

Research of Reinforced Concrete Bridge Fire Prevention and Disaster Reduction Mechanism

Concrete bridges constitute critical components of transportation infrastructure networks worldwide. However, these structures remain vulnerable to fire incidents arising from vehicular accidents, industrial activities, or arson. Fire-induced damage to concrete bridges can compromise structural integrity, reduce serviceability, and necessitate extensive rehabilitation. The scale and frequency of fires are also increasing. After being subjected to a fire, the mechanical properties of reinforced concrete bridge structures will undergo significant changes. Therefore, research on the post disaster performance of this structure is receiving increasing attention. This article first provides a brief overview of the current research status of bridge fire prevention in China. Then, through the failure mechanism of reinforced concrete bridge structures in fires, post disaster bearing capacity evaluation, and post disaster repair and reinforcement, the fire prevention issues of bridge engineering are discussed in detail. Furthermore, the future development and research directions of this discipline are analyzed and forecasted

Keywords: *Concrete bridges, fire damage, structural assessment, non-destructive testing, rehabilitation, material degradation*

Introduction

This paper focuses on With the development of China's social economy and the concentration of urban population, the factors leading to fires have also increased, and the scale and frequency of fires are also expanding. About 200000 fires occur in our country every year. Urban building fires account for over two-thirds of total fires, and the casualties and property losses caused by building fires are enormous. In the more than 30 years from 1971 to 2002, there were over 2.17 million fires and nearly 100000 deaths nationwide, with direct economic losses exceeding 18.7 billion yuan.

After a concrete bridge is subjected to a fire, the physical and chemical properties of the building materials change at high temperatures, causing damage to the components and resulting in a decrease in the bridge's load-bearing capacity. On June 24, 2004, a fire broke out at the Xiaoqiaotou overpass on the Zhajiasu Expressway. The 14 holes of the separated overpass were damaged to varying degrees, affecting the normal use of the bridge. In order to restore traffic as soon as possible after the fire, the performance, bearing capacity, and safety of the bridge were tested and evaluated. On the early morning of June 2, 2008, a fire broke out at a small commodity stall below the first bridge opening of the South Approach Bridge of the Nanjing Yangtze River Bridge, causing severe damage to the approach bridge. The cement precast arch beams of the bridge opening had peeled off cement, some steel bars were exposed, and the bridge arch was slightly deformed. Fortunately, there were no casualties. On the noon of July 24, 2008, a sudden fire broke out at the construction site of the east approach bridge of Minpu Bridge in Shanghai due to workers illegally using open flames. Due to the height of the cable-stayed bridge reaching up to 100 meters, it

1 posed great difficulties for firefighting work. Later, with the efforts of firefighting and
2 rescue personnel, four trapped workers were rescued from a height of 100 meters on
3 the bridge.
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6 **Current Research Status at home and abroad**

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8 In order to understand the fire behavior and post disaster performance of
9 reinforced concrete components and structures, scholars at home and abroad have
10 conducted fire (high temperature) tests on various components (such as beams,
11 columns, slabs, walls, etc.) and structures, and obtained some qualitative
12 understanding. However, there are still many shortcomings in experimental and
13 theoretical research, including the lack of unified experimental standards, large
14 dispersion of experimental data, weak comparability of data, etc., which make the
15 results and conclusions of experimental research not universally applicable. In terms
16 of research content, the strength of components after a fire has been mainly studied
17 from a static perspective. However, there is still insufficient research on the changes
18 in structural dynamic characteristics and the potential safety hazards caused by the
19 decrease in seismic performance of structures after a fire. At present, the analysis and
20 safety evaluation of the performance of concrete structures after fire mainly rely on
21 material property testing, structural performance testing, and necessary calculations
22 of the actual structure. Analyze and comprehensively evaluate its performance (such
23 as bearing capacity, stiffness, seismic performance, etc.) and stress state.

24 At present, research on damage assessment, maintenance, and reinforcement of
25 concrete structures after a fire mainly focuses on the strength of reinforced concrete
26 materials, the stiffness of structures, and the appearance characteristics of fire
27 deformation, while neglecting the damage assessment, maintenance, and
28 reinforcement of the durability, seismic performance, and overall integrity of
29 structures after a fire. In engineering practice, the assessment and identification of
30 damage to reinforced concrete structures after a fire is generally based on on-site
31 investigation and testing, combined with previous fire experience and research results,
32 to identify the affected temperature and residual strength of the structure, and then
33 propose reinforcement and repair plans according to the bearing capacity and
34 implement them. In the evaluation process, there is often a lack of numerical
35 theoretical analysis, which tends to be qualitative rather than quantitative, resulting in
36 a rough assessment of damage to many structures after a fire. Many engineering
37 personnel, due to their lack of knowledge on how to assess the durability and seismic
38 performance of structural components after a fire, have neglected these aspects of
39 damage assessment, resulting in a lack of accuracy, scientificity, and systematicity in
40 the assessment of damage to structural components after a fire. In the actual work of
41 engineering inspection and evaluation, the complexity of the detection methods and
42 fire damage often makes the assessment and identification of post fire damage too
43 simple and incomplete.
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1 **The Failure Mechanism of Concrete Bridges in Fire**

2 3 *Destruction of concrete*

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5 For reinforced concrete bridges, when the temperature reaches above 500 °C in
6 a fire, the parameters that affect the structural strength, such as strength, elastic
7 modulus, bonding strength, compressive deformation of concrete, mechanical
8 properties of steel bars, and thermal expansion coefficient, will undergo significant
9 changes. The specific changes are as follows:

10 The loss of concrete strength during a fire mainly depends on the temperature at
11 which the components are exposed to the fire. When the temperature is below 300 °C,
12 the hydration of cement accelerates, promoting the setting of cement slurry. At the
13 same time, due to the evaporation of free water in the cement slurry, the bonding
14 between cement particles is tight, and the strength of concrete may not necessarily
15 decrease, but may even increase; When the temperature exceeds 300 °C, due to the
16 decomposition of C-S-H, concrete begins to crack and its strength begins to decrease;
17 When the temperature exceeds 400 °C, due to severe damage to C-S-H colloids, the
18 strength of concrete decreases sharply; When the temperature continues to rise to
19 580 °C, Ca (OH) 2 in the concrete dehydrates and decomposes; After reaching 600 °C,
20 the microstructure of the concrete is severely damaged, resulting in overall failure.

21 When the temperature environment is below 200 °C, the compressive strength of
22 concrete structures decreases relatively little, and the residual strength is generally
23 around 70%. After the temperature exceeds 200 °C, the strength of concrete decreases
24 very quickly. When the temperature reaches 600 °C, the compressive strength of the
25 concrete structure decreases to zero. The reason is that as the temperature rises,
26 concrete hydrates decompose and cracks occur between the aggregate and cement
27 slurry. When the temperature rises to 450 °C, calcium carbonate decomposes. When
28 the temperature approaches 600 °C, the quartz in the aggregate peels off the concrete
29 protective layer, exposes the reinforcement, and undergoes expansion changes,
30 resulting in stress in the structural concrete and ultimately causing the loss of structural
31 strength.

32 The type of steel reinforcement also has an impact on the strength loss of concrete
33 components during a fire: when round steel reinforcement is installed in the structure,
34 the bonding strength rapidly decreases with increasing temperature; For threaded steel
35 bars, at temperatures below 200 °C, the adhesive strength of concrete can still remain
36 at 70%, and only when the temperature exceeds 200 °C, the adhesive strength rapidly
37 decreases.

38 Research has shown that fires not only reduce the strength of concrete, but also
39 affect its deformation: at a temperature of 500 °C, micro cracks occur between the
40 aggregate and cement slurry, and the quartz in the aggregate undergoes expansion
41 changes, resulting in a compression deformation of about 2.2 times that at room
42 temperature. The elastic modulus of concrete is also quite sensitive to temperature, as
43 shown in Table 1.

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Table 1. *Reduction coefficient of elastic modulus of concrete at high temperature*

Temperature (°C)	100	200	300	400	500	600	700
Reduction coefficient	1.0	0.8	0.7	0.6	0.5	0.4	0.3

The type of aggregate, curing conditions, and testing methods all have an impact on the stress-strain curve of concrete at high temperatures. Experiments have shown that as the test temperature increases, the compressive strength of concrete prisms, i.e. the peak value of the curve, gradually decreases, while the corresponding peak strain increases significantly. Therefore, the stress-strain curve gradually tends to flatten.

Damage to steel bars

When the fire temperature is above 200 °C, with the increase of temperature, the tensile strength, yield point, and elastic modulus of steel all change, and the overall trend is a decrease in strength and an increase in plasticity. When the temperature is around 250 °C, the tensile strength of the steel slightly increases, while the plasticity decreases, resulting in brittleness of the material. In this area, further increase in temperature may cause cracking of the steel when reheated. When the temperature reaches the range of 250-350 °C, the steel will experience creep, and the material's properties will be damaged to varying degrees. The temperature test results show that for 16Mn steel bars with yield steps, after heating for 1 hour and constant temperature heating for 1 hour, the strength and elongation of the material change very little below 900 °C. When the temperature reaches 1000 °C, the strength decreases by 10%; For cold drawn low-carbon steel wire without yielding steps, after 2 hours of heating, the material strength is not significantly affected when the temperature is below 600 °C, while the ultimate strength of the material decreases by up to 40% when the temperature is above 600 °C. According to experts' testing of steel reinforcement in most fire accident sites, in general, the impact of fire on steel reinforcement is smaller than that on concrete, and it only has a significant effect on grade I and II steel reinforcement when the temperature reaches 900 °C or above. Due to the protective layer of reinforced concrete components, the temperature of the steel bars in the components is usually below 900 °C, so it can be said that fires generally have little impact on grade I and II steel bars. However, high temperatures above 600 °C can significantly reduce the strength of cold drawn low-carbon steel wire by about 40%, indicating that fire has a significant impact on prestressed concrete components.

After a fire, the ultimate strength and yield strength of the steel bars inside the concrete components will decrease with the increase of temperature during the fire, while the elongation and expansion coefficient of the steel bars will increase with the increase of temperature, and the degree of change will vary with the different types of steel bars. When the fire temperature is below 200 °C, the strength of ordinary steel bars remains almost unchanged; When the fire temperature exceeds 200 °C, the intensity begins to decrease. The strength of prestressed steel bars decreases faster than non prestressed steel bars after a fire, and the bond strength also decreases significantly. The trend of changes in the elastic modulus of steel bars with increasing

1 temperature is similar to that of changes in strength: when the temperature does not
2 exceed 200 °C, the decrease in elastic modulus is limited; The temperature drops
3 rapidly between 300-700 °C; When the temperature is 800 °C, the elastic modulus is
4 very low, generally not exceeding 10% of the elastic modulus at room temperature.
5 The stress-strain relationship of steel bars at high temperatures is often described using
6 a two fold line method.

7 The bond strength between steel bars and concrete is mainly composed of the
8 frictional force between concrete and steel bars, the bonding force between the surface
9 of steel bars and cement colloids, and the mechanical biting force on the contact
10 surface between concrete and steel bars. At high temperatures, due to the smaller
11 expansion coefficient of concrete compared to steel bars, the concrete compresses the
12 steel bars in a circumferential direction, increasing the friction between the concrete
13 and the steel bars. On the other hand, the tensile strength of concrete at high
14 temperatures significantly decreases with increasing temperature, thereby reducing
15 the bonding force between concrete and steel bars. The high temperature has a serious
16 impact on the bond strength between round steel bars and concrete, while it has a
17 relatively small impact on the bond strength between threaded steel bars and concrete.
18 In addition, the bond strength between rusted and rust free round steel bars and
19 concrete varies at high temperatures.

20 21 *Damage to bridge components*

22
23 In a fire, the prestressed concrete main beam is in the most unfavorable position,
24 and the temperature at the bottom of the beam can usually rise from 20 °C to 600 °C
25 within 5-15 minutes. Due to the rapid temperature rise at the bottom of the beam and
26 the high thermal inertia of concrete, the damage to the main beam is often more severe
27 than that of the cover beam and column. When local combustion is concentrated, the
28 temperature of the fire rises rapidly and the instantaneous heat generation is large,
29 which can lead to high burning temperatures on the surface of concrete components,
30 large temperature gradients along the cross-section of the components, and rapid
31 deformation of the internal concrete due to the large difference in expansion rate,
32 resulting in concrete cracking.

33 In addition to the main beam structure, other parts of the bridge are also prone to
34 significant damage in a fire. During a fire, the cover beam is in a state of being exposed
35 to fire on three sides, and the bottom of the beam (tension zone) is directly exposed to
36 fire, causing longitudinal cracks along the main reinforcement direction of the beam,
37 and even causing damage such as concrete cracking, peeling, and exposed steel bars
38 on the bottom surface of the beam. Reinforced concrete columns are affected on the
39 side in a fire, and the harm is not as great as that of the main beam and cover beam,
40 but the upper part is also more severely affected. Due to the use of rubber bearings in
41 most modern bridges, high temperatures can cause surface cracking of the bearings,
42 causing some bearings to tilt and accelerating their aging.

43 Accidents of bridge fires occur frequently, and bridges affected by fires have a
44 significant impact on traffic safety. Therefore, it is necessary to study the internal
45 forces of bridges caused by fires. When a fire breaks out on a bridge, the temperature
46 increases sharply, causing objects to expand or contract. When the thermal

1 deformation of an object is free, no stress is generated, but if the thermal deformation
2 of the object is constrained or restricted, stress will be generated, which is called
3 temperature stress. In statically indeterminate structures, deformation caused by
4 temperature is often constrained, resulting in temperature stress.

5 Due to the deterioration of concrete and steel reinforcement materials after a fire,
6 there may be widespread spalling of concrete. Concrete cracking and detachment can
7 cause changes in the dimensions of the main beam structure of the bridge, resulting in
8 a decrease in the bending and shear capacity of the normal section, a decrease in the
9 stiffness of the section, and an increase in deformation, accompanied by stress
10 redistribution. This will inevitably cause the structural stress state to deviate from the
11 original design requirements. The long-term impact of fires on structures mainly
12 includes increased creep and loss of prestress caused by the deterioration of concrete
13 materials, accelerated carbonation of concrete, and increased possibility of steel
14 corrosion, all of which reduce the durability of bridge structures.

17 **Evaluation of the Bearing Capacity of Burnt Structures**

18
19 Generally speaking, from a static perspective, the decrease in mechanical
20 properties of components after a fire includes two aspects: a decrease in strength and
21 a decrease in stiffness. Strength damage will reduce the load-bearing capacity of the
22 component, while changes in stiffness will cause redistribution of internal forces in
23 various parts of the structure and may lead to significant deformation of the
24 component.

25 The damage assessment of bridge structures after a fire includes the following
26 steps: firstly, data collection and on-site investigation are carried out at the fire scene,
27 and then the fire temperature zone is divided to determine the fire temperature of the
28 structure; Determine the level of structural damage based on the temperature of the
29 fire, and determine the distribution of the internal temperature field of the component;
30 Next, determine the strength loss of concrete, steel bars, prestressed steel bars, as well
31 as the loss of bond strength between steel bars, and the changes in elastic modulus of
32 steel bars and concrete after a fire; Furthermore, by combining static load and dynamic
33 experiments, the bearing capacity of the components is evaluated and the damage to
34 the bridge structure is determined. Finally, the bridge repair plan and maintenance
35 reinforcement treatment opinions are determined.

36 In a fire, the apparent characteristic changes of concrete are an important
37 indicator for evaluating the temperature of the concrete fire scene. Usually, the surface
38 of concrete burned by a fire undergoes physical and chemical changes, and the color
39 change can roughly indicate the temperature of the fire and the degree of concrete
40 damage. From the survey results, it can be seen that when the temperature of the fire
41 is above 450 °C, the strength of the concrete has already suffered a significant loss.
42 The carbonation depth of concrete is also an important indicator for detecting concrete
43 damage. Under normal circumstances, cement generates a large amount of Ca (OH)
44 2 during the hydration reaction of concrete, making the concrete alkaline; When the
45 burning temperature reaches 500-580 °C, the free alkali in the cement undergoes
46 thermal decomposition, making the concrete neutral. When measuring, drill holes or

1 knock off the edges and corners on the concrete surface, and spray a 1%
 2 phenolphthalein solution on it. If the color does not change, it is the neutral zone,
 3 indicating that the concrete surface of the component has carbonized, which is called
 4 fire carbonization. The durability of concrete with a carbonized layer and its anti-
 5 corrosion protection effect on steel bars will be greatly reduced.

6 The compressive strength and elastic modulus of concrete decrease significantly
 7 under combustion. In a fire environment below 500 °C, the natural recovery of
 8 concrete strength and elastic modulus is significant. After one year, its strength can
 9 recover by 90% and elastic modulus can recover by 50%. When the temperature of
 10 carbon steel reinforcement is within 850 °C, its crystallization remains basically
 11 unchanged and the yield point is not affected, but the tensile strength and hardness
 12 increase, elongation and twisting decrease, and brittleness increases. When the
 13 temperature exceeds 1000 °C, the crystallization of steel increases, resulting in a
 14 decrease in yield point and tensile strength, while ductility increases. It can be seen
 15 that the strength reduction of steel bars in concrete structures is much smaller than that
 16 in concrete.

17 The commonly used method for estimating the post disaster temperature of
 18 concrete is to determine the combustion temperature by the amount of free lime and
 19 the amount of CO₂ absorbed by the concrete, combined with the carbonation depth.
 20 The general method is to determine the ratio of the difference in carbonation depth
 21 between after and before the fire to the carbonation depth before the fire $((T_2-T_1)/T_1)$
 22 by looking up the table, as shown in Table 2. In addition, the fire temperature can also
 23 be determined by measuring the residual compressive strength of concrete: when the
 24 residual compressive strength of concrete is 50% of the original structure, it can be
 25 concluded that the combustion temperature inside the structure is below 500 °C. After
 26 one year, the compressive strength can be restored to over 90%, and the elastic
 27 modulus can be restored to over 50%. In addition to the testing methods for concrete
 28 carbonation depth and residual compressive strength mentioned above, commonly
 29 used methods for determining the fire temperature of components include concrete
 30 color and appearance method, concrete surface burn layer thickness method,
 31 ultrasonic rebound comprehensive method, and electron microscopy analysis method.
 32

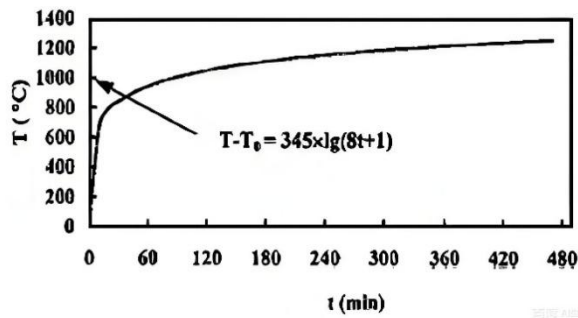
33 **Table 2.** $(T_2-T_1)/T_1$ Relationship with Component Fire Temperature

Carbonization depth ratio	0	0.7	1.6	3.5	7.6
Concrete fire temperature °C Normal temperature	30	200	400	600	800

34
 35 After determining the remaining strength of concrete through on-site testing, it is
 36 necessary to calculate the temperature field distribution of the component through
 37 numerical simulation to obtain the degree of damage inside the component. The
 38 calculation of the internal temperature field distribution of components is mainly to
 39 determine the external boundary conditions, especially the fire temperature rise curve
 40 of the fire receiving surface. The two commonly used methods currently are: (1) the
 41 formula method for fire temperature rise, which uses the recommended standard
 42 temperature rise curve for fire given by the International Organization for

1 Standardization, as shown in Figure 1. (2) CFD simulation method, which is currently
 2 a rapidly developing regional simulation method that uses commercial software such
 3 as CFAST for calculations. After obtaining the curve of fire temperature over time and
 4 the thermal performance of reinforced concrete using the above two methods, finite
 5 element software ANSYS or FLUENT can be used to simulate the temperature
 6 history inside the component.

7
 8 **Figure 1.** *Standard heating curve specified in ISO 834*



18
 19 Uneven overheating on the cross-section of reinforced concrete components can
 20 result in corresponding unequal compressive strength and elastic modulus values,
 21 which complicates the calculation of bearing capacity. The current main calculation
 22 approach is to convert the cross-section into an equivalent homogeneous concrete
 23 cross-section, and then apply the methods and formulas in the current specifications
 24 for calculation. The United States, the United Kingdom, Japan and other countries use
 25 the visual grading table for concrete fire damage and concrete components provided
 26 by the British Concrete Institute to comprehensively evaluate the damage of structural
 27 components. At present, only the "Evaluation Standards for Concrete Components
 28 after Fire" (DBJ08-219-96) issued by Shanghai in 1996 can be referred to in China.
 29 In the assessment of fire damage, the components are often directly evaluated, but
 30 there is still little research and evaluation on the overall impact of fire on the structure.
 31 During a fire, the expansion and deformation of components affected by the fire are
 32 constrained by adjacent components, while also exerting forces on adjacent
 33 components, causing damage or destruction to them. After component damage,
 34 internal force redistribution will also occur. Therefore, it is necessary to strengthen the
 35 research on the impact of fire on the overall structure.

36 37 38 **Repair and reinforcement of bridges after a fire**

39
 40 The repair and reinforcement process of bridges after a fire is generally carried
 41 out by collecting original data, determining the degree of damage, conducting
 42 comprehensive analysis of the structural status, and then establishing a mechanical
 43 model. Using the actual physical and mechanical performance indicators of concrete
 44 and steel bars measured, the ultimate bearing capacity and normal use state of the
 45 structure are verified, and a reinforcement treatment plan is proposed based on this.

46 The commonly used methods for bridge reinforcement include increasing the

1 section, anchor spraying concrete reinforcement, pasting steel plates, and changing
2 the structural stress system. Due to the damage to the original structure, there are the
3 following requirements for reinforcement:

- 4
- 5 (1) It do not changed the foundation structure, and reinforcement is based on the
6 premise of not increasing the self weight of the structure;
- 7 (2) The bridge piers are reinforced with external concrete;
- 8 (3) It is better to reinforce the beam with sprayed fiber reinforced concrete;
- 9 (4) Thoroughly chisel away the burnt concrete as much as possible to eliminate
10 the weak bond between the repaired material and the old concrete caused by
11 it;
- 12 (5) Due to prolonged exposure to the external environment, bridge structures are
13 prone to accelerated carbonation of concrete after being burned, resulting in
14 damage to the concrete protective layer or even detachment of concrete,
15 corrosion of steel bars, and other phenomena. Therefore, rust inhibitors should
16 be applied to the surface of the structure within the range of fire temperature
17 to restore its durability.
- 18
- 19

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