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Experimental research on the creep buckling of fire-resistant steel columns at elevated temperature

Kuo-Chen Yang* and Zong-Han Yu[a]

National Kaohsiung First University of Science and Technology, Department of Construction Engineering, Kaohsiung, 824, Taiwan

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Abstract. The thermal creep is one of the major factors causing the buckle of steel columns in the fire events. But, few related studies have been reported to evaluate the factors affecting the thermal creep of steel column experimentally or numerically. In this study a series of Fire-resistant steel columns with three different slenderness ratios under a sustained load are tested under a uniform temperature up to six hours in order to evaluate the creep upon three selected factors, temperature, applied load, and column slenderness. Based on experimental results, a proposed creep strain rate model is established as the function of a single parameter of the load ratio of temperature $LR(T)$ to determine the buckling time of steel column due to creep. Furthermore it is found that the creep can be neglected when $LR(T)$ is smaller than 0.77.

Keywords: thermal creep; load ratio; elevated temperature; steel columns

1. Introduction

At room temperature, the material properties of a given steel remains constant so that the column strength is determined based on the geometric properties of width-to-thickness ratio, the slenderness ratio, and the boundary conditions of axial or rotational restraint. In this case, the creep effect is insignificant and normally neglected when design steel columns at room temperature. But material properties are deteriorated with temperature so that the creep effect is accelerated and becomes crucial when steel columns exposes to fire. Therefore if the structure designed upon the assumption of room temperature has enough resistance in fire will be a lesson needed more attention.

In previous researches (Skowroński 1993, Zeng *et al*. 2003, Huang *et al*. 2006, Li and Zhang 2012), the importance of creep effect has been highlighted. They proposed that the critical temperature and the fire resistance of steel columns would be overestimated if the creep effect was not taken into consideration after temperature reaches 400°C. Though the effect of thermal creep to the fire performance of steel columns has been recognized, few related studies (Furumura *et al*. 1986) have been done to evaluate the factors of the thermal creep. Most of previous researches were focus on the fire performance of steel columns heated based upon the standard

*Corresponding author, Ph.D., E-mail: kcyang@nkfust.edu.tw
[a] Graduate Student

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temperature-time relationship (Valente and Neves 1999, Franssen 2000, Ali and O'Connor 2001, Neves *et al*. 2002, Wang and Davies 2003, Wong 2005, Tan *et al*. 2007, Li *et al*. 2009, Correia and Rodrigues 2012). Under the fire of standard temperature-time relationship, the temperature increases rapidly so the temperature of the columns cannot be uniformly distributed. Therefore, it is difficult to identify whether the thermal creep, deteriorated material properties or applied loads induced the failure of column.

Creep is a phenomenon of the progressive deformation of a structure under a constant sustaining load at specified temperature. To evaluate the thermal creep effect, it will be more rational to examine the creep behavior of steel columns under uniform temperature. The creep buckling of steel columns under uniform temperature has been examined by Furumura *et al*. (1986) with varied eccentricities and load ratios from temperature 425°C to 550°C. In their study, it was found that creep strain is greatly enlarged by larger eccentricity, higher load and higher temperature. The buckling time of steel column due to thermal creep was observed to be dominated by the steadily increased strain rate in the secondary creep stage. In Furumura's studies, the modified creep strain curves derived from steel material (Fujimoto *et. al*. 1981) were used to calculate the creep buckling time of steel columns but the calculated values are scattering to the experimental results.

This study is therefore focus on the bucking behavior of centrally loaded Fire-resistant steel columns with various slenderness ratios of 29, 40, and 50 under a specified temperature level up to six hours. The objective is to establish a creep strain rate curve based upon the test results to calculate the buckling time. The parameters affecting the creep buckling behavior of steel columns at elevated temperature are determined first to build up the relation of the creep strain rate with the load ratios of temperature for steel column.

2. Material properties of steel at elevated temperature

The material of SN490FR used in this study is a newly developed structural steel. SN490FR could retain at least 2/3 of its nominal room temperature yielding strength at 600°C (Sakumoto *et. al*. 1994) while the conventional steel reduces to 2/3 of its room temperature strength at about 350°C. The Fire-resistant steel SN490FR is able to retain 232 MPa at 600°C (Table 1). The yielding strength of SN490FR steel keeps more than 80% of the values at 500°C. The strength decreases to approximately 2/3 of the room temperature strength if the temperature exceeds 600°C. The values listed in Table 1 are the average yielding strength derived from two tensile coupons of the steady-state test.

Table 1 Mechanical properties of SN490FR steel used in this study

Temperature (°C)	Room temperature	100	200	300	400	500	600	700
Yield strength (MPa)	397	392	390	346	318	310	232	135
Young's Modulus (GPa)	206	208	192	166	157	155	112	86

3. Experimental study of column specimens under fire loads

3.1 Test setup and loading sequence

An overview of the test setup is shown in Fig. 1. To minimize the second order effect on column strength, the column specimens were carefully fabricated to fulfill the maximum initial crookedness less than 1/1000 of the length (LSD 1999). Both ends of the column were milled to ensure the flatness of the loading surface. In addition, the dial gages were instrumented longitudinally to ensure the load was centrally applied and to calculate the axial displacement of the specimens under axial load.

To investigate the creep behavior of the columns at elevated temperature, a constant compressive load was applied to the column specimens and then the specimens were heated to the specified temperature at 500°C or 600°C. Temperature of 600°C is the target temperature in developing Fire-resistant steel. The constant load is to simulate the sustained service load carried by steel columns. The loading sequence, strain and temperature distribution of columns were recorded as a function of time shown in Figs. 2(a)-(c). During the heating process, the column was

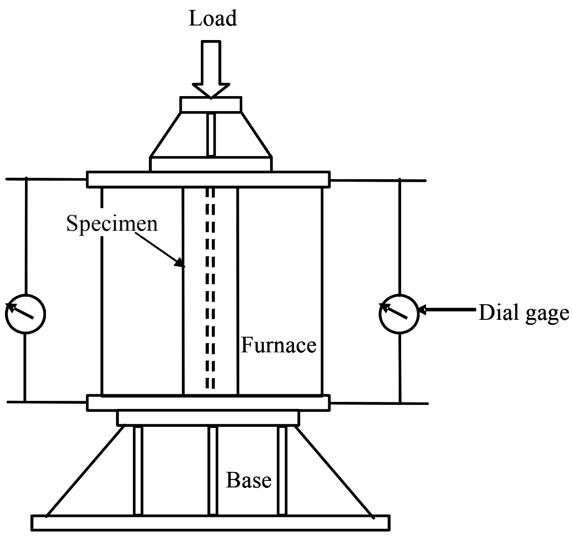
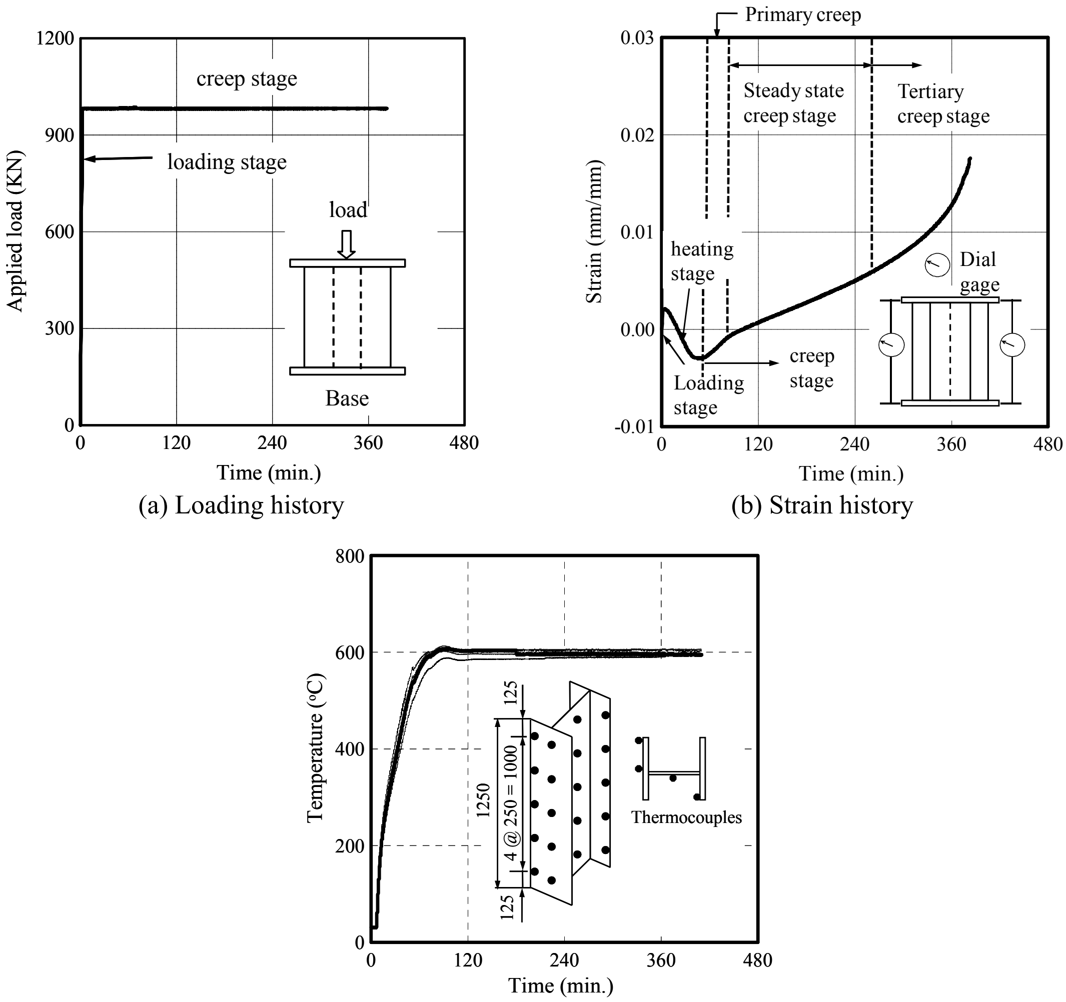


Fig. 1 Test setup

Table 2 Ultimate strengths of SN490FR steel columns at room temperature and at elevated temperature (Yang *et al*. 2006)

Dimensions of column	L/r	Ultimate strength		
		Room temp. ($P_{u,RT}$)	500°C ($P_{u,500}$)	600°C ($P_{u,600}$)
H 180 × 180 × 12 × 12	29	2851	2362	1470
H 130 × 130 × 12 × 12	40	1960	1607	1068
H 100 × 100 × 12 × 12	50	1372	1095	794



(a) Loading history

(b) Strain history

(c) Temperature history

Fig. 2 Typical loading sequence

free to extend without inducing thermal force to ensure the column was under the selected constant load so that the enlarged deformation would be from creep effect only. Then the temperature was hold at the specified value till failure occurred or after six hours under the specified temperature. This is to exclude the effect from the deterioration of material properties due to various temperatures. To monitor the temperature distribution of the column specimens and to ensure the temperature remains steadily after reaching the desired level, the thermocouples were installed on each specimen, following BS476 regulation (BS476-20 1987). The recorded data illustrated in Fig. 2(c) shows the close correlation between the temperature of the furnace and the columns.

4. Discussion of experimental results

Table 3 Primary parameters and experimental results

Specimen No.	Test temperature	Applied load (KN)	Load ratio *LR*	Load ratio of temperature *LR*(*T*)	Average creep strain rate in steady state stage (mm/mm/hrs)	Total time to failure (min)
H2946	600°C	1137	0.4	0.77	3.10E-04	> 360
H2956	600°C	1421	0.5	0.97	1.89E-02	110
H2955	500°C	1421	0.5	0.60	2.16E-05	> 360
H2985	500°C	2274	0.8	0.96	4.54E-03	225
H4056	600°C	980	0.5	0.92	3.05E-03	384
H5036	600°C	412	0.3	0.52	3.29E-05	> 360
H5046	600°C	549	0.4	0.69	1.36E-04	> 360
H5056	600°C	686	0.5	0.86	2.39E-03	393

An experimental study of thermal creep performance is conducted on eight column specimens. ix loaded column specimens under uniform temperature 600°C and two at 500°C were tested. The creep characteristics of column specimens in fire condition are examined based on the strain curve versus testing time shown in Figs. 3-6. Under a sustained load and uniform temperature, the creep deformation of steel column increases gradually in the steady-state stage then enlarges sharply in the beginning of tertiary stage which leads to an unstable buckling. Therefore the fire resistance is highly related to the strain rate in the primary and the steady state stage.

The test results indicate the thermal creep can be evaluated by the following four factors, load ratio *LR*, temperature *T*, steady-state creep rate, and column strength. In this study, the effects of these four factors on thermal creep are examined separately as discussed in the following sections. A single parameter *LR*(*T*) is proposed at the end to cover these four factors in order to consider the creep effect to steel column at elevated temperature.

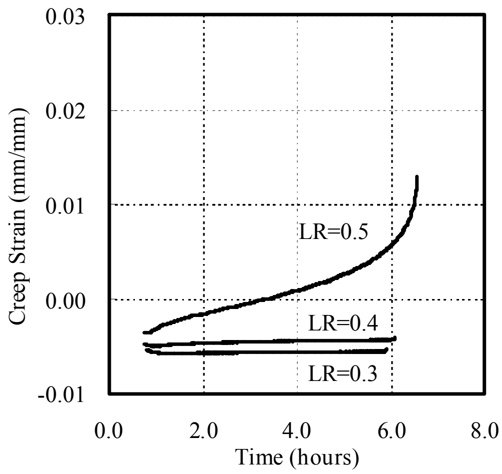


Fig. 3 Effect of load ratios on buckling behavior of specimens with column slenderness of 50 at 600°C

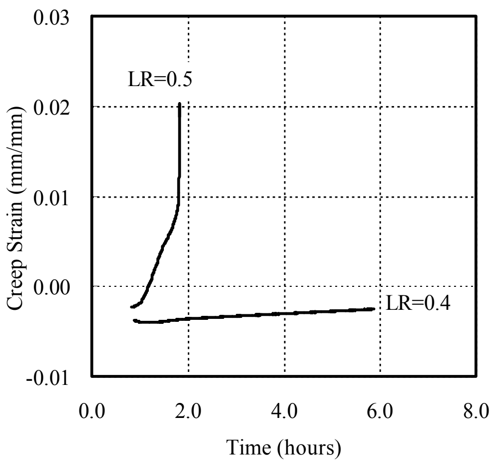


Fig. 4 Effect of load ratios on buckling behavior of specimens with column slenderness of 29 at 600°C

4.1 Effect of load ratio, LR, for columns loaded at 600°C

Three specimens (Specimen Nos. H5036, H5046, H5056) with the same slenderness ratio (L/r) of 50 were loaded at 600°C under load ratios of 0.3, 0.4 and 0.5 (Fig. 3). These three specimens were designed to examine the effect of the load ratio on the creep behavior of Fire-resistant steel columns at temperature level of 600°C. As shown in Fig. 3, the average creep strain is enlarged and the fire resistance is degraded under a higher load ratio of 0.5. In the case of the load ratio 0.5, the column specimen buckles at the ultimate strain of 0.01 in six hours and the strain rate is derived as 2.39E-03 (mm/mm/hrs.) in the steady-state stage. When the load ratios are 0.3 or 0.4, the specimens are able to remain stable for more than six hours with the calculated strain rate of 3.29E-05 and 1.36E-04 (mm/mm/hrs.) in the steady-state stage, respectively. The calculated strain rates of column specimens in the stage of steady-state are listed in Table 3. It is observed from tests that the creep effect is not significant for columns with a slenderness ratio of 50 when the load ratio is less than 0.4 at 600°C.

Another two specimens (Specimen Nos. H2946, H2956) with a slenderness ratio of 29 are also tested at 600°C under the load ratios of 0.4 and 0.5. Similar results are observed for columns of slenderness ratio 29 tested at 600°C. That is, the creep effect is insignificant for the load ratio 0.4; but, buckling occurs on steel columns of the load ratio 0.5. As shown in Fig. 4, the steel column of load ratio 0.4 retains its load-carrying capacity more than six hours with a strain rate of 3.10E-04 (mm/mm/hrs.). But the creep deformation is greatly enlarged with a creep strain rate of 1.89E-02 (mm/mm/hrs.) for the load ratio 0.5. Steel column of load ratio 0.5 fails due to sharply increased creep strain within two hours. The test results confirm the higher of the applied load the larger of the creep strain rate and the weakest of the fire resistance.

Based on the above data, when the load ratio for columns with slenderness ratios of 29 and 50 at 600°C is less than 0.4 the thermal creep is not significant. Four hours fire resistance difference is noted between the columns of slenderness ratio of 29 and 50, even they are under the same load ratio of 0.5. Therefore the slenderness will be under further study in the following paragraph.

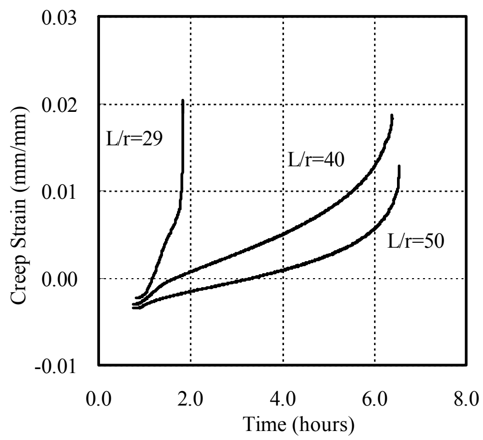


Fig. 5 Effect of column slenderness on buckling behavior of specimens under load ratio of 0.5 at 600°C

4.2 Effect of slenderness ratio for columns loaded at 600°C

The effect of column slenderness on creep buckling at elevated temperature is investigated from the columns with various slenderness ratios under identical load ratio of 0.5 and temperature level of 600°°C. Fig. 5 illustrates the creep performance of three specimens with slenderness ratios of 29, 40, and 50 (Specimen Nos. H2956, H4056, H5056). It is observed that the column with larger slenderness ratios of 40 and 50 possess higher creep resistance. Steel column having the smallest slenderness ratio of 29 failed in two hours at a sharply increased creep strain of 1.89E-02 (mm/mm/hrs.). The columns with higher slenderness ratios of 40 and 50 failed at a steadily increased creep strain of 3.05E-03 and 2.39E-03 (mm/mm/hrs.) after exposed to approximately five-hour fire. The strain rate of the column with slenderness ratio 29 is more than five times of that with slenderness ratios of 40 and 50 (Table 3). In the other words, the fire resistance against thermal creep is more critical for columns with smaller slenderness ratios.

At elevated temperature, the columns of slenderness ratio of 29 fail for local buckling; while, the slenderness ratio 50 fails for global buckling. It shows different failure modes might result in the difference of the fire resistance.

In the traditional steel design, a column with smaller slenderness ratio is preferred because its strength is higher at room temperature. Based on the results of this study, the resistance against thermal creep is lower for the columns with smaller slenderness ratio so special attention is recommended for the columns with smaller slenderness ratios when the fire safety is concerned.

4.3 Effect of temperature

The effect of temperature is examined by applying a load ratio of 0.5 on two identical specimens with the slenderness ratio 29 at temperature of 500°C and 600°C (Specimen Nos. H2955, H2956). The strain history of these two specimens is shown in Fig. 6. The behavior of the third identical specimen under a load ratio of 0.8 at temperature of 500°C is also shown in Fig. 6. With the same slenderness ratio 29, both the specimen of load ratio 0.5 under temperature 600°C and the load ratio 0.8 under temperature 500°C fail in two hours. Under the load ratio 0.5, the

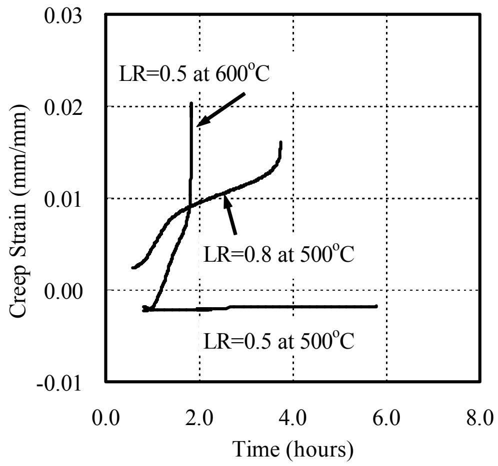


Fig. 6 Effect of temperature and load ratios on buckling behavior of specimens with column slenderness of 29

specimen at 500°C remains stable over six hours while the specimen at 600°C fails within two hours. Different creep behavior was observed from the specimens of the load ratio 0.5 because the column retained higher strength at 500°C than column at 600°C. The reduction of column strength results in an increasing of the creep strain rate from 2.16E-05 (mm/mm/hrs.) of 500°C to 1.89E-02 (mm/mm/hrs.) of 600°C. In short, for columns having the same slenderness ratio under the same load ratio, the effect of thermal creep is more severe when columns were loaded at higher temperature.

4.4 Load ratio and creep strain rate

Based on the experimental results discussed above, it is found that creep behavior of steel column depends on load ratio (*LR*), column slenderness (L/r), and temperature. Creep resistant is more severe for column with smaller slenderness ratio and under higher load ratio and temperature. A normalized load ratio of temperature, *LR*(*T*) combining the effects of applied load, temperature and column slenderness is introduced herein to evaluate the creep effect of steel column at elevated temperature. Different from previous load ratio, *LR* representing the applied load to the column strength at room temperature, the load ratio of temperature *LR*(*T*) here is the applied load to the ultimate strength of steel column at elevated temperature.

As listed in Table 3, Fire-resistant steel columns are able to sustain the load ratio of temperature, *LR*(*T*), of 0.96 at 500°C for more than three hours. Creep buckling occurred within two hours with an sharply increasing creep strain rate when *LR*(*T*) is larger than 0.97. The buckling time of steel column due to thermal creep can extend to more than six hours for *LR*(*T*) less than 0.77. Therefore this study shows when *LR*(*T*) is less than 0.77, the creep strain is insignificant and creep deformation can be neglected in design.

From the creep behavior of steel columns (Figs. 3-6), it is also found that the buckling time due to creep is highly related to the creep strain rate in the secondary creep stage. Based on the experimental results of this study, a simple creep model is proposed by expressing the creep strain

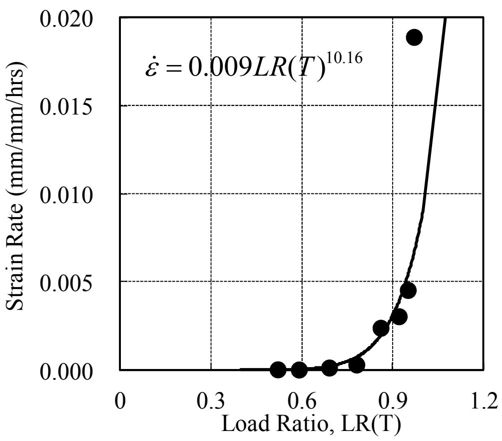


Fig. 7 Comparison of proposed creep model and the experimental results

rate as a function of the load ratio of temperature $LR(T)$ as follow

$$\dot{\varepsilon} = 0.009LR(T)^{10.16} \qquad (1)$$

where $\dot{\varepsilon}$ is the average strain rate in the secondary creep stage. In Fig. 7, the creep strain rate curve matches the experimental results with a coefficient of determination of 0.91.

5. Conclusions

The creep buckling behavior of columns made of SN490FR steel were examined by conducting the creep test in fire up to six hours. Based on this study, the creep behavior of SN490FR steel columns is sensitive to the applied load, the temperature, and the column slenderness. The buckling time against thermal creep is higher for columns with larger slenderness ratio or under smaller load ratio or lower temperature. A single parameter, $LR(T)$, is introduced to consider the combined effects of column slenderness, applied load and temperature. The buckling time of steel column due to creep would be more than six hours at 600°C when $LR(T)$ is less than 0.77. For the case of $LR(T)$ exceeds 0.77, the creep strain rate could be determined based on the proposed creep model in this study. Then the buckling time of steel columns due to thermal creep could be evaluated from the strain rate curve.

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Nomenclature

$\dot{\varepsilon}$	Strain rate;
$\varepsilon_{u,RT}$	Ultimate strain of steel columns at room temperature;
$\varepsilon_{u,500}$	Ultimate strain of steel columns at 500°C;
ε_{creep}	Creep strain;
ε_{i}	The strain induced by the service load;
ε_{th}	Thermal strain;
ε_{total}	Total strain;
ε_{u}	Ultimate strain;
L/r	Slenderness ratio;
LR	Load ratio; the applied load divided by the ultimate strength of steel columns at room temperature;
$LR(T)$	Load ratio of temperature; the applied load divided by the ultimate strength of steel columns at elevated temperature;
P_y	Yield strength of steel columns at room temperature;
$P_{u,RT}$	Ultimate strength of steel columns at room temperature;
$P_{u,500}$	Ultimate strength of steel columns at 500°C ;
$P_{u,600}$	Ultimate strength of steel columns at 600°C.