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# FIRE RESISTANCE OF STRUCTURAL STEEL

by T. T. Lie



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## SOMMAIRE

L'article décrit une méthode de calcul du rendement de l'acier de charpente durant un incendie. Une formule simple permet de comparer la résistance au feu de l'acier de charpente lorsqu'il est soumis à un essai de résistance au feu et celle obtenue dans le cas d'un véritable incendie. Une analyse a indiqué que la charge thermique à laquelle une pièce de charpente peut résister au cours d'un incendie est proportionnelle à la résistance au feu normale attribuée à l'élément de charpente. L'article traite aussi de l'influence des facteurs importants qui déterminent la charge thermique critique, soit le facteur d'ouverture, l'épaisseur du revêtement protecteur et la masse de l'acier.

# Fire Resistance of Structural Steel

T. T. LIE

Because a factor of safety is incorporated in design calculations, load-bearing members in a building generally possess reserve strength. This gives the member resistance to extreme loads such as floor load concentrations, wind, snow, and earthquake, and at the same time resistance to fire.

During a fire, the member may be exposed to heating at extremely high temperatures, and as a consequence its strength may decrease substantially in a short time. To prevent such loss of strength it is essential to protect the member against excessive temperature rise.

One of the problems in selecting appropriate protection is the evaluation of its effect on the fire performance of the member. Usually, fire performance is determined by subjecting a member to a standard fire.[1] In practice, however, the severity of fire conditions can vary over a wide range. It is desirable, therefore, to find some means by which the performance of a member in a standard fire can be used to assess its performance under fire conditions more representative of those that might actually be expected.

How standard fire resistance can be related to fire resistance in practice has been introduced, in principle, in a previous study.[13] In the present paper the method is applied to structural steel protected by materials having various thermal properties. The influence of fire severity on the fire performance of steel members, as well as the influence of other important factors that determine their fire resistance, are examined.

## FACTORS AFFECTING FIRE SEVERITY

It is known that the temperatures reached in a room fire and their duration are determined by such factors as quantity, nature, dimensions, and configuration of the combustible materials, the dimensions of the room, and the openings through which air, necessary for combustion, can enter the room.[4,5,7,14,15,19,20]

At present it is possible to estimate the fire temperature course if the values of the various factors that determine it are known. However, several factors, such as amount and dimensions of combustible materials, are unpredictable in practice, because they change with time and often vary from room to room in a building. It is not possible, therefore, to know at the time a building is constructed the temperature course to which a member may be exposed should fire occur during the service life of the building.

It is possible, however, to make conservative assumptions with regard to the values of various uncertain factors and to derive fire temperature-time curves that probably will not be exceeded in the event of a fire. This is the case, for example, if the fire is controlled by the amount of air entering the room, which, in turn, is determined by the dimensions of openings into the room. For such fires, which are known as ventilation-controlled fires, the number of factors that determine the temperature course can be reduced to three:[9]

1. The opening factor, $F$, defined as:

$$F = \frac{A_w\sqrt{H}}{A_T} \quad \text{(see Ref. 7)}$$

where
$A_w$ = area of openings in the room
$H$ = height of openings in the room
$A_T$ = area of internal bounding surfaces (walls, floor, and ceiling)

2. The fire load, $Q$, which may be defined as the amount of combustible material per unit area of the internal bounding surfaces
3. A factor, $C$, that takes into account the influence of the thermal properties of the bounding material on the fire temperature course

An analytical expression exists for the dependence of the temperature of ventilation-controlled fires on these three factors.[9] Figure 1 shows (for an opening factor of $F = 0.009$ ft$^{1/2}$) how fire load affects the fire temperature course. In general, the duration of the fire increases with the fire load, and the intensity of the fire increases with the opening factor. The wall material also affects the intensity of the fire. The better the insulating quality of the walls, the higher the temperature in the room. The influence of the wall material, however, is relatively small in comparison with that of the fire load and ventilation. In this study, therefore, a constant value of $C = 0$ will be assumed, rep-

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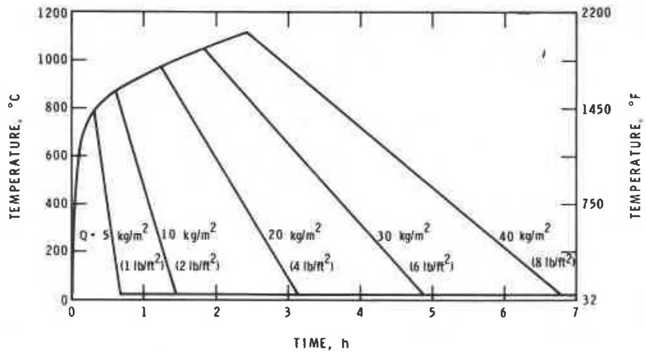


*Fig. 1. Characteristic fire temperature curves for various fire loads (Q)*

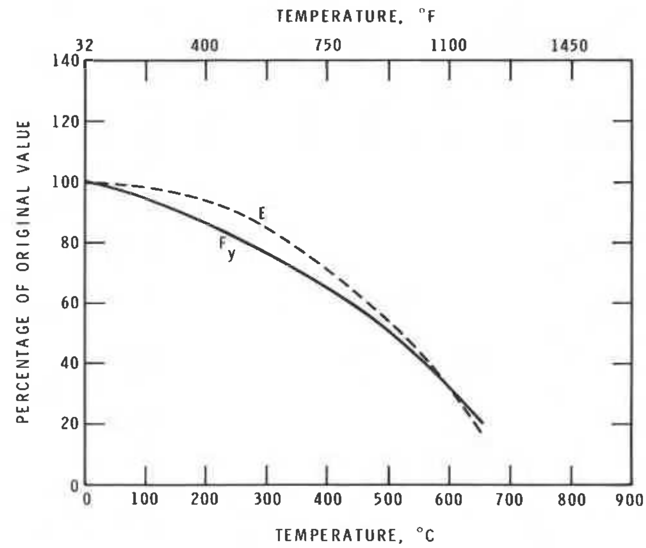


*Fig. 2. Yield strength ($F_y$) and modulus of elasticity (E) of carbon steels as a function of temperature*

resenting a heavy wall material such as normal weight concrete and most clay and sand lime bricks. The influence of the two most important factors, i.e., fire load and ventilation, on the fire temperature course and the fire performance of steel members will be considered in more detail.

## CRITICAL STEEL TEMPERATURE AND CRITICAL FIRE LOAD

It is known that the strength and rigidity of steel decreases when it is heated to elevated temperatures. In Fig. 2, curves derived from existing data[12] illustrate how these properties vary with temperature. If the duration of the fire is sufficiently long, a point will be reached at which the member can no longer perform its load-carrying function. The average temperature of the cross section of a steel member at which this occurs is defined as the *critical temperature.*

Whether, during a fire, the steel temperature rises to the critical temperature depends to a large extent on the fire load. The higher the fire load the longer the duration of the fire and the higher the maximum steel temperature. If there is sufficient fire load, the critical temperature will be reached. A fire load that is just sufficient to raise the steel temperature to the critical temperature is defined as the *critical fire load.*

The critical temperature of steel members depends on several factors. For steel beams, the most important are loading, steel properties, and end conditions. In general, the critical temperature of beams fixed at the ends is higher than that of simply supported beams. For columns, the same factors also play an important role in determining the critical temperature, with the addition of the slenderness of the column.

A survey indicates that, owing to the influence of various factors, the critical steel temperature can vary over a wide range normally lying between 750 and 1200°F. For the purpose of this study, which is intended to examine the influence of fire load and ventilation on the fire performance of protected steel, it will be assumed that the critical temperature of the steel is given. In this case, it will be assumed that the critical temperature of the steel is 1000°F, which is equal to the critical temperature specified by ASTM E119[1] for steel beams and columns.

If the critical temperature is known, determination of the length of time a specific steel member can resist exposure to fire can be simplified to calculation of the temperature rise of the steel and determination of the time to reach the critical steel temperature.

## METHOD OF CALCULATING STEEL TEMPERATURE

Recent developments, particularly with respect to numerical techniques, have made it possible to calculate accurately the temperature of fire-exposed protected steel members. In this study, a procedure based on a finite difference method is used for the calculation of the steel temperature. The method is described in detail in Ref. 11, and will therefore not be discussed here. Using it, it is possible to predict the temperature of steel with an accuracy of better than 1 percent if the material properties of the protection are known precisely. In practice, this is usually not the case and the accuracy is less.

Accuracy of prediction of steel temperatures is illustrated in Figs. 3 to 5, where calculated results are compared with experimental results for a number of steel sizes and protecting materials. In Figs. 3 and 4, measured and calculated temperatures are compared for protected steel exposed to heating in accordance with the standard temperature-time relation specified in ASTM E119.[1] In Fig. 5, the comparison is for a steel member exposed to heating according to a temperature-time curve that more closely resembles an actual fire temperature curve. The graphs indicate that

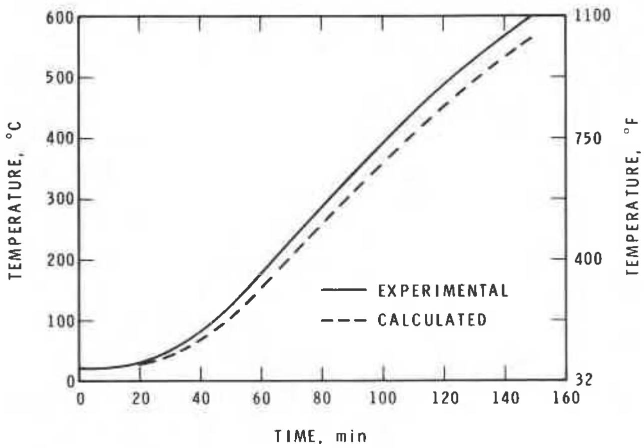


*Fig. 3. Steel temperature as a function of time (size steel core: 6 in. × 6 in.; insulation of insulating fire brick)*

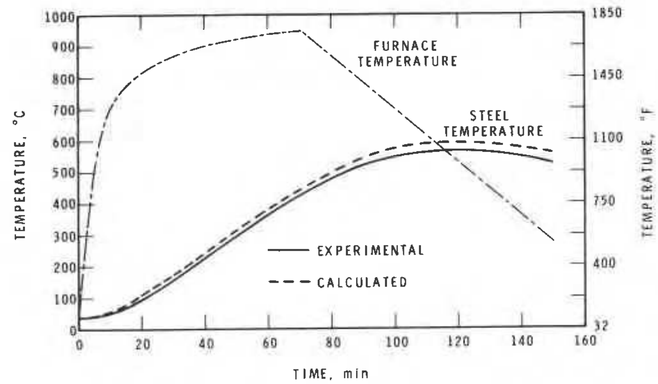


*Fig. 5. Steel and furnace temperature as a function of time (size steel core: 10 in. × 10 in.; insulation of vermiculite board)*

in the prediction of steel temperatures an accuracy of the order of 10 to 15 percent can be obtained, and this is adequate for practical purposes.

In investigating the influence of the various factors that determine fire resistance of protected steel members, hypothetical values were used for the material properties of the protection. Two sets of extreme values were selected to cover the wide range of properties of commonly used protecting materials, one set representing the thermal properties of a light insulating material of low conductivity and the other representing those of a heavy, more conductive material. The assumed volumetric specific heat and thermal conductivity of these materials were, respectively, 7.5 Btu/ft$^3$°F and 0.115 Btu/ft h°F for the lighter material, and 30 Btu/ft$^3$°F and 0.7 Btu/ft h°F for the heavier material.

In addition to dependence on the thermal properties of the protection, fire resistance also depends on the thickness of the protection and the size and shape of the steel. It has been shown[12] that the influence of the size and shape of the steel and that of the thickness of the protection can be taken into account by one combined factor, $Ml/A$, where

$M$ = mass of the steel section per unit length
$A$ = area of the protection at the interface between protection and steel through which heat is transferred to the steel, per unit length
$l$ = thickness of the protection

In general, the fire resistance of a protected steel member increases with this factor, since a higher factor means more mass ($M$) of the steel to be heated, thicker protection ($l$), or less area ($A$) through which heat can be transferred to the steel. How this factor affects the fire performance of a steel member will be examined further for various practical conditions.

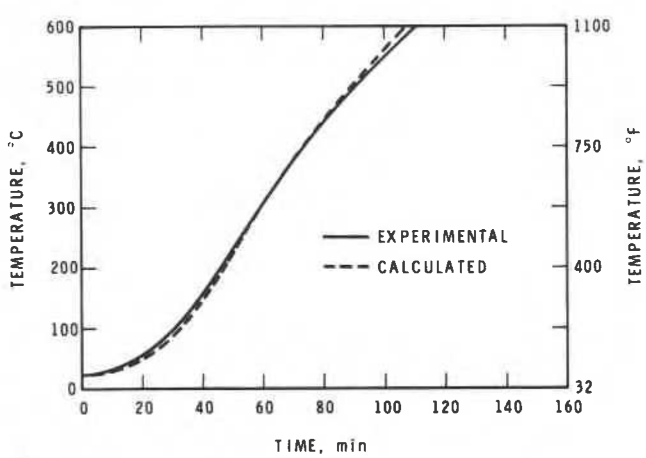


*Fig. 4. Steel temperature as a function of time (size steel core: 8 in. × 8 in.; insulation of heavy clay brick)*

### CALCULATION OF CRITICAL FIRE LOAD

Figures 6 to 8 show the calculated critical fire loads for the two selected protecting materials as a function of $Ml/A$ for various opening factors and thicknesses of protection. It may be seen that the critical fire load increases as the opening factor increases, and that the increase is more pronounced for the higher opening factors. Increase of the critical fire load with opening factor means that the probability of failure of a protected steel member decreases with increasing opening factor of the building. This indicates that less fire resistance is required in buildings with a high opening factor than in buildings with a small opening factor.

The influence of the thickness of protection on the critical fire load is also strong. It is relatively more pronounced for low values of $Ml/A$, and affects the critical fire load in two ways: in Figs. 6 to 8, the critical fire load varies not only with the factor $Ml/A$ (which comprises the thickness of the protection), but to a lesser degree with thickness, if it varies

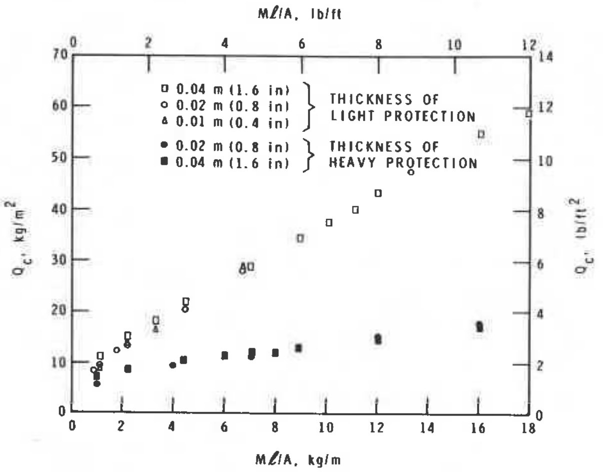


*Fig. 6. Critical fire load as a function of Ml/A for a low opening factor ($F = 0.036\ ft^{1/2}$)*

independently without changing the value of $Ml/A$. This illustrates the well known fact that insulation has a stronger effect on fire performance of steel than does the mass and geometry of the steel section.

The results in Figs. 6 to 8 indicate that the influence of the various factors determining critical fire load for protected steel members can be given, approximately, by an expression of the form

$$Q_c = \left(C_1 \frac{M}{A} + C_2\right) l \qquad (1)$$

where $C_1$ and $C_2$ are coefficients depending on the opening factor and the thermal properties of the protection, and $M/A$ is the well known size and shape factor of the steel.

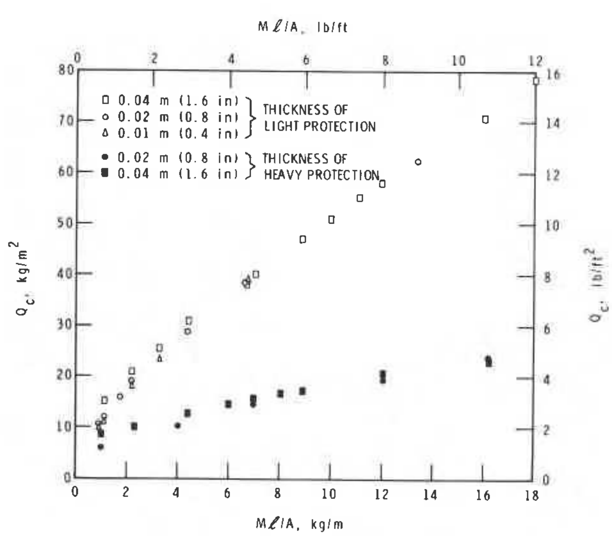


*Fig. 7. Critical fire load as a function of Ml/A for an intermediate opening factor ($F = 0.09\ ft^{1/2}$)*

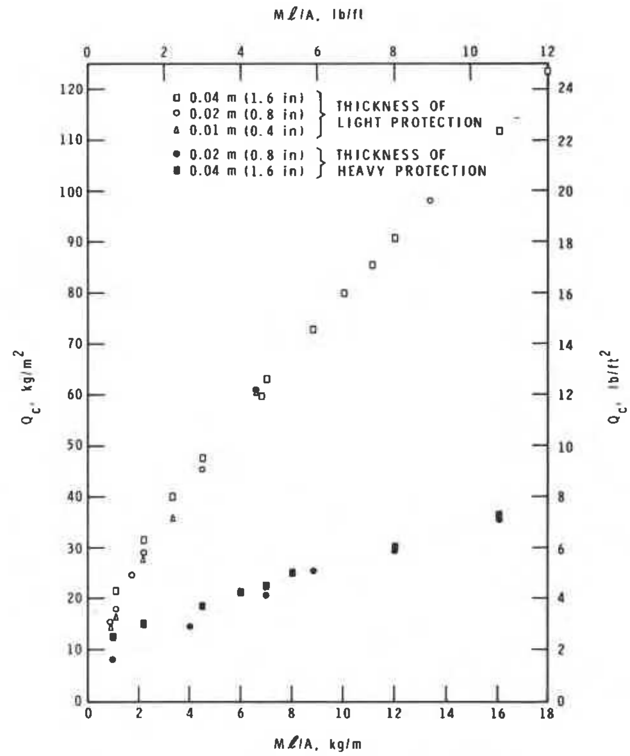


*Fig. 8. Critical fire load as a function of Ml/A for a large opening factor ($F = 0.18\ ft^{1/2}$)*

In the following, an attempt will be made to correlate critical fire load and ventilation factor, using results of previous work. Studies[12] have already shown that the standard fire resistance of a protected steel member can be given, approximately, by a relation similar to that of Eq. (1), i.e.,

$$R = \left(K_1 \frac{M}{A} + K_2\right) l \qquad (2)$$

where $R$ is the standard fire resistance of the member and $K_1$ and $K_2$ are coefficients. Experimental results[6,11] indicate that $R$ is also approximately proportional to $Q/\sqrt{F}$. It can be deduced that a more or less linear relation may exist between the size and shape factor $M/A$ and $Q_c/\sqrt{F}/l$.

Calculated values of $Q_c/\sqrt{F}/l$ have been plotted in Figs. 9 and 10 as a function of $M/A$. Although there is some scatter of points, it is possible to draw straight lines in such a way that nowhere is there a deviation of these points from the lines of more than 30 percent. Because of the many factors that determine the development of fire[9] and the performance of fire-exposed steel members, an accuracy of 30 percent in predicting the critical fire load of steel members is, for practical purposes, acceptable.

In the range investigated (Table 1), covering steel shapes and sizes, thermal properties and thicknesses of the protecting material, and the opening factors normally met with

Table 1. Range of Values of Variables Investigated

| Variable | Range |
|---|---|
| Opening factor | 0.036–0.18 $ft^{1/2}$ |
| Mass of steel | 33–1075 lb/ft length |
| Heated area of steel | 3.3–13 $ft^2$/ft length |
| Thickness of protection | 0.4–1.6 in. |
| Thermal conductivity of protection | 0.115–0.7 Btu/ft h °F |
| Volumetric heat capacity of protection | 7.5–30 Btu/$ft^3$ °F |

in practice, the relation shown in Figs. 9 and 10 of critical fire load and the factors that determine it can be given by an equation of the form

$$Q_c = \left(K_3 \frac{M}{A} + K_4\right) l\sqrt{F} \qquad (3)$$

where $K_3$ and $K_4$ are coefficients that depend on the thermal properties of the protection.

It is possible to derive for a particular protecting material, as for the two protecting materials selected in this study, the equation for critical fire load, if the thermal properties of the material are known. Often this is not the case and the only way to determine the critical fire load is by testing.

### RELATION OF CRITICAL FIRE LOAD TO STANDARD FIRE RESISTANCE

Tests are usually carried out by subjecting a specimen to heating according to a standard temperature-time curve until it fails.[1,3] The time to failure, known as the standard fire resistance, is determined during the test and used as a relative measure for the fire performance of the member. The standard fire resistance, however, does not give direct information on the critical fire load. To be able to express the fire performance of the member in terms of the critical fire load, the relation between the standard fire resistance and critical fire load must be known.

At present, empirical relations exist between fire load and the severity of fire it produces, expressed in terms of duration of exposure to the standard fire. Ingberg[6] found from experiments that a fire load of 10 lb/$ft^2$ floor area produces a fire with a severity approximately equivalent to that of a standard fire of 1-h duration; that 20 lb/$ft^2$ is equivalent to 2 h; 30 lb/$ft^2$ to 3 h; 40 lb/$ft^2$ to 4½ h; and 60 lb/$ft^2$ to 7.5 h. Thus, according to Ingberg, fire severity increases directly with fire load for the first 3 h. After that the relation between fire severity and fire load is linear, with a different slope.

This relation does not take into account the effect of ventilation on fire severity. It was examined in later studies by Law,[8] who introduced the following relation of fire severity, fire load, and ventilation:

$$t_f = C\left(\frac{L}{\sqrt{A_w A_T \sqrt{H}}}\right) \qquad (4)$$

where

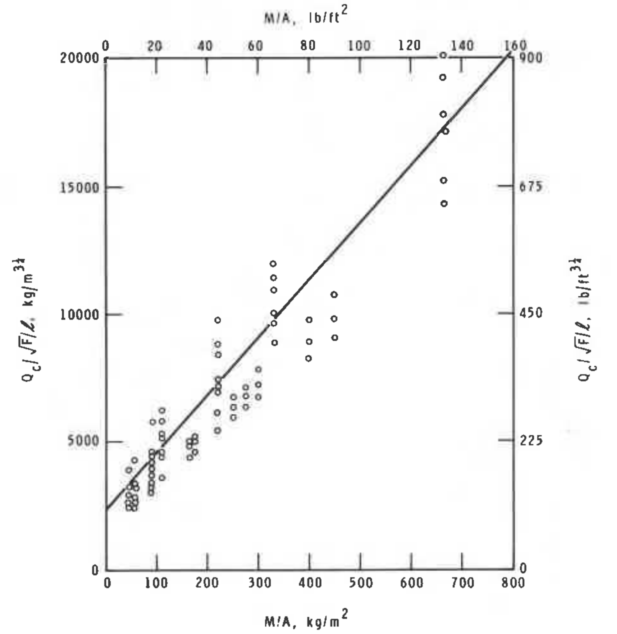


*Fig. 9. Relation of factors that determine the fire resistance of protected steel (light protection)*

$t_f$ = fire severity expressed as duration of exposure to a standard fire
$L$ = total fire load
$A_w$ = area of the openings in the room
$A_T$ = total bounding surface area of the room
$H$ = height of the openings in the room
$C$ = a coefficient

Based on the results of a large number of experimental fires, Law derived that for protected steel Eq. (4) can be given as

$$t_f = 0.077 \frac{L}{\sqrt{A_w A_T}} \qquad (5)$$

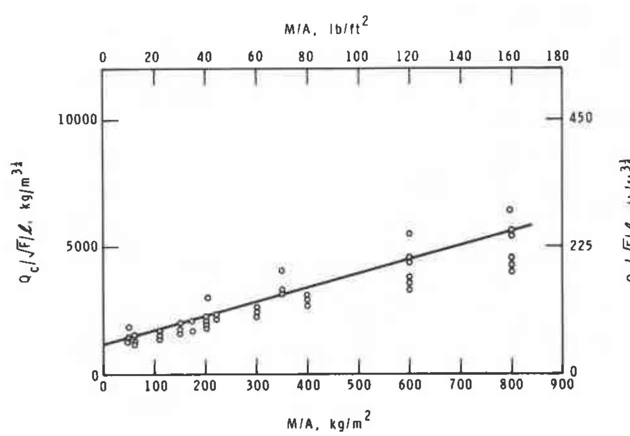


*Fig. 10. Relation of factors that determine the fire resistance of protected steel (heavy protection)*

In this derivation, it was assumed that the critical temperature of steel is 1020°F, and that the influence of window height $H$ is so small that it can be neglected. A relation similar to Eq. (4) was used by Pettersson,[16] based on a critical steel temperature of 930°F.

In the present study, the relation of fire load, ventilation, and fire severity is derived theoretically, using as a basis the heat and mass transfer equations that determine the temperature history in the fire compartment and in the steel member exposed to the fire. These equations are described in detail in Refs. 7, 9, 11, and will not be given here; only the results will be presented.

Values for a large number of calculations are shown in Fig. 11, covering a range of conditions normally met in practice with regard to opening factor, steel shapes and sizes, thermal properties of the protecting materials, and their thicknesses (Table 1). A critical steel temperature of 1000°F was chosen, which is the critical temperature specified in ASTM E119, implying that in this case fire severity is defined as the duration of exposure to the ASTM E119 standard fire required to raise the steel temperature to the critical value of 1000°F.

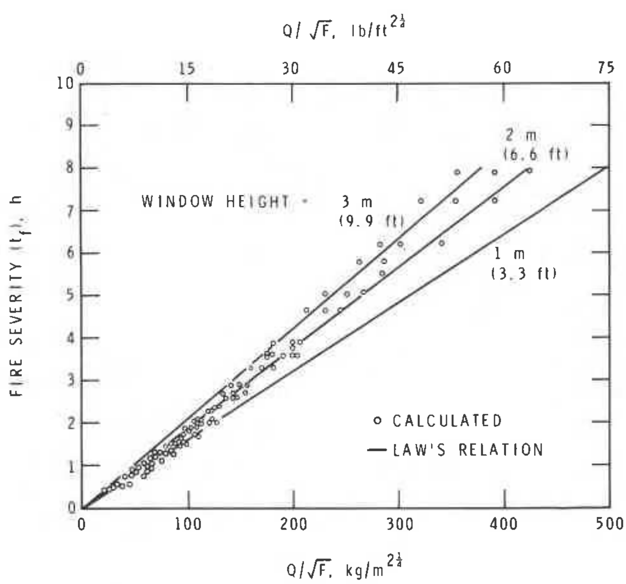


*Fig. 11. Comparison of Law's relation with calculated values*

In Fig. 11, the fire severity has been plotted as a function of $Q/\sqrt{F}$, where $Q$ is the fire load per unit bounding surface area of the room and $F$ is the opening factor. The quantity $Q/\sqrt{F}$ has been selected as a parameter because it is also the quantity that determines the fire severity $t_f$ in Law's Eq. (4), which can be transformed to the form

$$t_f = C \frac{Q}{\sqrt{F}} \tag{6}$$

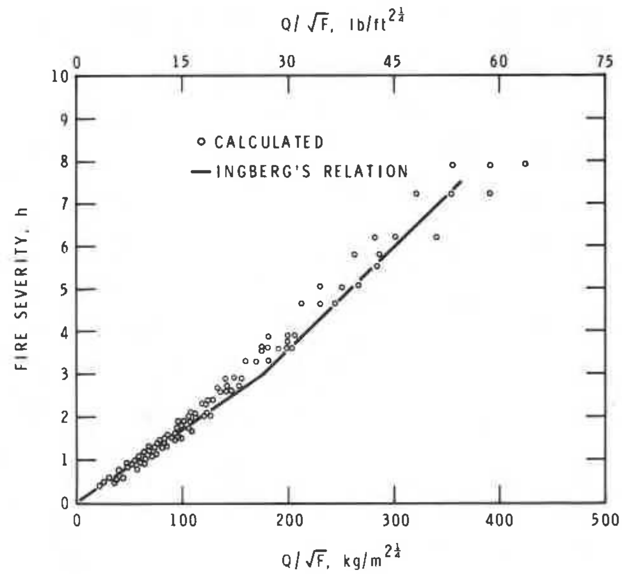


*Fig. 12. Comparison of Ingberg's relation with calculated values*

For comparison, Law's relation [Eq. (5)] has been plotted in Fig. 11. As the window height does not appear in this relation, it was modified to

$$t_f = 0.077 \frac{Q}{\sqrt{F}} (H)^{1/4} \tag{7}$$

and $t_f$ evaluated for three values of window height $H$: 3.3 ft, 6.6 ft, and 9.9 ft. It may be seen that for a window height of about 6.6 ft there is good agreement between calculated and experimental results. For greater heights the calculated fire severities are, on the average, somewhat lower than the experimental fire resistances. For smaller heights, calculated fire severities are somewhat higher than the experimental values. As expected, however, the influence of window height on fire severity is relatively small from a practical point of view.

Figure 12 compares calculated fire severities with those given by the Ingberg relation. Unfortunately, accurate information on the opening factor $F$ for Ingberg's tests is not available. It is possible, however, to estimate it by assuming that Ingberg's relation is a particular case of Law's more general relation, given by Eq. (7). In this case there is a certain value of the opening factor for which both relations are identical. Substituting in Eq. (7) the value of $Q$ in Ingberg's experiment (2.7 lb/ft$^2$ bounding surface area of the room for each hour fire duration)[6,18] and $H$ = 5 ft, gives for the opening factor the value $F = 0.1$ ft$^{1/2}$.

Analysis of the available information on the test room used by Ingberg and the test results indicated that this is a reasonable value for the opening factor. According to existing information the window area was 84 ft$^2$ during the tests. As the bounding surface area of the test room was 1600 ft$^2$, the opening factor would be 0.117. In Ingberg's experiment, however, the windows were partially closed, so that the opening factor was lower than 0.117. On the other hand, the temperatures reached in the room were higher than those of the standard fire temperature curve and indicate that the opening factor must have been more than, for example, 0.07. It would not have been possible, otherwise, to produce in a concrete enclosure the temperatures measured during the test. Using an opening factor of $F = 0.1$ ft$^{1/2}$, it may be seen in Fig. 12 that there is a good agreement between the Ingberg relation and the calculated values.

The comparisons indicate that there is reasonable agreement between the experimental and calculated relations of fire load and fire severity. Using these relations as a basis, it is possible to develop for protected steel members a correlation between the critical fire load under practical conditions and the fire resistance under standard test conditions. In actual practice, however, many more factors affect both fire severity and fire resistance than those taken into account so far; for example, fire severity is affected by fire load surface area, fire load arrangement, wind, and the properties of the walls of the fire compartment; fire resistance is affected by structural load, restraint, slenderness of columns, and actual thickness of protection, which often differs from that specified. Their influence may be substantial. They may, for example, cause deviations of the order of 50 percent from the predicted fire severity or fire resistance. In comparison with the influence of the two most important factors, fire load and opening factor, that can have values, in practice, in a range extending over a factor of 10, their influence is relatively small. It is justifiable, therefore, to express the correlation between critical fire load and fire resistance only in terms of the most important factors, and to take into account the influence of the other factors, which are often unpredictable and uncontrollable, by incorporating an appropriate factor of safety in the fire resistance requirements.

The following general correlation formula, expressing the relation of fire load, standard fire resistance, and opening factor, is suggested

$$R = 0.13 \frac{Q}{\sqrt{F}} \quad (8)$$

where $R$ is the standard fire resistance (hours) required to resist burn-out of a fire load $Q$ (lb/sq ft bounding area) in a compartment with an opening factor $F$ (ft$^{1/2}$).

If the standard fire resistance of a steel member is known, the critical fire load can be derived using this equation. The critical fire load $Q_c$ is given by

$$Q_c = 7.6 R\sqrt{F} \quad (9)$$

In Fig. 13, Eq. (8) is compared with calculated values. The comparison indicates that Eqs. (8) and (9) may be applied with good confidence in the 1- to 4-h range, the range in which most fire resistance problems of practical significance lie.

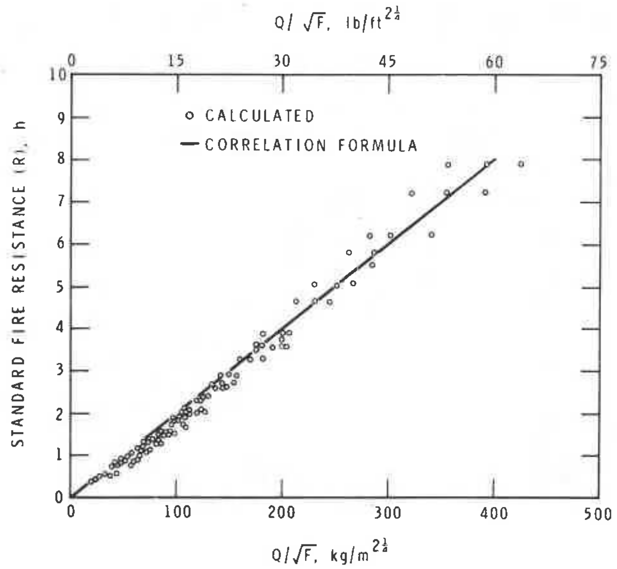


*Fig. 13. Comparison of suggested correlation formula with calculated values*

The somewhat higher standard fire resistances given by Eq. (8), in comparison with calculated values, also permit its use, along with Eq. (9), for protection thicknesses greater than the maximum thickness of 1.6 in. investigated. As can be seen in Figs. 14 to 16, the standard fire resistance required to withstand burn-out of a specific fire load increases slightly if the thickness of the protection is increased. Although the range of opening factors investigated, i.e., 0.036 to 0.18 ft$^{1/2}$, will normally cover those met in practice, Eqs. (8) and (9) may also be used for extremely small or for large opening factors. As can be shown by replotting the data in Figs. 14 to 16, the results will lie on the safe side in these cases.

## APPLICATION OF CORRELATION FORMULAS

It is possible to determine the critical fire load for a member directly by solving the basic heat and mass transfer equations for the fire in the compartment and the fire-exposed steel member. The method, however, is complicated and requires a fast computer and knowledge of the thermal properties of the protection, which is, at present, often inadequate. At this stage, therefore, the method is not very suitable, although in the future it might be the shortest way to determine the fire performance of structural members.

A more practical method of determining the critical fire load of a member is to determine the standard fire resistance of the member and convert it to critical fire load, using the correlation formulas. This method is particularly useful because there is a large amount of information on the standard fire resistance of protected steel and many facilities available for determining it.

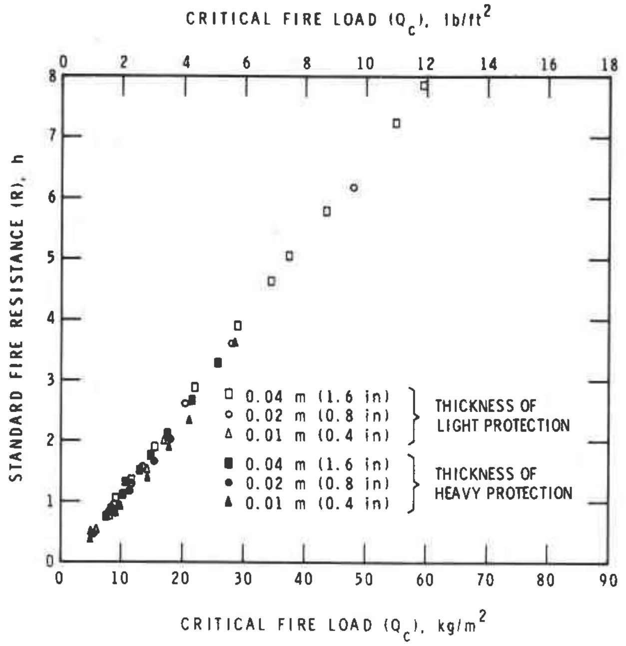


*Fig. 14. Relation of standard fire resistance (R) and critical fire load ($Q_c$) for an opening factor $F = 0.036\ ft^{1/2}$*

In the following, examples will be given of the use of correlation formulas for fire resistance design of steel members. A 10-story office building of average size will be considered. Each story may be regarded as a fire-resisting compartment. From data of fire load surveys,[2] it can be derived that the mean fire load in each story of an office building is about 2 lb/ft$^2$ bounding area. A typical fire load safety factor for a 10-story building of average size is 2.[10] Assuming that this safety factor also applies to the building under consideration, the design fire load can be put at 4 lb/ft$^2$ bounding surface area.

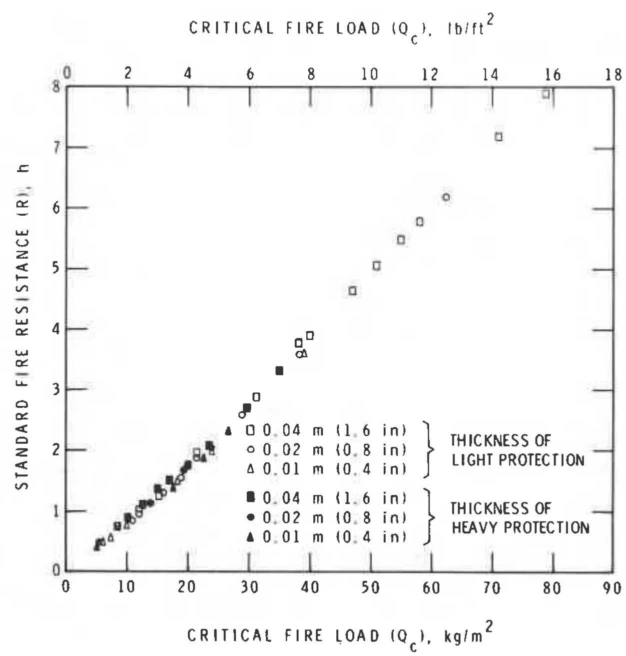


*Fig. 15. Relation of standard fire resistance (R) and critical fire load ($Q_c$) for an opening factor $F = 0.09\ ft^{1/2}$*

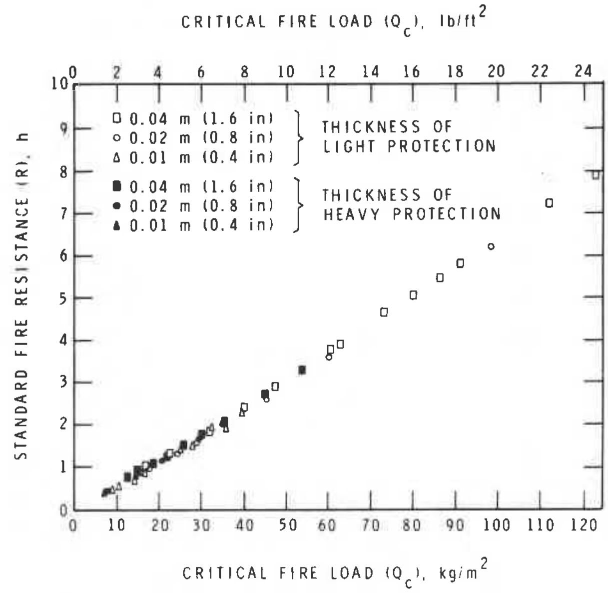


*Fig. 16. Relation of standard fire resistance (R) and critical fire load ($Q_c$) for an opening factor $F = 0.18\ ft^{1/2}$*

### Example 1

*Given:*

| | |
|---|---|
| Floor area of story: | 160 × 160 ft |
| Height of story: | 10 ft |
| Window area: | 2000 ft$^2$ |
| Window height: | 5 ft |

The task is to determine the fire resistance required to withstand burn-out of the design fire load.

*Solution:*
According to Eq. (8), the standard fire resistance $R$ required to withstand burn-out of a fire load $Q$ is

$$R = 0.13 \frac{Q}{\sqrt{F}} \tag{8}$$

where

$$F = \frac{A_w \sqrt{H}}{A_T}$$

Using the given information, it can be derived that:

$$A_T = 2\,(160 \times 160) + 4\,(160 \times 10) = 57{,}600\ \text{ft}^2$$

Substituting values of $A_T$, $A_w$, and $H$ for the opening factor gives:

$$F = \frac{2000\sqrt{5}}{57{,}600} = 0.078\ \text{ft}^{1/2}$$

Substituting values of $F$ and $Q$ in Eq. (8) for the fire resistance gives:

$$R = 0.13 \frac{4}{\sqrt{0.078}} = 1.9 \text{ h}$$

Thus, for the building under consideration a standard fire resistance of 1.9 h is adequate to withstand burn-out of the design fire load.

**Example 2**—One method of determining the standard fire resistance of structural members in the building is by testing. For various protecting materials, however, the relation between the standard fire resistance of a member and the factors that determine it is known. In such cases the conditions, for example, the thickness of protection to obtain the required fire resistance, can be determined by calculation. In the following, an example will be given of the method of calculation of the required thickness for columns protected by a specific protection.

*Given:*
In this example it will be assumed that the building is supported by W-type steel columns, and that they are protected by a box type encasing of vermiculite board. The size of the cross section of the column is 1 ft × 1 ft and the mass of the steel is 160 lb/ft length.

*Solution:*
For the protection under consideration it has been established[12,17] that the standard fire resistance of a column protected by this material is given approximately by the relation

$$R = \left(0.75 \frac{M}{A} + 6\right) l \qquad (10)$$

In this example, the values of $R$, $M$, and $A$ are, respectively:

$R = 1.9$ h
$M = 160$ lb/ft column length
$A = 4 \times 1 = 4$ ft$^2$/ft column length

Substituting these values in Eq. (10) and rearranging gives:

$$l = 0.053 \text{ ft}$$

or

$$l = 0.64 \text{ in.}$$

Thus, a protection of 0.64 in. thickness will provide the desired fire resistance.

## CONCLUSIONS

With an accuracy adequate for practical purposes, the following conclusions may be drawn regarding protected steel members:

1. There is approximate agreement of computed results with Ingberg's experimental relation for fire load and fire severity, and with that of Law for fire load, fire severity, and ventilation.
2. It is possible to develop simple design formulas for the calculation of the performance of protected steel members under standard fire test conditions, as well as in natural fires.
3. The severity of standard test fires can be related to those met with in practice using the equation $R = 0.13\, Q/\sqrt{F}$, where $R$ is the standard fire resistance, $Q$ the fire load per unit bounding surface area of the compartment, and $F$ the opening factor.
4. The fire load that a member can resist in a burn-out fire, i.e., the critical fire load, is proportional to the standard fire resistance of the member and to the square root of the opening factor of the compartment.
5. Both the critical fire load and the standard fire resistance increase directly with the thickness of the protection and linearly with the size and shape factor, $M/A$, of the steel.


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