ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20240925002017
Original scientific paper

Research on Damage Assessment and Reinforcement Method of Concrete Bridge After Fire

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Abstract: As a member of the highway transportation network, the small bridge has the advantages of simple structure, clear stress, durability, and strong applicability. It is still used in a large number of road network applications. With the development of the bridge business, the number of fires on the bridges has also increased, and the damage caused to the bridges after the fire has also been considerable. The destruction of any component of the road network will affect the normal operation of the entire traffic. This article provides a quick scientific assessment method for small bridges after a fire, including the rapid estimation of fire high temperature based on the fire temperature formula and surface color determination, and describes the characteristics of various properties of reinforced concrete structures subjected to high temperatures.The rebound-residual bearing capacity comprehensive calculation provides a feasible method for the rapid calculation of bridge bearing capacity. This will provide a reference for the rapid and effective evaluation and reinforcement of similar bridges in the future.

Keywords: concrete bridge; fire; reinforcement research; quick detection

1 INTRODUCTION

According to statistics in recent years, China will surpass the United States in the future to become the country with the largest number of bridges and the longest mileage. The world's longest cross-sea bridge, the Hong Kong-Zhuhai-Macao Bridge and the largest cross-border Yangtze River Bridge of 1092 meters, all show that China will become a major bridge country. Small bridges are widely used in highway network construction due to their advantages of simple structure, durability, and strong adaptability [1-6]. With the development of the bridge industry, the number of bridge fires is also increasing, and the harm caused by the fire is also quite large. The damage of any part of the road network will affect the normal operation of the whole traffic. Therefore, it is necessary to quickly evaluate and apply the reinforcement measures of small bridges after the fire, so as to provide reference for similar bridges after the occurrence. Professor Liu Qiwei of Southeast University in China has done a lot of studies on the detection, evaluation and reinforcement of bridge piers, prestressed hollow slabs and bridges after bridge fire damage, but the research on how to quickly evaluate the procedures and indicators of small bridges is in the exploratory stage [7-12].

2 PROJECT OVERVIEW AND FIRE BACKGROUND

2.1 Project Overview

The bridge is a small-scale structure in the expressway network of a city in southern China. The span of the bridge is 310 m, the total length is 35.08 m; the width of the bridge is (0.75 m + 15.75 m lane + 0.75 m corrugated steel guardrail) 2 + 0.5 m = 35 m, with six lanes. The superstructure of the bridge consists of precast ordinary reinforced concrete simply-supported hollow slab beams, with 13 hollow slab beams in each bridge, the height is 0.45 m, the slab width is 1.24 m, the center spacing of the slab beam is 1.25 m, the side plate cantilever is C = 0.5 m, the concrete design mark is No. 40; the hinge joint between the slab beams is a deep hinge joint. The substructure piers adopt single row three-column piers and pile foundation, with pier diameter of 0.8 m, concrete design number C30, pile foundation diameter 1.0m, and concrete design number 25; abutment adopts rib plate light abutment and pile foundation. The bridge deck pavement is 10 cm cement concrete pavement + HB-V waterproof layer +9 cm asphalt concrete pavement, and the anti-collision guardrail adopts double-wave corrugated steel plate guardrail. The design load standard of the bridge is automobile-super 20, trailer-120. The bridge was completed and opened to traffic in 2005. Bridge elevation layout is shown in Fig. 1, and cross-section arrangement is shown in Fig. 2. The overall overview of the bridge is shown in Fig. 3 to Fig. 5.

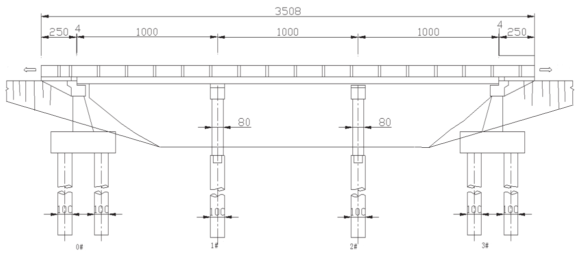

Figure 1 Layout drawing of the bridge elevation

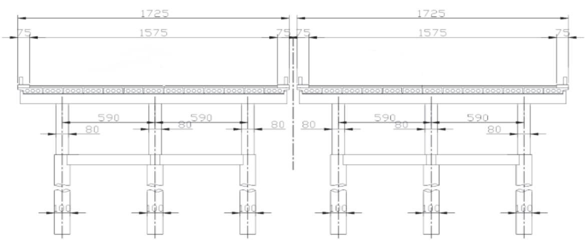

Figure 2 Arrangement drawing of bridge cross-section

Figure 3 Bridge facade illumination

Figure 4 Bridge bottom illumination

Figure 5 Bridge upper structure

2.2 Fire Background

The fire accident was caused by the accumulation of debris burning under the bridge, and the temperature was about 28 °C at that time. After the fire occurred, firefighters used the fire department to fight. The most severely affected component was the L1-1 # pier column. After investigation, the duration of the fire was about 30 min [13].

The bottom of the first hollow plate of the left and right width of the bridge was smoked by flame, and the concrete surface was black. The fire occurred near pier 1 - 1 of the left bridge, and the cover beam on the pier also was burned to fire. The concrete outside the cover beam was smoked, and the surface of the concrete was dark black. The L1-1 # pier column under the bridge was badly burned, and the apparent concrete about 2 m above the ground was smoked into black. In the body of no. 1-pier 1 close to the ground, the peeling area was about 2.2 × 0.8 m², and the stirrup and longitudinal main reinforcement were exposed. Details are shown in Fig. 6 to Fig. 8.

Figure 6 After the hollow plate and cover beam

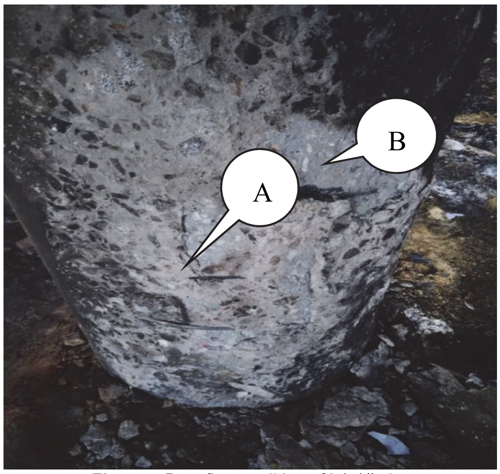

Figure 7 Post-fire condition of L1-1# pier

Figure 8 Post disaster condition under the bridge

2.3 Instruments and Equipment

The appearance inspection of bridges is mainly based on visual inspection, combined with necessary auxiliary instruments such as magnifying glasses, cameras, crack observation instruments, etc. The instruments and equipment used to check the scope and degree of fire impact mainly include rebound gauges, carbonization depth measuring instruments, coring machines, etc. The requirements for the main instruments and equipment are shown in Tab. 1.

Table 1 List of Main Instruments and Equipment

No.	Name of instrument and equipment	Model of instrument and equipment	Use
1	digital camera	Canon 1300D	Audio and video records
2	Crack width observation meter	ZBL-F120	fissure observation
3	range finder	Hongcheng Technology HT-307 UNI-T UT395	distance measurement
4	telescope	/	Observe the disease
5	hammer	/	Check the empty drum area
7	The core machine	/	Drilling core
8	tape	0-3m	dimensional measurement
9	elasticity tester	Type ZC 3-A rebound apparatus	The rebound measurement is strong
10	Carbonization depth measuring meter	Leling City rebound instrument factory	Carbon depth measurement

The bridge channel is divided into left and right parts, and the number of each component is equal. The summary of the number of single bridge components is shown in Tab. 2.

Table 2 Quantity table of single bridge components

Order number	Bridge parts	Bridge parts	Component main beam	remarks
1	Super structure	Upper load bearing member	39	13 Piece beam / span
2		Upper general components	36	12 hinge joint / span
3		abutment	156	52 supports / span
4	Infra structure	Wingwall, ear wall	2	
5		Cone slope, slope protection	2	
6		pier	2	
7		bank pier	2	
8		Pier platform foundation	4	
9		riverbed	0	No riverbed
10		regulating structure	0	No tuned structures
11	bridge deck system	deck pavement	3	
12		Expansion joint device	2	
13		footwalk	0	There is no sidewalk
14		Balustrade, guardrail	2	
15		drainage system	0	Vertical slope drainage
16		Lighting, signs	1	

2.4 The Content and Methods of Emergency Special Inspections

The content and methods of emergency special inspections after bridge fires include:
(1) Investigation of the fire occurrence process, including time, location, and duration;
(2) Detection of the extent and degree of damage caused by concrete spalling, bulging, cracking, reduced strength, and increased carbonation depth on bridges affected by fires;
(3) Perform post disaster bearing capacity calculation on severely damaged components;
(4) Propose maintenance and reinforcement suggestions based on the results of special testing and load-bearing capacity calculation;
(5) Preliminary division of the affected areas based on the degree of damage to the appearance of the bridge after fire and changes in the color of the concrete;
(6) Use of equipment such as box rulers and crack observation devices to inspect the cracking and damage of concrete in each area;
(7) Use of the hammer tapping echo method to inspect the concrete hollowing area;
(8) Use of rebound tester, alcohol phenolphthalein solution, and carbonation ruler to check the strength and carbonation depth of concrete in each area;
(9) In areas with severe concrete spalling damage, core sampling method is used to check the depth of fire impact.

3 THE INFLUENCE OF THE FIRE AND HIGH TEMPERATURE ON THE REINFORCED CONCRETE STRUCTURE

Reinforced concrete is mainly composed of steel and concrete composite materials; when reinforced concrete structure is in fire high temperature, steel, concrete strength and elastic modulus with the temperature and duration of the fire, physical and chemical properties produce unstable changes, so it is bound to affect the bearing capacity of reinforced concrete structure [14-17].

3.1 Impact of Fire High Temperature on Concrete Performance

Concrete is a heterogeneous composite material composed of cement as the main body and other materials. Therefore, under the action of fire and high temperature, the internal water of the concrete structure evaporates, and the aggregate also expands and even bursts, causing the internal damage of the concrete, thus worsening its mechanical properties.

3.1.1 Change of Concrete Strength Caused by Fire and High Temperature

Through numerous tests on the performance of concrete at high temperature, when the fire temperature is below 300 ℃, concrete, except for the internal non-bound water evaporation of cement crystal, basically does not change. Due to the different thermal expansion coefficient of aggregate and cement stone, concrete strength is slightly reduced. When the temperature is between 300 ℃ and 600 ℃, dehydration and decomposition of calcium hydroxide in the cement stone, the crystal is slightly broken, the cement stone begins to appear loose, concrete strength decreases. When the temperature is between 600 ℃ and 800 ℃, Dolomite and calcium carbonate in the concrete begin to decompose. The aggregate is no longer stable, concrete compression degree drops sharply. When encountering a high temperature above 800 ℃, the cement slurry becomes in discontinuous clumps, concrete strength is basically lost [18]. The changes of compressive strength of concrete and tensile strength of concrete decreasing with fire high temperature are shown in Tab. 1. In fact, concrete may spall and crack due to thermal expansion even at relatively low temperatures when subjected to rapid heating. When the fire is put out with water, the hot concrete surface is rapidly cooled by water, resulting in the stress difference inside and outside the concrete member, which will aggravate the peeling of the concrete. Therefore, the main damage of the bridge in the fire is the concrete burst and peeling, resulting in the thickness of the protective layer and even the exposed steel bars. At the same time, the section area of the component decreases. For the plate beam, the bending stiffness decreases, the deflection increases, and tensile cracks appear in the bottom plate. Unpeeling concrete will also become loose because of the high temperature, reduced strength and durability, the internal steel bar is easy to rust, and other associated negative effects.

3.1.2 Change of the Elastic Modulus of Concrete Caused by Fire and High Temperature

The initial elastic modulus and peak deformation modulus of concrete are shown in Tab. 3 and Tab. 4. From the table, we can see that when the fire temperature is greater than 300 °C ~ 600 °C, the decrease of the elastic modulus of concrete decreases significantly and rapidly.

Table 3 Changes in initial elastic modulus and peak deformation modulus of concrete

Temperature / 0C	20	100	300	500	700	900
Compressive strength reduction coefficient	1.00	0.95	1.10	0.85	0.40	0.10
Reduction coefficient of tensile strength	1.00	0.70	0.45	0.30	0.20	0

Concrete will eventually recover to room temperature after a fire, and the residual strength of concrete after fire damage is the main basis for evaluating the degree of structural damage. The variation law of residual compressive strength of concrete cube specimens with temperature after cooling can be expressed by Eq. (1) [4].

$$\frac{f_{cu}^{TR}}{f_{cu}} = \frac{1}{1+26\times\left(\frac{T}{1000}\right)^{6.5}} \tag{1}$$

f_{cu}^{TR} is the resistance of concrete when the temperature T / °C is reduced to room temperature compressive strength, f_{cu} is the compressive strength of concrete at room temperature.

Table 4 Changes in initial elastic modulus and peak deformation modulus of concrete

Temperature / 0C	20	100	300	500	700	900
E_{0T} Reduce the coefficient	1.00	0.80	0.45	0.25	0.10	0
E_{PT} Reduce the coefficient	1.00	0.75	0.50	0.25	0.10	0

3.2 Impact of Fire High Temperature on the Performance of Steel Bars

3.2.1 Strength of Steel Reinforcement

As the fire temperature increases and the time continues, the steel bar temperature also gradually increases, especially after the protective layer peels off. The strength of the reinforcement does not change much when the fire temperature is within 200 °C. The ultimate strength, yield strength and elastic modulus of the steel bar will decrease with the increase of the fire temperature. The temperature reaches 450 °C and begins to soften. When the temperature is 600 °C ~ 700 °C, the internal crystal structure of the steel bar changes, resulting in a very serious reduction of strength and elastic modulus, and the loss of strength is about half. When cooled down, the strength of the steel bar is partially restored, but the internal crystal rearrangement of the steel, the yield strength and ultimate strength are reduced, and the ductility increases; if the fire is extinguished with water, the steel bar is equivalent to the quenching process, and will become brittle. Prestressed steel bars and prestressed steel hinge lines have high carbon content, and are much more affected by fire than ordinary steel bars. High temperature relaxation will cause great prestress loss. If the protective layer is completely stripped off the steel bar, it is directly affected by fire, and the surface oxidizes and rusts. If not treated in time, the steel bar corrosion will develop rapidly, and it also affects its strength.

3.2.2 Change of Elastic Modulus of Reinforcement

Like concrete, the elastic modulus of steel bar will decrease with the increase of fire temperature and time. According to the performance test of steel bar under high temperature in the past, the change rule of elastic modulus of steel bar under high temperature is:

$$E_s\left(T\right) = \frac{E_s}{1.03+7\times\left(T-20\right)^6\times 10^{-17}} \tag{2}$$

where: E_s (T) is the elastic modulus of steel bar at the time T; E_s is the elastic modulus of steel bar at room temperature.

3.3 Impact of Fire High Temperature on the Bonding Performance of Steel Bar and Concrete

In the initial stage of a fire, the bond strength between steel reinforcement and concrete is enhanced due to the higher thermal expansion coefficient of the steel, which improves their mechanical interlock. However, as the fire progresses, spalling of the concrete cover accelerates the degradation of this bond strength. At the initial stage of a fire, the bond strength between steel reinforcement and concrete increases due to the higher thermal expansion coefficient of the steel, which enhances their mechanical interlock. See Tab. 5 for the strength coefficient of reinforcement bond.

Table 5 Strength coefficient of reinforcement bonding

Temperature / 0C	20	100	300	500	700
Reduction coefficient of bonding strength of light circular reinforcement	1.00	0.70	0.40	0.05	0
Reduction coefficient of bonding strength of thread steel bar	1.00	1.00	0.85	0.45	0.10

4 RAPID ASSESSMENT PROCEDURE

Because small bridges often occupy a high percentage in the road network, the damage degree of small bridges should be judged quickly and accurately after fire, and timely maintenance and reinforcement measures should be taken to ensure the safety performance of bridges and the normal operation of the road network.

4.1 Damage Appearance Detection

Observe and check the upper structure, substructure and bridge deck of the bridge after the fire, not necessarily damaged. The strength and carbonization depth of the damaged parts of reinforced concrete are checked by rebound instrument, alcohol phenolphthalein solution and carbonization ruler. Test the thickness of the protective layer of reinforced concrete structure, and check the depth of fire impact. Check the concrete cracking and damage of each area with the use of box ruler, crack observation instrument and other equipment. Check the cavity in the concrete drum area as shown in the following Fig. 9 below.

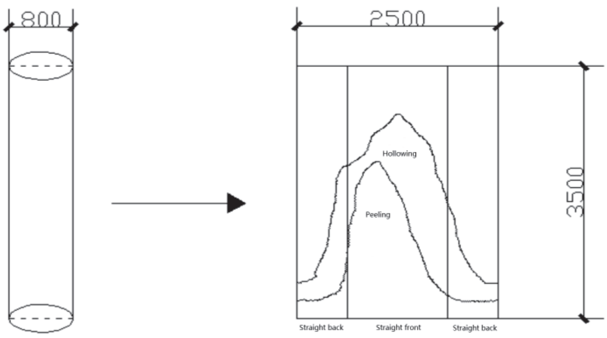

Figure 9 L1-1 # Column Disease Plan Unfolding Diagram

4.2 Division of the Bridge Damaged Area Under the Action of Fire and High Temperature

4.2.1 Division of Fire Areas

According to the detection results of the severity and appearance of the fire bridge, the damaged bridge structure can be divided into several areas, and the bridge damaged by the fire is divided into 4 areas. Zone 1: Concrete spalling area.

This area is the area where the concrete spalling of the 1 - 1 # pier of the left bridge occurs, with an area of 2.2 × 0.8 m². The deepest peeling thickness reaches 4 cm, with some stirrups and main bars exposed. Zone 2: The main areas where the concrete strength is significantly reduced due to the impact of the fire are the 1 - 1 # pier columns of the left bridge, except for Zone 1, as well as the heavily damaged 1 # cover beam and the end area of the first orifice beam of the left bridge. Zone 3: The durability of concrete has been reduced by the impact of fire, but the strength of concrete has not significantly decreased. The main ones are the 1 # pier cover beam of the left bridge, which was severely affected by the fire, and the hollow slab beams of the 1st to 5th spans of the left bridge. Zone 4: Areas that have been slightly or not affected by the fire are mainly those that are slightly blackened and have not been ignited by smoke.

4.2.2 Calculate the Intensity of the Fire Area

Area one: the concrete strength is obviously reduced, and the depth is larger, the concrete cover spalling renders rebound hammer testing inapplicable. The core extraction method was used to detect the depth of fire impact, and 2 cores were taken in the area, as shown in Fig. 10.

Core sample A is drilled in the horizontal direction at the bottom of the pier column, with a diameter of 6 cm and a length of about 29 cm, which is broken into three sections in the process of drilling. Core sample B is drilled in the horizontal direction at the bottom of the pier column slightly higher than hole A. Its diameter is 6 cm and its length is 28 cm, which breaks into 2 sections in the process of drilling.

According to the damage of the core sample, it can be seen that the maximum fire impact depth is 8 to 9 cm, and the core sample is as in Fig. 11 and Fig. 12.

There are hollow areas around the concrete spalling area. The rebound method was used to test the concrete strength, and the strength decreased by about 10 MPa.

Figure 10 Core location

Figure 11 A sample

Figure 12 B sample

4.3 Determination of Fire Temperature and Temperature

Scientific and accurate determination of the high temperature of the fire is helpful to make a correct evaluation of the degree of bridge damage, but it is difficult to accurately measure the high temperature when the fire occurs, so the presumptive method is generally used to judge. The commonly used methods include material melting point determination method, surface color determination method, fire temperature formula method, damage degree determination method and so on, the application of more mature fire temperature formula method, surface color determination method.

4.3.1 Surface Color Determination Method

After the fire, the temperature and duration will change the color of the concrete structure outside, based on which the fire temperature can be determined as shown in Tab. 6.

Table 6 Fire temperature determination

Temperature / 0C	< 300	300 ~ 600	600 ~ 900	900 ~ 1000
Concrete surface color and characteristics	Black soot is attached to the surface	The surface is pine-red or light-red	The surface is gray	The surface is light yellow

4.3.2 Fire Formula Method

The standard temperature-time curves and fire time-temperature curves from various countries are shown in Fig 13. The fire formula method Eq. (3) is based on the ISO834 fire time-temperature curve and statistical analysis of a large number of fire buildings. Because it conforms to the fire rules, it is more used as shown in the figure.

$$T = T_0 + 345 \times lg\left(8t + 1\right) \tag{3}$$

where, T is fire temperature (°C), T_0 is the natural temperature quasi-temperature (°C), t is the duration of the fire (min). The duration of this fire is 30 min, according to the formula and the maximum temperature is 821 degrees [19, 20].

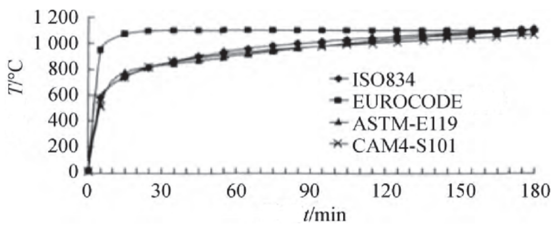

Figure 13 Fire time-temperature curve

4.4 Assessment of Bridge Technical Condition

According to the Evaluation Standard for Technical Conditions of Highway Bridge [11] (JTGTH21-2011), firstly, evaluate each component of the bridge, then evaluate each part of the bridge, and then evaluate the bridge deck system, upper structure, and lower structure separately. Finally, evaluate the overall technical condition of the bridge. According to the direction of the bridge, the bridge is divided into left and right parts.

The overall score of the left bridge by the stratified comprehensive evaluation method is 85.96, and the technical status grade of the bridge is 2 categories. Since the bearing capacity of the pier column due to fire, the technical condition grade of the bridge can be assessed as class 3 according to the worst defect condition of the main components. The calculation process of the technical condition rating is shown in Tab. 7.

Table 7 Calculation of Technical Condition Rating for Left Bridge

Bridge name	Structure	Structure score	Structural class	Structural weight	Technical condition rating	Grade
K32+828 Bridge channel (Left panel)	Superstructure	86.39	2	0.4	85.96	2
	substructure	89.05	2	0.4		
	Bridge deck system	78.91	3	0.2		

Table 8 Calculation of Technical Condition Rating for Left Bridge

Bridge name	Structure	Structure score	Structural class	Structu al weight	Technical condition rating	Grade
K32+828 Bridge channel (Rightpanel)	Super structure	91.38	2	0.4	90.83	2
	substructure	96.41	1	0.4		
	Bridge deck system	78.56	3	0.2		

The overall score of the right bridge using the stratified comprehensive evaluation method is 90.83, and the technical status grade of the bridge is 2 categories.The calculation process of the technical condition rating is shown in Tab. 8.

4.5 Residual Bearing Capacity Calculation

According to the damage detection of the bridge, it is necessary to recalculate the bearing capacity of the bridge. The literature (bridge construction) illustrates the temperature gradient curve of the pier along the section direction at different time. Meanwhile, the core sample A also confirmed that the damage at the fire location was serious, with the fire event of 30 min and the depth of 10 cm, and the concrete temperature at this depth was up to 600 °C, the elastic modulus and bonding performance of rebar and concrete are reduced by nearly half. At a depth of 20 cm, the temperature of concrete at this depth is up to 400 °C; the elastic modulus and bonding performance of thread rebar and concrete are reduced by nearly 10%. However, sample B originating from 30 cm above sample A broke at 3 cm from the surface when cored, indicating that the damage at high temperature here is decreasing. At the same time, according to the determination of no. 1 and No. 2 main beam, cover beam and bridge pier, the strength of the peeling and empty drum area was reduced, but the rest of the strength did not change. The intensity of the peeling and empty drum area decreased by about 10 MPa by intensity comparison with other undamaged sites.

The calculation model is established for calculation. The depth affected by the peeling of the fire pier column and the unilateral disaster in the empty drum area is 8 to 9 cm, and the opposite protective layer is not peeling. The height of the pier column is 3.9 m, the diameter is 80 cm, and 10 longitudinal rebar bars are arranged. The eccentricity is considered by 15 cm to simulate the damage of one side of the pier column; the pier column concrete is designed as 30 concrete, and the concrete strength design value of one grade C25 is used to simulate the impact of fire on concrete strength. After the special inspection, rebound measurement and rapid structural calculation of the L1 - 1 # pier column, the remaining bearing capacity can still meet the requirements, and the bearing capacity of the pier column is reduced, but it can still meet the use requirements.

5 COMPREHENSIVE EVALUATION AND REINFORCEMENT

Based on the division of fire areas and analysis of calculation results, different reinforcement maintenance measures are taken for different damaged areas:

Area 1, area 2: mainly concentrated in the 1 - 1 # pier column, the strength of concrete and reinforcement is reduced, and the bond force between reinforcement and concrete is reduced. The depth of the damage range is about 8 to 9 cm. Under the condition of considering various influencing factors, the bearing capacity of the pier column can still meet the design requirements, so the damage of the pier column can be repaired. Therefore, it is suggested that the maintenance plan of this area is to remove the concrete of the damaged area (including the empty drum area), repair with epoxy mortar, restore the original section size, and restore the bearing capacity and durability of the pier column.

Area 3: It is recommended to paste one or two layers of carbon fiber cloth after the surface is dusted to carry out durability protection and improve the durability.

Other areas: It is recommended to treat the diseases found together according to the results of regular inspections, to timely close the asphalt concrete pavement layer cracks of the bridge deck, so as not to affect the durability and driving comfort.

6 CONCLUSION

When the bridge suffers from fire, the bridge should be evaluated quickly and timely and take reinforcement measures.

(1) This paper provides the method of rapid scientific evaluation of a small bridge after fire, including the rapid presumption of fire high temperature based on fire temperature formula and surface color, and introduces the change characteristics and characteristics of various properties of reinforced concrete structure under high temperature.

(2) The comprehensive calculation of rebound-residual bearing capacity provides a feasible method for the quick calculation of bridge bearing capacity. Through the operation of the bridge in the later period, it is found that the bridge is in good condition.

(3) It provides a reference for the rapid and effective evaluation and reinforcement of similar bridges in the future.

Acknowledgements

This study is funded by the Henan Province Science and Technology Research Project (242102240035), Doctoral Research Start-up Fund Project of Nanyang Institute of Technology (NGBJ-2024-17), supported by Interdisciplinary Sciences Project, Nanyang Institute of Technology (24NGJY013), which are gratefully acknowledged.

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