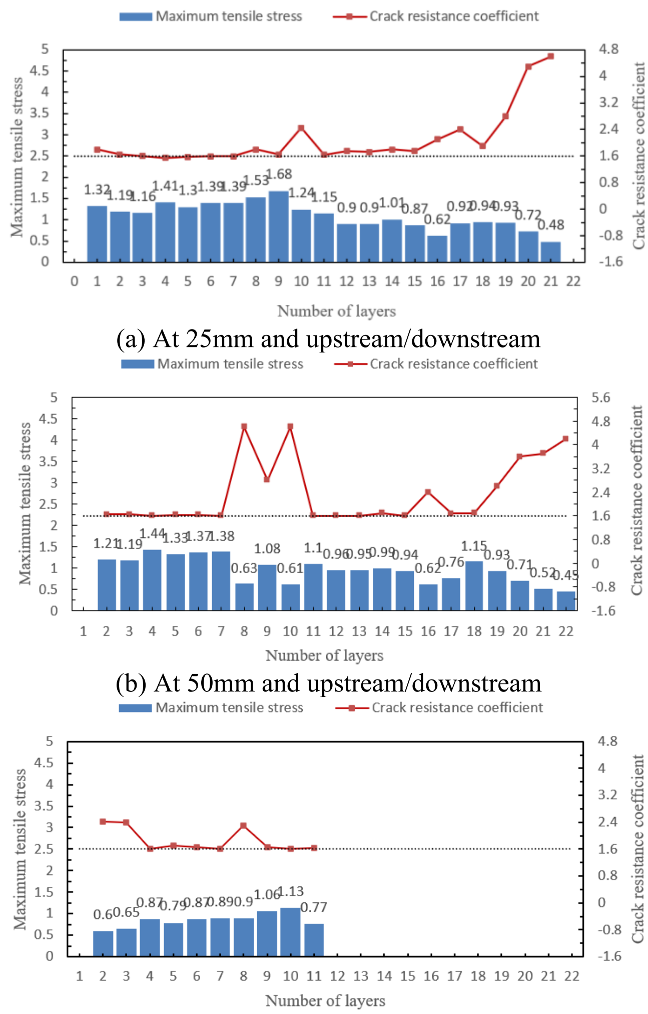
$$\beta_u = \frac{1}{M_u}\frac{M_{u+1} - M_{u-1}}{Y_{u+1} - Y_{u-1}} \tag{16}$$

During experiment, when temperature was below 450℃, the differential thermal expansion coefficient of concrete bridge was almost a constant, indicating that within this temperature range, the structure of the material of the concrete bridge changed little, while within the temperature range between 450℃ and 550℃, the differential thermal expansion coefficient of concrete bridge exhibited a linear increase, which might be caused by the thermal expansion and chemical reaction of quartz sand, stone and other substances contained inside the concrete bridge. When the temperature reached above 550℃, the differential thermal expansion coefficient of concrete bridge rose rapidly, and then declined after hit a maximum value at 580℃. When the temperature was between 620℃ and 680℃, the differential thermal expansion coefficient of concrete bridge showed a second increase and a second decrease, and finally fluctuated stably within the range of 725℃ and 800℃. Based on above calculations and experimental results, following conclusions were drawn: the correction of the differential thermal expansion coefficient should take into account the changes in the structure of the material of the concrete bridge and the changes in the thermal expansion characteristics. Especially when temperature exceeded 450℃ in the thermal stress-load coupling test of concrete bridge, the test results of strain need to be corrected to eliminate the impact caused by thermal expansion and the structural changes of material inside the concrete bridge. In case that the accuracy of data below 130℃ is ensured, the data before 450℃ could be fitted to attain the corrected differential thermal expansion coefficient.

4. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 4-(a) shows the maximum tensile stress and crack resistance coefficient of different concrete layers at 25mm position of the concrete bridge surface and its upstream/downstream. The figure can help us understand the thermodynamic properties of the bridge at high temperatures, especially the possibility of thermal crack formation.

According to the data of maximum tensile stress, the maximum tensile stress of concrete layers fluctuated between 116 and 1.68, the value of the eighth layer reached a highest 1.68 at a depth of 8*25mm=200mm, and the lowest value 0.48 appeared in the second layer, which might indicate that the concrete subjected to a maximum thermal stress at 200mm position inside the bridge, so possibility of cracking at this position was the highest. In deeper part of the bridge, the thermal stress the concrete subjected to was smaller, so the possibility of cracking was lower. In terms of the crack resistance coefficient, its value reflects the ability of the concrete to resist the formation of thermal cracks, and the larger the value, the stronger the ability. As can be seen from the data, the value of crack resistance coefficient varied between 1.54 and 4.6, with the lowest point 1.54 appeared in the third layer, and the highest point 4.6 appeared at the second layer, indicating that at 75mm position inside the bridge, the concrete's ability to resist thermal cracks was the weakest, while in deeper part of bridge, the concrete's ability to resist thermal cracks was stronger.



(a) At 25mm and upstream/downstream

(b) At 50mm and upstream/downstream

(c) At 75mm and upstream/downstream

Figure 4. Maximum tensile stress and crack resistance coefficient of different concrete layers

Figure 4-(b) shows the maximum tensile stress and and crack resistance coefficient of different concrete layers at 50mm position of the concrete bridge surface and its upstream/downstream. These data reflect the thermodynamic properties of the bridge at high temperatures, especially the possibility of thermal crack formation.

The value of maximum tensile stress was observed to vary between 0.45 and 1.44, the highest value 1.44 showed in the third layer (at a depth of 75mm), and the lowest value 0.45 showed in the 22^{nd} layer (at a depth of 550mm), indicating that at the 75mm depth position inside the bridge, the thermal stress the concrete layers subjected to was the highest, so the possibility of thermal crack formation was the largest. In contrast, in deeper part inside the bridge (at a depth of 550mm), the thermal stress the concrete layers subjected to was smaller, and the possibility of thermal crack formation was lower. The crack resistance coefficient describes the ability of the concrete to resist the formation of thermal cracks, the higher the value, the greater the ability. As can be seen in the table, the value of crack resistance coefficient fluctuated between 1.6 and 4.6, with the minimum value 1.6 showing in the sixth layer, and the maximum value 4.6 showing in the seventh layer and the ninth layer, indicating that at a depth of 150mm inside the bridge, the concrete's resistance to thermal cracks was the weakest, while at deeper depths (175mm and 225mm), the resistance ability of the concrete reached the strongest.

Figure 4-(c) shows the maximum tensile stress and and crack resistance coefficient of different concrete layers at 75mm position of the concrete bridge surface and its upstream/downstream. These data reflect the thermodynamic properties of the bridge at high temperatures, especially the possibility of thermal crack formation. As can be known from the figure, the data of maximum tensile stress varied between 0.6 and 1.13, with the highest value 1.13 showing in the ninth layer (at a depth of 225mm) and the lowest value 0.6 showing in the first layer (at a depth of 75mm), indicating that at the 225mm depth position inside the bridge, the thermal stress the concrete layers subjected to was the highest, so the possibility of thermal crack formation was the largest. In contrast, in shallower part of the bridge (such as at a depth of 75mm), the thermal stress the concrete subjected to was smaller, so the possibility of thermal crack formation was lower. Data of the crack resistance coefficient changed between 1.61 and 2.41, with the highest value 2.41 showing in the first layer (at a depth of 75mm), and the lowest value 1.61 showing in the third and the ninth layer, indicating that at the 75mm depth position inside the bridge, the concrete's resistance to thermal cracks was the strongest, while in deeper part (at depths of 150mm and 225mm), the resistance ability was the weakest.

Table 1. Temperature, strain, and corrected strain at different positions

***Time*(*min*)**	**Temperature at 25*mm* (℃)**	**Strain at 25*mm* (Uncorrected) (μ*m*/*m*)**	**Strain at 25*mm* (Corrected) (μ*m*/*m*)**	**Temperature at 50*mm* (℃)**	**Strain at 50*mm* (Uncorrected) (μ*m*/*m*)**	**Strain at 50*mm* (Corrected) (μ*m*/*m*)**
0	18.9	0	0	18.8	0	0
1	19.7	40	40	18.7	20	20
2	20	45	45	19.9	34	34
3	22.1	90	91	20	43	43
4	21.8	120	121	22.1	94	95
5	22.8	161	163	21.7	116	117
6	26.8	137	138	25.9	99	102
7	31.2	101	104	29.1	82	86
8	32.1	95	99	31.2	61	64
9	31.4	72	76	32.1	52	55
10	36.4	62	65	35.1	28	32
11	37.6	33	41	36.7	12	19

Table 1 lists the temperature, strain, and corrected strain at two depths (25mm and 50mm) of the concrete bridge over time. Based on these data, the thermal stress of concrete bridge at different depths and temperatures could be analyzed. At first, it's noted that at both depths (25mm and 50mm), with the passing of time, the temperature of the concrete rose gradually because of the heat accumulated inside the concrete under the action of heat source; besides, the internal temperature of the concrete was related to depth, at positions closer to the heat source, the temperature rise was faster. According to the data, at the sixth minute, the temperature at 25mm position was 26.8℃, and the temperature at 50mm was 25.9℃. Further data observation shows that during the process of temperature rise, the strain value increased first and decreased later, exhibiting the influence of temperature on strain. The strain value at 25mm position reached the maximum at the fifth minute, while the strain value at 50mm position reached the maximum at the fourth minute. After reaching the maximum strain, the strain value started to decrease, which might be due to the thermal stress release within the concrete or the thermal expansion of the material itself. In can be seen from the data that the corrected strain values were generally greater than the strain values before correction, this is because through the correction calculations, the thermal expansion factors of strain gauges and concrete materials had been eliminated, so the attained strain values can better reflect the actual state of thermal stress.

Figure 5 shows the strain versus time curves at two depths (25mm and 50mm) of the concrete bridge with and without reinforcement. Since no temperature data was given in the problem, the focus was laid on the analysis of the strain. As can be seen from the figure, with or without steel bars, the strain of the concrete bridge would change with time, exhibiting complex dynamic behaviors, wherein the strain change of unreinforced concrete bridge was more obvious, which may be due to the lack of constraint of steel bars, so the thermal expansion and contraction of the concrete were freer. In contrast, the strain change of reinforced concrete bridge was smaller, which might be caused by the constraint provided by the steel bars, so the thermal expansion and contraction of the concrete had been reduced. These results indicate that the state of thermal stress of concrete bridges is not only related to the depth of the concrete, but also to whether or not the concrete is reinforced by steel bars. To a certain extent, steel bars can improve the state of thermal stress of concrete, reduce strain variation, and enhance the stability of the bridge, and this is a main consideration in the design and stability analysis of reinforced concrete bridges.

Figure 6 gives the temperature versus time curves at two depths (25mm and 50mm) of the concrete bridge under high ambient temperatures. According to the figure, in a high temperature environment, the internal temperature of concrete bridge increased with the passing of time, but the increase speed was determined by the depth of the concrete. The temperature at positions (such as at 25mm position) closer to the environment (heat source) rose faster than that at positions (such as at 50mm position) further away from the environment. Also, the ambient temperature changes can affect the internal temperature distribution of the concrete and its change trend.

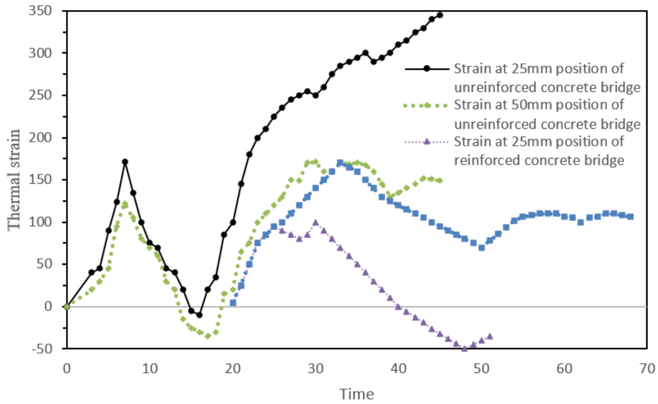


Figure 5. Temperature versus time curves at different positions of reinforced and unreinforced concrete bridges

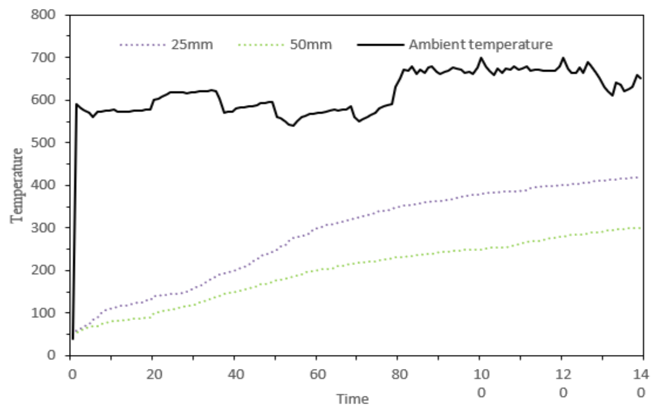


Figure 6. Temperature versus time curves at different positions under high ambient temperatures

5. CONCLUSION

The changes of strain and temperature of concrete bridges in high temperature environment were investigated in this study, the maximum tensile stress and crack resistance coefficient of concrete layers at different depths were studied, and the changes of strain and temperature under various conditions (with and without steel bar reinforcement), at different positions (at different distances from the surface of concrete bridge), and in different environments were discussed as well.

The experimental results suggest that in a high temperature environment, the internal temperature and strain of concrete bridge would increase with the passing of time. In shallower part of the bridge (such as at a depth of 25mm), the temperature growth of the concrete was faster than that at deeper part (such as at a depth of 50mm) since the former was closer to the heat source (environment). Strain showed different trends in unreinforced and reinforced concrete, indicating that the steel bars have a significant impact on the thermal stress and thermal fatigue behavior of concrete. Variations of crack resistance coefficient and the maximum tensile stress revealed the crack resistance and mechanical properties of different concrete layers.

Therefore, environmental conditions (especially high temperature environment) have a significant impact on the strain and temperature distribution of concrete bridges, and factors such as the depth and steel bars can also affect these variables. Research results attained in this study are important for researchers to understand and predict the thermal stress, thermal fatigue behavior, and stability of concrete structures in complex environment, thereby providing useful references for the design, construction and maintenance of concrete bridges.

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