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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 was800°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

1Introduction

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 staticallyindeterminate 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 wereburned, butthe 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 reducethe 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 structuresissignificant in the evaluation and repair ofpost-fire structures.

(a)Duringfire(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 thatgenerally, the strength andstiffness of steels significantly decreasewith increasedtemperature. Furthermore, corresponding recommendations have been provided in design guides, such as the British Standard BS5950 Part 8 [11] and EC3 [12].

Currently, an increasingnumber of studies that are still limited [13–22] are being conducted on the post-fire mechanical properties of steels mainlyin 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 veryhigh-strengthsteel S960 after cooling from an elevated temperatureof 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 studiesfocused on the post-fire mechanical properties of pre-stressedsteel wires [20], reinforcedsteels [21], and stainless steels [22]. In Annex B of BS 5950-8 (2003) [11], severalrecommendations are available for the reuse of mild steels after fire exposure.

Bolt and welded connections are the two major connectiontypes of steel space structures and are key points in the identification of the residual carrying capacity of post-fire steel structures. Most previous studiesfocused 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 usedbutt weld. In this study, butt welds with Q235-E4303 and Q345-E5016 welding wereutilized, and the influence of excessively high temperature during afire on the tensile strength and damage position of the butt weld was analyzed. The research results not only revealthe mechanical performance properties,including yield and ultimate strengths, of the butt weld after treatment with different high temperatures, but also provide a scientific basisto evaluate the residual mechanical propertiesof the butt weld connection of steel structure after a fire.

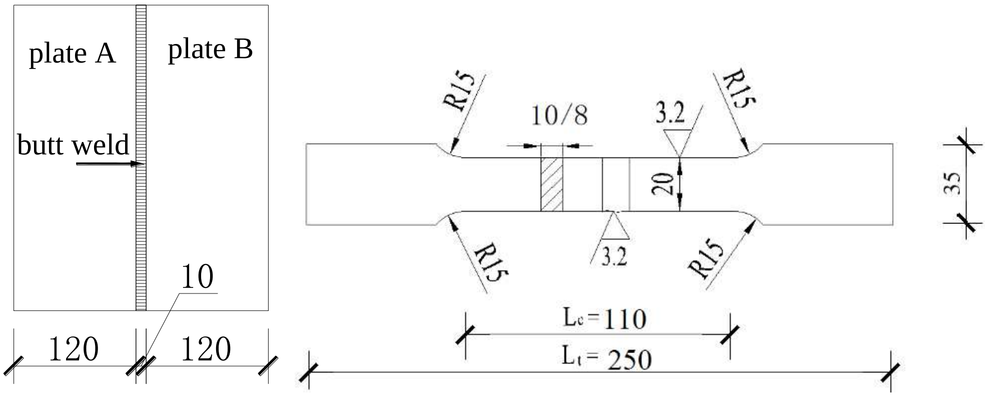
2Experiment Design

2.1Test specimen

To study the effects of steel grade and welding rod typeon 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 arelisted in Table 1. Two hot-rolled steel plates with a width of 120mm were connected toa completely welded butt weld, as shown in Figure 2a., The butt weld was then cut into a standard shape throughcold line cutting, as shown in Figure 2b. The butt weld of the specimens was subsequentlypolished, 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



(a)Steel plate size (dimensions in mm)(b)Specimen size (dimensions in mm)

(c) Specimen after polishing

Figure 2.Butt weld specimens

2.2Test equipmentand 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/mm^2; 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

3Experimental Results and Analysis

3.1Test phenomenon

The appearance of thespecimens afterbeing subjected tohigh temperature is shown in Figure 4. After subjecting the specimens to 500°C, a carbonization zone appeared on the surface. At800°C, the carbonization became increasingly serious.

The fracture modes of the typical specimens after the tensile testareshown in Figure 5. The positions of the constriction and fracture of the Q235 butt weld specimen were both inthe 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 exceeded700°C. This result indicates that the rigidity and strength of the parent metal of the Q345 butt weld specimen weregreater than thoseof 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.

(a) Q235-E4303 (b) Q345-E5016

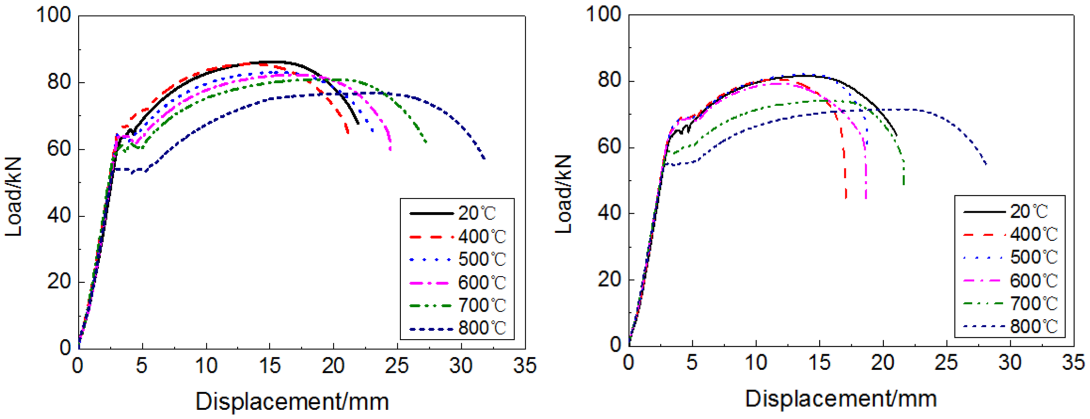
Figure 4.Specimens after high-temperature processing

(a)Q235-E4303 **(b)Q345-E5016**

Figure 5. Fracture modes of the specimens

3.2Force–displacement relationships

The force–displacement curve of the Q235 and Q345 butt weld specimens obtained from the tensile test isshown 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 changedwhen the temperaturewasbelow 500°C, but the ductility of the specimen increasedrelatively when the temperature exceeded600°C. The ductility ofthe Q345 butt weld specimen decreasedwhen the temperature wasbetween 400°C and 600°C and significantlyincreasedwhen the temperaturewas800°C.



(a)Q235-E4303(b)Q345-E5016

Figure 6. Force–displacement curves of the butt weld specimensafterbeing subjected to high temperature

3.3Yield and ultimate strengths

The yield and ultimate loads of all the specimenswere obtained from the force–displacement curves. Tables 2 and 3 showthe 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 certaintemperature to the average yield strength under normal temperature. The reduction factor of ultimate strength corresponding toeach temperature can be obtained in a similar manner.

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

No.	T（℃）	Yield strength/MPa			Ultimate strength/MPa		
		F_y	F_{ay}	R_y	F_u	F_{au}	R_u
Q235-20-1		320.0			435.0		
Q235-20-2	20	310.0	316.9	1.00	425.0	427.3	1.00
Q235-20-3		320.7			422.0		
Q235-400-1		338.0			432.0		
Q235-400-2	400	345.0	338.0	1.07	435.0	430.7	1.01
Q235-400-3		331.0			425.0		
Q235-500-1		311.6			418.5		
Q235-500-2	500	314.5	318.3	1.00	420.5	419.5	0.98
Q235-500-3		328.7			419.6		
Q235-600-1		310.7			414.7		
Q235-600-2	600	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		

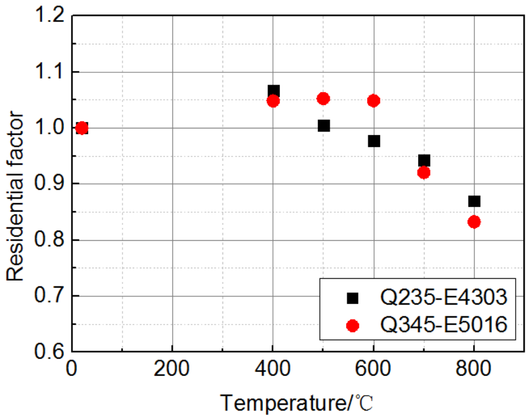
Table 3. Experimental results of the Q345 butt-welded joint specimens

No.	T（℃）	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]. Materialgrade and temperatureexerteda significant influence on the reduction factor of the yield and ultimate strengths of the butt weld specimens.

When the temperature wasbelow 600°C, the yield strength of the Q235 and Q345 butt weld specimenswas almostconstant. Yield strengthbeganto decrease when the temperature exceeded600°C, and the decrementrange of the Q345 butt weld specimenwasgreater than that of the Q235 specimen. When the temperature reached800°C, the yield strength of the Q235 and Q345 butt weld specimensdecreasedto 87% and 83% of that under normal temperature, respectively.

At 800°C, the ultimate strength of the Q235 butt weld specimensand the Q345 butt weld specimensdecreasedto 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.



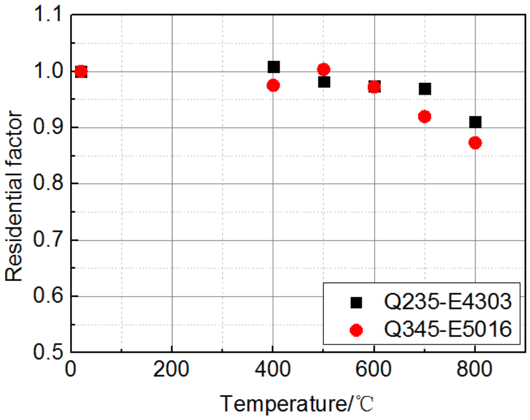


Figure 7.Reduction factor of yield strength

Figure 8. Reduction factor of ultimate strength

3.4 Ductility

The ductility is ankey parameterto reflect the plastic deformationcapacity 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 extentbefore 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℃, 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(℃)	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

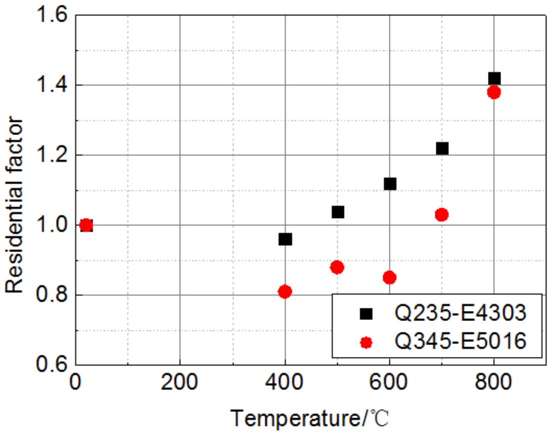


Figure 9Reduction factor of ductility

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.

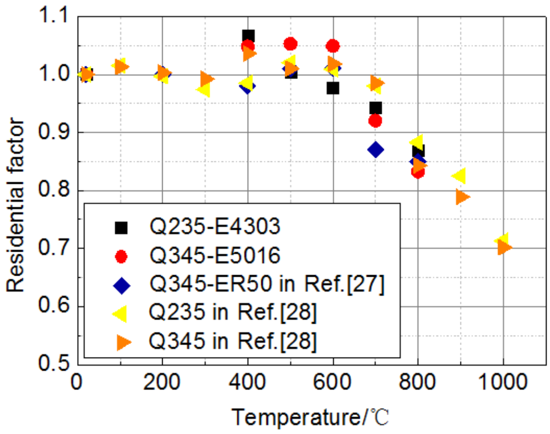


Figure 10. Yielding strength comparison of various specimens after exposure to high temperature

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 ofthe Q345-ER50 butt weld specimens, but more than that of Q345 steel.

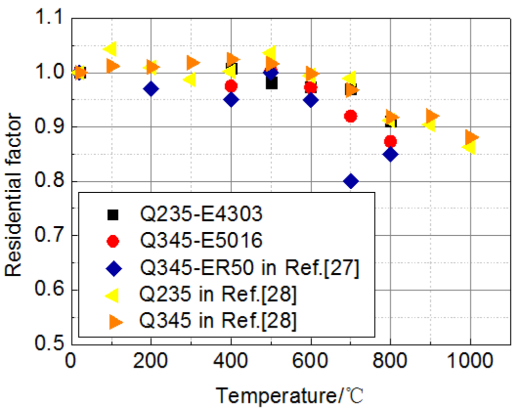


Figure 11.Ultimate strength comparison of various specimens after exposure to high temperature

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.

5.1Yield 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:

$$20 \leq T \leq 800℃ \quad f_{yT}/f_y = 0.994 + 4.139\times10^{-4}T - 7.129\times10^{-7}T^2 \quad (1)$$

Q345-E5016:

$20\leq T\leq 800$℃ $f_{yT}/f_y=1.002-1.582\times10^{-4}T+1.527\times10^{-6}T^2-2.011\times10^{-9}T^3$ （2）

Q345-ER50:

$20\leq T\leq 800$℃ $f_{yT}/f_y=1.004-1.872\times10^{-4}T+9.748\times10^{-7}T^2-1.257\times10^{-9}T^3$ （3）

5.2Ultimate 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:

$20\leq T\leq 800$℃ $f_{uT}/f_u=0.997+1.384\times10^{-4}T-2.919\times10^{-7}T^2$ (4)

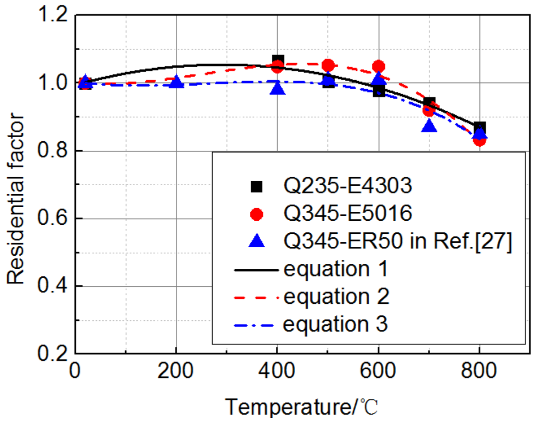
Q345-E5016:

$20\leq T\leq 800$℃ $f_{uT}/f_u=1.006-3.422\times10^{-4}T+1.259\times10^{-6}T^2-1.310\times10^{-9}T^3$ （5）

Q345-E5016:

$20\leq T<500$℃ $f_{uT}/f_u=1$ （6a）

$500\leq T\leq 800$℃ $f_{uT}/f_u=-10.750-5.850\times10^{-2}T+9.500\times10^{-5}T^2-5.000\times10^{-8}T^3$ （6b）



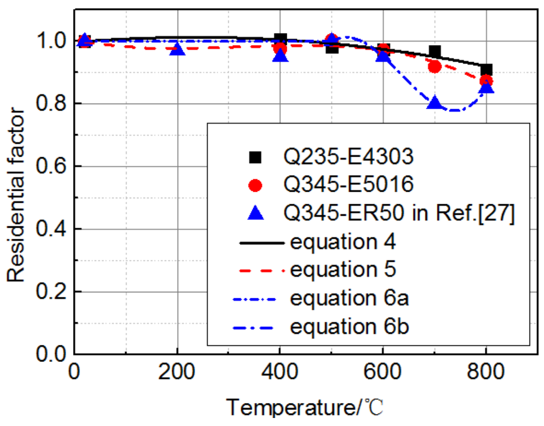


Figure 8. Reduction factors of yield strength and the corresponding fitting formula

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

6Conclusions

Anexperimental study was conducted onthe mechanical propertiesof Q235-E4303 and

Q345-E501butt weld subjected to high temperatures ranging from 400°Cto 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 wasbelow 600 °C, the yield strength of Q235 and Q345wasconstant. Yield strength began to decrease when the temperature exceeded600°C, and the strength reduction of the Q345-E5016 specimen wasgreater than that of Q235-E4303.

3)The ultimate strengths of both the Q345 and Q235 butt weld specimens began to decrease when the temperature exceeded400°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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References

[1] http://www.atlasobscura.com/places/biosphere-of-montreal

[2] Outinen J, Kesti J, Makelainen P. Fire design model for structural steel S355based upon transient state tensile test results. Journal of constructional steel research, 1997, 42(3): 161-169.

[3] Makelainen P, Outinen J, Kesti J. Fire design model for structural steel S420M based upon

transient-state tensile test results. Journal of constructional steel research, 1998, 48(1): 47-57.

[4] Outinen J, Kaitila O, Makelainen P. High-temperature testing of structural steel and modelling of structures at fire temperatures. Helsinki, Finland: Helsinki University of Technology Laboratory of Steel Structures; 2001.

[5] Chen J, Young B, Uy B. Behavior of high strength structural steel at elevated temperatures. Journal of Structural Engineering, 2006, 132(12): 1948-1954.

[6] Lange J, Wohlfeil N. Examination of the mechanical properties of the microalloyed grain refined steel S460 at elevated temperatures. Bautechnik, 2007, 84(10): 711-720.

[7] Chen J, Young B. Experimental investigation of cold-formed steel material at elevated temperatures. Thin-Walled Structures, 2007, 45(1): 96-110.

[8] Ranawaka T, Mahendran M. Experimental study of the mechanical properties of light gauge cold-formed steels at elevated temperatures. Fire safety journal, 2009, 44(2): 219-229.

[9] McCann F, Gardner L, Kirk S. Elevated temperature material properties of cold-formed steel hollow sections. Thin-Walled Structures, 2015, 90: 84-94.

[10] LuoYongfeng, Wang Xiyu, QiangXuhong, Liu Xiao. Progress in application of high strength steel to engineering structures. Journal of Tianjin University, 2015, 48 (Suppl.): 134-141.

[11] BS 5950. Structural use of steelwork in building. Part 8: code of practice for fire resistant design. Institution BS; 1998.

[12] Eurocode 3. Design of steel structures. Part 1-2: general rules-structural fire design. CEN; 2005.

[13] Outinen J, Makelainen P. Mechanical properties of structural steel at elevated temperatures and after cooling down. Fire and materials, 2004, 28(2-4): 237-251.

[14] Outinen J. Mechanical properties of structural steels at high temperatures and after cooling down [Ph.D. thesis]. Helsinki, Finland: Helsinki University of Technology; 2007.

[15] Qiang X, Bijlaard F S K, Kolstein H. Post-fire mechanical properties of high strength structural steels S460 and S690. Engineering Structures, 2012, 35: 1-10.

[16] Qiang X, Bijlaard F S K, Kolstein H. Post-fire performance of very high strength steel S960. Journal of Constructional Steel Research, 2013, 80: 235-242.

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

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

[19] Wang W, Liu T, Liu J. Experimental study on post-fire mechanical properties of high strength Q460 steel. Journal of Constructional Steel Research, 2015, 114: 100-109.

[20] Atienza J M, Elices M. Behavior of prestressing steels after a simulated fire: Fire-induced damages. Construction and Building Materials, 2009, 23(8): 2932-2940.

[21] Tao Z, Wang X Q, Uy B. Stress-strain curves of structural and reinforcing steels after exposure to elevated temperatures. Journal of Materials in Civil Engineering, 2012, 25(9): 1306-1316.

[22] Wang X Q, Tao Z, Song T Y, et al. Stress–strain model of austenitic stainless steel after exposure to elevated temperatures. Journal of Constructional Steel Research, 2014, 99: 129-139.

[23] Yu L. Behavior of bolted connections during and after a fire [D]. Austin: University of Texas at Austin, 2006.

[24] Hanus F, Zilli G, Franssen J M. Experimental tests and analytical models for welds and Grade 8.8 bolts under heating and subsequent cooling [J] Journal of Structural Fire Engineering, 2011, 2(3): 181-194.

[25] Lou Guobiao, Zhu Meichun, Li Ming, Zhang Chao, Li Guoqiang. Experimental research on slip-resistant bolted connections after fire [J]. Journal of Constructional Steel Research, 2015, 104(1): 1-8.

[26] GB/T 50661-2011. Code for Welding of Steel Structure. Standards Press of China; 2011.

[27] GB/T 2651-2008. Tensile Test Method for Welded Joint. Standards Press of China; 2008.

[28] Cheng Liang, Zhu Meichun, Li Guoqiang. Experimental study on post-elevated temperature mechanical properties of butt-welded connections [J].Engineering Mechanics, 2015, 32(Suppl):298-303. (in Chinese)

[29] Lu Jie, Liu Hongbo, Chen Zhihua, Liao Xiangwei. Experimental investigation into the post-fire mechanical properties of hot-rolled and cold-formed steels [J]. Journal of Constructional Steel Research, 2016. 121: 291-310.