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Experimental Examination of Creep Buckling of Steel Columns in Fire

M.A. Morovat[1], M.D. Engelhardt [2], T.A Helwig[3], E.M. Taleff[4]

Abstract
This paper presents highlights of an extensive testing program undertaken by the authors to investigate the time-dependent or creep buckling behavior of columns of ASTM A992 steel subjected to fire temperatures. Twenty two buckling tests on W4×13 wide flange columns under pin-end conditions were conducted to characterize short-time and creep buckling loads at temperatures up to 700 °C. In addition to the details about experimental setup and procedure, results from seven column tests at 600 °C are presented and discussed. The column test results at 600 °C and 700 °C are further compared with code-based predictions from Eurocode 3 (2006) and the AISC Specification (2010). Column test results presented in this paper show that neglecting creep effects can lead to significant errors in predicting the strength of steel columns subjected to fire.

1. Introduction
At elevated temperatures due to fire, the strength of steel columns is a complicated phenomenon that is not well understood or quantified. Factors that affect column strength at high temperatures include: reductions in stiffness and strength of steel, changes to residual stress patterns, effects of restrained thermal expansion, column bowing due to thermal gradients, and the effects of material creep. A number of past studies on the behavior of steel columns subjected to fire have considered several of these factors (Furumura and Ave 1984; Furumura, et al. 1986; Pauli, et al. 2012). Of all these factors that may affect column strength at elevated temperatures, the factor that has seen the least attention in experimental, analytical and computational studies is the effect of thermal creep of structural steel (Morovat 2014).

Under fire conditions, the thermal creep of structural steel may cause a phenomenon known as creep buckling, where the critical load for a steel column depends not only on slenderness and temperature, but also on the duration of applied load. The phenomenon of creep buckling that can significantly impact the safety of steel columns exposed to fire temperatures is not currently explicitly considered in code-based design formula for steel columns at elevated temperatures, such as those in the Eurocode 3 (2003) or in the AISC Specification (2010).

[1] Research Scientist Associate, University of Texas at Austin, <morovatma@utexas.edu>
[2] Professor, University of Texas at Austin, <mde@mail.utexas.edu>
[3] Professor, University of Texas at Austin, <thelwig@mail.utexas.edu>
[4] Professor, University of Texas at Austin, <taleff@mail.utexas.edu>

To better understand the time-dependent or creep buckling behavior of steel columns at elevated temperatures, the authors conducted an extensive experimental program, highlights of which are presented in this paper. After a brief overview on the effect of material creep on stability of columns, some details about the experimental setup and procedure will be provided. Results from seven buckling tests on W4×13 wide flange columns under pin-end conditions at 600 °C are then presented and discussed. The column test results at 600 °C and 700 °C are further compared with code-based predictions from Eurocode 3 (2006) and the AISC Specification (2010).

2. Effect of Material Creep on Stability of Columns

An imperfect column experiences an elastic or plastic increase in curvature upon the application of an axial load. Bending in the column consequently results in different stress magnitudes in the compression (concave) and tension (convex) sides of the column. If the column is made of a material that creeps, the compression and tension sides of the column will be subjected to different creep rates. In other words, the strains will change with time at different rates causing further deflections of the column. Therefore, under constant load, the column continues to deflect at an increasing rate. Growing lateral deflections combined with nonlinear stress-strain behavior of the column material at high stresses will ultimately result in collapse of the column.

The fact that structural steels in general and ASTM A992 steel in particular exhibit creep behavior when exposed to fire temperatures has already been demonstrated and discussed by different researchers and by the authors in previous publications (Norton 1929; Bailey 1929; Dorn 1955; Harmathy 1967; Skinner 1972; Fields and Fields 1989; Luecke, et al. 2005; Morovat, et al. 2010; Morovat, et al. 2013; Morovat 2014; Morovat, et al. 2014a; Morovat, et al. 2014b). The focus of the current paper is on the creep buckling behavior of steel columns at elevated temperatures due to fire.

3. Buckling Tests on ASTM A992 Steel Columns: General Considerations

3.1 Testing Machine and Equipment

A 550 kip (2500 kN) capacity MTS 311.41 servohydraulic load frame was used to conduct the column tests at elevated temperatures. Fig. 1 shows a picture of this MTS 311.41 test frame. The closed-loop accuracy provided by this MTS load frame was essential in having good control on both force and cylinder-displacement rates. To prevent the MTS load frame from damage due to exposure to high temperatures, a cooling system consisting of water-cooled wedges and a pipe-loop system was implemented to dissipate high heat from the hydraulic grips and the load cell. Throughout the column tests, a constant circulation of cold water was maintained to keep the temperature of the wedges and their adjacent parts at approximately room temperature.

The heating system consisted of an electric furnace, the furnace temperature controller, and the data acquisition system for recording and monitoring column temperatures (Fig. 1). An ATS split box furnace with 54 in. × 26.5 in. × 16.5 in. heated enclosure was used as the heating device. The furnace generates heat using electrical coils embedded in its walls, and is separated into upper, middle and lower heating zones that can be individually controlled using an ATS temperature controller. The ATS split box furnace was capable of achieving temperatures up to 1000 °C with the maximum heating rate of about 6 °C/min. Three thermocouples were located inside the furnace walls to measure the furnace air temperature.

Figure 1: Testing Frame and Equipment Used in Column Experiments at Elevated Temperatures

3.2 Testing Setup

A special test setup was designed to perform buckling tests on ASTM A992 steel columns at elevated temperatures under pin-end conditions. Since the buckling capacity of steel columns at high temperatures is very sensitive to the end restraints, as shown for example, by Furumura and Ave (1984), a fixture consisting of knife-edges was designed to obtain pin-end conditions and to minimize the effect of friction (end rotational restraint) in column tests. The knife-edges were made out of Viscount 44, a hardened tool steel with high yield strength, so that they could be used for several tests with negligible wear. Moreover, to minimize uneven stress distribution in the column specimens during the elevated-temperature buckling tests, the end surfaces of the column specimens were machined by milling. This important consideration with major impact on the column test results is usually overlooked in column experiments (Morovat 2014). Care was further taken to eliminate load eccentricity in column buckling tests by careful alignment of the column specimens. To have better control on the alignment, a system of clamp plate and spacers was implemented to serve as a base-plate of the column specimens, thereby avoid welding. Finally, to achieve uniform temperature over the height of column specimens, the end fixtures of the test setup were designed so that the column specimens were entirely inside the furnace. All column specimens consisted of W4×13 wide-flange sections, and all were constructed using the same heat of steel. This section was chosen due to the height and capacity limitations of the test equipment.

Details of the test setup and its components are presented schematically in Fig. 2. Fig. 3 further shows pictures of the column test setup after being constructed and assembled. As also seen in Fig. 3, extra safety measures were taken by loosely attaching chains to the specimen, to make sure that column specimens stay in their positions under large lateral displacements and stay in place as their temperature returns to room temperature after completion of a test. The position of the column specimens and the test setup including the end parts relative to the electrical furnace can also be observed in pictures shown in Fig. 3.

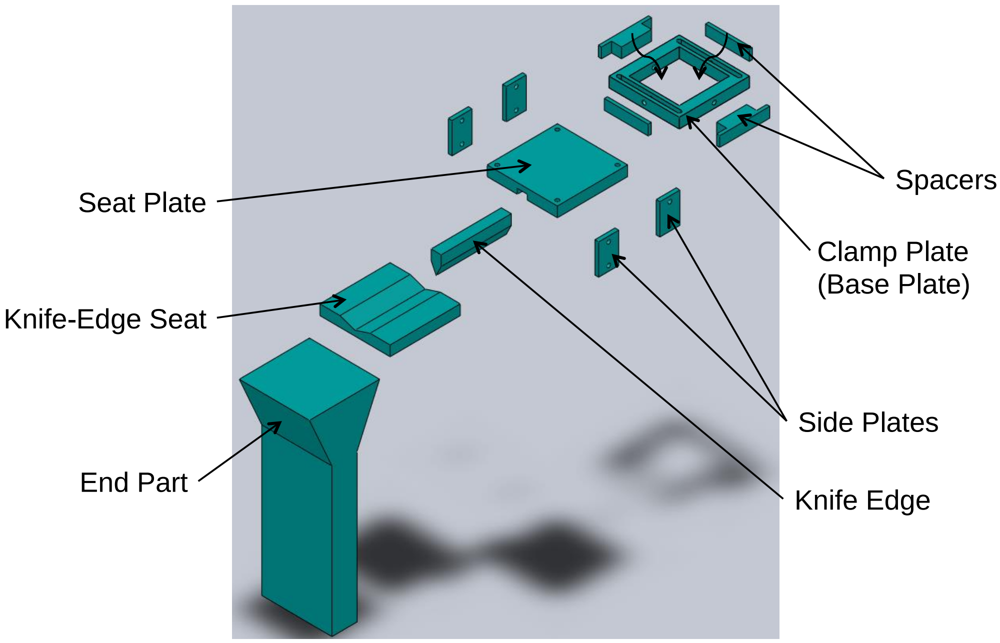

Figure 2: Column End Fixture

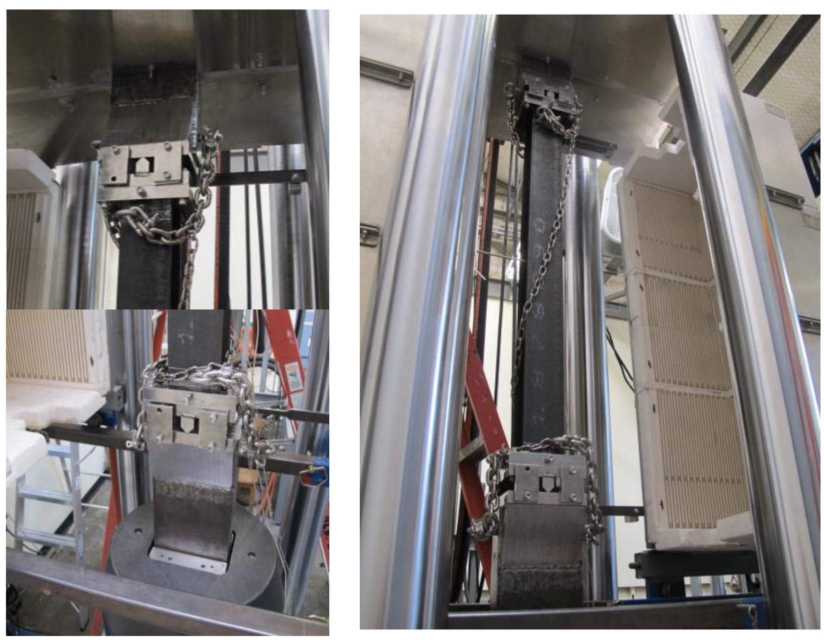

Figure 3: The Column Test Set-up and a Column Specimen Positioned in the Testing Machine

3.3 Measurements

Different measurements were made before and during the elevated-temperature column tests. Measurements before testing included measuring the actual geometry of the specimens, and measuring initial geometric imperfections. Residual stresses at room temperature were also measured before the column tests at elevated temperatures. Details of all these measurements are reported in a publication by Morovat (2014). Recording column loads, column displacements and column temperatures were the major measurements taken during elevated-temperature buckling tests. A brief overview of different measurements made during buckling tests is provided in the following.

Accurate measurements of both the furnace air and specimens' temperatures are crucial during buckling tests at high temperatures. The furnace air temperatures were controlled and monitored at all three heating zones using type K thermocouples located in the wall of the furnace. The temperatures of the W4×13 column specimens were probed using type K wire thermocouples. As shown in Fig. 4, five thermocouples were attached to the column specimens at different locations along their heights. The thermocouples designated as TC1 and TC2 were attached to the web and flange of the W4×13 column specimens at mid-height, respectively. The thermocouples designated as TC3 and TC4 were both attached to the web of the W4×13 column specimens close to the ends at the top and bottom, respectively. All these thermocouples were glued to the surface of the web and flanges using high-temperature cement as further depicted in Fig. 4. In addition, to verify the effect of application of high-temperature cement on the temperature measurements made by thermocouples, an extra thermocouple, TC5, was utilized. As seen in Fig. 4, the TC5 was attached to the safety chain around the column specimens and secured against the flange at mid-height. Based on observations from the literature on steady-state temperature buckling tests on steel columns, it was believed that five thermocouples should be enough to ensure reasonably uniform temperature along the height of the steel column specimens (Morovat 2014).

Figure 4: Thermocouple Arrangements for Monitoring Temperatures of the Column Specimens

As an example, Fig. 5 shows the temperature history of a column specimen measured during a test at 600 °C. For this specific test, thermocouple TC1 was lost during the heating phase and therefore no history is shown for it. The temperature history presented in Fig. 5 includes the heating phase before the test, the constant-temperature phase during the test and the cooling phase after the test is completed. Note that the sharp decrease in the column temperature at about 250 °C occurred due to opening of the furnace. It is clear from the temperature history shown in Fig. 5 that a uniform temperature of 600 °C was achieved along the column height during the test.

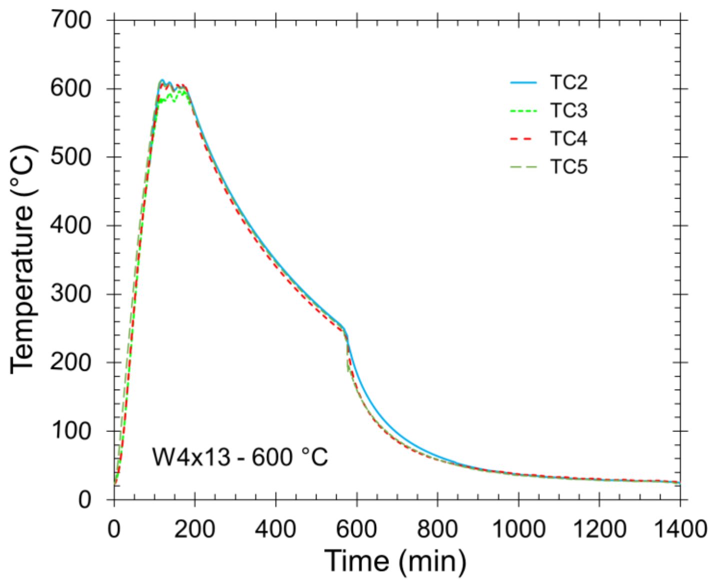

Figure 5: Complete Temperature History of a Column Specimen in a Test at 600 °C

In addtion to temperatures, column loads were also measured during buckling tests. The load cell built in the MTS testing machine with a nominal capacity of 550 kip (2500 kN) was used to record column loads during tests. Mesurements were also made on axial and lateral displacements of the column specimens during buckling tests at elevated temperatures. Details of all these measurements can be found in a publication by Morovat (2014).

4. Buckling Tests on ASTM A992 Steel Columns: Testing Procedure and Results

In the experimental program conducted by the authors, an extensive series of buckling tests were performed on W4×13 pin-ended columns that were 51-inches in length and made of ASTM A992 steel. All the column tests were steady-state temperature buckling tests, in which columns were first heated to the target temperature under no load and then tested under uniform temperature conditions. To make sure that the column specimens stayed in contact with the setup during the heating process, a small force of 1.0 kip was applied to the columns. Buckling tests were run until the columns could no longer hold their loads or until two hours elapsed, whichever occurred first.

At each temperature, two types of buckling experiments were conducted in this research. The first series of elevated-temperature column buckling tests were displacement-controlled tests. For these tests, the columns were first heated to the target temperature under no load. Once the column reached the target temperature, the load was increased until buckling. The peak load resisted by the column is referred to as the short-time buckling capacity. These tests are referred to herein as “Short-Time Buckling” tests. These tests were conducted using two different displacement-controlled loading rates: 0.01 in./min and 0.05 in./min.

The second series of elevated-temperature column buckling experiments were force-controlled creep buckling tests. For these tests, the column was first heated to the target temperature under no load. A load was then applied to the column that was less than the “Short-Time Buckling” capacity. The load was held constant on the column, and the time to buckling was measured. In this paper, these tests are referred to as “Creep Buckling” tests.

In the following, results from these two types of buckling tests at elevated temperatures will be presented and discussed. All the column specimens in elevated-temperature buckling tests were tested about their minor axes. This can be seen in Figs. 6 and 7, in which the overall deflected shape of a column specimen following an elevated-temperature test at 600 °C is presented. Fig. 6 also shows the safety measures taken to make sure that column stays in place as its temperature is getting back to room temperature.

Figure 6: A Representative W4×13 Steel Column (51 in. Long) Following a Buckling Test at 600 °C

Figure 7: Deflected Shape of a W4×13 Steel Column (51 in. Long) Following a Buckling Test at 600 °C

4.1 Short-Time Buckling Tests

As mentioned above, in these tests, the columns were first heated to the target temperature under no load. Once the column reached the target temperature, the load was increased until buckling. Column loads were applied at two specific displacement rates of the testing ram (0.01 in./min and 0.05 in./min) and were increased until column specimens reached their buckling strengths, i.e. the peak of the load-deflection curve. The column specimens were compressed further until their capacities dropped to about 20% of their ultimate strengths.

Fig. 8 shows the load versus mid-height lateral deflection curves corresponding to the short-time buckling tests performed under two different displacement rates at 600 °C. Moreover, the results from short-time buckling tests in the form of load versus axial displacement of the column specimens is presented in Fig. 9 for 600 °C. As can be seen clearly from Figs. 8 and 9, the buckling capacity of the steel columns at high temperatures is quite sensitive to the loading rate, reflecting the creep behavior of steel at elevated temperatures. For example, at 600 °C, the buckling capacity is 68-kips when loaded at 0.05 in./min, and is 63-kips when loaded at 0.01 in./min. It can also be observed that the initial parts of load-deflection curves are not sensitive to the testing rate. This observation further confirms the previous observations that the elastic modulus of structural steel at elevated temperatures is not time-dependent (Morovat, et al. 2010; Morovat, et al. 2013; Morovat 2014; Morovat, et al. 2014a; Morovat, et al. 2014b).

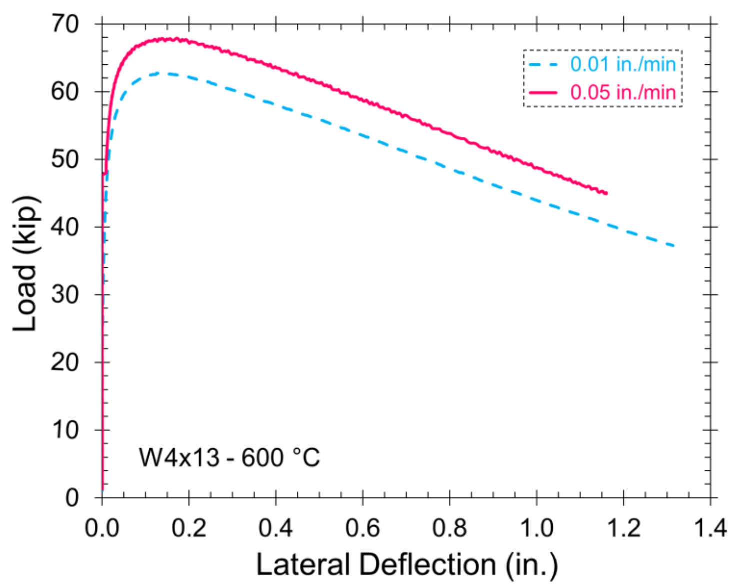

Figure 8: Load versus Mid-Height Lateral Deflection for Short-Time Column Buckling Tests at 600 °C

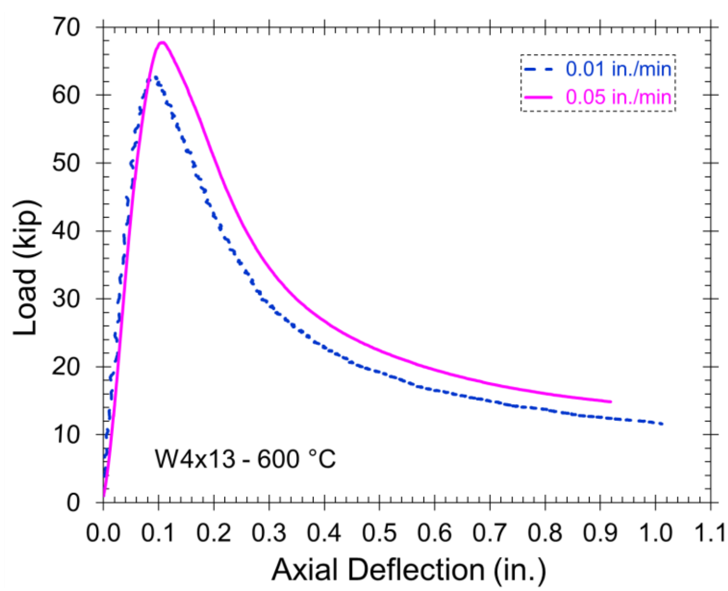

Figure 9: Load versus Axial Displacement for Short-Time Column Buckling Tests at 600 °C

4.2 Creep Buckling Tests

As described earlier, the second series of elevated-temperature column buckling experiments conducted in this research were force-controlled creep buckling tests. For these tests, the column was first heated to the target temperature under no load. A load was then applied to the column that was less than the "Short-Time Buckling" capacity. The load was held constant on the column, and the time to buckling was measured.

The creep buckling phenomenon can best be visualized by plotting either mid-height lateral deflection versus time curves, or axial displacement versus time curves, samples of which are presented, respectively, in Figs. 10 and 11 for creep buckling tests under various applied loads at 600 °C. As can be seen in Figs. 10 and 11, the rate of change of deflection with time increases very slowly at the beginning and then increases more rapidly until the column no longer can support its load. The time at which the displacement-time curves become nearly vertical represents the failure time. For example, as shown in Figs. 10 and 11, the column tested at 600 °C and under a load of 61 kips buckled after 5 minutes.

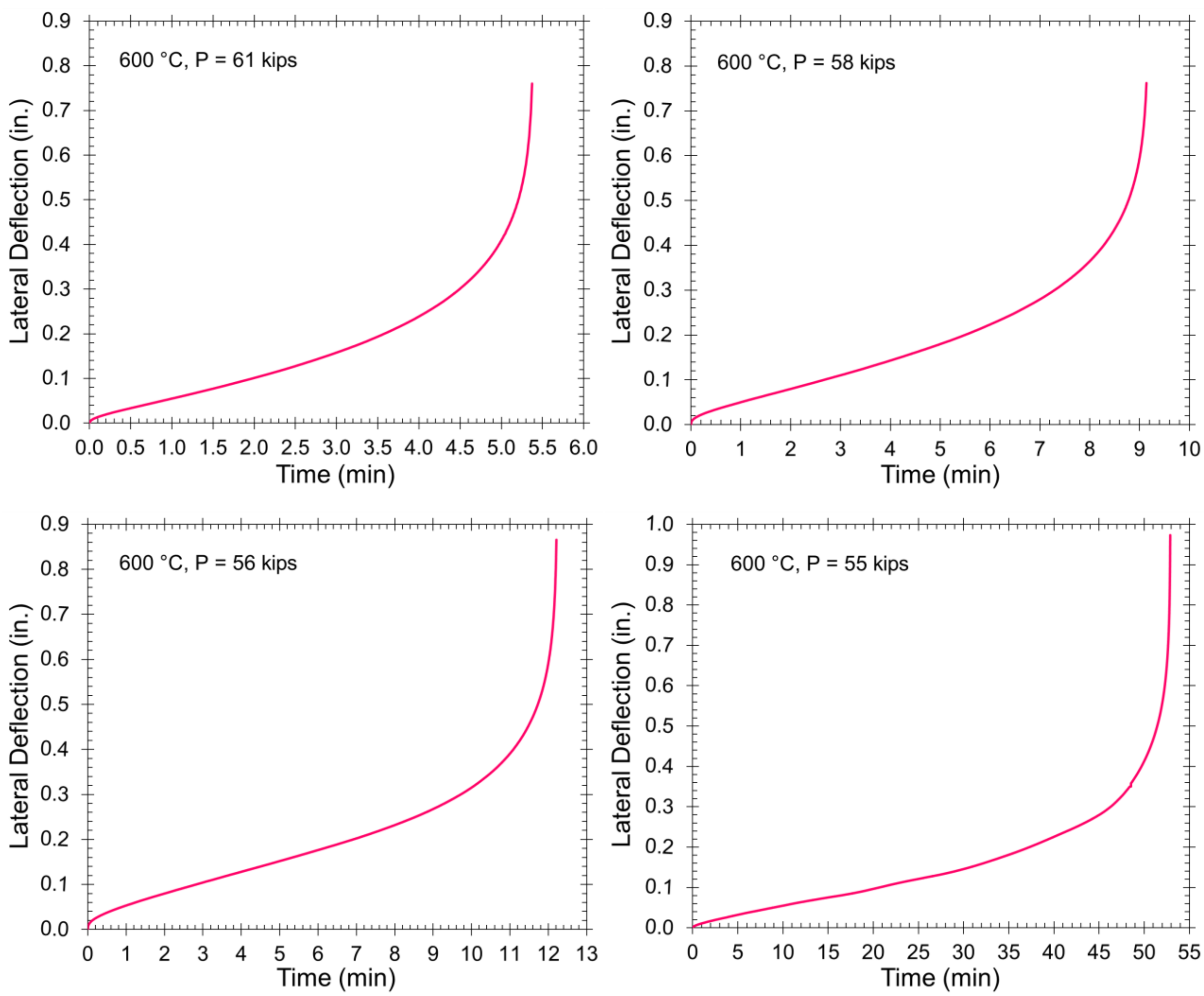

Figure 10: Mid-Height Lateral Deflection as a Function of Time for Creep Buckling Tests under Various Applied Loads at 600 °C

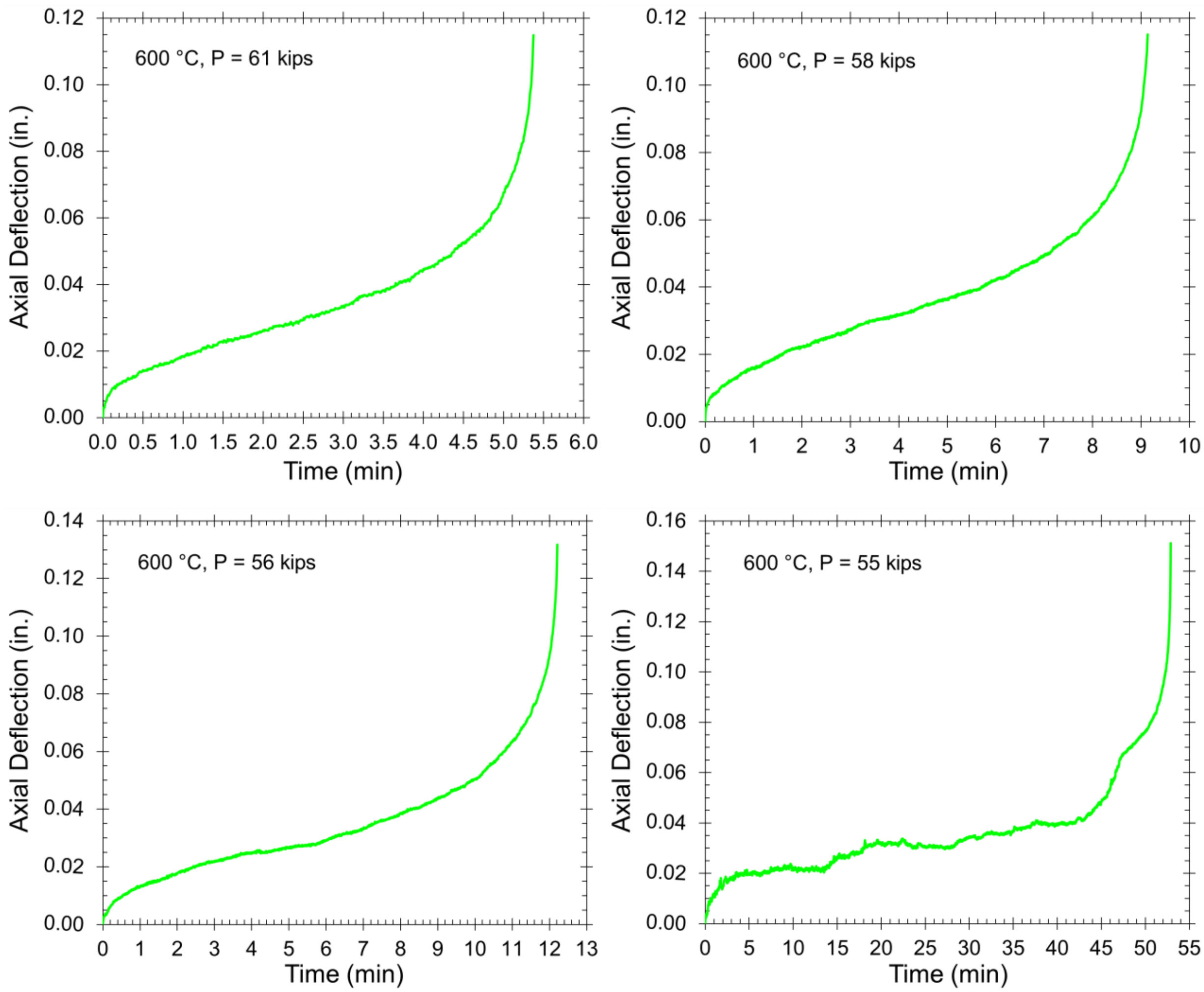

Figure 11: Axial Deflection as a Function of Time for Creep Buckling Test under Various Applied Loads at 600 °C

Furthermore, the importance of the primary creep of ASTM A992 structural steel on predicting the buckling behavior of steel columns in fire is also apparent, specifically in Fig. 11, as column displacements grow rapidly in the early stages of buckling tests.

One important point to note about curves shown in Figs. 10 and 11 is that the displacements plotted as functions of time are displacements due to creep only. In other words, load-induced displacements are not presented in Figs. 10 and 11. The rate at which the loads are applied to the column specimens at the start of steady-state temperature creep buckling tests can make a significant difference in time-dependent buckling behavior, especially at high levels of temperatures and stresses (Morovat 2014). In all steady-state temperature creep buckling tests reported in this paper, the loads were applied in 1 second at the start of each test.

To more clearly demonstrate the highly time-dependent and nonlinear buckling behavior of steel columns at elevated temperatures, the creep buckling curves shown in Figs. 10 and 11 are plotted together and presented in Figs. 12 and 13, respectively. From Figs. 12 and 13, it is clear that the buckling behavior, as characterized by the time-to-failure, of steel columns subjected to fire is significantly affected by the load level at elevated temperatures like 600 °C. For example, at 600

°C, when a load of 61 kips was applied to the column, the column buckled after 5 minutes. When a load of 54 kips was applied to the column, the column buckled after 85 minutes. In fact, the highly nonlinear nature of creep buckling phenomenon as indicated in Figs. 12 and 13 can potentially be used in analysis and design of steel columns subjected to elevated temperatures. This is true since from Figs. 12 and 13, it can be seen that, at 600 °C, there is a load level, below which the impact of thermal creep of structural steel on buckling capacity of steel columns becomes less significant for structural-fire design applications.

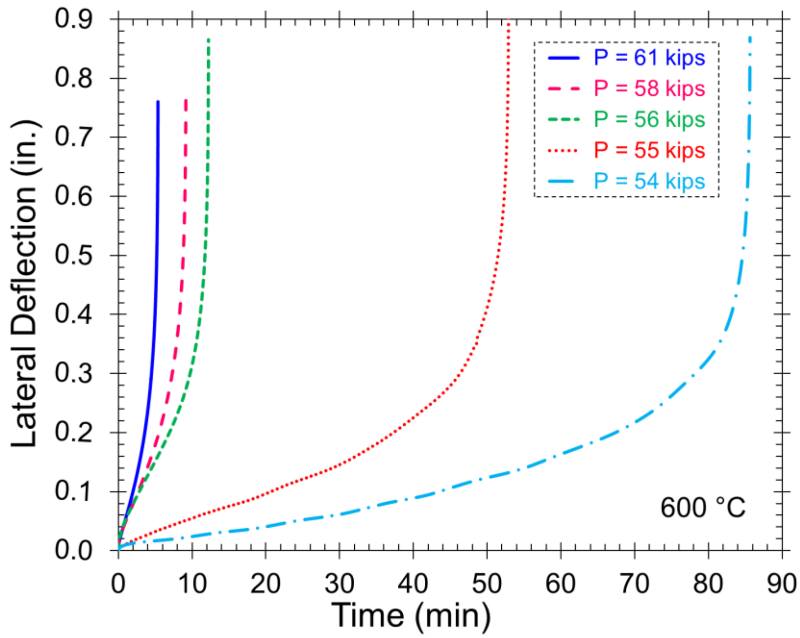

Figure 12: Mid-Height Lateral Deflection as a Function of Time for Creep Buckling Tests at 600 °C and under Different Applied Loads

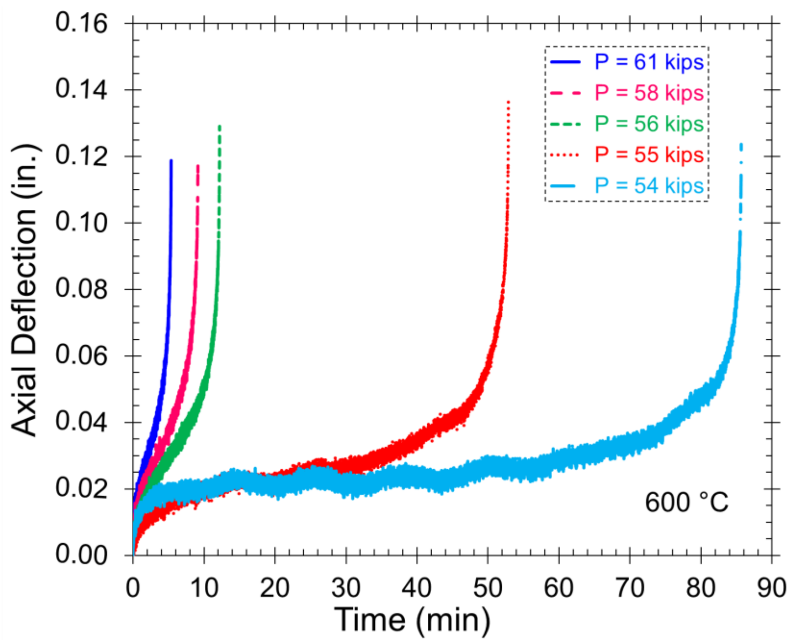

Figure 13: Axial Deflection as a Function of Time for Creep Buckling Tests at 600 °C and under Different Applied Loads

4. Comparison with AISC and Eurocode 3 Predictions

In this section results obtained from creep buckling tests are compared with the corresponding elevated-temperature column strength predictions of the AISC Specification (2010) and of Eurocode 3 (2006). It should be pointed out here that formula to predict column strength at high temperatures in Appendix 4 of the 2010 edition of the *AISC Specification for Structural Steel Buildings* are based on work by Takagi and Deierlein (2007). Both the Eurocode 3 (2006) column strength formula and that proposed by Takagi and Deierlein (2007) predict column strength as a function of temperature, but do not consider duration of load and temperature exposure; i.e., they do not consider creep buckling effects. These formulas are based on computational studies using elevated-temperature stress-strain curves for steel that do not explicitly include creep effects, and are verified against high-temperature column buckling experiments that also did not explicitly consider time dependent effects on buckling.

Measured buckling capacities corresponding to buckling times in the range of 5 to 85 minutes at 600 °C (as illustrated in previous section and summarized in Table 1) are plotted in Fig. 14. Creep buckling predictions from buckling tests at 700 °C are also shown in Fig. 14. Buckling capacities from buckling tests at 700 °C correspond to buckling times in the range of 10 to 133 minutes (Morovat 2014). For comparison, buckling predictions for the W4×13 section are also presented using both Eurocode 3 (2006) and using AISC Specification (2010).

Table 1. Results of Buckling Tests on 51 in. W4×13 Columns at 600 °C

P_{cr} (kip)						
Short-Time Buckling Rate (in./min)		Creep Buckling Time-to-Buckling (min)				
0.01	0.05	5	9	12	53	85
63.0	67.8	61.0	58.0	56.0	55.0	54.0

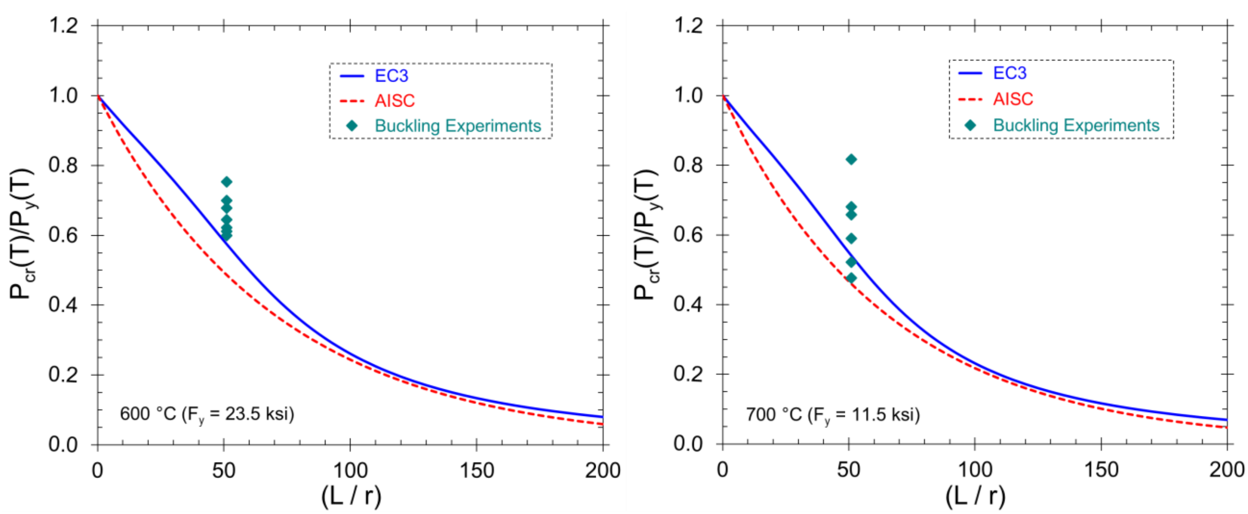

Figure 14: Comparison of Experimental Creep Buckling Predictions with Code-Based Buckling Estimates

As can be observed in Fig. 14, although both the Eurocode 3 (2006) and AISC Specification (2010) predict column strength as a function of temperature, and do not consider duration of load and temperature exposure (i.e., they do not explicitly consider creep buckling effects), their predictions for the buckling capacity of the column in consideration, with KL/r of 51-inches and temperatures of 600 °C and 700 °C, are conservative (in case of Eurocode 3 for buckling times less than 60 minutes at 700 °C). This observation, however, should not be construed to suggest that the code-based predictions of column buckling would generally be conservative. It should be specifically noted that the column specimens in the experimental study had very small geometric imperfections (in the order of L/5000), while the initial crookedness of typical steel columns are in the order of L/1000. Since creep buckling of steel columns is sensitive to the magnitude of initial imperfections, predictions from design codes might not be conservative for some temperatures and slenderness ratios.

5. Conclusions

Highlights of an extensive testing program conducted by the authors to investigate the effects of time-dependent or thermal creep of ASTM A992 structural steel on buckling of steel columns subjected to fire were presented in this paper. Buckling tests on W4×13 wide flange columns under pin-end conditions were conducted to characterize short time and creep buckling loads at elevated temperatures up to 700 °C. The column test results were further compared against code-based predictions from Eurocode 3 (2006) and the AISC Specification (2010).

The results from experiments presented in this paper clearly show that the buckling capacity of steel columns becomes highly time-dependent within the time, temperature, and stress regimes expected in a building fire. In addition, results show that neglecting creep effects can lead to erroneous and potentially unsafe predictions of the strength of steel columns subjected to fire. Since the thermal creep of steel has a very large effect on strength of steel columns at high temperatures due to fire, any predictions of column capacity using code-based equations that do not explicitly include time-dependent response of structural steel should be viewed with considerable caution.

Acknowledgments

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