

## Post-fire mechanical properties of high strength steels

H. T. Li<sup>a</sup> and B. Young<sup>a\*</sup>

<sup>a</sup>Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

\*corresponding author, e-mail address: [young@hku.hk](mailto:young@hku.hk)

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### Abstract

High strength steels are becoming increasingly attractive for structural and architectural applications due to their superior strength-to-weight ratio which could lead to lighter and elegant structures. The stiffness and strength of high strength steels may reduce after exposure to fire. The post-fire mechanical properties of high strength steels have a crucial role in evaluating the residual strengths of these materials. This paper presents an experimental investigation on post-fire mechanical properties of cold-formed high strength steels. A series of tensile coupon tests has been carried out. The coupon specimens were extracted from cold-formed square hollow sections with nominal yield stresses of 700 and 900 MPa at ambient temperature. The specimens were exposed to various elevated temperatures ranged from 200 to 1000 °C and then cooled down to ambient temperature before tested to failure. Stress-strain curves were obtained and the mechanical properties, namely, Young's modulus, yield stress (0.2% proof stress) and ultimate strength, of the cold-formed high strength steel materials after exposure to elevated temperatures were derived. The post-fire retention factors that obtained from the experimental investigation were compared with existing predictive equations in the literature. New predictive equations are proposed to determine the residual mechanical properties of high strength steels after exposure to fire. It is shown that the proposed predictive equations are suitable for both cold-formed and hot-rolled high strength steel materials with nominal yield stresses ranged from 690 to 960 MPa.

**Keywords:** Cold-formed; Elevated temperature; High strength steel; Mechanical properties; Post-fire; Tubular sections.

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### 1. Introduction

High strength steels are being increasingly used in various structural applications, such as bridges, high-rise buildings and offshore structures. With advanced metallurgical and manufacturing technologies, high strength steel products with yield stress above 1300 MPa are currently available in the steel market [1, 2]. Structures might inevitably expose to fire hazards and the capacities of steel structural members are normally significantly reduced in fire. After the September 11 attacks, the mechanical properties of high strength steels at elevated temperatures have attracted much research attention [2–9], leading to a sound understanding of the behaviour of high strength steel materials in fire. On the other hand, after cooling from elevated temperatures to ambient temperature, the fire damage needs to be

assessed from the structural safety point of view. It is crucial and necessary to decide whether the residual stiffness and strength of steel members are still sufficient for future utilization. The post-fire mechanical properties of steels are essential for such evaluations.

In this study, research efforts are made in order to provide suitable rules to predict post-fire mechanical properties of high strength steels with nominal yield stresses ranged from 690 to 960 MPa. A series of tensile coupon tests was carried out to investigate the residual mechanical properties of cold-formed high strength steels after exposure to elevated temperatures up to 1000 °C. The coupon specimens were extracted from cold-formed high strength steel square hollow sections with nominal yield stresses of 700 and 900 MPa at ambient temperature. Post-fire mechanical properties including the Young's

modulus, yield stress and ultimate strength were obtained. The derived post-fire retention factors were compared with existing proposals in Gunalan and Mahendran [10], Qiang et al. [11, 12] and Li et al. [13] in order to evaluate their applicability to cold-formed high strength steels. Moreover, predictive equations are proposed to determine the residual mechanical properties of high strength steels after fire exposure. It is illustrated that the proposed predictive equations can be used for cold-formed and hot-rolled high strength steels with nominal yield stresses ranged from 690 to 960 MPa of various steel grades.

## 2. Experimental investigation

### 2.1. Test specimens

Tensile coupon tests were conducted to investigate the residual mechanical properties of cold-formed high strength steels after exposure to fire. Coupon specimens were extracted from two cold-formed square hollow sections of different steel grades, i.e., H140×140×6 and V120×120×4. The nominal yield stresses (0.2% proof stresses) of the sections are 700 and 900 MPa, which were indicated by the letters H and V in their section labels, respectively. The nominal cross-sectional dimensions  $D \times B \times t$  were 140×140×6 and 120×120×4, where  $D$ ,  $B$  and  $t$  were the overall depth, width and thickness in millimetres, respectively. The coupon specimens were obtained from the centre of the face at 90° angles from the weld face of the sections. The coupon dimensions were prepared in accordance with the ASTM [14] using 6 mm wide coupon with 25 mm gauge length. The chemical composition of the cold-formed high strength steels can be found in Ma et al. [1], which reported the ambient temperature material properties of the same batch of sections.

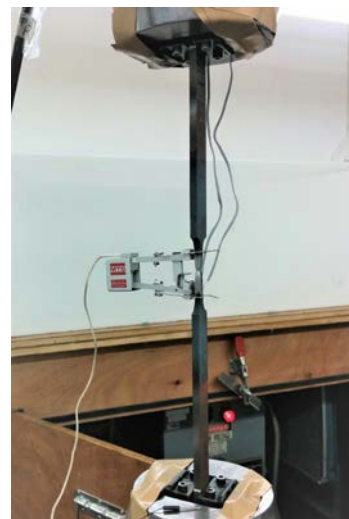
The specimens were labelled such that their nominal yield stress, thickness and exposed temperature can be easily identified, as shown in Tables 1-3. For example, the label H6-T500-R defines the following specimen. The first letter of the label indicates the nominal yield stress of the coupon specimen was 700 MPa. The following number shows the nominal thickness of the coupon specimen was 6 mm. The following notation T500 indicates the specimen was exposed to an elevated temperature of 500 °C. Finally, the letter “R”, if any, indicates it is a repeated test.

### 2.2. Test setup and procedure

An MTS high-temperature furnace, as shown in Fig. 1(a), was used to heat up the specimens to target temperatures. The furnace consists of three pairs of independent-controlled heating elements enabling to heat the specimens at a maximum rate of 100 °C/min up to 1400 °C. The furnace was controlled and monitored by an MTS temperature controller. Two external thermocouples were mounted on the surface of the coupon specimens to measure the real-time temperature of the specimens.



(a) Heating



(b) Tensile testing  
Fig. 1. Test setup.

A total of 11 different target temperatures was selected in this study. The selected temperatures were 20 °C (ambient temperature), 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 750 °C, 800 °C, 900 °C and 1000 °C. The post-fire coupon specimens were heated from ambient temperature to the specific target temperatures at a rate of 10 °C/min. This heating rate has been reported to be similar to the rate of

temperature increase for protected steelwork exposed to fire [15, 16]. It is noteworthy that for all the post-fire coupon specimens, an additional 20 mins of soak time was employed after the target temperatures reached to ensure uniform temperature distribution could be obtained in the coupon specimens. During this heat soak period, the independent-controlled heating elements were adjusted to ensure the readings of the two external thermocouples, one near each end of the reduced section, stabilized within a difference of less than 1% compared to the target temperature. After the heat soak period, the furnace was deactivated and the coupon specimens cooled down in the furnace naturally. A data acquisition system was employed to record the time and temperatures at regular intervals during both the heating and cooling processes.

After the coupon specimens cooled down to ambient temperature, sandpapers were used to remove any oxide and coating that formed on the post-fire coupon surfaces. An MTS 50 kN material testing machine was used to conduct the tensile coupon tests. All the post-fire tensile coupon tests were conducted at ambient temperature. As shown in Fig. 1(b), a calibrated MTS 25 mm gauge length extensometer and two strain gauges were used to measure the longitudinal strains of the post-fire coupon specimens. Displacement control was employed during testing and the coupon test procedures recommended by Huang and Young [17] were adopted herein. A data acquisition system was used to record the loads as well as the readings of the strain gauges and extensometer at regular intervals. The static stress-strain curves were obtained from the test curves using the method detailed in Huang and Young [17]. It should be noted that tensile coupon tests were also carried out on specimens H6-T20 and V4-T20, which were directly tested at ambient temperature without exposure to fire.

### 3. Test results and discussions

#### 3.1. Stress-strain curves

The static stress-strain curves of the H6 (H140×140×6 section) and V4 (V120×120×4 section) series are shown in Figs. 2 and 3, respectively. The mechanical properties, namely, the Young's modulus ( $E$ ), yield stress ( $f_y$ ) and ultimate strength ( $f_u$ ), obtained from the tensile coupon tests that directly tested at ambient temperature are reported in Table 1.

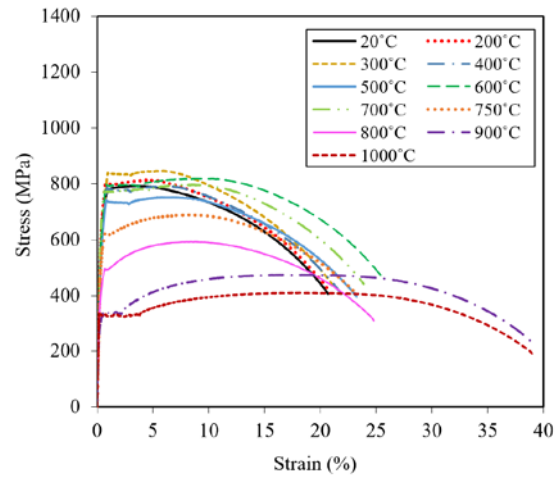


Fig. 2. Stress-strain curves of H6 series.

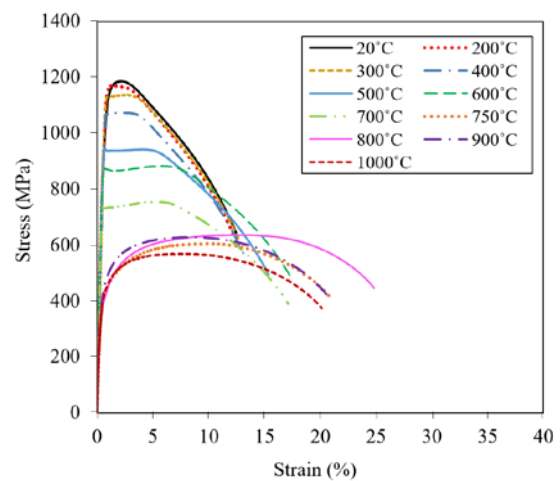


Fig. 3. Stress-strain curves of V4 series.

Table 1. Mechanical properties of cold-formed high strength steels at ambient temperature.

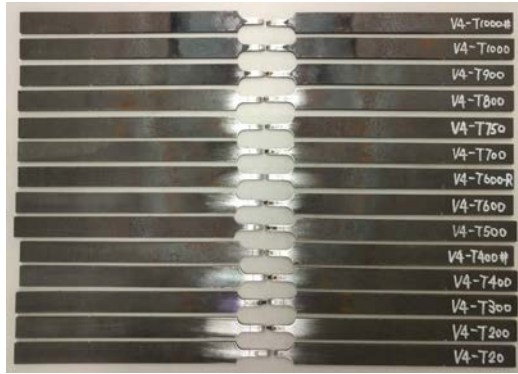
Specimen	$E$ (GPa)	$f_y$ (MPa)	$f_u$ (MPa)
H6-T20	213.4	673	793
V4-T20	208.2	991	1187

It is shown that the stress-strain curves at ambient temperature had gradual yielding, in other words, had no distinct yield plateau in the stress-strain curves. In this study, therefore, the 0.2% proof stress was taken as the yield stress of the high strength steel materials. Overall, the stress-strain curves obtained from the post-fire coupon specimens in the temperatures ranged from 300 to 1000 °C exhibited linear elastic regions followed by yield plateaus, except for the stress-strain curves for specimens of the V4 series in the range of 750 to 1000 °C. Note that for the H6 series, the ductility of the material enhanced significantly after exposure to temperatures above 800 °C. For the V4 series,

the ductility of the material enhanced quite significantly at 800 °C compared to other 10 temperatures. It is also noteworthy that all the test specimens exhibited ductile failure undergoing necking before fracturing near the middle of the coupons, as shown in Fig. 4.



(a) H6 series



(b) V4 series

Fig. 4. Cold-formed high strength steel specimens after testing.

### 3.2. Young's modulus

The influence of fire exposure on the Young's modulus is discussed in this subsection. The post-fire retention factor of the Young's modulus was determined from the ratio of the residual Young's modulus ( $E_T$ ) after exposure to elevated temperature  $T$  over the corresponding Young's modulus at ambient temperature ( $E$ ). The retention factors of the Young's modulus ( $E_T/E$ ) for H6 and V4 series are tabulated in Tables 2 and 3, respectively. The  $E_T/E$  values are plotted and compared with the predictive equations proposed by Gunalan and Mahendran [10] for cold-formed high strength steel grades G500 and G550, Qiang et al. [11] for hot-rolled S690 steel sheet, Qiang et al. [12] for hot-rolled S960 steel sheet as well as Li et al. [13] for hot-rolled Q690 steel plate, as shown in Fig. 5.

Table 2. Post-fire retention factors for mechanical properties of H6 series.

Specimen	$T$ (°C)	$E_T/E$	$f_{y,T}/f_y$	$f_{u,T}/f_u$
H6-T20	21.3	1.000	1.000	1.000
H6-T200	201.3	1.010	1.076	1.026
H6-T300	300.9	1.016	0.991	1.067
H6-T400	401.2	1.018	0.988	0.998
H6-T500	498.7	1.017	0.914	0.948
H6-T500-R	501.2	1.013	0.916	0.954
H6-T600	599.2	1.002	1.030	1.032
H6-T700	699.6	1.022	1.126	1.005
H6-T750	749.7	0.991	0.845	0.869
H6-T800	800.1	0.982	0.647	0.747
H6-T900	899.5	0.917	0.476	0.597
H6-T1000	999.9	0.906	0.491	0.516

Table 3. Post-fire retention factors for mechanical properties of V4 series.

Specimen	$T$ (°C)	$E_T/E$	$f_{y,T}/f_y$	$f_{u,T}/f_u$
V4-T20	21.6	1.000	1.000	1.000
V4-T200	201.4	0.997	1.065	0.987
V4-T300	300.3	1.002	1.084	0.959
V4-T400	400.4	0.991	1.035	0.905
V4-T500	501.2	1.008	0.951	0.795
V4-T600	600.5	1.001	0.881	0.744
V4-T600-R	601.2	1.009	0.882	0.746
V4-T700	700.2	1.008	0.738	0.637
V4-T750	750.3	0.984	0.369	0.511
V4-T800	800.8	0.964	0.354	0.537
V4-T900	900.0	0.954	0.389	0.530
V4-T1000	1000.0	0.899	0.368	0.481

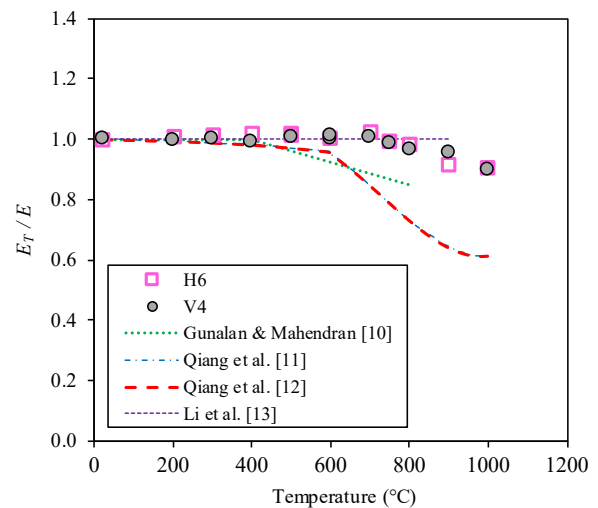


Fig. 5. Retention factors for Young's modulus of cold-formed high strength steels.

It can be observed that the cold-formed high strength steels regained more than 96 % of their Young's modulus up to 800 °C, above which the deterioration became relatively more noticeable. Even after exposure to an elevated temperature of 1000 °C, the cold-formed high strength steel



materials were still able to regain about 90% of their Young's modulus at ambient temperature. It is shown that the predictive equations in Gunalan and Mahendran [10] and Qiang et al. [11, 12] could be conservatively used for the cold-formed high strength steels. The retention factors proposed by Li et al. [13] are taken as unity for temperatures up to 900 °C, which gives quite good predictions for the tested materials for temperatures up to 800 °C.

### 3.3. Yield stress

The post-fire retention factor of the yield stress, which is taken as the 0.2% proof stress in this study, was determined from the ratio of the residual yield stress ( $f_{y,r}$ ) after fire exposure to the corresponding yield stress at ambient temperature ( $f_y$ ). The  $f_{y,r}/f_y$  values are plotted against temperatures and compared with the predictive equations proposed by Gunalan and Mahendran [10], Qiang et al. [11, 12] and Li et al. [13] in Fig. 6.

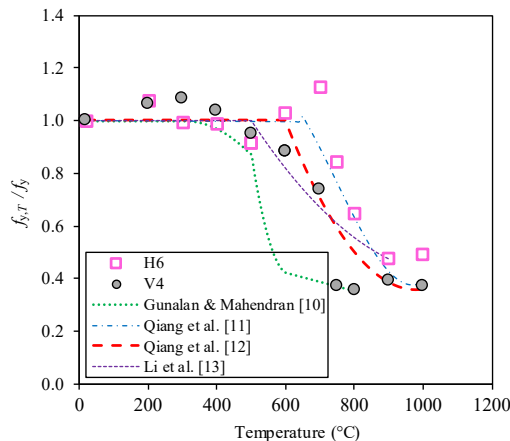


Fig. 6. Retention factors for yield stress of cold-formed high strength steels.

The post-fire retention factors of the yield stress were greater than 0.91 for the H6 series up to 700 °C, beyond which the yield stress deteriorated rapidly up to 900 °C. For the V4 series, the yield stress retention factors remained generally unchanged for temperatures up to 500 °C, and the cold-formed high strength steel regained more than 95 % of its yield stress in this temperature range. For temperatures ranged from 500 to 700 °C, the  $f_{y,r}/f_y$  ratio of the V4 series gradually reduced to 0.738, after which a sudden drop to 0.369 was found at 750 °C. For temperatures ranged from 750 to 1000 °C, the deterioration of the yield stress remained at the same level with the discrepancy of the  $f_{y,r}/f_y$  values within 3.5%. Overall, the predictive

equations proposed by Qiang et al. [11] for the S690 steel are able to provide conservative predictions for the H6 series. The predictive equations proposed by Qiang et al. [12] for the S960 steel give more conservative predictions than the rules in Qiang et al. [11] for temperatures ranged from 600 to 1000 °C. The predictive equations proposed by Qiang et al. [11, 12] provide unconservative predictions for some of the data in V4 series especially for temperatures at 750 and 800 °C. On the other hand, although providing accurate predictions for the V4 series for temperatures at 750 and 800 °C, the proposal by Gunalan and Mahendran [10] give overly pessimistic predictions for the tested cold-formed high strength steels. Overall, the retention factors proposed by Li et al. [13] provide conservative predictions for the cold-formed high strength steels up to 700 °C, beyond which the proposal by Li et al. [13] overestimated the residual yield stresses for the V4 series.

### 3.4. Ultimate strength

The ultimate strength retention factor was determined from the ratio of the residual ultimate strength after heating and cooling down from the elevated temperature ( $f_{u,r}$ ) to the corresponding ultimate strength at ambient temperature ( $f_u$ ). The derived  $f_{u,r}/f_u$  results were compared with the predictive equations proposed by Gunalan and Mahendran [10], Qiang et al. [12] and Li et al. [13] in Fig. 7.

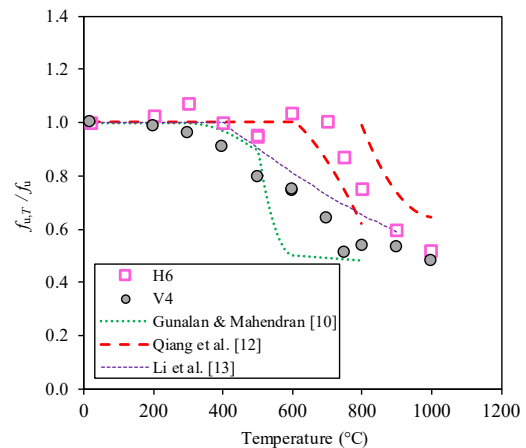


Fig. 7. Retention factors for ultimate strength of cold-formed high strength steels.

The  $f_{u,r}/f_u$  values were close to unity for the H6 series up to 700 °C, beyond which the residual ultimate strength reduced rapidly up to 1000 °C. For the V4 series, the residual ultimate strength deteriorated gradually as temperature

increased for temperatures up to 700 °C. A relatively more rapid deterioration of the residual ultimate strength for the V4 series was found at 750 °C, and beyond this temperature, the  $f_{u,r}/f_u$  ratio generally remained similar with the values ranged from 0.481 to 0.537. The predictive equations in Gunalan and Mahendran [10] provided overly conservative predictions for the H6 series, while gave unconservative predictions for the V4 series for temperatures up to 500 °C. Qiang et al. [12] suggested discontinuous retention factors for the S960 steel, which aligns well with their own test data. However, this discontinuity proposed by Qiang et al. [12] could not compare well with the cold-formed high strength steel data obtained in the present study. Overall, the retention factors suggested by Li et al. [13] provided conservative predictions for the H6 series, while providing unconservative predictions for the V4 series.

#### 4. Proposed predictive equations

Predictive equations were proposed by Gunalan and Mahendran [10] for cold-formed G500 and G550 steels, Qiang et al. [11] for hot-rolled S690 steel, Qiang et al. [12] for hot-rolled S960 steel and Li et al. [13] for hot-rolled Q690 steel to predict the post-fire mechanical properties of high strength steels. However, these proposals were calibrated with their own test data, which may restrain the applicability of being extended to other steel grades. In this study, predictive equations are proposed to determine the residual mechanical properties of high strength steels after exposure to fire. The cold-formed high strength steel data obtained in this study and the hot-rolled high strength steel data reported by Qiang et al. [11, 12], Li et al. [13] and Chiew et al. [18] were employed to propose the post-fire retention factors. Therefore, the predictive equations proposed in this study are not restricted to the materials that tested and reported herein, but can be applied for both cold-formed and hot-rolled high strength steels with nominal yield stresses ranged from 690 to 960 MPa of various steel grades. The post-fire mechanical properties retention factors of the cold-formed high strength steels obtained herein are plotted together with those of the hot-rolled high strength steels [11–13, 18] in Figs. 8–10.

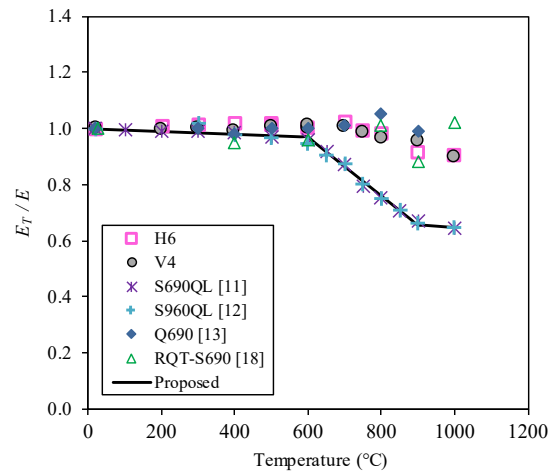


Fig. 8. Proposed Young's modulus retention factors for high strength steels.

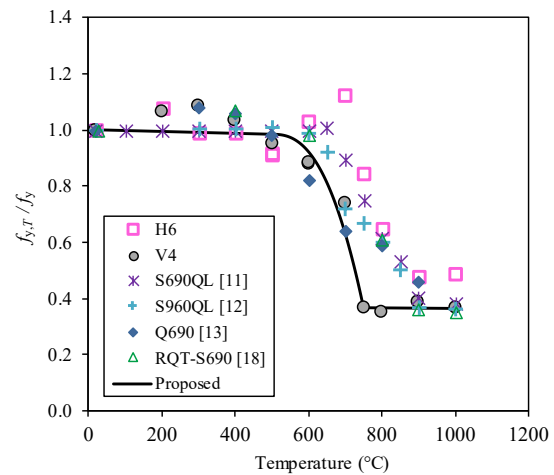


Fig. 9. Proposed yield stress retention factors for high strength steels.

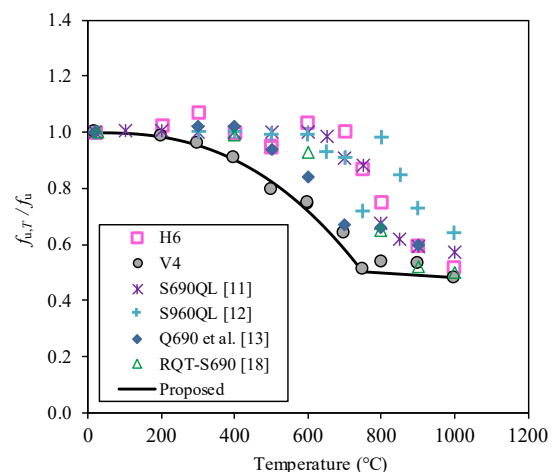


Fig. 10. Proposed ultimate strength retention factors for high strength steels.

The unified equation, which was proposed by Chen and Young [19] for mechanical properties of stainless steels at elevated temperatures, is

employed herein for the mechanical properties of high strength steels after exposure to fire. The proposed predictive equations for post-fire Young's modulus, post-fire yield stress and post-fire ultimate strength are expressed in Eqs. (1)-(3), respectively.

$$\frac{E_T}{E} = a - \frac{(T-b)^n}{c} \quad (1)$$

$$\frac{f_{y,T}}{f_y} = a - \frac{(T-b)^n}{c} \quad (2)$$

$$\frac{f_{u,T}}{f_u} = a - \frac{(T-b)^n}{c} \quad (3)$$

in which,  $T$  is the temperature in °C;  $a$ ,  $b$ ,  $c$  and  $n$  are the coefficients as tabulated in Table 4.

Table 4. Proposed post-fire retention factor coefficients for high strength steels.

	$T$ (°C)	$a$	$b$	$c$	$n$
	$20 < T \leq 600$	1	20	$2.0 \times 10^4$	1
$\frac{E_T}{E}$	$600 < T \leq 900$	0.971	60	$9.5 \times 10^2$	1
	$900 < T \leq 1000$	0.655	90	$1.0 \times 10^4$	1
	$20 < T \leq 500$	1	20	$3.0 \times 10^4$	1
$\frac{f_{y,T}}{f_y}$	$500 < T \leq 750$	0.984	50	$1.6 \times 10^6$	2.5
	$750 < T \leq 1000$	0.366	75	$1.0 \times 10^5$	1
	$20 < T \leq 750$	1	20	$2.9 \times 10^7$	2.5
$\frac{f_{u,T}}{f_u}$	$750 < T \leq 1000$	0.504	75	$1.2 \times 10^4$	1

Overall, the proposed predictive equations are capable of providing conservative predictions for the retention factors, as shown in Figs. 8-10. Therefore, the proposed prediction equations are suggested to be used for post-fire mechanical properties of cold-formed and hot-rolled high strength steels with nominal yield stresses ranged from 690 to 960 MPa.

## 5. Conclusions

An experimental investigation on residual mechanical properties of cold-formed high strength steels after exposure to fire has been presented. The measured yield stresses (0.2% proof stresses) of the cold-formed high strength steels without fire exposure were 673 and 991 MPa. The specimens were exposed to 10

different elevated temperatures up to 1000 °C before cooled down to ambient temperature. Residual mechanical properties including Young's modulus, yield stress and ultimate strength were obtained from the coupon tests.

The cold-formed high strength steel materials regained more than about 90% of their original Young's moduli even after being exposed to 1000 °C, while the post-fire yield stresses and ultimate strengths remained less than 60% after being exposed to elevated temperatures beyond 800 °C. The post-fire retention factors for mechanical properties of cold-formed high strength steels were compared with the proposals in Gunalan and Mahendran [10] for cold-formed high strength steels as well as proposals in Qiang et al. [11, 12] and Li et al. [13] for hot-rolled high strength steels. Overall, it is shown that the predictive equations in the literature are not suitable to predict the residual strengths of the tested cold-formed high strength steels after exposure to fire. The cold-formed high strength steel data obtained in this study and the hot-rolled high strength steel data reported by Qiang et al. [11, 12], Li et al. [13] and Chiew et al. [18] were used to propose residual mechanical properties for high strength steels after exposure to fire. It is illustrated that the proposed predictive equations are suitable for both cold-formed and hot-rolled high strength steel materials with nominal yield stresses ranged from 690 to 960 MPa.

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