Research on the material properties of prestressed concrete girder bridge after exposed to fire

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Abstract: The factors such as maximum temperature, duration, diffusion condition and concrete bursting at high temperature increase the difficulty of obtaining material properties by using temperature. In order to quickly obtain the real performance parameters of the materials of the prestressed concrete beam bridge in the post-disaster bridge evaluation, the appearance classification and material test of 32 hollow slabs demolished after the fire of the existing beam bridge in a highway were carried out. The relationship between the commonly used testing indexes and the properties of materials is obtained by measuring the properties of materials after fire. The applicability of these indexes is verified by the ultimate bearing capacity test and finite element simulation. The results show cracking and spalling of concrete at high temperature not only results in significant loss of section, but also significantly reduces the strength of concrete and prestressing steel strand in this area, which leads to the reduction of bearing capacity. When the spalling depth of concrete exceeds 2/3 of the net protective layer of steel strand after overfire, the reduction coefficient of compressive strength and tensile strength of prestressed steel wire reaches 0.7, which will seriously affect the ultimate bearing capacity. The normal plain round steel bar can be deviated safely to the design standard value when calculating the ultimate bearing capacity of the structure. The ultimate bearing capacity of the prestressed hollow beam after fire is analyzed by using the reduction relationship between the conventional inspection indexes and the material properties, and the finite element simulation, so as to meet the engineering precision.

1. Introduction

In recent years, with the development of highway traffic in China, the number of highway bridges suffering from fire has been also increasing\([1-2]\). Fire-stricken bridges not only cause economic losses, but also bring potential safety hazards to the service of bridges, affecting the normal operation of highways. Prestressed concrete bridges account for a large proportion of the bridges built in China. Japan, the United States, the United Kingdom, France, Germany and the former Soviet Union and other countries have studied the degree of damage to the building structure and fire-resistant grade after the fire. At present, the study of structural fire prevention abroad has shifted from structural component to overall structure, and discussed the influence of local fire on the whole structure. At the same time, the calculation method and the technology of structural fire prevention diagnosis have been studied. In recent years, scholars at home and abroad have carried out a lot of fire resistance research in recent years in view of the characteristics of prestressed concrete structures. Kodur V K R, Dwaikat M B\([3-4]\) studied
the influence of stress-temperature path on the prestressed concrete beam and slab, and proposed a numerical method considering the thermal-mechanical coupling effect and combined with experimental data to study the fire resistance of the prestressed concrete beam and slab. Ellobody E, Bailey CG[5] studied the fire resistance of unidirectional post-tensioned unbonded prestressed concrete slabs. The influence of different aggregate types, different boundary constraints at the end of slabs on the fire resistance of structures was studied. The results show that the deformation of prestressed concrete slabs under high temperature is significantly different with different end restraints and aggregate types. Krishnamoorthy[6] through the experimental study of prestressed concrete frame at high temperature, the influence of non-uniform temperature field on the deformation performance, internal stress and bending moment of the structure with time is analyzed.

Wang Jun[7] studied the creep of high-strength prestressing tendons under high temperature through experiments, established a high-temperature creep model of high-strength prestressing tendons, and verified the necessity of taking into account the creep of prestressing tendons in fire resistance analysis of prestressing concrete structures. Zhang Xiaodong[8] evaluates the fire resistance of prestressed concrete T-section girder bridges under vehicle-induced fire, studies the randomness of fire and structural parameters, and sampled parameters based on central composite test design, forms test samples and test samples, and establishes a vulnerability analysis method based on RSM-MCS. Vulnerability analysis of T-section beam with expanded prestressing concrete. Zheng Xuesong[9] takes the long-span PC box girder bridge as the research object, adopts the statistical and numerical simulation methods, sums up and puts forward a set of finite element analysis method to simulate the fire damage effect of long-span PC box girder bridge. Zhang Gang[10] Aiming at the damage problem of prestressed concrete T-section beam bridge under fire, the fire high temperature conduction mode and the mixed boundary condition of heat conduction are studied, the fire action mode of prestressed concrete T-section beam is set up, the distribution state of temperature field is analyzed. The calculation details and judging conditions of the deformation and failure of the T-section beam of the prestressing concrete are given. The results show that the failure time of beam rib is the same as that of flange plate when only the beam rib of T-section beam is fired, and the fire resistance time of beam rib is longer than that of other fire modes.

In the above studies, the study of bridge material properties after fire mostly focuses on the relationship between material properties and temperature field. Affected by the maximum temperature, duration and diffusion conditions of the fire field, it is difficult to restore the real temperature distribution of the fire field after the fire, thus increasing the difficulty of judging material properties by determining the fire temperature. In addition, when using numerical simulation to determine the temperature field distribution, the temperature field changes caused by cracking and bursting of concrete are not considered, and the temperature distribution is independent of stress. However, at real high temperatures, the temperature at cracks will be higher than that at non-cracks after concrete cracking. Ignoring this factor will affect the applicability of this method in predicting material properties after overheating.

In this paper, the material properties of a prestressed hollow slab beam in operation after fire are tested. The relationship between the commonly used detection indexes and the material properties is obtained by statistical analysis. The applicability of these indexes is verified by finite element simulation and ultimate bearing capacity test, which provides a reference for rapid detection and evaluation of similar bridges after fire.

2. General situation of project and fire site temperature
A 9×20m simple-supported pre-tensioned concrete prefabricated slab bridge of a highway is designed in different sections. A single bridge is equipped with 16 hollow slab beams. The intersection angle of the bridge is 52.74 degrees. Design value of standard cube compressive strength of concrete 50Mpa. There are 14 steel bundles per beam (effective length between 780cm and 1996cm). Each pre-stressed steel bundle is composed of 6×Φ15.2, whose net protection is 37.4mm, arranged in a straight line. The yield strength of prestressing tendons is 1860Mpa, and the tension control stress is 1395 Mpa. The reinforcement of elevation and middle plate is shown in Fig. 1. At 2:15 a.m. on a certain day, a tanker
car rolled over under the bridge, the tank broke and burned, resulting in a large area of combustion on the bottom of the two adjacent holes of the bridge. The fire was extinguished at about 4:10 a.m., and the overfire lasted nearly 2 hours. After detection and evaluation, 32 pieces of overheated beams were demolished and reconstructed, which provided abundant samples for this study.

The temperature of the fire site is determined mainly by the color of damaged concrete, the thickness of sparseness and the temperature of fuel exterior flame. The judgment basis is shown in Table 1-2. According to the judgement of concrete color change of hollow slab after fire with eyes and touch on site, it can be seen that the concrete of multi-beam after fire is slightly yellowish or pink, and the local sparse thickness is more than 6mm. In addition, the maximum temperature of gasoline combustion can reach 1000℃. Therefore, the temperature of the fire site is determined to be more than 1000℃.

![Diagram](image)

(a) Elevation

(b) Medium plate reinforcement drawing

Fig 1. The bridge layout

| Surface color | Normal | Pink appears pale grey-white at first | Pale grey | Pale grey with a slight yellowish tinge | Pale yellow |
|---------------|--------|--------------------------------------|-----------|-----------------------------------------|------------|
| Temperature/℃ | <300   | 300~500                              | 800~850   | 850~900                                 | >900       |

Table 1. Corresponding relationship between fire temperature and concrete color

| Burning thickness /mm | 1~2 | 2~3 | 3~4 | 4~5 | 5~6 | >6 |
|-----------------------|-----|-----|-----|-----|-----|----|
| Field temperature /℃  | <700| 700~800 | 800~850 | 850~900 | 900~1000 | >1000 |

Table 2. Corresponding relationship between fire temperature and thickness of concrete sparse layer

3. Sample classification

In order to facilitate field sampling and meet the sample classification, hollow slab girder bottom is divided and numbered. The longitudinal bridge is 0.5m grid and the transverse bridge is 0.5m grid. Samples are classified into 7 categories according to the depth, area, burst crack and rebound value of the floor, as shown in Table 3. In the table below, \( \delta_s \) is the net protective layer thickness of steel strand; \( \delta \) is the spalling depth of concrete; \( S_{\text{test}} \) is the measured area; \( S \) is the measured spalling area; \( R_{\text{im}} \) is the rebound value of the strength curve corresponding to the concrete label used for the pre-stressed concrete beam with the corresponding carbonization depth of zero (considering the correction of angle and test surface); \( R \) is the measured rebound value. The strength and modulus of elasticity of concrete, the strength and modulus of elasticity of steel strands, the strength and modulus of elasticity of ordinary steel bars in each region were measured.

When measuring the spalling thickness, the floor is divided into a small area of 5cm×5cm. The maximum spalling depth of the small area is taken as the representative value, and then the average
value of all the small areas in the measuring area is calculated as the average depth of the measuring area. The spalling scale A–C is distinguished according to the above values. Typical exfoliation is shown in Figure 2. In addition, there are two beams which are not directly burned by fire and can be used as reference beams basically.

Table 3. Basis and Number of Sample Classification

| NO. and Classification | Classification basis                                |
|------------------------|----------------------------------------------------|
| 1# reference           | Unaffected by fire                                  |
| 2# A shedding          | 0<d<1/3δs                                         |
| 3# B shedding          | 1/3δs≤d<2/3δs, S>0.2S_test                         |
| 4# C shedding          | d≥2/3δs, S>0.2S_test                               |
| 5# B cracks            | A slight crack network on the surface              |
| 6# A cracks            | A coarse crack network on the surface              |
| 7# rebound             | The R<0.9Rim of the area without concrete spalling and crack |

For areas where there have been fire bursts, the cracks in the measuring area are detected one by one by naked eye and portable crack width comparison card, and only the cracks caused by fire are considered. The typical concrete burst is shown in Figure 3. No concrete peeling and fire cracking areas are found. Only by distinguishing the rebound values, considering that the test angle and the revised rebound values of the test surface are less than Rim, it is considered that material damage can not be neglected, and the materials in this area are sampled. The field rebound measurement is shown in Figure 4.

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**4. Test results and analysis**

In accordance with the relevant requirements[11], the field sampling of concrete strength and modulus of elasticity specimens of the superstructure of the bridge is carried out. Cylindrical specimens with a diameter of 70mm and a height of 70mm are used for core size, and the aspect ratio is 1. The research in document[12] shows that for small diameter core specimens. The ratio of height to diameter should not exceed the range of 0.85 to 1.20, otherwise the test results will have a larger error. The yield strength, tensile strength and modulus of elasticity of steel can be obtained by tensile test. The tensile test is carried out in accordance with the national standard[13]. When measuring the elastic modulus of steel, the general standard distance length of the test is 20mm, 50mm and 100mm. The total length of the test should make the distance between the two clamps of the test machine not less than 150mm. The sampling length of the test site is 400mm. The mechanical properties of steel strands were tested according to the relevant provisions[14]. The sampling length was 0.5m. When the fracture of the steel strand within the nominal diameter of the clamp is less than two times the distance between the clamp and the clamp, the test is invalid, and the core sample is added again.

**4.1 Test results of concrete**

The test results of concrete compressive strength are shown in Table 4. The cube compressive strength values in the table are the arithmetic average values after eliminating the data with large differences. It can be seen from the surface that the cubic compressive strength of concrete slab before fire is 58.5Mpa.
When the spalling depth after fire is less than a third of the net protective layer of steel strand, the strength reduction coefficient is 0.85. When the spalling depth is more than two thirds of the net protective layer of steel strand, the strength reduction coefficient is 0.68, that is, the strength reduction coefficient after fire is positively correlated with the spalling depth. The strength of concrete decreases slightly in areas where slight crack network appears after overfire and the rebound value is lower than the normal value. The changes of physical, chemical and mechanical properties of the internal composition of concrete floor caused by high temperature burning include evaporation of moisture in concrete, relaxation of bonding force between hydration and unhydrated cement particles, dehydration of hydrated calcium hydroxide to form calcium oxide, decomposition of hydrate to destroy the structure of cement stone and hydration of hydrate. The transformation from high alkali to low alkali products, the increase of internal cracks in cement paste and the evacuation of porous, the transformation of crystal state of quartz in rock from alpha beta to beta, the volume increase of cracks and the increase of decomposition volume of calcium carbonate in high temperature, etc., all of these reasons reduce the compressive strength of concrete.

| Survey area | fck/Mpa | SD/Mpa | Reduction coefficient | Sample quantity |
|-------------|---------|--------|-----------------------|-----------------|
| reference   | 58.5    | 4.52   | 1.00                  | 6               |
| A shedding   | 49.7    | 4.15   | 0.85                  | 15              |
| B shedding   | 43.7    | 4.29   | 0.75                  | 15              |
| C shedding   | 39.6    | 5.21   | 0.68                  | 15              |
| A cracks     | 54.2    | 4.64   | 0.93                  | 15              |
| rebound      | 54.8    | 4.82   | 0.94                  | 15              |

4.2 Steel Strand Test Result

Crystal defects are large in the pre-stressed strand, and the point defects of the crystals increase the strength of the material, but there is a tendency to recover at high temperature, and the strength decreases a lot when the fire temperature exceeds 500℃. In addition, due to other physical and chemical effects at high temperature, such as the reduction of interatomic binding force (partial recovery after high temperature) and decarbonization, the strength of the alloy is further reduced and its plasticity is increased[15]. After high temperature, the material inequality increases, and the test data are dispersed. The test results are shown in Table 5. It is known that the strength reduction coefficient of steel strands in three types of areas, i.e. The area with less than a third drop depth after high temperature, the area with slight crack network and the area with lower rebound value than normal value, is not large. The main reason is that the thermal conductivity of concrete is poor. As the distance from the fire surface increases, the temperature decreases rapidly. When it is about 4cm from the bottom of the fire beam, the maximum temperature drops obviously[13]. When the spalling depth is greater than a third of the net protective layer after overheating, the yield strength of the steel strand decreases obviously; when the spalling depth is greater than two thirds of the net protective layer of the steel strand, the average reduction coefficient of the yield strength is about 0.75, and the strength reduction coefficient of individual steel strand is 0.52, which will seriously endanger the safety of bridge structure.

| Survey area | yield strength /Mpa | SD /Mpa | Reduction coefficient |
|-------------|---------------------|---------|-----------------------|
| reference   | 1888                | 9.71    | 1.00                  |
| A shedding   | 1816                | 46.32   | 0.96                  |
| B shedding   | 1687                | 73.62   | 0.89                  |
| C shedding   | 1441                | 99.53   | 0.76                  |
| A cracks     | 1881                | 23.53   | 1.00                  |
| B cracks     | 1718                | 35.88   | 0.91                  |
| rebound      | 1780                | 52.42   | 0.94                  |
4.3 Test results of common steel bars
The test beam is only equipped with one HRB400 steel bar with nominal diameter of 12mm. The strength test results of hot-rolled ribbed steel bar are shown in Table 6. It is shown that the ultimate strength reduction coefficient of hot-rolled ribbed steel bars in seven regions is very small after high temperature, approaching 1.00 basically. The yield strength of steel bars in only a few regions decreases slightly, which can be neglected compared with the strength reduction coefficient of steel strands after overheating. The main reasons are as follows: the thermal conductivity of concrete is poor, with the increase of the distance from the fire surface (bottom of beam), the temperature drops rapidly, the actual net protective layer of HRB400 steel bar is slightly larger than that of steel strand, that is, the actual overfire temperature in fire is lower than that of steel strand; the point defect of crystal in steel internal structure makes the strength of material increase. However, there is a tendency to recover at high temperature. Because of the large defects of the crystal of the prestressing steel bar, the strength of the prestressing steel bar decreases more than that of the ordinary steel bar at high temperature[16].

| Survey area | Yield /Mpa | SD /Mpa | Reduction coefficient |
|-------------|------------|---------|-----------------------|
| Reference   | 401        | 540     | <20                   | 1.00 | 1.00 |
| A shedding   | 388        | 551     | <20                   | 0.97 | 1.02 |
| B shedding   | 384        | 553     | <20                   | 0.96 | 1.02 |
| C shedding   | 398        | 556     | <20                   | 0.99 | 1.03 |
| A cracks     | 377        | 536     | <20                   | 0.94 | 0.99 |
| B cracks     | 376        | 529     | <20                   | 0.94 | 0.98 |
| Rebound      | 368        | 525     | <20                   | 0.92 | 0.97 |

The results of tensile strength test of round bars are shown in Table 7. The regularity of yield strength and ultimate strength is not significant after overheating. The strength of individual regions is slightly increased, and the strength of individual regions is slightly reduced compared with that of complete regions. In post-fire performance evaluation, the design value of round bars can be taken directly.

| Survey area | Yield Strength /Mpa | SD /Mpa | A cracks | B cracks | Rebound |
|-------------|---------------------|---------|----------|----------|---------|
| Reference   | 373                 | <20     | 359      | 362      | 369     |
| A shedding   | 382                 | <20     | 360      | 359      | 362     |
| B shedding   | 388                 | <20     | 360      | 359      | 362     |
| C shedding   | 507                 | <20     | 487      | 486      | 484     |
| A cracks     | 503                 | <20     | 487      | 486      | 484     |
| B cracks     | 529                 | <20     | 487      | 486      | 484     |
| Rebound      | 525                 | <20     | 487      | 486      | 484     |

5. Examples verification
By measuring the material strength of concrete, steel strand and reinforcing bar after overfire, the relationship between the commonly used detection indexes and material properties is given. Through the above relationship, the bearing capacity of such bridges after overfire can be further evaluated. It is illustrated by an example. The appearance of the selected example beam is shown in tables 8.

| NO. | The appearance of bottom plate of girder |
|-----|----------------------------------------|
| R-8-6# | The area where concrete is pink or loess accounts for 98%; the area where concrete hammering sound is dull accounts for 96%; the floor concrete falls off completely, and its characteristic depth is 3.6 cm; the area where steel strands are exposed accounts for 25%, which is distributed between the fulcrum and half span. |

5.1 Finite Element Simulation
In order to obtain the bending load-bearing capacity of hollow slab beams, it is necessary to obtain the material parameters after overheating. According to the relationship between the above test indexes and the material properties, it is known that 100% of the concrete of the example beams falls off with an
average depth of 3.6cm, which exceeds two thirds of the net protective layer thickness of the steel strand. Literature[16] shows that only when the floor is directly fired, the maximum temperature of the fire is controlled at 800℃. When the distance between the concrete and the fire surface is greater than 15cm, the maximum temperature of the concrete in the fire process is lower than 50℃, and the effect of the fire temperature can be neglected. Therefore, the material parameters of intact area are used for the modeling above 15cm from the bottom of the beam, and the material parameters of falling concrete area are used for the area below 15cm. The elastic modulus of 481 pre-stressed steel bars after high temperature was measured in reference[17]. The results show that the elastic modulus of pre-stressed steel bars after high temperature hardly changes with the change of temperature and initial stress level. Therefore, the elastic modulus of steel strand after high temperature is taken as the elastic modulus of material at room temperature.

The model of hollow slab after fire is established by ANSYS. The element SOLID65 is used to simulate the mechanical behavior of concrete after fire. The LINK8 element is used to simulate the mechanical behavior of steel bar and strand after fire (bond slip with concrete is not considered, prestress is applied through cooling). The stress-strain relationship model of concrete is an important part of the non-linear analysis of concrete hollow slabs after fire. The follow-up hardening model is used in the simulation. The shear transfer coefficient of the tension crack in the failure criterion of concrete is 0.7 based on relevant experience and trial calculation. The shear transfer coefficient of the closed crack is 0.95 after several adjustments. The uniaxial stress-strain relationship of concrete combines the requirements of Hognestad and GB 50010-2002, as shown in Figure 5. Bilinear isotropic hardening model is used to simulate the steel strand after overheating, as shown in Figure 6. The effect of ordinary reinforcing bars is considered by diffusing them into concrete elements in the form of defining the real constants (longitudinal, transverse reinforcing bars and stirrup reinforcement ratios). When dividing the elements, the hexahedron mapping grid is adopted, the number of elements of the whole bridge is 5918, and the number of nodes is 8266.

![Fig 5. σ-ε curve of concrete(Mpa)](image)

![Fig 6. σ-ε curve of concrete of steel strand(Mpa)](image)

![Fig 7. The finite element model](image)
5.2 Bearing Capacity Test
In order to verify the relationship between commonly used testing indexes and material properties and to analyze the applicability of hollow slab beams after fire by finite element simulation, the ultimate bearing capacity of selected examples of beams was tested. The loading test site is shown in Figure 8. The maximum bending moment of the normal section and the shear capacity of the section at 1/3L~2/3L should be taken into account in the loading arrangement of the test. Finally, the spacing of the distributing beams is determined to be 3m. The loading arrangement is detailed in Figure 9. The loading device is loaded by hydraulic jack of reaction frame, and the enlarged concrete block is used as anchorage foundation. The force is transmitted through the finely rolled threaded steel and the transverse reaction beam. The loading process and termination conditions of the test are referred to the relevant specifications.

![Fig 8. The bearing capacity test](image)

![Fig 9. The loading layout (unit: cm)](image)

The test beam is divided into two loading conditions. The first condition is that the test section reaches or approaches the designed ultimate load-carrying capacity state, and the second condition is that the test beam reaches the actual ultimate failure state or the loading termination condition. The loading process is shown in Table 9.

| Step | Description |
|------|-------------|
| 1    | Deadweight (including distributing beam and Jack deadweight). |
| 2    | Preloading, one loading and unloading (loading amount is 30% of the ultimate load value). |
| 3    | Under formal loading, the ultimate load of hollow slab beams is calculated by 10 stages, and the ultimate load of hollow slab beams is calculated by 10% for each stage. After 100% ultimate load, unloading is carried out, and then four stages of secondary loading to 100%. Finally, the hollow slab beam is destroyed by intensive loading. The ultimate load of each stage is calculated by 5% ultimate load. |
| 4    | If the deformation of all hollow slab beams can not converge with time, that is, the deformation can not stop, it means that they have entered the ultimate load-bearing state, immediately stop loading, record the corresponding data and unload. |

The net height of the test bench is 1.2m because of the need of the appearance and non-destructive
testing in the early stage. For safety considerations and Jack travel reasons, the test has not been loaded to completely destroy the hollow slab beam, so there is no complete destruction of the concrete crushed beam and the collapse of the beam and slab. The main structure in the test process is the cracking of the concrete crushed beam and the collapse of the beam and slab. The phenomena are as follows: with the increase of load, the deflection of the beam increases continuously, and the deformation develops from linear to non-linear step by step; cracks first appear in the span of 5 m, and with the increase of load, cracks increase continuously, original cracks expand gradually, the width increases continuously, and the cracking range extends gradually to the end of the beam; The load termination condition is that the maximum vertical crack width at the tensile main reinforcement bar exceeds 1.5mm (The crack at the oblique crack near 5.5m in the middle of the span is overwide at first).

5.3 Comparison of results

The results of finite element simulation and test are compared with those in Table 10 and Figure 10. It is shown that it is feasible to obtain the ultimate bearing capacity of pre-tensioned prestressed concrete beam bridge after fire by means of the commonly used testing indexes, and then to obtain the ultimate bearing capacity of pre-tensioned pre-stressed concrete beam bridge by means of finite element method, which meets the engineering accuracy.

| Method     | Load/t | M_max/kN-m | d_max/cm |
|------------|--------|------------|----------|
| Trial      | 49.2   | 2610       | 10.95    |
| Simulation | 49.4   | 2619       | 10.62    |

6. Conclusion

The spalling of concrete at high temperature not only leads to the loss of section, but also significantly reduces the strength of concrete and prestressing strand in this area, which leads to the reduction of bearing capacity. When the spalling depth of concrete exceeds two thirds of the net protective layer of steel strand after over-fire, the reduction coefficient of compressive strength and tensile strength of prestressed steel wire reaches 0.7, which will seriously affect the ultimate bearing capacity of the structure. When calculating the ultimate bearing capacity of the structure after fire, the design standard value of the ordinary round bars can be taken safely. The ultimate bearing capacity of pre-stressed hollow slab beams after fire is analyzed by using the reduction relationship between conventional testing indexes and material properties, and combined with finite element simulation, which meets the engineering accuracy. In this paper, the relationship between the commonly used detection indexes and the reduction coefficient of material performance is proposed. Only the bottom of small-span prestressed concrete hollow slab beam is directly fired, and other types of bridges and different surface fires need to be further studied.
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