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Nondestructive Post-fire Damage Assessment of Structural Steel Members Using Leeb Harness Method

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Abstract. Assessment of steel damage is one of the key methods in retrofitting and reconstruction of the steel structures after fire. The traditional assessment method is to cut the samples from the steel members and check the levels of damage. This method will damage the structural members and the process is time consuming. In this paper, a quick, simple and efficient nondestructive detection method to measure the strength of steel after fire is developed using so called Leeb hardness method by means of establishment the relationship between the residual strength of steel members after fire and the Leeb hardness, the post-fire steel strength can be fast determined without damage to the structural members. In this paper, in total 120 Chinese H-shaped steel sections were selected for testing the Leeb hardness after fire. The influence of the parameters such as the duration of the fire exposure, cooling mode, steel grade, stress state and location of the Leeb hardness test on the test results was investigated. The relationship between the steel Leeb hardness and the parameters were developed. In addition, regression functions between the residual strength of steel members after fire and the Leeb hardness was established based on these test results which can accurately predict the residual strength of the steel members after fire, providing the engineers a new fast assessment method for the residual strength of the steel after fire.

Keywords: Post fire damage assessment, Leeb hardness, Steel strength, Cooling mode, Fire exposure

1. Introduction

Some steel structures can be repaired and reconstructed after the fire has been extinguished. Post-fire assessment facilitates the decision making on the possibility of further operation of the facility after fire accident. In order to determine the residual capacity of structural steel members, it is necessary to test and assess the

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structural steel members before repairing [1–3]. As part of this process, the strength of the steel is an important parameter. Being able to know the residual strength of the steel, it can accurately determine the retrofitting methods for the whole structure which plays a significance role for the restoration of the designed bearing capacity and the serviceability of the steel structure after the fire disaster.

The method for testing the residual strength of steel after fire includes on-site coupon tensile testing, chemical composition analysis method and surface hardness method [4–10] (including Brinell hardness method, Rockwell hardness method, Victoria hardness method, Leeb hardness method), etc. The most accurate one is on-site coupon tensile testing. This method is to cut the coupon from the structural members of the building and perform tensile testing. However, this method causes different degrees of damage to the structure, which are not suitable to post-fire restoration work. The chemical composition analysis method also needs on-site sampling and the process is tedious.

At present, there is little research on the non-destructive method for testing of steel strength after the fire. Some work of [11, 12] provide non-destructive method for testing the concrete strength after fire. Little work has been done for steel members.

Leeb Hardness testing is a non-destructive method for testing the strength of the steel members. This method is easy, flexible and can be tested directly on the structural members without cutting the coupons. It is invented by Dietamar Leeb in 1975. The benefit of using Leeb method is that as it shown in Fig. 5, the drop hammer is small and it is easy to maneuver, especially in narrow place where access may become a problem. The whole test process is fast. The disadvantage of this method is that the surface needs to be processed first.

The method of the Leeb hardness testing is to drop certain weight of object through a tube to the surface of the specimens and test the impact velocity of object and the velocity of the object at 1 mm distance of the surface when it bounces back. The formula is show as follows:

$$HL = 1000 \frac{V_R}{V_A} \quad (1)$$

where

HL —is the Leeb hardness,

V_R —is the bounce back velocity of the object,

V_A —is the impact velocity of the object.

In this paper, the conventional Chinese H-shaped steel sections were used for fire testing. After fire test, the Leeb hardness method is used to measure the hardness of H-shaped sections after fire. The influence of different parameters such as duration of fire exposure, steel grade, stress state and locations of different parts on the Leeb hardness was studied. In addition, regression functions between the residual strength of steel members after fire and the Leeb hardness was established based on these test results which provides the engineers a new fast assessment method for the residual strength of the steel after fire.

2. Experimental Program

2.1. Fire Test Set Up

The fire test is conducted in an electric heating furnace, as shown in Fig. 1, and schematic diagram of test rigs is shown in Fig. 2. The test rigs shown in Fig. 2 can apply axial load simultaneously during the heating of the specimen in the furnace. The dimension of the furnace is $\phi 500 \times 600$ mm, with interior dimension of $\phi 280 \times 400$ mm.

2.2. Test specimens

In order to develop this new post-fire assessment method, Chinese steel section H100 \times 100 \times 6 \times 8 was used for fire tests and subsequent Leeb hardness tests. The steel grades were Q235, Q345 and Q390 respectively with the member length of 500 mm. Among them, Q390 steel sections was cold welded by three steel plates and the remaining sections were hot-rolled sections. 108 specimens were tested after fire exposure with the other 12 specimens was tested at ambient temperature for comparison, altogether 120 specimens. The numbers of the specimens are given in Table 1.

2.3. Parameters Investigated During the Tests

In order to completely understand the response of the structure after fire, the factors such as the duration of fire exposure, cooling mode, steel grade, stress state and different parts of H-beam were considered in the fire tests. The tests focused on the effect of the selected parameters on the mechanical properties of steel components after fires:

1. The fire temperatures during the tests are 100°C, 200°C, 300°C, 400°C, 500°C and 600°C respectively. This is because that, when the temperature reaches 600°C, according the characteristic of the steel material, the yield strength of the steel has degradation to 60% of its original strength. The steel members will lose almost all the strength and rigidity the structural steel member will experience serious buckling, deformation and even complete damage. It is not suitable to take any load. However, if the load taken by the fire affected member is small, the steel structure can still survive. However, the cost won't allow us to consider all the possibility such as different load ratio, so in the tests, all the specimens were heated up to 600°C and stopped.
2. Two types of cooling mode were used after fire testing: water cooling and natural cooling.
3. Stress state and non-stress stage are both investigated.

2.4. Test Procedure and Parameters

2.4.1. Fire Test

2.4.1.1. The Fire Temperature and Furnace Temperatures Range The purpose of this experiment is to investigate the mechanical properties of steel components



Figure 1. Electric heating furnace.

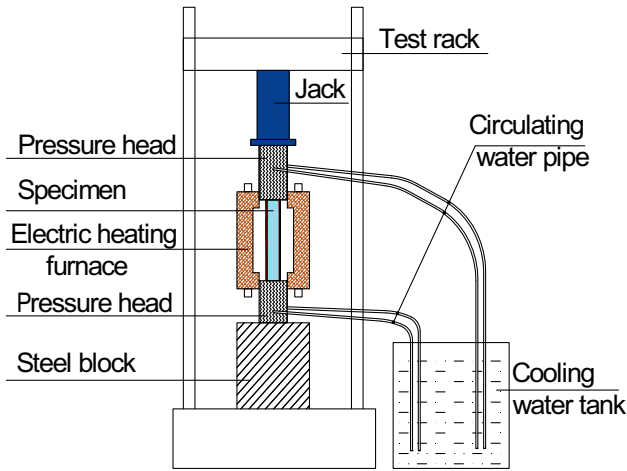


Figure 2. Schematic diagram of test rigs.

after the fire [13–17]. As it has been explained, maximum temperature of 600°C (as it shown in Fig. 3) was used in the fire tests. Figure 3 shows the actual furnace temperature during the test.

2.4.1.2. Heating Rate and Duration of Fire Exposure The heating rate is shown Fig. 3. When the furnace reached each control temperature 100°C, 200°C, 300°C, 400°C, 500°C and 600°C respectively, the temperature was kept constant for a certain time before raising further. According to the relevant research [18–25] and the

Table 1
Specimen Details

Steel grade	Cooling mode	Fire exposure time (min)	Temperature (°C)					
			100	200	300	400	500	600
Q235	Water cooling	5	AW ₁ ⁵	AW ₂ ⁵	AW ₃ ⁵	AW ₄ ⁵	AW ₅ ⁵	AW ₆ ⁵
		10	AW ₁ ¹⁰	AW ₂ ¹⁰	AW ₃ ¹⁰	AW ₄ ¹⁰	AW ₅ ¹⁰	AW ₆ ¹⁰
		15	AW ₁ ¹⁵	AW ₂ ¹⁵	AW ₃ ¹⁵	AW ₄ ¹⁵	AW ₅ ¹⁵	AW ₆ ¹⁵
	Natural cooling	5	AN ₁ ⁵	AN ₂ ⁵	AN ₃ ⁵	AN ₄ ⁵	AN ₅ ⁵	AN ₆ ⁵
		10	AN ₁ ¹⁰	AN ₂ ¹⁰	AN ₃ ¹⁰	AN ₄ ¹⁰	AN ₅ ¹⁰	AN ₆ ¹⁰
		15	AN ₁ ¹⁵	AN ₂ ¹⁵	AN ₃ ¹⁵	AN ₄ ¹⁵	AN ₅ ¹⁵	AN ₆ ¹⁵
Q345	Water cooling	5	BW ₁ ⁵	BW ₂ ⁵	BW ₃ ⁵	BW ₄ ⁵	BW ₅ ⁵	BW ₆ ⁵
		10	BW ₁ ¹⁰	BW ₂ ¹⁰	BW ₃ ¹⁰	BW ₄ ¹⁰	BW ₅ ¹⁰	BW ₆ ¹⁰
		15	BW ₁ ¹⁵	BW ₂ ¹⁵	BW ₃ ¹⁵	BW ₄ ¹⁵	BW ₅ ¹⁵	BW ₆ ¹⁵
	Natural cooling	5	BN ₁ ⁵	BN ₂ ⁵	BN ₃ ⁵	BN ₄ ⁵	BN ₅ ⁵	BN ₆ ⁵
		10	BN ₁ ¹⁰	BN ₂ ¹⁰	BN ₃ ¹⁰	BN ₄ ¹⁰	BN ₅ ¹⁰	BN ₆ ¹⁰
		15	BN ₁ ¹⁵	BN ₂ ¹⁵	BN ₃ ¹⁵	BN ₄ ¹⁵	BN ₅ ¹⁵	BN ₆ ¹⁵
Q390	Water cooling	5	CW ₁ ⁵	CW ₂ ⁵	CW ₃ ⁵	CW ₄ ⁵	CW ₅ ⁵	CW ₆ ⁵
		10	CW ₁ ¹⁰	CW ₂ ¹⁰	CW ₃ ¹⁰	CW ₄ ¹⁰	CW ₅ ¹⁰	CW ₆ ¹⁰
		15	CW ₁ ¹⁵	CW ₂ ¹⁵	CW ₃ ¹⁵	CW ₄ ¹⁵	CW ₅ ¹⁵	CW ₆ ¹⁵
	Natural cooling	5	CN ₁ ⁵	CN ₂ ⁵	CN ₃ ⁵	CN ₄ ⁵	CN ₅ ⁵	CN ₆ ⁵
		10	CN ₁ ¹⁰	CN ₂ ¹⁰	CN ₃ ¹⁰	CN ₄ ¹⁰	CN ₅ ¹⁰	CN ₆ ¹⁰
		15	CN ₁ ¹⁵	CN ₂ ¹⁵	CN ₃ ¹⁵	CN ₄ ¹⁵	CN ₅ ¹⁵	CN ₆ ¹⁵

A, B, C respectively represents Q235, Q345 and Q390 steel grades; W and N respectively represent water cooling mode and natural cooling mode, the subscripts 1–6 respectively represents the temperature of 100°C to 600°C, and the superscripts 5, 10 and 15 respectively represent the fire exposure time at the specific test temperature

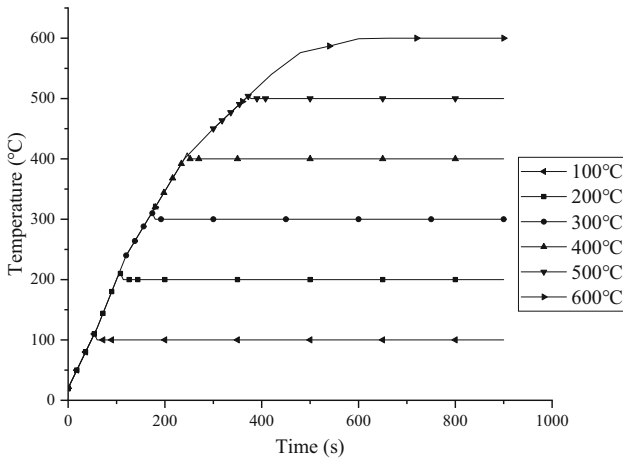


Figure 3. Time temperature curve in furnace for each test.

observation of structure fire tests, the strength and rigidity of bare steel members will start to lose after exposure to fire temperature for 20 min. The purpose of this experiment is to provide experimental and theoretical basis for the reinforcement

and repair of steel structure after the fire. Therefore, the durations of constant fire exposure of the test are 5 min, 10 min and 15 min respectively.

2.4.1.3. Temperature Control The thermal couples are evenly placed inside the furnace along the height to monitor the temperature of the furnace. The precision for each control temperature is $\pm 1^\circ\text{C}$. It is also presume that after fire exposure, the temperature of steel structural is the same as the temperature inside the furnace.

2.4.2. Cooling Process and Parameters Two cooling modes are used, natural cooling and water cooling.

1. The water cooling is to use water with ambient temperature to pour directly on the specimens after they were taken out from the furnace. During the cooling stage, an infrared thermometer is used to test the surface temperature of the specimen, the cooling stopped when the surface temperature dropped to around 20°C .
2. In natural cooling, after the specimens were taken out from the furnace, it would be placed on the ground for 24 h. Then the surface temperature of the specimen was tested using an infrared thermometer to make sure the surface temperature dropped to around 20°C before Leeb test.

2.4.3. Different Stress State The measurement of Leeb hardness under different stress states: stress state and non-stress state. As it shown in Fig. 4a, the stress is almost 0. As it shown in Fig. 4b, the load is applied through a hydraulic jack, the load is applied to 70% of the design load of the steel structural member. So, the stress level for the different grade of specimens are 146 N/mm^2 (Q235), 207 N/mm^2 (Q345), 232 N/mm^2 (Q390) respectively.

2.5. Post-fire Leeb Hardness Tests

Both the stress and non-stress states are considered in the hardness test scheme [23–26], different thickness of steel flange and web and different location of the steel beam are considered for testing. In term of stress state, the load applied to the specimen in the high-temperature test furnace can better reflect the actual state of the steel structural members after the fire and at the scene of the fire.

The tests are conducted under the Chinese standard [27, 28]. A digital Leeb hardness tester TIME5351 was used (Fig. 5). As it shown in Fig. 6, the specimens were first grinded into three separate smooth zones ($30 \times 60\text{ mm}$) for the test. The surface roughness was first assessed as it shown in Fig. 7. 9 tests were done for each smooth zone, the average the 9 readings after remove the maximum and minimum value was used.

As it shown in Fig. 8, the measurement of Leeb hardness is performed in both the stress and non-stress states. In the non-stress state, in order to prevent partial

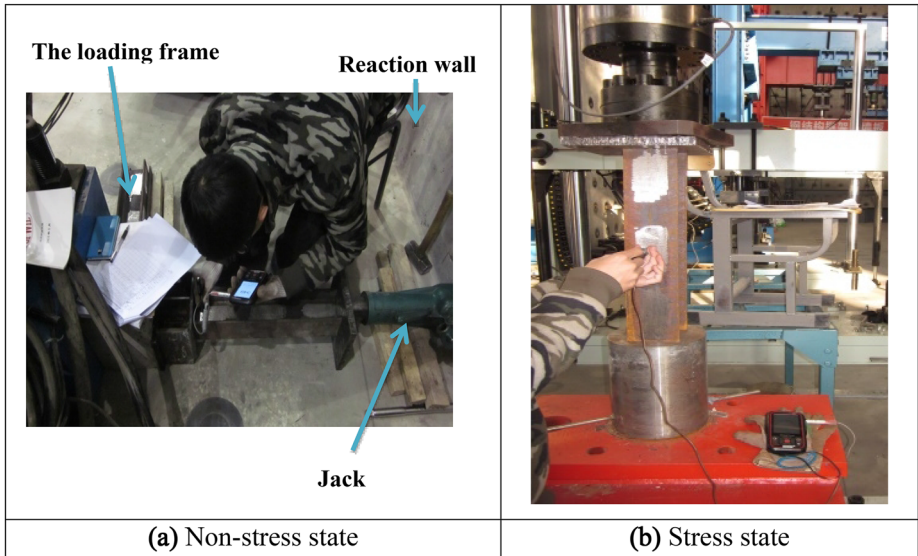


Figure 4. The measurement of Leeb hardness under different stress state.



Figure 5. TIME5351 Leeb hardness tester.

energy loss caused by displacement or vibration of the specimen during the impact, this test uses a reaction frame, a reaction wall and a mechanical jack to restrain the specimens, as it shown in Fig. 8a, to ensure no shaking and no movement would occur during the Leeb hardness test.



Figure 6. Grinding zone.



Figure 7. Roughness assessment.

The stress state is to exert pressure to the specimens after the cooling from fire exposure, as it shown in Fig. 8b. The load is applied as 70% of the residual bearing capacity of the test specimen through the hydraulic loading system, and the Leeb hardness of the specimens is tested under the pressure.



Figure 8. Buckling deformation at temperatures of 400°C to 600°C.

3. Test Results Analysis

For most of the specimens, they were loaded up to 70% of their design load. The test results show that when fire tests were carried out at the temperature of 100°C to 300°C, the axial capacity of the specimens was basically unaffected, and there was no buckling observed. The axial capacity of the specimen decreased with various degrees of buckling deformation occurred when the temperature increased to the range of 400°C to 600°C, which results in a small fluctuation in the loading actuator is observed [26]. The different degrees of buckling deformation at temperatures of 400°C to 600°C are shown in Fig. 6. Some specimens were loaded up to 50% of their design load, it is found that, buckling was not observed [29].

3.1. Effect of Cooling Mode and Fire Exposure Duration of Fire Exposure on Leeb Hardness

After the fire tests, Leeb hardness test of Q235 specimens under water cooling and natural cooling methods are both performed. The effect of different cooling modes on Leeb hardness are considered with the other factors such as fire temperature, stress state and detection portion are constant. Figure 9 shows the relationship between the fire exposure time and Leeb hardness at the temperature of 100°C, 200°C, 300°C, 400°C, 500°C and 600°C. Leeb hardness of both cooling modes shows a slight growth trend with the increase of fire exposure time. The corresponding Leeb hardness scale increased by about 3 HLD when the fire exposure duration of fire exposure changed from 5 min to 15 min, the effect of fire exposure duration of fire exposure is very limited. When fire exposure duration is the same, the value Leeb hardness under water cooling method is about 35 HLD higher than that of natural cooling. When the specimen is suddenly cooled by water at high temperature, it is equivalent to a quenching process for the steel,

which results in its surface hardness increased. Therefore, the cooling method has a great influence on the Leeb hardness. Apart from this, the cooling process is determined by the way of putting off the fire, therefore, it is an important factor need to be considered.

The water-cooling method is to pour Watering at high temperature, is equivalent to a quenching process for steel. When the temperature reaches 400°C or higher, the cementite of the internal structure becomes pearlite, the yield strength increase, and the ductility deteriorates increase. The natural cooling method (air cooling) is equivalent to a normalizing process for steel. The internal structure of the grain becomes finer, the mechanical properties are improved, and the hardness is slightly lowered [30].

3.2. Effect of Steel Strength Grade on Leeb Hardness

As it shown in Figs. 10 and 11, the relationship between the hardness and the steel strength grades at different fire exposure under water cooling is analyzed. In the same conditions of cooling mode and fire exposure time, no matter what kind of steel strength grade of the specimen its hardness is increased with the increase of the fire temperature. Average Leeb hardness increases by 12 HLD when the fire temperature raises from 100°C to 600°C, so the fire temperature has a certain influence on the Leeb hardness. In the same conditions of cooling mode and fire exposure time, Leeb hardness increases greatly with the increase of steel strength grade. In the case of watering cooling, the average Leeb hardness of Q345 specimen is about 28 HLD higher than that of Q235 specimen, the hardness of Q390 specimen is about 43 HLD higher than that of Q345 specimen. The results show that the Leeb hardness increases linearly with the increase of steel strength. The steel strength grade is the main factor affecting the Leeb hardness.

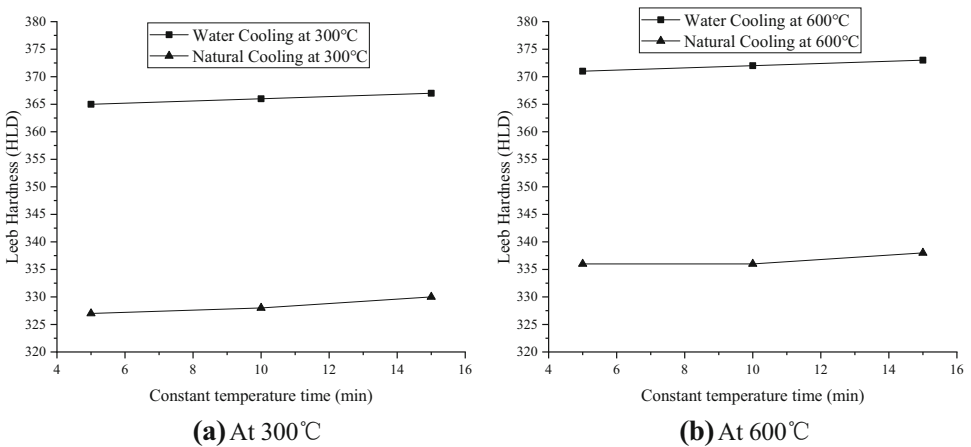
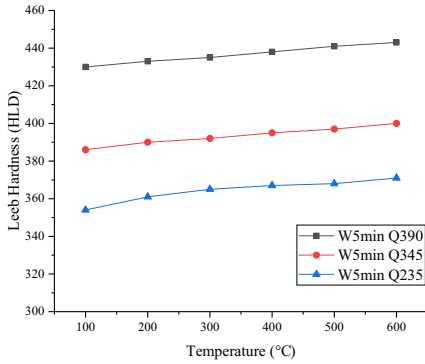
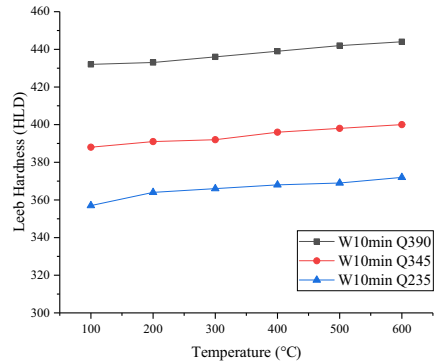


Figure 9. Influence of cooling mode on Leeb hardness.

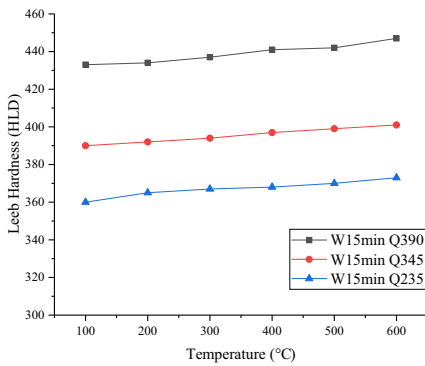
Nondestructive Post-fire Damage Assessment



(a) Fire exposure of 5mins



(b) Fire exposure of 10mins



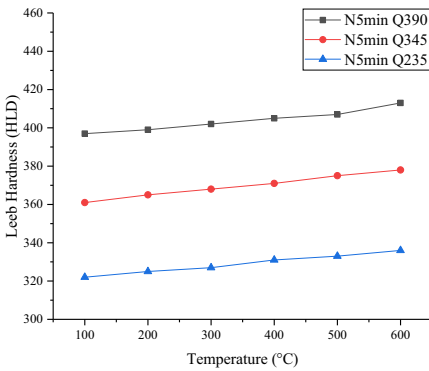
(c) Fire exposure of 15mins

Figure 10. Relation between Leeb hardness steel grades under water cooling.

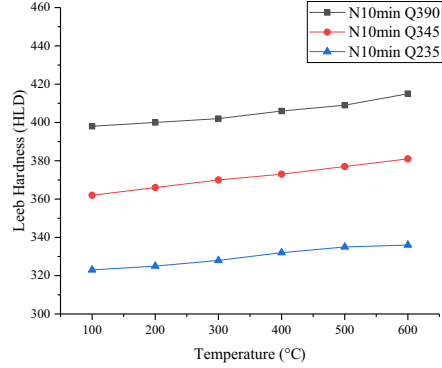
3.3. Effect of Stress State on Leeb Hardness

The Leeb hardness of Q235 specimens of stressed and non-stress state with natural cooling increases slightly with the increase of fire temperature when the fire exposure duration is the same. At the same fire temperature, the Leeb hardness of the stress state is higher than that of the non-stress state, and the general variation range is within 5 HLD. Only when the fire temperature is between 200°C and 300°C, the difference between the two reaches about 8 HLD. It can be seen that the influence of the stress state on the hardness value is not evident.

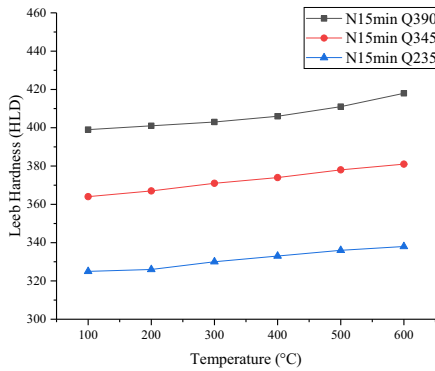
When the fire exposure duration is the same with water cooling, Leeb hardness of the stress state is close to that of the non-stress state, and the general variation range is about 3 HLD. When the fire temperature is 600°C, the difference in hardness between the two reaches 10 HLD, and the abnormal value appears.



(a) Fire exposure of 5mins



(b) Fire exposure of 10mins



(c) Fire exposure of 15mins

Figure 11. Relation between the Leeb hardness and steel grades under natural cooling.

In summary, Leeb hardness of the stress state and that of the non-stress state is relatively close, and Leeb hardness of the stress state is slightly higher, which has less influence on the Leeb hardness.

3.4. Different Leeb Hardness on Steel Flange and Web

As it is shown in Fig. 12, there is difference of the Leeb hardness at flange and web. So, it is worth further investigating. Leeb hardness of flange and web increases slightly with the increase of fire exposure duration under natural cooling condition. In the case of the same fire temperature and fire exposure duration, Leeb hardness of the flange is about 34 HLD higher than that of the web.

In the case of water cooling, Leeb hardness of flange and web also showed a slight growth trend with the increase of fire exposure duration. In the case of the

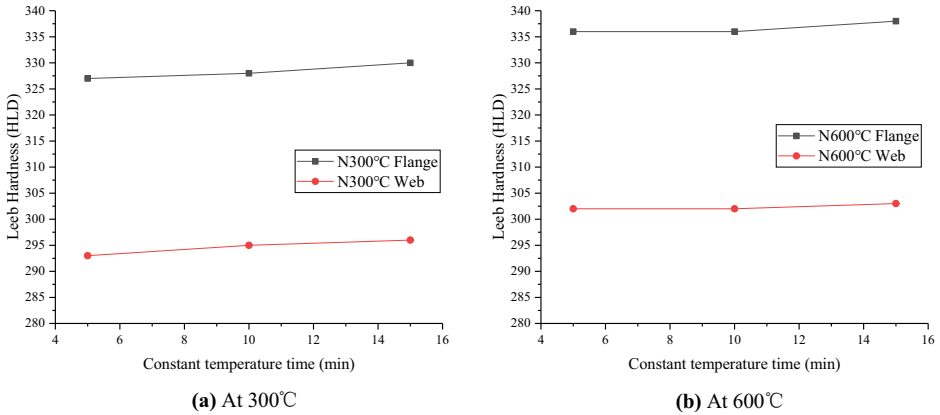


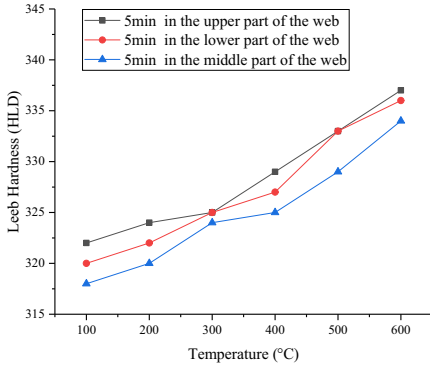
Figure 12. Different Leeb hardness on steel flange and web under natural cooling.

same fire temperature and fire exposure duration, Leeb hardness of the flange is about 36 HLD higher than that of the web.

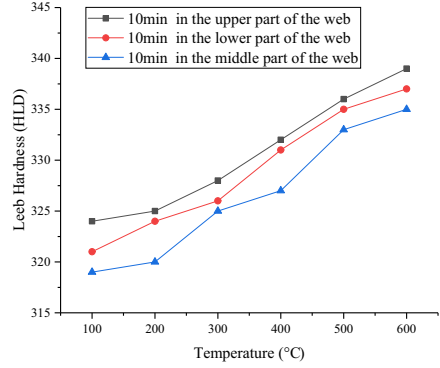
Regardless of which cooling mode is used, Leeb hardness of the flange is higher than that of the web. The main reasons are as follows: the flange thickness of the specimen is 8 mm, the web thickness is 6 mm, and the weight of a single flange is higher than that of the web. Due to the flange plate is thicker, and is restrained in the middle by the web, the vibration amplitude of the flange is smaller when performing the hardness test, which leads to a higher Leeb hardness than that of the web. The web is usually thinner than the flange, therefore, the amplitude of the vibration induced during the measurement of the Leeb hardness is larger, which causes partial loss of the kinetic energy and the measured value of the Leeb hardness is relatively small. The test results show that the different test positions of the steel are also the main factors affecting the Leeb hardness, and the Leeb hardness of the flange is about 35 HLD higher than that of the web.

3.5. Effect of Different Test Locations in the Steel Members on Leeb Hardness

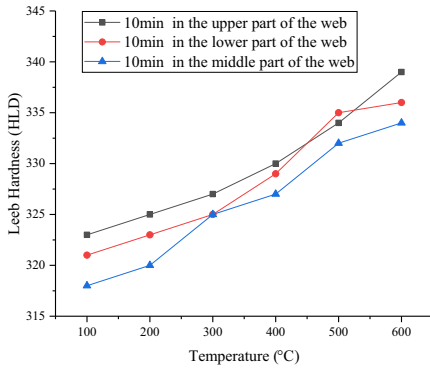
As it shown in Figs. 13 and 14, the upper, middle and lower detection positions of the flange and web were tested along the height of the specimens to study the influence of different parts of Leeb hardness. Leeb hardness of the upper and lower parts of the web differs by 1–2 HLD when the specimen is cooled by water at the same fire exposure time. While in the same conditions, Leeb hardness in the middle part of the web is lower, which is 4–5 HLD different from the Leeb hardness in the upper part of the web. When the fire exposure time is the same, Leeb hardness of upper and lower portions of the flange differ by 1–2 HLD, which is very close to each other. While in the same conditions, Leeb hardness in the middle of the flange is lower, and the maximum difference between the hardness values in the upper part of the flange is 7 HLD. The Leeb hardness in the middle of



(a) Fire exposure of 5mins



(b) Fire exposure of 10mins

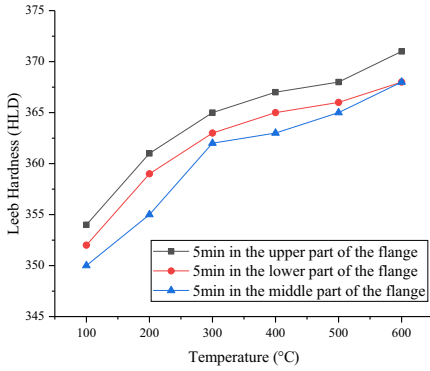


(c) Fire exposure of 15mins

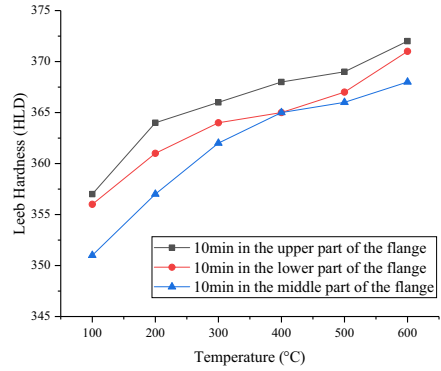
Figure 13. Hardness of different test location of the web.

the flange is 7 HLD different from that in the upper part of the flange when the fire temperature is 100°C. When the fire temperature is 400°C, the Leeb hardness of the middle part of the flange is equal to that of the lower part of the flange and is very close to the hardness value at the upper of the flange.

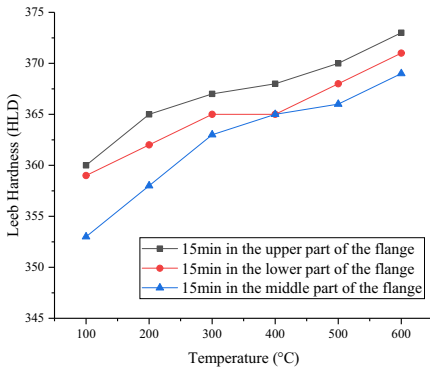
The above observation shows that Leeb hardness of the flange and web of the section steel increase with the increase of the fire temperature. The upper and lower detection points of the flange and the web have a higher Leeb hardness than the middle part of the flange, and the hardness of the middle portion is lower. The reason is that the amplitude of the vibration cause in Leeb hardness test is measured in the middle of the specimen is larger than that of the upper part or the lower part, causing partial loss of the impact kinetic energy, and the measured value of the Leeb hardness is relatively small.



(a) Fire exposure of 5mins



(b) Fire exposure of 10mins



(c) Fire exposure of 15mins

Figure 14. Hardness of different test locations of the flange.

3.6. Limitation of Leeb Hardness Method

From the test results it can be seen that Leeb hardness method is an effective post fire assessment method, however, it also has its limitations. It can only assess the strength of the structural steel member but cannot assess the ductility and deformation reduction due to fire. Other techniques need to be further invested.

4. Correlation Between the Post Fire Residual Strength of the Steel and Leeb Hardness

In this section, several regression methods were used to correlate the relation between the Leeb hardness to the residual strength of steel structural members after fire [31–34]. They are: linear regression methods and three non-linear regression methods (quadratic polynomial, exponential function and power function).

Table 2
Linear and Nonlinear Regression Analysis Under Ambient Temperature

Regression method	Correlation coefficient	Mean error (%)	Standard deviation of error (%)
$\sigma_b = 1.929 \times HLD - 245.439$	0.975	2.01	2.49
$\sigma_b = 0.008 \times HLD^2 - 3.729 \times HLD + 807.022$	0.987	12.17	12.82
$\sigma_b = 102.574 \times e^{0.004 \times HLD}$	0.985	1.46	1.96
$\sigma_b = 0.055 \times HLD^{1.531}$	0.979	1.98	2.42

σ_b is tensile strength of steel (N/mm²); *HLD* is Leeb hardness

4.1. Relation Between Tensile Strength and Leeb Hardness Under Ambient Temperature

Based on the analysis of the test results of 12 specimens at room temperature, the relationship between Leeb hardness and tensile strength of steel was developed. Leeb hardness was measured at upper flange. The tensile strength of coupons from the same position was tested through tensile testing. The correlative equation between Leeb hardness and tensile strength was detailed in Table 2.

As it can be seen from Table 2, the correlation coefficient of polynomial regression equation is the highest, but its mean and standard deviation of errors are larger. The correlation coefficient mean and standard deviation of errors for exponential regression equation are better than linear regression and power function regression equation. Therefore, the exponential regression equation can better reflect the relationship between Leeb hardness and tensile strength at room temperature.

4.2. Relation Between the Post-fire Tensile Strength and Leeb Hardness at Flange

The test results show that the Leeb hardness of flange is higher than that of web, so the regression analysis of flange and web were carried out respectively. The Leeb hardness of the upper part of flange with high stability is measured under the condition of 70% residual capacity after fire. The tensile strength of the corresponding flange obtained in the tensile test. The influence of cooling mode should also be considered in statistical analysis.

4.2.1. Cooling by Water The regression results by different regression methods are depicted in Fig. 15. There are 0.974 of correlation coefficient, 2.23% of mean error and 2.87 of standard deviation of error in the exponential equation. It shows that the exponential equation is the best to represent the correlation.

4.2.2. Natural Cooling The regression results by different regression methods are depicted in Fig. 16. There are 0.941 of correlation coefficient, 3.26% of mean

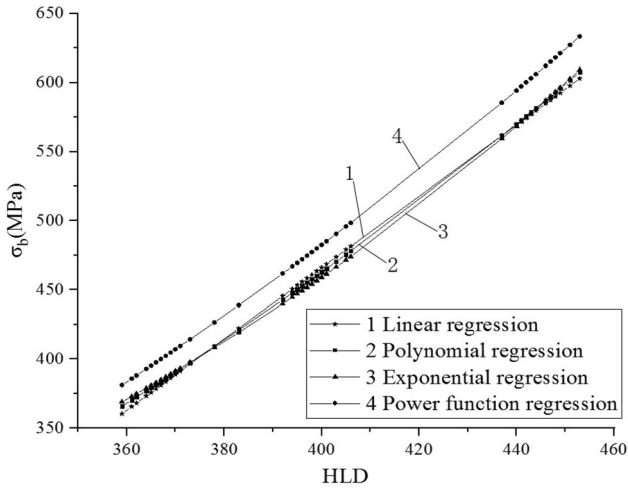


Figure 15. Leeb hardness and tensile strength of flange under water cooling.

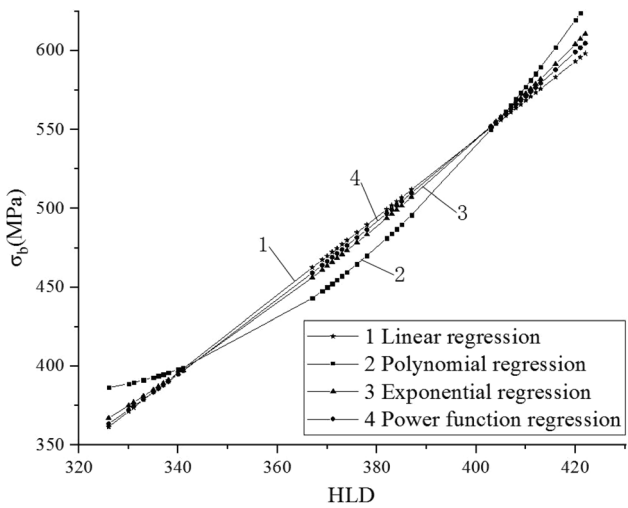


Figure 16. Leeb hardness and tensile strength of flange under natural cooling.

error and 4.20 of standard deviation of error in the exponential equation. It shows that the exponential equation is the best to represent the correlation.

4.2.3. *Comparison of Regression Results to Test Results* From the comparison of the regression analysis in Figs. 15 and 16, it can be seen that the exponential regression equation can be used to fit the relationship between Leeb hardness and tensile strength of flange under two cooling modes after fire. Figure 17 shows the

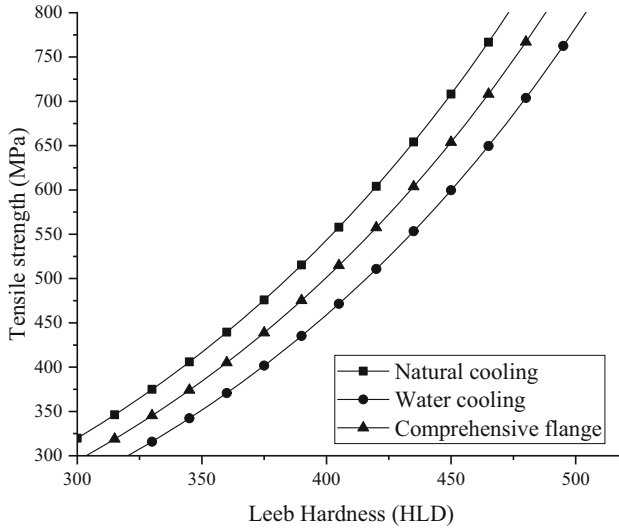


Figure 17. The correlation between the Leeb hardness and the residual tensile strength of flange.

relationship curve between Leeb hardness and tensile strength of flange using exponential regression under two cooling modes, and the relationship curve between Leeb hardness and tensile strength of flange synthetically obtained by fitting the two curves. The influence of two cooling modes is considered comprehensively in this curve. The relationship between Leeb hardness and tensile strength of composite flange after fire is developed as in Eq. (2).

$$\sigma_b = 59.722 \times e^{0.005 \times HLD} \tag{2}$$

Figure 17 shows that the tensile strength of watering cooling is lower than that of natural cooling under the same Leeb hardness; under the same tensile strength, the Leeb hardness of watering cooling is higher than that of natural cooling; and the watering cooling method is equivalent to quenching high-temperature specimens, resulting in the increase of surface hardness.

Table 3 gives the comparison between the calculated values of the formula 2 of Q345 specimen and the measured tensile strength of steel. It can be seen from the table that the maximum error is less than 10% and the average error is about 5%. It shows that the equation of relationship between Leeb hardness and tensile strength of flange after fire is in good agreement with the measured results.

4.3. Relation Between the Post-fire Tensile Strength and Leeb Hardness at Web

Figure 18 shows the relationship curve between Leeb hardness and tensile strength of webs with exponential regression under two cooling modes, and the relation-

Table 3
The Calculated Strength Using Leeb Hardness and Tested Strength of Flange for Q345 Steel Members

	HLD	Tested tensile strength (MPa)	Calculated tensile strength (MPa)	Errors (%)
BW_1^5	392	463.69	423.99	8.6
BW_1^{10}	394	475.44	428.25	9.9
BW_1^{15}	394	425.25	428.25	0.7
BW_2^5	394	454.38	428.25	5.8
BW_2^{10}	395	427.63	430.39	0.6
BW_2^{15}	396	443.06	432.55	2.4
BW_3^5	397	452.00	434.72	3.8
BW_3^{10}	397	476.81	434.72	8.8
BW_3^{15}	398	456.00	436.90	4.2
BW_4^5	399	438.31	439.09	0.2
BW_4^{10}	400	457.13	441.29	3.5
BW_4^{15}	401	462.81	443.50	4.2
BW_5^5	403	464.06	447.96	3.5
BW_5^{10}	403	476.56	447.96	6.0
BW_5^{15}	403	483.31	447.96	7.3
BW_6^5	405	474.31	452.46	4.6
BW_6^{10}	405	490.94	452.46	7.8
BW_6^{15}	406	476.56	454.73	4.6

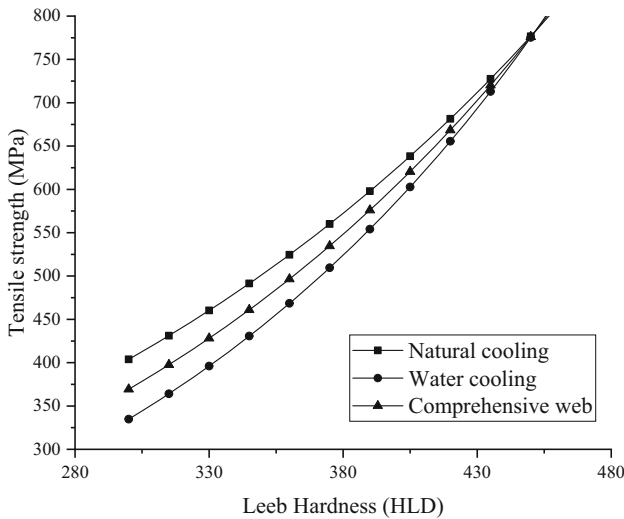


Figure 18. The correlation between the Leeb hardness and the residual tensile strength of web.

Table 6
The Calculated Strength Using Leeb Hardness and Tested Strength of
Web for Q390 Steel Members

	HLD	Tested tensile strength (MPa)	Calculated tensile strength (MPa)	Errors (%)
CN_1^5	371	551.67	571.37	3.6
CN_1^{10}	372	544.75	574.24	5.4
CN_1^{15}	373	574.50	577.12	0.5
CN_2^5	373	557.25	577.12	3.6
CN_2^{10}	374	568.33	580.01	2.1
CN_2^{15}	374	555.50	580.01	4.4
CN_3^5	376	549.42	585.84	6.6
CN_3^{10}	376	564.75	585.84	3.7
CN_3^{15}	376	551.67	585.84	6.2
CN_4^5	378	585.08	591.73	1.1
CN_4^{10}	379	559.33	594.69	6.3
CN_4^{15}	379	570.83	594.69	4.2
CN_5^5	380	562.17	597.67	6.3
CN_5^{10}	381	581.75	600.67	3.3
CN_5^{15}	381	588.08	600.67	2.1
CN_6^5	382	578.58	603.68	4.3
CN_6^{10}	383	572.25	606.70	6.0
CN_6^{15}	384	575.83	609.75	5.9

ship curve between Leeb hardness and tensile strength of webs obtained by fitting the two curves. The influence of two cooling modes is considered comprehensively in this curve. The relationship between Leeb hardness and tensile strength of composite web after fire is developed in Eq. (3).

$$\sigma_b = 82.393 \times e^{0.005 \times HLD} \quad (3)$$

Figure 18 shows that the relationship between Leeb hardness and tensile strength of web is basically the same as that between Leeb hardness and tensile strength of flange, but with the increase of Leeb hardness or tensile strength, the difference between flange and web becomes smaller and smaller.

Formula (3) is developed based on 3 grades of steel specimens Q345, Q345 and Q390. Table 6 gives a comparison between the calculated value of web using formula (3) and the measured tensile strength of Q390 steel specimens. It can be seen from the table that the maximum error is 6.6% and the average error is about 5%. It shows that the equation of relationship between Leeb hardness and tensile strength of web after fire is in good agreement with the measured results. Table 6 is not to validate the equation but to show the error range for each equation.

5. Conclusion

In this paper, a new nondestructive Post-fire Damage Assessment method using Leeb hardness test was first time developed. 120 steel sections were first tested in fire. The post fire Leeb Hardness tests were conducted afterwards. The influence of relevant factors on the Leeb hardness of structural steel members after fire was first time studied. The correlation function between Leeb hardness and the residual tensile strength of the steel members after fire has been developed. The following conclusions can be drawn:

- (1) The new nondestructive Post-fire Damage Assessment method developed in this paper provides a simple, fast and accurate way for the residual strength assessment of the structural steel after fire.
- (2) The correlation function between Leeb hardness and the residual tensile strength of the steel members after fire is developed; it can accurately predict the residual strength of steel members after fire.
- (3) When the fire exposure time is the same, Leeb hardness of members using water cooling method exhibit higher value than that of members using the natural cooling method are with an average increase of about 35 HLD, so the cooling mode has great influence on the Leeb hardness.
- (4) The Leeb hardness increases with the increase of the fire temperature. When the fire temperature rises from 100°C to 600°C, Leeb hardness increases by 12 HLD on average; with the increase of fire exposure time, the Leeb hardness shows a slight growth rate. The fire exposure time was from 5 min to 15 min, the corresponding increase of the Leeb hardness was around 3 HLD.
- (5) The hardness of the steel increases greatly with the increase of steel strength grade in the same conditions of cooling mode and fire exposure time, and it increases substantially linearly. The strength grade of steel has the greatest influence on the hardness of the steel.

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