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Experimental study on post-fire mechanical properties of Q235 cold-formed steels

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Abstract

Cold-formed steels have been commonly applied in construction. However, there is a lack of understanding on its post-fire mechanical properties. This paper presents an experimental investigation into the post-fire mechanical properties of cold-formed steels. The test specimens were cut from the flat portion and corners of cold-formed channel sections, which were exposed to temperatures ranging from ambient temperature to 800°C, and then cooled with water and air. The specimens are of grade Q235, and of thickness 1mm and 2mm. The stress-strain curves and mechanical properties of all specimens were obtained from tensile coupon tests. A comparison of mechanical properties between coupon samples cut from flat portion and corners is presented. Moreover, the evolution of microstructure and fracture morphology of specimens after being cooled by air and water were examined. Finally, predictive equations are proposed for evaluating the post-fire mechanical properties of Q235 cold-formed steel channel sections.

Key Words: *Cold-formed steel; Post-fire; Cold forming process; Microstructure;*

Tensile coupon tests; Mechanical properties

1. Introduction

In the past few decades, cold-formed steel sections have become increasingly popular for residential, commercial and industrial buildings, because they are convenient to construct, transport and assemble. However, owing to the quick deterioration of their stiffness and material strength at high temperature, fire safety design is crucial for their structural applications.

Substantial researches on steel material and structural members under fire conditions have been carried out, and the results have been adopted in design codes such as the European Code (EC3) [1], Australian Standard (AS4100) [2], and American Specification (AISC Specification) [3]. Mechanical properties of various steel materials, including cold-formed steels [4-6], high strength steels [7-9] were reported under fire conditions. Furthermore, many researchers [10-13] investigated the cold-formed members at various elevated temperatures. Qiang et al. [14] and Gunalan and Mahendran [15] performed an experimental study on high-strength and cold-formed steels, and found that their post-fire behaviours are influenced by steel grade. Lu et al. [16] experimentally investigated the post-fire behaviour of hot-rolled and cold-formed steels and found that they have different reduction factors. Kesawan and Mahendran [17] demonstrated that cold-formed steel hollow and open channel sections have different post-fire material properties. Sajid and Kiran [18] conducted an experimental study and found that cooling methods have important influences on post-fire mechanical behaviour of ASTM A36 steels. In addition, works were also presented on the post-fire behaviour of steel connections [19, 20], pre-stressing steels [21, 22], reinforcing steels [23], stainless steels [24-26], high strength steels [27-28,29,30] and hot-rolled steels [31]. The post-fire mechanical properties affect the reusability and repair of structures after fire hazards. The literature survey on the post-fire mechanical properties mentioned above provides a reliable basis for the assessment of the behaviour of steel structures after fire hazards. However, there is a lack of study on the effects of cooling method on the post-fire performance of cold-formed steels [16]. Current design standards have also not provided applicable information on the behaviour of cold-formed steels after fire hazards.

It is well known that strength hardening due to cold-forming process occurs at corners, which results in an increase of yield strength. Previous studies mainly focus on the flat portion, and thus the prediction of residual strength of structural members after a fire based on their flat portion might be over-conservative. In addition, the post-fire mechanical properties and microstructure transformations of cold-formed steel are different from hot-rolled steels because of the cold-working, which were reported and reviewed by Yu et al. [32]. A few investigations were reported on the performance of corner portion at room temperature [33-35] and being cooled from high temperatures [36]. Chen et al. [37] conducted the experiments on cold-formed steels and pointed out that the material behaviour of flat portion and corners are different at room temperature but similar under fire condition. While the flattened ends of corner specimens, which are convenient to fix in tensile coupon test, cause the bending effect, which obviously did not accord with the actual situation. Lu et al. [16] conducted an experiment on cold-formed steel rods instead of real corner specimens to investigate the post-fire behaviour of corners. Therefore, it is far from enough for investigating the mechanical properties of corner portion. Mechanical response is a result of evolution of material microstructure caused by external factors. Azhari et al. [38] investigated the microstructures of MS, HSS and UHSS tube specimens both in initial situation and after being cooled from 600 °C in order to give a detailed description of the changes in material properties. It was found that the effect of temperature on microstructure differs greatly in low and high temperatures. Summers et al. [39] conducted the experiments to examine the evolution of aluminium alloy residual mechanical properties in detail, focused on the governing effect of microstructure. Furthermore, there are other studies on the microstructure and fracture morphology of austenitic steel [40-42], hot-rolled steel [43, 44], stainless steel [45, 46], and aluminium alloy [47]. However, the study concerning the micro-performance of cold-formed steel is not enough due to the limitation knowledge of Material Science and Engineering in the field of Civil Engineering. The changes occurred in microstructure and fracture morphology of cold-formed steel material during heating-cooling process result in a change of post-fire material behaviour. Therefore, this paper elaborates the details in microstructure and fracture morphology to understand the characteristics of the cold-formed steel after being cooled with different cooling methods.

This paper reports an experimental investigation on the mechanical properties of flat portion and corners of Q235 cold-formed steel channel section, which were cooled by air and water after being exposed to different high temperatures. Tensile coupon tests were then conducted at ambient temperature to obtain post-fire mechanical properties of the specimens. Moreover, the influences of cooling methods and exposure temperatures on post-fire performance, and the differences of microstructure and fracture morphology between flat and corner portion were examined. Finally, predictive equations are proposed for evaluating the post-fire mechanical properties.

2. Experimental program

2.1. Test specimens

A total of 132 specimens were extracted from Q235 cold-formed steel channel sections (Fig. 1a). The configuration of coupon specimens conforms to GB/T 2651-2008 [48], as shown in Fig. 1b and 1c. The nominal thicknesses of the specimens are 1 mm and 2 mm. Detailed dimensions of specimens are presented in Tables 1 and 2.

2.2. Heating and cooling processes

The electric furnace used in this study is shown in Fig. 2. The steel specimens were heated up to five target temperatures, i.e., 200 °C, 400 °C, 600 °C, 700 °C and 800 °C. A group of 6 specimens (1mm and 2mm) was tied to a steel rod, and each specimen was connected to a thermocouple recording the specimen temperature, as shown in Fig. 3. Two groups of specimens were placed in the furnace at the same time. After the temperature reached to the target, it was kept for 10 minutes for stabilisation, and then one group of specimens was rapidly moved out from the furnace into water, while the other group was taken out and hung in the air. Fig. 4 demonstrates the entire heating–cooling procedure. The variation of specimen temperature with time for air cooling is shown in Fig. 5.

2.3. Tensile coupon test

Tensile coupon tests were conducted on the test specimens at ambient temperature, after being cooled down from high temperatures. According to GB/T 228.1-2010 [49], tensile coupon tests were performed using a MTS electromechanical universal testing machine. The stress-strain curves and key mechanical properties of each specimen were obtained from tensile coupon tests. Mechanical properties were determined by the mean value of three test results obtained from identical coupon specimens. For the corner coupon tests, a specially designed grip and steel rods with rough surface were used to clamp the two ends of the coupon specimen, in order to apply tensile force through the centroid of cross-section, and thus to avoid any eccentricity during loading. The clamp is shown in Fig. 6.

2.4. Microstructure and Fracture Morphology

Microstructure affects the mechanical response of steel materials. For the sake of investigating the differences of strength between flat and corner specimens, and the effects of cooling method on strength of cold-formed Q235 steel, the microstructures of 6 samples respectively taken from unheated flat and corner specimens and those after being cooled from 800 °C were analysed by means of Olympus BX41M metallographic microscope. Before the observation, 6 samples were grounded by sandpaper and polished with diamond compounds, and then chemically etched with alcohol solution containing 4% of nitric acid.

The fracture morphologies of failure coupons after being stretched were observed using Zeiss scanning electron microscope. A total of 10 samples were cut from flat and corner specimens, including two samples being exposed to high temperatures, and four samples being respectively exposed to 600 °C and 800 °C. These samples were washed via ethanol-sonication method and observed from micro perspective to figure out the evolution of ductility of Q235 cold-formed steel after being cooled with two cooling methods. The number of samples for microscopic analysis can be seen in Table 3.

3. Test results

The visual observation, microstructure, fracture morphology, elongation and stress-strain relationship were obtained from tensile test and metallograph and scanning electron microscope in this study. However, it should be noted that the influence of fire experience on the elastic modulus is insignificant since the elastic moduli remain almost unchanged after cooling down from elevated temperatures up to 800°C in recent researches [16, 31]. Therefore, the elastic modulus was not considered in this study.

3.1. Visual observations

The failed flat and corner test specimens cooled down from various temperatures with air and water cooling methods are shown in Fig. 7. As shown in these pictures, due to the consequence of oxidation, the surface colour of steel is blue at temperature of 400 °C, which means that the temperature has reached blue brittle temperature [50]. Blue brittleness refers to the phenomenon that the steel colour becomes blue. Meanwhile, brittleness and strength increase in a certain temperature range for steels with different composition reported by Wang et al. [51] in 200-450° C and Qiang et al. [14] in 300° C. Furthermore, the oxidation has an important influence on corrosion rate and visual observation of steels reported by Sajid and Kiran [18], which provide details about the type of oxidation for ASTM A36 steels. In this study, the elevated temperature effect makes surface of specimens rougher with producing oxidations at high temperatures, especially experiencing water cooling, as shown in Fig. 7. Meanwhile, it becomes increasingly dark after experiencing temperatures above 600 °C. The surface colour of steel can be a helpful indicator to judge the experienced temperatures of steel members and structure after a practical fire condition.

3.2. Microstructure evolution

The optical micrographs of the microstructures of the flat and corner unheated samples and those cooled from 800 °C with air and water cooling methods are shown in Fig. 8. The change of microstructures of the specimens cooled from 800 °C is more obvious and easier to observe than those after being cooled from other temperatures. The black lines are boundaries between the different grains and delineate the white regions, which are the ferrite grains highlighted, as an example, in Fig. 8a. The microstructure is mainly composed of ferrite and granular pearlite at ambient temperature. Compared with the samples at ambient temperature, the ferrite grains in the samples that are cooled from 800°C are larger, and some black regions, which represent a certain proportion of pearlite, can be found. It indicates that new pearlites are formed after heating and cooling. It can be noticed that corner samples show more pearlites than flat sample, while the samples being water cooled have more pearlites than those being air cooled, as shown in Fig. 8. The material strength is affected by the amount of pearlites and size of ferrite grains, as more pearlites and smaller grain lead to a higher strength. The amount of pearlites within the same area of the optical micrographs of different specimens, indicated by red line squares in Fig. 8, were measured. The proportions of pearlites within the red line square are 6.54 %, 14.21 %, 8.01 %, 20.57 % for air-cooled flat sample, air-cooled corner sample, water-cooled flat sample and water-cooled corner sample, respectively. This indicates that corner portion of Q235 cold-formed steel has a higher strength than flat portion, and the strength of specimens after water cooled can be gained compared with those after being air cooled from 800 °C. These are in accordance with the tensile test results mentioned in later sections.

3.3. Stress–strain curves

The stress–strain curves of tensile coupon tests obtained at ambient temperature and those cooled from 200 - 800 °C with two cooling methods are shown in Fig. 9. The stress–strain curves obtained from coupon specimens at ambient temperature and 200 °C exhibit gradual yielding without the presence of yield plateau. The same behaviour was observed in coupon specimens that were water cooled from 700 °C and 800 °C. Thus, for these specimens with yield plateau, the yield strength was determined according to the 0.2% proof stress, otherwise the yield strength was defined as lower boundary of yield plateau. For the flat specimens after water cooling form temperatures above 600°C (above 400°C for corner specimens), a sharp decline was found in ultimate strain. And the ultimate strength increased significantly after being water cooled from 700 °C and 800 °C. While the differences between the stress–strain curves of air-cooled specimens are relatively insignificant. This indicates that the strength and ductility are susceptible to water-cooling for Q235 cold-formed steel. Furthermore, the ultimate strengths of the corner specimens were generally larger than those of the flat specimens, while the ductility of the corner specimens was weaker than that of the flat specimens. The yield strength, ultimate strength, strain at ultimate strength and their corresponding reduction factors for different thickness are presented in Tables 4-9.

3.4. Yield strength

The yield strength reduction factor ($f_{y,T}/f_y$) represents the ratio of the residual yield strength $f_{y,T}$ cooled from high temperatures T, to the yield strength f_y obtained from ambient temperature. The reduction factors as a function of exposed temperature are shown in Fig. 10.

The residual yield strengths from two cooling methods behave quite differently, as shown in Fig. 10(a). When adopting the air cooling method, corner specimens show a maximum increase of 16% in yield strength after exposure to temperature of 400°C, while yield strength of flat specimens gradually increased above 400 °C and rose by approximately 37% up to 800 °C. When adopting the water cooling method, the yield strengths of all specimens increased gradually. The flat coupons have a higher increase rate than the corner coupons. The yield strength for flat and corner specimens are respectively increased by 134 % and 66 % after exposed to 800 °C, compared with the yield strength obtained at ambient temperature. Such significant increase indicates that the cold-formed Q235 steel can gain extra yield strength after being water cooled, which is a response of quenching. No decrease of yield strengths is observed for specimens with both cooling methods. Additionally, owing to cold forming process, the corner portion has higher yield strength than flat portion, as shown in Tables 4 and 5.

3.5. Ultimate strength

The reduction factor ($f_{u,T}/f_u$) for ultimate strength represents the ratio of the residual ultimate strength $f_{u,T}$ after being cooled from high temperatures T to the ultimate strength f_u obtained from ambient temperature. The change of ultimate strength for flat and corner specimens display a similar trend with respect to their exposed temperatures, as shown in Fig. 10(b). Under air cooling conditions, the ultimate strength of all flat and corner specimens almost remains the same after experiencing high temperatures. For water-cooled specimens, the ultimate strengths increased significantly beyond 600 °C because of the microstructure transformations occurring in the steel on account of rapid cooling. A maximum increase of 79% was observed in ultimate strengths when the exposed temperature reached 800 °C, compared with the ultimate strength obtained from ambient temperature. This suggests that Q235 cold-formed steel can gain a higher ultimate strength after water cooling.

3.6. Ductility

The ductility as an indicator reflects the capacity of plastic deformation of materials, in which the ductility is calculated from the ratio of elongate length to initial length. The reduction factor ($\delta_{u,T}/\delta_u$) of ductility represents the ratio between the percentage elongation of fracture $\delta_{u,T}$ cooled from high temperature T to that without experiencing elevated temperatures δ_u. As shown in Tables 8 and 9, flat specimens show higher ductility than corner specimens at ambient temperature, which can ascribe to the local work hardening caused by cold forming process. Fig. 10(c) shows the post-fire behaviour of ductility for the two cooling methods. This demonstrates that the post-fire ductility is affected by heating-cooling process. When adopting air cooling method, the ductility reduced steadily at 20 - 400 °C and 600 - 800 °C, but increased by about 5% and 20% from 400 °C to 600 °C for flat and corner specimens, respectively. When adopting water cooling method, the ductility of flat specimens reduced gradually from ambient temperature to 600 °C, but sharply decreased when exposed temperature reached 700 °C. While the ductility of corner specimens showed an increase of about 5% from 400 °C to 600 °C. Approximately 75% reduction was observed in all specimens after experiencing temperatures of 800 °C, compared with those obtained from ambient temperature. Therefore, the reuse of Q235 cold-formed steels after being exposed to fire and being cooled by water should be cautious. The variation regularity of ductility in Fig. 10(c) is quite in accord with length variation of the failed test specimens shown in Fig.7.

3.7. Fracture morphology

Fracture morphology has been used to explaining the change of ductility after experiencing elevated temperatures in recent researches [18,52]. In order to figure out the evolution of ductility of Q235 cold-formed steel cooled with air and water cooling method from both macro and micro perspectives, the ductility was analysed in terms of the elongation percentage of fracture as well as fracture morphology. The fracture cross-section of flat and corner specimens, which had not been exposed to high temperatures, contain many deep and small dimples. Deeper dimple indicates more plastic deformation, i.e. good ductility. The number and depth of dimples of flat and corner samples decreased with the increase of exposed temperatures for both cooling methods, but the size of dimples increased. It is also observed that the number of dimples of corner samples are less than that of flat samples at each temperature. Both flat and corner samples show a large number of cleavage planes after being air cooled from 800°C, as shown in Fig. 11(b) (cleavage plane indicates reduction in ductility). Moreover, there are fewer cleavage planes on fracture face of flat sample, and more of corner sample after being water cooled from 600°C. The fracture faces of the flat and corner samples show relatively large dimples after experiencing the temperature of 800 °C, indicating that the ductility of Q235 cold-formed steel decreases significantly in this circumstance. These observations indicate that the ductility of these samples decreases with increasing temperature, the plasticity of flat portion is better than that of corner portion, and the post-fire ductility dropped significantly for water cooling method. All of these coincide with the tensile coupon results as shown in Tables 8 and 9. It is further verified that the reuse of cold-formed steels cooled by water should be very cautious, and the difference between the flat and the corner portion should be given enough attention.

4. Predictive equations for post-fire mechanical properties

The test results in this paper indicate that the flat and corner portions differ in post-fire material properties. In the previous research, the corner specimens were not directly cut from corner parts of steel sections and tested via specially designed grips and rod, which means that the commonly used equations to predict the post-fire properties of cold-formed steels proposed based on previous experiments may not be accurate. Thus, equations for flat and corner part of Q235 cold-formed steel should be proposed separately. Test results also show that mechanical property reduction factors are affected by cooling methods, and the influence of thickness is insignificant. In many previous researches [14-17] concerning post-fire mechanical properties, the prediction equations are polynomials. Therefore, the predictive polynomial equations were separately proposed for air and water cooling method in this paper.

4.1. Yield strength

Eqs. (1-2) and (3-4) are the prediction equations for the yield strength reduction factors under air and water cooling methods, respectively. As a simple guide, it can be conservatively assumed that the yield strength of corner portion of cold-formed Q235 steel does not change after being air cooled from high temperatures. The predictions and test results are in good agreement as shown in Fig. 10(a). Hence these equations are capable of predicting the reduction factors.

Under air cooling condition,

For flat portion:

20°C≤T≤200°C,

$$f_{y,T}/f_y=0.97 \tag{1a}$$

200°C≤T≤600°C,

$$f_{y,T}/f_y=0.78+9.50\times10^{-4}T \tag{1b}$$

600°C≤T≤800°C,

$$f_{y,T}/f_y = 1.35 \tag{1c}$$

For corner portion:

20°C≤T≤800°C,

$$f_{y,T}/f_y = 1 \tag{2}$$

Under water cooling condition,

For flat portion:

20°C≤T≤800°C,

$$f_{y,T}/f_y = 1.00 + 2.59 \times 10^{-4} T + 1.02 \times 10^{-7} T^2 + 1.63 \times 10^{-9} T^3 \tag{3}$$

For corner portion:

20°C≤T≤600°C,

$$f_{y,T}/f_y = 0.995 + 2.24 \times 10^{-4} T \tag{4a}$$

600°C≤T≤800°C,

$$f_{y,T}/f_y = 0.042 + 1.81 \times 10^{-3} T \tag{4b}$$

4.2. Ultimate strength

For both flat and corner specimens, the ultimate strength remains almost the same after air-cooled from 800°C. Therefore it can be assumed that the ultimate strength reduction factor is 1. Thus, Eq. (5) was derived for both flat and corner portion after air-cooled.

20°C≤T≤800°C,

$$f_{u,T}/f_u = 1 \tag{5}$$

When adopting water-cooling method,

For both flat and corner portion:

20°C≤T≤800°C,

$$f_{u,T}/f_u=1.00+1.86\times10^{-4}T+9.89\times10^{-9}T^2-2.47\times10^{-9}T^3+4.37\times10^{-12}T^4 \quad (6)$$

4.3. Ductility

Eqs. (7)-(10) are recommended for determining the reduction factors of the post-fire ductility. Fig.10(c) shows that prediction equations coincide with test results.

Under air cooling condition,

For flat portion:

20°C≤T≤400°C,

$$\varepsilon_T/\varepsilon=1.00+1.23\times10^{-4}T-1.38\times10^{-6}T^2 \quad (7a)$$

400°C≤T≤600°C,

$$\varepsilon_T/\varepsilon=0.31+1.11\times10^{-3}T \quad (7b)$$

600°C≤T≤800°C,

$$\varepsilon_T/\varepsilon=4.65-1.02\times10^{-2}T+6.64\times10^{-6}T^2 \quad (7c)$$

For corner portion:

20°C≤T≤400°C,

$$\varepsilon_T/\varepsilon=1.00-1.87\times10^{-4}T-1.30\times10^{-6}T^2 \quad (8a)$$

400°C≤T≤600°C,

$$\varepsilon_T/\varepsilon=0.30+1.04\times10^{-3}T \quad (8b)$$

600°C≤T≤800°C,

$$\varepsilon_T/\varepsilon=-1.86+8.84\times10^{-3}T-6.98\times10^{-6}T^2 \quad (8c)$$

Under water cooling condition,

For flat portion:

20°C≤T≤600°C,

$\varepsilon_T/\varepsilon$=$1.00-1.96\times10^{-4}T+7.70\times10^{-7}T^2-2.11\times10^{-9}T^3$ (9a)

600°C ≤ T ≤ 800°C, $\varepsilon_T/\varepsilon$=$8.73-2.15\times10^{-2}T+1.35\times10^{-5}T^2$

(9b)

For corner portion:

20°C≤T≤400°C, $\varepsilon_T/\varepsilon$=$1.00+8.52\times10^{-5}T-2.53\times10^{-6}T^2$ (10a)

400°C≤T≤600°C, $\varepsilon_T/\varepsilon$=$0.55+1.95\times10^{-4}T$ (10b)

600°C≤T≤800°C, $\varepsilon_T/\varepsilon$=$8.89-2.25\times10^{-2}T+1.47\times10^{-5}T^2$ (10c)

4.4. Reliability analysis

The proposed predictive equations in this paper are reliable if the calculated reliability index is larger than target one of 2.5 using reliability analysis detailed in AISI S100 Specification [53]. The load combination of 1.2DL + 1.6LL was adopted to obtain the resistance factor (ϕ) for post-fire mechanical property reduction factor (x), where DL and LL respectively represent dead and live load, and x_e = reduction factor of mechanical properties obtained from experiment and x_p = reduction factor of mechanical properties calculated from predictive equations. The statistical parameters M_m= 1.10, F_m= 1.00 are the mean values of material factor and fabrication factor, and V_M = 0.10, V_F= 0.05 are the coefficients of variation. The above statistical parameters can be determined from the table in AISI S100 Specification [53]. Moreover, P_m and V_p are the mean value and coefficient of variation of experimental-to-predicted load ratio, respectively. Considering the influence of the number of data, the correction factorC_p is also adopted in calculation. Where $C_p = \left(1 + \frac{1}{n}\right) m/(m-2)$. $m = n - 1$, n≥4. $n =$ number of data.

The specimens were labelled such that the extracted position, thickness, cooling methods and experienced temperature could be identified in Table 10. According to AISI S100 Specification [53], the maximum resistance factor ϕ_0 is calculated using the target reliability index β_0 of 2.5. The resistance factor ϕ_1 is suggested slightly smaller than ϕ_0 and calculated reliability index β_1 can be calculated based on ϕ_1. And the resistance factor ϕ_1 are recommended for Q235 cold-formed steel yield strength, ultimate strength and its corresponding strain. As shown in Table 10, all values of calculated reliability index β_1 are larger than the target reliability index (2.5), which mean that the proposed design method is reliable with recommended resistance factor 0.9 of post-fire mechanical properties for Q235 cold-formed steels.

4.5. Comparisons with normal strength and high strength structural steels.

Fig.12 shows the comparison of reduction factors (yield strength, ultimate strength and ductility) between normal strength (Q235) and high strength (Q460) structural steels, where the Q235 cold-formed steel (CFS), the Q235 hot-rolled steel (HRS) and the Q460 steel have been chosen. Due to the significant difference of thickness between present study (1mm and 2mm) and other studies (larger than 7mm), it can be found from Fig.12 that the specimens used in present study have more sensitiveness on yield strength to elevated temperature larger than 400°C. When adopting the water cooling method, all selected samples (Q235 and Q460) show significant change on post-fire mechanical properties owing to the influence of quenching. In addition, compared with the high strength steel (Q460), the normal strength steel (Q235) presents an obvious influence on fire experience, which indicates that steel structures using normal strength steels need to be evaluated after a fire, especially.

5. Conclusions

This paper has presented an experimental investigation into the post-fire mechanical properties of Q235 cold-formed steel channel section. Coupons with thickness of 1 mm and 2 mm extracted from the flat portion and the corner portion of cold-formed section were exposed to high temperatures up to 800 °C, and then cooled down to ambient temperature with air and water cooling methods. Tensile coupon tests were then conducted at ambient temperature to obtain their post-fire mechanical properties. The tensile coupon test results showed that the post-fire mechanical properties of cold-formed steels were affected by cooling methods and their exposed temperatures, while the effects of thickness were negligible. The difference between the flat and the corner parts of cold-formed steel sections is obvious, and it has been proven via microstructure and fracture morphology analyses. It should be noted that the yield strength increased after exposure to high temperatures and being cooled with both cooling methods, but increased more with water cooling. Under air cooling condition, ultimate strengths of all flat and corner specimens almost remained the same. However, the ultimate strengths increased significantly after being water cooled from exposed temperatures beyond 600 °C. A maximum reduction of approximately 26%

and 76% in ductility for air-cooled and water-cooled specimens were found after exposure to 800°C, respectively. As has been discussed above, corner coupons in previous investigations did not accord with the actual situation. Hence, new predictive equations were proposed to reasonably predict the post-fire yield strength, ultimate strength and ductility of flat and corner portions of Q235 cold-formed steel considering air and water cooling method.

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References

[1] EN 1993-1-2, Eurocode 3: Design of Steel Structures-Portion 1-2: General Rules-Structural Fire Design, European Committee for Standardization (CEN), Brussels, 2005.

[2] AS 4100, Steel Structures, Australian Standard, Australia, 1998.

[3] ANSI/AISC 360-16, Specification for Structural Steel Buildings, American Institution of Steel Construction, Chicago, USA, 2016.

[4] J. Chen, B. Young, Experimental investigation of cold-formed steel material at

elevated temperatures, *Thin-Walled Structures*. 45 (2007) 96–110.

[5] N. D. Kankanamge, M. Mahendran, Mechanical properties of cold-formed steels at elevated temperatures, *Thin-Walled Structures*. 49 (2011) 26–44.

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

[7] J. Chen, B. Young, B. Uy, Behaviour of high strength structural steel at elevated temperatures, *Journal of Structural Engineering*. 132 (2006) 1948–1954.

[8] X. Qiang, F. Bijlaard, H. Kolstein, Dependence of mechanical properties of high strength steel S690 on elevated temperatures, *Construction and Building Materials*. 30 (2012) 73–79.

[9] H. T. Li, B. Young, Material properties of cold-formed high strength steel at elevated Temperatures. *Thin-Walled Structures*. 115 (2017) 289–299.

[10]H. T. Li, B. Young, Cold-formed high strength steel SHS and RHS beams at elevated temperatures, *Journal of Constructional Steel Research*. 158 (2019) 475-485.

[11]M. Feng, Y. C. Wang, J. M. Davies, Structural behaviour of cold-formed thin-walled short steel channel columns at elevated temperatures, Portion 1: Experiments, *Thin-Walled Structures*. 41 (2003) 543–70.

[12]J. Chen, B. Young, Cold-formed steel lipped channel columns at elevated temperatures. *Engineering Structures*, 29 (2007) 2445-2456.

[13]L. Laím, J. P. C. Rodrigues, L. S. D. Silva, Experimental analysis on cold-formed steel beams subjected to fire, *Thin-Walled Structures*. 74 (2014) 104–117.

[14]X. H. Qiang, F. S. K. Bijlaard, H. Kolstein, Post-fire mechanical properties of

high strength structural steels S460 and S690, *Engineering Structures*. 35 (2012) 1–10.

[15] S. Gunalan, M. Mahendran, Experimental investigation of post-fire mechanical properties of cold-formed steels, *Thin-Walled Structures*. 84 (2014) 241–254.

[16] J. Lu, H. B. Liu, Z. H. Chen, X. W. Liao, Experimental investigation into the post-fire mechanical properties of hot-rolled and cold-formed steels, *Journal of Constructional Steel Research*. 21 (2016) 291-310.

[17] S. Kesawan, M. Mahendran, Post-fire mechanical properties of cold-formed steel hollow sections, *Construction and Building Materials*. 161 (2018) 26–36.

[18] H. U. Sajid, R. Kiran, Influence of stress concentration and cooling methods on post-fire mechanical behavior of ASTM A36 steels. Construction and Building Materials, 186, 920-945.

[19] V. Kodur, M. Yahyai , A. Rezaeian, M. Eslami, A. Poormohamadi, Residual mechanical properties of high strength steel bolts subjected to heating-cooling cycle, *Journal of Constructional Steel Research*. 131 (2017) 122-131.

[20] H. B. Liu, X. W. Liao, Z. H. Chen, S. S. Huang, Post-fire residual mechanical properties of steel butt weld – Experimental study, *Journal of Constructional Steel Research*. 129 (2017) 156–162.

[21] J. M. Atienza, M. Elices, Behavior of pre-stressing steels after a simulated fire: fire-induced damages, *Construction and Building Materials*. 23 (2009) 2932–2940.

[22] Z. Tao, Mechanical properties of pre-stressing steel after fire exposure, *Materials and Structures*. 48 (2015) 3037–3047.

[23]Z. Tao, X. Q. Wang, B. Uy, Stress-strain curves of structural and reinforcing steels after exposure to elevated temperatures, *Civil and Environmental Engineering*. 25 (2012) 1306–1316.

[24]X. Q. Wang, Z. Tao, T. Y. Song, L.H. Han, Stress–strain model of austenitic stainless steel after exposure to elevated temperatures, *Journal of Constructional Steel Research*. 99 (2014) 129–139.

[25]Y. Huang, B. Young, Mechanical properties of lean duplex stainless steel at post-fire condition, *Thin-Walled Structures.*130 (2018) 564-576.

[26]Y. Huang, B. Young, Post-fire behaviour of ferritic stainless steel material, *Construction and Building Materials.* 157 (2017) 654-667.

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

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

[29]H. U. Sajid, R. Kiran, Post-fire mechanical behavior of ASTM A572 steels subjected to high stress triaxialities. *Engineering Structures*, 191, 323-342.

[30]H. T. Li, B. Young, Residual mechanical properties of high strength steels after exposure to fire, *Journal of Constructional Steel Research*. 148 (2018) 562–571.

[31]G. Q. Li, H. B. Lyu, C. Zhang, Post-fire mechanical properties of high strength Q690 structural steel, *Journal of Constructional Steel Research*. 132 (2017) 108–116.

[32] Y. J. Yu, L. F. Lan, F. X. Ding, L. P. Wang.Mechanical properties of hot-rolled and cold-formed steels after exposure to elevated temperature: A review. *Construction and Building Materials*, 213 (2019) 360–376.

[33] A. Chajes, S. J. Britvec, G. Winter, Effect of cold-straining on structural sheet steels, *Journal of the Structural Division*. 89 (1963) 1–32.

[34] K. W. Karren, Corner properties of cold-formed steel shapes, *Journal of the Structural Division*. 93 (1967) 401–32.

[35] K. W. Karren, G. Winter, Effects of cold-forming on light-gage steel members, *Journal of the Structural Division*. 93 (1967) 433–69.

[36] Y.J. Zhang, Y. Zhu, S. Zhao, K.X. Hu, Experimental research on mechanical properties of steel cooled in different modes after high temperature treatment, *Structural Engineers*. 25(5) (2009) 104–109 (in Chinese).

[37] J. Chen, B. Young, Corner properties of cold-formed steel sections at elevated temperatures, *Thin-Walled Structures*. 44 (2006) 216–223.

[38] F. Azhari, A. Heidarpour, X. L. Zhao, CR. Hutchinson, Mechanical properties of ultra-high strength (Grade 1200) steel tubes under cooling phase of a fire: An experimental investigation, *Construction and Building Materials*. 93 (2015) 841–850.

[39] P. T. Summers, S. W. Case, B. Y. Lattimer, Residual mechanical properties of aluminum alloys AA5083-H116 and AA6061-T651 after fire, *Engineering Structures*. 76 (2014) 49–61.

[40] M. Wang, Z. Zhou, H. Sun, H. Hu, S. Li, Effects of plastic deformations on microstructure and mechanical properties of ODS-310 austenitic steel, *Journal of*

Nuclear Materials. 430 (2012) 259-263.

[41]M. Wang, Z. Zhou, H. Sun, H. Hu, S. Li, Microstructural observation and tensile properties of ODS-304 austenitic steel, *Materials Science & Engineering A*. 559 (2013) 287-292.

[42]T. Gräning, M. Rieth, J. Hoffmann, A. Möslang, Production, microstructure and mechanical properties of two different austenitic ODS steels, *Journal of Nuclear Materials*. 487 (2017) 348-361.

[43]C. W. Shao, W. J. Hui, Y. J. Zhang, X. L. Zhao, Y. Q. Weng, Microstructure and mechanical properties of hot-rolled medium-Mn steel containing 3% aluminum, *Materials Science & Engineering A*. 682 (2017) 45–53.

[44]G. Mishraa, A. K. Chandan, S. Kundu, Hot rolled and cold rolled medium manganese steel: Mechanical properties and microstructure, *Materials Science & Engineering A*. 701 (2017) 319–327.

[45]X. Chang, J. Liu, J. W. Fan, L. Y. Cheng, R. L. Tao, Study on microstructure and fracture morphology of 2205 duplex stainless steel resistance spot welds, *Materials Science Forum*. 804 (2015) 289-292.

[46]Y. J. Li, Z. D. Zou, M. Thompson, Microstructure and fracture morphology in the welding zone of Cr18Mo2 ferritic stainless steel, *Journal of Materials Science & Technology*. 12 (1996) 452-456.

[47]D. Maisonnettea, M. Suery, D. Nelias, P. Chaudet, T. Epicier, Effects of heat treatments on the microstructure and mechanical properties of a 6061 aluminium alloy, *Materials Science and Engineering A*. 528 (2011) 2718–2724.

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

[49] GB/T 228.1-2010, Metallic materials-Tensile testing-Part 1: Method of test at room temperature, Standards Press of China, 2010.

[50] I. E. Dolzhenkov. The nature of blue brittleness of steel. *Metal Science & Heat Treatment*, 13(1971) 220-224.

[51] W. Y. Wang, B. Liu, V. Kodur. Effect of Temperature on Strength and Elastic Modulus of High-Strength Steel. *Journal of Materials in Civil Engineering*, 25(2013):174-182.

[52] Kiran R, Khandelwal K. A micromechanical model for ductile fracture prediction in ASTM A992 steels. *Engineering Fracture Mechanics*, 102 (2013) 101–117.

[53] AISI, North American Specification for the Design of Cold-formed Steel Structural Members, AISI S100-16, American Iron and Steel Institute, Washington, D.C., 2016.