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Empirical Method for Calculating Fire Resistance of Protected Steel Columns

by

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La méthode empirique du calcul de la résistance au feu des poteaux d'acier protégés

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Les auteurs examinent, au moyen de methodes techniques experimentales et analytiques, la résistance au feu des poteaux d'acier protégés par des matières isolantes à faible densité. Ils calculent les températures critiques de ruine et décrivent des méthodes servant à calculer l'augmentation de la température. Ils proposent des méthodes simples et pratiques pour la protection des poteaux métalliques de construction contre le feu, avec exemples à l'appui.

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Empirical Method for Calculating Fire Resistance of Protected Steel Columns

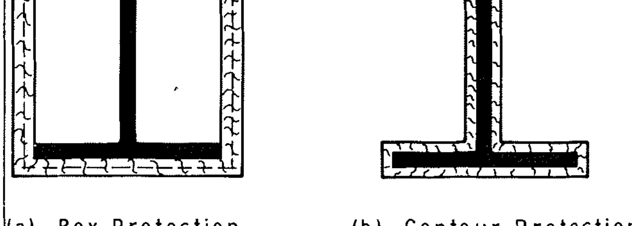
Fully developed building fires generally attain gas temperatures in the order of 2000°F. As the mechanical properties of steel deteriorate rapidly at temperatures of about one half this magnitude, it is necessary to provide some means of keeping steel columns relatively cool during exposure to fire, with the possible exception of extremely massive steel sections.[1] External insulation of a steel section to prevent excessive heat transfer during the expected period of fire exposure * is the most common method of providing fire resistance, although internal liquid-cooling has recently proved to be a viable fire protection method as well.

Typical forms and methods of fire protection in current use are illustrated in Figures 1 to 4. Light protection (Figure 1) using low density materials applied either to the profile of a section or in box form is most popular from an economic point of view. Massive protection, particularly concrete encasement, is used in special cases and forms the subject of a separate study.[2] External protections, which do not readily fall into either of these categories, have been labelled "complex protection" (Figure 3) because their analysis may require special methods or engineering judgement. Box protected H-columns with core filling or very thick contour protection are examples. Liquid-filling as fire protection (Figure 4) can be accomplished by use of design methods described in References 3 and 4. This paper will confine itself to an examination of the fire resistance of steel columns protected by relatively low-density materials, examining the problem by both fundamental and experimental engineering methods.

The ability to maintain its load carrying capacity is the only performance requirement of a building column during fire exposure. Consequently, the first applicable North American fire test standard[5] required a sample at least 9 ft in length to be tested under an applied load calculated to develop the theoretical working stresses of the design. In this standard the column is required to sustain the applied load for a period equal to the length of time for which classification is desired. Such classifications, measured in hours, form the basis of column protection required by building regulations.

Experience with the loaded column fire test indicated that failure of a protected steel column was reasonably predictable on the basis of the temperature attained by the steel cross-section. This 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. The 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 at any level above 1000°F, or above 1200°F at any one of the measured points. These methods are stated in the current version[6] of the fire test standard and standard test methods used in other countries are essentially similar.

The expense involved with large-scale fire testing (in the order of several thousand dollars per test) has encouraged a more fundamental approach to the evaluation of fire resistance. The present paper is the most recent effort and is based on the findings of other research workers and the results of many calculations and experiments by the authors.



(a) Box Protection (b) Contour Protection

Figure 1. Light protection.

** Fire regulations and 'standards' concern themselves only with performance during a fire test, not with the degree of damage suffered by a structure or its possible re-usability after a fire.*

Critical Temperatures and Structural Design

The critical temperature of a steel column is defined as that cross-sectional average temperature at which the member can no longer perform its load-carrying function; it is the cross-sectional average temperature at which the factor of safety incorporated in the structural design becomes unity. With axially-loaded members the temperature at which the column buckles is usually regarded as the critical temperature in fire resistance studies and depends on several factors. The most significant are: load intensity (stress); mechanical properties of the steel; shape, unit mass and length; end conditions; and contribution of the protection to the strength of the structural unit.

In the present study it was assumed that the protection does not contribute to column strength and that the column is axially loaded to the allowable stress permitted by CSA S16 - 1969[7]. Accordingly, the following expressions were used in the calculations:

$$KL/r \leq C_o \qquad F_a = 0.60\,F_y \tag{1}$$

$$C_o < KL/r \leq C_p \qquad F_a = 0.60\,F_y - m(KL/r - C_o) \tag{2}$$

$$C_p < KL/r \qquad F_a = \frac{149{,}000}{(KL/r)^2} \tag{3}$$

where $C_o = 30 - F_y/5$ but not more than 20:

$$C_p = \sqrt{\frac{286{,}000}{F_y - 13}} \text{ but not less than 78}$$

$$m = \frac{0.60\,F_y - \dfrac{149{,}000}{(C_p)^2}}{C_p - C_o}$$

The allowable stresses calculated with the above equations are similar to those specified in several other countries.[8-11]

The mechanical properties that most significantly affect the critical temperature of a steel column are modulus of elasticity and yield strength of the steel. Both decrease as temperature increases. Data concerning the dependence of these properties on temperature have been reported by several authors.[12-19] Measured values of the modulus of elasticity and the yield strength of various structural carbon steels (ASTM A-36, St-37, CSA G40. 12) as a function of temperature are plotted in Figures 5 and 6. The wide spread in the data can be attributed to many factors, the most important being the variability of steel chemical composition and the influence of strain rate and creep properties on the test results.

Curves have already been drawn[20] to suit an analytical expression as well as the data reported in the literature. These will be used to evaluate the critical temperatures of steel columns and their dependence on column size, shape and length. The authors point out that the yield strength curve represents the average decrease with temperature, but that modulus of elasticity curve, because it represents the more important variable, is somewhat conservative. The appropriate analytical expressions for yield strength and modulus of elasticity are:

$$F_y = F_{yo}(1 - 0.78\theta - 1.89\theta^4), \tag{4}$$

and

$$E = E_o(1 - 2.48\theta^2) \tag{5}$$

respectively. In the above equations

$$\theta = \frac{T - 68}{1800}$$

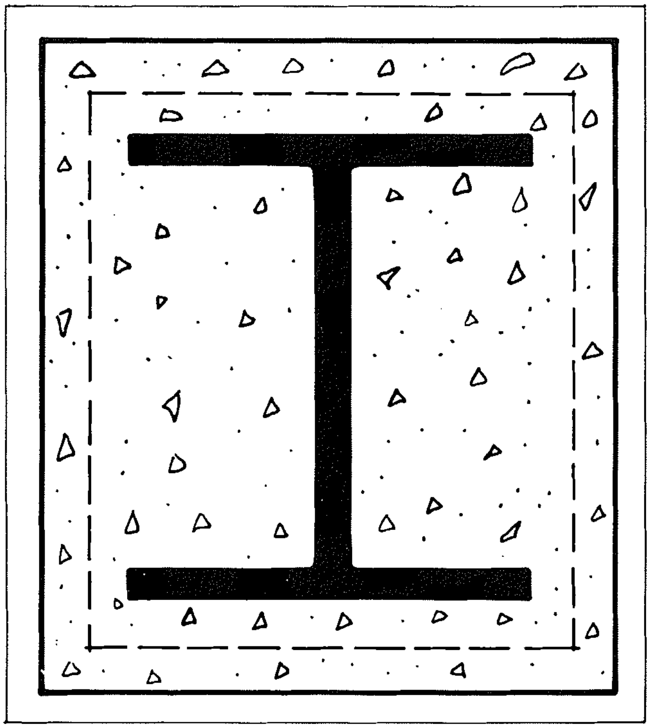


Figure 2. Massive protection.

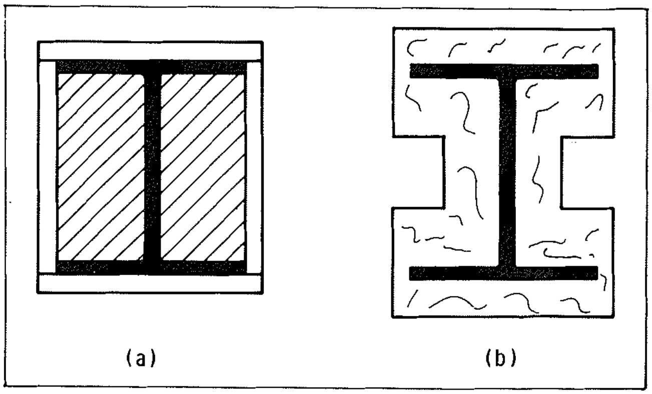


Figure 3. Complex protection.

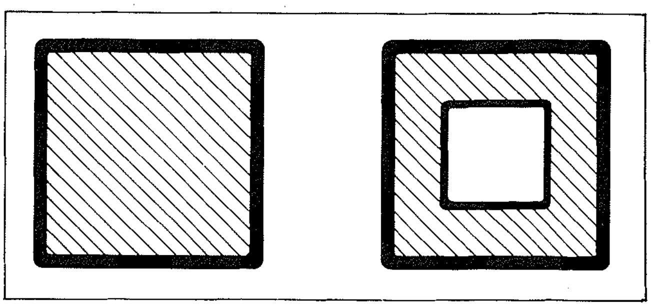


Figure 4. Liquid-filling as fire protection.

The following assumptions were made in the calculations:

1) The column is free to expand during heating.
2) The influence of creep is negligible at temperatures below approximately 950°F[19] and will not be separately taken into account. It should be realized, however, that the presence of creep deformation is already inherent in the expressions for mechanical properties used in the calculations.
3) The stress-strain curve at elevated temperatures can be obtained from an expression similar to that proposed by Galambos[21] for normal service temperatures:

$$\epsilon = \frac{F}{E} + \frac{3F_y}{7E}\left(\frac{F}{F_y}\right)^{10} \tag{6}$$

The following method was used to calculate buckling stresses and critical temperatures for steel columns with various slenderness ratios:

For stresses below the yield strength of the steel the buckling stress F_{cr} is given by

$$F_{cr} = \frac{\pi^2 E_t}{(KL/r)^2} \tag{7}$$

where E_t is the tangent modulus obtained by differentiating equation (6), so that

$$E_t = \frac{dF}{d\epsilon} = \frac{E}{1 + \dfrac{30(F/F_y)^9}{7}} \tag{8}$$

For low slenderness ratios the calculated values of F_{cr} will exceed the yield strength of steel. In this case buckling stress is considered to be the yield strength of the steel at the temperature under consideration, a temperature that can be determined by means of equation (4).

Using equations (4) to (8), and assuming values of F_{yo} and E_o of 36 and 29.000 ksi respectively, column curves have been calculated for various steel temperatures. These curves are plotted in Figure 7, along with the CSA S-16 design curves given by equations (1) to (3). The curves show that the critical temperature of the shorter columns is approximately 880°F and that of intermediate and long columns about 950°F. Many fire tests on loaded columns[22-24] indicate that, for columns whose protection does not add significantly to the strength of the structural unit, complete failure occurs at temperatures 50 to 100F deg higher than the temperature at which the column begins to buckle. Consequently, the 1000°F critical cross-sectional temperature permitted in the current ASTM and CSA standards[6 25] appears appropriate because fire tests are not considered terminated until complete structural failure has occurred.

Temperature Rise of Protected Steel Columns

The temperature rise in a protected steel column is most reliably obtained by conducting a fire test, but it can also be calculated by engineering methods with a reasonable degree of accuracy. The problem, unlike fire resistance problems concerning more complex structural elements, is one of heat conduction and has, over the years, been the subject of several theoretical studies. The following methods already exist to explain the mechanism of heat transfer from a fire through insulation to the steel core (see Figure 1(a)).

Method 1, originally proposed by Geilinger and Bryl,[26] assumes one-dimensional heat transfer through the insulation. Accordingly, the model representing a protected steel column exposed to fire is a steel plate having the same weight to heated surface area ratio as the four sides of a unit length of the heated column, protected on the fire side and perfectly insulated on the other side.* The heat capacity of the protective material is neglected and the temperature gradient therein is assumed to be linear. Thermal resistance to heat transfer between the fire and an exposed surface is taken into account, but is usually negligible in comparison with the resistance of the protection, for which constant values of the thermal properties are assumed. If desired, the temperature dependence of the heat capacity of steel can be accounted for, but this is usually superfluous, considering the inaccuracies normally inherent in the assumptions previously made for protection.

Method 2 is the same as method 1, with the following exceptions: the heat capacity of the protection is accounted for by adding one half its value to the heat capacity of the steel core, as proposed by McGuire et al.[27] Others have used

** This model has already been employed with good results in calculating the temperature rise of unprotected steel columns.*

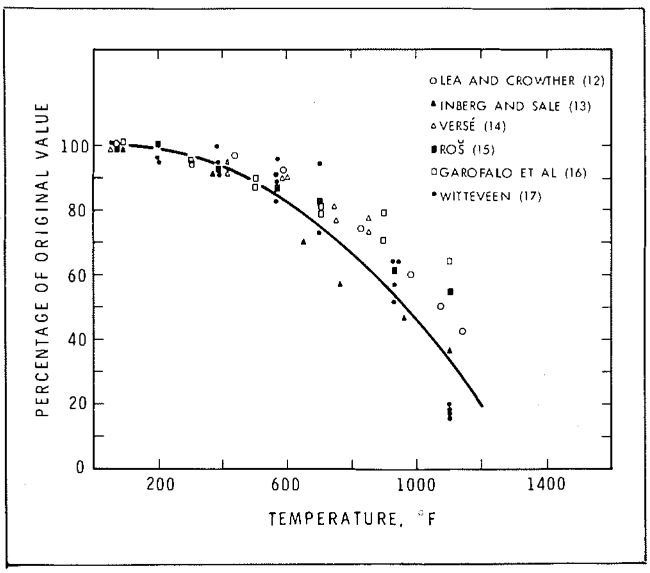


Figure 5. Modulus of elasticity of carbon steels as a function of temperature.

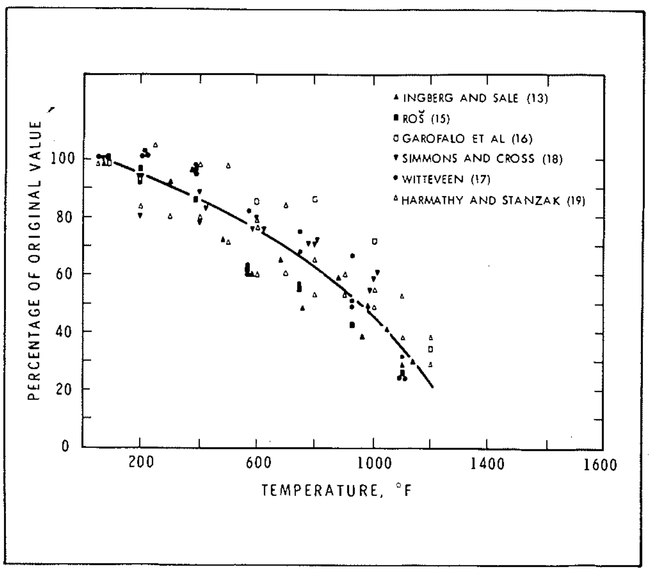


Figure 6. Yield strength of carbon steels as a function of temperature.

one third of the heat capacity.[28, 29] It is also assumed that the surface temperature of the protection is the same as the fire temperature.

Method 3, proposed by Lie,[30] again assumes one-dimensional heat transfer through the protection, but takes into account the actual heat capacity of the insulation. The temperature gradient in the protection is calculated but, as with the previous methods, constant thermal properties for insulation and steel are assumed. The surface temperature of the protection is taken as the fire temperature, as in method 2.

Method 4, originally investigated by Lie and Harmathy,[31] assumes two-dimensional heat transfer through the insulation. Radiative heat transfer is assumed from the fire to the surface of the insulation, and heat transfer through the insulation proceeds by a conduction mechanism. The thermal properties of the protection and steel core at any temperature can be taken into account. Of the four methods, this most realistically represents the actual physical situation and its accuracy has been borne out by experiment.[31]

The authors have examined these methods in detail with a view to determining their relative merits and limitations. A large number of fire resistance calculations, based on a 1000°F critical temperature, were performed for each. The influence on fire resistance of section size and shape as well as thickness and material properties was examined, and the results are listed in Table 1. Both light and heavy protective materials were considered.

Calculations were based on an expression that accurately approximates the ASTM curve[32]

$$T - T_o = 1844.2 - 699.5\,e^{-0.02022t} - 1638\,e^{-0.3827t} + 493.3\,e^{-206.7t} \qquad (10)$$

where $t \leq 120$

and $t \geq 120$

$$T - T_o = 1632 + 1.25t \qquad (11)$$

(An expression of e-powers for a boundary condition is necessary to make the heat transfer equations integrable.) The results are given in the last column of Table 1, which also shows that method 3 gives practically the same results as method 4, provided the assumptions of method 3 are closely satisfied. In summary the calculated results of Table 1 show the following:

1. Method 1, which neglects the heat capacity of the protective material, gives low values of fire resistance when compared with experimental data[33] and values calculated by other methods. An estimate[34] indicates that results obtained by method 1 have practical value when the ratio heat capacity of insulation ∠ 0.5. heat capacity of steel
$$\frac{\text{heat capacity of insulation}}{\text{heat capacity of steel}} \leq 0.5.$$
2. Adding one third of the insulation's heat capacity to that of the steel gives better values than method 1, but they are still low compared with the values produced by other methods and experiment.
3. Adding one half of the insulation's heat capacity or using method 3 (analytical) provides very good agreement with values obtained by method 4 (numerical) for light insulat-

Column No.	Size in.	Thickness Insulation in.	Thermal Properties of Insulation* (ρc) Btu/ft³°F	(k) Btu/ft h°F	W lb/ft	W/D lb/ft/in.	Fire Resistance (Time in minutes to reach 1000°F steel temperature) According to Method: No. 1 Capacity = 0	No. 2 1/3 Capacity Added	No. 2 1/2 Capacity Added	No. 3 Exact Solution	No. 4 (Numerical Method) ASTM Curve
			(Light Insulation)								
1	4x4	1	11.12	0.165	15	0.9375	42	50	54	54	55
2	6x6	1	"	"	25	1.042	45	53	57	58	60
3	10x10	1	"	"	15	0.375	21	30	34	34	37
4	10x10	1	"	"	40	1.0	44	52	54	56	59
5	10x10	1	"	"	70	1.75	69	76	79	80	83
6	16x16	1	"	"	70	1.094	47	55	59	59	63
7	4x4	2	"	"	15	0.9375	72	100	113	118	109
8	6x6	2	"	"	25	1.042	78	105	118	124	124
9	10x10	2	"	"	15	0.375	35	67	81	84	85
10	10x10	2	"	"	70	1.75	119	143	155	161	166
11	12x12	2	"	"	70	1.458	103	127	140	144	147
12	16x16	2	"	"	70	1.094	82	108	121	126	128
			(Heavy Insulation)								
13	4x4	1	29	0.7	15	0.9375	17	20	23	23	31
14	6x6	1	"	"	25	1.042	19	21	24	24	33
15	10x10	1	"	"	15	0.375	9	16	18	19	26
16	16x16	1	"	"	70	1.094	16	22	28	25	35
17	4x4	2	"	"	15	0.9375	23	45	54	56	61
18	6x6	2	"	"	15	0.625	18	39	48	50	59
19	6x6	2	"	"	25	1.042	25	46	56	57	65
20	10x10	2	"	"	15	0.375	13	35	45	47	56
21	12x12	2	"	"	70	1.458	33	52	62	64	72
22	16x16	2	"	"	70	1.004	27	47	57	58	67

* In the calculations, a value of 0.11 Btu/lb°F has been used for the specific heat of steel.

Table 1. Comparison of fire resistances calculated by various methods.

ing materials. For more dense materials the results obtained by adding one half of the insluation's capacity or by method 3 are somewhat lower than those of method 4. In this case, the assumption that the surface temperature of the insluation is equal to the fire temperature is probably not sufficiently satisfied. It can be shown[35] that with a heavy material, i.e., the product $k\rho c_i$ large, the temperature of the surface will be appreciably lower than the fire temperature.

4. Values obtained by using method 4 are the most realistic, provided the thermal properties of the protective material are accurately known.

It should be pointed out that where methods 1 to 3 are used for the solution of fire resistance problems a value can usually be obtained with the aid of a slide rule or desk calculator using materials properties reasonably representative of those at elevated temperatures and often found in the literature. Application of method 4 requires a high-speed digital computer and materials properties obtainable from only a limited number of laboratories, including the authors'. Method 4 is, however, the one most suitable for calculations involving protective materials containing components that undergo significant chemical reactions at elevated temperatures, for example, cement paste and gypsum. The change in thermal properties of such materials, particularly increase in specific heat, will result in an increased fire resistance. Unfortunately, the variation of specific heat with temperature for these materials follows an irregular pattern and representative values at elevated temperatures are often difficult to provide, rendering methods 1 to 3 unsuitable for such protective materials.

For lighter materials whose heat capacity is relatively small, on the other hand, the influence on fire resistance of changes in heat capacity with temperature is also relatively small. By examining the results obtained by means of methods 1 to 4 it was possible to derive simple formulas for the fire resistance of steel columns thus protected. These are accurate enough for most practical purposes, as will be shown.

Design Formulae

The derivation of the design formulae was based on an examination of the parameters governing the rise of steel temperature during fire exposure. Empirical formulas based on the most significant parameters were derived as will now be described.

One of the assumptions common to all methods used in the analysis is that heat transmitted through the insulation to the steel core is equal to the increase in the heat content of the steel (the heat capacity of air spaces enclosed by the insulation is always so small that it is neglected). Thus, where one-dimensional heat transfer is assumed (methods 1 to 3), the temperature rise of the steel is given by:

$$c_s W \frac{\partial T_s}{\partial t} = Ak \frac{\partial T_i}{\partial x} \qquad (12)$$

where

c_s = specific heat of steel
W = mass of steel per unit length
A = area of protection at the interface between protection and steel through which heat is transferred to the steel, per unit length
k = thermal conductivity of insulation
T_s = steel temperature
T_i = insulation temperature
t = time
x = coordinate perpendicular to insulation surface

If thermal resistance between the insulation surface and fire is neglected and a linear temperature gradient through the insulation assumed, it becomes

$$\frac{\partial T_i}{\partial x} = \frac{T_f - T_s}{l} \qquad (13)$$

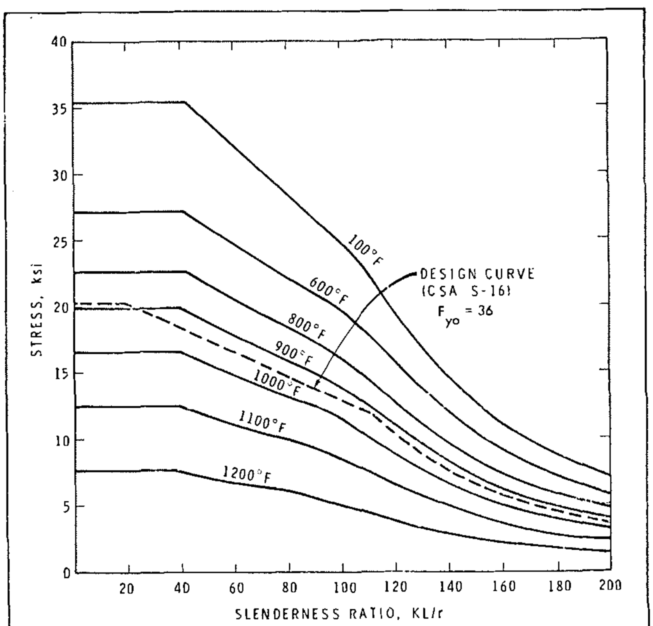


Figure 7. Buckling stress as a function of the slenderness ratio for various steel temperatures.

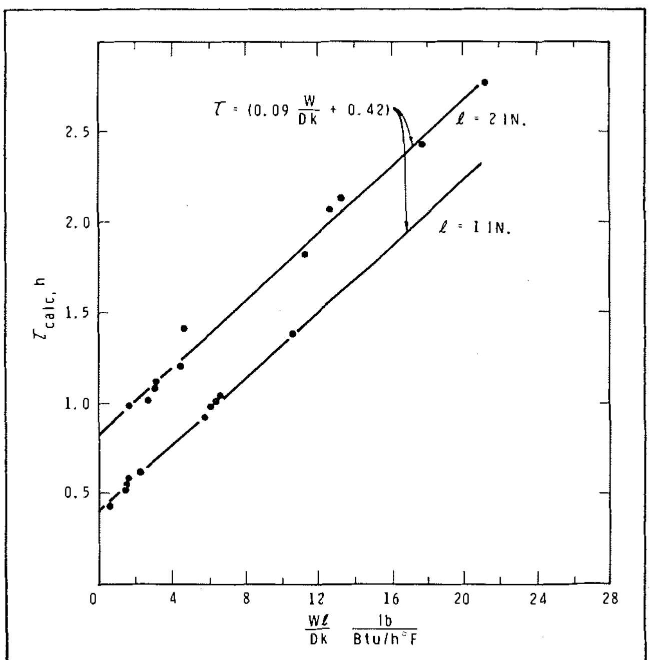


Figure 8. Calculated fire resistance as a function of Wℓ/Dk for two protection thicknesses.

where T_f = fire temperature
ℓ = thickness of insulation
Substitution in equation (12) then yields

$$\frac{c_s W l}{A k} \frac{\partial T_s}{\partial t} = T_f - T_s, \tag{14}$$

which shows that the steel temperature is a function of the parameter $W\ell/Ak$, if the specific heat of steel is taken as a constant. Because the heated area A is proportional to the heated perimeter D, the steel temperature is also a function of $W\ell/Dk$.

A plot of the fire resistances obtained by means of model 4 and the ASTM fire curve against the parameter $W\ell/Dk$ (Figure 8) shows that this parameter alone cannot sufficiently describe the fire resistance of a protected steel column. This is not unexpected because the parameter does not include the influence of the heat capacity of the insulation on the steel temperature. Adding another parameter, however, that is a function of ℓ only and can thus take into account to a certain degree the insulation's heat capacity makes it possible to express the computed fire resistance by a single formula:

$$\tau = 0.09 \frac{W l}{D k} + C l, \tag{15}$$

where C is a constant. As indicated, the term $C\ell$ takes into account the heat capacity of the insulation and a value of 0.42 for C gives a good fit with the computed fire resistances (Figure 8).

All parameters in the formula can be determined readily except the thermal conductivity of the insulation, k, which almost always varies with temperature. If a constant value of k is used, therefore, it should be chosen so as to characterize approximately the actual thermal conductivity at elevated temperatures. Such approximate values are given in References 35 and 36.

Normally, thermal conductivity increases with density. As density is a quantity that can be readily determined, an

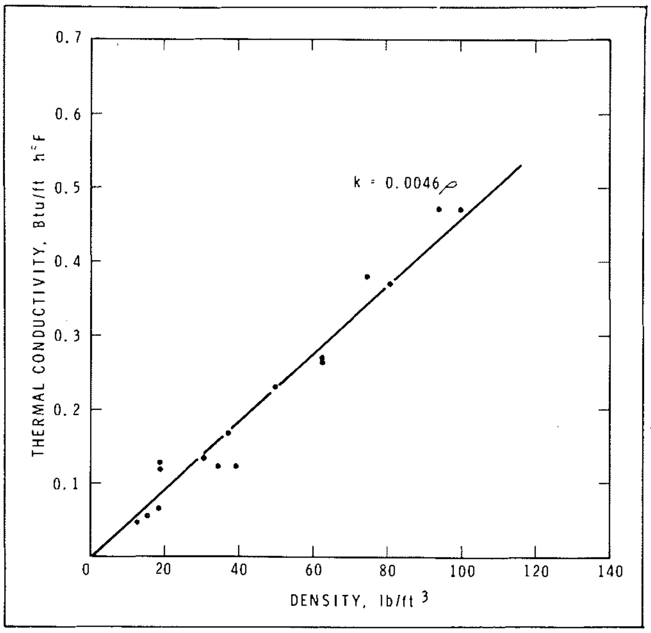


Figure 9. Approximate thermal conductivity (k) at elevated temperatures of various materials as a function of their density (ρ).

attempt was made to find a relation between density and thermal conductivity for use in equation (15). Figure 9 is a plot of k versus ρ and indicates that the two can be approximately related by the expression:

$$k = 0.0046\rho \tag{16}$$

It should be noted that gypsum boards, whose thermal properties vary irregularly with temperature because of dehydration, are not included in the graphs. Neither is equation (16) applicable to porous mineral wood products with a density of less than about 20lb/ft^3 because their thermal conductivity increases very rapidly with temperature owing to radiation from fibre to fibre.[35] The reference states, however, that a value of approximately k = 0.15 Btu/ft h °F can be used in formula (15) for the conductivity of mineral wool in the density range 7 to 20 lb/ft^3. This illustrates that caution should be applied in the correct use of these formulas.

Generally, light, fibrous, porous materials such as mineral wool products will provide lower fire resistances than those calculated. Others that undergo chemical changes (gypsum, cement paste, some concrete or plaster aggregates) will provide higher fire resistance. Chemically stable materials (vermiculite, perlite, dense mineral wool, asbestos, clay) are expected to yield fire resistances very close to those calculated by the design formula. On substitution of equation (16) into equation (15), this becomes:

$$\tau = 20 \frac{W l}{D \rho} + C l \tag{17}$$

All parameters in this expression can be readily determined.

Using a value of C = 0.42 (which gave the best fit with fire resistances computed by method 4), the accuracy of expression (17) was examined by comparing calculated fire resistances with experimental data from laboratories in Britain (JFRO), Canada (NRCC), Holland (TNO), Japan (BRI) and the United States (ULI). The materials in the

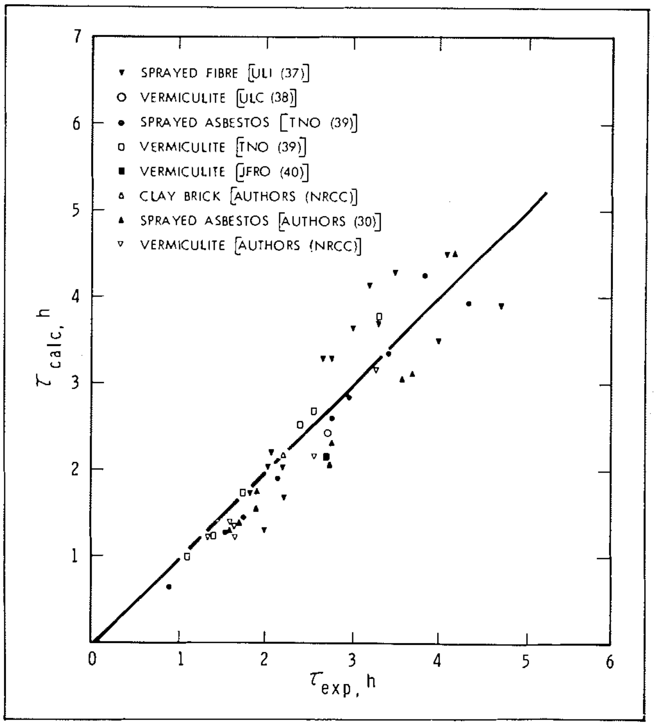


Figure 10. Comparison between calculated and experimental fire resistances (calculated from formula (18) for light and chemically stable protections).

tests were for the most part common protective materials such as vermiculite, perlite and sprayed fibres with various binders, and mineral wool. One test involved a clay brick. Both box and contour type protections were represented. The comparison shows that calculated values of fire resistance are in fair agreement with experimental results, although generally slightly lower for chemically stable materials. As a result, the following expression was chosen as yielding the most representative answers (Figure 10):

$$\tau = \left(20\,\frac{W}{D\rho} + 0.5\right)l \qquad (18)$$

for relatively lightweight protective materials ($\rho \leq 50$ lb/ft^3).

For materials that contain cement paste or gypsum, formula (18) provides conservative answers. Using C - 1.2 gives good results (Figure 11) and for these materials the expression

$$\tau = \left(20\,\frac{W}{D\rho} + 1.2\right)l \qquad (19)$$

should be used ($\rho \angle 50$ lb/ft^3).

Design formulas (18) and (19) were developed by a semi-empirical approach and offer a far simpler solution to column fire resistance problems than has previously been available. Users should appreciate, however, that because of their generality certain pitfalls can be encountered if they are applied to a problem indiscriminately, as has already been illustrated for mineral wool products. The accuracy of calculated results can be improved for any material by returning to equation (15) whenever sufficient test data are available.

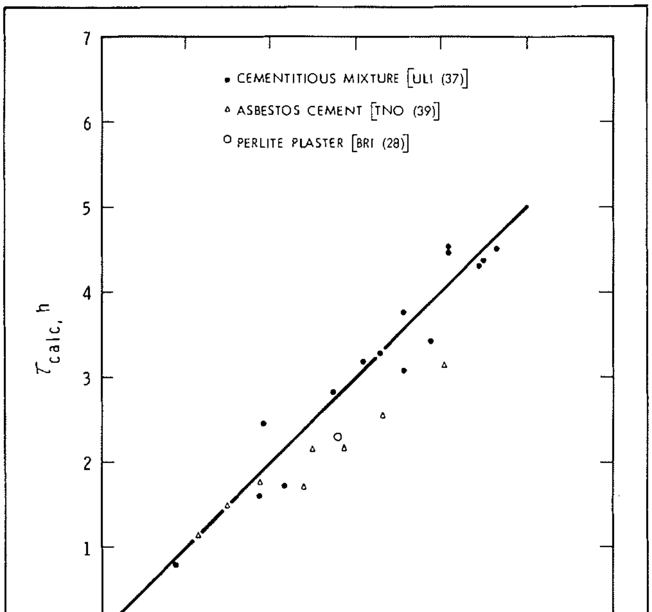


Figure 11. Comparison between calculated and experimental fire resistances (calculated from formula (19) for light protections containing cementitious components).

Further examination of low-density mineral wool protections serves as an example. It has been stated that equation (16) and hence equation (17) are not valid for these protections. If the actual thermal conductivity of k = 0.15 Btu/ft h °F is used in equation (15), as has been recommended, reasonable agreement with experimental data may be obtained for the density range 7 to 20 lb/ft^3. With even lighter products, such as those normally used for sound absorption, a value of k = 0.25 Btu/ft h°F or higher was found to be appropriate.

An important practical application of the derived formulae is to show how column fire resistance varies with the so-called "size and shape" factor, W/D. This variation is illustrated in Figure 11 for a typical sprayed fibre on various commonly used column sections. As may be seen, the effect of the "size and shape" factor on fire endurance is extremely significant and should not be ignored in the design of column fire protection.

Conclusion

Means for solving fire resistance problems of protected steel columns have been presented. All rely on careful engineering judgment in the choice of solution and assessment of the confidence level of that solution. With known and widely used materials, for which considerable fire test data are available, it is suggested that formulae (18) and (19) be incorporated in building regulations in the form

$$\tau = \left(20\,\frac{W}{D\rho} + C\right)l \qquad (20)$$

where C = 0.5 – for protections mainly consisting of chemically stable materials such as vermiculite, perlite, sprayed asbestos with various binders, and dense ($\rho \leq 20$ lb/ft^3) mineral wool;

C = 1.2 for protections containing cement paste or gypsum, such as asbestos-cement board, plasters and cementitious mixtures.

Formula (20) is valid for relatively light protective materials ($\rho \leq 50$ lb/ft^3). When used for heavier materials, it is expected to give conservative estimates of fire resistance.

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Nomenclature

Notations

a thermal diffusivity, ft^2/h
c specific heat, Btu/lb °F
C constant taking into account the heat capacity of insulation
D heated perimeter of steel, in. (developed length of protection at the interface between protection and steel, through which heat is transferred to steel)
E modulus of elasticity, ksi
F stress, ksi
k thermal conductivity of insulation, Btu/h ft °F
K effective length factor
l thickness of insulation, in.
L height of column, ft
r radius of gyration, ft
t time, hr
T Temperature, °F
W mass of steel section per ft, lb/ft
x coordinate perpendicular to insulation surface

Greek Letters

α fraction of insulation capacity added to that of steel
ϵ strain, in/in.
ρ density of insulation, lb/ft^3
τ fire resistance, h

Subscripts

a allowable
cr critical
f of fire
i of insulation
o at room temperature
s of steel
t tangent
y yield

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