Experiment on the Mechanical Behaviors of High Strength Steel Reinforced Concrete Beam at High Temperature in Fire

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Abstract: High temperature had very serious impact on steel reinforced concrete beam, its strain would increased very much, particularly when the temperature of concrete beam was over 600℃. When temperature was above 600℃ and the loading was above 200kN, the section strain distribution was in linear. However, when the loading was more than 250kN, strain distribution deviated from a straight line. Along the cross section of height was not significantly influenced by concrete strength, the deformation of the beam accelerated until destroyed or broken. Above 600℃, horizontal and oblique cracks obviously appeared along the interface of steel and concrete, the flexural bearing capacity of beam could not be fully developed. When their temperatures changed from 20℃ to 400℃, the effects of concrete on their limits of bond stress and steel slip were not obvious. After 400℃, limit of bond stress dropped faster. When temperature was over 700℃, the bond strengths of different specimen of concrete were close, the effects of concrete strength on limit of bond stress significantly reduced. Damage on the interface of steel and concrete varied with temperature, the damage reduced as the temperature increased.
Keywords: High temperature; steel reinforced concrete; high strength concrete; beam; mechanical behavior.

1. Introduction

The combination of high strength steel reinforced concrete had many advantages, such as high strength, durability and volume stability, not only it had the dual advantages of steel and concrete structures, but also it avoided the weakness of brittleness and poor ductility. The combination could make the two kinds of materials collaborated with each other better, which could effectively improve the stress performance of steel reinforced concrete structure and reduced the section size of components, it had excellent seismic performance, stiffening, anti-yield capacity, that kind of structure could effectively prolong its service life in building[1-4]. With widely its use in many buildings, the limitation of original theory and inadaptability was increasingly exposed[5]. But, for steel reinforced concrete, its poor fire-proof performance was certainly restricted its application in some areas, so fire-prevention property of concrete beam was also paid extensive attention [6-16].

2. Experimental details

2.1 Design of test samples

In test, there were 8 concrete beams, all of the designed parameters were shown in table 1.

Table 1. Specimen parameters of test beams

No.	Concrete strength /MPa	Shear-span ratio	Heating temperature/℃
A0	49.8	1.0	20
A1	49.8	1.0	300
A2	49.8	1.0	400
A3	49.8	1.5	500
A4	49.8	1.5	600
A5	49.8	2.0	700
A6	49.8	2.0	800
A7	49.8	2.0	900

In the test, the section dimension of test samples was 200mm×300mm, it was shown in Fig.1. The sectional steel ratio was 3.93%, longitudinal reinforcement was used 4×Φ12 with double limb hoop stirrup Φ6@100.

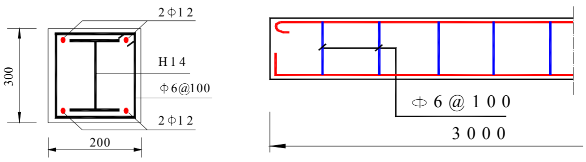


Fig.1. Sketch and dimensions of test samples

2.2 Layout of measuring points

The test samples were heated to different temperature. The load and measured point was shown in Fig.2.

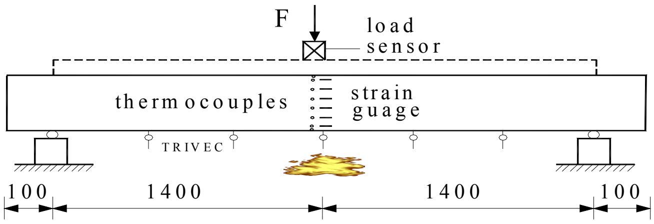
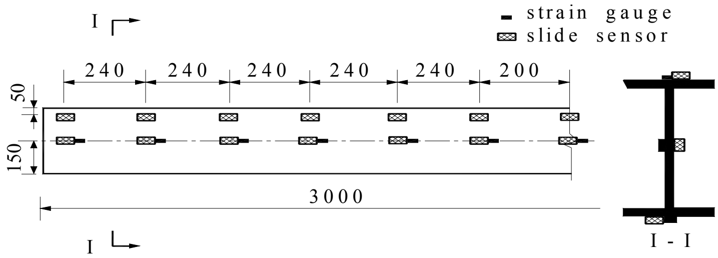
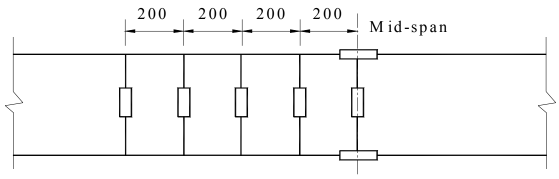


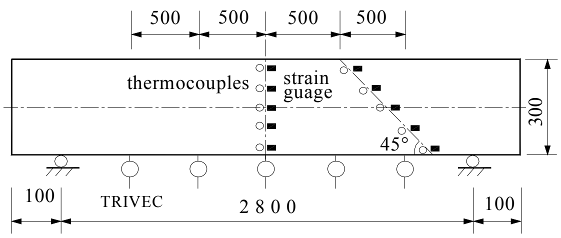
Fig.2. Sketch of load and measured points



(a). Sketch of measuring points on the flange of steel



(b). Sketch of measuring points of strain and slide on rebar



(c). Sketch of instruments layout on surface of specimen

Fig.2. Layout of measuring points

The heat release rate of fire was about 20.0MW, and the heating curve was shown in Fig.3. During heating up, the test samples all around by fire and with no external load, heating was stopped when the test samples were heat up to the expected temperature, and then the beam was loaded. The load was driven by a hydraulic jack, its maximum load was 800kN. Vertical deformations of beam were measured by 5 deformation sensors, and the horizontal displacements were measured by 5 tri-vector (TRIVEC) displacement sensors, the oblique displacement was also measure by 5 deformation sensors. Load was carried out after the beam heated up to the expected temperature. When the test samples were loaded, the average strains along the height of the section at the middle of span were measured by the strain sensors, the deflections were measured by the electronic dial indicators, the loading was measured by an installed load sensor. Strength of concrete was measured according to China National Standard Concrete Mechanics Performance Test Methods (GBJ81-1985). The loading rate was controlled by hydrate pump, it was about 50kN/mim until broken.

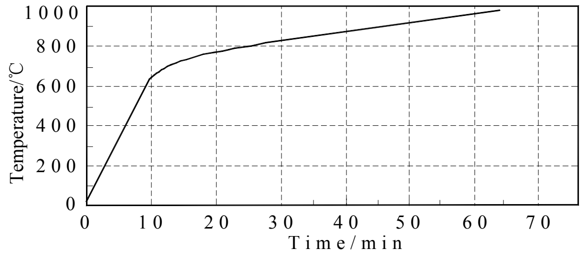
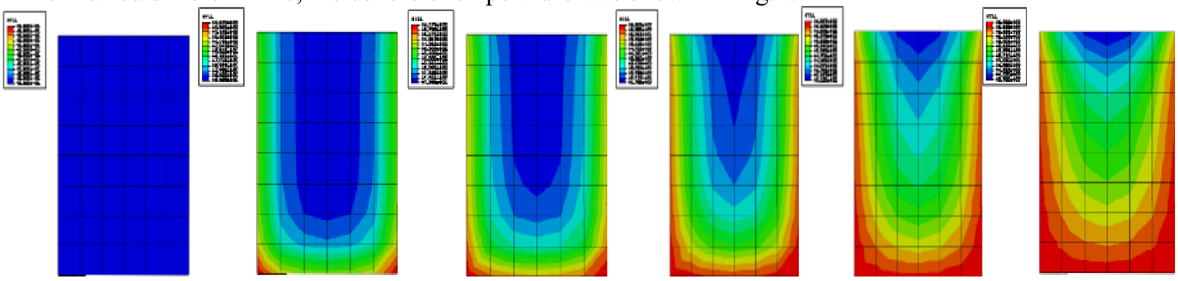


Fig.3. Temperatures on surface of beams

3. Results and discussion

3.1 The cooling effects on concrete

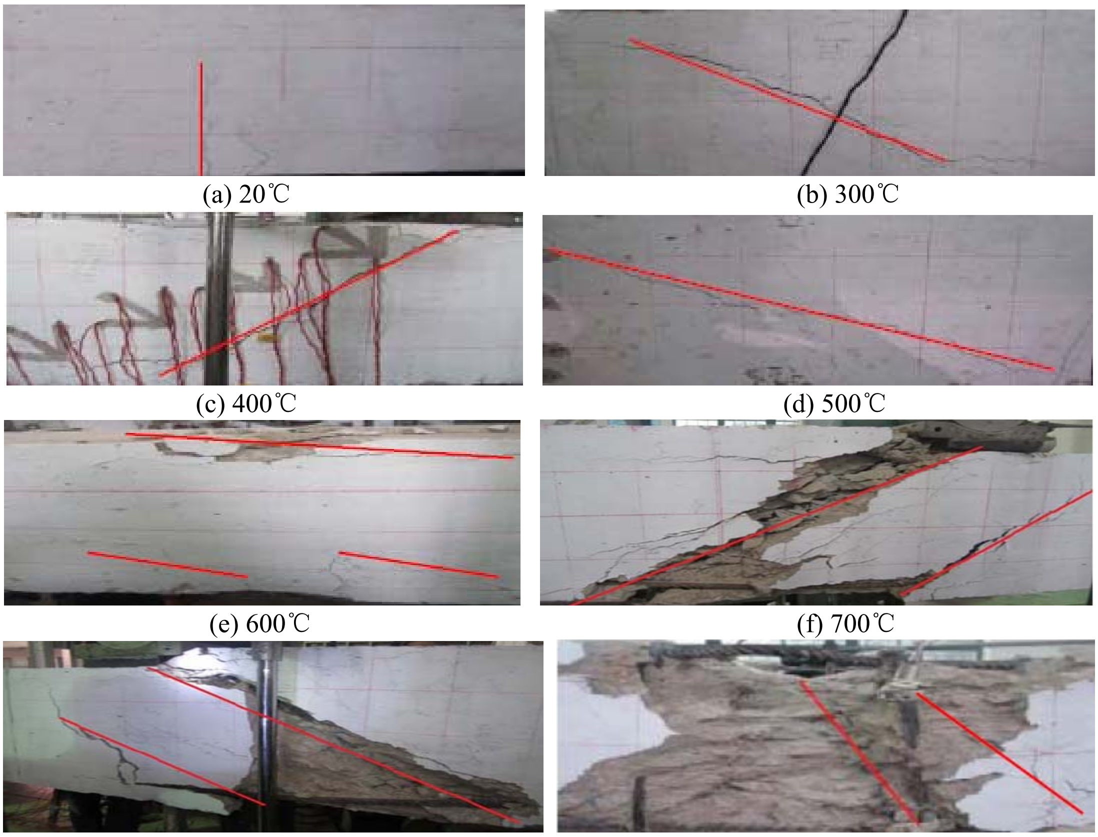
After heated different time, the concrete temperature was shown in Fig.4.



0min 10min 20min 30 min 40 min 50 min

Fig.4. Temperature distribution inside of concrete beam at mid-span at different time

When the steel reinforce concrete beam at different temperature, the destruction models were shown in Fig.5.



(a) 20℃ (b) 300℃

(c) 400℃ (d) 500℃

(e) 600℃ (f) 700℃

(g) 800℃ (h) 900℃

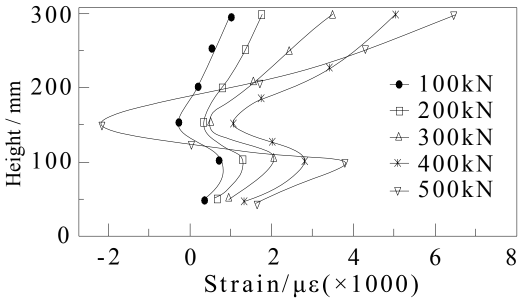
Fig.5. Destruction models of the test beam at different temperature

When concrete temperature was low, damage cracks of specimen was very less, and the distance between was also larger, the maximum width of crack was smaller, and crack was obvious throughout. At high temperature, along the interface between steel and concrete appeared obvious oblique crack, the interface between steel and concrete oblique cracks was basically run-through when the specimen damaged, and concrete was cracking and atomizing at high temperature.

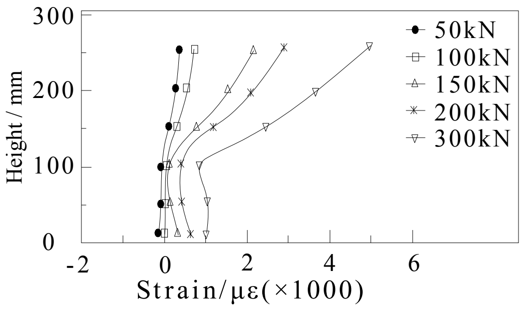
3.2 Strain distribution at mid-span

When the beam was at different temperature, the strain distributions along the height of cross section at mid-span were shown in Fig.6.

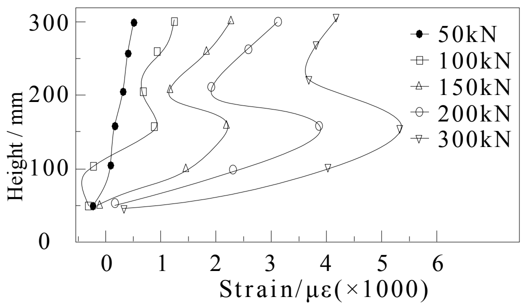
According to Fig.6, The final failures of the test samples A1-A4 were baroclinic destruction, which was influenced by the appearance and expansion of shear oblique cracks. The strain distribution in height direction was irregular from starting load to failure.



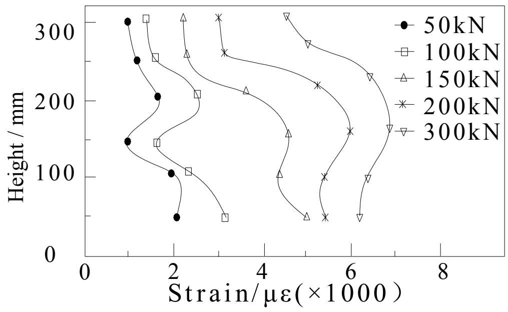
(a) A1



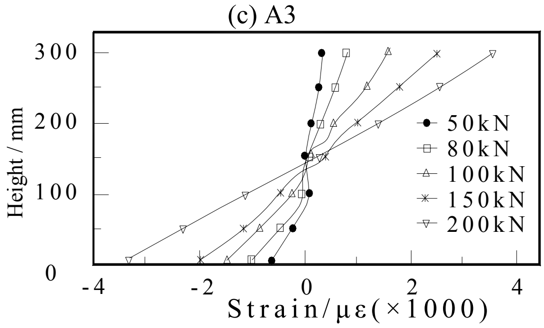
(b) A2



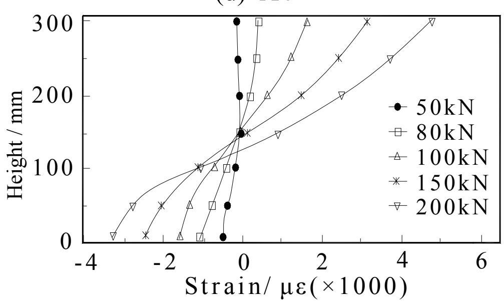
(c) A3



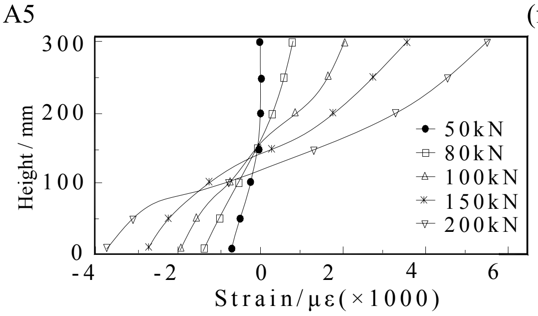
(d) A4



(e) A5



(f) A6



(g) A7

Fig.6. Strain distribution of concrete along height of cross-section at mid-span

The final failure of test sample A5 was bond damage. When load was low, the neutral axis basically remained no change, but the strain was not the linear distribution because of the influence of bond-slip between structural steel and concrete. The strain of concrete near neutral axis compressive zone grew slower, but the strain outside of compressive flange grew faster. When load was more than 200kN, concrete started to crack at the compressive flange, the deformations between cracks were relaxed, the growth rate of strain decreased.

The two test samples A6 and A7 were bending failure. When the load was lower than 200kN, the height of neutral axis changed very small, it basically remained the same, the strain at each point on the section was proportional to its distance to neutral axis, the strain distribution was in a straight line. However, when the load was more than 250kN, the neutral axis began to move up. Because of the occurrence of cracks in the compressed areas of concrete and the relative slip between concrete and the compressive edge of structural steel, the strain on the edge of concrete grew slowly, strain distribution deviated from a straight line. However, the strain distribution under the compression flange part of the cross section still stayed in a straight line. That indicated the bond-slip between steel and concrete would affect the late bending bearing capacity for test beams.

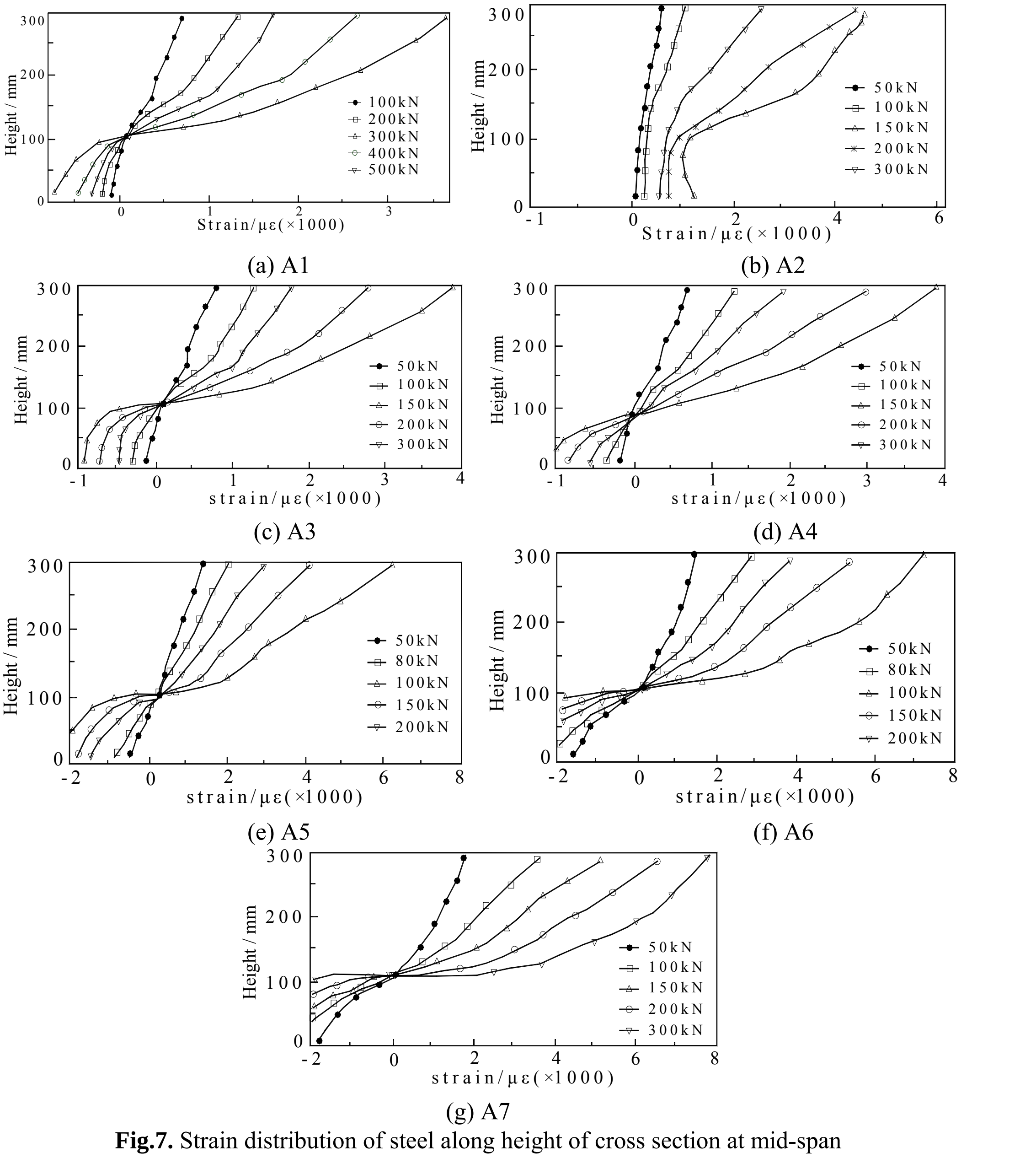


Fig.7. Strain distribution of steel along height of cross section at mid-span

Strain distribution along the cross section of height was not significantly influenced by concrete strength. Due to steel flange could effectively constraint core concrete, which made the beam have much more distribution of strain, and its mechanics and deformation properties was also significantly improved. At low temperature, the relationship between stress and strain, and the relation between them was basically in linear at the beginning of loading. After cracks produced, steel could inhibit the development of concrete cracks, they began bond-slip between steel and concrete, their synergy was weakened, the rate of crack growth accelerated, the compression steel yielded when loading reached ultimate load, crushing concrete was destroyed. At high temperature, load, horizontal cracks obviously appeared along the interface of steel and concrete, its bonding capacity could not guarantee their synergy, so the flexural bearing capacity of beam could not be fully developed.

When the beam was heated to different temperature, its deflection at mid-span was shown in Fig.8.

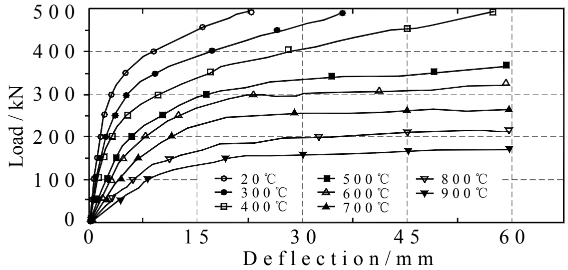


Fig.8. Deflection of beam at mid-span

As shown in Fig.8, at high temperature, the deflection was larger than that in ambient at the same load, and with the increase of temperature, deflection also increased. Especially, the deflection increased quickly when its temperature was above 500℃, which showed that the bearing capacity degraded rapidly.

3.3 Flexural capacity

At different temperature, the relations between flexural capacity (FC) of normal section and steel ratio were shown in Fig.9. The relations between FC of normal section and flange width ratio were shown in Fig.10.

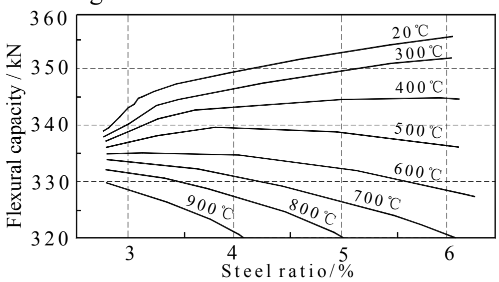


Fig.9. Relation between FC and steel ratio

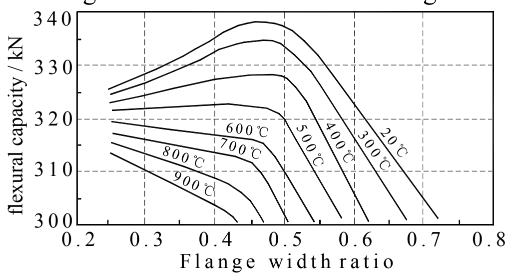


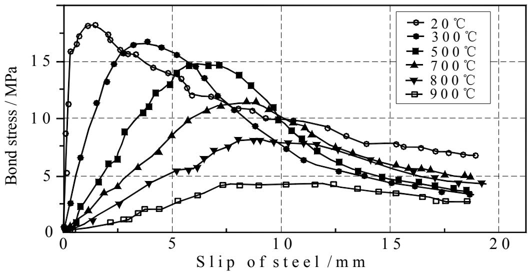
Fig.10. Relation between FC and steel ratio

As shown in Fig.9 and Fig.10, when temperature increased, flexural capacity reduced with the increase of steel ratio and flange width ratio (ratio between the width of steel flange and width of beam section), flexural capacity was reduced, too. When temperature was above 600℃, FC always decreased with the increase of steel ratio and flange width ratio, but when temperature was equal to or below 400℃, FC always increased with steel ratio. However, for the effect of flange width ratio on FC, it was a different from that of steel ratio. When temperature was equal to or below 400℃, FC increased at first, and then it reduced quickly.

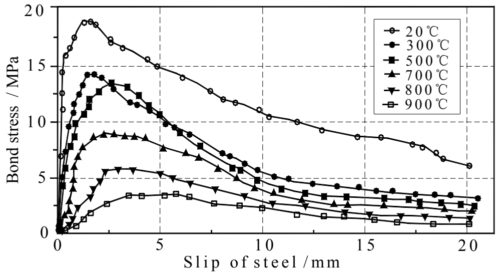
3.4 The slip between concrete and steel

When the increase rate of loading was at 5kN once until the test specimen was broken down, the relations between bond stress and slip of steel in fire and after fire were shown in Fig.11.

According to Fig.11, at high temperature, when temperatures of the test specimen was lower, steel and concrete squeezed with each other because their thermal expansions mismatched between them, the dehydration and shrinkage of concrete near 100℃ increased its extrusion pressure on steel, and it made the adhesive surface become more dense, but the strength of concrete did not decline basically. On the other hand, the dehydration of concrete weakened bond stress between all of the colloids inside it, it also made it fail to connect with steel, and the two effects counteracted each other, so the damage at the interface did not change. Only when the loading was small, the bond stress had a large effect on the slip of steel, the failure of bond stress made the premature slip between concrete and steel, the bond stress mainly came from friction and biting force when the loading was large, both the increase naturally helped to improve the bond strength, so the bond strength decreased at high temperature.



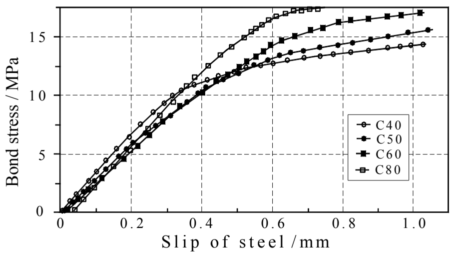
(a) In fire



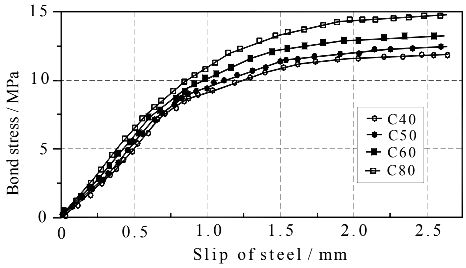
(b) After fire

Fig.11. The relations between bond stress and slip of steel

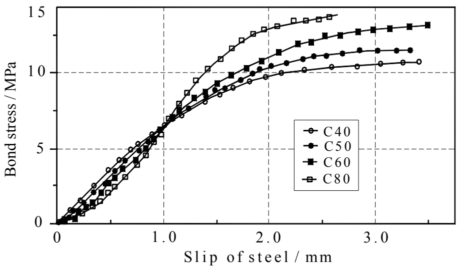
For different high strength concrete, the relations between bond stress and slip of steel were shown in Fig.12, and their limits of bond stress and steel slip at different temperature were shown in Fig.13 and Fig.14.



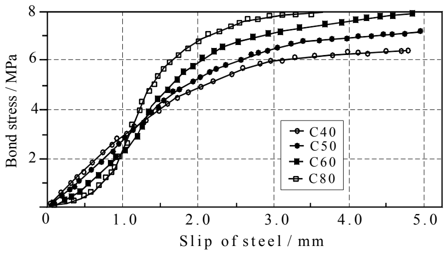
(a) 20℃



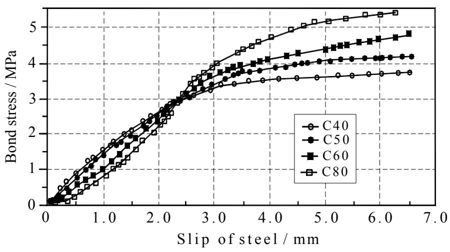
(b) 300℃



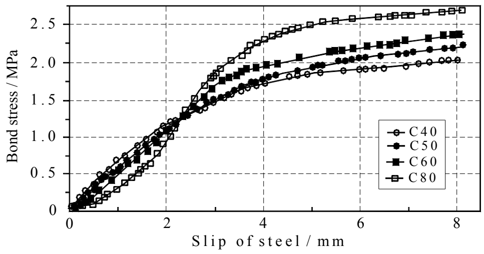
(c) 500℃



(d) 700℃



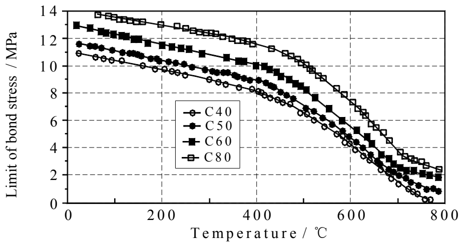
(e) 800℃



(f) 900℃

Fig.12. Relations between bond stress and slip of steel at different temperature

According to the above Fig.12, the strength of 4 types of test specimens became flatten when their temperature increased, their bond strength decreased with the increase of temperature, the slip also increased with the increase of temperature under the same bond stress.



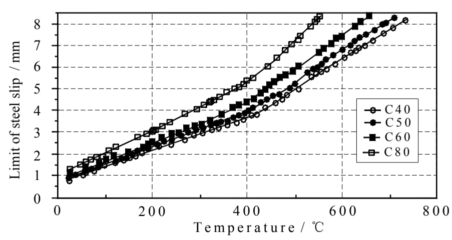
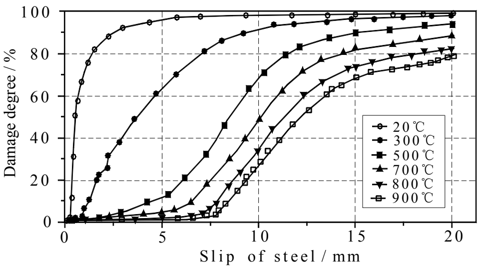


Fig.13. Limit of bond stress at different temperature **Fig.14.** Limit of steel slip at different temperature

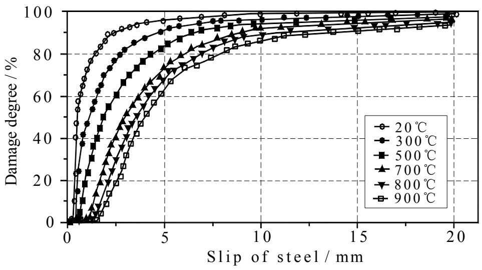
Seen from Fig.13 and Fig.14, when their temperature changed from 20℃ to 400℃, the effects of concrete on their limits of bond stress and steel slip were not obvious. After 400℃, limit of bond stress dropped faster for higher strength concrete, and at higher temperatures (T >700 ℃), the bond strengths of different specimen of concrete were close, the effects of concrete strength on limit of bond stress significantly reduced. But in Fig.13, the limit of steel slip was more sensitive to change in temperature for the increase of concrete strength, and the difference of limit of steel slip increased with the increase of temperature for different strength of concrete.

3.5 The relation between damage and slip of steel

The relations between damage degree and slip of steel at different temperature were shown in Fig.15.



(a) In fire



(b) After fire

Fig.15. The relations between damage degree and slip of steel

It was obvious that damage on the interface of steel and concrete varied with temperature. At ambient temperature, they rapidly increased at first, and then they became flatten at higher slip of steel. However, when their temperatures were above 300℃, the increase rate became flat, that was because that the bond stress reached its limit of bond stress when the slip of steel got to 1.0mm at ambient temperature, but it was 3.50mm above 300℃, and interfacial failure was relatively slower, the material properties of the interface had no serious deterioration. When the temperature continued to rise and reached 500℃, apparent shape of the curves changed obviously, the segments of curves were flat in 0~5.0mm, then they increased quickly, but they became flat again when the slip of steel was above 7.5mm. That was due to the increase of plasticity at high temperature on the interface between steel and concrete, the elastic modulus of concrete and steel gradually reduced, but it decreased slowly when the slip of steel was smaller, then it reduced rapidly, and then it decreased slowly again. And the damage increased slowly, then it increased rapidly, and then it increased slowly again. When temperature of concrete was above 700℃, curve section from 0 to 5.5 was gentle, then it increased, and then it became flat again. Therefore, the damage at the interface of steel and concrete was obvious when the temperature was below 300℃, which indicated that the bond stress began to serious deterioration. Comparing damage at the same slip and different temperature, the damage reduced as the temperature increased, which was due to damage grew slowly when the ductility on the interface of steel and concrete increased.

4. Conclusions

In a fire, high temperature had a strong influence on steel reinforce concrete. When the temperature of steel reinforce concrete beam was higher than 600℃, some corners were loose and degenerated. When load was low, the strain did not distribute in linear because of bond-slip. When load was more than 200kN, the section strain distribution was in linear. At high temperature, the strain distribution was in linear. However, when the load was more than 250kN, strain distribution deviated from a straight line. The strain distribution under the compression flange part of the cross section still stayed in linear. Along the cross section of height was not significantly influenced by concrete strength. After cracking, steel could inhibit the development of concrete cracks, the deformation of steel reinforce concrete beam accelerated until destroyed or broken. At high temperature, horizontal and oblique cracks obviously appeared along the interface of steel and concrete, the flexural bearing capacity of beam could not be fully developed. When their temperature changed from 20℃ to 400℃, the effects of concrete on their limits of bond stress and steel slip were not obvious. After 400℃, limit of bond stress dropped faster for higher strength concrete, and at higher temperatures (T >700℃), the bond strengths of different specimen of concrete was close, the effects of concrete strength on limit of bond stress significantly reduced. Damage on the interface of steel and concrete varied with temperature, damage at the interface of steel and concrete was obvious when the temperature was below 300℃, which indicated that the bond stress began to seriously deteriorate. Comparing damage at the same slip and different temperature, the damage reduced when temperature increased.

Acknowledgments

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