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# Post-fire residual mechanical properties of Q460GJ steel under different pre-tensile stresses

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**Abstract:** Previous studies on the post-fire mechanical properties of steel were conducted with unstressed state, without considering the influence of pre-stress which subjected to structures in reality. In this article, the post-fire residual mechanical properties of Q460GJ steel under different pre-tensile stresses were studied. The stress-strain curve, elastic modulus, yield strength, ultimate strength and fracture elongation of Q460GJ steel after different elevated temperatures heating are analyzed in detail. The experimental results are compared with that of Q460 steel and S460 steel in the existing literatures. At last, the predictive equations of post-fire mechanical properties of Q460GJ steel under different pre-tensile stresses are established. Q460GJ steel still maintains good ductility after elevated temperature heating, which increases the possibility of reuse of Q460GJ steel element after fire. The Q460GJ steel has better post-fire ductility than that of Q460 and S460 steels. The predictive equations for the post-fire residual mechanical properties for Q460GJ steel under different pre-tensile

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stresses were proposed. The variation coefficients of yield strength for Q460GJ steel under different pre-tensile stresses after 20 min different elevated temperatures heating were within 0.065. The findings should have a great significance to providing theoretical support for design of reusing or restoring steel building after fire.

**Keywords:** Q460GJ steel; Post-fire; Mechanical properties; Stress–strain curve; Reduction factor

# 1. Introduction

Comparing with traditional concrete building, steel building with applying steel plates or steel sections has the following advanced properties such as light weight, good ductility and better seismic resistance [1-4]. And because the steel components can be manufactured in factory and installed on site while building steel structure, the steel building construction period can be greatly reduced. With long-term consideration, the reusability of steel material can greatly reduce construction waste and make steel building more environmentally friendly [5-8]. Therefore, it is widely adopted by countries around the world and applied in industrial and civil constructions [9-11]. With the continuous improvement of steel manufacture technologies, the control of trace elements in steel production is becoming more and more accurate. Therefore, the mechanical properties of constructional steel, such as yield to strength ratio and ductility could be becoming more and more excellent. The emergence of high-performance structural steel is the inevitable trend of the modern construction industry development [12-14]. High-performance steel has the advantages of high strength and good ductility, which has a good engineering application prospect. Although steel structures have widely recognized advantages such as light weight, good seismic performance and convenient construction, the relatively weak fire resistance of steel structures has still been considered as a major safety hazard [15-18].

The elevated temperature caused by fire changes the microstructure of steel, thus changing its mechanical properties. Structural fire safety is one of the key factors in the design of high-rise buildings. Through reasonable fire protection design, the steel structure can withstand fire or elevated temperature for more than 90 minutes without obvious fire resistance loss, so fire or elevated temperature does not always lead to the collapse of the steel structure [19-21]. However, the steel structure after fire will generate residual force and deformation again in the cooling stage and after cooling, which may lead to the insecurity of the structure. In order to reuse or restore the steel building after fire, it is necessary to further evaluate the reliability of steel structures after fire based on the post-fire residual mechanical properties of steel [22-24]. Therefore, the study of post-fire residual mechanical properties of steel has become one of the research hotspots in the field of civil engineering, especially the study of post-fire residual mechanical properties of high-performance steel.

In order to accurately evaluate the residual performance of steel structure after fire, it is necessary to accurately understand the influence of elevated temperature and cooling process on the mechanical properties of steel after fire [25-27]. In recent years, the researches on mechanical properties of structural steel after fire have been increasing continuously. Qiang et al. [28, 29] conducted tensile tests on high-strength S460, S690 and S960 steels after fire exposure. The test results showed that when the temperature was lower than 600 ºC, the mechanical properties of the steels after fire were less affected, while the properties of different grade steels after fire were greatly different. Lee et al. [30] conducted post-fire tensile tests of A992 steel with the elevated temperature range of 200 ºC ~1000 ºC with water cooling and air cooling modes, and found that, with air cooling mode, the yield strength did not significantly reduce until the elevated temperature exceeded 700 ºC. However, with water cooling mode, the yield strength increased and the fracture toughness decreased. Wang et al. [31] studied the mechanical properties of Q460 after fire, and proved that different elevated temperatures and cooling modes have effects on the stress-strain curve, yield strength, tensile strength and fracture elongation of Q460 steel. Zhou et al. [32] compared the mechanical properties of Q690 high-strength steel plates with different thicknesses (10 mm and 20 mm) after fire exposure, and found that the mechanical properties deteriorated seriously when the elevated temperatures were higher than 700 ºC. Huang et al. [33] conducted post-fire tensile tests for Q690 high-strength steel specimens at three pre-tensile stress ratios of 0.30, 0.55 and 0.80. The experimental results showed that the pre-tensile stress during heating and cooling improved the yield strength and ultimate strength of Q690 steel after fire. However, when the exposure temperature reached 800 ºC, the pre-tensile stress has a decreasing effect on the residual strength of Q690 steel after fire. In general, the current research objects were mainly focused on high-strength steel. At the same time, the effect of pre-tensile stress on post-fire residual mechanical properties is the main research direction.

# 2. Research significance

Without reliable mechanical properties of high-performance steel after fire, the performance evaluation of high-performance steel structure after fire is unreliable [34-36]. As an important basis for evaluating the performance of steel structures after fire, it is of great significance to study the material performance of steel after fire [37-39]. At present, there is a lack of evaluation on the mechanical properties of high-performance steel after fire, especially with pre-tensile stress. For example, in 2023, Chinese standard "Steel Plates for Building Structures" (GB/T 19879) [40]was updated to standardize the production and application of high-performance steel, with adding GJ after the original steel grade, such as Q345GJ, commonly known as "GJ steel". GJ steel plate is defined as a high-performance steel plate specially produced for high-rise civil building steel structures. In this article, the post-fire residual mechanical properties of Q460GJ steel with two kinds of plate thickness (8 mm and 12 mm) under different pre-tensile stresses are studied. The stress-strain curve, elastic modulus, yield strength, ultimate strength and fracture elongation of Q460GJ steel after different elevated temperatures heating are analyzed in detail. The experimental results are compared with that of Q460 steel and S460 steel in the existing literatures. At last, the predictive equations of post-fire mechanical properties of Q460GJ steel under different pre-tensile stresses are established. At the same time, the variation coefficient of yield strength of Q460GJ steel under different pre-tensile stresses after different elevated temperatures heating is analyzed based on the Weibull's probability distribution theory. These analyses are used to clarify the uniformity change of Q460GJ steel under different pre-tensile stresses after different elevated temperatures heating. The findings should have a great significance to providing theoretical support for design of reusing or restoring the steel building after fire, and have guiding significance for design, manufacturing, and application of high-performance steel.

# 3. Post-fire residual mechanical properties test

## 3.1 Materials and specimen

The commercial normalized Q460GJ steel plates manufactured according to the Chinese standard GB/T 19879-2023 (Steel plate for building structure) [40] were chosen. Table 1 shows the chemical compositions of the tested Q460GJ steel and the cited Q460 and S460 steels. The 8 mm thickness and 12 mm thickness Q460GJ steel plates were used. The tested specimen was made from the Q460GJ steel plate by wire-electrode cutting with the preparation process meets the requirements of the standards GB/T 228.1-2010(ISO 6892-1:2011) [41] and GB/T228.2-2015(ISO 6892-2:2011)[42]. The use of round bar specimens was to maintain the uniformity of specimen dimensions. Figure 1 shows the dimensions and photo image of tested specimen.

Table 1 Chemical compositions of Q460GJ steel, Q460 steel and S460 steel.

| Steel | Element (wt%) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Al | Cr | Ni | Cu | Mo | Nb | V | Ti | CEV |
| Q460GJ | 0.150 | 0.320 | 1.540 | 0.010 | 0.0008 | 0.039 | 0.050 | 0.020 | 0.030 | 0.004 | 0.034 | 0.037 | 0.003 | 0.420 |
| Q460[31] | 0.070 | 0.130 | 0.920 | 0.012 | 0.0030 | - | - | 0.020 | - | - | - | - | 0.064 | 0.246 |
| S460[28] | 0.172 | 0.483 | 1.500 | 0.012 | 0.005 | 0.037 | 0.020 | 0.018 | - | - | 0.046 | 0.087 | 0.002 | 0.447 |

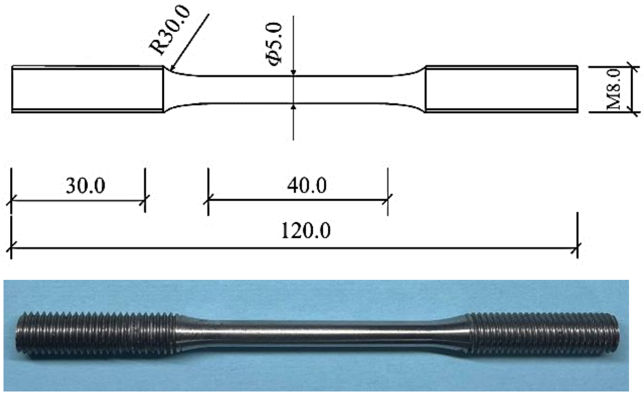



Fig. 1. Dimensions and photo image of tested specimen (mm).

### 3.2 Heating at elevated temperature with pre-tensile

Figure 2 shows the post-fire residual mechanical properties test procedure. The tested specimen was first processed on the electronic high temperature tension measurement, preloaded with a certain tensile stress, then heated to the target temperature, maintained for a period of time, and then naturally cooled to room temperature. The numbers of test specimens and corresponding test conditions are shown in Table 2. The pre-tensile stress was kept through the heating stage and the cooling stage. The pre-tensile stress ratio ($\gamma$) was defined as the ratio of the pre-tensile stress ($\sigma$) to the yield stress at elevated temperature ($f_{y,T}$). Four stress ratios were designed (0, 0.3, 0.55, 0.8). The yield stresses at elevated temperature of Q460GJ steel plates were tested according to the standards GB/T 228.1-2010 (ISO 6892-1:2011) and

GB/T228.2-2015 (ISO 6892-2:2011) and supplied by the Q460GJ steel manufacture. The elevated temperatures chosen were 300 ºC,400 ºC, 500 ºC, 600 ºC, 700 ºC, 800 ºC and 900 ºC, respectively. For 8 mm thickness Q460GJ steel plate, there were 56 specimens totally (2 specimens for each temperature 300, 400, 500, 600, 700, 800 and 900 ºC and each pre-tensile stress 0, 0.3, 0.55 and 0.8). Similarly, for 12 mm thickness Q460GJ steel plate, there were 56 specimens totally. The maximum test force of the electronic high temperature tension measurement (GWT 2105) is 100 kN and the relative error of test force indication is ≤ 0.5%. The high-temperature furnace was a split type atmospheric furnace. The operating temperature ranges from 200 ºC to 1100 ºC and the temperature fluctuation was within 3 ºC.

Table 2 Numbers of test specimens and corresponding test conditions.

| Test number | $T$ (ºC) | $f_{y,T}$ (MPa) | Pre-tensile stress $\sigma$ (MPa) | Stress ratio $\gamma$ |
|---|---|---|---|---|
| GJ-8-300 | 300 | 411.86 | 0/123.6/226.5/329.5 | 0/0.3/0.55/0.8 |
| GJ -8-400 | 400 | 375.82 | 0/112.7/206.7/300.7 | 0/0.3/0.55/0.8 |
| GJ -8-500 | 500 | 311.94 | 0/93.6/171.6/249.5 | 0/0.3/0.55/0.8 |
| GJ -8-600 | 600 | 220.42 | 0/66.1/121.2/176.3 | 0/0.3/0.55/0.8 |
| GJ -8-700 | 700 | 108.74 | 0/32.6/59.8/87.0 | 0/0.3/0.55/0.8 |
| GJ -8-800 | 800 | 53.78 | 0/16.1/29.6/43.0 | 0/0.3/0.55/0.8 |
| GJ -8-900 | 900 | 38.43 | 0/11.5/21.1/30.7 | 0/0.3/0.55/0.8 |
| GJ -12-300 | 300 | 443.13 | 0/132.9/243.7/354.5 | 0/0.3/0.55/0.8 |
| GJ -12-400 | 400 | 415.55 | 0/124.5/228.25/332.4 | 0/0.3/0.55/0.8 |
| GJ -12-500 | 500 | 365.29 | 0/109.6/200.9/292.2 | 0/0.3/0.55/0.8 |
| GJ -12-600 | 600 | 249.76 | 0/74.9/137.4/199.8 | 0/0.3/0.55/0.8 |
| GJ -12-700 | 700 | 120.18 | 0/36.1/66.1/96.1 | 0/0.3/0.55/0.8 |
| GJ -12-800 | 800 | 54.44 | 0/16.3/29.9/43.6 | 0/0.3/0.55/0.8 |
| GJ -12-900 | 900 | 35.38 | 0/10.6/19.5/28.3 | 0/0.3/0.55/0.8 |

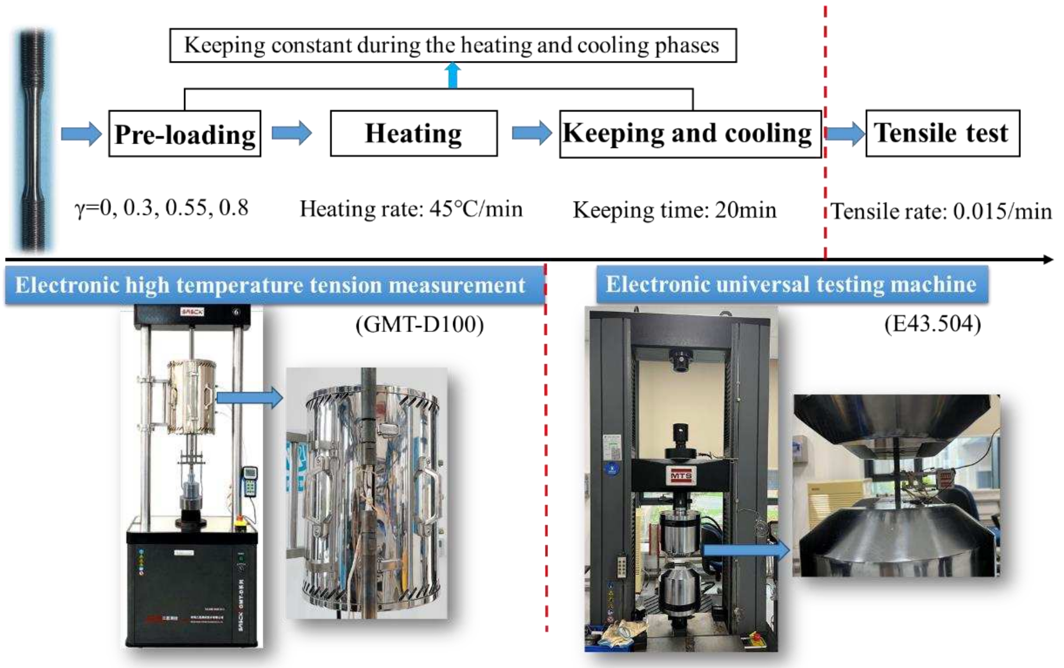



Fig. 2. Post-fire residual mechanical properties test procedure.

### 3.3 Tensile testing setup

The tensile test after heating at elevated temperature was carried out using the electronic universal testing machine (E43.504) as shown in Figure 2. The maximum load force of the electronic universal testing machine (E43.504) is 50 kN, and the controllable test speed is 500 mm/min~0.001 mm/min. The displacement extensometer was a ceramic rod extensometer, model 3448-025M-050, with a gauge length of 25.00 mm and a measurement accuracy of 0.001 mm. The loading system could apply constant stress through servo motor and driver(Test force control stability ± 0.2%) to ensure stress stability during the testing process. The numbers of test specimens and corresponding test conditions are shown in Table 2. For example, the specimen number 'GJ-8-300-0.3-1' represents 'Q460GJ steel - 8mm thickness plate - 300 ºC - pre-tensile stress ratio 0.3 - specimen 1'. Two specimens were tested for each tensile test to ensure the reliability of the test results and the two tested yield strength ($f_{yT}$) values were used for error estimations. If the error exceeds 5%, the third one was tested, using the average of the two acceptable test results as the representative value [33].

According to the stress-strain curve determined, four mechanical properties including yield strength, ultimate strength, elastic modulus and apparent fracture elongation were investigated. The elastic modulus was calculated by the slope of the elastic section of the stress-strain curve. The yield strength was the lower boundary of the yield platform. The ultimate strength was taken as the maximum value in the stress-strain curve. The elongation after fracture was measured according to the provisions of the standard GB/T 228.1 – 2010 (Tensile testing of metallic materials. Part 1: Room temperature test method)[41]. The specific method was to firmly stick the fractured parts of the specimen together, ensure that its axis was in the same straight line, and test the gauge distance of the broken sample. The accuracy of vernier caliper used in measurement was 0.01 mm, and the measurement error of elongation was 0.01%. The elongation after fracture is obtained by the following equation (1):

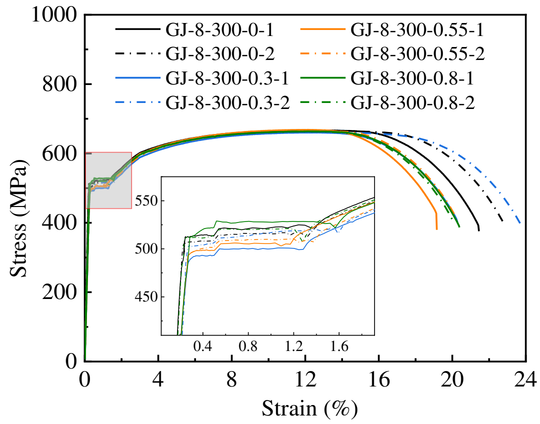
$$\varepsilon = (L_u - L_0)/L_0 \times 100 \tag{1}$$

where $\varepsilon$ is fracture elongation strain (%), $L_u$ is the gauge length after fracture (mm), $L_0$ is the gauge length (40 mm).

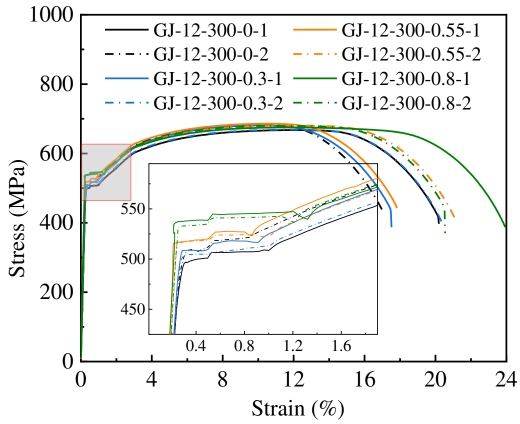
# 4. Post-fire tensile test results and discussions

### 4.1 Stress–strain ($\sigma$-$\varepsilon$) curves

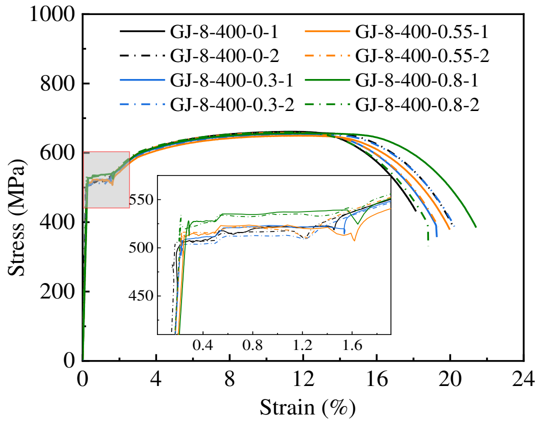
The stress-strain curves of Q460GJ steel after different elevated temperatures heating are analyzed in the following. Figure 3 shows the post-fire tensile $\sigma$-$\varepsilon$ curves of Q460GJ steel specimens. The results of two test specimens in each test group were similar after all temperatures heating. The pre-tensile stresses had no obvious effects on the stress-strain curves of Q460GJ steel plate specimens. Only when the pre-tensile stress ratio was 0.8, the yield strengths of the tested specimens were a little bite higher than the others.



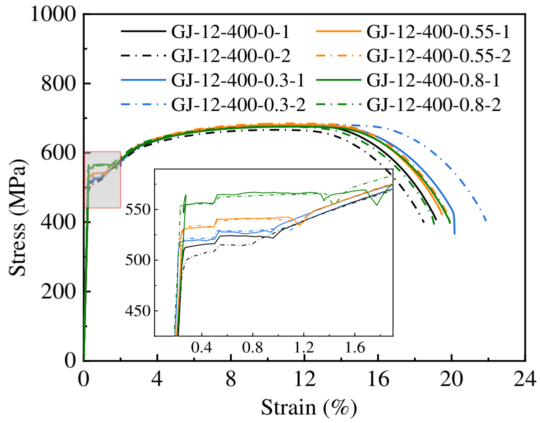

(a) GJ-8-300 specimens after 300 ºC heating.



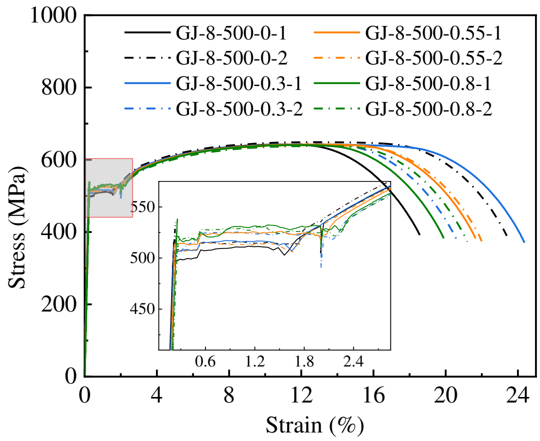

(b) GJ-12-300 specimens after 300 ºC heating.



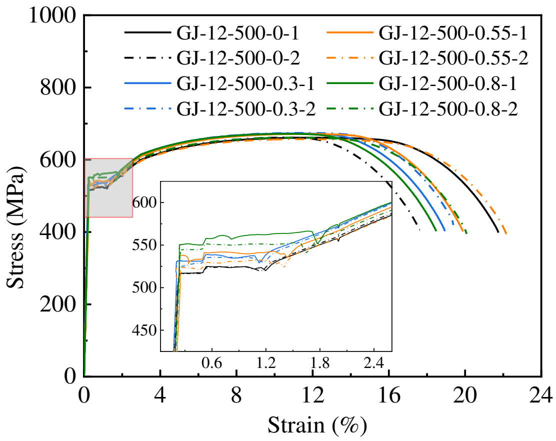

(c) GJ-8-400 specimens after 400 ºC heating.



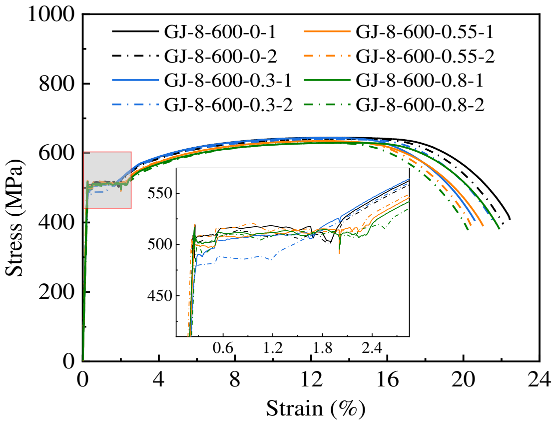

(d) GJ-12-400 specimens after 400 ºC heating.



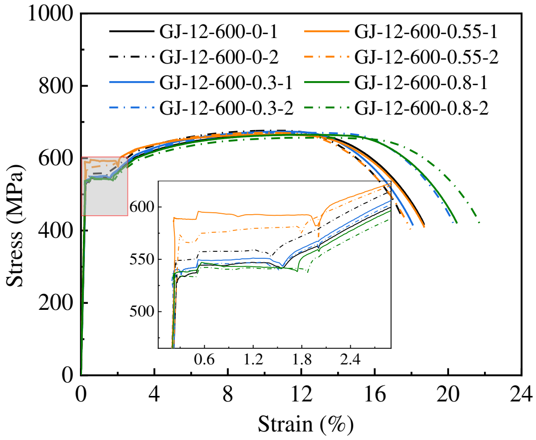

(e) GJ-8-500 specimens after 500 ºC heating.



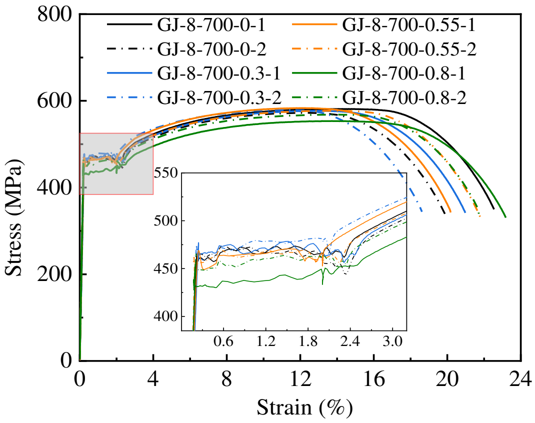

(f) GJ-12-500 specimens after 500 ºC heating.



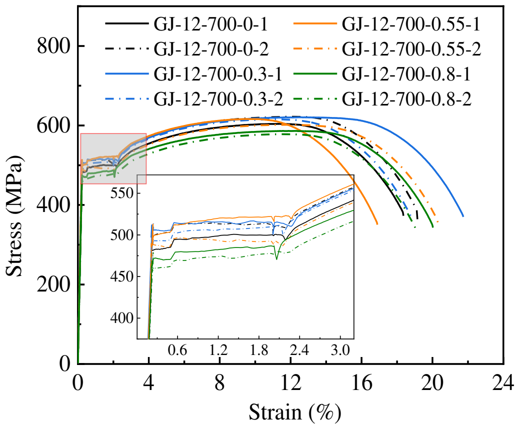

(g) GJ-8-600 specimens after 600 °C heating.



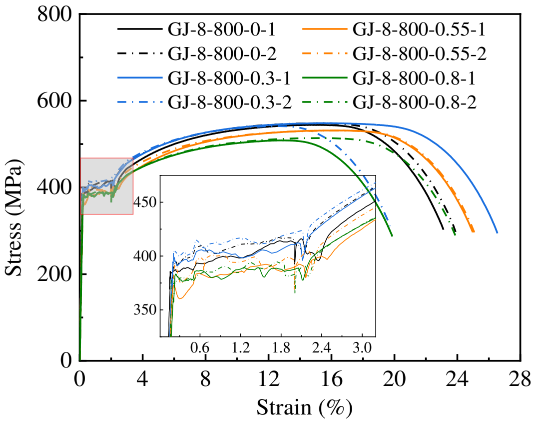

(h) GJ-12-600 specimens after 600 °C heating.



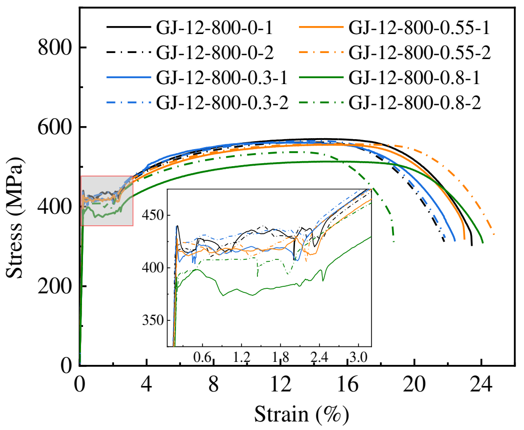

(i) GJ-8-700 specimens after 700 °C heating.



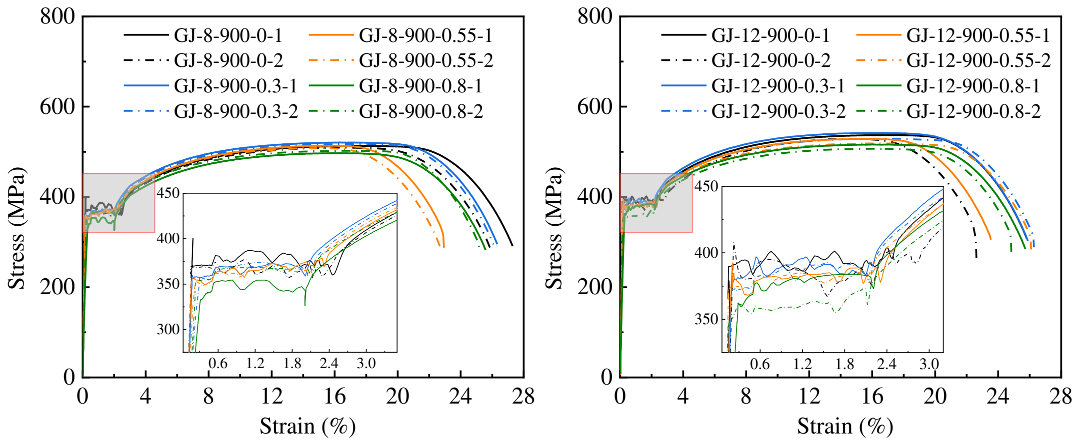

(j) GJ-12-700 specimens after 700 °C heating.




(k) GJ-8-800 specimens after 800 °C heating.




(l) GJ-12-800 specimens after 800 °C heating.




(m) GJ-8-900 specimens after 900 °C heating. (n) GJ-12-900 specimens after 900 °C heating.

Fig. 3. Post-fire tensile $\sigma$-$\varepsilon$ curves of Q460GJ steel specimens.

The stress-strain curves of all the specimens showed a relatively obvious yield stage, and the heating temperature has little effect on the trend of the stress-strain curves of the tested specimens. When the heating temperatures were lower than 700 °C, the stress-strain curves were basically not affected by the heating temperatures. When the heating temperatures exceeded 700 °C, the ultimate stresses decreased significantly with the increase of temperature, while the deformation capacity increased. That the stress-strain curves of two types of Q460GJ steel plates with different thicknesses at all testing conditions were quite similar. The pre-tensile stresses had no obvious effects on the stress-strain curves of Q460GJ steel plate specimens, except for when the pre-tensile stress ratio was 0.8. The residual elastic modulus, yield strength, ultimate strength and fracture elongation of Q460GJ steel after different elevated temperatures heating are analyzed in the following.

### 4.2 Elastic modulus ($E_T$) reduction factor

The elastic modulus ($E_T$) average was calculated based on the tested average results of 8 mm thickness Q460GJ steel plate and 12 mm thickness Q460GJ steel plate. Table 3 shows the post-fire elastic modulus reduction factors ($E_T/E_{20}$) with different pre-tensile ratios. The elastic modulus of Q460GJ steel plates were cited from the reference [43] as 230.490 GPa for 8 mm thickness Q460GJ steel plate and 205.180 GPa for 12 mm thickness Q460GJ steel plate. Then the post-fire elastic modulus reduction factors ($E_T/E_{20}$) of Q460GJ steel plates specimens were calculated and shown in Figure 4. It can be found that the elastic modulus of the two kinds of Q460GJ steel plates after elevated temperature heating remained relatively unchanged below 800 °C, and the fluctuation range was within 10%. While the elevated temperature was 400 °C and pre-tensile ratio was 0.3, the reduction coefficient was a little bit higher, this might be caused by experimental error. When the elevated temperature reached 900 °C, the elastic modulus decreased slightly when the applied stress ratio is within 0.55, but it decreased by about 30% when the stress ratio was 0.8. This indicates that the Q460GJ steel will lose part of its stiffness when exposed to 20 min 900 °C elevated temperature and with a high pre-tensile stress ratio at the same time.

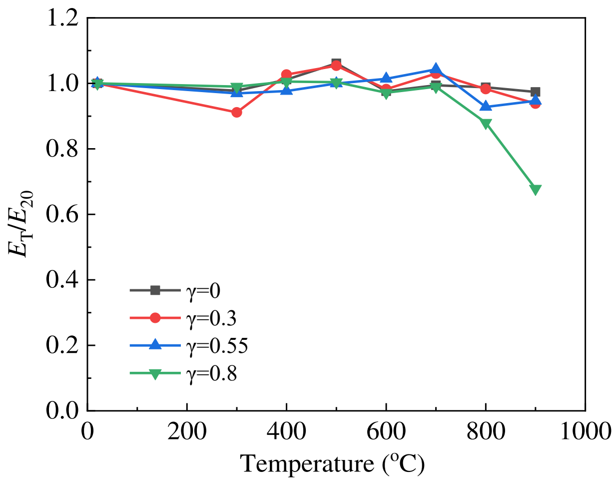



Fig. 4. The post-fire elastic modulus reduction factors ($E_T/E_{20}$) of Q460GJ steel plates.

Table 3 The post-fire elastic modulus reduction factors ($E_T/E_{20}$) with different pre-tensile ratios.

| Steel plates number | $E_T/E_{20}$ | | | |
|---|---|---|---|---|
| | γ = 0 | γ = 0.3 | γ = 0.55 | γ = 0.8 |
| GJ-20 | 1.000 | - | - | - |
| GJ-300 | 0.977 | 0.912 | 0.970 | 0.990 |
| GJ-400 | 1.012 | 1.027 | 0.977 | 1.005 |
| GJ-500 | 1.061 | 1.054 | 1.000 | 1.004 |
| GJ-600 | 0.976 | 0.982 | 1.014 | 0.972 |
| GJ-700 | 0.994 | 1.030 | 1.043 | 0.990 |
| GJ-800 | 0.988 | 0.983 | 0.928 | 0.880 |
| GJ-900 | 0.974 | 0.938 | 0.947 | 0.678 |

### 4.3 Yield strength ($f_{yT}$) reduction factor

The yield strength ($f_{yT}$) average was calculated based on the tested average results of 8 mm thickness Q460GJ steel plate and 12 mm thickness Q460GJ steel plate. Table 4 shows the post-fire yield strength reduction factors with different pre-tensile ratios. The yield strengths ($f_{y20}$) of Q460GJ steel plates were cited from the reference [43] as 475.6 MPa for 8 mm thickness Q460GJ steel plate and 495.7 MPa for 12 mm thickness Q460GJ steel plate. Then the post-fire yield strength reduction factors ($f_{yT}$/ $f_{y20}$) of Q460GJ steel plates specimens were calculated and shown in Figure 5. It can be found that the yield strengths of the two kinds of Q460GJ steel plates after elevated temperature heating remained relatively unchanged below 700 ºC. When the elevated temperature reached 700 ºC, the yield strength decreased significantly by more than 20%. The yield strength degraded seriously when exposed to 900 ºC elevated temperature. By comparing the yield strengths with different pre-tensile stress ratios, it was found that when the heating elevated temperatures were 600 °C and below, the pre-tensile stress ratio has little effect on the yield strength. When the heating elevated temperatures were above 700 °C, the yield strength decreased gradually with the increase of pre-tensile stress ratio, especially when the pre-tensile stress ratios were above 0.55.

Table 4 The post-fire yield strength reduction factors with different pre-tensile ratios.

| Steel plates number | $f_{yT}/f_{y20}$ | | | |
|---|---|---|---|---|
| | γ = 0 | γ = 0.3 | γ = 0.55 | γ = 0.8 |
| GJ-20 | 1.000 | - | - | - |
| GJ-300 | 1.069 | 1.057 | 1.071 | 1.107 |
| GJ-400 | 1.072 | 1.081 | 1.102 | 1.138 |
| GJ-500 | 1.073 | 1.094 | 1.091 | 1.121 |
| GJ-600 | 1.096 | 1.080 | 1.093 | 1.086 |
| GJ-700 | 1.005 | 1.012 | 0.999 | 0.953 |
| GJ-800 | 0.852 | 0.860 | 0.830 | 0.813 |
| GJ-900 | 0.796 | 0.774 | 0.758 | 0.749 |

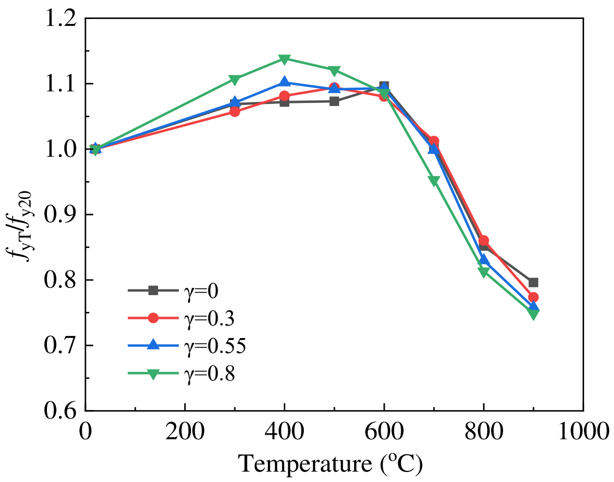



Fig. 5. The post-fire yield strength reduction factors ($f_{yT}/f_{y20}$) of Q460GJ steel plates.

The yield strength increased slightly when the heating elevated temperatures were within 300 ºC to 600 ºC, which might be due to the change of microstructure of Q460GJ steel caused by elevated temperature heating and cooling. Based on this study, the yield strength of Q460GJ steel did not lose when the heating elevated temperature was below 700 ºC and the applied pre-tensile stress ratio was within 0.8. It may be concluded that, if Q460GJ steel member is exposed to fire temperature below 700 ºC for no more than 20 minutes, it can be reused after fire.

### 4.4 Ultimate strength ($f_{uT}$) reduction factor

The ultimate strength ($f_{uT}$) average was calculated based on the tested average results of 8 mm thickness Q460GJ steel plate and 12 mm thickness Q460GJ steel plate. Table 5 shows the post-fire ultimate strength reduction factors with different pre-tensile ratios. The ultimate strengths ($f_{u20}$) of Q460GJ steel plates were cited from the reference [43] as 663 MPa for 8 mm thickness Q460GJ steel plate and 681.1 MPa for 12 mm thickness Q460GJ steel plate. Then the post-fire ultimate strength reduction factors ($f_{uT}/f_{u20}$) of Q460GJ steel plates specimens were calculated and shown in Figure 6. It can be found that the ultimate strengths of the two kinds of Q460GJ steel plates after elevated temperature heating remained relatively unchanged below 600 ºC. When the elevated temperature reached 800 ºC, the ultimate strength decreased significantly by more than 10%. The ultimate strength of Q460GJ steel degraded seriously when exposed to 900 ºC elevated temperature. By comparing the ultimate strengths with different pre-tensile stress ratios, it was found that when the heating elevated temperatures were 600 ºC and below, the pre-tensile stress ratio has little effect on the ultimate strength. When the heating elevated temperatures were above 600 ºC, the ultimate strength decreased gradually with the increase of pre-tensile stress ratio, especially when the pre-tensile stress ratios were above 0.55. The change trend of ultimate strength after elevated temperature heating and cooling was consistent with that of yield strength for Q460GJ steel.

Table 5 The post-fire ultimate strength reduction factors with different pre-tensile ratios.

| Steel plates number | $f_{uT}/f_{u20}$ | | | |
|---|---|---|---|---|
| | γ = 0 | γ = 0.3 | γ = 0.55 | γ = 0.8 |
| GJ-20 | 1.000 | - | - | - |
| GJ-300 | 1.012 | 1.008 | 1.018 | 1.012 |
| GJ-400 | 1.005 | 1.007 | 1.008 | 1.006 |
| GJ-500 | 0.986 | 0.993 | 0.985 | 0.985 |
| GJ-600 | 0.991 | 0.991 | 0.982 | 0.973 |
| GJ-700 | 0.897 | 0.902 | 0.897 | 0.862 |
| GJ-800 | 0.839 | 0.836 | 0.820 | 0.782 |
| GJ-900 | 0.788 | 0.795 | 0.780 | 0.763 |

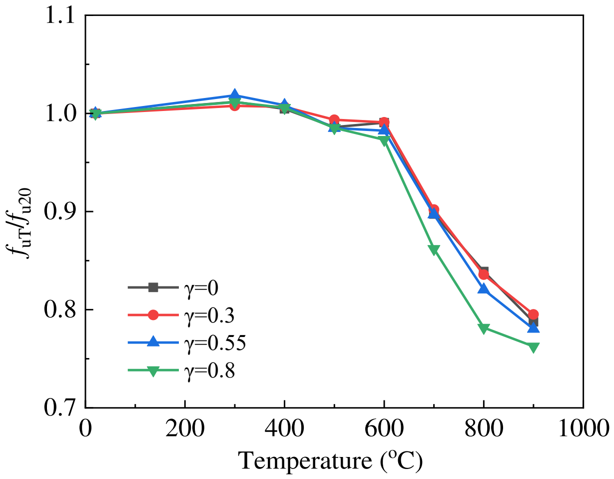



Fig. 6. The post-fire ultimate strength reduction factors ($f_{uT}/f_{u20}$) of Q460GJ steel plates.

### 4.5 Ultimate elongation ($\varepsilon_T$) reduction factor

The ultimate elongation ($\varepsilon_T$) average was calculated based on the tested average results of 8 mm thickness Q460GJ steel plate and 12 mm thickness Q460GJ steel plate. Table 6 shows the of post-fire ultimate elongation reduction factors with different pre-tensile ratios. The ultimate elongations ($\varepsilon_{20}$) of Q460GJ steel plates were cited from the reference [43] as 26.76% for 8 mm thickness Q460GJ steel plate and 23.94% for 12 mm thickness Q460GJ steel plate. Then the post-fire ultimate elongation reduction factors ($\varepsilon_T$/ $\varepsilon_{20}$) of Q460GJ steel plates specimens were calculated and shown in Figure 7. The ultimate elongation increased with the increase of heating temperature. By comparing the ultimate elongations with different pre-tensile stress ratios, it was found that pre-tensile stress ratio did not have obvious effect on the ultimate elongation. The specimens after elevated temperature heating and cooling showed higher ductility than those without elevated temperature heating and cooling. Q460GJ steel still maintains good ductility after elevated temperature heating, which increases the possibility of reuse of Q460GJ steel element after fire.

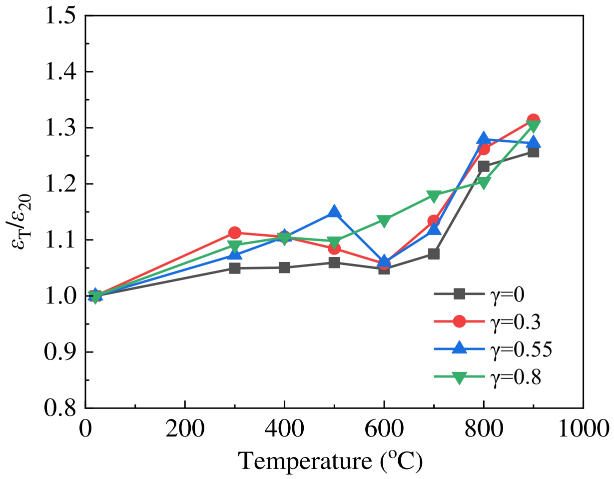


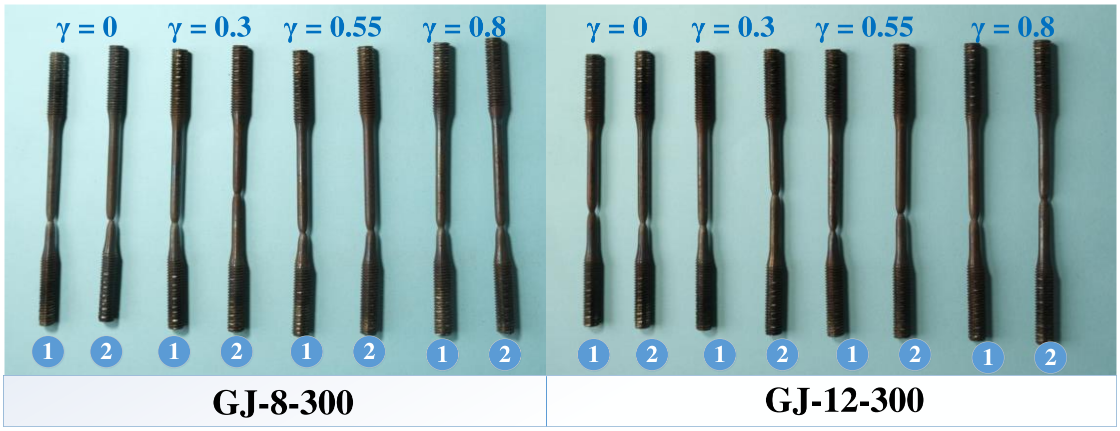

Fig. 7. The post-fire ultimate strength reduction factors ($\varepsilon_T$/ $\varepsilon_{20}$) of Q460GJ steel plates.

Table 6 The of post-fire ultimate elongation reduction factors with different pre-tensile ratios.

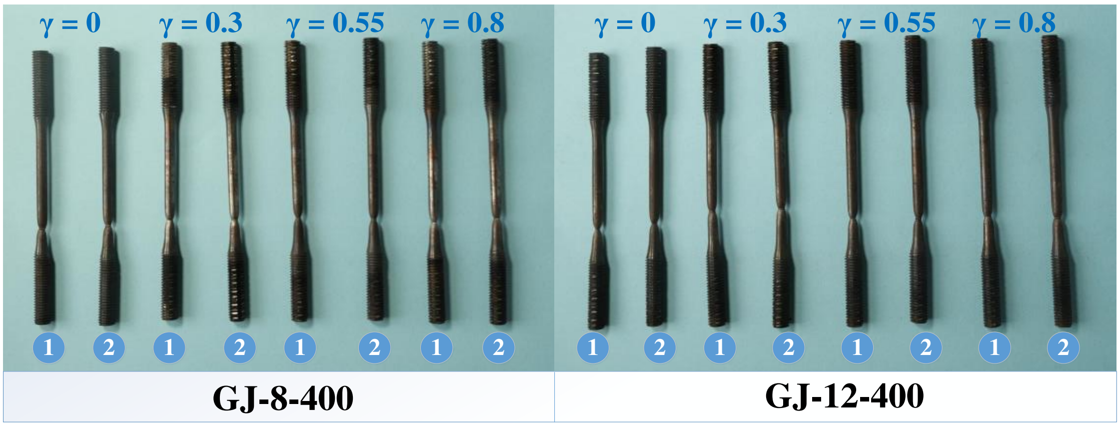
| Steel plates number | $\varepsilon_T/\varepsilon_{20}$ | | | |
|---|---|---|---|---|
| | γ = 0 | γ = 0.3 | γ = 0.55 | γ = 0.8 |
| GJ-20 | 1.000 | - | - | - |
| GJ-300 | 1.049 | 1.113 | 1.073 | 1.091 |
| GJ-400 | 1.051 | 1.106 | 1.105 | 1.104 |
| GJ-500 | 1.059 | 1.085 | 1.149 | 1.098 |
| GJ-600 | 1.048 | 1.058 | 1.060 | 1.136 |
| GJ-700 | 1.075 | 1.134 | 1.117 | 1.180 |
| GJ-800 | 1.231 | 1.262 | 1.279 | 1.204 |
| GJ-900 | 1.257 | 1.314 | 1.272 | 1.305 |

## 4.6 Apparent failure modes

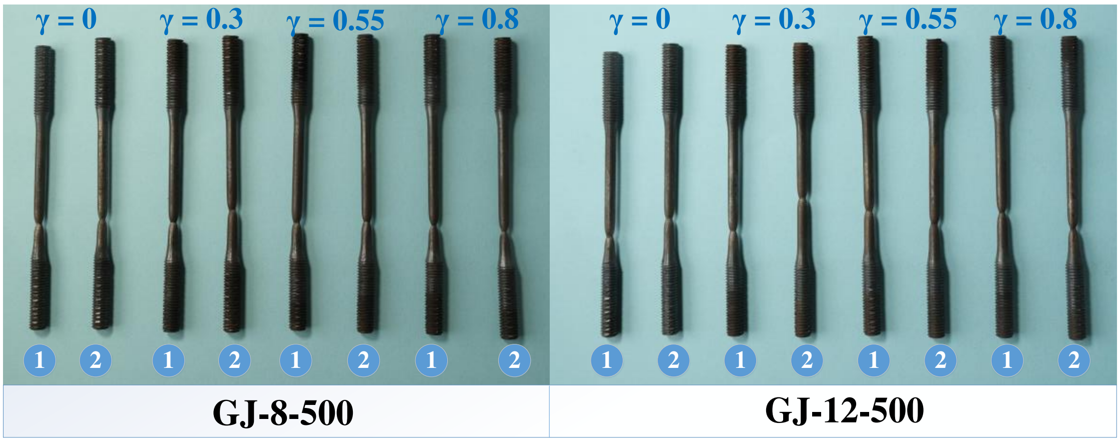
Figure 8 shows the apparent failure modes of the tensile specimens after elevated temperature heating and cooling. The typical fracture site side view photos of specimens after testing are shown in Figure 9. It can be seen that each specimen exhibited ductile and necking failure. With the increase of the heating elevated temperature, the length of the Q460GJ steel specimen at failure increased, so the ductility was better. It can be seen from the photos that the apparent color of the specimens gradually turns black with the increase of the heating temperature, indicating that the oxidation degree gradually increases. With 400 °C heating elevated temperature, the blue brittleness phenomenon was observed. With higher heating elevated temperature, the oxidation on the surface of the steel specimen is more severe. This causes the different color of the specimen surfaces formed at heating elevated temperatures. This surface color changing could be potentially used as a useful indicator of fire temperature.



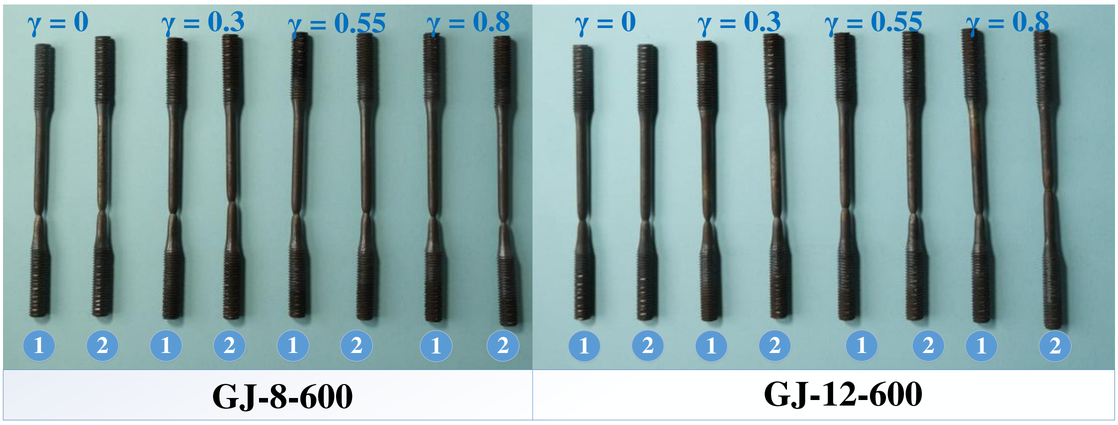

(a) After 20 min 300 °C heating.



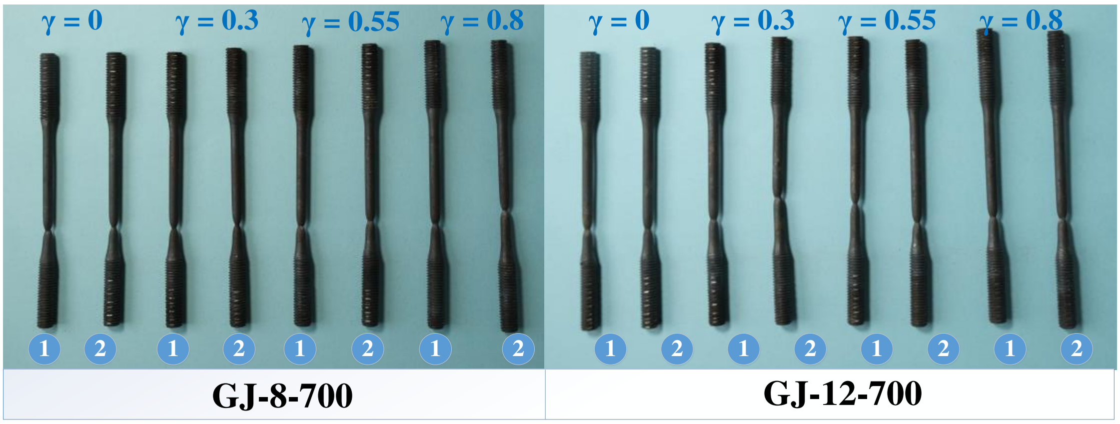

(b) After 20 min 400 °C heating.




(c) After 20 min 500 °C heating.

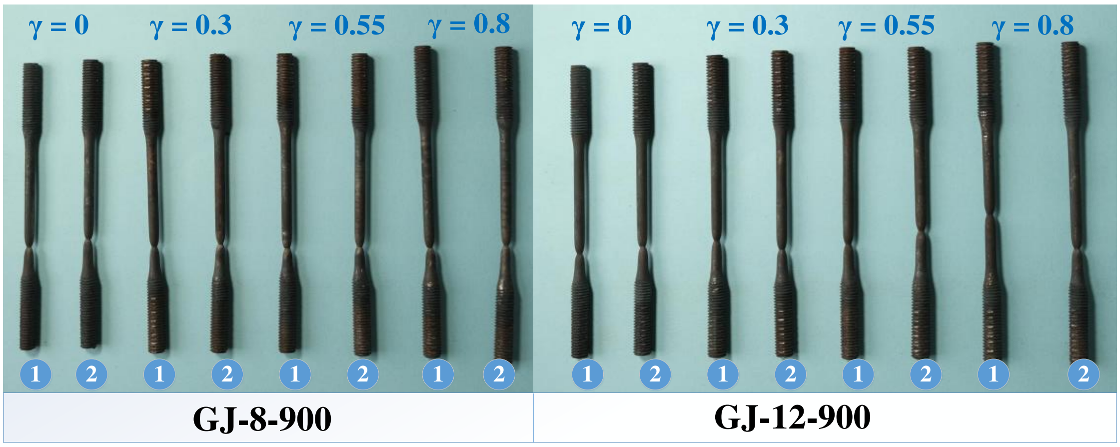



(d) After 20 min 600 °C heating.




(e) After 20 min 700 °C heating.


(f) After 20 min 800 °C heating.



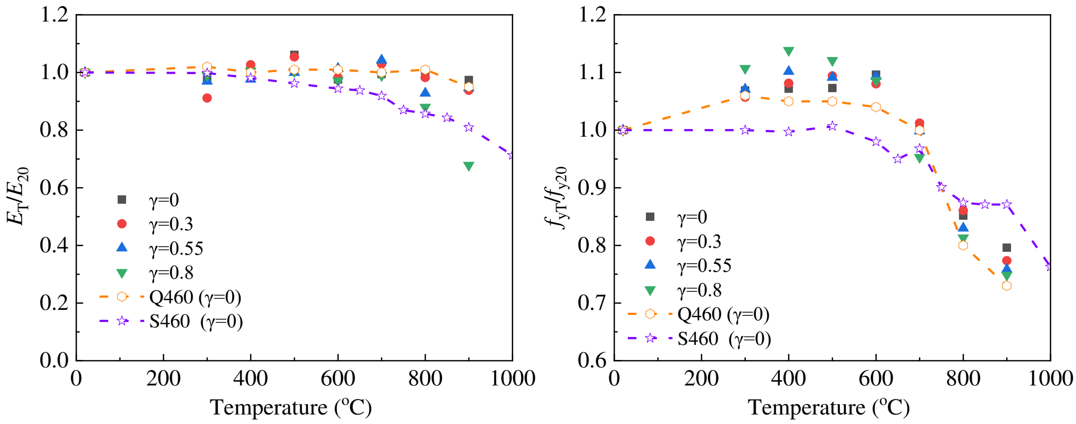

(g) After 20 min 900 °C heating.

Fig. 8. Apparent failure modes of specimens after testing.

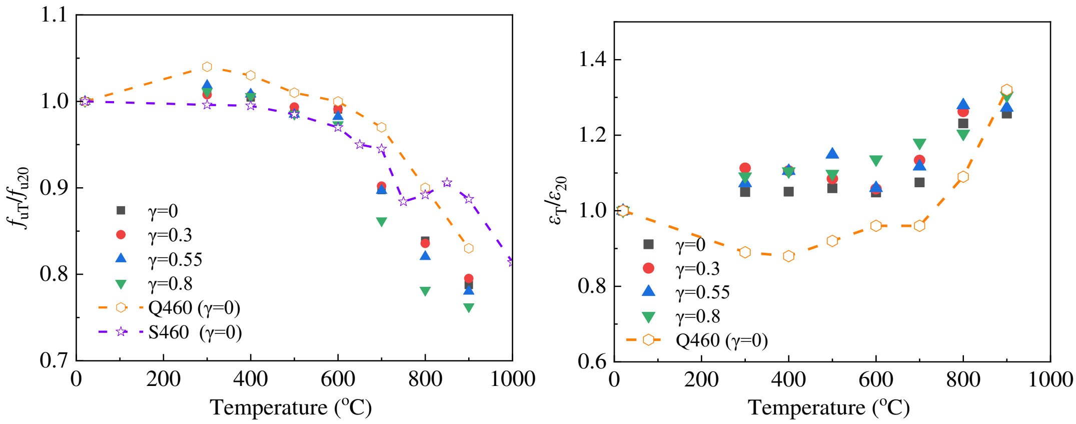

Fig. 9. Typical fracture site side view photos of specimens after testing.

# 5. Comparison with Q460 and S460 steels

Because the chemical composition and microstructure of different steels are different, the heating temperature and cooling mode may have different effects on the mechanical properties of different steels after heating and cooling. Figure 10 shows the comparison of the post-fire residual mechanical properties of Q460GJ steel and referred Q460 [31] and S460 [28] steels. The elastic modulus reduction factors are shown in Figure 10 (a). It can be found that Q460GJ steel had the same trend as Q460 and S460 steels, which was basically not affected by the heating elevated temperature, except for above 800 ºC, the elastic modulus reduction factors decreased significantly. The yield strength reduction factors are shown in Figure 10 (b). It can be found that Q460GJ steel had the same trend of yield strength reduction factor as Q460 steel. The yield strength reduction factors of Q460 steel after elevated temperature heating and cooling were higher than that of S460 steel when the heating temperatures were within 700 ºC, and lower than that of S460 steel when the heating temperatures were above 700 ºC. The ultimate strength reduction factors are shown in Figure 10 (c). It can be found that We found that Q460GJ steel and Q460 and S460 steels had similar overall trends. However, when the heating temperatures were above 700 ºC, the yield strength reduction factors of Q460GJ steel after elevated temperature heating and cooling were obviously lower than that of Q460 and S460 steels. The ultimate elongation reduction factors are shown in Figure 10 (d). On the whole, the ultimate elongation reduction factors of Q460GJ steel after elevated temperature heating and cooling were greater than that of Q460 steel. Especially within 700 ºC, the ultimate elongation reduction factors of Q460 steel were all less than 1.0. Therefore, to sum up, Q460GJ steel has better ductility after elevated temperature heating and cooling than that of Q460 steel.



(a) Elastic modulus reduction factors. (b) Yield strength reduction factors.




(c) Ultimate strength reduction factors. (d) Ultimate elongation reduction factors.

Fig. 10. Comparison of Q460GJ steel and referred Q460 and S460 steels.

# 6. Predictive equations for residual mechanical properties

Based on the above experimental results, it can be found that the residual mechanical properties of Q460GJ steel after elevated temperature heating and cooling were different with that of Q460 steel and S460 steel. It is necessary to establish the predictive equations for the residual mechanical properties for Q460GJ steel after elevated temperature heating and cooling under different pre-tensile stresses. The tested results also showed that the effect of plate thickness on the mechanical properties of Q460GJ steel could be ignored. Therefore, a set of unified prediction equations for the reduction factors of mechanical properties of two kinds of plate thickness are proposed as the followings.

## 6.1 Elastic modulus reduction factor

Experimental results in section 4.2 showed that the elastic modulus of Q460GJ steel had little change after elevated temperature heating and cooling, and it was reduced only at the pre-tensile stress ratio of 0.8. Therefore, in this paper the predictive equation of the elastic modulus reduction factors after elevated temperatures heating and cooling under the stress ratio of 0.8 was proposed only, and the predictive equation was shown as equation (2) and the predictive equation fitting with experimental results was shown in Figure 11(a).

$$E_{\mathrm{T}}/E_{20}=\begin{cases}1 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0/0.3/0.55\\ -2.571\times10^{-9}T_{\mathrm{s}}^{3}+2.704\times10^{-6}T_{\mathrm{s}}^{2}-7.111\times10^{-4}T_{\mathrm{s}}+1.016 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.8\end{cases} \tag{2}$$

### 6.2 Yield strength reduction factor

The tested results in section 4.3 show that although the yield strength of Q460GJ steel after elevated temperature heating and cooling had little change when the elevated temperatures were within 700 ºC, the yield strength of Q460GJ steel had a significant reduction above 700 ºC, and the reduction degree of yield strength was different under different pre-tensile stress ratios. The predictive equation of the yield strength reduction factors after elevated temperatures heating and cooling under different pre-tensile stress ratios was proposed, and the predictive equation was shown as equation (3) and the predictive equation fitting with experimental results was shown in Figure 11(b).

$$f_{\mathrm{yT}}/f_{\mathrm{y20}}=\begin{cases}-1.044\times10^{-9}T_{\mathrm{s}}^{3}+4.097\times10^{-7}T_{\mathrm{s}}^{2}+2.308T_{\mathrm{s}}+0.993 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0\\ -1.371\times10^{-9}T_{\mathrm{s}}^{3}+7.920\times10^{-7}T_{\mathrm{s}}^{2}+1.304T_{\mathrm{s}}+0.994 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.3\\ -1.066\times10^{-9}T_{\mathrm{s}}^{3}+2.620\times10^{-7}T_{\mathrm{s}}^{2}+3.418T_{\mathrm{s}}+0.989 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.55\\ 4.658\times10^{-12}T_{\mathrm{s}}^{3}-1.356\times10^{-6}T_{\mathrm{s}}^{2}+9.341T_{\mathrm{s}}+0.976 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.8\end{cases} \tag{3}$$

### 6.3 Ultimate strength reduction factor

The tested results in section 4.4 show that although the ultimate strength of

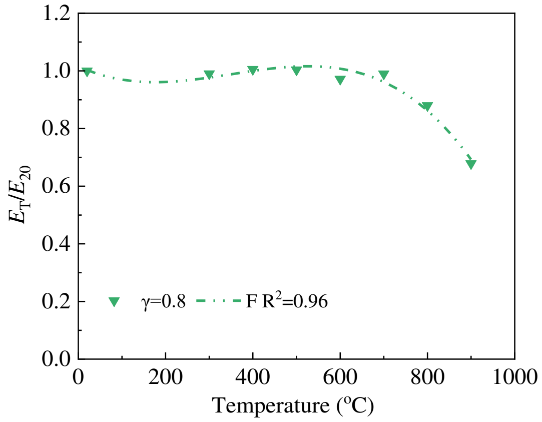
Q460GJ steel after elevated temperature heating and cooling had little change when the elevated temperatures were within 700 ºC, the ultimate strength of Q460GJ steel had a significant reduction above 700 ºC, and the reduction degree of ultimate strength was different under different pre-tensile stress ratios. The predictive equation of the ultimate strength reduction factors after elevated temperatures heating and cooling under different pre-tensile stress ratios was proposed, and the predictive equation was shown as equation (4) and the predictive equation fitting with experimental results was shown in Figure 11(c).

$$f_{\mathrm{uT}}/f_{\mathrm{u20}}=\begin{cases}-2.609\times10^{-10}T_{\mathrm{s}}^{3}-2.091\times10^{-7}T_{\mathrm{s}}^{2}+1.576\times10^{-4}T_{\mathrm{s}}+0.995 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0\\ -2.594\times10^{-10}T_{\mathrm{s}}^{3}-2.091\times10^{-7}T_{\mathrm{s}}^{2}+1.620\times10^{-4}T_{\mathrm{s}}+0.995 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.3\\ -8.686\times10^{-11}T_{\mathrm{s}}^{3}-4.797\times10^{-7}T_{\mathrm{s}}^{2}+2.516\times10^{-4}T_{\mathrm{s}}+0.994 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.55\\ 2.014\times10^{-10}T_{\mathrm{s}}^{3}-9.086\times10^{-7}T_{\mathrm{s}}^{2}+3.807\times10^{-4}T_{\mathrm{s}}+0.989 & 20℃\le T_{\mathrm{s}}\le 900℃,\ \gamma=0.8\end{cases} \quad (4)$$

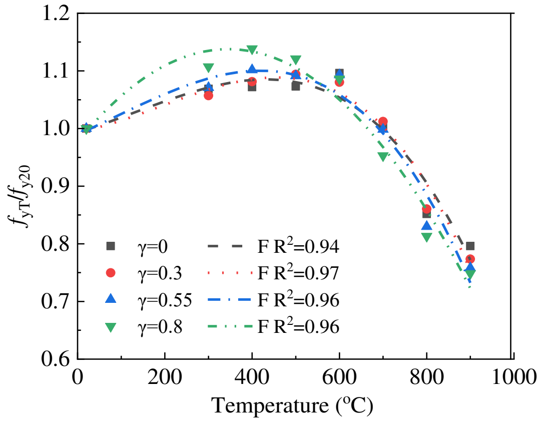
### 6.4 Ultimate elongation reduction factor

The predictive equation of the ultimate elongation reduction factors after elevated temperatures heating and cooling under different pre-tensile stress ratios was proposed, and the predictive equation was shown as equation (5) and the predictive equation fitting with experimental results was shown in Figure 11(d). In this article, three main pre-tensile stress ratios of 0.30, 0.55 and 0.80 were designed and the scope of tensile stress ratios basically covers the actual engineering situation. Linear interpolation method could be used to determine the retention of mechanical properties with other stress ratios.

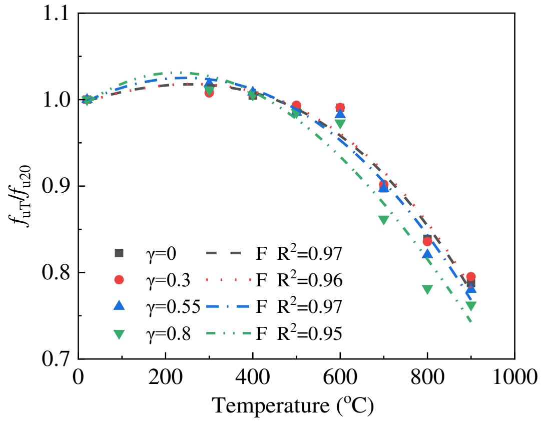
$$\varepsilon_T/\varepsilon_{20}=\begin{cases}1.387\times10^{-9}T_s^3-1.435\times10^{-6}T_s^2+4.869\times10^{-4}T_s+0.992 & 20℃\le T_s\le900℃,\ \gamma=0\\ 2.267\times10^{-9}T_s^3-2.714\times10^{-6}T_s^2+0.001T_s+0.984 & 20℃\le T_s\le900℃,\ \gamma=0.3\\ 1.355\times10^{-9}T_s^3-1.604\times10^{-7}T_s^2+6.933\times10^{-4}T_s+0.986 & 20℃\le T_s\le900℃,\ \gamma=0.55\\ 1.138\times10^{-9}T_s^3-1.347\times10^{-6}T_s^2+6.374\times10^{-4}T_s+0.988 & 20℃\le T_s\le900℃,\ \gamma=0.8\end{cases} \quad (5)$$



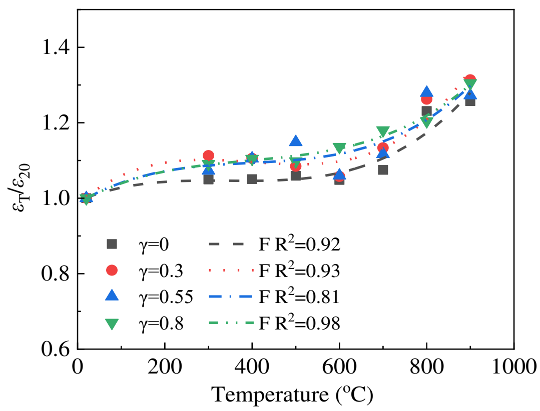

(a) Elastic modulus equation fitting.




(b) Yield strength equations fitting.




(c) Ultimate strength equations fitting.



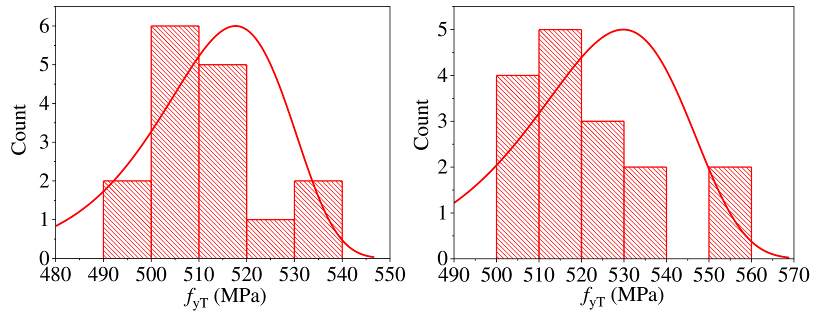

(d) Ultimate elongation equations fitting.

Fig. 11. Fittings of the predictive equations for the residual mechanical properties.

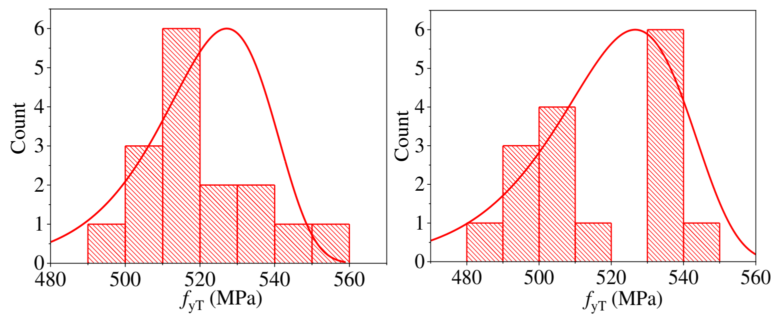
# 7. Variation coefficient of yield strength of Q460GJ steel

Since there are few references on the detailed specifications of mechanical parameters at elevated temperatures for Q460GJ steel in current design specifications, it is necessary to carry out a reliability analysis of yield strength of Q460GJ steel obtained with the test results. The frequency distribution histograms of $f_{yT}$ for Q460GJ steels after 20 min different elevated temperatures heating are shown in Figure 12. According to the AISI-S100 (2020) standard (Section K2.1.1) [44], the results of statistical analysis of yield strength are shown in Table 7. Table 7 shows the standard values of yield strength ($f_{yT}$) for the tested Q460GJ steel under different pre-tensile stresses after 20 min different elevated temperatures heating, which is determined by the 5% quantile of the Weibull's probability distribution. The standard value $\mu_{fyT}$, standard deviation $\sigma_{fyT}$ and variation coefficient $\delta_{fyT}$ of the yield strength for Q460GJ steel are shown in Table 7, which shows that based on the current sample conditions, the values of variation coefficient $\delta_{fyT}$ are reasonable ranged from 0.032 to 0.051, indicating that the standard values $\mu_{fyT}$ can provide a reference for the further reliability analysis of Q460GJ steel at the component level. The variation coefficient $\delta_{fyT}$ of the yield strength for Q460GJ steel at about 700 °C is slightly larger (0.051), mainly because the mechanical properties of steel change rapidly at about 700 °C.

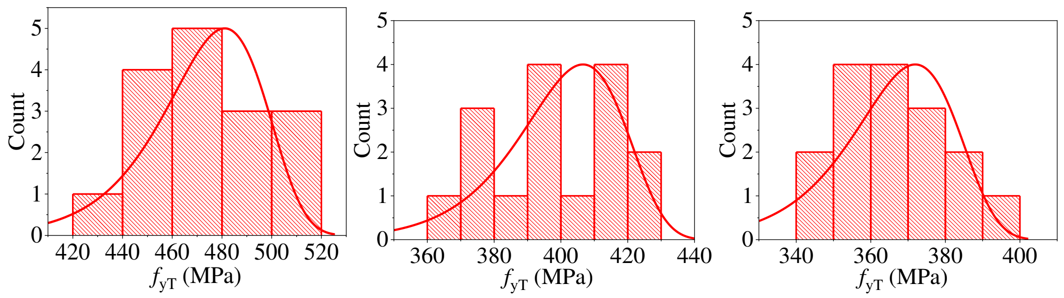
To sum up, the statistical analysis method (Weibull's probability distribution) was used to study the uniformity for Q460GJ steel under different pre-tensile stresses after different elevated temperatures heating. The results showed that the different pre-tensile stresses and different elevated temperatures heating did not affect the uniformity of steel yield strength. These experimental results demonstrate that uniform temperature and stress changes do not affect the uniformity of the material commonly. The variation coefficients $\delta_{fyT}$ of the yield strength for Q460GJ steel under different pre-tensile stresses after 20 min different elevated temperatures heating were within 0.065. The experimental results provide scientific support for the re-use determination of under different pre-tensile stresses after different elevated temperatures heating.




(a) After 20 min 300 °C heating. (b) After 20 min 400 °C heating.




(c) After 20 min 500 °C heating. (d) After 20 min 600 °C heating.




(e) After 20 min 700 °C heating. (f) After 20 min 800 °C heating. (g) After 20 min 900 °C heating.

Fig. 12. Frequency distribution histogram of $f_{yT}$ for Q460GJ steel after 20 min heating.

Table 7 The results of statistical analysis of $f_{yT}$ for Q460GJ steel after 20 min heating.

| $T$ (°C) | Statistical parameters | | |
|---|---|---|---|
| | $\mu_{fyT}$ | $\sigma_{fyT}$ | $\delta_{fyT}$ |
| 300 | 510.731 | 16.353 | 0.032 |
| 400 | 520.855 | 21.568 | 0.041 |
| 500 | 519.642 | 17.837 | 0.034 |
| 600 | 517.716 | 21.408 | 0.041 |
| 700 | 471.328 | 24.003 | 0.051 |
| 800 | 398.943 | 18.633 | 0.047 |
| 900 | 365.068 | 16.605 | 0.045 |

# 8. Conclusions

In this article, the post-fire residual mechanical properties of Q460GJ steel with two kinds of plate thickness (8 mm and 12 mm) under different pre-tensile stresses were studied. Based on the experimental results and calculation analyses, the following major findings are revealed.

(1) The stress-strain curves of two types of Q460GJ steel plates with different thicknesses at all testing conditions were quite similar. The difference in plate thickness does not affect the residual mechanical properties of the 8mm and 12mm Q460GJ steel plates. The pre-tensile stresses had no obvious effects on the stress-strain curves of Q460GJ steel plate specimens after 20 min elevated temperature heating, except for when the pre-tensile stress ratio was 0.8.

(2) The Q460GJ steel will lose part of its stiffness when exposed to 900 °C elevated temperature and with a high pre-tensile stress ratio at the same time. The yield strength of Q460GJ steel did not lose when the heating elevated temperature was below 700 °C

and the applied pre-tensile stress ratio was within 0.8. When the heating elevated temperatures were 600 ºC and below, the pre-tensile stress ratio has little effect on the yield strength. When the heating elevated temperatures were above 600 ºC, the ultimate strength decreased gradually with the increase of pre-tensile stress ratio, especially when the pre-tensile stress ratios were above 0.55. Q460GJ steel still maintains good ductility after elevated temperature heating, which increases the possibility of reuse of Q460GJ steel element after fire.

(3) The residual mechanical properties of Q460GJ steel after elevated temperature heating and cooling were different with that of Q460 steel and S460 steel. The Q460GJ steel has better ductility after elevated temperature heating and cooling than that of Q460 and S460 steels.

(4) The predictive equations for the residual mechanical properties for Q460GJ steel after elevated temperature heating and cooling under different pre-tensile stresses were proposed and were in good agreement with the experimental results of this study. The different pre-tensile stresses and different elevated temperatures heating did not affect the uniformity of steel yield strength. The findings should have a great significance to providing theoretical support for design of reusing or restoring the steel building after fire.

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# References


[1] Xing Y, Zhao O, Wang W. Testing, modelling and analysis of full-scale cold-formed steel center-sheathed shear walls in fire [J]. Engineering Structures, 2023, 284: 115970

[2] Zhai S Y, Lyu Y F, Cao K, et al. Seismic behavior of an innovative bolted connection with dual-slot hole for modular steel buildings[J]. Engineering Structures, 2023, 279: 115619.

[3] Xiong M X, Liew J Y R. Experimental study to differentiate mechanical behaviours of TMCP and QT high strength steel at elevated temperatures[J]. Construction and Building Materials, 2020, 242: 118105.

[4] Luo Z, Shi Y, Xue X, et al. Nonlinear patch resistance performance of hybrid titanium-clad bimetallic steel plate girder with web opening[J]. Journal of Building Engineering, 2023, 65: 105703.

[5] Kang Z, Liao Q, Zhang Z, et al. Carbon neutrality orientates the reform of the steel industry[J]. Nature Materials, 2022, 21(10): 1094-1098.

[6] Hua J, Fan H, Xue X, et al. Tensile and low-cycle fatigue performance of bimetallic steel bars with corrosion[J]. Journal of Building Engineering, 2021, 43: 103188.

[7] Hua J, Yang Z, Xue X, et al. Bond properties of bimetallic steel bar in seawater sea-sand concrete at different ages[J]. Construction and Building Materials, 2022, 323: 126539.

[8] Hua J, Wang F, Xue X, et al. Post-fire ultra-low cycle fatigue properties of high-strength steel via different cooling methods[J]. Thin-Walled Structures, 2023, 183: 110406.

[9] Jiang J, Bao W, Peng Z Y, et al. Experimental investigation on mechanical behaviours of TMCP high strength steel[J]. Construction and Building Materials, 2019, 200: 664-680.

[10] Zhang Z, Xu Y, Huang Y, et al. Experiment study on the mechanical properties and constitutive model of grade 1960 steel wires under and after elevated temperatures[J]. Journal of Building

Engineering, 2024, 82: 108318.

[11] Hua J, Wang F, Xue X, et al. Residual monotonic mechanical properties of bimetallic steel bar with fatigue damage[J]. Journal of Building Engineering, 2022, 55: 104703.

[12] Wang W, Li S, Ran T. Numerical Study on High Strength Q690 Steel Flush End-Plate Connections at Elevated Temperatures[J]. Fire Technology, 2024: 1-26.

[13] Xiong M X, Pi P W, Gong W, et al. Mechanical properties of TMCP high strength steels with different strength grades at elevated temperatures[J]. Journal of Building Engineering, 2022, 48:103874.

[14] Wu Z, Li L, Wu R, et al. Determination of high-temperature creep and post-creep response of structural steels[J]. Journal of Constructional Steel Research, 2022, 193: 107287.

[15] Kumar W, Sharma UK, Pathak P. Mechanical properties of low-alloyed YSt-355-FR (0.126% Mo) cold-formed steel tube at elevated temperatures[J]. Journal of Constructional Steel Research, 2022, 192:107198.

[16] Li G Q, Lyu H, Zhang C. Post-fire mechanical properties of high strength Q690 structural steel[J]. Journal of Constructional Steel Research, 2017, 132: 108-116.

[17] Hua J, Xue X, Huang Q, et al. Post-fire performance of high-strength steel plate girders developing post-buckling capacity[J]. Journal of Building Engineering, 2022, 52: 104442.

[18] Xing Y, Wang W, Zhao O. Experimental, numerical and analytical studies on full-scale cold-formed steel center-sheathed shear walls subjected to combined loading[J]. Engineering Structures, 2024, 307: 117910.

[19] Cao K, Zhai S Y, Lyu Y F, et al. Working mechanism evaluations of full-scale joints with bolted-cover plate connection for modular steel buildings[J]. Thin-Walled Structures, 2024, 199: 111772.

[20] Wang W, Li Y, Wang Z, et al. Experimental and numerical study on the behavior of high strength Q960 steel columns after fire exposure[J]. Thin-Walled Structures, 2024: 111748.

[21] Ren C, Dai L, Huang Y, et al. Experimental investigation of post-fire mechanical properties of Q235 cold-formed steel[J]. Thin-Walled Structures, 2020, 150: 106651.

[22] Tao Z. Mechanical properties of prestressing steel after fire exposure[J]. Materials and Structures, 2015, 48: 3037-3047.

[23] Lu J, Liu H, Chen Z. Post-fire mechanical properties of low-relaxation hot-dip galvanized

prestressed steel wires[J]. Journal of Constructional Steel Research, 2017, 136: 110-127.
[24] Zhang L, Wei Y, Au F T K, et al. Mechanical properties of prestressing steel in and after fire[J]. Magazine of Concrete Research, 2017, 69(8): 379-388.
[25] Du Y, Peng J, Liew J Y R, et al. Mechanical properties of high tensile steel cables at elevated temperatures[J]. Construction and Building Materials, 2018, 182: 52-65.
[26] Gao X, Zhang X, Liu H, et al. Residual mechanical properties of stainless steels S30408 and S31608 after fire exposure[J]. Construction and Building Materials, 2018, 165: 82-92.
[27] Shi G, Wang S, Chen X, et al. Post-fire mechanical properties of base metal and welds of Q235 steel[J]. Journal of Constructional Steel Research, 2021, 183: 106767.
[28] Qiang X, Bijlaard F S K, Kolstein H. Post-fire mechanical properties of high strength structural steels S460 and S690[J]. Engineering Structures, 2012, 35: 1-10.
[29] Qiang X, Bijlaard F S K, Kolstein H. Post-fire performance of very high strength steel S960[J]. Journal of Constructional Steel Research, 2013, 80: 235-242.
[30] Lee J, Engelhardt M D, Taleff E M. Mechanical properties of ASTM A992 steel after fire[J]. Engineering Journal, 2012, 49(1): 33.
[31] Wang W, Liu T, Liu J. Experimental study on post-fire mechanical properties of high strength Q460 steel[J]. Journal of Constructional Steel Research, 2015, 114: 100-109.
[32] Zhou H, Wang W, Wang K, et al. Mechanical properties deterioration of high strength steels after high temperature exposure[J]. Construction and Building Materials, 2019, 199: 664-675.
[33] Huang D, Zhang L, Wang W, et al. Test on post-fire residual mechanical properties of high strength Q690 steel considering tensile stress in fire[J]. Journal of Constructional Steel Research, 2022, 194: 107340.
[34] Yu Y, Lan L, Ding F, et al. Mechanical properties of hot-rolled and cold-formed steels after exposure to elevated temperature: A review[J]. Construction and Building Materials, 2019, 213: 360-376.
[35] Li Y, Wang M, Li G, et al. Mechanical properties of hot-rolled structural steels at elevated temperatures: a review[J]. Fire Safety Journal, 2021, 119: 103237.
[36] Huang D, Kodur V, Wang W. Temperature-dependent properties of high-strength steel for evaluating the fire resistance of structures[J]. Advances in Structural Engineering, 2023, 26(12): 2265-2281.

[37] Chiew S P, Zhao M S, Lee C K. Mechanical properties of heat-treated high strength steel under fire/post-fire conditions[J]. Journal of Constructional Steel Research, 2014, 98: 12-19.

[38] Gunalan S, Mahendran M. Experimental investigation of post-fire mechanical properties of cold-formed steels[J]. Thin-Walled Structures, 2014, 84: 241-254.

[39] Wang W, Zhang Y, Xu L, et al. Mechanical properties of high-strength Q960 steel at elevated temperature[J]. Fire Safety Journal, 2020, 114: 103010.

[40] GB/T 19879, Steel plates for building structures, Standards Press of China, Beijing, 2023 (in Chinese).

[41] GB/T 228, 1 Metallic Materials-Tensile Testing Part 1: Method of Test at Room Temperature, Standards Press of China, Beijing, 2010 (in Chinese).

[42] GB/T 228, 2 Metallic Materials-Tensile Testing Part 2: Method of Test at Elevated Temperature, Standards Press of China, Beijing, 2015 (in Chinese).

[43] Li S, Li A, Wang W. Mechanical properties and constitutive models of Q460GJ steel at elevated temperatures [J]. Journal of Constructional Steel Research, under review.

[44] American Iron and Steel Institute (AISI), S100-16, North American Specification for the Design of Cold-Formed Steel Structural Members, 2020.