- Technical Paper -

MECHANICAL PROPERTIES OF RC BEAM AFTER EXPOSED TO FIRE IN LOADING STATE

Qingtao LI[*1], Guanglin YUAN[*2], Zhuguo LI[*3]

ABSTRACT

In this study, the mechanical performances of RC beam were investigated after they were heated up to different temperatures levels in a loading state, followed by cooling in the air or by water jet. The test results show that, the air cooling results in a greater reduction in the ultimate strength of RC beam, as compared to the water jet cooling. Also, the residual deformation and the limit deflection of RC beam increase with raising the heating temperature for any cooling methods, and are smaller when the heated RC beam is cooled in the air than in case of water jet cooling for a given heating temperature.

Keywords: RC beam, heating in loading state, cooling method, mechanical property

1. INTRODUCTION

Up till now, there are many studies about the mechanical properties of reinforcement concrete (RC) beam subjected to high temperature. Almost the investigations have been focused on the mechanical behaviors of RC beams during heating [1-4] or after heated under an unloading state [5-8], only have a few studies been reported on the mechanical properties of RC beams after exposed to fire in a loading sate [9, 10].

When buildings suffer a fire, the structural members are certainly in a loading state. In order to evaluate, repair and strengthen a fire-damaged RC structure, it is more significant to clarify the mechanical behaviors of RC beam after it was subjected to high temperature in a loading state. However, the influence of loading state during heating on the mechanical properties of RC beam after exposed to fire is not yet definite.

In this work, the mechanic performances of RC beams are experimentally investigated, which are heated up to different temperature levels: 250℃, 450℃, 650℃, and then cooled in the air or by a water jet. During the RC beams are heated on three faces, a static load is applied at a level of about 40% of their ultimate load-bearing capacity at room temperature. A discussion is performed on the effects of heating temperature and cooling method on the ultimate strength, residual deformation, and limit deflection of the heated RC beam.

2. TEST PROGRAMS

2.1 Test Specimens

Ordinary portland cement, river sand, and crushed limestone, of which particle size range is 5～25mm, were used in the concrete. Mix proportions of concrete used in all the RC beams were the same, being cement : water : sand : coarse aggregate = 1 : 0.47 : 1.51 : 2.81 by mass. Unit weight of the cement used in the concrete is 423 kg/m^3.

Seven RC beams were produced, their serial numbers are given in Table 1. All the RC beams were cured by spraying water, and the compressive strength

Table 1 Test conditions of RC beams

Series	Heating type	Heating Temperature* (℃)	Cooling method	Time of elevating Temperature (min)	Elapsed time of high temperature (min)
L0	Non	-	-	-	
L1	3-face heating	250	In the air	25	90
L2			Water jet		
L3		450	In the air	45	
L4			Water jet		
L5		650	In the air	65	
L6			Water jet		

[Notes] * Air temperature inside of the furnace

*1 College student, Graduate School of Science and Engineering, Yamaguchi University, M. E., JCI Member
*2 Professor, Dept. of Structure Engineering, China University of Mining & Technology, Dr. E.
*3 Associate Prof., Graduate School of Science and Engineering, Yamaguchi University, Dr. E., JCI Member

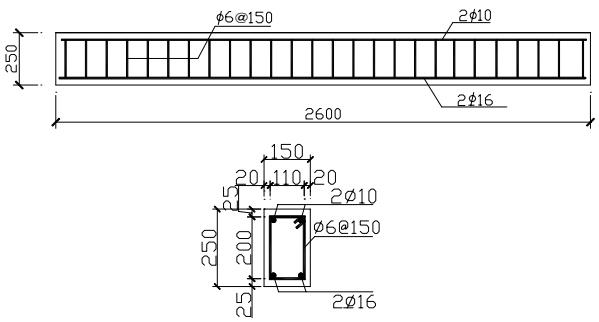
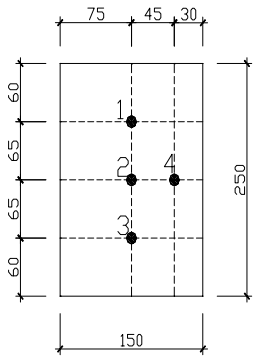


Fig. 1 Beam dimensions and reinforcement details



Cross section of beam

Fig. 2 Location of thermocouples in the beams

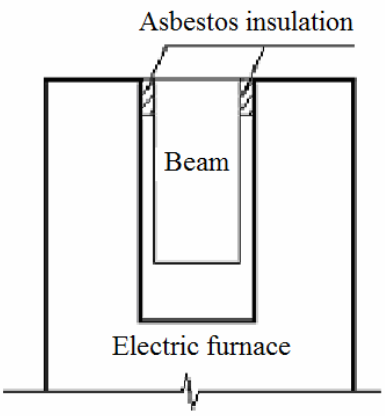


Fig. 3 Sketch of 3-face heating

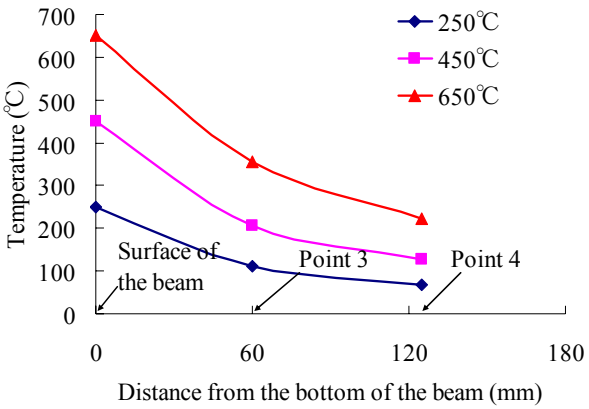


Fig. 4 Temperature distribution in concrete at the end of the heating course

of the concrete at 28 days is 35MPa. The RC beams, of

Fig. 5 Heating equipment and scene of third point loading

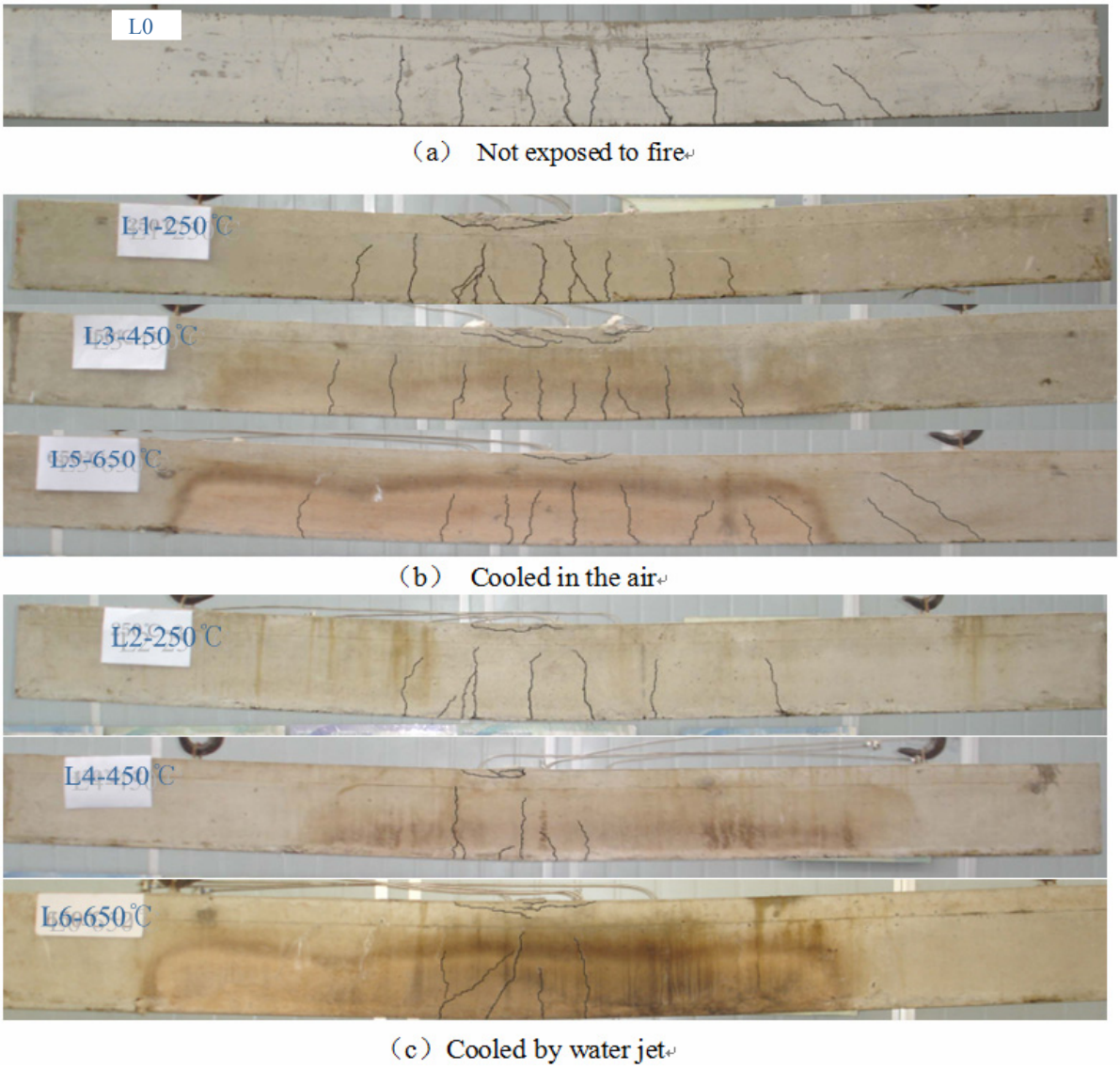
which height, width, and length were 250mm, 150mm, and 2600 mm, respectively, were reinforced by 2ϕ16 steel bars with yield strength of 377MPa as main reinforcement, 2ϕ10 steel bars with yield strength of 287MPa as secondary reinforcement, and ϕ6 stirrups at spacing of 150mm as shown in Fig. 1.

2.2 Heating and Cooling

Beam L0 is a normal beam that is not heated, but Beam L1-L6 were heated on three faces up to different temperatures as shown in Table 1, before testing their mechanical performances. The heating was performed in an electric furnace at a rate of 10℃/min. Internal temperatures of the beams were measured with thermocouples embedded in the beams. Locations of the thermocouples are given in Fig. 2. The sketch of 3-face heating is shown in Fig. 3. Measured internal temperatures distribution in the concrete at the end of the heating course are shown in Fig.4. After the beams suffered to the heating at each fixed temperature level for 1.5 hours, then were cooled down to the room temperature (20℃) in the air or by the water jet.

Fig. 5 shows the scene of loading during heating and the mechanical test. Hydraulic Jacks were used to apply a third point loading to the simple beams with a length of 2400mm. Displacement meters were used to measure the deflections at the middle point of the RC beam and the deformation at the two fulcrums. The load applied to the simple beams during heating was 25.44kN, being about 35% of the ultimate strength of the beams at the room temperature.

When heating, the electric furnace with a length of 1800mm was raised up to cover the RC beam. After the beams suffered from the heating at each fixed temperature level for 1.5 hours, the electric furnace was opened and moved down, then the beams were cooled down to the room temperature in the air or by water jet. Next, the mechanical tests of the RC beams were



（a） Not exposed to fire

（b） Cooled in the air

（c） Cooled by water jet

Fig. 6 Failure morphology of RC beams

Table 2 Test Results of the mechanical properties of the RC beams

Series	Heating Temperature * (℃)	Cooling type	Ultimate strength (kN)	$\frac{P_u(T)}{P_u}\times\%$	Maximum deflection (mm)	$\frac{f_u(T)}{f_u})\times\%$	Residual deformation (mm)
L0	—	—	77.2	100	16.86	100	—
L1	250	In the air	74.4	96.37	18.68	110.79	1.57
L2		Water jet	75.2	97.41	19.38	114.95	1.72
L3	450	In the air	72.0	93.26	19.80	117.43	4.36
L4		Water jet	75.0	97.15	25.27	149.88	4.91
L5	650	In the air	71.1	92.10	32.64	193.59	6.77
L6		Water jet	74.1	95.98	33.50	198.70	8.73

Notes: $P_u(T)$, f_u(T) are the ultimate strength and the maximum deflection of the beam subjected to high temperature, respectively; P_u, f_u is the ultimate strength and the maximum deflection of the beam not subjected to any high temperature, respectively.

* Air temperature inside of the furnace

performed after they were cured in the air of 20℃ for 15 days.

3. RESULTS AND DISCUSSION

3.1 Failure Pattern

The failure patterns of RC beams are shown in Fig. 6, which were subjected to different high temperatures while loaded, and then cooled by different methods.
All of the beams, whether heated or not, failed in bending. And when failing, the upper concrete of the heated beams was crushed more obviously than that of the beam L0 having no high temperature history as shown in Fig. 6. We also found that as the heating temperature increased, more breaking cracks occurred on the lower part of the beams in case of cooling in the air. However, the number of crack decreased with temperature increasing when the heated beams were cooled with the water jet.

When applying a load to the RC beams heated in the loading state and then cooled in the air, the previous cracks caused by the 3-face heating develop firstly to some content, followed by gradual occurrence of new cracks in the bottom of the beams. The new cracks tended to develop to join with the previous cracks. Hence, there were reticular cracks including several large connected ones on the surface of the ruptured beams.

The failure pattern of the RC beams cooled by the water jet was similar to the normal beam L0 that was not subjected to the heating. During the mechanical property test, new cracks firstly occurred at the bottom of the heated RC beams. After they developed to a certain degree, they connected with the previous cracks appeared during the heating, and several large cracks finally formed in the failed RC beams.

3.2 Ultimate Load-Bearing Capacities

The test results of the mechanical properties of the seven RC beams are shown in Table 2 and in Fig. 7.

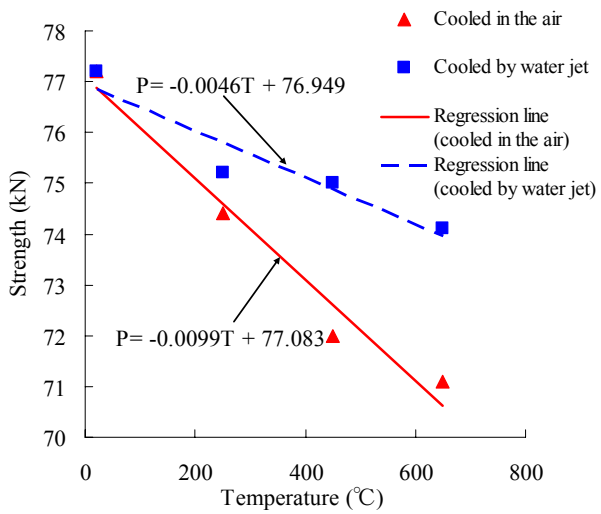


Fig. 7 Effects of heating temperature and cooling method on ultimate strength of heated RC beam

As shown in Fig. 7, ultimate strength of RC beams after exposed to fire in the loading state linearly deceases with an increase in heating temperature, and the air cooling results in a greater reduction in the ultimate strength of the RC beams, compared to the cooling with the water jet. When the heating temperatures were 250℃, 450℃, and 650℃, the ultimate strengths of the RC beams, heated and then cooled in the air, were 96.37%, 93.26%, and 92.10% of the normal RC beam L0, respectively. On the other hand, the ultimate strengths of the RC beams heated and then cooled by the water jet, were 97.41%, 97.15%, and 95.98% of the normal beam, respectively.

According to regression analyses using these test results, the ultimate load-bearing capacity of the RC beam after heated in the loading state can be expressed by Eq.(1).

Air cooling:

$$P = -0.0099T + 77.083$$

Water jet cooling:

$$P = -0.0046T + 76.949$$

$$(20℃ \le T \le 650℃) \qquad (1)$$

where P is the strength of the RC beam (kN), and T is heating temperature (℃).

3.3 Residual Deformation

Fig. 8 shows the residual deformation of the RC beams when rupturing in bending, which were heated and then cooled in the air or the water jet.

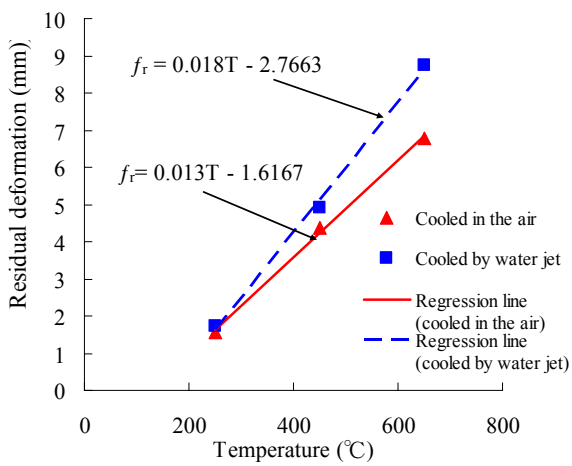


Fig. 8 Effects of heating temperature and cooling method on residual deformation

As can be seen from this figure, high temperature and cooling produced a great effect on the residual deformation of RC beams. The residual deformation of the RC beams increased with increasing heating temperature. The residual deformation of the RC beams cooled by the water jet was larger than that of the RC beams cooled in the air at 10- 30% for a certain high temperature. The residual deformation of the RC beams heated at 450℃ and 650℃ and then cooled in the air was 2.78 and 4.31 times of that of the

normal beam L1, respectively.

However, in case of the water jet cooling, the residual deformation of the RC beams heated at 450℃ and 650℃ was 2.85, 5.06 times of that of the beam L2, respectively. In Fig. 8 we can see that the residual deformation of RC beam increased remarkably with increasing the heating temperature. Also, to a certain heating temperature, the residual deformation of RC beam cooled in the air was smaller than that cooled by the water jet.

According to these test results, the residual deformation of the RC beams cooled in the air and by water jet can be expressed by Eq.(2).

Air cooling:

$$f_r = 0.013T - 1.6167$$

Water jet cooling:

$$f_r = 0.018T - 2.7663$$

$$(20℃ \leq T \leq 650℃) \qquad (2)$$

where f_r is the residual deformation of the RC beam (mm), and T is heating temperature (℃).

3.4 Limit Deflection

Limit deflection of the RC beams, exposed previously to the fire in loading state and then cooled in the air or by water jet, is shown in Fig. 9. Whether cooled in the air or by the water jet, the RC beams suffering from three-face heating had a lager limit deflection than the reference beam L0. The higher the heating temperature, the greater the limit deflection. Also, increasing rate of the limit deflection increases with the heating temperature as shown in Fig. 9.

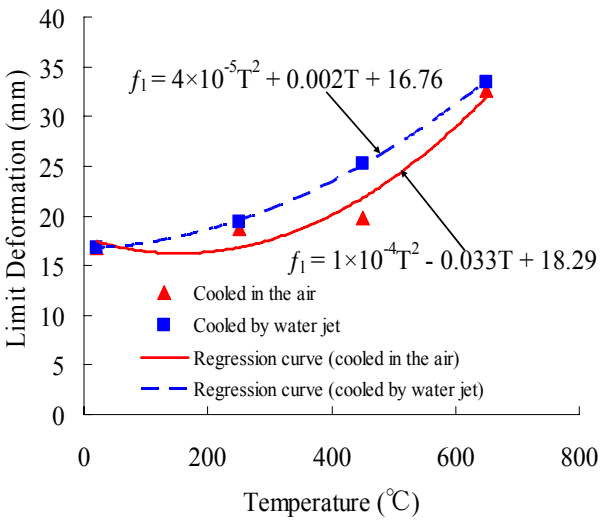


Fig. 9 Limit deflection of RC beams exposed previously to fire in loading state

When the heating temperatures were 250℃, 450℃, and 650℃, the limit deflection of RC beams cooled in the air were 1.11, 1.17, and 1.94 times of the normal beam L0, respectively. However, in case of the water jet cooling, the limit deflections of the RC beams were 1.18, 1.50, and 2.00 times of the normal beam L0, respectively. The water jet cooling yielded a greater increase in the limit deflection than the air -cooling.

By regression analyses, the limit deformation of the RC beams heated in loading state and then cooled in the air and by water jet can be expressed by Eq.(3).

Air cooling:

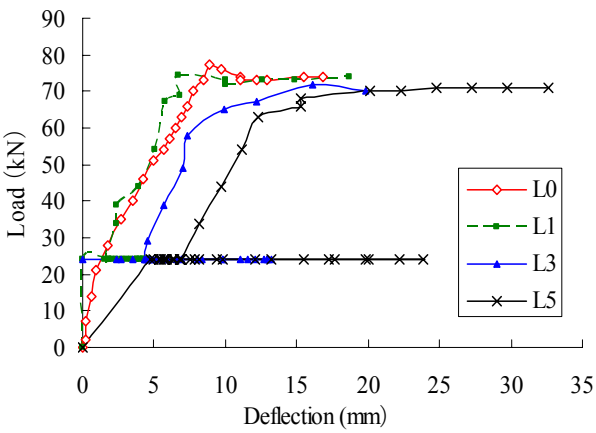
$$f_l = 1\times10^{-4}T^2 - 0.033T + 18.29$$

Water jet cooling:

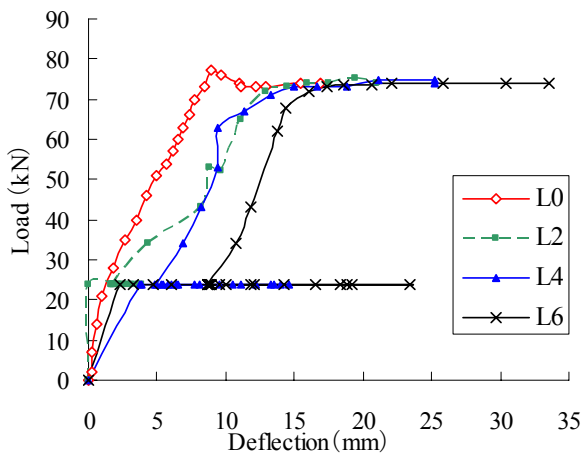
$$f_l = 4\times10^{-5}T^2 - 0.002T + 16.76$$

$$(20℃ \leq T \leq 650℃) \qquad (3)$$

where f_l is the limit deformation of the RC beam (mm), and T is heating temperature (℃).



(a) Cooled in the air



(b) Cooled by water jet

Fig. 10 Load-deflection relation of the RC beam beams exposed previously to fire in loading state

Fig. 10 shows the experimental load-deflection relation of the RC beams, which were heated at different high temperatures, followed by cooling in different types. The level lines in Fig.10 (a) and (b) characterize the load-deflection relationship during the beam had been heated, bearing a preload of 25.44 kN.

On the other hand, the load-deflection relational curves above the level part, of which the loads are above 25.44kN, refer to the mechanical behavior of the beams after they were cooled. The heating at a relatively lower temperature level of 250℃ did not produce a remarkable effect on the load-deflection relation of the RC beams L1, L2, for either the air cooling or the water jet cooling. However, when the heating temperature was increased above 450℃, the load-deflection relation of the RC beams was greatly affected by the heating in the loading state. As shown in Fig.10, the load-bearing capacity of the RC beam decreased with increasing temperature, however, the deflection of the RC beam increased with increasing temperature. This result is different from the past result reported in reference [8], which is that the limit deflection of RC beam after heated in unloading state decreases sharply with increasing the heating temperature. This is probably duo to the deformation of the RC beams during being heated in loading state.

Moreover, as shown in Fig.10, the limit deflection of the RC beams cooled in the air was smaller than that of the RC beams cooled by the water jet. From this result, we can conclude that if an RC beam is subjected to high temperature, and followed by a sudden cooling, its deformation recovery ability will reduce significantly.

4. CONCLUSIONS

This paper presents the mechanical performances of RC beam, which are heated at different temperature levels under a load-bearing condition, and then cooled in the air or by the water jet. Obtained main conclusions are as follows.

(1) The ultimate strength of RC beam, which is exposed previously to a fire and then cooled, deceases linearly with an increase in heating temperature, and the air cooling results in a greater reduction in the ultimate strength of RC beam.

(2) For a given magnitude of load during hearting and cooling method, the residual deformation of RC beam increases remarkably with increasing heating temperature can be found. Also, to a certain heating temperature, the residual deformation of RC beam cooled in the air was smaller than that cooled by water jet.

(3) The limit deflection of the RC beam having no high temperature history is smaller than that of the RC beam exposed previously to fire. For a certain heating temperature, the limit deflection of the RC beam cooled in the air is smaller than that cooled by water jet. Water jet cooling after heated impairs the deformation recovery ability of the RC beam.

(4) The limit deflection of RC beam, heated previously and then cooled by water jet, is greater than that of the reference beam not subjected to high temperature, and greatly increases with raising the heating temperature.

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