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Cold-formed steel properties at elevated temperature: review and proposed equation

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Abstract

Cold-formed steel members are increasingly used in the construction industry due to their favorable strength-to-weight ratio and cost efficiency. Knowledge of the elevated temperature behavior of cold-formed steels is fundamental for the fire design of cold-formed steel members. The literature describes experimental tests on different types of cold-formed steels under different elevated temperature regimes, but no specification pertaining to elevated temperature behavior of cold-formed steel is currently available in the United States and no unified model has established itself for grades commonly used in the US. In this work, we conducted a review of available test data and specifications in other countries (including the Eurocode 3 and the Australian AS/NZS 4600), complemented with previously unpublished test data obtained at Johns Hopkins University. Reviewed data covered steady-state and transient-state tests performed on a wide range of material grades and thicknesses. The data was analyzed to characterize the reduction in stiffness and strength with temperature, including the effects of testing regime, material grade, and plate thickness. Then, a unified three-coefficient equation was formulated to capture the reduction of mechanical properties of cold-formed steels with temperature. Four sets of coefficients of the unified equation were calibrated to characterize, respectively, the reduction of elastic modulus, 0.2% proof stress, 2.0% yield stress, and ultimate stress at elevated temperature. The reduction factors obtained with the proposed equation generally agree with the Eurocode 3 and AS/NZS 4600 factors. Yet, the proposed equation is a continuous function of temperature in the range 20°C-1000°C, provides a single curve for a given mechanical property, is more exhaustive (capturing also ultimate stress), and applies to cold-formed steels typically used in the U.S. The proposed equation is suitable for steel grades up to G550 and thickness up to 3.5 mm.

1. Introduction

Cold-formed steels have been widely used in structural applications and their mechanical properties at elevated temperature are essential parameters for structural fire design. Recent experimental studies have provided data to characterize the elevated temperature behavior of cold-formed steels, especially the degradation of stiffness and strength with temperature. These data have supported the implementation of provisions in Australian [1] and European [2] design codes. The Section 9 on fire design of cold-formed steel building members in Australian standard AS/NZS 4600:2018 [1] provides relationship of elastic modulus, yield stress, and stress-strain curves with temperature. The Annex E for class 4 sections in Eurocode EN1993-1-2 [2] also contains relationship of yield stress and ultimate stress with temperature that apply to cold-formed steel.

However, there is no specification concerning the mechanical properties of cold-formed steels at elevated temperature in American design codes [3]. While the European and Australian standards provide useful benchmark, they cannot necessarily be directly transposed to the US context. Therefore, this study, which was conducted within the context of a Task Group of the committee on member design with the American Iron and Steel Institute (AISI), performed a review of the available test data with the aim to provide recommendations for elevated temperature properties of cold-formed steels in the US. The review includes published data as well as new tests conducted at Johns Hopkins University and covers nominal yield stress ranging from 230 MPa to 550 MPa under both steady-state and transient-state conditions. Based on the review, a novel equation for retention factors of material

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properties is proposed which is a three-coefficient continuous function of temperature. The equation allows characterizing the elastic modulus, 0.2% proof stress, 2.0% stress, and ultimate stress at elevated temperature range of 20°C-1000°C. The proposed equation in this study is compared with the retention factors in European and Australian standards.

2. Materials and test methods

2.1 Cold-formed steels

Cold-formed steel structural members for building construction are typically made from coiled sheet steel with thickness of 0.8 mm to 3.0 mm. The most commonly used cold-formed steels in the US are mild steels with nominal 0.2% proof stress of 250 MPa or 350 MPa, and G550 with nominal 0.2% proof stress of 550 MPa. The steel sheets are bent into structural member shapes, such as channels, lipped zees, and deck, by roll-forming machines. The members are then used to frame vertical (wall) and horizontal (floor, roof) panels in repetitive framing methods. Based on the commonly used cold-formed steels in the US, and on the availability of test data at elevated temperature, this study focuses on cold-formed steels with nominal yield stress up to 550 MPa and thickness up to 3.5mm.

2.2 Test methods
2.2.1 Steady-state test

In steady-state tests, a specimen is first heated up in an unstressed state to a target elevated temperature with a controlled heating rate. The heating rate may be selected to be representative of real fire conditions (note the steel heating rate in real conditions depends greatly on the thermal protection). A force-controlled mode is usually adopted to allow for free thermal expansion of the specimen during the heating process; in any case it must be ensured that restraint axial forces do not build up in the specimens during the heating stage. Once the target temperature has been reached, a soak time is observed to ensure the stabilization and uniformity of steel temperature, as measured by thermocouples applied on the steel specimen. After that, tensile testing is carried out with a controlled loading rate, while the temperature is maintained constant. The loading can be prescribed in terms of displacement-controlled rate to capture the post-peak part of the stress-strain response. The loading continues until the facture of the specimen. Continuous stress-strain curves at the target (elevated) temperature are directly obtained from steady-state tests.

2.2.2 Transient-state test

While steady-state tests are easier to conduct, transient-sate tests are intended to capture more accurately the state of the material when used in a structure subject to fire. In transient-state tests, the specimen is first loaded in tension to a target stress state. Then the (stressed) specimen is heated, while the stress state is maintained constant. During heating, a force-controlled mode is usually implemented to maintain the constant stress state since thermal expansion is induced during heating. The strain measured during the heating process is the sum of mechanical strain and thermal strain. Thus, a zero-load transient heating test is also performed to measure the free thermal strain during heating. By subtracting the free thermal strain from the total strain, the mechanical strain as a function of temperature under different stress states can be obtained. The obtained strain-temperature curves are then converted to stress-strain curves at several temperatures.

3. New tests by Yan and Gernay

Steady-state tests have been carried out on conventional cold-formed steels with nominal yield stress of 345 MPa by Yan and Gernay at Johns Hopkins University. The material was obtained from the NIST Fire Research Division, based on leftover from the test campaign on the influence of fire on the lateral resistance of strap braced cold-formed steel shear walls [4]. The test specimens were prepared in accordance with ASTM E8 [5] and E21 [6] for pin-loaded tensile tests with 50 mm (2 inches) gauge length, as show in Figure 1.

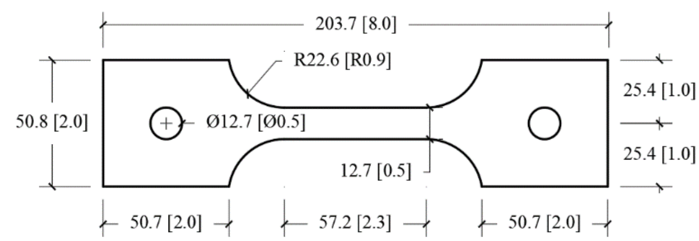

Figure 1: Shape and dimension of test specimen (in mm and inch).

A high temperature furnace with three independent heating zones and capacity of 1150°C was used to heat up the specimens. Tensile loading was applied by an MTS loading frame. During heating, the steel temperature was measured by three external thermocouples located at the two ends and center of the reduced parallel section. The strain was measured by both a high-temperature extensometer (-10%/20%) and a digital image correlation (DIC) method (40%).

Test temperatures include 20°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, and 800°C. Heating rate for the steady-state test was 10°C/min. Once the target temperature was reached, an extra 20 min of heating was observed to ensure the uniform temperature inside the specimens. After that, tensile loading was applied in a displacement mode with a rate of 0.25 mm/min until facture of the specimen. Results are reported in the next section.

4. Literature data

Research on the mechanical properties of cold-formed steel at elevated temperature has attracted attention from many researchers [7–17]. Test data on elevated temperature mechanical properties of cold-formed steels with conventional grade are summarized in Table 1 and those of cold-formed G550 are summarized in Table 2.

The reduction trends of mechanical properties including elastic modulus, 0.2% proof stress, stress at 2.0% strain, and ultimate stress, in terms of retention factors, with increasing temperature are plotted in Figure 2 to Figure 5. Filled black are used to denote steady-state test data of conventional grade cold-formed steels, filled red symbols are used for steady-state data of G550, and empty black symbols for transient-state test data. The filled blue symbol is used for the new test data by Yan and Gernay (Section 3).

The mechanical properties decrease with increasing temperature. The reduction in elastic modulus is progressive while the reduction in strength exhibits an S-shape with noticeable drop in temperature range of 300°C to 600°C. Generally, no significant discrepancy is found between cold-formed conventional steel and G 550 (i.e. black versus red symbols), suggesting a unified equation can be used across these steel grades. Comparing the steady-state test data and transient-state test data (i.e. filled versus empty symbols), there is no discernable difference in terms of strength. Regarding the modulus, one of the transient datasets lies below the general trend, but the other transient dataset lies within the rest of the data. As a result, it is reasonable to provide a unique relationship that captures both steady-state test data and transient-state test data.

Table 1: Test information of conventional grade cold-formed steels.

Source	Steel type	Thickness (mm)	Test type*	Temperature (°C)
Lee et al. [17]	G300	0.4, 0.6, 1.0	SS	20-800
Outinen and Makelainen [16]	S355J2H	3	TS	20-1000
Chen and Ben [15]	G450	1.9	SS/TS	20–1000
Ranawaka and Mahendran [14]	G250	0.6, 0.8, 0.95	SS	20-800
Kankanamge and Mahendran [13]	G250	1.55, 1.95	SS	20–700
	G450	1.5, 1.9		
Ye and Chen [12]	Q345	1.5	SS/TS	30-700
McCann et al. [10]	S355J2H		SS/TS	20-1000
Imran et al. [8]	G350	2, 3.5	SS	20-800
Batista Abreu [9]	ASTM A653	1.44		20-600
		2.58, 1.15	SS	
	ZAR-345	1.55		20-700
Yan et al. [7]	Mild 395	1.4	SS	20-700
	DP 340	1.4		20-700
Yan et al.	CFS-345	1.8	SS	20-800

* SS is steady state; TS is transient state.

Table 2: Test information of cold-formed G550.

Source	Steel type	Thickness (mm)	Test type*	Temperature (°C)
Lee et al. [17]	G550	0.42, 0.6, 0.95	SS	20-800
Chen and Ben [15]	G550	1	SS	20–1000
Ranawaka and Mahendran [14]	G550	0.6, 0.8, 0.95	SS	20-800

* SS is steady state; TS is transient state.

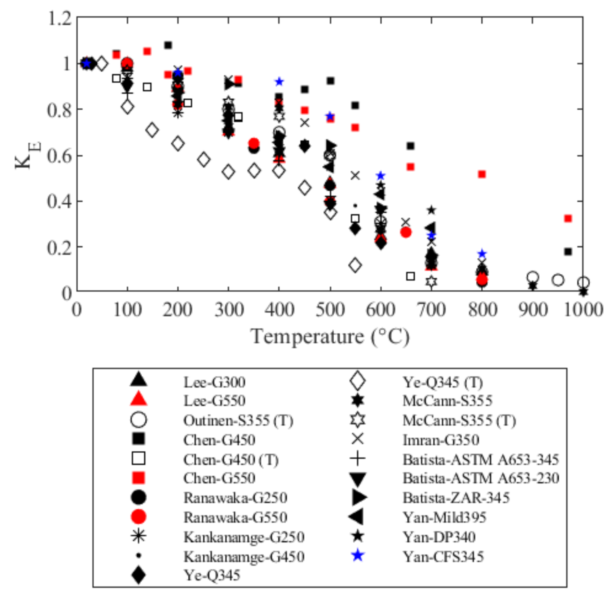

Figure 2: Retention factors of elastic modulus of cold-formed conventional grade steels and G550 at elevated temperature.

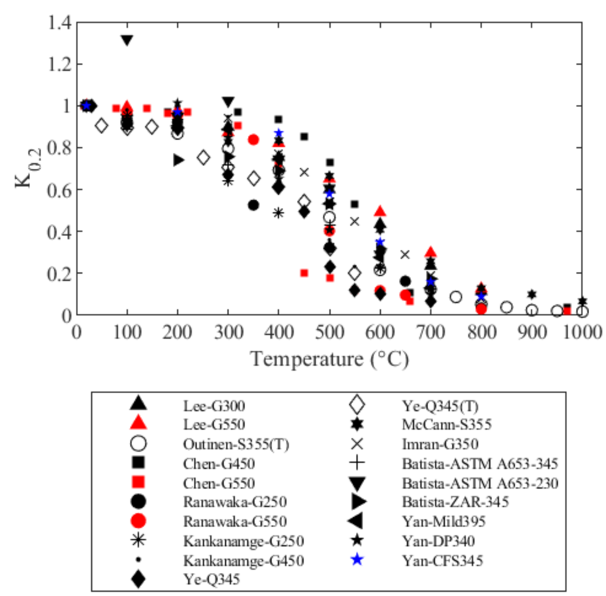

Figure 3: Retention factors of 0.2% proof stress of cold-formed conventional grade steels and G550 at elevated temperature.

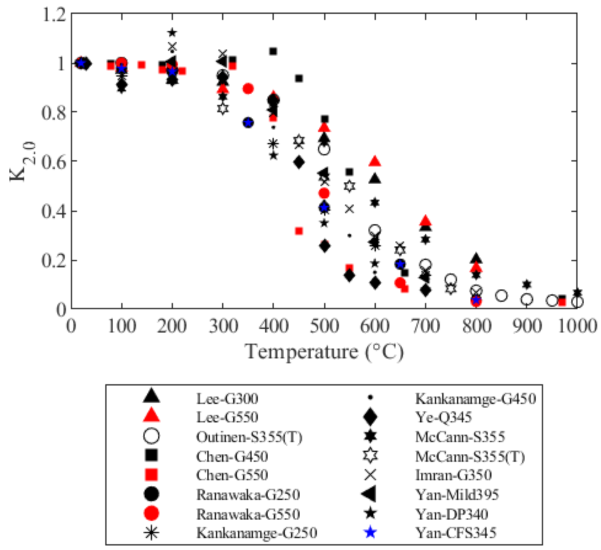

Figure 4: Retention factors of stress at 2.0% strain of cold-formed conventional grade steels and G550 at elevated temperature.

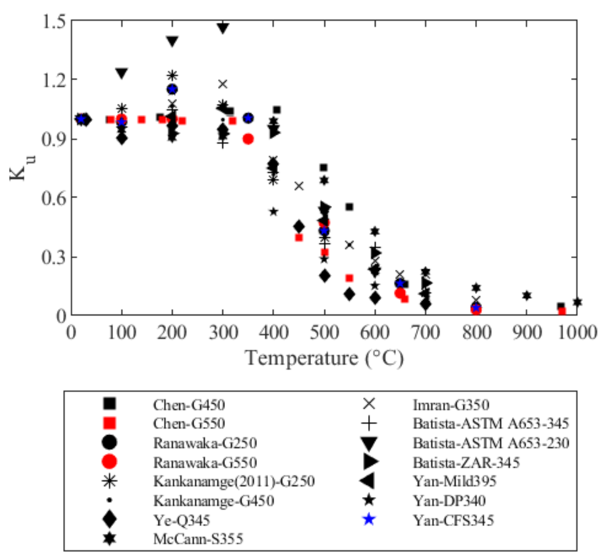

Figure 5: Retention factors of ultimate stress of cold-formed conventional grade steels and G550 at elevated temperature.

5. Proposed new model

5.1 Standardized retention factor equation

A standardized retention factor equation, in the form of Eq. (1), is proposed to fit the data.

$$k = (1-c)\frac{1-x^b}{1+ax^b} + c \tag{1}$$

where

$$x = \frac{T - T_1}{T_2 - T_1} \tag{2}$$

and a, b, c are three coefficients that are calibrated from the test data summarized in Section 3, and T_1 and T_2 are the steel temperature range (in °C). Here, the temperature range is selected as $T_1 = 20$℃ and $T_2 = 1000$℃ based on the test data.

5.2 Retention factors for mechanical properties of cold-formed steel

The coefficients of the proposed retention factor equation are summarized in Table 3. For each property, the retention factors were first estimated separately for (1) conventional grade steels under steady state, (2) conventional grade steels under transient state, (3) G550 under steady state. Then, the whole dataset is provided for (4) best statistical fit and (5) final rounded values. For elastic modulus, the R-squares for the fitted models from (1)-(4) data set were 0.876, 0.872, 0.798, and 0.849, while that for the final rounded model is 0.839. Comparison of the different fitted curves confirmed the observation made in Section 4 that there is no significant discrepancy between the separated datasets. Thus, a single curve is adequate to capture the whole dataset. The same exercise is conducted for the other properties (0.2% proof stress, 2.0% stress, and ultimate stress) and leads to the same conclusion. For 0.2% proof stress, the R-squares for the fitted models from (1)-(4) data set are 0.894, 0.968, 0.910, and 0.903, while that for the final rounded model is 0.903. For 2.0% stress, the R-squares for the fitted models from (1)-(4) data set are 0.922, 0.988, 0.894, and 0.925, while that for the final rounded model is 0.924. For ultimate stress, the R-squares for the fitted models from (1), (3), and (4) data set are 0.903, 0.987, and 0.913, while that for the final rounded model is 0.910. The curves for separate and aggregated dataset align closely with each other. This further verifies the observation in Section 4 that the steady-state test data and transient-state test data of conventional grade steels, as well as G500 test data can be aggregated. As a conclusion, a single curve is proposed for each property, based on Eq. (1) and with the coefficients of Table 3.

Table 3: Coefficients to determine retention factors for mechanical properties of cold-formed steel.

Property	a	b	c
Modulus	8	3	0.04
0.2% proof stress	20	4	0.03
2% stress	70	6	0.05
Ultimate stress	185	7	0.04

6. Discussion and comparison

The retention factors are compared with the predictions in published literature and design standards, Eurocode EN1993-1-2 [2] and Australian standard AS/NZS 4600 [1]. Figure 6 shows the comparison of elastic modulus. The proposed model generally agrees well with the models by

Lee et al. [17] and the models in EC3 and AS/NZS 4600. The model by Lee et al. [17] is almost identical with the one in AS/NZS 4600 and they provide more conservative values, while EN provides slightly higher prediction than the proposed model from 400°C to 600°C. Figure 7 shows the comparison of 0.2% proof stress. The AS4600 generally provides a lower bound and the proposed retention factors lie within the range of the code values. The model by Lee et al. [17] shows good agreement with the model proposed in this study in the temperature range of 20°C-300°C and 700°C-800°C, while the model by Lee et al. [17] provides slightly larger values at 400°C-700°C. Figure 8 shows the comparison of stress at 2.0% strain. The grey virtual line denotes the values in Eurocode for the 2.0% stress. In Eurocode, the 0.2% proof stress (for class 4 section) of Figure 7 is the value that is adequate for cold-formed steel design. As can be seen, the Eurocode 3 retention factors for 2.0% stress are not adequate to capture the behavior of cold-formed steel at elevated temperature, as the test data largely lie below the Eurocode curve. Figure 9 shows the comparison of ultimate stress. The proposed model predicts lower values than the EN model. Overall, the proposed model, which is calibrated on an extensive dataset for cold-formed steel under steady-state and transient conditions from multiple researchers, provides a continuous equation to capture the reduction of properties with temperature that generally agree with existing code provisions in other countries.

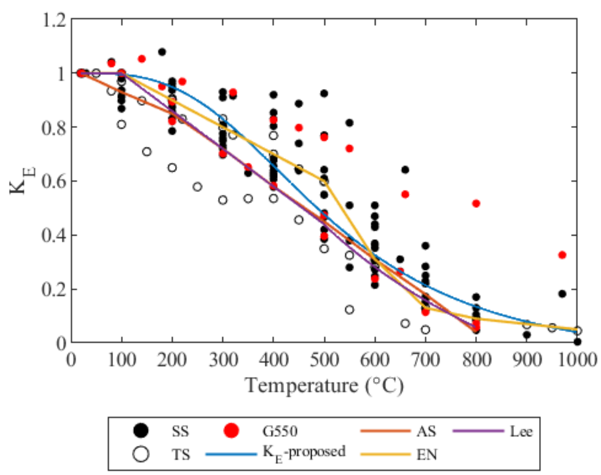

Figure 6: Comparison of proposed retention factors for elastic modulus with EN and AS4600.

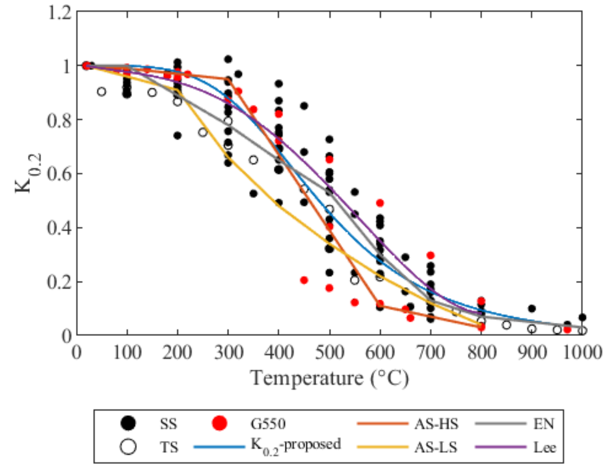

Figure 7: Comparison of proposed retention factors for 0.2% proof stress with EN and AS4600.

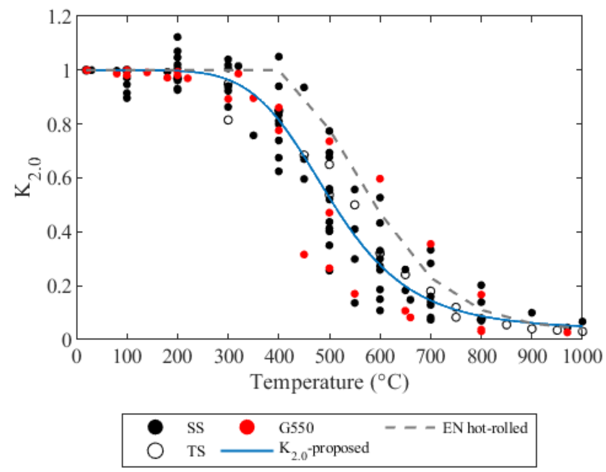

Figure 8: Comparison of proposed retention factors for 2.0% stress.

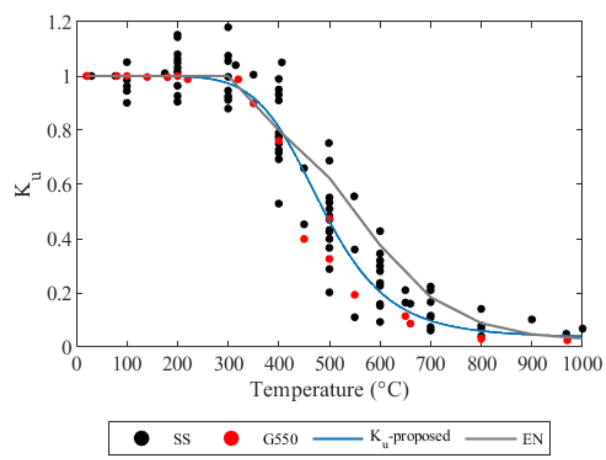

Figure 9: Comparison of proposed retention factors for ultimate stress with EN.

7. Conclusion

A review of the test data on cold-formed conventional grade steels and G550 at elevated temperature is presented in this paper, in addition to original data recently obtained by the authors. A simple three-coefficient equation is then proposed to capture the degradation of mechanical properties of cold-formed steels with temperature. The coefficients have been calibrated based on the test data to characterize the reduction of elastic modulus, 0.2% proof stress, 2.0% stress, and ultimate stress with temperature. The established relationships are compared with Australian and European codes, as well as models in published papers, and a general agreement can be observed. The proposed relationships are applicable to steel grades up to G550 and thickness up to 3.5 mm, at temperatures up to 1000°C. The proposed relationships have the advantage of being continuous functions of temperature, adopting a consistent format, providing a single curve for a given property, and being calibrated on a large dataset from several authors, materials, and testing regimes.

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