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Post-Fire Residual Mechanical Properties of Steel Butt Weld- Experimental Study

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Abstract: Butt weld connection is one of the most commonly used connection types in steel structures, and its post-fire mechanical property is crucial for the estimation of the residual mechanical capacity of steel structures after building fires. To study the mechanical properties of butt weld connections after being exposed to high temperatures, Q235 and Q345 butt weld specimens were designed, heated to various high temperatures between 400 °C and 800 °C, and then naturally cooled to room temperature. Tensile tests were conducted on these butt weld specimens to obtain the force–displacement curves and relevant mechanical properties (yield and ultimate strengths) at various temperatures. The following conclusions were obtained from the test results: (1) The post-fire mechanical properties of the butt weld specimens were affected by material grade and heating temperature; (2) When the temperature exceeded 600 °C, the yield and ultimate strengths of the Q235 and Q345 butt weld specimens began to decrease; the strength reduction of the latter was greater than that of the former; (3) When the temperature was 800 °C, the yield strength and ultimate strength of Q235 decreased to 87% and 91% of the ambient-temperature yield and ultimate strengths, respectively; and (4) the yield and ultimate strengths of Q345 decreased to 83% and 87% of those at room temperature. Computational formulas for the yield and ultimate strengths of the butt weld specimens at high temperatures were

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also fitted and verified with test data to provide a safety evaluation method for steel structures after a fire.

Keywords: Butt Weld; Post-Fire; Mechanical Property; Reduction Factor; Calculation Formula

1 Introduction

A review of past fire accidents has indicated that most steel structures exhibit severe local damage after a fire, but overall structure collapse is rare because of the highly statically indeterminate times, the cooperative spatial bearing of the steel members, and the adoption of passive and active fire protection solutions. For instance, the Biosphere Building of the 67th World Expo in 1976 suffered from a big fire [1], as shown in Figure 1. All the cladding materials were burned, but the space steel truss structure was not seriously damaged. After careful investigation, the steel structure was reused in 1995. After a fire, the strength of steel can partially recover after cooling, and the structure retains some of its design loading-bearing capacity. Therefore, most post-fire structures can be reused through damage detection, repair, and consolidation to reduce the loss caused by fire. However, the high temperature of a fire influences the properties of steel materials, reduces the loading-bearing capacity of the steel members and joints, and affects the load-carrying properties of the overall structure. Therefore, systematic experimental study on the residual bearing capacity of common steel materials, connections, and joints of steel structures is significant in the evaluation and repair of post-fire structures.



(a) During fire (b) After repair

Figure 1. Biosphere Dome in Canada during fire and after repair [1]

Extensive studies have been conducted to investigate the high-temperature performance of steels of various grades and types [2–10]. These studies have revealed that generally, the strength and stiffness of steels significantly decrease with increased temperature. Furthermore, corresponding recommendations have been provided in design guides, such as the British Standard BS5950 Part 8 [11] and EC3 [12].

Currently, an increasing number of studies that are still limited [13–22] are being conducted on the post-fire mechanical properties of steels mainly in Europe, USA, Australia, and China. Outinen and Makelainen [13, 14] conducted an experimental study to determine the mechanical properties of S355 cold-formed steels at elevated temperatures and after cooling. Qiang et al. [15, 16] conducted experimental studies to estimate the mechanical properties of high-strength structural steels S460 and S690 and the very high-strength steel S960 after cooling from an elevated temperature of 1000 °C. A similar experimental study was performed by Gunalan and Mahendran [17] to identify the post-fire mechanical properties of cold-formed steels G300, G500, and G550 after exposure to temperatures reaching 800 °C. Chiew et al. [18] investigated the mechanical properties of reheated, quenched, and tempered high-strength steel plates (Grade S690) at elevated

temperatures and after cooling. Wang et al. [19] conducted an experimental research on the mechanical properties of high-strength Q460 steel after exposure to temperatures reaching 900 °C. The researchers considered natural air and water cooling methods. Other studies focused on the post-fire mechanical properties of pre-stressed steel wires [20], reinforced steels [21], and stainless steels [22]. In Annex B of BS 5950-8 (2003) [11], several recommendations are available for the reuse of mild steels after fire exposure.

Bolt and welded connections are the two major connection types of steel space structures and are key points in the identification of the residual carrying capacity of post-fire steel structures. Most previous studies focused on the residual mechanics of bolt connections after a fire [23–25], and only a few studies focused on the post-fire residual carrying capacity of butt weld connections.

A brief review of existing literature showed that few studies have explored the post-fire mechanical properties of the extensively used butt weld. In this study, butt welds with Q235-E4303 and Q345-E5016 welding were utilized, and the influence of excessively high temperature during a fire on the tensile strength and damage position of the butt weld was analyzed. The research results not only reveal the mechanical performance properties, including yield and ultimate strengths, of the butt weld after treatment with different high temperatures, but also provide a scientific basis to evaluate the residual mechanical properties of the butt weld connection of steel structure after a fire.

2 Experiment Design

2.1 Test specimen

To study the effects of steel grade and welding rod type on the post-fire mechanical properties

of butt weld, two specimen types were selected and tested based on Chinese standards [26,27]. The parameters of the two specimens are listed in Table 1. Two hot-rolled steel plates with a width of 120mm were connected to a completely welded butt weld, as shown in Figure 2a., The butt weld was then cut into a standard shape through cold line cutting, as shown in Figure 2b. The butt weld of the specimens was subsequently polished, as shown in Figure 2c.

Table 1. Parameters of the butt weld specimens

Specimen No.	Steel	Thickness (mm)	Welding Rod	Rod Diameter	Welding Current	Arc Voltage	Welding Speed
Q235-E4303	Q235B	10	E4303	4mm	160A	26V	15–20cm/min
Q345-E5016	Q345B	8	E5016	4mm	190A	22V	15–20cm/min

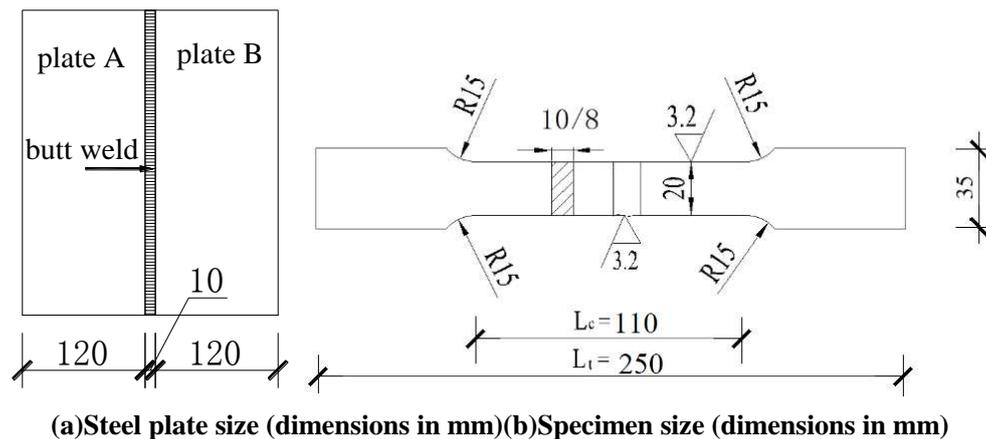


Figure 2. Butt weld specimens

2.2 Test equipment and procedure

Based on the test results presented in References [28] and [29] in revised paper, the residual mechanical properties of Q235 and Q345 butt weld specimens stay the same as the

ambient-temperature properties when the test temperatures were below 400°C and the test temperatures were mostly below 800°C. Therefore, five test temperatures between 400 °C and 800 °C were adopted in this study and three repeating tests were conducted at each temperature.

A middle-ring energy-saving electric box furnace(Figure 3a)was utilized as the equipment to heat the specimens (maximum temperature of 1200°C). Six different temperatures of 20°C, 400°C, 500°C, 600°C, 700°C, and 800°Cwereutilized. A SANS 600kN universal testing machine with microprocessor control and electro-hydraulic servo(Figure 3b)was used for the tensile test onthe specimens after high-temperature treatment.

The test proceeded as follows.

- 1) High-temperature processing. The butt weld specimens were placed in ahigh-temperature furnace and heated to the target temperature at a rate of 10°C/min to 20°C/min. The temperature was maintained for 30min, after which the specimens were removed from the furnace. The specimens were cooledtoindoor temperaturein air and labeled individually afterward.

- 2) Tensile test. Before this test, the sectional dimension of the specimens was measured with a Vernier caliper. The specimenswere placed on a universal testing machine and stretched until damage occurred. The force–strain curve of the specimens was recorded. The load was controlled by force inthe preliminary stage of the tensile test with rate of 10N/mm²; upon entering the stage of yield, the load was controlled by displacement at a rate of 4mm/min.



(a) High-temperature furnace (b) Universal testing machine

Figure 3. Test equipment

3 Experimental Results and Analysis

3.1 Test phenomenon

The appearance of the specimens after being subjected to high temperature is shown in Figure 4. After subjecting the specimens to 500°C, a carbonization zone appeared on the surface. At 800°C, the carbonization became increasingly serious.

The fracture modes of the typical specimens after the tensile test are shown in Figure 5. The positions of the constriction and fracture of the Q235 butt weld specimen were both in the parent metal. This condition indicates that the rigidity and strength of the Q235 butt weld connection were greater than those of the parent metal both at normal temperature and after experiencing 400°C to 800°C. For the Q345 butt weld specimen, the constriction and fracture positions were at the butt weld when the temperature was below 600°C. The specimen fractured at the parent metal when the temperature exceeded 700°C. This result indicates that the rigidity and strength of the parent metal of the Q345 butt weld specimen were greater than those of the weld joint when the temperature was below 600°C. Meanwhile, the rigidity and strength of the parent metal of Q345 were greater than those of the weld joint when the temperature exceeded 700°C.

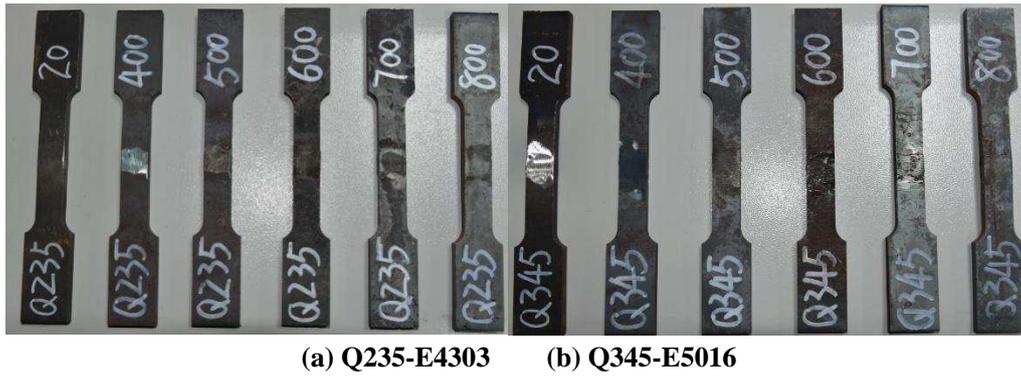


Figure 4. Specimens after high-temperature processing

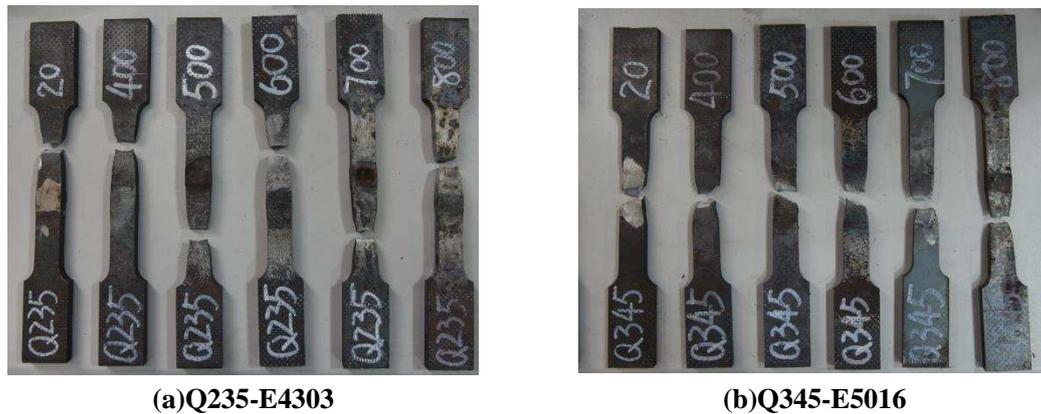


Figure 5. Fracture modes of the specimens

3.2 Force–displacement relationships

The force–displacement curve of the Q235 and Q345 butt weld specimens obtained from the tensile test is shown in Figure 6. It is clear that the force–displacement curve of the Q235 and Q345 butt weld specimens changed considerably after exposure to high temperature. The ductility of the Q235 butt weld specimen barely changed when the temperature was below 500°C, but the ductility of the specimen increased relatively when the temperature exceeded 600°C. The ductility of the Q345 butt weld specimen decreased when the temperature was between 400°C and 600°C and significantly increased when the temperature was 800°C.

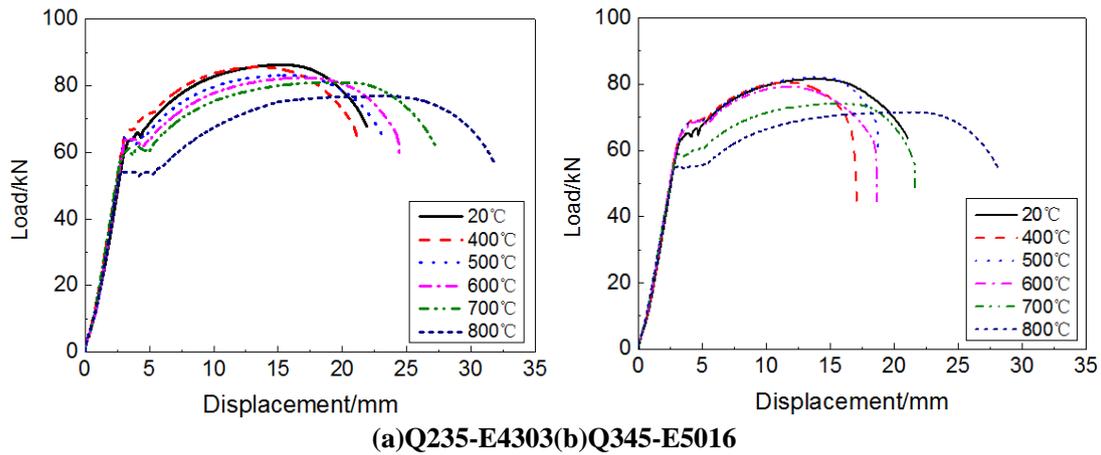


Figure 6. Force–displacement curves of the butt weld specimens after being subjected to high temperature

3.3 Yield and ultimate strengths

The yield and ultimate loads of all the specimens were obtained from the force–displacement curves. Tables 2 and 3 show the test results of Q235 and Q345 butt weld specimens, respectively. In the results, the reduction factor of yield strength under different temperatures is the ratio of the corresponding average yield strength under a certain temperature to the average yield strength under normal temperature. The reduction factor of ultimate strength corresponding to each temperature can be obtained in a similar manner.

Table 2. Experimental results of the Q235 butt-welded joint specimens

No.	T (°C)	Yield strength/MPa			Ultimate strength/MPa		
		F_y	F_{ay}	R_y	F_u	F_{au}	R_u
Q235-20-1	20	320.0			435.0		
Q235-20-2		310.0	316.9	1.00	425.0	427.3	1.00
Q235-20-3		320.7			422.0		
Q235-400-1	400	338.0			432.0		
Q235-400-2		345.0	338.0	1.07	435.0	430.7	1.01
Q235-400-3		331.0			425.0		
Q235-500-1	500	311.6			418.5		
Q235-500-2		314.5	318.3	1.00	420.5	419.5	0.98
Q235-500-3		328.7			419.6		
Q235-600-1	600	310.7			414.7		
Q235-600-2		308.4	309.7	0.98	416.2	416.1	0.97
Q235-600-3		309.9			417.5		
Q235-700-1	700	301.1			407.3		
Q235-700-2		301.6	298.8	0.94	414.4	414.4	0.97

Q235-700-3		293.6			421.4		
Q235-800-1		282.9			392.7		
Q235-800-2	800	271.7	274.9	0.87	383.3	388.7	0.91
Q235-800-3		270.1			390.2		

Table 3. Experimental results of the Q345 butt-welded joint specimens

No.	T (°C)	Yield strength/MPa			Ultimate strength/MPa		
		F _y	F _{ay}	R _y	F _u	F _{au}	R _u
Q345-20-1		410.0			520.0		
Q345-20-2	20	402.7	411.5	1.00	520.6	522.7	1.00
Q345-20-3		421.7			527.6		
Q345-400-1		420.0			515.0		
Q345-400-2	400	439.0	431.3	1.05	504.0	509.7	0.98
Q345-400-3		435.0			510.0		
Q345-500-1		430.0			520.0		
Q345-500-2	500	437.3	433.1	1.05	532.0	524.5	1.00
Q345-500-3		431.9			521.5		
Q345-600-1		440.0			515.0		
Q345-600-2	600	431.7	431.5	1.05	511.0	508.3	0.97
Q345-600-3		422.8			498.8		
Q345-700-1		370.0			475.0		
Q345-700-2	700	386.9	378.8	0.92	489.4	480.8	0.92
Q345-700-3		379.4			477.9		
Q345-800-1		345.0			460.0		
Q345-800-2	800	351.8	342.6	0.83	461.9	456.4	0.87
Q345-800-3		330.9			447.4		

Figures 7 and 8 show the changing curve of the reduction factor of the yield and ultimate strengths of the Q235 and Q345 butt weld specimens under different temperatures. A comparison was conducted with the test results (Q345-14) in Reference [28]. Material grade and temperature exerted a significant influence on the reduction factor of the yield and ultimate strengths of the butt weld specimens.

When the temperature was below 600°C, the yield strength of the Q235 and Q345 butt weld specimens was almost constant. Yield strength began to decrease when the temperature exceeded 600°C, and the decrement range of the Q345 butt weld specimen was greater than that of

the Q235 specimen. When the temperature reached 800°C, the yield strength of the Q235 and Q345 butt weld specimens decreased to 87% and 83% of that under normal temperature, respectively.

At 800°C, the ultimate strength of the Q235 butt weld specimens and the Q345 butt weld specimens decreased to 81% and 87% of that under normal temperature, respectively. The decreases in the ultimate strengths of the Q235 butt weld specimens were less than the Q345 butt weld specimens.

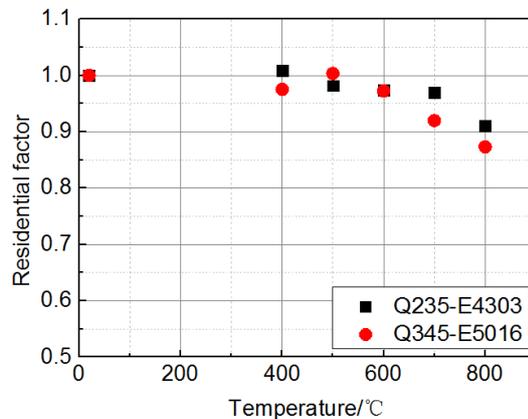
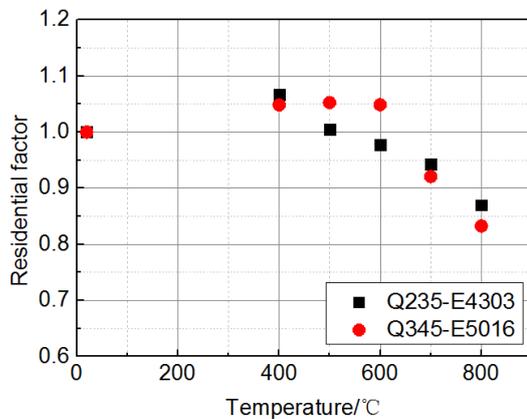


Figure 7. Reduction factor of yield strength Figure 8. Reduction factor of ultimate strength

3.4 Ductility

The ductility is a key parameter to reflect the plastic deformation capacity of the steel butt welds, which is quantitatively evaluated by elongation. The elongation and corresponding reduction factor of the steel butt welds after exposure to high temperature was shown in Table 4 and Figure 9. Following conclusions were obtained from Table 4 and Figure 9:

1) When the thermal treating temperature below 500°C, the ductility of Q235 steel butt welds had little change, and when the thermal treating temperature above 600°C, the ductility of Q235 steel butt welds was significantly increasing with temperature before and after exposure to high temperature.

2) When the thermal treating temperature below 700°C, the ductility of Q345 steel butt welds were reducing to some extent before and after exposure to high temperature, and when the thermal treating temperature above 800°C, the ductility of Q345 steel butt welds was significantly

increasing before and after exposure to high temperature.

3)The ductility of Q235 and Q345 butt weld specimensincreased by 42% and 38%respectivelyafter exposure to high temperature with 800°C, and the ductility of Q235 butt weld specimenswas higher than that of Q345 butt weld specimens.

Table 4. Experimental results of the butt-welded joint specimens

T(°C)	percentage elongation of fracture (%)		Residual factors	
	Q235-E4303	Q345-E5016	Q235-E4303	Q345-E5016
20	24.3	23.8	1.00	1.00
400	23.4	19.2	0.96	0.81
500	25.3	20.9	1.04	0.88
600	27.1	20.2	1.12	0.85
700	29.7	24.6	1.22	1.03
800	34.4	32.8	1.42	1.38

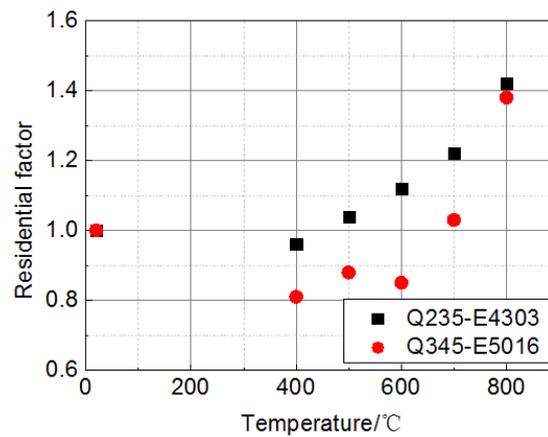


Figure 9 Reduction factor of ductility

4 Results comparison with previous test data

In this section, the residual factors of the mechanical properties of the Q235 and Q345 butt weld specimensafter exposure to high temperatures are compared with the corresponding data for the Q345-ER50 butt weld specimens in [28] and the hot-rolled Q235&Q345 steels in [29]. In this study, the Q235 and Q345 butt weld specimens were welded with E4303 and E5016 welding rod, respectively. While in reference [28], the Q345 butt weld specimens were welded with ER50 welding wire.

The yielding strength comparison was shown in Figure 10. The yield strength residual factors of the Q235-E4303 butt weld specimens decrease when the exposure temperature exceeds 500°C,

while the yield strength of the Q235 steel remained almost the same when the temperatures were below 700°C. As showed in Fig.10 the decreases in the yield strengths of the Q235 steels were less than that of the Q235-E4303 butt weld specimens. The reduction factors of the yield strength of the Q345-E5016, Q345-ER50 butt weld specimens and the Q345 steel begins to decline when the temperature exceeds 600°C. And the yield strength of the Q345-E5016 butt weld specimens decreased more than that of Q345.

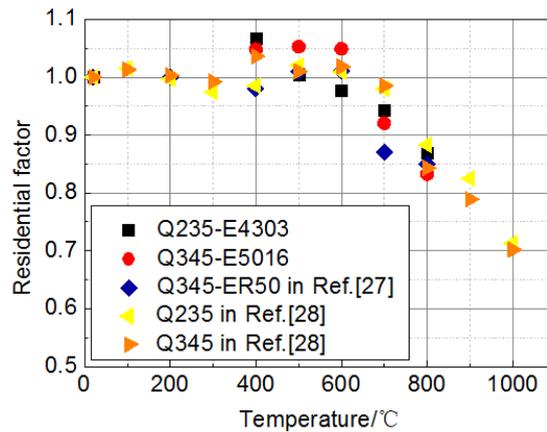


Figure 10. Yielding strength comparison of various specimens after exposure to high temperature

The ultimate strength comparison was shown in Figure 11. The ultimate strength of the Q235-E4303 butt weld specimens and Q235 steel decrease when the exposure temperature exceeded 400°C and 500°C respectively. And the decreases of ultimate strengths of the Q235-E4303 butt weld specimens were more than that of Q235 steels. The reduction factors of the ultimate strength of the Q345-E5016, Q345-ER50 butt weld specimens and the Q345 steel begins to decline when the temperature exceeds 500°C. And the yield strength of the Q345-E5016 butt weld specimens decreased less than that of the Q345-ER50 butt weld specimens, but more than that of Q345 steel.

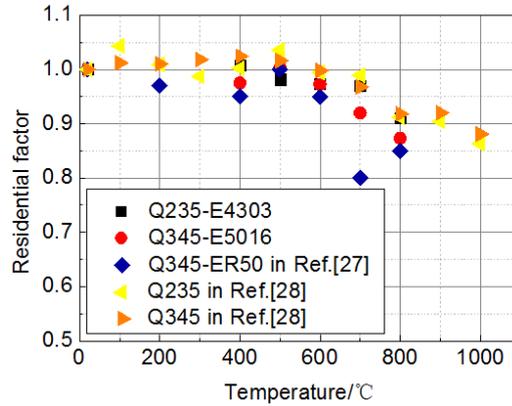


Figure 11. Ultimate strength comparison of various specimens after exposure to high temperature

5 Development of design equations

The experimental results show that the mechanical properties of the Q235 and Q345 butt weld specimens degrade as temperature rises. Design equations have been developed for the reduction factors of the yield and ultimate strengths of Q235 and Q345 butt weld.. Given that the maximum temperature that a test specimen experienced was the main reason for the degradation of its mechanical properties, the reduction factors were presented as functions of temperature. Since the residual mechanical properties of steel butt welds in this study were different from that in reference [28], the developed equations were presented for each steel butt welds based on their tested data as it shown in this section.

5.1 Yield strength

Equations(1)-(3) are proposed for the reduction factors of the yield strength of Q235 and Q345 butt weld based on test data, where f_{yT} is the yield strength corresponding to temperature T and f_y is the yield strength under room temperature.

Q235-E4303:

$$20 \leq T \leq 800^\circ\text{C} \quad f_{yT}/f_y = 0.994 + 4.139 \times 10^{-4}T - 7.129 \times 10^{-7}T^2 \quad (1)$$

Q345-E5016:

$$20 \leq T \leq 800^\circ\text{C} \quad f_{yT}/f_y = 1.002 - 1.582 \times 10^{-4}T + 1.527 \times 10^{-6}T^2 - 2.011 \times 10^{-9}T^3 \quad (2)$$

Q345-ER50:

$$20 \leq T \leq 800^\circ\text{C} \quad f_{yT}/f_y = 1.004 - 1.872 \times 10^{-4}T + 9.748 \times 10^{-7}T^2 - 1.257 \times 10^{-9}T^3 \quad (3)$$

5.2 Ultimate strength

Equations(4)-(6) are proposed for the reduction factors of the ultimate strength of Q235 and Q345 butt weld based on test data, where f_{uT} is the ultimate strength corresponding to temperature T and f_u is the ultimate strength under normal temperature.

Q235-E4303:

$$20 \leq T \leq 800^\circ\text{C} \quad f_{uT}/f_u = 0.997 + 1.384 \times 10^{-4}T - 2.919 \times 10^{-7}T^2 \quad (4)$$

Q345-E5016:

$$20 \leq T \leq 800^\circ\text{C} \quad f_{uT}/f_u = 1.006 - 3.422 \times 10^{-4}T + 1.259 \times 10^{-6}T^2 - 1.310 \times 10^{-9}T^3 \quad (5)$$

Q345-E5016:

$$20 \leq T < 500^\circ\text{C} \quad f_{uT}/f_u = 1 \quad (6a)$$

$$500 \leq T \leq 800^\circ\text{C} \quad f_{uT}/f_u = -10.750 - 5.850 \times 10^{-2}T + 9.500 \times 10^{-5}T^2 - 5.000 \times 10^{-8}T^3 \quad (6b)$$

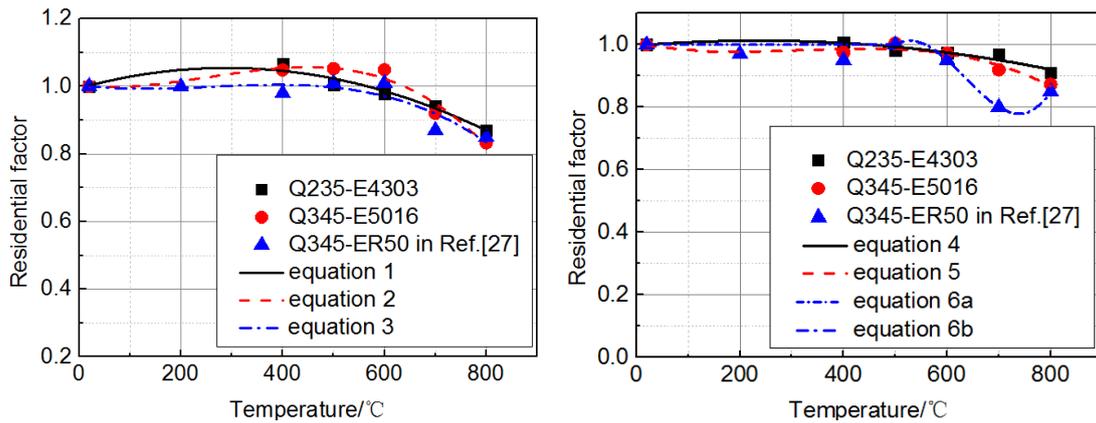


Figure 8. Reduction factors of yield strength and the corresponding fitting formula

Figure 9. Reduction factors of ultimate strength and the corresponding fitting formula

6 Conclusions

An experimental study was conducted on the mechanical properties of Q235-E4303 and

Q345-E501 butt weld subjected to high temperatures ranging from 400°C to 800°C. The following conclusions were obtained from the experimental data.

1) The yield and ultimate strengths of the butt weld specimens were affected by the grade of the material and temperature.

2) When the temperature was below 600 °C, the yield strength of Q235 and Q345 was constant. Yield strength began to decrease when the temperature exceeded 600°C, and the strength reduction of the Q345-E5016 specimen was greater than that of Q235-E4303.

3) The ultimate strengths of both the Q345 and Q235 butt weld specimens began to decrease when the temperature exceeded 400°C.

4) Design equations were developed for the yield and ultimate strengths of Q235 and Q345 butt weld subjected to high temperatures on the basis of the experimental results. This will be very useful for the post-fire safety assessment, repair and consolidation of steel structures.

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