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BY

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LA RESISTANCE AU FEU DES POUTRES D'ACIER NON PROTEGEES

SOMMAIRE

Les auteurs étudient la résistance au feu des poutres d'acier non protégées au moyen d'essais d'incendie standards et de l'analyse numérique. On a découvert que la durée de la résistance au feu varie selon le facteur forme du poids de la poutre divisé par le périmètre chauffé. Les auteurs ont établi deux équations simples pour calculer les durées de résistance au feu des poutres d'acier non protégées et ils recommandent de les utiliser dans les normes du bâtiment.

JOURNAL OF THE STRUCTURAL DIVISION

FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

By W. W. Stanzak[1] and T. T. Lie[2]

In the past the fire resistance of unprotected steel columns has been considered so small a quantity that it could be ignored. Fire experience and controlled fire tests on structural steel columns of small cross-sectional area showed that unprotected steel columns could not survive the effects of fire exposure for more than 10 min to 20 min. However, it will now be shown that the heavier columns required to carry the vertical loads in modern high-rise buildings are capable of much better fire performance than had previously been realized, and that some can attain fire resistance classifications of 1 hr or better.

Fire fatality statistics (1) show that the number of deaths attributable to structural collapse during a building fire is negligible. The main causes of life loss have been shown to be asphyxiation and burns (1,3,7). Therefore, to provide life safety to occupants, enough fire resistance to allow people time to escape must be provided. Except where escape routes are extremely long or the number of occupants is very large, 10 min to 20 min is usually assumed to be sufficient. However, with very tall buildings it has become evident that evacuation by stairs can be so time consuming that complete evacuation is impractical (4). In such buildings sufficient fire resistance to withstand a burnout of the contents must be provided.

Provision of fire resistance beyond that required to prevent life loss is determined largely be economic considerations. A recent study on the optimum fire resistance of structures (11) has shown that for buildings with a small-loss poten-

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tial it would be uneconomical to provide any fire protection beyond that inherent in the structure, provided such fire resistance is sufficient to allow evacuation by the occupants. Buildings representing a small-loss expectation are those that are small in size and not valuable; those with no valuable contents; those for which the probability of a serious fire is low (e.g., completely sprinklered buildings); or those having a low fire load. The use of unprotected steel columns in such buildings is generally justified if these elements have the minimal fire resistance required to prevent loss of life.

Accordingly, the writers have investigated the fire resistance of unprotected steel columns by methods of numerical calculation and by full-scale fire tests in their laboratory, with a view to developing simple expressions for calculating the fire resistance of these building elements.

Test Methods and Critical Temperature

On this continent, two test methods are acceptable. The most recent ASTM Standard prescribing these is E119-71 (16).

The older load test requires a sample at least 9 ft in length to be tested under an applied load calculated to develop theoretical working stresses contemplated by the design. The column is required to sustain the applied load for a period of fire exposure equal to that for which classification is desired.

The newer alternate test of protection for structural steel columns requires that a sample at least 8 ft in length be tested in a vertical position without applied load. This test is applicable when the protection is not required by design to carry any part of the column load. The applied protection must be restrained against longitudinal thermal expansion greater than that of the steel column. Temperatures are measured by at least three thermocouples located at each of four levels (cross sections). The upper and lower levels are 2 ft from the ends of the steel column, and the two intermediate levels are equally spaced. The test is considered successful if the transmission of heat through the protection, during the period of fire exposure for which classification is desired, does not raise the average (arithmetical) temperature of the steel to any level above 1,000° F (538° C), or above 1,200° F (649° C) at any one of the measured points.

The 1,000° F average allowable temperature that usually determines the fire endurance time in a test may be regarded as a critical temperature for structural failure established for protected columns as a result of many fire tests on axially loaded column sections. Thus, for the analysis in this paper, it has been assumed that structural failure is imminent when the steel cross section attains an average temperature of 1,000° F as all calculations and fire tests were made on the basis of heat conduction alone.

While complete theoretical justification for the use of temperature criteria is beyond the scope of this paper, it can readily be shown that 1,000° F is a reasonable value. For long columns, assuming that the member is uniformly heated, the buckling stress is given by Euler's formula:

$$\sigma_{cr} = \frac{\pi^2 E_T}{\lambda^2} \quad (1)$$

and the allowable design stress for long columns is given by CSA S16-1969 (17) as:

$$\sigma_a = \frac{\pi^2 E_o}{1.92 \lambda^2} \quad (2)$$

in which 1.92 is a safety factor prescribed by the Code and $\sqrt{286{,}000}/(\sigma_y = 13) < \lambda \leq 200$.

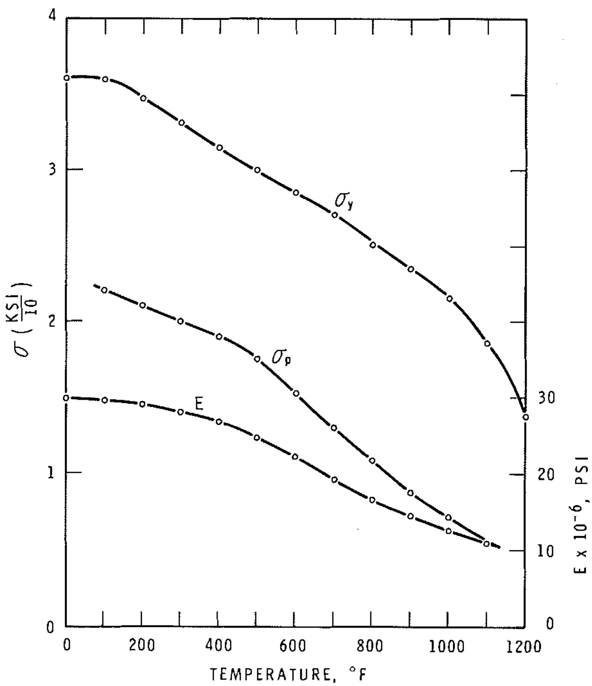


FIG. 1.—Average Compressive Properties of ASTM A36 Structural Steel

At elevated temperatures failure is due to occur when the left-hand sides of the equations are equal, i.e.:

$$E_T = \frac{E_o}{1.92} \quad (3)$$

Accepting the commonly assumed value for carbon steels of $E_o = 29 \times 10^3$ ksi, then

$$E_T = 15.1 \times 10^3 \text{ ksi } (104 \times 10^9 \text{ N/m}^2) \quad (4)$$

Using Fig. 1, based on data reported by Ingberg and Sale (10), it is found that the temperature at buckling is approximately 880° F (471° C). Fire tests of loaded columns (9) have shown that the point of maximum expansion (approximately the point at which the column buckles) is followed by a further 100° F–150°

F (55° C-83° C) rise in temperature before complete failure of the column occurs. Thus failure of columns can be expected at cross-sectional temperatures of from 950° F-1,050° F, (510° C-565° C), depending on the design method and slenderness ratio. A value of 1,000° F has been assumed as a reasonable average for any column, as has been indicated by the ASTM fire test standard.

Temperature Rise in Unprotected Steel Columns

The column is exposed on four sides to the heat of a fire that follows approximately the temperature-time course prescribed in *ASTM E119* for the standard fire of "controlled extent and severity." Heat is transferred from the flames in the furnace and from the furnace walls to the specimen by convection and radiation, with radiation as the primary mechanism when the flames have sufficient thickness (18). The coefficient of heat transfer (the quantity of heat received per unit area of the column, per unit time, and temperature difference between the column surface and fire) depends on many factors. The most significant are: emissivity of the flames; thickness of the flames between furnace walls and column; size of specimen; and thermal properties of the furnace walls. Experimental data (5) have indicated that the heat transfer to the specimen in test furnaces approximates the radiative heat transfer from a black body at the so-called "furnace temperature." Similar heat transfer may also be expected in most building fires because the flames are luminous and usually have considerable thickness, giving them a correspondingly high emissivity.

The coefficient of heat transfer can vary significantly, however, for different individual conditions, and the effect of varying this quantity will be examined later herein.

Calculation of Temperature Rise

Two-Dimensional Numerical Procedure.—To determine the temperature distribution in massive square steel columns, a number of calculations based on a two-dimensional procedure (12) were carried out. In these tests black body radiation at the prescribed furnace temperature was assumed as the only mechanism of heat transfer. The two equations used for the calculation are:

$$T^{j+1}_{1,n} = T^{j}_{1,n} + \frac{\Delta t}{(\rho c)^{j}_{1,n} (\Delta \xi)^2} \{[k^{j}_{2,(n-1)} + k^{j}_{1,n}] [T^{j}_{2,(n-1)} - T^{j}_{1,n}]$$
$$+ [k^{j}_{2,(n+1)} + k_{1,n}] [T^{j}_{2,(n+1)} - T^{j}_{1,n}] + 2\sqrt{2}\, \Delta \xi \, \sigma \, \epsilon_s \, [(T^{j}_{f})^4 - (T_{1,n})^4]\} \quad . . . (5)$$

for the temperature of an elementary surface element of the column, and

$$T^{j+1}_{m,n} = T^{j}_{m,n} + \frac{1}{2} \frac{\Delta t}{(\rho c)^{j}_{m,n} (\Delta \xi)^2} \{[k^{j}_{(m-1),(n-1)} + k^{j}_{m,n}] [T^{j}_{(m-1)(n-1)}$$
$$- T^{j}_{m,n}] + [k^{j}_{(m+1),(n-1)} + k^{j}_{m,n}] [T^{j}_{(m+1),(n-1)} - T^{j}_{m,n}] [k^{j}_{(m-1),(n+1)}$$
$$+ k^{j}_{m,n}] [T^{j}_{(m-1),(n+1)} - T^{j}_{m,n}] + [k^{j}_{(m+1),(n+1)} + k^{j}_{m,n}] [T^{j}_{(m+1),(n+1)} - T^{j}_{m,n}]\} \quad . . (6)$$

for the temperature at any point inside the steel cross section, in which T is expressed in degrees Rankine and t in hours. It should be noted that the term, ϵ_s, in Eq. 5 is, strictly speaking, a material and temperature dependent quantity, but it is sufficiently accurate, for the purpose of this study, to be regarded as a constant. Also, since most building materials have emissivities in the range of 0.85 to 0.95 (13) a value of 0.9 was used, although the results indicated that a value of 0.95 would have been more appropriate.

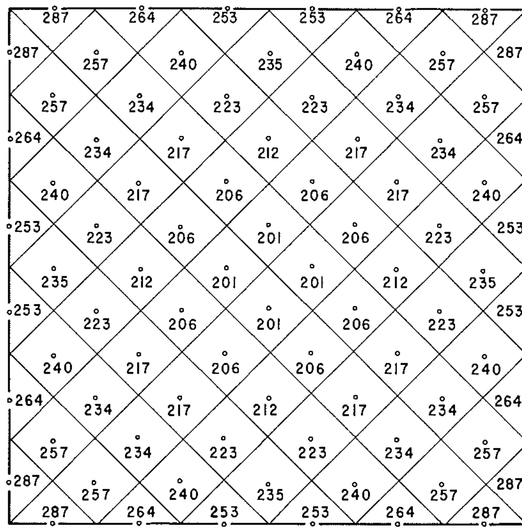
The dependence of the thermal properties of steel on temperature was taken into account in the calculations. The material properties used were derived

TABLE 1.—Thermal Properties of Steel

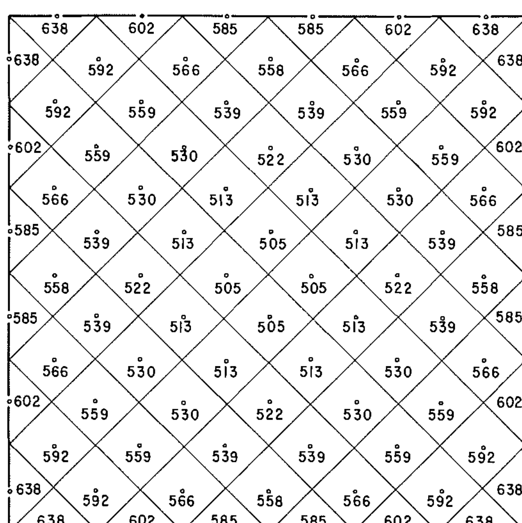
Temperature, in degrees Fahrenheit (1)	Volumetric heat capacity, in British thermal units per cubic foot-degrees Fahrenheit (2)	Thermal conductivity, in British thermal units per foot-hour-degrees Fahrenheit (3)
70	54.30	26.60
100	54.86	26.60
200	56.36	26.82
300	58.27	26.43
400	60.35	25.87
500	62.44	25.34
600	64.90	24.71
700	67.52	23.72
800	70.56	22.80
900	74.59	21.86
1,000	80.32	21.06
1,100	85.72	20.07
1,200	90.52	18.98
1,250	94.29	18.55
1,300	127.85	18.16
1,350	164.15	17.87
1,400	117.75	17.60
1,450	84.58	17.34
1,500	66.16	16.78
1,550	62.23	15.69
1,600	60.74	15.26
1,650	62.01	15.45
1,700	66.09	15.48
1,900	67.96	16.03
2,100	69.65	16.85
2,350	70.97	17.56

from available data (15) and are reproduced in Table 1. As is apparent, the involved nature of the calculation makes utilization of a high speed digital computer almost mandatory.

Calculated temperature profiles for a 6-in. (0.152-m) square unprotected steel column are shown in Fig. 2 at 10-min intervals. Similar profiles for a 12-in. (0.304-m) square column are shown in Fig. 3 after 50-min and 60 min of fire exposure. Fig. 3(*b*) shows that at 60 min the maximum temperature difference between the surface and the core was 225° F (125° C) and the temperature at

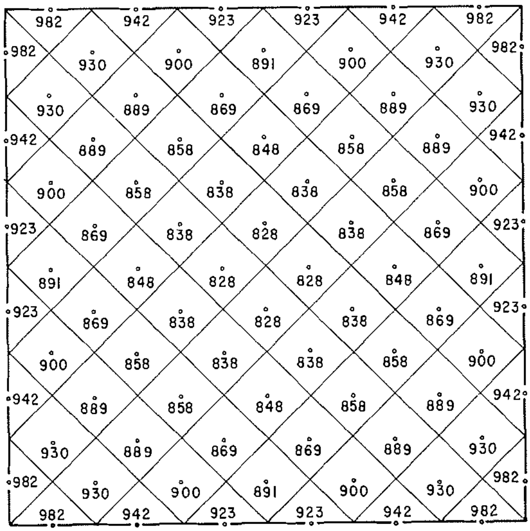


(a) 10 MIN.

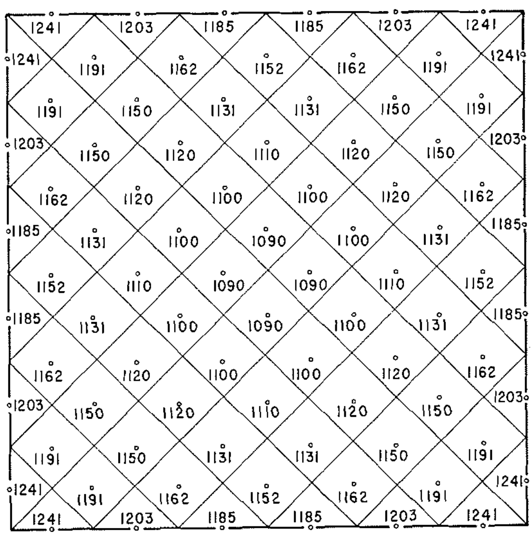


(b) 20 MIN.

FIG. 2.—Temperature Rise in Unprotected Steel Square Column (6 in.)



(c) 30 MIN.

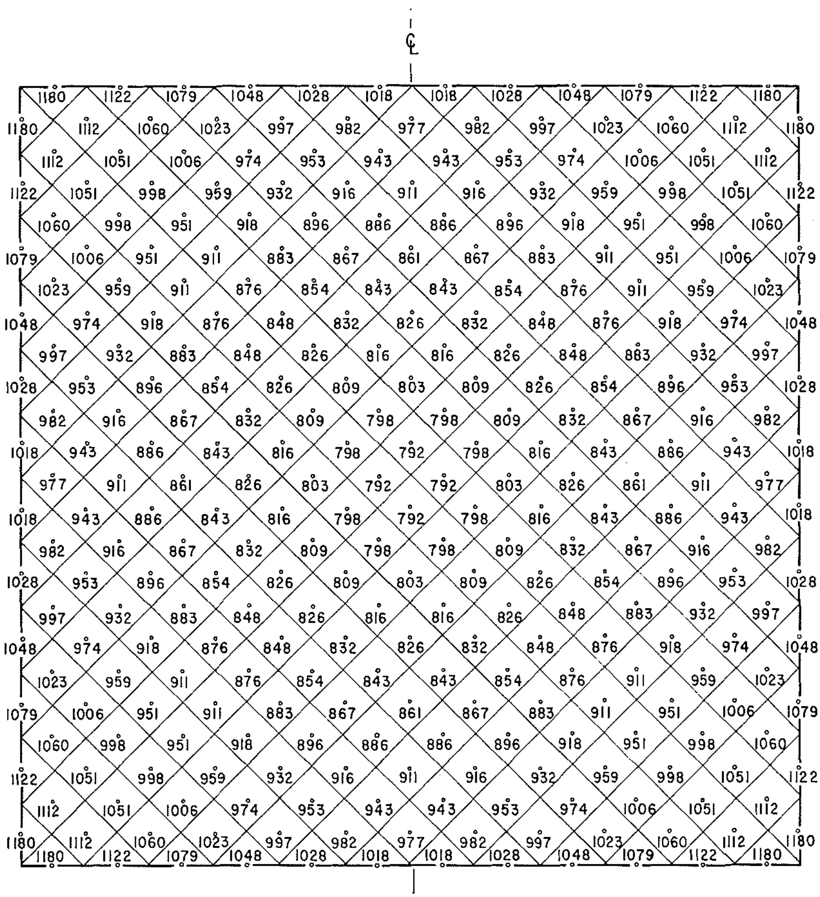


(d) 40 MIN.

FIG. 2.—*Continued*

the point midway between the surface and core was about 1,000° F. From Figs. 2(*c*) and 2(*d*) it is seen that the maximum temperature difference between the surface of the 6-in. column and the core is about 100° F. This can be regarded as a reasonable maximum for most steel columns likely to be encountered in building practice. For the purpose of determining fire endurance time by temperature rise, the temperature at the point halfway between the surface and core of the cross section (or flange in the case of a wide flange section) may be regarded as representing the average temperature of the cross section. For all but very thick sections this temperature will be almost equal to the temperature at the column surface.

Fig. 4 shows temperature rise curves for a 6-in. square column (calculated or measured as was just described). As is seen, the assumption of radiative heat transfer only does not adequately represent the conditions prevailing in

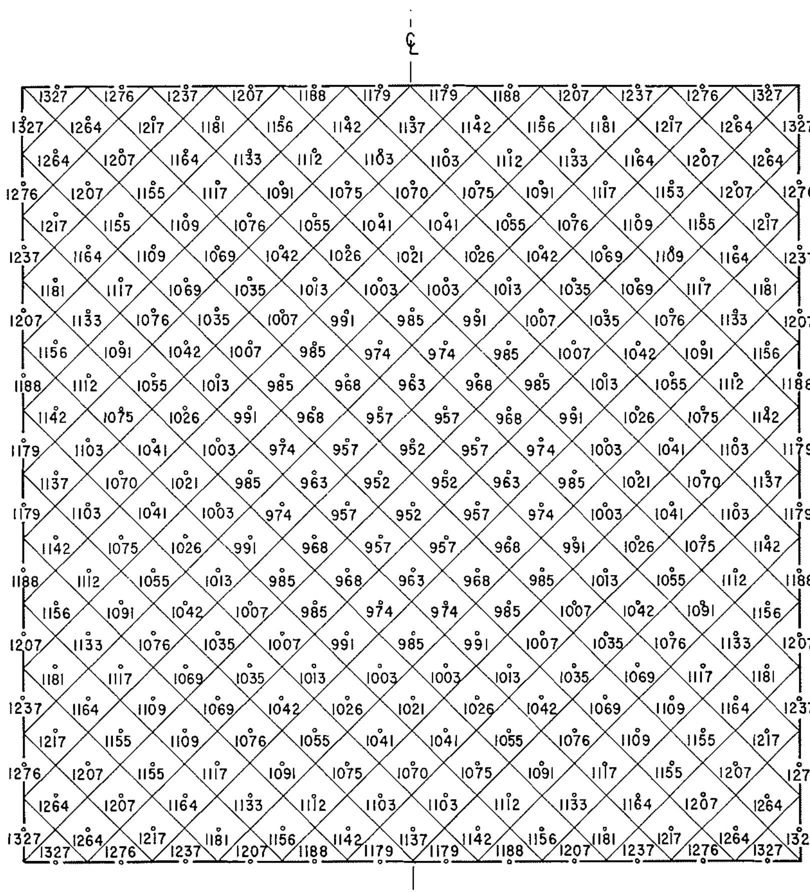


(a) 50 MIN.

FIG. 3.—Temperature Rise in Unprotected Steel Square Column (12 in.)

the DBR/NCR furnace when short fire endurance times are involved. The curve labeled (2) in Fig. 4 was calculated by assuming that 20% of the heat transfer is due to convection and produces good agreement with the experimental result. Unfortunately, this finding is of no general value because the convective heat transfer varies with each individual situation. With most fires of short duration the convection component of heat transfer can be in the order of 10% to 20%. In the calculation the effect of convective heat transfer was simulated by raising ϵ_s from 0.9 to the ficticious value of 1.1.

The heat transfer coefficients to columns of square cross section were calculated based on an emissivity (ϵ_s) of 0.9 using results obtained by Eqs. 5 and 6. The results are shown in Fig. 5, where the coefficient of heat transfer has been plotted as a function of the duration of standard fire exposure. As is seen, the heat transfer coefficient rises almost linearly with time, and the smaller



(b) 60 MIN.

FIG. 3.—*Continued*

the column the higher the coefficient of heat transfer.

One-Dimensional Numerical Procedure.—The temperature distributions, determined by the two-dimensional calculation method described previously, show

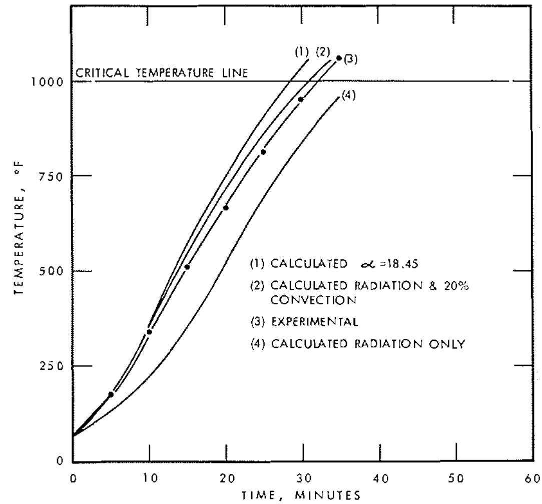


FIG. 4.—Temperature Rise Curves, 6 × 6 Solid Column

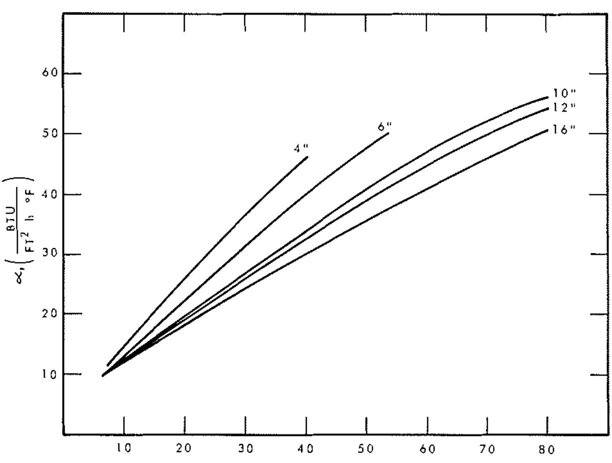


FIG. 5.—Coefficients of Heat Transfer for Unprotected Columns During Exposure to Standard Fire

that the temperature differences in the steel are relatively small, except for very thick sections. Most columns used in buildings have sections less than 10 in. (0.25 m) thick. In such cases detailed calculation of temperature distribution in the steel cross section is unnecessary, and a one-dimensional model of the heated column can be usefully employed. The model consists of a steel plate having the same cross-sectional and surface areas per unit height as the four sides of the heated column, with the edges and unexposed side perfectly insulated. This model permits use of a one-dimensional numerical procedure by which

TABLE 2.—Sample Calculation for 10-in. Square Column

t (1)	T_f (2)	T_a (3)	$(T_a - T_s)$ (4)	ΔT_s (5)	T_s (6)
0	70	535	465	58	70
5	1,000	1,150	1,022	128	128
10	1,300	1,350	1,094	137	256
15	1,399	1,431	1,038	130	393
20	1,462	1,486	963	120	523
25	1,510	1,530	887	111	643
30	1,550	1,567	813	102	754
35	1,584	1,599	743	93	856
40	1,613	1,626	677	85	949
45	1,638				1,034

Note: α = 18.45; c = 0.12; D = 3.33; W = 340; ΔT_s = 0.125 $(T_f - T_s)$ for Δt = 1/12 hr.

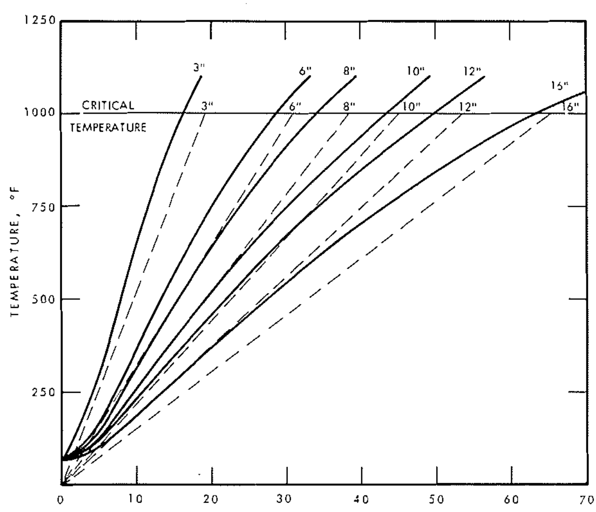


FIG. 6.—Temperature Rise of Square Solid Steel Columns (Calculated, α = 18.45)

the temperature of the steel cross section can be calculated with only a desk calculator or slide rule. In the calculation, with each interval of time, Δt, the rise in steel temperature, ΔT_s, is given by:

$$\Delta T_s = \frac{\alpha}{c}\frac{D}{W}(T_f - T_s)\,\Delta t \quad \text{. . . . .} \quad (7)$$

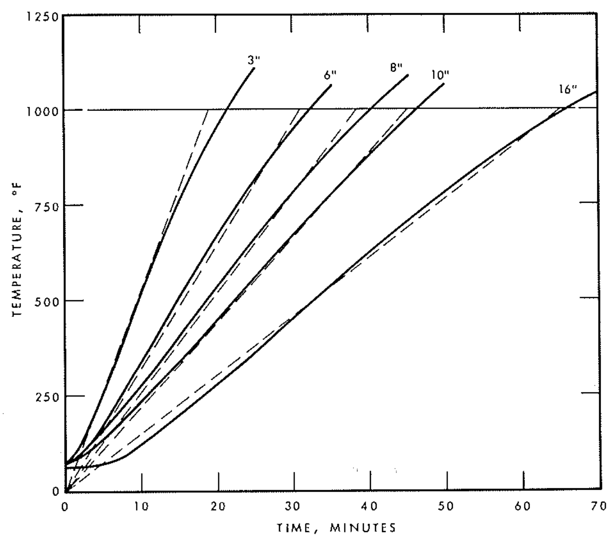


FIG. 7.—Temperature Rise of Square Solid Steel Columns (Experimental data)

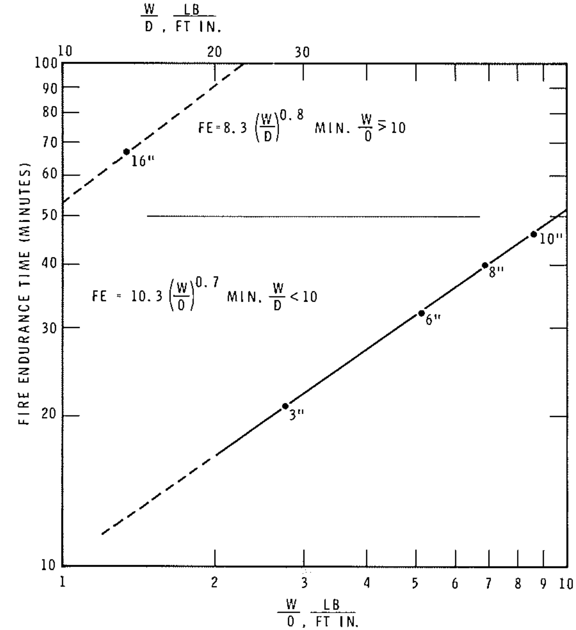


FIG. 8.—Fire Endurance of Square Columns (Experimental)

in which Δt is expressed in hours. The results of sample calculation for a 10-in. square column with α = 18.45 (104.8) and c = 0.12 (502) are shown in Table 2. A family of temperature rise curves obtained by similar calculations is shown by the solid lines in Fig. 6.

Experimental Results.—To obtain information on the temperature rise of unprotected steel columns in the DBR/NRC floor furnace, five fire tests were carried out on square solid columns of various cross sections. The temperatures measured at the point halfway between the surface and the core at mid-height of the columns are plotted in Fig. 7. Fig. 8 shows a plot of fire endurance time versus the dimensional parameter, W/D, on logarithmic scales. As is seen, the relationship is linear and, from the graph, it is possible to obtain the following relation directly:

$$t = 10.3 \left(\frac{W}{D}\right)^{0.7} \quad (8)$$

in which $W/D < 10$. To obtain a relation for columns whose $W/D \geqslant 10$,

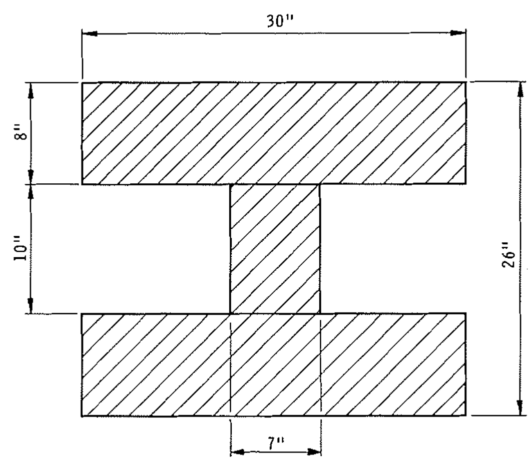


FIG. 9.—Built-up Column—3 Plates

a straight line temperature rise for the 16-in. square column is assumed, as shown by the dashed line in Fig. 7. From this it is possible to obtain the relation:

$$T_5 = 120 \left(\frac{D}{W}\right)^{0.8} \quad (9)$$

and by setting T_s equal to the critical temperature of 1,000° F:

$$t = 8.3 \left(\frac{W}{D}\right)^{0.8} \quad (10)$$

The lines resulting from Eq. 9 are plotted in Figs. 6 and 7 (dashed lines). The line resulting from Eq. 10 is plotted in Fig. 8 and that equation should be used for columns having $W/D \geqslant 10$. However, as is seen from Fig. 7, it can be conservatively applied to any column section, and provides a relation that could readily be incorporated into a building by-law. (Although the experimental data are confined to solid square columns, numerical analyses show that Eqs. 9 and 10 can apply to any shape of cross section.)

As an example of the fire resistance typical in columns of very tall buildings, a calculation for the section shown in Fig. 9, one of several massive sections used in Toronto's 56-story Toronto Dominion Centre, is worked out:

$$D = 2(30 + 16) + 2(30 - 7) + 2(10) = 174 \text{ in.} \quad (11)$$

$$W = 1{,}870 \text{ lb per ft}, \frac{W}{D} = 10.75 \quad (12)$$

Eq. 10 yields a fire endurance time of:

$$t = 8.3\,(10.75)^{0.8} = 56 \text{ min} \quad (13)$$

As is seen, these massive sections can have fire endurance times approaching 1 hr, even when unprotected.

Recent North American practice has seen increased installation of sprinkler systems in large (especially tall) buildings, including some that are not considered to have a very high fire load (2,6). Once complete sprinklering of high buildings becomes more common, the use of unprotected massive column sections with a fire resistance capability of about 1 hr should prove adequate for fire safety, provided that the fire load is no more than 5 lb/sq ft to 10 lb/sq ft, which should not result in a fire of severity greater than a 1-hr standard fire (8). (Fire load is the heat of combustion of the combustible contents expressed in equivalent pounds of wood per unit floor area.) It can be reasonably deduced from Refs. 4 and 14 that no safety factor need be applied to the actual fire load if the building is fully sprinklered, although such a safety factor is implied by all current North American building regulations now in force.

Acknowledgments

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Appendix II.—Notation

The following symbols are used in this paper:

c = specific heat of steel, in British thermal units per pound—degrees Fahrenheit (or degrees Rankine) (joules per kilogram—degrees Kelvin);
D = heated perimeter, in inches (meters);
E = modulus of elasticity of steel, in kips per square inch (newtons per square meter);
FE = fire endurance time, in minutes;
k = thermal conductivity, in British thermal units per foot-hour-degrees Fahrenheit (watts per meter-degrees Kelvin);
T = temperature, in degrees Fahrenheit (degrees Celsius);
t = time, in minutes (unless specified otherwise);
W = mass of steel section, in pounds per foot (kilograms per meter);
α = coefficient of heat transfer, in British thermal units per foot-hour-degrees Fahrenheit (watts per meter-degrees Kelvin);
Δ = increment;
$\Delta \xi$ = mesh width, in feet (meters);
ϵ = emissivity;
λ = slenderness ratio;

ρ = density of steel, in pounds per cubic foot (kilograms per cubic meter); and

σ = stress, ksi (N/m^2); Stefan-Boltzmann constant, 0.1713×10^{-8}, in British thermal units per hour-square foot-degrees Rankine to the fourth power (watts per square meter—degrees Kelvin to the fourth power);

Subscripts

a = allowable, average;

cr = critical;

f = of furnace;

m = at or around mesh point in mth row;

n = at or around mesh point in nth column;

o = at room temperature;

s = of steel cross section;

T = at temperature T; and

y = at yield stress.

Superscripts

j = at $t = j\Delta t$.

9719 FIRE RESISTANCE OF UNPROTECTED STEEL COLUMNS

KEY WORDS: **Buildings (codes); Columns; Fire protection;** Fire resistance; Heat transfer; Steel; **Structural engineering; Temperature**

ABSTRACT: Fire resistance of unprotected steel columns is examined by standard fire test and numerical analyses based on a 1,000 D F (538 D C) critical temperature for failure. It is shown that fire resistance time varies with the shape factor of column weight divided by the heated perimeter, and two simple equations for calculating the fire resistance times of unprotected steel columns are established. A practical example shows that large columns used in high-rise buildings can have fire resistance times of up to one hr. The more conservative of the two equations is recommended for use in building standards.

REFERENCE: "Fire Resistance of Unprotected Steel Columns," *Journal of the Structural Division,* ASCE, Vol. 99, No. ST5, **Proc. Paper 9719**, May, 1973, pp. 837-852