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# Effect of Boundary Conditions on the Creep Buckling of Steel Columns in Fire

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**Abstract**
This paper presents highlights of a preliminary computational study conducted using Abaqus to investigate the influence of boundary conditions on the creep buckling behavior of steel columns at elevated temperatures due to fire. W12×120 wide flange columns with the unsupported length of 240 inches are used in the simulations. Thermal creep of steel is modeled following equations proposed by Fields and Fields for the creep of ASTM A36 steel. Four different classical support conditions and seven imperfection amplitudes are considered to quantify the effect of boundary conditions on the time-dependent strength of steel columns in fire. Thermal restraints, both axial and rotational, were ignored in the analyses. Representative results from creep buckling tests simulated at 500 °C are presented and discussed. Results from creep buckling simulations presented in this paper indicate that the rotational and translational restraint at the column ends along with the initial crookedness of the column have a significant impact on the predictions of the time-dependent strength of steel columns subjected to fire.

## 1. Introduction

The behavior of steel columns subjected to elevated temperatures due to fire is affected by many factors. One of the critical factors affecting the strength of steel columns in fire is the influence of material creep. Defined as time-dependent inelastic deformation, thermal creep of structural steel results in the creep buckling phenomenon, in which the buckling capacity of a steel column depends on the duration of applied load as well as the slenderness and temperature.

In addition to the influence from material creep, buckling capacity of steel columns at elevated temperatures is significantly affected by their boundary conditions, mainly the end-support conditions and initial imperfections. The effect of boundary conditions on the buckling behavior of steel columns at room temperature is very well documented in the literature on the stability of steel columns (Ziemian 2010). However, literature on the impact of boundary conditions on the buckling capacity of steel columns exposed to fire temperatures is quite meager (Morovat 2014). Specifically, there is very little study on the effect of boundary conditions on the time-dependent

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or creep behavior of steel columns when subjected to fire (Huang 1976; Morovat et al. 2013; Morovat 2014). The effect of boundary conditions on the time-dependent or creep behavior of steel columns exposed to fire is therefore not well understood and clearly treated in building codes and standards including Eurocode 3 (2003) and the AISC Specification (2010).

To develop a better understanding of the effect of boundary conditions on the time-dependent or creep buckling behavior of steel columns at elevated temperatures, the authors performed a series of creep buckling simulations, highlights of which are presented in this paper. Some details about buckling tests simulated in Abaqus will first be provided. Results from both short-time and creep buckling tests on W12×120 wide flange columns under different end-support conditions and initial imperfections at 500 °C are then presented and discussed.

## 2. Simulations of Column Tests: General Considerations

To study the effect of boundary conditions on the time-dependent buckling strength of steel columns at elevated temperatures, two types of column tests were simulated in Abaqus. These two column tests are referred to in this paper as *Short-Time Buckling Tests* and as *Creep Buckling Tests*. Short-time buckling tests were simulated to characterize the time-independent strength of steel columns at elevated temperatures. To obtain the time-independent or short-time buckling loads in Abaqus, inelastic load-deflection analyses, using a nonlinear analysis scheme called Riks, were performed under the steady-state temperature conditions. Following the short-time buckling tests, creep buckling tests were simulated to characterize the time-dependent strength of steel columns at elevated temperatures. In creep buckling simulations, temperature was first increased to the desired level, and then a fraction of the ultimate load predicted in the corresponding short-time buckling test was applied to the column. No material creep was considered in these two steps. Next, incorporating a nonlinear analysis scheme called Visco, the column was allowed to creep over the time period of 6 hours under the sustained load. Finally, the time-to-buckle due to creep was estimated. Note that, to model initial geometric imperfections in both column tests, eigen-value buckling analyses were performed. The initial shape of the column was taken as the shape of the first buckling mode, and the magnitude of the imperfection was chosen as a fraction of the column length.

To account for material nonlinearities in column buckling simulations, an idealized bilinear stress-strain relation with isotropic hardening was used to model the time-independent inelastic behavior of structural steel at elevated temperatures. The time-dependent or creep behavior of structural steel at elevated temperatures is defined using the model developed by Fields and Fields (1989) based on material tests by Skinner (1972). The creep model proposed by Fields and Fields (1989) incorporates a power law and represents creep strain, $\varepsilon_c$, in the form of a Norton-Bailey (Norton 1929; Bailey 1929) equation as follows:

$$\varepsilon_c = at^b\sigma^c \tag{1}$$

In this equation, $t$ is time and $\sigma$ is stress. The parameters $a$, $b$ and $c$ are temperature-dependent material properties. Fields and Fields (1989) derived equations for these temperature-dependent material properties for ASTM A36 steel. The model developed by Fields and Fields (1989) is capable of predicting creep in the temperature range of 350 °C to 600 °C and for creep strains up to 6-percent. Note that the strain-hardening format of the power law creep shown in Eq. 1 was incorporated in the column simulations. In addition, 3D hexahedral eight-node linear brick elements, *C3D8R*, were utilized to model the columns in Abaqus.

## 3. Simulations of Column Tests: Results

The two types of column buckling simulations introduced above were used to examine the effect of boundary conditions on the time-dependent response of steel columns to fire temperatures. W12×120 wide-flange columns made of ASTM A36 steel and having length of 240 inches were utilized in the study. Boundary conditions in the forms of end-support conditions and initial geometric imperfections were considered. Results of these buckling simulations are presented and discussed in this section.

### *3.1 Effect of End-Support Conditions*

The effect of boundary conditions in the form of end-support conditions on the creep buckling capacity of steel columns were investigated in the column buckling simulations. Specifically, four idealized support conditions were considered in the simulations. These support conditions were pin-pin, pin-fix, fix-fix, and fix-free.

Sample results of column buckling simulations indicating the impact of end-support conditions on the creep behavior of W12×120 steel columns at 500 °C are shown in Fig. 1. Column buckling results presented in Fig. 1 are for columns with four initial out-of-straightness amplitudes of L/3000, L/1500, L/1000, and L/500. Note that, in Fig. 1, time effects on the buckling behavior of steel columns are depicted as plots of buckling load versus time for each initial imperfection and column-end condition. Therefore, each point on these curves represents a creep buckling test simulated in Abaqus, and as a result values on the time axis are indicative of *failure time* or *time-to-buckle*. Further, results from short-time buckling simulations are indicated as buckling loads at time zero on creep buckling curves in Fig. 1.

As seen in Fig. 1, columns with rotational restraint at the ends are less affected by thermal creep of steel at 500 °C since the buckling strength of both fix-fix and pin-fix columns drops more slowly with time compared to that of pin-pin columns. Further, it can be observed in Fig. 1 that thermal creep of steel has very minor impact on the buckling behavior of fix-free columns with relative lateral displacement of the ends. As will be discussed in more details, this is mainly due to the fact that buckling stresses for fix-free columns are very small compared to the yield strength of the column material at 500 °C and therefore do not result in large creep strains.

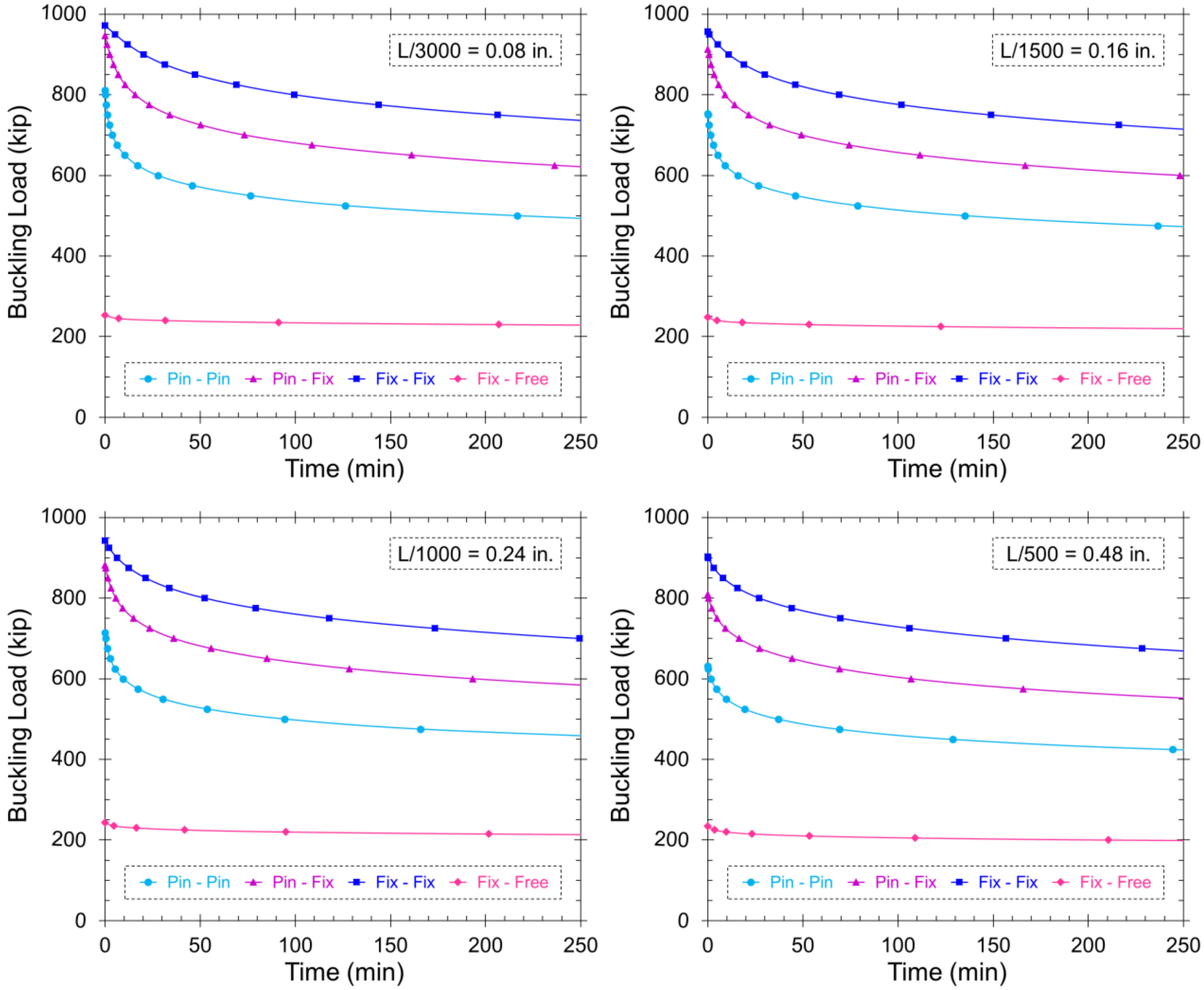



Figure 1: Effect of End-Support Conditions on the Creep Buckling Curves at 500 °C

To better gauge the effect of column-end conditions on the time-dependent response of steel columns at elevated temperatures, column test results in Fig. 1 are normalized with respect to the corresponding short-time buckling loads and replotted in Fig. 2. As seen more clearly in Fig. 2, the buckling capacity of fix-fix columns with rotational restraint at both ends is less time dependent compared to those of pin-fix and pin-pin columns. The buckling behavior of fix-free columns is again seen to be the least affected by the thermal creep of steel at the representative temperature of 500 °C. The normalized representation of creep buckling curves is also helpful in indicating that, except for the fix-free end-support conditions, the buckling strength of columns with larger amplitudes of initial crookedness is less time-dependent.

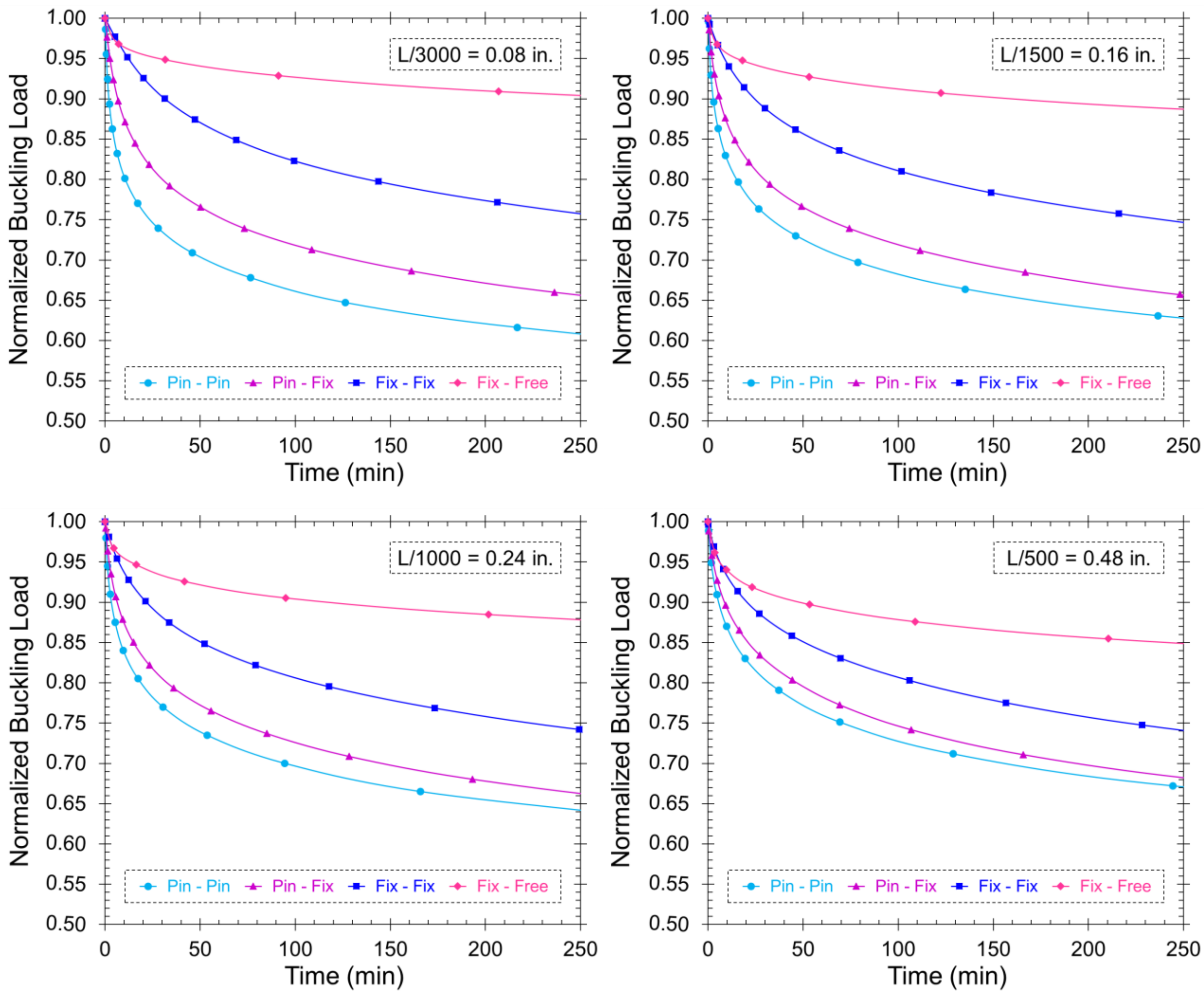
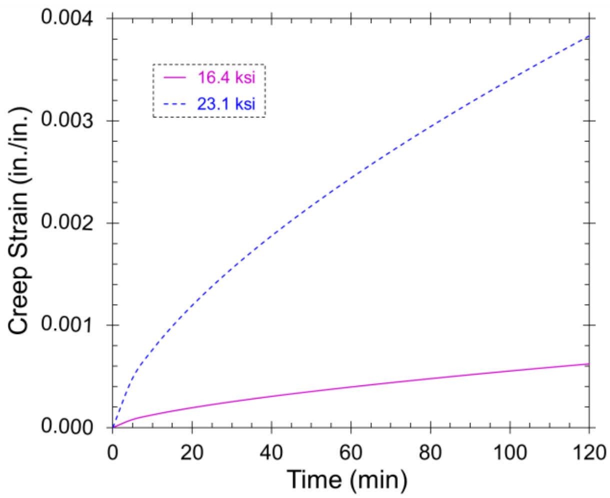
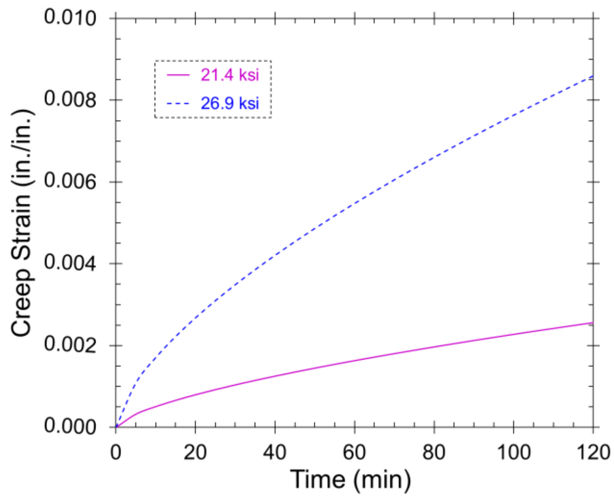



Figure 2: Effect of End-Support Conditions on the Normalized Creep Buckling Curves at 500 °C

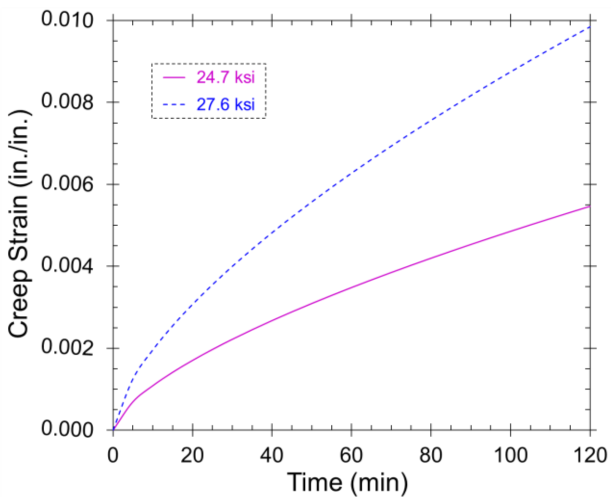
Some of the observations in Figs. 1 and 2 can be better explained by investigating the average column stresses resulting from buckling loads and the material creep predictions using Fields and Fields (1989) model for those stresses. This is presented in Fig. 3 where predictions from creep model by Fields and Fields (1989) are plotted for stresses corresponding to the short-time buckling loads for columns with different end-support conditions and initial imperfection amplitudes. For example, in the case of pin-pin columns, the maximum and minimum short-time buckling loads corresponding to the initial imperfection amplitudes of L/3000 and L/333 were 811 kips and 576 kips, respectively. With the cross-sectional area of W12×120 steel columns being equal to 35.2 in.$^2$, the maximum and minimum buckling stresses were obtained as 23.1 ksi and 16.4 ksi. For these stresses, the creep behavior of the column steel at 500 °C is depicted in Fig. 3(a). Note that the yield strength of the column material at 500 °C is 28.1 ksi. As specifically indicated in Fig. 3 (d), at 500 °C, the creep strains resulted from the column stresses are very small and consequently the strength behavior of fix-free columns is not much affected by creep. As will be emphasized later, the significance of the column load magnitude on the time-dependent buckling strength of steel columns becomes even more clear when investigating the effect of initial imperfections.



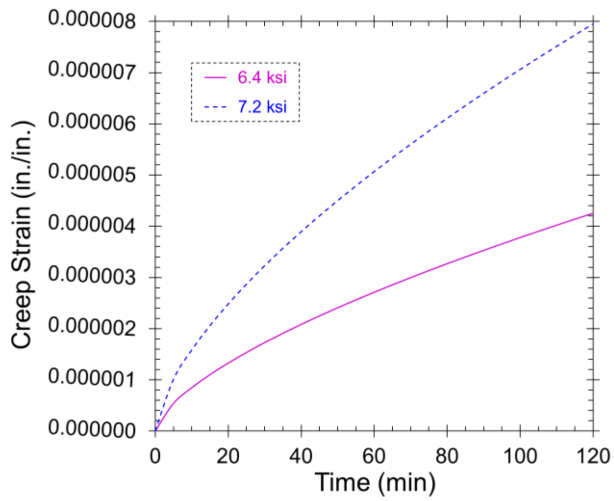

(a) Pin-Pin Columns




(b) Pin-Fix Columns




(c) Fix-Fix Columns




(d) Fix-Free Columns

Figure 3: Creep Material Predictions Using Fields and Fields (1989) for Stresses Corresponding to Short-Time Buckling Loads at 500 °C

*3.2 Effect of Initial Geometric Imperfections*

The strong influence of initial imperfections on reducing the column buckling capacity at ambient temperature is well understood and accounted for in modern design codes (Southwell 1932; Timoshenko 1936; Shanley 1947; Ziemian 2010; AISC 2010). As for the role of initial crookedness in elevated-temperature instabilities, while there are published data in the literature suggesting their importance in predicting the buckling strength of steel columns, their influence in the creep buckling analysis is not well established. Therefore, the goal in this section is to provide some insight on how initial geometric imperfections affect creep buckling behaviors through computational column buckling studies using Abaqus.

Fig. 4 shows the results of a series of Abaqus simulations of creep buckling tests on 240-inch long, W12×120 steel columns with different initial out-of-straightness at 500 °C. As it is clear from Fig. 4, regardless of the end-support conditions, initial geometric imperfections have major impact on the short-time or time-independent buckling load predictions, which in turn result in different creep buckling behaviors. More specifically, Fig. 4 indicates that higher initial crookedness values result in lower short-time buckling capacities of the steel columns in consideration at 500 °C. Fig. 4, however, does not clearly show how the initial imperfections affect the creep buckling capacities.

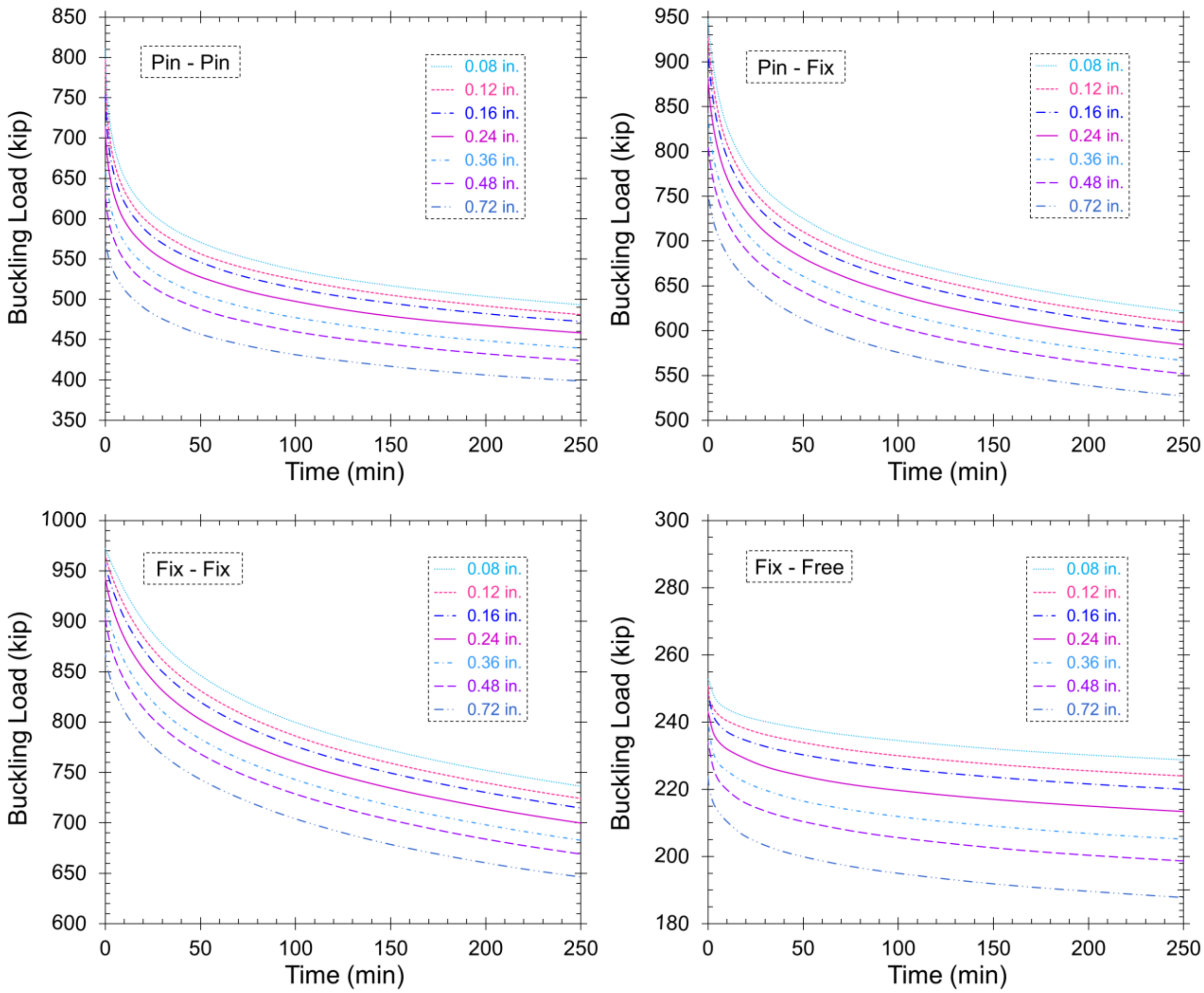


Figure 4: Effect of Initial Imperfections on the Creep Buckling Curves at 500 °C

To better understand the effect of initial imperfections on the time-dependent response of steel columns at elevated temperatures, column test results in Fig. 4 are normalized with respect to the corresponding short-time buckling loads and replotted in Fig. 5. An important observation from Fig. 5 is that, for columns without relative lateral displacement of the ends, higher initial imperfection amplitudes result in less time-dependency of the buckling capacities at 500 °C. As emphasized before, these columns are less prone to creep buckling since they have smaller short-time buckling capacities. In other words, their material is exposed to smaller stresses. It can be further observed from Fig. 5 that the time-dependent buckling strength of steel columns with fix-fix end conditions are essentially insensitive to initial imperfections. Finally, Fig. 5 indicates that, in contrast to the columns without relative lateral displacement of the ends, the fix-free columns with higher initial imperfection amplitudes are more susceptible to creep buckling at

500 °C. This is true since the time-dependent behavior of fix-free columns is more controlled by second-order effects than by magnitudes of the axial compressive loads.

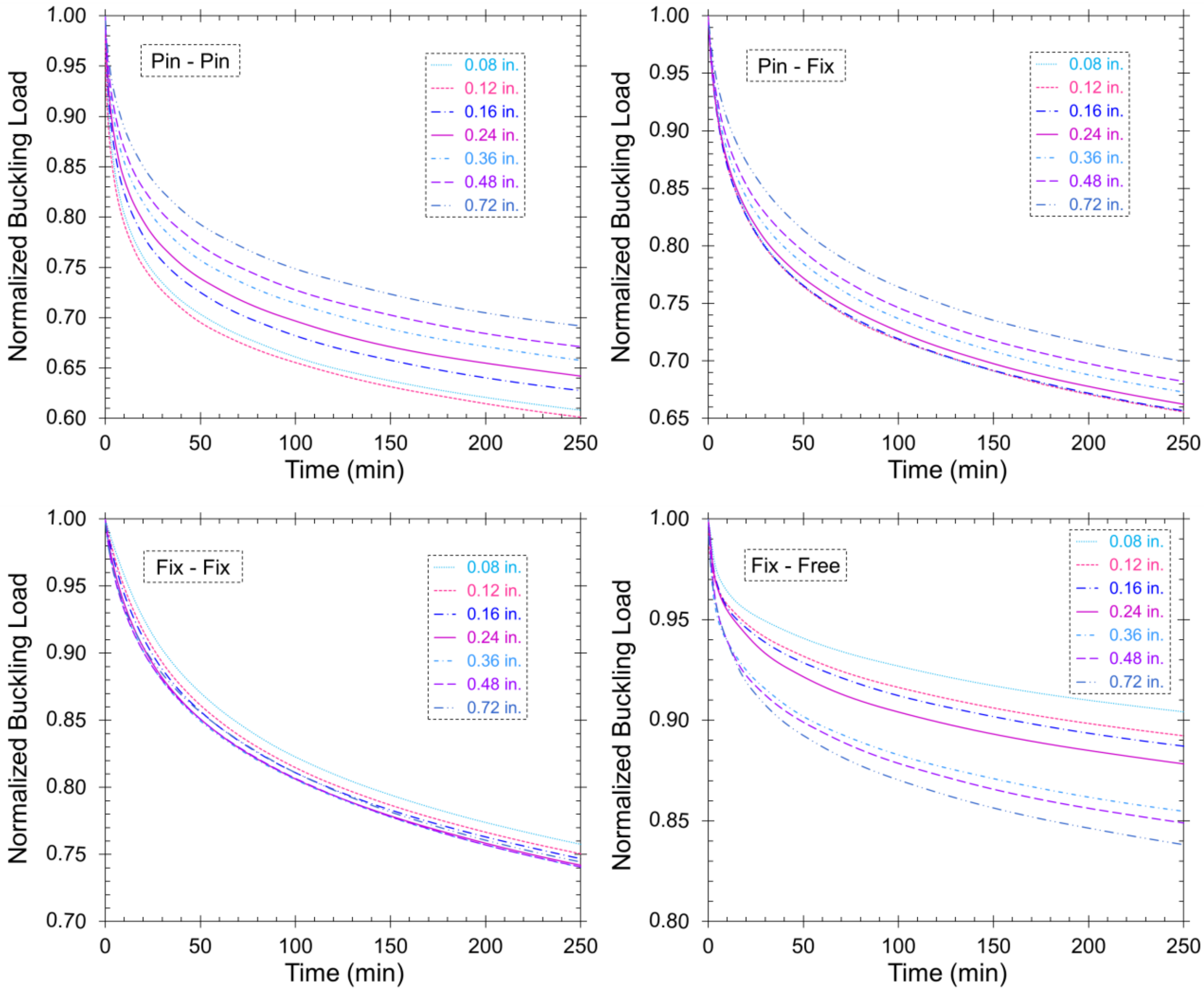
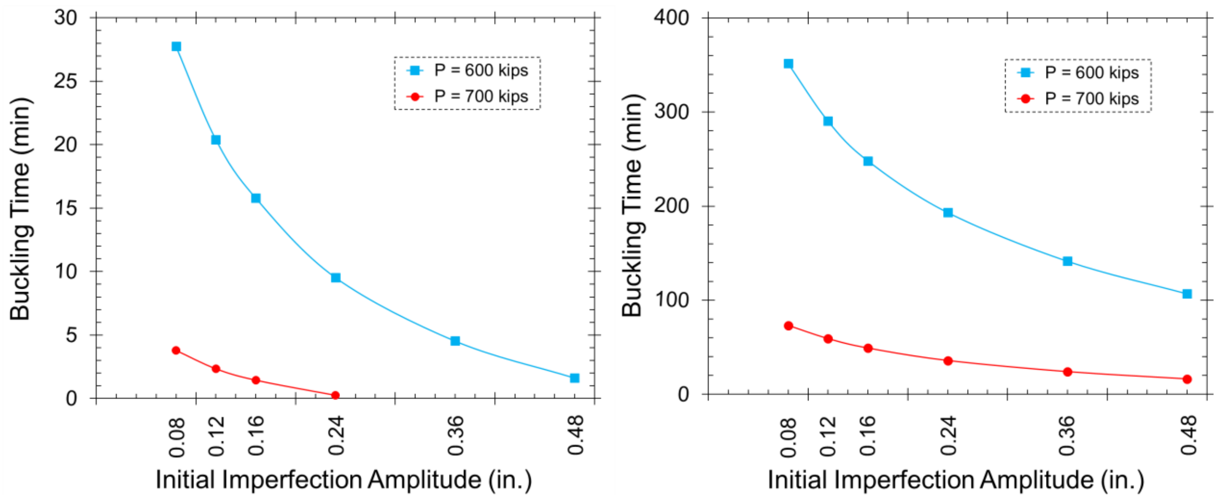


Figure 5: Effect of Initial Imperfections on the Normalized Creep Buckling Curves at 500 °C

The effect of initial out-of-straightness on creep buckling strength of steel columns at elevated temperatures can also be studied by constructing curves of creep buckling time versus initial imperfection magnitude for a given column load. Two samples of such curves are presented in Fig. 6 corresponding to sustained loads of 600 and 700 kips. As can be seen from Fig. 6, the creep buckling time drops significantly as the applied load approaches the short-time buckling load for a specific initial crookedness. In other words, initial imperfections can have a profound impact on creep buckling time of steel columns with low to moderate imperfections, typical of imperfections expected in structural steel columns. For example, in the case of a pin-fix column with an initial imperfection of 0.240 inches, Fig. 6 (b), increasing the applied load from 600 to 700 kips reduces the creep buckling time of the column from 193 to 36 minutes.




(a) Pin-Pin Columns (b) Pin-Fix Columns

Figure 6: Representative Creep Buckling Time vs. Maximum Initial Imperfection Curves at 500 °C

In all analyses presented so far, the effect of thermal creep of structural steel on predictions of the buckling strength of steel columns subjected to fire temperatures is visualized through a plot of buckling load versus time (time-to-buckle) curve for a specific column and at a specific temperature of 500 °C. However, presenting the results of elevated-temperature creep buckling analyses in the form of buckling load versus time curves may not be very convenient for direct use in structural engineering design applications. The effect of thermal creep of steel on the buckling behavior of steel columns subjected to fire can further be presented in the conventional method of plotting buckling load versus slenderness ratio, referred to commonly as the buckling curve. This can be achieved by constructing isochronous buckling load-slenderness ratio curves like the ones presented in Fig. 7. As seen in Fig. 7, the shape of buckling curves changes with time even for short exposure times. It can be further observed that time effects become more significant for columns with KL/r in the range of 40 to 60, a range representative of steel columns in majority of buildings.

The creep buckling behavior of steel columns in the form of isochronous buckling load-slenderness ratio curves, a sample of which depicted in Fig. 7, can alternatively be presented by separating the time-independent buckling behaviors from the time-dependent ones. For instance, as shown in Fig. 8, buckling curves can be constructed using the short-time buckling loads of columns with specific end-support condition and initial imperfection amplitude. Fig. 8 clearly indicates the effect of initial imperfections on the time-independent buckling behavior of pin-pin columns at 500 °C. Specifically, the buckling curves in Fig. 8 show that the time-independent buckling capacities decrease with the increase in amplitudes of initial imperfections for slenderness ratios in the range of 40 to 60.

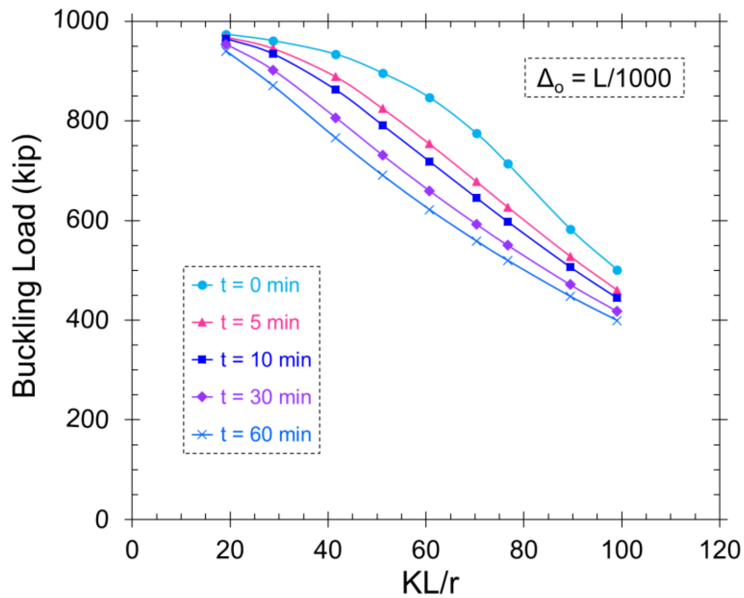



Figure 7: Isochronous Buckling Load vs. Slenderness Ratio Curves for Pin-Pin Columns at 500 °C

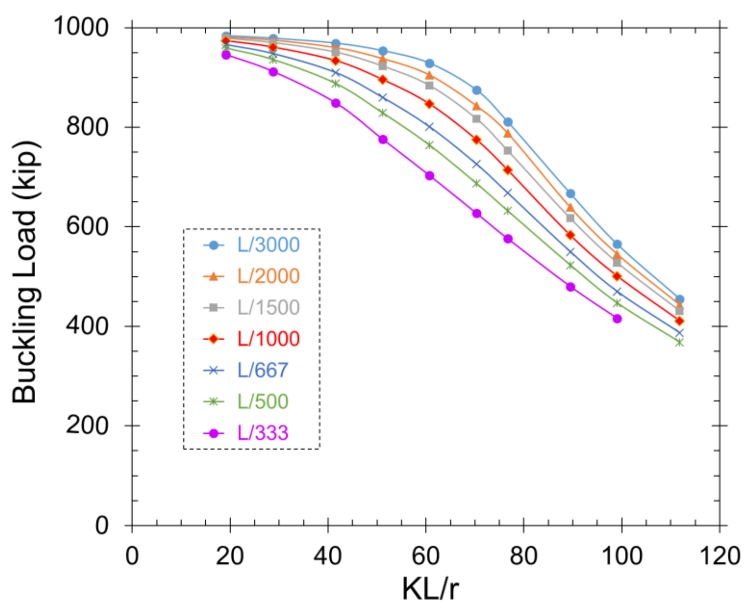



Figure 8: Buckling Curves Corresponding to the Short-Time Buckling Simulations of Pin-Pin Columns at 500 °C

Fig. 9 further illustrates the effect of initial imperfections on the time-dependent strength of pin-pin columns at elevated temperatures by plotting isochrones corresponding to the buckling time of 5 minutes for columns with initial out-of-straightness amplitudes of L/500, and L/1000. The effect of larger initial imperfections on reducing the creep buckling capacities, especially for slenderness ratios in the range of 40 to 60, can again be observed in Fig. 9.

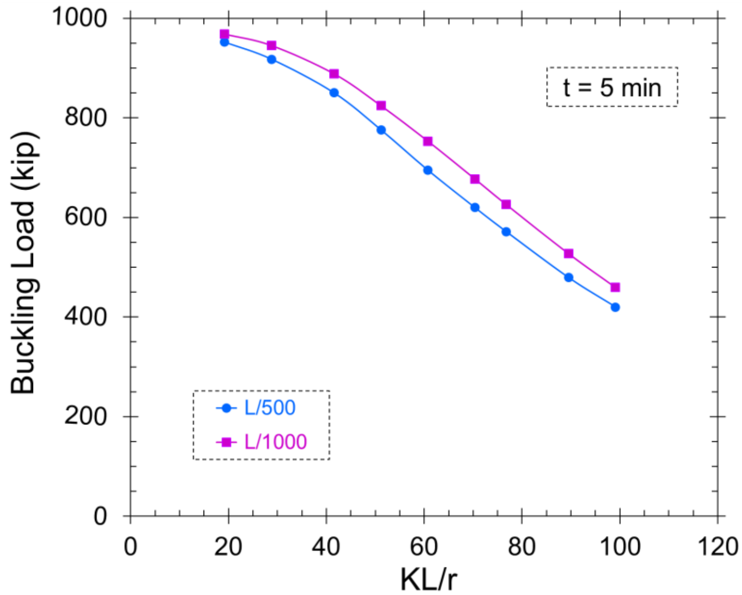


Figure 9: Isochronous Buckling Load vs. Slenderness Ratio Curves for Pin-Pin Columns at 500 °C – Effect of Initial Imperfections

## 5. Conclusion

Highlights of an extensive computational study conducted by the authors to investigate the effect of boundary conditions on the time-dependent or creep buckling of steel columns subjected to fire were presented in this paper. Both time-independent and creep buckling tests on W12×120 wide flange columns under different boundary conditions were simulated in Abaqus to characterize short-time and creep buckling loads at elevated temperature of 500 °C.

The results from creep buckling simulations clearly indicate that the rotational and translational restraint at the column ends along with the initial crookedness of the column have a significant impact on the predictions of the time-dependent strength of steel columns subjected to fire. Specifically, simulation results show a strong correlation between initial geometric imperfection and the short-time buckling load predictions at high temperatures. Results from buckling simulations further suggest a close relationship between the short-time or time-independent buckling load predictions and the overall creep buckling behavior of steel columns at elevated temperatures due to fire.

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## References


American Institute of Steel Construction (AISC). (2010). *Specification for Structural Steel Buildings*, Standard ANSI/AISC 360-10, Chicago.

Bailey, R.W. (1929). “Creep of Steel under Simple and Compound Stress.” *Engineering*, 148, 121, 528-529.

Eurocode 3 (2006). *Design of Steel Structures. Part 1-2: General rules. Structural Fire Design*, EN 1993-1-2 European Committee for Standardization, CEN.

Fields, B.A., and Fields, R.J. (1989). *Elevated Temperature Deformation of Structural Steel*, Report NISTIR 88-3899, NIST, Gaithersburg, MD.

Huang, N.C. (1976). “Creep Buckling of Imperfect Columns.” *Journal of Applied Mechanics, Trans. ASME*, 43(3) 131-136.

Morovat, M.A., Engelhardt, M.D., Helwig, T.A., and Taleff, E.M. (2013). “Influence of Creep on the Stability of Steel Columns Subjected to Fire,” *Proceedings of the Annual Stability Conference,* Structural Stability Research Council, St. Louis, Missouri, April 16-20.

Morovat M.A. (2014). *Creep Buckling of Steel Columns Subjected to Fire*, Ph.D. Dissertation, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin.

Norton, F.H. (1929). *The Creep of Steel at High Temperatures*, McGraw-Hill Book Company, Inc., New York.

Shanley, F.R. (1947). “Inelastic Column Theory.” *Journal of the Aeronautical Sciences*, 14(5) 261-267.

Skinner, D.H. (1972). “Determination of High Temperature Properties of Steel.” *Broken Hill Proprietary Company, Technical Bulletin*, 16(2) 10-21.

Southwell, R.V. (1932). “On the Analysis of Experimental Observations in Problems of Elastic Stability.” *Proceedings of the Royal Society of London, Series A*, 135(4) 601-616.

Timoshenko, S.P. (1936). *Theory of Elastic Stability*, McGraw-Hill Book Company, Inc., New York.

Ziemian, R.D. Editor (2010) *Guide to Stability Design Criteria for Metal Structures*, 6th Edition, John Wiley & Sons, Inc., New York