CAPACITY REDUCTION AND FIRE LOAD FACTORS FOR STEEL COLUMNS EXPOSED TO FIRE

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Keywords: Reliability-Based Design, Steel Columns, Fire Design, Safety Factors

Abstract. *Capacity reduction and fire load factors are developed for load and resistance factor design of axially loaded steel column exposed to fire. Fire load, opening factor, ratio of floor area to the total area of compartment boundaries, thermal inertia of compartment boundaries, thickness, density and thermal conductivity of insulation, yield strength and modulus of elasticity of steel, cross-sectional area and radius of gyration of steel, dead load, and live load are taken as random variables. The chosen statistics of the live load, fire load and ratio of floor area to the total area of compartment boundaries are representative of typical office buildings in the U.S. The effect of active fire protection systems such as sprinklers in reducing the probability of occurrence of a severe fire is accounted for. It is found that the capacity reduction and fire load factors are not constant for all design situations as suggested in design specifications, and vary depending on the presence of active fire protection systems in a building.*

1 INTRODUCTION

Until recently, steel columns exposed to fire were designed using prescriptive approaches that do not account for actual loading conditions and real fire scenarios. Performance-based codes which allow more rational engineering approaches for the fire design of steel members are being promoted. For example, Appendix 4 of the 2005 AISC Specifications (referred to hereafter as "AISC Specifications") [1] now allows steel columns to be designed against fire using room temperature design specifications and reduced material properties. The AISC Specifications [1] suggest using a capacity reduction factor ϕ_f = 0.9 for fire design. Most other codes suggest that a capacity reduction factor of 1.0 be used (e.g., in the Eurocode 3 [2], the partial safety factor is 1.0 for fire design). The Commentary to the AISC Specifications [3] states that the fire load should be reduced by up to 60%, if a reliable automatic sprinkler system is installed in the building. However, no substantial work has been done to develop capacity reduction and fire load factors based on rigorous reliability analysis. The companion paper by Iqbal and Harichandran [4] describes a general methodology for reliability-based design of steel members exposed to fire. This paper presents specific capacity reduction and fire load factors for load and resistance factor design (LRFD) of axially loaded steel columns exposed to fire.

2 APPROACH FOR DESIGN OF STEEL COLUMNS EXPOSED TO FIRE

In the AISC specifications [1], the required axial capacity for fire design is determined from the load combination given by

$$P_u = 1.2P_D + 0.5P_L + 0.2P_S + P_T \qquad (1)$$

where P_D,P_L and P_S are nominal dead, live and snow loads, respectively, and P_T includes loads induced by the fire itself, especially due to restraint from the surrounding structures preventing thermal expansion.

Takagi and Deierlein [5] compared the AISC and Eurocode 3 design specifications with finite element simulations for columns exposed to fire. They reported that the AISC Specifications are unconservative at elevated temperatures, particularly for slenderness ratios between 40 and 100 and temperatures above 500°C. For instance, at 500°C the nominal strengths predicted by the AISC specifications are up to 60% larger than strengths predicted by simulations. On the other hand, the Eurocode 3 column strength equations were within 20% of the simulated results. We used the equations proposed by Takagi and Deierlein [5] in this study, which have a format similar to those in the AISC Specifications and predict strengths similar to the Eurocode 3 [3] columns strength equations (see figure 6 of reference [5]):

$$P_{n,f} = \{0.42^{\sqrt{\frac{k_y(T_s)F_y}{F_e(T_s)}}}\} A_s k_y(T_s) F_y \tag{2}$$

where

$$F_e(T_s) = \frac{\pi^2 k_E(T_s) E_s}{\left(\frac{KL}{r}\right)^2} \tag{3}$$

$P_{n,f}$ = nominal axial capacity of column under fire, A_s = cross-sectional area, KL = effective length, r = radius of gyration about the buckling axis, $k_y(T_s)F_y$ = reduced yield strength, $k_E(T_s)E_s$ = reduced elastic modulus, and F_y and E_s are the yield strength and elastic modulus of steel at room temperature, respectively. $k_y(T_s)$ and $k_E(T_s)$ are the yield strength and elastic modulus reduction factors, respectively, and their values at different temperatures are given in the AISC Specifications and Eurocode 3.

From equations (2) and (3) it is obvious that the capacity of steel columns at elevated temperatures depends on the steel temperature, T_s, that can be estimated as described in the companion paper by Iqbal and Harichandran [4].

3 DEVELOPMENT OF CAPACITY REDUCTION AND FIRE LOAD FACTORS

3.1 Statistics of random parameters

The statistics (mean, coefficient of variation, and the distribution type) of fire parameters that significantly affect the fire design of steel columns are provided in the companion paper by Iqbal and Harichandran [4]. The other parameters that affect the design of steel columns are the same as those used for developing LRFD specifications for ambient temperature conditions and their statistics are given in table 1. The statistics of all the parameters in table 1 were reported by Schmidt and Bartlett [6], and the distributions were assumed to be normal.

Table 1: Mean and COV of room temperature design parameters

	Characterizes variation in	Mean	COV
m_1	Yield strength, F_y	1.03*nominal	0.063
m_2	Modulus of elasticity, E_s	1.04*nominal	0.045
f_1	Cross-sectional area , A_s	1.03*nominal	0.031
f_2	Radius of gyration, r_y	1.00*nominal	0.016

3.2 Performance function for reliability analysis

The applied axial load, W_f, for the reliability analysis of steel columns exposed to fire can be determined as described in the companion paper by Iqbal and Harichandran [4].

The actual capacity of steel columns under fire can be obtained by modifying the nominal capacity given in equations (2) and (3) to

$$P_f = P\{0.42^{\sqrt{\frac{k_y(t_sT_s)m_1F_y}{F_e(T_s)}}}\} f_1 A_s k_y(t_sT_s) m_1 F_y \quad (4)$$

$$F_e(T_s) = \frac{\pi^2 k_E(t_sT_s)m_2E_s}{\left(\frac{KL}{f_2 r}\right)^2} \quad (5)$$

where P, f_i, m_i, and t_s are non-dimensional random variables as defined in the companion paper by Iqbal and Harichandran [4]. The statistics of f_i and m_i are given in table 2 and that of t_s were reported in the companion paper by Iqbal and Harichandran [4]. The statistics of P are described in the next sub-section.

The limit state equation for reliability analysis under fire conditions may be written as

$$g(\mathbf{X}) = P_f - W_f \quad (6)$$

where $\boldsymbol{X}$ denotes a vector containing all the random design parameters. The probability of failure, p_F , of a steel column under fire is $p_F = P[g(\boldsymbol{X}) < 0]$.

3.3 Professional factor (model error) for axial capacity of columns

To account for differences between axial capacity of columns measured in the laboratory and that predicted by equation (2), the professional factor, P, was characterized using the test results presented by Janss and Minne [7] and Franssen et al. [8]. Janss and Minne [7] reported results for eighteen columns with slenderness ratio between 25 and 102 for which the yield strength was measured. Franssen et al. [8] reported test results for twenty one fire tests with slenderness ratio between 20 and 140. The nominal capacity of these tested columns was calculated using equations (2) and (3). P (ratio of measured axial capacity to nominal capacity) has a mean of 1.10 and a COV of 0.18, and is best described by the normal distribution.

4 RELIABILITY ANALYSES

Twenty steel columns with slenderness ratios ranging from 25 to 200 and axial load capacities ranging from 133 kN (30 kips) to 10,675 kN (2400 kips) were selected for the reliability study. Columns with smaller capacity are representative of those in upper stories and those with higher capacity are representative of those in lower stories of typical office buildings. Live to dead load ratios ranging from 0.5 to 5.0 were considered. The AISC design specifications were used to first design the columns for ambient temperature conditions. The same columns were then designed for fire exposure using the engineering approach described in section 2 and the required thickness of insulation was determined. As suggested in most codes, a capacity reduction factor of 1.0 was used to design for fire. The columns were assumed to be protected by gypsum board insulation, which is generally the case in the U.S. Load ratios (ratio of applied load under fire to room temperature nominal capacity) ranging from 0.35 to 0.66 were considered.

The FERUM (Finite Element Reliability Using Matlab) software [9] was used to perform the reliability analysis. FERUM is a general purpose structural reliability software written using Matlab. It can be used to perform reliability analysis using different methods, including the first order reliability method (FORM). The output for FORM analysis for a particular design situation includes the reliability index, the probability of failure, the values of all design parameters at the failure/design point, and the direction cosines of the design point for each design parameter.

FORM analysis was performed for each design situation (each of the 20 columns) using the performance function given in equation (6). Using the direction cosines obtained from the reliability analysis, the partial safety factors, ϕ_i, for each design parameter were obtained as described in the companion paper by Iqbal and Harichandran [4]. These individual partial safety factors, except for the fire load, were then combined into a single capacity reduction factor through

$$\phi_f = \frac{\left\{0.42^{\sqrt{\frac{k_y(\phi_1 T_s)\phi_2 F_y}{F_{e\phi}(T_s)}}}\right\}\phi_3 A_s k_y(\phi_1 T_s)\phi_2 F_y}{P_{n,f}} \tag{7}$$

where

$$F_{e\phi}(T_s) = \frac{\pi^2 k_E(\phi_1 T_s)\phi_4 E_s}{\left(\frac{KL}{\phi_5 r}\right)^2} \tag{8}$$

where, ϕ_i are the partial safety factors for each design parameter. Thus, 20 different capacity reduction factors (one for each column) were obtained. Thereafter, a single optimized capacity reduction factor was obtained using the optimization procedure described in the companion paper by Iqbal and Harichandran [4]. Since the capacity reduction factors were obtained for target reliability index (β_t) values, ranging from 0 to 2, this procedure was repeated for each β_t. A similar procedure was used to obtain the fire load factors corresponding to each value of β_t.

4 RESULTS

4.1 Capacity reduction and fire load factors

The plot of the optimized capacity reduction factor, ϕ_f, vs. β_t is shown in figure 1. The value of ϕ_f is given by

$$\phi_f = \begin{cases} 1.0 & \text{for} \quad \beta_t \le 1.25 \\ 1.25 - 0.2\beta_t & \text{for} \quad 1.25 \le \beta_t \le 2.0 \end{cases} \tag{9}$$

Most codes suggest that $\phi_f = 1.0$ be used (e.g., in the Eurocode 3, the partial safety factor γ_M is 1.0 for fire design). The AISC specifications [1] use $\phi_f = 0.9$ for fire design of steel columns. Results obtained in this study indicate that the nominal capacity need not be reduced (i.e. $\phi_f = 1.0$) if β_t is less than 1.25, which in turns depends on the effectiveness of active fire protection systems in reducing the probability of occurrence of a severe fire. Since most office buildings in the U.S. are required to have automatic sprinklers, β_t is not likely to exceed 1.25. Therefore, using $\phi_f = 1.0$ is reasonable for most design situations.

The plot of the fire load factor, γ_q, vs. β_t is also shown in figure 1. The nominal value of the fire load was taken as the 90th percentile [10]. The value of γ_q is given by

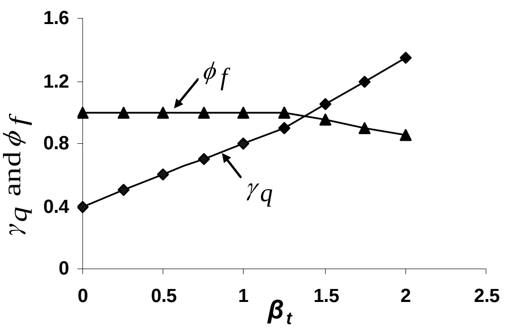

Figure 1: Capacity reduction and fire load factors vs. target reliability index

$$\gamma_q = \begin{cases} 0.4 + 0.4\beta_t & \text{for} \quad \beta_t \le 1.25 \\ 0.15 + 0.6\beta_t & \text{for} \quad 1.25 \le \beta_t \le 2.0 \end{cases} \tag{10}$$

When β_t is less than 1.42, γ_q given by equation (10) is less than 1.0 indicating that the fire load can be reduced as suggested in the Commentary to the AISC Specifications [2] and the ECSC study [11].

4.2 Validity of capacity reduction and fire load factors for multiple fire scenarios

The capacity reduction and fire load factors shown in figure 1 were developed for a fire compartment assumed to be constructed of lightweight concrete blocks having a thermal absorptivity, b = 640 $Ws^{0.5}/m^2K$, and having an opening factor, F_v = 0.02 $m^{1/2}$.

In reality, the compartments may be constructed using different bounding materials such as gypsum board, lightweight concrete blocks, etc., having different values of b. Kirby et al. [12] studied the equivalency between standard and realistic fire scenarios by carrying out nine real fire tests. Different types and combinations of lining materials were used as bounding material in these tests, and the value of b ranged from 350-755 $Ws^{0.5}/m^2K$. The statistics of b shown in table 1 in the companion paper by Iqbal and Harichandran [4] effectively cover the range of b values used by Kirby et al. [12], and values of 423, 640 and 1127 $Ws^{0.5}/m^2K$ were used in this study to obtain multiple fire scenarios. Similarly, the ventilation conditions in different compartments may vary considerably. Opening factors of 0.04 $m^{1/2}$, 0.08 $m^{1/2}$ and 0.12 $m^{1/2}$ are typical low, medium and high values in actual building compartments [13] and were used in this study to obtain multiple fire scenarios.

Nine fire scenarios obtained from different combinations of the three opening factors and the three thermal absorptivity values were selected for validating the capacity reduction and fire load factors derived above. For these nine fire scenarios, five columns were designed for fire conditions using the capacity reduction and fire load factors shown in figure 1. The steel sections used for these columns, and their room and elevated temperature capacities are given in table 2. For all columns, a live to dead load ratio of 2.0 was assumed. Each column was designed for β_t values of 0, 0.5, 1.0, 1.5 and 2.0 for all nine fire scenarios. Thus, for each β_t value we had 45 design situations yielding a total of 225 design situations. Reliability analysis was then performed and the computed reliability index values, β, for all five columns are compared with the β_t values in figure 2.

The β values compare quite well with the β_t values, indicating that the derived capacity reduction and fire load factors work well for all design situations considered. The β values are conservative for β_t values less than about 1.5. For β_t values less than 1.5 (see figure 1), the ϕ_f found from reliability analysis was greater than 1.0, and the nominal capacity could be increased. However, since ϕ_f is generally always taken to be less than or equal to 1.0 in LRFD specifications, we restrained the ϕ_f for fire design to also not exceed 1.0. Because of this inherent conservatism, the β values are higher than the β_t values.

Table 2: Properties of columns used for validation

Parameter	W10x19	W10x30	W18x65	W14x90	W12x190
H (m)	3.66	3.66	3.66	3.66	3.66
P_n (KN)	231	876	2497	5276	10751
$P_{n,f}$ (KN)	104	394	1124	2375	4837
Load ratio	0.45	0.45	0.45	0.45	0.45

Note: H is the height of column, and P_n and $P_{n,f}$ are nominal capacities at room temperature and under fire, respectively.

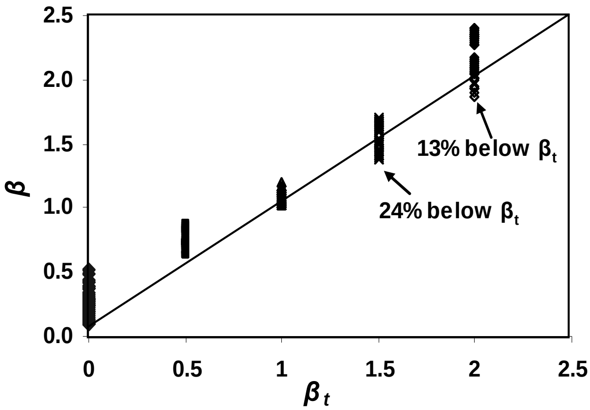

Figure 2: Computed and target reliability index values for different fire scenarios

5 CONCLUSION

Capacity reduction and fire load factors are developed for steel columns in U.S. office buildings exposed to fire. The effect of active fire protection systems (e.g., sprinklers, smoke and heat detectors, fire brigade, etc.) in reducing the probability of occurrence of a severe fire is included by adjusting the target reliability index appropriately.

From detailed reliability analyses, it is found that the capacity reduction and fire load factors should not be constant for all design situations as suggested in design specifications, but should vary depending on the presence of active fire protection systems in a building and the compartment size.

As suggested in the AISC Specifications and Eurocode provisions, the fire load factor should be reduced for typical fire compartment sizes when active fire protection systems are present.

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