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INFLUENCE OF MATERIAL MODELS ON PREDICTING THE FIRE BEHAVIOR OF STEEL COLUMNS

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Abstract

Finite-element (FE) analysis was used to compare the high-temperature responses of steel columns with two different stress-strain models: the Eurocode 3 model and the model proposed by National Institute of Standards and Technology (NIST). The comparisons were made in three different phases. The first phase compared the critical buckling temperatures predicted using forty seven column data from five different laboratories. The slenderness ratios varied from 34 to 137, and the applied axial load was 20–60 % of the room-temperature capacity. The results showed that the NIST model predicted the buckling temperature as or more accurately than the Eurocode 3 model for four of the five data sets. In the second phase, thirty unique FE models were developed to analyze the W8×35 and W14×53 column specimens with the slenderness ratio about 70. The column specimens were tested under steady-heating conditions with a target temperature in the range of 300–600 °C. The models were developed by combining the material model, temperature distributions in the specimens, and numerical scheme for non-linear analyses. Overall, the models with the NIST material properties and the measured temperature variations showed the results comparable to the test data. The deviations in the results from two different numerical approaches (modified Newton Raphson vs. arc-length) were negligible. The Eurocode 3 model made conservative predictions on the behavior of the column specimens since its retained elastic moduli are smaller than those of the NIST model at elevated temperatures. In the third phase, the column curves calibrated using the NIST model was compared with those prescribed in the ANSI/AISC–

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360 Appendix 4. The calibrated curve significantly deviated from the current design equation with increasing temperature, especially for the slenderness ratio from 50 to 100.

Keywords

Fire loading; Elevated temperature; Steel column; Finite element method; Stress-strain relationship; Inelastic buckling; Thermal strain

1. Introduction

Fire safety design and analysis for steel building structures require material constitutive models to accurately predict the performance of steel members, connections, and systems in fire. For structural steels, the majority of effort to develop full constitutive laws began in Europe during the early 1980s and culminated in the development of the Eurocode 3 stress-strain model [1]. In the United States, the ANSI/AISC-360 [2] specification for steel building design provides a table of temperature-dependent retention factors for steel mechanical properties (proportional limit, yield strength, and elastic modulus), which was essentially adopted from the Eurocode 3 stress-strain model. These retention factors are primarily intended to consider the high-temperature degradation of steel in the structural design of load-carrying members and components at elevated temperatures; they are of limited use for analyzing structural system-level response to fire. The fire behavior of steel systems is far more complex since the heat exposure is rarely uniform during a fire. Prediction of system-level fire behavior requires more advanced computation tools, the finite-element (FE) models in particular, and a reliable high-temperature stress-strain model to analyze the comprehensive fire-structural interactions between individual structural components.

Recent research at the National Institute of Standards and Technology (NIST) improved the high-temperature stress-strain model for its use in the structural-fire analysis of steel-framed building systems and components. As part of investigations on the World Trade Center (WTC) collapse, NIST reported the high-temperature mechanical properties of structural steels collected from the collapse site [3]. These properties were used for numerical simulations of the fire-induced failure of the WTC buildings [4]. Thereafter, the NIST researchers proposed the stress-strain model [5] which was calibrated using 431 individual tests of 43 different hot-rolled carbon and high-strength low-alloy steels with a specified minimum yield stress ranging from 250 MPa to 520 MPa. The NIST model was developed based on standard high-temperature tensile tests in accordance with ASTM E21 [6], ISO 783 [7], or ISO 6892-2 [8]. The mathematical form of the NIST model is applicable to other specialty steels, such as high strength bolt steels (ASTM A325 [9] or ASTM A490 [10]), quenched-and-tempered steels (e.g., ASTM A514 [11] plate), and fire-resistant steels that meet the ASTM A1077 [12] specification. The complete formulation and parameters of the NIST stress-strain model are summarized in Appendix I of this paper.

Figure 1 presents a comparison of the NIST and the Eurocode 3 retention factors, which are temperature-dependent elastic moduli, $E(T)$, and yield strengths, $F_y(T)$, normalized by the room-temperature values (E_0 and F_{y0} respectively). It should be noted that the Eurocode 3

standard specifies the yield strength at 2 % strain based on the strain-temperature relationship from the transient heating tests at various stress levels. However, the NIST model, which was based on ASTM standard tensile tests, defines the yield strength at the maximum elastic strain (about 0.2% strain). One could observe from Figure 1 that the Eurocode 3 retention factors for elastic modulus are smaller than those of the NIST model at elevated temperatures, and the yield strength from the NIST model smoothly degrades from the room-temperatures values and becomes similar to that from the Eurocode 3 model as temperature reaches at 600 °C and above.

The NIST stress-strain model is relatively new and has not been widely used yet. In this paper, the NIST stress-strain model was used for analyzing the flexural buckling of steel columns at elevated temperature. Accurately predicting the fire performance of columns is particularly critical to evaluate the stability of a building system in fire. Three different studies were conducted to evaluate the effect of material models on predicting the flexural buckling behavior of columns: (1) The failure temperatures of the 47 tested columns were calculated using the FE models with the NIST and the Eurocode 3 stress-strain relationship and compared with those reported values from experiments. The modeling approach used in this phase assumed the time independence of loading and heating conditions, uniform temperature distribution, and the temperature independence of thermal strains. (2) The high-temperature strength and response of the six tested columns were predicted using thirty unique finite-element models. These models were developed in combination with two different material models (NIST and Eurocode 3), two different temperature distributions (uniform and non-uniform heating), and two different numerical approaches (modified Newton Raphson and arc-length). More detailed test data of temperature and axial load histories were used in the analyses. The responses of the column specimens analyzed by the NIST and the Eurocode 3 stress-strain models were compared with those measured in the tests. The effect of thermal gradients on the inelastic column buckling was also discussed. (3) The new flexural buckling curve was calibrated using the NIST model and compared with that prescribed in the current ANSI/AISC–360 Appendix 4 [2]. As a future topic, it is recommended to further evaluate the applicability of the NIST model for analyzing other structural components and systems under various fire conditions.

2. Phase I: Critical temperature of steel columns

The critical temperature of steel columns involves inelastic behavior that is a function of both the modulus of elasticity and the yield strength of the steel. At temperatures which steel experiences in building-contents fires, both the stiffness and strength are significantly diminished, and, therefore, the actual buckling strength of a steel column in fire can be a small fraction of that at ambient temperature. To evaluate the high-temperature behavior of steel columns, many laboratories tested loaded columns under various boundary conditions and heating regimes. The approach described in this section employs experimental data from as many laboratories as possible in an attempt to understand the behavior of steel columns at elevated temperatures.

2.1 Test data on steel columns

The NIST stress-strain model was evaluated using five data sets from different laboratories, which were chosen from much larger data sets compiled by Zhang et al. [13]. Table 1 shows a total of forty-seven individual column specimens considered in the present study along with the reported failure temperatures (T_f) and test parameters, such as the room-temperature yield strength (F_{yo}), column length (L), slenderness ratio ($\lambda = L/r$, where r is the radius of gyration), the applied axial load (P_f), the boundary conditions (Ends, where P-P is pinned-pinned; F-F is fixed-fixed; and P-R is pinned-rotationally restrained). In Zhang's study, the failure temperatures of the column specimens were calculated using the Eurocode 3 standard [1], whereas the present study used the FE models instead. Table 1 includes the failure temperature (T_f) predicted from the FE simulations using the Eurocode 3 and the NIST stress-strain models.

The column specimens in Table 1 were tested in the non-U.S. laboratories (Europe and Asia). The experimental tests were conducted by applying the load to the prescribed stress level and then ramping the temperature until failure. No axial restraint was imposed on the specimens at elevated temperatures. The mode of failure was flexural buckling accompanied by a sharp increase in the lateral displacements (runaway displacements). The failure temperature and failure time were reported when the applied axial load was no longer maintained due to instability of the specimens.

Figure 2 shows schematic of the various structural models and the boundary conditions of the column specimens from the five data sets. Details of the five data sets and the original descriptions of the tests are available in the technical literature and briefly summarized here as follows. Ali et al. [14] tested nine bare steel columns with pinned-pinned ends. The column length was approximately 1.8 m. The axial load ratio, which was defined as the ratio of the applied load to the capacity at ambient temperature, was between 0.2 and 0.6. A single-burner furnace heated the column specimens at a rate of 15 °C/min to 400 °C and then 2 °C/min above 400 °C. Franssen et al. [15] described a total of seventeen steel column tests at elevated temperatures which were originally reported by Azpiazu and Unanue [16]. The column lengths varied from 1.2 m to 3.5 m. All the column specimens were supported by knife edges to achieve the pin-ended boundary conditions but loaded eccentrically ($e = 5$ mm). Unlike the other tests which used a furnace, ceramic heating mats attached to the column supplied the heat with a rate of 5 °C/min. Note that Table 1 includes the data from thirteen column tests only; other four column tests were omitted due to uncertainty about the test conditions [17]. Lie and Macauley [18] reported three tests on protected steel columns with rotationally fixed-fixed ends. The column length was 3.8 m. The axial load ratio was about 0.5. The heating condition followed the ASTM E119 [19] time-temperature curve. Tan et al. [20] tested four steel columns with pinned-pinned ends. The column length was 1.5 m. Initial column crookedness and eccentricity of loading was measured. The axial load ratio was 0.5. An electric furnace heated the columns at a rate of 8 °C/min until buckling occurred. It should be noted that no failure temperature of the column specimens was reported, and therefore the measured failure temperature for Tan's columns in Table 1 was calculated using the heating rate (8 °C/min) multiplied by the reported failure time. Wang and Davies [21] performed eighteen bare steel column tests at elevated temperatures. The

column length was 3.7 m. The roller bearings were attached at the column ends, but near one of the ends two beams were connected through either fin plate or extended end plate to provide the rotational restraints at this end. The effective lengths of the test columns were reported as presented in Table 1. The axial load ratio varied from 0.3 to 0.7. The furnace temperature increased at a rate of 16.7 °C/min.

2.2 Modeling approach

Each column specimen was modeled using ANSYS 14.0.0 [22] three-dimensional shell element, SHELL181, which is suitable for analyzing thin to moderately thick shell structures. It is a four node element with six degrees of freedom at each node. SHELL181 is well suited for linear, large rotation, and large-strain non-linear applications. The cross-sections of the column specimens were discretized into twenty elements based on a mesh optimization study. The shape of initial column crookedness was assumed to the first eigenmode obtained from an elastic buckling analysis (typically, the flexural buckling mode about the weak axis). The initial deflection amplitude at mid-height, if not specified, was taken as 0.1 % of the column length as specified in the Eurocode standard. The effect of residual stress was omitted. For restrained column specimens, the model was modified such that the corresponding degrees of freedom were restrained to represent the support conditions as reported in test literature. No thermal gradient was modeled explicitly.

To numerically simulate the buckling failure of the specimens, structural analyses were conducted such that the column model was subjected to the axial load of the reported value (P_r), and then the temperature was increased monotonically until inelastic column buckling occurred. At this moment, the analyses failed to converge since force equilibrium could not be archived. The maximum temperature at the last increment where the force equilibrium was achieved was defined as the failure temperature (T_p). Thus, the failure criteria used in the analyses were comparable to failures observed in the tests.

2.3 Comparison results

Figure 3 shows the predicted failure temperature (T_p) from the ANSYS analysis as a function of reported failure temperature (T_r). The solid line indicates $T_p = T_r$, and the dashed lines delineate $T_p = T_r \pm 50$ °C to show the scattering of the data around the solid line. The Eurocode 3 model accurately predicted the failure temperatures for both Franssen's and Lie's column tests but made conservative predictions for three other data sets. Those data sets are below the line of $T_r - 50$ °C. Conversely, the NIST model indicated more accurate predictions for the four tests (Ali, Tan, Lie, and Wang) but systematically overestimated Franssen's column tests. As shown, Franssen's data are above the line of $T_r + 50$ °C.

Further comparisons were made with the relative difference in the failure temperatures for each test of the five data sets. Figure 4 shows the relative difference plotted as a function of slenderness ratio (λ), and also includes the average relative differences (μ) for both models. Although the average relative difference for the data set of Franssen and Lie were only -3 % and -2 %, respectively, that for other data sets (Ali, Tan, and Wang) was about 15–17%. However, the NIST model overestimated the failure temperatures for Franssen's tests by 21 % on average, whereas the average relative differences for other data sets stayed in the

range of 1–6%. Table 2 shows the statistics of the deviation from reported failure temperature for all data along with that excluding the data of Franssen.

3. Phase II: High-temperature responses of steel columns

This section presents the detailed FE models to analyze the flexural buckling load and the responses of steel columns at elevated temperatures. The effects of the material models on the FE solutions were evaluated using the data from the column tests conducted at Purdue University. Choe [23] performed two different test series on the full-scale column specimens: the first test series evaluated the strength and behavior of the column specimens subjected to axial loading to failure under steady heat exposure; the second series focused on the fire resistance of the axially loaded specimens subjected to thermal gradients resulting from transient heating conditions. The data from the second test series were recently analyzed with the FE models using the NIST and the Eurocode 3 stress-strain models. The comparisons indicated that the NIST stress-strain model made a better prediction on the fire resistance and failure temperature of the column specimens tested under transient heating conditions [24]. In this section, the two stress-strain models were used for analyzing the columns specimens subjected to steady-heating and compared with test data reported in Choe et al. [25] and Choe [23].

3.1 Column test data

Table 3 summarizes the column test matrix of the six specimens analyzed in this study. The column specimens were made from ASTM A992 steel. The length (L) of the W8×35 and the W14×53 column specimens was 3.5 m and 3.45 m with the corresponding slenderness ratios (L/r) of 69 and 71, respectively. The measured room-temperature yield strength (F_{yo}) for the W8×35 and W14×53 columns was 413 MPa and 406 MPa, respectively. One specimen (W8×35–AMB) was tested at ambient temperature while the other five specimens were loaded to failure at a target temperature (300 to 600 °C). All the column specimens had the pinned-pinned condition that allowed free rotations about the weak axis and free axial thermal elongation. The specimens had no fire protection. Axial loading was applied through the centroid of the column cross-sections. In Table 3, T_{flange} and T_{web} are the average temperature values in flanges and web over the heated region; dP/dt is the average rate of applied axial loading; P_{cr} is the measured critical buckling load.

Figure 5 shows the column test setup and instrumentation layout. Four radiant heaters were placed next to the column flanges. The temperature variation over the exposed flanges was less than 30 °C. Thermal gradients were observed in the web and in the column portions outside of the heated zone. Steel temperatures, axial loads, and deformations of the column specimens were measured. The relevant standard uncertainty in measurements was estimated as $\pm 1\%$ based on calibration of the data acquisition system and instruments [23].

Figure 6 show the axial load-temperature-time (P – T – t) data recorded during the tests. Each plot includes the average temperatures in the flanges and the web of the cross-sections B, CL, and D shown in Figure 5. The axial loads were increased while temperatures were maintained. All the column specimens failed by inelastic flexural buckling about the weak axis, and no local failures were reported [25].

3.2 Modeling approach

The FE models were developed using the four-node shell elements with reduced integration (S4R) implemented in ABAQUS [26]. These elements have six degrees of freedom per node, five integration points through the thickness of a shell element, and one integration point to form the element stiffness. Based on the mesh convergence study, the cross section of the column specimen was discretized into nineteen nodes; the flange and the web were divided into six elements each.

In this study, the FE models accounted for both material and global geometric imperfection as recommended by Agarwal and Varma [27]. Residual-stress distributions for a typical hot-rolled steel shape were modeled by creating uneven thermal strains over the cross section. The corresponding maximum residual stress was approximately equal to 30% of the ambient-temperature yield strength. The global geometric imperfection (sweep) was assumed equal to $L/1500$ which is the initial out-of-straightness considered in the ANSI/AISC-360 standard [28]. The initial stresses and deformations due to the horizontal alignment of the column specimen (Figure 5) were also included as initial imperfection. The column ends were modeled as the pinned-end conditions that allow free rotation about the weak axis of the cross-section and free thermal expansion. Similar to the actual boundary conditions used in the tests, rotations about the strong axis of the cross-section and about the longitudinal axis of the specimen were restrained.

Table 4 shows the analytical matrix for the FE simulations. Thirty unique models were developed in combinations of three factors: (i) the temperature-dependent material model for steel (Eurocode 3 or NIST), (ii) temperature distribution in columns (uniform or non-uniform), and (iii) the numerical analysis scheme (modified Newton-Raphson or arc-length). The FE models were divided into five different groups (A through F) for comparisons. The FE solutions included the load-displacement response, the load-end rotation response, and the critical buckling load (P_{FE}) of the specimens. These analytical results were also compared with the experimental test results.

Figure 7 shows the material models used in the analyses. In the FE model, either the Eurocode 3 or the NIST stress-strain model was used to define (i) isotropic elastic behavior with Poisson's ratio of 0.3 and (ii) plastic behavior defined by the Von Mises yield surface, associated flow rule, and kinematic hardening functions implemented in ABAQUS. The measured room-temperature yield strength (F_{yo} in Table 3) and the elastic modulus (E_o) of 210 GPa were used to define the elastic and plastic behavior of steel at elevated temperatures. The temperature-dependent coefficients (α) of thermal expansion of steel were also used to compute thermal strains in the column specimens. As indicated in Table 4, the FE models in groups A, C, and E included the Eurocode 3 α - T model, whereas those in groups B, D, and F used the model (Equation 1) given in the NIST report [29]. Thermal creep properties were not explicitly included.

$$\alpha(T) = 1.67 \times 10^{-16} T^3 - 9.70 \times 10^{-12} T^2 + 1.34 \times 10^{-8} T + 1.17 \times 10^{-5} \quad \text{for } 20^\circ\text{C} < T < 730^\circ\text{C}$$

(1)

The FE analyses assumed two different temperature distributions in the column specimens. For groups A through D, the thermal analyses were conducted using thermocouple readings and the Eurocode 3 thermal properties. The temperatures of the shell elements located between two thermocouple locations (in Figure 5) were assumed to be the average temperatures of two adjacent thermocouple readings. Column ends remained cool (20 °C). The output from thermal analyses included the spatially varying temperature distribution of the specimens similar to those observed in the tests. The predicted nodal temperatures were mapped into the structural model to compute the behavior of the column specimens with thermal gradients. Groups E and F assumed the uniform temperature equal to the reported value of T_{flange} in Table 3.

The analyses were conducted with three steps similar to actual tests: (1) the initial axial loading to 133 kN at room temperature, (2) thermal loading to a target temperature value while the initial axial load was maintained, and (3) axial loading to buckling failure under steady heating conditions. Two different analyses schemes were considered for the FE solutions. As shown in Table 4, the FE models in the groups A and B used the modified Newton-Raphson method to predict the responses (e.g., displacements and end rotations) of the column specimens to the measured axial load-temperature-time (P - T - t) histories. This method allows the temperature change in the elements for non-linear structural analysis. Groups C through F considered the modified Riks (arc-length) algorithm instead. Although this method does not allow the change in the element temperatures during the structural analysis, it is suitable to estimate the critical buckling load of columns with fixed temperature distribution resulting from steady heat exposure [25].

3.3 Comparison results

All thirty FE models made a consistent prediction that the column specimens (with slenderness ratio about 70) failed by inelastic flexural buckling about the weak at elevated temperatures. Figure 8 shows the typical buckling shape of the specimen W14×53-T600 when analyzed with the NIST stress-strain model and the Eurocode 3 model. It also indicates a contour of the displacements (U2) in the y-axis direction at buckling failure. Figures 9 and 10 show comparisons of the predicted column responses using the models in Groups A and B with the test data.

Figure 9 shows the axial load–end rotation (P - θ) responses of the column specimens. The results from the FE models with the NIST material properties were comparable to the test data. The analyses indicated that the columns analyzed with the Eurocode 3 material model buckled at an axial load about 20 % smaller than that measured experimentally. Since the initial column crookedness ($L/1500$) was assumed, the second-order moments induced prior to heating remained unchanged between the NIST and the Eurocode 3 models. As shown in

Figure 9, however, under high-temperature conditions, the Eurocode 3 model revealed a significant reduction in the column stiffness at the earlier stage of axial loading. This phenomenon is thought to result from the elastic behavior conservatively predicted by the Eurocode 3 stress-strain model. As shown in Figure 1, the retained elastic moduli from the Eurocode 3 and the NIST model start deviating at temperature above 100 °C. At 600 °C the Eurocode 3 elastic modulus of steel is only 52% of the NIST elastic modulus, whereas there is essentially no difference in the yield strength (3% difference). Therefore, the Eurocode 3 model tends to underestimate the column stiffness at elevated temperatures and make a conservative prediction for the inelastic buckling analyses where the influence of elastic moduli could be significant.

Figure 10 shows a comparison of the predicted axial displacements with test data. In each plot, the positive slope indicates the thermal elongation while steel temperature was increased to a target value; the negative slope indicates the axial shortening in response to increasing axial loads under steady-heating conditions. The axial shortening of the specimen W8×35–T300 in Figure 10(a) was not recorded due to the malfunction of an axial displacement transducer [23]. The comparison indicates that both the Eurocode-3 and NIST thermal expansion ($\alpha-T$) models accurately predicted the thermal elongations of the column specimens. The predicted axial shortening shows a trend similar to the test results. Although the thermal creep for steel was not explicitly included in the analyses, the NIST models more accurately predicted the time of failure (at the onset of buckling) as shown in Figure 10. The failure time is indicated by the time corresponding to an asterisk symbol (*) on each plot. The Eurocode 3 models conservatively predicted the time at failure. Since the period of axial loading was shorter than 1 hour and the average temperatures of the column cross-sections were lower than 600 °C, the effects of thermal creep on the column experiments presented in this paper appeared to be negligible.

Figure 11 shows the normalized difference between the measured critical buckling loads (P_{cr}) and the predicted critical buckling loads (P_{FE}) using the thirty unique FE models. Individual values of P_{cr} and P_{FE} are listed in Tables 3 and 4, respectively. Table 5 summarizes the statistics including the average ratio ($\bar{X}$) of P_{FE}/P_{cr} , the standard deviation (S), and the coefficient of variation (CV) defined as the ratio of $S/\bar{X}$. Overall, the Eurocode 3 model estimated the strength of the tested specimens conservatively, regardless of temperature distributions and the analysis methods. Some findings from this study are summarized here.

When the test conditions were simulated using the measured load-temperature-time ($P-T-t$) histories and the modified Newton-Raphson method algorithm, the critical buckling load predicted by the NIST models (Group B, ID 6 to 10) compared favorably with the test results. The average difference was less than 1 %. In contrast, the critical buckling load predicted by the Eurocode 3 models (Group A, ID 1 to 5) was 18 % lower than the test results on average.

While other conditions (material models and temperature distributions) remained the same, the models using the modified Riks (arch-length) method provided the results comparable to those using the modified Newton-Raphson scheme. The average difference between the two

analytical methods was less than 1%. The modified Riks method is more computationally efficient to compute the critical buckling load of a column; the modified Newton-Raphson procedure often required a user's best estimate of the maximum load and a proper size of time steps (increments) for non-linear analyses.

Also, the assumed temperature variations in the model could influence the accuracy of the calculated flexural buckling strength. Assuming the uniform temperature conditions in the analyses might lead to inaccurate predictions for inelastic buckling of the column specimens that actually developed thermal gradients in the tests. When the model temperature was assigned with the maximum flange temperature (T_{flange}) in Table 3, both the Eurocode 3 and the NIST models inaccurately predicted the critical buckling loads compared to the test results. The Eurocode 3 models (Group E, ID 21 to 25) significantly underestimated the critical buckling loads that were 25% lower than the actual P_{cr} ; the NIST models (Group F, ID 26 to 30) estimated 12 % higher than the actual P_{cr} .

4. Phase III: Column curve

The current 2010 edition of the ANSI/AISC-360 Appendix 4 specifies the following equations to determine the nominal flexural buckling stress of a steel column, $F_{cr}(T)$, at elevated temperatures:

$$F_{cr}(T) = F_y(T) \cdot a^{(F_y(T)/F_e(T))^b} \quad (2)$$

where $a = 0.42$ and $b = 1/2$. $F_y(T)$ is the Eurocode 3 yield strength at elevated temperature, and $F_e(T)$ is the critical elastic buckling stress, which can be determined by

$$F_e(T) = \frac{\pi^2 E(T)}{\left(\frac{KL}{r}\right)^2} \quad (3)$$

where $E(T)$ is the Eurocode 3 high-temperature modulus of elasticity.

Takagi and Deierlein [30] proposed Equation 2 which was essentially a curve fit to the FE solutions using the Eurocode 3 stress-strain model. In their study, the critical buckling loads for W14×90 and W14×22 columns were calculated using various parameters: two different grade of steels ($F_y = 345$ MPa and 250 MPa), slenderness ratios ($L/r = 20$ to 200), and steel temperatures (200 °C to 800 °C). Their FE analyses also assumed (i) uniform temperature distributions in columns, (ii) initial column crookedness (sweep) of $L/1000$, and (iii) the pin-ended boundary condition. The study showed that the critical buckling stress determined from Equation 2 agreed well with that from the Eurocode 3 standard equations. However, unlike the Eurocode equations, Equation 2 is limited to temperatures above 200 °C and is only valid when the Eurocode 3 stress-strain model is assumed. So the curve fit parameters, a and b , would need to be recalibrated if other stress-strain models are used.

In this phase of study, the FE analysis of Takagi and Deierlein was replicated using the NIST stress-strain model. With the FE results using the NIST stress-strain model and the test data in Table 1, the values of a and b in Equation 2 were recalibrated through non-linear, least-squares regression of the predicted critical buckling stresses. The regression analysis shows that $a = 0.61 \pm 0.003$ and $b = 0.86 \pm 0.011$ with residual standard error of 8.88 on 358 degrees of freedom. Figure 12 shows a comparison of the nominal compressive strength normalized to the yield strength, which include the recalibrated column curve with the new a and b , the FE models for W14×90 and W14×22 columns, the 2010 AISC equation (i.e., Equation 2) with the Eurocode 3 $F_y(T)$ and $E(T)$. It shows that the critical buckling stress calculated using Equation 2 does not pass through 1.0 at zero slenderness. The column strength calculated using newly calibrated NIST equation differs significantly from that calculated using Equation 2 with increasing temperature, especially in the range of (50 L/r 100).

5. Summary, conclusions, and limitations

This paper presents a comparison of two high-temperature stress-strain models, Eurocode 3 model and the NIST model, used in the finite-element (FE) models. The comparisons were made through three different studies.

Phase I compared the critical buckling temperatures of 47 column specimens from five different laboratories using two stress-strain models. All the column specimens were loaded to the prescribed stress level and then heated until failure occurred. The FE models were developed with the assumption that the effects of test protocols and thermal gradients in the steel columns are negligible. The results showed that the NIST model predicted the buckling temperature as accurately as or more accurately than the Eurocode 3 model for four of the five data sets.

Phase II developed thirty unique FE models to analyze the behavior of the six columns tested at Purdue University. The variables considered in the FE model included the temperature distributions in the column specimens (uniform vs. non-uniform), material models (Eurocode 3 vs. NIST), and numerical approaches for nonlinear analyses (modified Newton-Raphson vs. arc-length). Overall, the analyses with the NIST material model and the measured temperature variations showed the results comparable to the test data (with 1% difference). The deviations in the FE solutions from two different numerical approaches were negligible. The Eurocode 3 model made conservative predictions on the flexural buckling behavior (with 18% difference on average) since its retained elastic moduli are smaller than those of the NIST model at elevated temperatures.

In Phase III, the new column curve was calibrated using the NIST stress-strain model and compared with the flexural buckling equation prescribed in the ANSI/AISC–360 Appendix 4. The flexural buckling strengths of the calibrated curve significantly deviate from that estimated by the current design equation with increasing temperature, especially for the slenderness ratios in the range of 50 to 100. The current design equation is only valid when the Eurocode 3 retention factors are considered, and could be updated by substituting the behavior of the yield strength and elastic modulus from the NIST stress-strain model.

The findings from this study are limited to the range of parameters included in the tests and the FE models. This paper is not intended to draw any conclusions about steel columns with failure modes other than inelastic flexural buckling or cases where the thermal creep behavior is critical. Further work is recommended for evaluating predictions using the NIST material model for other failure mechanisms (yielding and lateral-torsional buckling), various design fire scenarios, various boundary conditions (axial and rotational restraints), and cases where the thermal creep behavior is critical.

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Appendix I

The general equation (Equation A1) of the NIST true stress–true strain (σ – ϵ) model for steel accounts for temperature dependence of elastic modulus, yield strength, strain-hardening behavior, and strain sensitivity. The model was developed from a survey of many reported values of high-temperature structural steel behavior. The NIST technical report [31] contains supporting data, details of regression analyses and approaches, and estimates of the uncertainties in the fitted parameters.

$$\sigma = E(T) \epsilon \quad \text{for } \epsilon < F_y(T)/E(T)$$

$$\sigma = \left(RF_{y0} + (k_3 - k_4 F_{y0}) \exp \left(- \left(\frac{T}{k_2} \right)^{k_1} \left(\epsilon - \frac{RF_{y0}}{E(T)} \right)^n \right) \right) \left(\frac{\epsilon'}{\epsilon_0} \right)^m \quad \text{for } \epsilon \geq F_y(T)/E(T) \quad (\text{A1})$$

where T = temperature, E = Temperature-dependent steel modulus (Equation A2), R = retained yield strength (Equation A3), $\dot{\epsilon}'/\dot{\epsilon}_0'$ = normalized strain rate, and m = strain-rate sensitivity (Equation A4).

Elastic modulus

The decrease in elastic modulus with increasing temperature was taken from reported literature data from tensile tests of structural steel.

$$E(T) = E_0 \exp \left(-\frac{1}{2} \left(\frac{T^*}{e_3} \right)^{e_1} - \frac{1}{2} \left(\frac{T^*}{e_4} \right)^{e_2} \right) \quad (\text{A2})$$

where E_0 is the elastic modulus at $T = 20^\circ\text{C}$, and $T^* = T - 20^\circ\text{C}$ in $^\circ\text{C}$. The elastic modulus function decays smoothly from room temperature.

Yield strength behavior

The normalized retained yield strength, R , as a function of temperature for 42 individual structural steels from 16 different literature sources described in [3].

$$R = \frac{F_y(T)}{F_{yo}} = r_5 + (1 - r_5) \exp \left(-\frac{1}{2} \left(\frac{T^*}{r_3} \right)^{r_1} - \frac{1}{2} \left(\frac{T^*}{r_4} \right)^{r_2} \right) \quad (\text{A3})$$

Like the elastic modulus, it decays smoothly from the room-temperature value to a small minimum value with increasing temperature. The parameters of the equation were specially chose to have the greatest fidelity to the reported literature data in the range ($400 < T < 650$) $^\circ\text{C}$.

Yield strength dependence of the strain hardening

For structural steel, the amount of strain hardening after yield generally decreases with increasing room-temperature yield strength. The parameters of the strain hardening behavior (k_1 , k_2 , k_3 , k_4 and n) were determined by a non-linear regression of the stress-strain curves of eight different structural steels taken from the NIST WTC investigation [3]. This form joins the elastic portion of the stress strain curve.

Temperature dependence of the strain-rate sensitivity

The strain-rate sensitivity, m , of structural steels is nearly zero at room temperature and increases to a maximum at high temperature.

$$m=m_0+m_3 \left[1-\exp \left(-\left(\frac{T}{m_2} \right)^{m_1} \right) \right] \quad (\text{A4})$$

Table 6 shows the values of the individual parameters in Equation A1 for various structural steels. All were developed from literature data that had been evaluated for completeness and quality.

Table 6

Values of the parameters in the NIST stress-strain model for structural, fire-resistive (FR), quenched-and-tempered plate (Q&T), and bolt steels

Parameter	Structural	FR	Q&T	Bolt	Units
r_1	7.514	9.782	10.143	4.697	
r_2	1.000	1.000	1.000	1.000	
r_3	588	625	589	456	°C
r_4	676	1334	837	2040	°C
r_5	0.090	0	0	0	
k_1	7.820	9.832	9.753		
k_2	540	616	809		°C
k_3	1006	5651	959		MPa
k_4	0.759	15.339	0.766		
n	0.503	0.446	0.344		
m_0		0.0108			
m_1		7.308			
m_2		613			°C
m_3		0.126			
e_0'		8.333×10^{-5}			s ⁻¹
E_0		206.0			GPa
e_1		3.768			
e_2		1.000			
e_3		639			°C
e_4		1650			°C

Fig. 1.
The Eurocode 3 and the NIST retention factors for yield strength and elastic modulus of structural steel

Fig. 2.
Schematic of structural models for column tests

Fig. 3.

Predicted vs. reported failure temperatures for (a) the Eurocode 3 and (b) the NIST models

Fig. 4.
Normalized difference in failure temperature as a function of slenderness ratio (λ)

Fig. 5.
Column test setup instrumentation layout

Fig. 6.
Axial load-temperature-time histories used in the Purdue column tests

Fig. 7.
 (a) Thermal expansion model of steel, (b) Eurocode 3 stress-strain model, (c) NIST stress-strain (σ - ϵ) model

Fig. 8.
The final deflected shape of the W14×53–T600 specimen predicted using the NIST and the EC 3 model

Fig. 9.
Axial load-rotation (P - θ) responses of the column specimens

Fig. 10.
Axial displacements (δ_a) of the column specimens

Fig. 11.
Normalized difference in critical buckling loads of the FE models

Fig. 12.
Column curves

Table 1

Test data used in the phase 1 study

Data	Test	Shape	F_{y0} (MPa)	L (mm)	λ	P_r (kN)	e (mm)	Ends	T_r (°C)	Eurocode	NIST
Tan	RS45 1	UC152×152×37	326	1500	38	708.5	1.74	P-P	647	507	588
Tan	RS55 1	UB203×133×25	357	1500	47	444.3	3.19	P-P	571	520	557
Tan	RS81 1	UB152×89×16	312	1500	70	260.6	2.38	P-P	499	401	567
Tan	RS97 1	UB127×76×13	320	1500	83	134	4.08	P-P	606	501	617
Ali	Ali1	UC152×152×23	320	1800	47	186	0	P-P	701	643	758
Ali	Ali2	UC152×152×23	320	1800	47	373	0	P-P	626	550	676
Ali	Ali3	UC152×152×23	320	1800	47	559	0	P-P	557	403	594
Ali	Ali4	UB178×102×19	320	1800	75	202	0	P-P	629	541	662
Ali	Ali5	UB178×102×19	320	1801	75	303	0	P-P	539	395	582
Ali	Ali6	UB178×102×19	320	1802	75	101	0	P-P	644	643	745
Ali	Ali7	UB127×76×13	320	1803	97	50	0	P-P	717	661	730
Ali	Ali8	UB127×76×13	320	1804	97	101	0	P-P	658	555	647
Ali	Ali9	UB127×76×13	320	1805	97	151	0	P-P	567	438	567
Lie	Lie1	W10×60	300	3810	34	1760	0	F-F	565	574	591
Lie	Lie2	W10×49	300	3810	34	1424	0	F-F	586	566	591
Lie	Lie3	W10×49	300	3810	34	1424	0	F-F	584	566	591
Franssen	AL5	HEA100	280	2770	108	127	5	P-P	457	428	589
Franssen	BL3	HEA100	287	1272	50	292	5	P-P	390	377	528
Franssen	BL5	HEA100	287	2772	108	73	5	P-P	587	573	699
Franssen	BL6	HEA100	287	3510	137	105	5	P-P	446	356	527
Franssen	CL3	HEA100	293	1271	50	251	5	P-P	474	478	581
Franssen	CL5	HEA100	293	2771	108	34	5	P-P	587	677	783
Franssen	CL6	HEA100	293	3510	137	90	5	P-P	493	447	601
Franssen	DL3	HEA100	283	1269	49	24	5	P-P	749	875	818
Franssen	DL6	HEA100	283	3510	137	12	5	P-P	727	802	840
Franssen	SL40	HEA100	280	2020	79	170	5	P-P	525	475	600
Franssen	SL41	HEA100	280	2026	79	174	5	P-P	509	445	584

Data	Test	Shape	F_{yo} (MPa)	L (mm)	λ	P_r (kN)	e (mm)	Ends	T_r (°C)	Eurocode	NIST
Franssen	SL42	HEA100	280	2020	79	171	5	P-P	485	458	591
Franssen	SL44	HEA100	280	2023	79	173	5	P-P	495	448	586
Wang	SCRI1	UC203×203×46	301	2968	57	357.5	0	P-R	646	613	707
Wang	SCRI2	UC203×203×46	301	2875	56	360.3	0	P-R	681	616	707
Wang	SCRI3	UC203×203×46	301	2875	56	360	0	P-R	668	616	707
Wang	SCRI4	UC203×203×46	301	3061	59	600	0	P-R	604	527	640
Wang	SCRI5	UC203×203×46	301	2463	48	600	0	P-R	597	552	647
Wang	SCRI6	UC203×203×46	301	2745	53	600	0	P-R	613	540	644
Wang	SCRI7	UC203×203×46	301	3001	58	840	0	P-R	556	400	571
Wang	SCRI8	UC203×203×46	301	2894	56	840	0	P-R	553	414	574
Wang	SCRI9	UC203×203×46	301	3001	58	840	0	P-R	530	400	571
Wang	SCRI11	UC203×203×46	301	2820	55	358	0	P-R	680	619	708
Wang	SCRI12	UC203×203×46	301	2849	55	360	0	P-R	670	617	707
Wang	SCRI13	UC203×203×46	301	2876	56	360	0	P-R	675	620	707
Wang	SCRI14	UC203×203×46	301	3079	60	600	0	P-R	609	526	639
Wang	SCRI15	UC203×203×46	301	2883	56	600	0	P-R	604	534	643
Wang	SCRI16	UC203×203×46	301	2823	55	600	0	P-R	629	537	643
Wang	SCRI17	UC203×203×46	301	2916	56	840	0	P-R	542	411	573
Wang	SCRI18	UC203×203×46	301	2916	56	840	0	P-R	550	411	573
Wang	SCRI19	UC203×203×46	301	2842	55	840	0	P-R	549	421	575

Table 2

Summary statistics for column buckling analysis

Statistics	Eurocode 3	NIST
Model deviation: mean	−0.11	0.09
Model deviation: standard deviation	0.10	0.09
Model deviation: mean less Franssen	−0.14	0.05
Model deviation : standard deviation less Franssen	0.08	0.04

Table 3

Column test matrix and results

Specimen	F_{y0} (MPa)	L/r_y	T_{flange} (°C)	T_{web} (°C)	P_{cr} (kN)	dP/dt (kN/min)
W8×35-AMB	413	69			2000	
W8×35-T300	413	69	320	190	1413	1.3
W8×35-T500	413	69	477	406	1134	28
W8×35-T600	413	71	609	451	800	35
W14×53-T500	406	71	504	324	1435	33
W14×53-T600	406	71	608	363	1070	26

Table 4

Column analysis matrix

		Material Model			Temperature Distribution			Analysis Scheme		
Group	ID	Specimen	EC 3	NIST	Uniform	Non-uniform	Modified Newton-Raphson	Modified Riks	P_{FE} (kN)	
A	1	W8×35-T300	x			x	x		1134	
	2	W8×35-T500	x			x	x		921	
	3	W8×35-T600	x			x	x		639	
	4	W14×53-T500	x			x	x		1260	
	5	W14×53-T600	x			x	x		865	
B	6	W8×35-T300		x		x	x		1392	
	7	W8×35-T500		x		x	x		1141	
	8	W8×35-T600		x		x	x		788	
	9	W14×53-T500		x		x	x		1442	
	10	W14×53-T600		x		x	x		1091	
C	11	W8×35-T300	x			x		x	1171	
	12	W8×35-T500	x			x		x	921	
	13	W8×35-T600	x			x		x	605	
	14	W14×53-T500	x			x		x	1267	
	15	W14×53-T600	x			x		x	869	
D	16	W8×35-T300		x		x		x	1417	
	17	W8×35-T500		x		x		x	1135	
	18	W8×35-T600		x		x		x	827	
	19	W14×53-T500		x		x		x	1445	
	20	W14×53-T600		x		x		x	1097	
E	21	W8×35-T300	x		x			x	1320	
	22	W8×35-T500	x		x			x	903	
	23	W8×35-T600	x		x			x	443	
	24	W14×53-T500	x		x			x	1217	
	25	W14×53-T600	x		x			x	641	

Material Model		Temperature Distribution			Analysis Scheme				
Group	ID	Specimen	EC 3	NIST	Uniform	Non-uniform	Modified Newton-Raphson	Modified Riks	P_{FE} (kN)
F	26	W8×35–T300		x	x			x	1646
	27	W8×35–T500		x	x			x	1244
	28	W8×35–T600		x	x			x	815
	29	W14×53–T500		x	x			x	1713
	30	W14×53–T600		x	x			x	1189

Table 5

Summary statistics for the normalized column buckling load

Group	A	B	C	D	E	F
Material Model	EC 3	NIST	EC 3	NIST	EC 3	NIST
Temperature Distribution	Non-Uniform	Non-Uniform	Non-Uniform	Non-Uniform	Uniform	Uniform
Analysis Scheme	Modified Newton- Raphson	Modified Newton- Raphson	Modified Riks	Modified Riks	Modified Riks	Modified Riks
$\bar{X}$	0.82	1.00	0.82	1.01	0.75	1.12
S	0.03	0.01	0.05	0.01	0.16	0.07
CV	0.04	0.01	0.06	0.01	0.22	0.06