Research Article

Mechanical Properties of Steels for Cold-Formed Steel Structures at Elevated Temperatures

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It is highly important to clarify the high-temperature mechanical properties in the design of cold-formed steel (CFS) structures under fire conditions due to the unique deterioration feature in material properties under fire environment and associated reduction to the mechanical performance of members. This paper presents the mechanical properties of widely used steels for cold-formed steel structures at elevated temperatures. The coupons were extracted from original coils of proposed full annealed steels (S350 and S420, with nominal yielding strengths 280 MPa and 350 MPa) and proposed stress relieving annealed steels (G500, with nominal yielding strength 500 MPa) for CFS structures with thickness of 1.0 mm and 1.2 mm, and a total of nearly 50 tensile tests were carried out by steady-state test method for temperatures ranging from 20 to 700°C. Based on the tests, material properties including the yield strengths, ultimate strengths, the elasticity modulus, and the stress-strain curve were obtained. Meanwhile, the ductility of steels for CFS structures was discussed. Then, the temperature-dependent retention factors of yield strengths and elasticity modulus were compared to those provided by design codes and former researchers. Finally, a set of prediction equations of the mechanical properties for steels for CFS structures at elevated temperatures was proposed depending on existing tests data.

1. Introduction

As the main components in light weight steel structural buildings worldwide, cold-formed thin-walled steel (CFS) members are manufactured from cold-rolled thin-walled steel sheets or strips, approximately from 0.3 mm to 3.0 mm thickness, with grades from 200 to 1000 [1–5]. The applicable steels for CFS structures are specified in codes [1–5] with different elongation and nominal yield strength. In these standards [1–5], elongation of 10% is a significant boundary for dividing the category of steel materials. In the meantime, 450 MPa is also a rough line for separating massive steels used for CFS structures [1–5]. Generally, the steel coils for manufacturing of CFS sections are made from both hot-rolled steel sheets and cold-rolled steel sheets [1–5], in which cold-rolled steel sheets may involve the annealing process. Also, for cold-forming process into cross section shapes, stress-hardening effect takes place leading to reduced ductility of the raw material. Hence, annealing [6] may be

involved after the cold-forming process to improve the mechanical properties or to relieve the residual stress. Steels with a specified minimum elongation of 10% or greater are full annealed steels, and the remaining part is the stress relieving annealed steels (the classification approach is proposed in this paper based on the manufacturing process of steels). For instance, G250 and G300 steels are widely used in North America, Australia, and Europe [1–4]; S280, with a nominal yielding strength of 280 MPa, and S350, with a nominal yielding strength of 350 MPa, steels, suggested by Chinses code [5], belong to the full annealed steels. On the other hand, G550 class steels, including G450, G500, and G550 steels [2, 5], are typical stress relieving annealed steels.

At ambient temperatures, besides the yield strength, there is a significant difference on ductility between the full annealed and stress relieving annealed steels as mentioned above. These different characteristics of those two kinds of steels are determined by the variety in the manufacturing process especially heat treatment procedures [6].

At elevated temperatures, the strain hardening in cold-rolled thin-walled steels is relieved with time; accordingly the strength reduction of this type of steel may be higher than that of hot-rolled steels. Meanwhile, these steels develop faster heating rates for having higher thermal conductivity ratio and thinner thickness than hot-rolled steels. However, current specifications [7–10] of steel structural fire designs on the mechanical properties at elevated temperatures were based on hot-rolled steels. Particularly, an integrated provision of high-temperature material models for the entire cold-formed thin-walled steel family has not been provided in current Chinese CFS design codes [5]. In recent years, there is already a considerable database established by global researches on material properties of flat steel sheets for CFS structures at elevated temperatures [11–19]. In general, tested specimens range from 0.50 mm to 2.50 mm thick, with yield strengths from 250 MPa to 550 MPa at ambient temperature. However, no systematic discussion on classification of steels for CFS structures has been conducted when exploring temperature-dependent mechanical properties. From the perspective of steel grades and the ductility at ambient temperature, tested steels in current researches can be divided into two groups: full annealed steels [11, 12, 14, 15, 17–19] (with nominal yielding strength under 450 MPa and elongation greater than 10%) and stress relieving annealed steels [12–16] (with nominal yielding strength over 450 MPa and elongation less than 10%).

This paper presents a detailed experimental investigation of the material properties of two full annealed flat steel sheets (S350 and S420) and one stress relieving annealed flat steel sheet (G500) cut from original steel coils. Here, S350 is the most common grade in past tests [11, 17, 18]; however few data exist on S420 and G500 steels at elevated temperature. Then, by means of comparative study, discussion is conducted on the failure mode, ductility, constitutive relationships, and retention factors for both full annealed steels and stress relieving annealed steels. Meanwhile, after accumulating the existing test data so far, further comparison is made on the reduction trend of mechanical properties at elevated temperatures for two different group steels. Finally, a set of prediction equations of mechanical properties for the entire family of steels used in CFS structures at elevated temperatures is proposed.

2. Manufacturing Process of Steels for CFS Structures

Cold-rolled thin-walled steels are manufactured by cold working mild sheet steels on cold reducing roll to a thickness ranging from 0.3 mm to 3.0 mm. Cold reducing produces distinct deformations of the microcosmic grain texture and structure, which cause a strengthening in strength and hardness, a decrease in F_u/F_y ratio, and a reduction in ductility. The effects of cold working are cumulative and harmful for steels that are used for structural members. Thus, it is necessary to change and recover the grain structure and to control the steel properties through subsequent heat treatment after cold rolling [6].

The process of heat treatment is carried out first by heating the material and then cooling it in the brine, water, and oil. The purpose of heat treatment is to soften the metal, to change the grain size and structure, to modify the properties of the material, and to relieve the stress setup in the material after hot and cold working. The various heat treatment processes commonly employed in engineering practice include annealing, normalizing, quenching, and tempering. Specifically, annealing is the most commonly used heat treatment method in manufacturing of steels for CFS structures. Further, based on the heating temperatures, when annealing is carried out, there are several types annealing as follows [20, 21]:

Full annealing - The steel is heated to above the critical temperature A_{c3} (eutectoid point, 700°C–750°C for low carbon steel) for some time and then cooled in a specific rate. Here all the ferrite transforms into austenite. Full annealed steel is soft and ductile with no internal stress. Partial annealing - The steel is heated to a temperature below to the critical temperature A_{c3} , held at this temperature for some time, and then cooled slowly. The purpose is to relieve stress and lower the hardness of the steel. Stress relieving annealing - The steel is heated to below the critical temperature A_{c1} (pearlite transforms into austenite at this temperature point, 500°C–600°C for low carbon steel), held until the temperature is constant throughout its thickness, then cooled slowly. In this process, the steel is stress relieved; however recrystallization does not occur. Figure 1 illustrates the typical annealing process of steels.

Table 1 shows the chemical composition of tested metals, and Table 2 indicates the key temperatures during manufacturing procedures of tested steels, which are acquired from original manufacturer. It is easily find that the G500 steel experienced a significant lower annealing temperature than that of S350 and S420 steels. Thus, we can safely say that S350 and S420 steels are fully annealed, although the G500 steel is stress relieving annealed according to definitions of different annealing process. In other words, S350 and S420 steels are typical full annealed steels, and the G500 steel is the stress relieving annealed steels. Furthermore, after consulting CFS design standards provisions on materials, collecting current tested steels information, and exploring manufacturing process of steels, commonly used steels for CFS steel structures are divided into two categories: Full annealed steels—steels that experience full annealing process during manufacturing, with nominal yielding strength under 450 MPa and elongation greater than 10%. Stress relieving annealed steels—steels that experience stress relieving annealing process during manufacturing, with nominal yielding strength over 450 MPa and elongation less than 10%.

Specifically, stress relieving annealed steels are basically equivalent to G550 series steels widely used in Australian and Chinese building industry. G550 series steels [2, 5], including three grades (G450, with thickness greater than or equal to 1.5 mm, G500 with thickness greater than 1.0 mm and less than 1.5 mm, and G550, with thickness less than or equal to 1.0 mm.), share similar features on mechanical properties at ambient temperatures [2, 5], and these features

FIGURE 1: Annealing process.

TABLE 1: Chemical composition* of S350, S420, and G500 steels.

S350 (1.0 mm)	C (%)	Mn (%)	Al (%)	S (%)	Nb (%)
	0.06	0.8	0.045	0.02	0.015
S420 (1.0 mm)	C (%)	Mn (%)	Al (%)	S (%)	Nb (%)
	0.06	0.6	0.045	0.015	0.09
G500 (1.2 mm)	C (%)	Mn (%)	Al (%)	S (%)	B (%)
	0.04	0.22	0.038	0.015	0.002

*Percentage of element by mass.

TABLE 2: Manufacturing key temperatures of S350, S420, and G500 steels.

Manufacturing key process	Hot rolling (°C)	Final rolling (°C)	Annealing (°C)
S350	1220	Room temperature	730
S420	1200	Room temperature	700
G500	1200	870	500

(high strength and low ductility) come from stress relieving annealing process [6] on production line.

3. Experimental Study

3.1. Test Method. Two major methods [11–19] may be used to evaluate the mechanical behavior of construction materials under high-temperature environment [11–19]. The most common method currently used for investigating the mechanical properties of steels at elevated temperatures is the steady-state test in which the specimen is heated up to a target temperature and held for a period of time until the temperature is stable and uniform along the specimen, then gradually subjected to a tensile load through to fracture. Another well-known method is the transient-state test in which the specimen applied a static load and then is heated up slowly until failure criteria are met. Most researchers employ steady-state test technique since it is able to obtain stress-strain curves directly, avoids fluctuant temperature environment, eliminates the influence of thermal expansion, and generally saves resources. According to current papers, there is no final conclusion [11, 13, 16] yet on which method is more accurate for testing and predicting the mechanical properties of steels at elevated temperatures. Also, the main focus of this investigation is on the prediction of different

types of steels for CFS structures material properties under high temperatures. Therefore, the steady-state test method was adopted in this test study.

3.2. Test Specimens. All coupons were cut by a wire cutting machine from original coils of S350 and S420 steels with nominal thickness of 1.0 mm, and G500 steels with nominal thickness of 1.2 mm. The dimension of the test specimens was determined by ISO standard [22], as presented in Figure 2. There were four small lugs at the edge of parallel part for fixing extensometer system and two holes for pinning extension tension rods. The metal thickness and gage width of the specimens were average of those values measured at three points within gauge lengths by using a micrometer before testing. The base metal thickness and real gage width were used in the calculations of the initial cross sectional area.

3.3. Test Devices and Procedure. The experiment setup is the EDC222 Doli testing system shown in Figure 3, which is an integrated closed loop digital control thermal and mechanical testing system. The tensile testing machine is an electronic servo system with 100 kN capacity, which was calibrated before testing. A high-temperature stove with a

FIGURE 4: Details of the testing devices.

FIGURE 5: Refractory heat insulation ceramic fiber cloth.

FIGURE 6: High-temperature extensometer system.

TABLE 3: Number of tests performed in this study.

T ($^{\circ}\text{C}$)	20	100	200	300	350	400	500	600	700
S350 (nominal thickness 1.00 mm)	2	2	2	2	1	2	2	2	1
S420 (nominal thickness 1.00 mm)	2	2	2	2	1	2	2	2	1
G500 (nominal thickness 1.20 mm)	2	2	2	2	—	2	3	2	—

the gauge length scope expectedly, which means the stress-strain curves recorded from data acquisition system were real stress-strain relationships within the gauge length. Meanwhile, the carburization layer coated the specimen for all tested grades

when temperature reached 500°C , illustrated by the dark surface of those coupons in Figures 8–10. This carburization coating was incompact and could be scratched using thin sheet metal. Specifically, steel plates presented a blue brittle

FIGURE 7: Typical temperature curves.

FIGURE 8: Failure modes for S350 steels.

FIGURE 9: Failure modes for S420 steels.

phenomenon like normal steels around 300°C, evidenced by the dark blue colored oxidation film on the fracture section of specimens, shown in Figure 11 for the fracture details.

For two full annealed steels, visually noticeable elongation and necking of the coupons occurred from ambient and continued to higher temperatures. For G500 steels, significant elongation and necking could not be observed until temperature exceeds 500°C. Considering the distinction on heat treatment temperatures between full annealed and stress relieving annealed steels, the G500 steel is more

brittle at ambient temperature since the cold work forming effect is not eliminated during annealing. However, when temperature went up to 600°C, which was higher than the critical temperature A_{c1} for low carbon steel, it was possible that the steel was partially annealed in the oven and lost part of the hardening influence. Afterwards, significant change on the failure mode of G500 at 600°C could partially support this assumption and we still need more data investigation to explore the relationship between temperatures and material properties for various steels used in CFS structures.

FIGURE 10: Failure modes for G500 steels.

FIGURE 11: Blue brittle phenomenon for steel plates.

Some of the failed specimens appear to be distorted after 500°C. During the tests at temperatures above 500°C, the specimens were stretched at a much higher displacement rate after the extensometer range was exceeded. In this case, the fracture of these specimens seems to be abnormal. It should be pointed that both ends of the tested specimens have been clamped tightly in the slot of extension loading rods by inserting shims at two sides of the coupon to avoid eccentric load.

4.2. Ductility. In this part, percentage elongation after fracture [22], as shown in equation (1), calculated from original gauge length and final gauge length after fracture, is used to indicate the ductility of specimens. The final gauge length for fractured and cooled down specimens was measured by piecing the segments of specimens tightly at the fracture. Table 4 presents the average percentage elongation after fracture at different temperatures for specimens and its curves are shown in Figure 12.

$$A_T = \frac{l_{u,t} - l_0}{l_0} \times 100. \quad (1)$$

It is interesting to find that S350 and S420 steels, when the temperature increased from 20°C to 200°C, lose their ductility obviously. Some researchers [11, 12] noted a similar behavior for full annealed steels. This material behavior may be attributed to chemical transformations taking place in the steel base. After 300°C, since chemical reactions were taken over by temperature effects as the dominate factor, the ductility grows continually as expected. At the same time, S350 and S420 steels presented a very close trend on ductility development with temperature rising.

Stress relieving annealed steels showed lower ductility than that of full annealed steels at ambient temperature due to the different heat treatments in manufacturing process as mentioned before. Under 200°C, the ductility of G500 steels

TABLE 4: Average percentage elongation after fracture (cooled down).

T (°C)	Percentage elongation after fracture (%)		
	S350	S420	G500
20	32.02	29.99	2.76
100	22.71	20.82	6.06
200	22.40	23.92	3.94
300	40.25	41.41	12.01
400	43.18	45.67	10.34
500	49.07	54.17	10.68
600	63.80	66.97	68.38
700	64.00	56.80

FIGURE 12: Average percentage elongation after fracture at different temperatures.

maintained low values, even close to room temperature value. Then there was a higher platform of ductility in the range of 300°C~500°C, though it was still lower than that of full annealed steel at the same temperatures. Up to 600°C, the effect of strain hardening and heat treatment has been eliminated, so that both full annealed and stress relieving annealed steels showed the same level of ductility. Since the

flashover temperature of fire is over 600°C, the lack of ductility cannot be considered as a characteristic for stress relieving annealed steels at fire conditions.

4.3. Constitutive Relationship. Since the measurement range of the displacement grating is 12.5 mm, the stress-strain curves are given within the strain of 0.2, as shown in Figures 13–15. All stress-strain curves of tested specimens (shown in Figure 3) are summarized together for S350, S420, and G500 steels, respectively. For each of the temperature conditions (marked in the same black circles), curves of repeated tests accord well with each other, indicating the stability of tested materials, test devices, and test operations.

As shown in Figures 13 and 14, the stress-strain curves of S350 and S420 steels present a similar variation trend: (1) For temperatures below 200°C, an obvious yield plateau occurs when the load reaches the ultimate strength and disappears after temperatures beyond 200°C. (2) From 20–300°C, the strain-hardening ranges at different temperatures pinch into a small zone, which illustrates that only yield strength experiences degradation at those temperature cases but ultimate strength dose not. (3) At temperatures beyond 200°C, the stress-strain curves were of the gradual yielding type, and both yield strength and ultimate strength deteriorate with temperature rising. The yield plateaus with multiple yield points are the result of interrupted motion of the Luders band along the specimen. The movement of dislocations near the band front becomes locked when temperature reaches 300°C, and thus yield plateaus disappeared over these temperatures [23].

Unlike the full annealed steels, the G500 steel gave gradual yielding type stress-strain curves at both ambient and elevated temperatures, referring to Figure 15. Then, it appears that the yield strengths do not decrease much up to 200°C. Furthermore, the stress-strain curves have a similar shape and ultimate deformation at temperatures from 300°C to 500°C. When temperature reaches 600°C, the ultimate strain increases significantly. Meanwhile, the load decreases very slowly after the ultimate strength at this condition, and the corresponding failure mode changes to ductile fracture with clear necking.

4.4. Retention Factors. Primarily, Table 5 shows the tensile test results of all three steels at ambient temperature, which are fundamental parameters for calculating high-temperature material properties. Besides the apparent higher strength of G500 steels, the elastic modulus of this high strength steel is also higher than that of full annealed steels at room temperature.

Retention factors for the elastic modulus, yield strength, and ultimate strength were computed as the ratios of material properties at high temperatures to their values at ambient conditions, which is 20°C in this paper. The elastic modulus was calculated by fitting the initial portion of the stress-strain curves via using the least squares method, following ISO standard [22]. For the curves with smooth and long yield plateau, the yield strength was taken as the average value of stresses in the plateau. Then for the gradual yielding

cases, the yield strength was determined by the 0.2% proof stress method, which uses the intersection point of the stress-strain curve and the proportional line offset by 0.2% strain. Results are shown in Table 6.

Figures 16 and 17 provide the retention factors for full annealed and stress relieving annealed steels obtained through steady-state tests from this study and current steel structural fire design codes.

By comparing tests data in this paper for cold-rolled thin-walled steels with current design codes, retention factors from existing steel design codes are generally unsafe, especially for yield strength prediction. As for elastic modulus, retentions factors predicted by Eurocode 3 [9] and AISC 360 [7] agree well with the present full annealed steels tests data before 500°C, but somewhat are unsafe beyond 500°C. These two curves are also suitable for G500 steels, although being a little conservative around 300°C and slightly unsafe beyond 400°C. In addition, the elastic modulus retention factors curve provided by AS 4100 [8] are unsafe beyond 400°C for both full annealed and stress relieving annealed steels. Yield strength retentions factors from hot-rolled steel experimental data provisioned by AISC and Eurocode 3 were the most unsafe, whereas AS 4100 and BS5950-8 [10] are less unsafe relatively. This confirms that, by directly using retention factors developed for hot-rolled steel to calculate yield strength, they are not suitable for cold-rolled thin-walled steels.

Therefore, the provisioned curves in current codes cannot be used to calculate the retention factors for cold-rolled thin-walled steels considered in this study.

In order to investigate the relationship on high-temperature material properties between the steels for CFS structures with different manufacturing process, this paper collected the existing test data of cold-rolled thin-walled steels at elevated temperatures in the recent 20 years, as presented in Table 7. Specifically, based on previous discussion, S420 steel shares a very similar trend on failure mode, ductility, constitutive relationship, and retention factors with S350 steel (typical full annealed steels), even though its nominal yield strength is close to G450 steel (stress relieving annealed steels). Thus, in Table 7, the level of ductility (elongation) is the reliable and significant classification standard for commonly used steels for CFS structures, which is mainly due to the different annealing process during manufacturing.

Figures 18 and 19 illustrate the retention factors for full annealed and stress relieving annealed steels in this test study and other publications available in the literature.

Those two scatter diagrams show a significant dispersion in the existing data on the retention factors of elastic modulus and yield strength, which can be mainly attributed to the measuring method, strain rate, heating rate, material type, and the criteria used to determine the parameters. Consequently, most of the provisioned equations based on past investigations are not suitable for predicting the degradation properties of cold-rolled thin-walled steels due to significant scatters existence.

Despite the discrete of those scatters, there are still basic regulations to follow when scatters have been divided into

FIGURE 13: Stress-strain curves of S350 steels at different temperatures.

FIGURE 14: Stress-strain curves of S420 steels at different temperatures.

two groups: full annealed and stress relieving annealed steels. As shown in Figure 18, there is a consistent trend for retention factors of elastic modulus for both full annealed steels and stress relieving annealed steels. Therefore, the influence from different manufacturing process on elastic modulus of steels for CFS structures is less obvious. In the

yield strength case contrarily, as Figure 19, red scatters and black scatters went to two different shapes obviously, though they agree well generally with the distribution of themselves. Under 300°C, the yield strength of full annealed steels reduces much faster than stress relieving annealed steels when temperatures rise. From 300°C to 600°C, the

FIGURE 15: Stress-strain curves of G500 steels at different temperatures.

TABLE 5: Mechanical properties of cold-rolled thin-walled steels at ambient temperature.

Steel grade	E_{20} (GPa)	$F_{y,20}$ (MPa)	$F_{u,20}$ (MPa)
S350 (1.0 mm)	211.9	411.3	472.2
S420 (1.0 mm)	212.9	434.6	488.1
G500 (1.2 mm)	218.5	686.8	689.8

TABLE 6: Retention factors for the elastic modulus, yield strength, and ultimate strength.

T (°C)	S350, $t = 0.96$ mm			S420, $t = 0.96$ mm			G500, $t = 1.16$ mm		
	E_T/E_{20}	$F_{y,T}/F_{y,20}$	$F_{u,T}/F_{u,20}$	E_T/E_{20}	$F_{y,T}/F_{y,20}$	$F_{u,T}/F_{u,20}$	E_T/E_{20}	$F_{y,T}/F_{y,20}$	$F_{u,T}/F_{u,20}$
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	0.938	0.870	0.949	0.941	0.937	0.966	1.026	0.959	0.971
200	0.967	0.787	1.052	0.967	0.677	1.004	0.976	0.977	1.057
300	1.076	0.593	1.054	1.056	0.573	1.041	0.913	0.836	0.914
350	0.938	0.488	0.845	0.821	0.524	0.857	—	—	—
400	0.891	0.467	0.680	0.785	0.467	0.689	0.610	0.665	0.707
500	0.602	0.321	0.381	0.578	0.319	0.384	0.466	0.357	0.396
600	0.287	0.176	0.181	0.314	0.182	0.192	0.253	0.065	0.094
700	0.159	0.070	0.068	0.167	0.070	0.074	—	—	—

yield strength for stress relieving annealed steels drops drastically with temperatures elevating, although those for full annealed steels fall smoothly at this stage. After 600°C, the descending slope of stress relieving annealed steels becomes gentler than full annealed steels again. In this case, steels with different manufacturing process behave totally different for reduction rules on yield strength at elevated temperatures.

In conclusion, it is meaningful to produce statistical conclusion and raise general equations for predicting the

reduction of material properties on steels used for CFS structures at elevated temperatures.

5. Prediction Equations

5.1. Retention Factors Prediction for Elastic Modulus. Due to the weak dependence of manufacturing procedure of steels for CFS structures on the elastic modulus reduction development, a single equation is provided here for calculating retention factors of elastic modulus by fitting the scatters

FIGURE 16: Comparison of the retention factors of elastic modulus according to test results with the current design codes.

FIGURE 17: Comparison of the retention factors of yield strength according to test results with the current design codes.

(polynomial regression) in the entire database (compiled in Table 6).

$$\frac{E_T}{E_{20}} = 4.826E - 16T^5 + 1.224E - 12T^4 - 5.808E - 10T^3 - 1.742E - 06T^2 - 2.070E - 04T + 1.004, \quad 20^\circ\text{C} \leq T \leq 800^\circ\text{C}. \quad (2)$$

Figure 20 shows the fitting curve of the retention factors for elastic modulus with original scatters, and Figure 21 gives the comparison of the proposed equation curves with code curves for predicting elastic modulus. Recommended retention factors for the elastic modulus extracted from fitting equation at temperatures of hundreds are provided in Table 8.

5.2. Retention Factors Prediction for Yield Strength. Considering the separation of full annealed and stress relieving annealed steels on retention factors for yield strength, two sets of equations were promoted here through polynomial and exponential regressions for predicting retention factors of yield strength correspondingly, as equation (3) for full annealed steels and equation (4) for stress relieving annealed steels. Figures 22 and 23 show the fitting curves of the retention factors for yield strength of full annealed steels and stress relieving annealed steels separately. Meanwhile, Figure 24 gives the comparison of the proposed equation curves with code curves for predicting yield strength. Recommended retention factors for the yield strength extracted from fitting equation at temperatures of hundreds are provided in Table 9. In general, as revealed by Figures 21 and 24, equations provided by current standards [1–6] are unsafe for predicting elastic modulus and yield strength.

TABLE 7: Compilations of basic information for current test data.

Year	Researchers	Grade	Thickness (mm)	Elongation* (%)
Full annealed steels				
1999	Qutinen [11]	S350	2.00	>20
2003	Lee et al. [12]	G300	0.40	No information
			0.60	No information
			1.00	No information
2009	Ranawaka and Mahendran [14]	G250	0.60	>30
			0.80	>30
			0.95	>30
2011	Kankanamge and Mahendran [15]	G250	1.55	>30
2013	Ye and Chen [17]	Q345	1.95	>30
			1.50	>30
2015	Batista Abreu [18]	S230	1.44	>20
			1.15	>20
			1.55	>20
2016	Craveiro et al. [19]	S345	2.58	>20
			2.50	>20
			1.00	32.02
	This research	S420	1.00	29.99
Stress relieving annealed steels				
2003	Lee et al. [12]	G500	1.20	No information
			0.42	No information
			0.60	No information
			0.95	No information
2007	Chen and Young [13]	G450	1.90	11.3
			G550	1.00
2009	Ranawaka and Mahendran [14]	G550	0.60	<3
			0.80	<3
			0.95	<3
2011	Kankanamge and Mahendran [15]	G450	1.50	<10
2012	Chen and Ye [16]	G550	1.90	<10
			1.00	<10
	This research	G500	1.20	2.76

*The elongation here represents the percentage elongation after fracture of specimens at ambient temperatures. However, most researches have not given the elongation data directly; stress-strain curves are major clues to estimate the ductility of steels.

FIGURE 18: Comparison of the retention factors of elastic modulus for cold-rolled thin-walled steels according to test results with available research results.

FIGURE 19: Comparison of the retention factors of yield strength for cold-rolled thin-walled steels according to test results with available research results.

FIGURE 20: Fitting curve of the retention factors for elastic modulus.

FIGURE 21: Comparison of the proposed equation curves with code curves for predicting elastic modulus.

TABLE 8: Recommendation retention factors for the elastic modulus.

T (°C)	20	100	200	300	400	500	600	700	800
E_T/E_{20}	1.000	0.966	0.891	0.781	0.642	0.484	0.324	0.182	0.086

FIGURE 22: Fitting curve of the retention factors for yield strength of full annealed steels.

FIGURE 23: Fitting curve of the retention factors for yield strength of stress relieving annealed steels.

$$\begin{aligned} \frac{F_{y,T}}{F_{y,20}} = & -2.272E - 14T^5 + 4.931E - 11T^4 - 3.418E - 08T^3 \\ & + 7.512E - 06T^2 - 1.230E - 03T + 1.023, \\ & 20^\circ\text{C} \leq T \leq 800^\circ\text{C}, \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{F_{y,T}}{F_{y,20}} = & 2.855E - 14T^5 - 9.820E - 12T^4 - 1.991E - 08T^3 \\ & + 8.483E - 06T^2 - 1.030E - 03T - 1.018, \\ & 20^\circ\text{C} \leq T \leq 600^\circ\text{C}, \\ \frac{F_{y,T}}{F_{y,20}} = & 9.467E + 07T^{-3.222}, \quad 600^\circ\text{C} \leq T \leq 800^\circ\text{C}. \end{aligned} \quad (4)$$

FIGURE 24: Comparison of the proposed equation curves with code curves for predicting yield strength.

TABLE 9: Recommendation retention factors for the yield strength.

T (°C)		20	100	200	300	400	500	600	700	800
Full annealed steels	$F_{y,T}/F_{y,20}$	1.000	0.946	0.876	0.751	0.575	0.385	0.229	0.138	0.095
Stress relieving annealed steels	$F_{y,T}/F_{y,20}$	1.000	0.98	0.986	0.925	0.731	0.415	0.104	0.065	0.042

TABLE 10: Ramberg–Osgood hardening parameters from regression fitting, with $K_T = 0.002$.

T (°C)	η_T for S350 steels	η_T for S420 steels	η_T for G500 steels
200	—	—	0.980
300	0.946	0.980	0.986
400	0.876	0.986	0.925
500	0.751	0.925	0.731
600	0.575	0.731	0.042
700	0.095	0.042	—

TABLE 11: Constants for Ramberg–Osgood hardening parameters.

Steel grades	T (°C)	a ($\times 10^{-4}$) (1/°C ²)	b ($\times 10^{-1}$) (1/°C)	c
S350	[300, 500]	2.646	−1.696	33.231
	(500, 700]	4.577	−3.616	80.909
S420	[300, 500]	2.111	−1.287	25.946
	(500, 700]	−6.360	8.264	−239.832
G500	[200, 400]	10.400	−5.779	110.897
	(400, 600]	6.639	−8.364	274.440

5.3. Constitutive Relationship Models. In order to carry out advanced FEA simulation and fire safety design, complete constitutive models are required. Generally, temperature-dependent constitutive relationship models are based on the Ramberg–Osgood three-parameter (elastic modulus, yield strength, and temperature) gradual yielding model [24]. As for equation (5), ε_T , σ_T , E_T and $F_{y,T}$ are the strain, stress, elastic modulus, and yield strength at T (°C), respectively; and K_T and η_T are parameters obtained from regression analysis.

In Ramberg–Osgood model, K_T is strength coefficient and η_T is hardening parameter. In past researches, some

researchers [13–15] use temperature-dependent K_T and η_T simultaneously, some researchers [12] use fixed η_T and the rest of researchers [16–18] use constant K_T . Considering that the yield strength was obtained through the 0.2% offset method, stress-strain data was fitted to equation (5) (exponential regression) with the Ramberg–Osgood strength parameter K_T set to 0.002. Therefore, the strain computed at the 0.2% offset stress corresponds with the yield strain. Furthermore, the temperature-dependent Ramberg–Osgood hardening parameters η_T were fitted to equation (6) (polynomial regression) for the entire temperature range.

(a)

(b)

FIGURE 25: Continued.

FIGURE 25: Stress-strain test curves (solid lines) and fitting curves (dashed lines). (a) S350 steels. (b) S420 steels. (c) G500 steels.

$$\varepsilon_T = \frac{\sigma_T}{E_T} + \left(\frac{\sigma_T}{F_{y,T}} \right)^{\eta_T}, \quad (5)$$

$$\eta_T = aT^2 + bT + c. \quad (6)$$

For S350 and S420 steels, since there is an obvious yield plateau for stress-strain curves up to 200°C, it was reasonable to apply elastic-perfectly plastic model under 200°C. Meanwhile, due to the lacking of strengthening stage for G500 steel up to 100°C, elastic-perfectly plastic model was adopted also for G500 steel under 100°C. Consequently, Ramberg–Osgood model regression fitting started from 300°C for S350 and S420 steels, and from 200°C for G500 steel. The resulting Ramberg–Osgood hardening parameters are shown in Table 10, constants for Ramberg–Osgood hardening parameters are shown in Table 11, and stress-strain fitting curves are compared with test results in Figure 25. Based on Figure 25, there is a very good agreement between the predicted stress-strain curves from equations (5) and (6) and test results. Therefore, these equations are recommended for the determination of the stress-strain curves of S350 (1.0 mm), S420 (1.0 mm), and G500 (1.2 mm) steels at elevated temperatures.

6. Conclusions

This paper has reported a detailed experimental study of the mechanical properties of steels for CFS structures at elevated temperatures. Different manufacturing processes and their influence on the properties of steels for CFS structures were discussed. The experimental study included tensile coupon tests conducted on S350, S420, and G500 steels via steady-state test methods, and a careful discussion of the test results

was provided. The failure mode, ductility, stress-strain relationship, and material reductions were elaborated in a comparison way. Then based on the testing and literature data, retention factors for elastic modulus and yield strength were established for the two types of steels used in CFS structures as functions of temperature. At last, constitutive relationship models were proposed based on tests data for S350, S420, and G500 steels separately.

Abbreviations

A_{20} :	Percentage elongation after fracture at 20°C
A_T :	Percentage elongation after fracture at T (°C)
E_{20} :	Elastic modulus at 20°C
E_T :	Elastic modulus at T (°C)
$F_{y,20}$:	Yield strength at 20°C
$F_{y,T}$:	Yield strength at T (°C)
$F_{u,20}$:	Ultimate strength at 20°C
$F_{u,T}$:	Ultimate strength at T (°C)
L_0 :	Original gauge length
$l_{u,T}$:	Final gauge length at T (°C)
T :	Temperature
ε_T :	Strain at T (°C)
σ_T :	Stress at T (°C)
K_T :	Strength coefficient in Ramberg–Osgood model at T (°C)
η_T :	Hardening parameter in Ramberg–Osgood model at T (°C).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

No conflicts of interest exist in the submission of this manuscript.

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