An Investigation of the Reduction in Fire Resistance of Steel Columns Caused by Loss of Spray-Applied Fire Protection

NOAH L. RYDER,[1] STEVEN D. WOLIN[2] AND JAMES A. MILKE[3,]*

[1]*Combustion Science and Engineering, Columbia, MD, USA*

[2]*Code Consultants, Inc., St. Louis, MO, USA*

[3]*University of Maryland, College, Park, MD, USA*

ABSTRACT: The effect of the loss of fire protection material on the fire resistance of steel columns is examined. A three-dimensional finite element heat transfer analysis is conducted to simulate the ASTM E119 fire resistance test. The predicted temperature distributions within the member over time are used in conjunction with the thermal endpoint criteria specified in ASTM E119 to provide an estimate of the fire resistance of the member. Several variables are then examined with respect to their effect on the fire resistance of a member. For a given exposure, the area of the missing protection and the size of the column are found to have an appreciable effect upon the fire resistance of the column regardless of the protection thickness. The area of the missing protection seems to be the primary factor in the temperature rise and fire resistance assessment of the column. The temperature rise in the column is primarily sensitive to the amount of missing protection, with the size of the column gaining significance only later in the test.

KEY WORDS: fire resistance, spray-applied protection, missing protection, steel columns.

INTRODUCTION

THE STANDARD TEST for the fire resistance of structural members, ASTM E119, provides for a furnace test of structural members and a failure criteria specified by temperature within the member [1]. Because the ASTM E119 test for steel columns is rarely run with an applied load, the temperature endpoint criteria (649°C at a single point and an average temperature of 538°C) are the governing criteria for assessing the fire

*Author to whom correspondence should be addressed. E-mail: milke@eng.umd.edu

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resistance of steel column assemblies in most cases. One method of protecting steel columns is through the use of a spray-applied fire protection material. Several such materials are listed in the Underwriters Laboratories (UL) Fire Resistance Directory for use in the protection of steel columns from fire [2].

The ASTM E119 test is performed with the spray-applied coating in nearly pristine condition. The potential vulnerability of spray-applied fire resistive coatings to damage has been recognized for many years [3]. Even in the case of meticulous construction, small cracks would be expected to form in the coating during curing [2]. These cracks are required to be filled in according to the listing of the spray-applied product but, in practice, it may be difficult to provide a completely protected column. More significantly, spray-applied coatings may become damaged as a result of improper application, accidental damage during the course of normal construction or operations, or removal in order to make a connection to the column [3]. In each of these cases, the steel column is left partially exposed.

The intent of this study is to provide an estimate of the impact of the temperature rise within the steel column where some portion of the fire resistive coating is missing. Using the temperature endpoint criteria noted in ASTM E119, the differences in temperature rise noted are related to changes in the level of fire resistance. It is impractical to perform an analysis of every possible case of missing protection. Thus, an attempt has been made to provide not only an analysis of the specific cases examined, but also a generalized analysis that can be applied to a variety of situations. In addition, the methodology followed for the investigation described in this paper could be duplicated by a practising engineer for a specific case. The analysis of a single member in three dimensions, however, is extremely time consuming. The number of elements that need to be input into the model are in the order of 100 for a two-dimensional analysis, while a three-dimensional analysis requires elements into the thousands. Defining each of the elements and then entering the information into the program then becomes a much more daunting task.

Assessing the impact of the local temperature rise on the structural performance of the column is beyond the scope of this paper. However, it would be useful in performance-based analyses and to assess the appropriateness of the single point temperature criterion included in ASTM E119.

PREVIOUS WORK

This issue has been studied in a somewhat simpler fashion by Tomecek and Milke [4]. They performed a two-dimensional, finite element analysis of the heat transfer characteristics of a partially protected column using FIRES-T3 [5]. The limitation of using a two-dimensional model is that a section of protection material can only be removed along the entire length of the column instead of over a finite length. The advantages of a two-dimensional analysis are that it is much easier to implement and is far less computationally demanding.

Tomecek and Milke showed that a 4% loss of protection resulted in a 15% reduction in fire resistance for a one-hour rated W10 × 49 column and a 40% reduction in fire resistance for a two-hour rated W10 × 49 column. An important conclusion was that the reduction in fire resistance was not nearly as severe for a more massive column. For instance, a W14 × 233 column showed only a 15% reduction in fire resistance with the loss of 4% of protection during a two-hour exposure. This is appreciably less than that experienced with the W10 × 49 column. Thus, the massiveness of the column appears to be an important factor in assessing the temperature rise of the column.

A three-dimensional analysis provides a more accurate depiction of actual situations involving missing protection, where the missing protection is limited to a small section of the column. The three-dimensional analysis preserves the protection along the remainder of the length of the column, providing more protected mass to dissipate the heat transferred through the unprotected portion of the column.

METHODOLOGY

The fire resistance of the column given an area of missing protection is controlled by two factors. The first is the time it takes for heat transfer to occur from the unprotected surface through the cross section of the column. The second is the dissipation of heat associated with the thermal capacity of the column. The interaction between these two factors for a given exposure determines the time it takes for the column to reach the thermal endpoint criteria specified in ASTM E119.

The three-dimensional analysis conducted by FIRES-T3 solves the heat diffusion equation using a finite element method and a piecewise integration technique. The governing partial differential equation is as follows.

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \qquad (1)$$

where x, y, and z are spatial coordinates, t is time, T is temperature, ρ is density, c_p is specific heat, k is thermal conductivity, and $\dot{q}$ is internal heat generation.

The temperature is a function of both space and time. The material properties, density, specific heat, and thermal conductivity are temperature dependent and thus also vary throughout the column assembly and as a function of time. Nonlinearities in the analysis due to varying material properties are considered using a discretized solution method.

The FIRES-T3 finite element program was used for this analysis. In FIRES-T3 the spatial variables are discretized by a finite element method and the time variable is discretized by a piecewise integration technique. A three-dimensional grid is created over the assembly being examined. Nodes are assigned to spatial coordinates and the nodes are then grouped into elements. Heat transfer properties are then assigned to each of the elements, depending on the material properties and location of the element. The surface boundary conditions are specified to represent a fire.

Convective and radiative heat transfer to the column are specified in order to recreate the environment of the ASTM E119 furnace. Convection is modeled using Equation (2) [5]:

$$q = CA(\Delta T)^n \tag{2}$$

where q is the rate of heat transfer (W), C is the convection constant ($W/m^2\,K^n$), A is the surface area of the element (m^2), ΔT is the temperature difference between the element and the environment (°C) and n is the convection exponent.

Radiation is modeled using Equation (3) [5]:

$$q = \sigma FA(\alpha_s \varepsilon_f T_f^4 - \varepsilon_s T_s^4) \tag{3}$$

where q is the rate of heat transfer (W), F is the view factor, A is the surface area of the element (m^2), α_s is the absorptivity of the surface, ε_s is the emissivity of the surface, ε_f is the effective emissivity of the furnace environment, T_f is the furnace temperature (K), and T_s is the surface temperature (K).

The convective and radiative heat transfer properties used as input for the model are provided in Table 1.

Implementing the problem in three dimensions makes the computation much more demanding. The computational effort for a FIRES-T3 calculation increases roughly with the cube of the number of nodes [5]. Several cases have recently been examined in the FIRES-T3 program using two-dimensional analysis of a large column cross section. The calculations took only a few minutes using a very fine grid. A three-dimensional analysis is far more demanding. Calculations of the three-dimensional columns

Table 1. Convective and radiative heat transfer properties.

Property	Value
Convection constant (W/m^2 K^n)	0.27
Convection exponent	1.25
Emissivity of furnace environment	0.8
Absorptivity and emissivity of surface	0.9
View factor	1.0

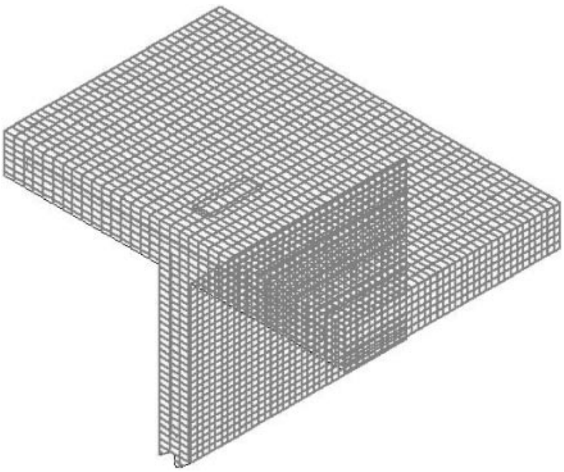

Figure 1. *Mesh representation of the structural column.*

examined in this project took from several hours to several days on a 650 MHz personal computer with 256 MB of RAM. Gigabytes of hard disk storage space are also needed during the calculation in order to store the operating system swap file which is generated to hold the calculation matrices. Creation and input of the grid into the program is far more time consuming for a three-dimensional case than a two-dimensional case. A portion of the column mesh is shown in Figure 1. The completed column had element volumes of approximately 0.256 cm^3 which resulted in the column being divided into approximately 63,000 elements.

The column assembly considered in this analysis consists of a steel column protected with a spray-applied fire protection material, such as that described in the listed design ULX738 [2]. The material properties used in the analysis are presented in Table 2.

An initial estimate of the necessary protection thickness was done using a one-dimensional heat transfer analysis. Lie and Stanzak determined that a

Table 2. Material properties.

	Conductivity (W/m-°C)	Specific Heat (kJ/kg-°C)	Density (kg/m³)
Steel			
20°C	51.9	0.448	7700
315°C	42.7		
400°C		0.602	
590°C	34.8	0.719	
1090°C	26.0		
1650°C		0.719	
Fire Protection Material			
20°C	0.0598	1.09	240
205°C	0.0598	1.09	
400°C	0.116	1.27	
1090°C	0.289	1.46	

simple equation could be created using a one-dimensional heat transfer analysis that allowed an estimate of the necessary fire protection thickness to be determined [6]. The solution is of the following form:

$$h = \frac{R}{C_1(W/D) + C_2} \tag{4}$$

where h is the protection thickness, R is the fire resistance, and W/D is the ratio of the weight of the steel column to the heated perimeter of the steel column. Constants for one protection material are noted in Equation (5).

$$h = \frac{25.4R}{0.179(W/D) + 0.61} \quad \text{for } W/D = 19 - 388 \tag{5}$$

where h is in mm, R is in hours, and W/D is in kg/m^2. The values for the constants are those included in ULX738 [2], based upon extensive test data gathered by UL.

The thickness is determined using Equation (5) for the case of full protection to attain a one-hour or two-hour fire resistance rating. The baseline cases analyzed as part of this study are summarized in Table 3.

The case with full protection could then be used as a baseline for the expected temperature profile within the column over time. The estimate of the protection thickness determined using Equation (5) was found to provide a fire resistance greater than the intended level. That is, according to

Table 3. Baseline column assembly designs.

	Thickness of Protection Material (mm)	
Column Shape	**1 h**	**2 h**
W6 × 16	22.9	45.7
W14 × 233	7.9	15.7

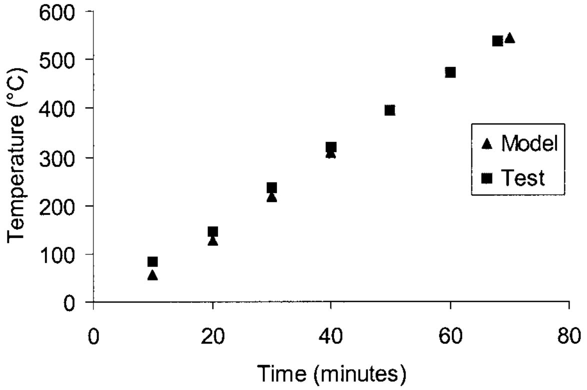

***Figure 2.** Average temperature of W10 × 49 steel column with 19 mm of protection.*

the FIRES-T3 analysis, the temperature of the steel column did not reach the thermal endpoint criteria until after the specified failure time.

Milke [7] and Gandhi [8] applied FIRES-T3 to analyze the heat transfer in steel column assemblies subjected to the ASTM E119 furnace test [7,8]. In both cases, the steel columns were protected with spray-applied materials. Using FIRES-T3, Milke determined that the predicted time for the average steel temperature to reach 538°C was within 13% of that determined from conducting the test. As an example, Figure 2 illustrates a comparison of the predicted average steel temperature versus that obtained from measurements for one column assembly. Gandhi has compared tests conducted at UL to calculations made using FIRES-T3 [7]. For protected steel columns, the failure time determined by FIRES-T3 and the experimental results agree within approximately 6%. The results of the analysis are therefore expected to be of sufficient accuracy for the current research.

RESULTS

The depth of the thermal penetration was examined in an effort to describe the degree of exposure of the member as a result of the missing protection. For instance, if a high temperature at the exposed surface of the column is quickly dissipated to give a near-uniform temperature over the cross section, then a failure criterion based upon a single point temperature at the surface may not be appropriate. Alternatively, if an elevated temperature at the surface is preserved, then the single point criterion at the flange surface is relevant to assessing fire resistance. Further, if the temperature distribution over the cross section was uniform, then an analysis of the problem might be conducted in two dimensions, a length and a radial dimension (i.e. distance from the centroid), rather than three dimensions.

The protection was removed as a strip on the top of the flange. This is depicted in Figure 3. A rectangular exposed area was used in keeping with the nodal scheme for the analysis. The missing protection extended across the entire width of the flange.

Figure 4 illustrates the exposed section on the web of the column. Once again, a rectangular section of protective material was removed. The length of the missing protection is along the entire height of the web except for a small part of the top and bottom where there is overlapping protection from the flange.

The temperature profile along the depth of the column, i.e., perpendicular to the flange in a direction toward the centroid of the column, is presented in Figure 5 at the elevation of the missing protection. This was done for a W6 × 16 column with 2 h of protection. A section of protective material, 7.7 cm^2 in area, was removed from the flange of the column. The profile is taken normal to the exposed surface.

Figure 5 shows a relatively uniform profile for the temperature distribution over the column cross section. This is consistent with the

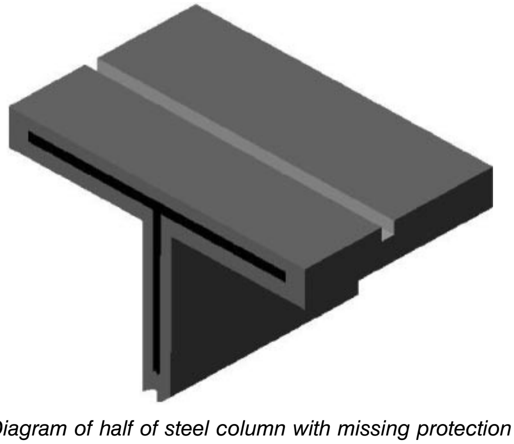

Figure 3. *Diagram of half of steel column with missing protection on flange.*

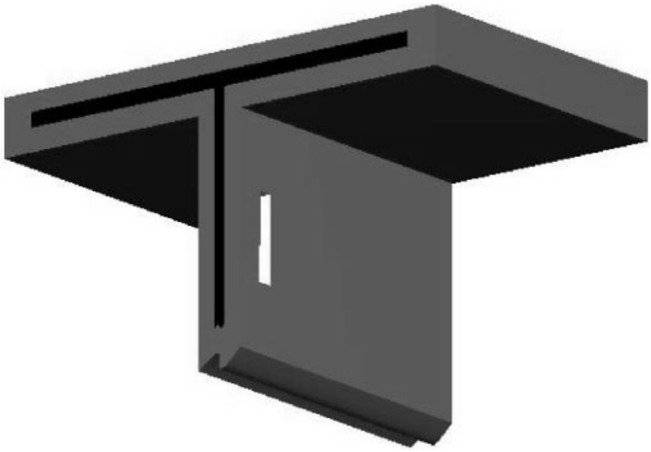

Figure 4. *Diagram of half of steel column with missing protection on web.*

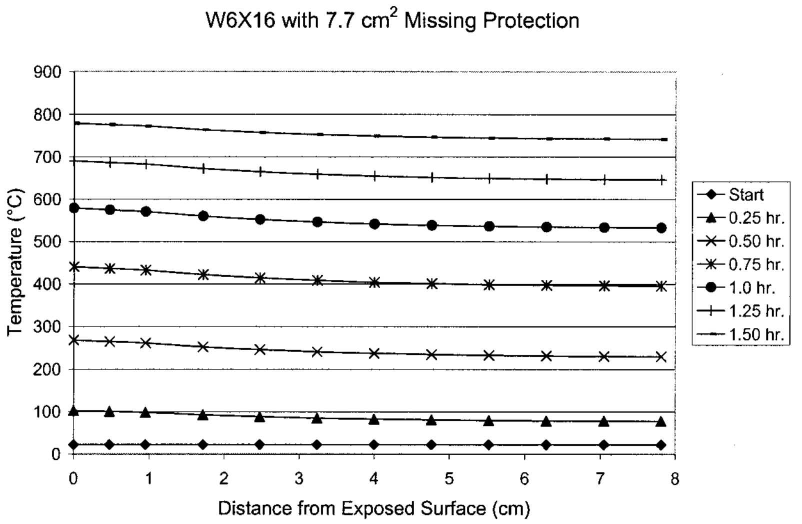

Figure 5. *Temperature profile perpendicular to the flange.*

results of Tomecek and Milke who found the reduction in fire resistance of a partially protected column to be dependent on the size of the column [4]. Since the temperature rapidly equilibrates over the cross section, the dissipation of heat by the mass of steel in that cross section is an important factor in maintaining the fire resistance of the column.

The temperature profile over the length of the column on the flange containing the missing protection is illustrated in Figure 6. The entire length of the column is not represented as the temperature rise at the exposed section of the column does not seem to significantly influence the temperature rise at distances more than 20 cm from the exposure.

The temperature rise at the surface of the column where the protection is missing provides a failure criterion for the column. Given the relative uniformity in the temperature along and through the column, the average temperature criterion is applicable for the assessment of fire resistance. The temperature rise of the exposed flange is plotted in Figure 7 along with the fully protected columns for a W6 × 16 column.

Very small areas of protection were removed from the column, yet a significant reduction in the level of protection occurred. Consequently, the temperature reaches 538°C in approximately 0.6 h for the one-hour design with 7.7 cm^2 of missing protection area, representing a 40% reduction in fire resistance for the one-hour protected column.

An interesting result is that the thickness of the protection material is negated when a partial loss of protection occurs. The temperature rise at the exposed surface then becomes a strong function of the area of the missing protection seemingly without regard to the original fire resistance rating provided by the protection.

The temperature rise was also plotted in Figure 8 as a function of time for missing protection on the web of the column.

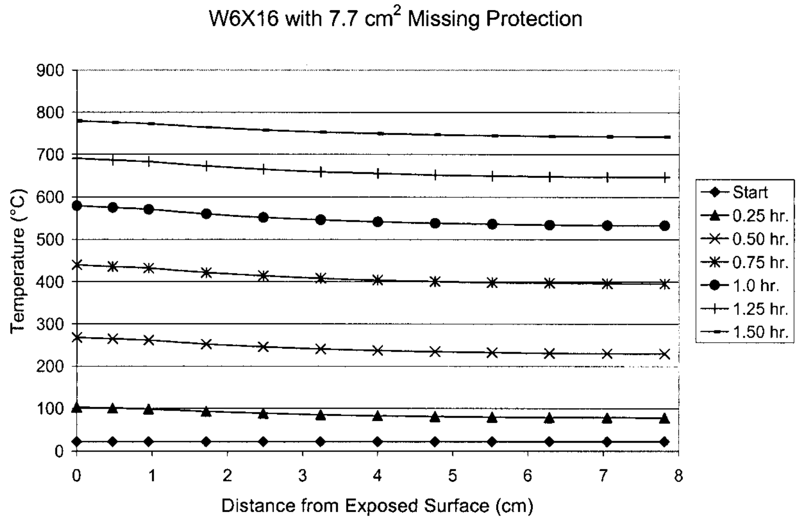

Figure 6. *Temperature profile over the column length.*

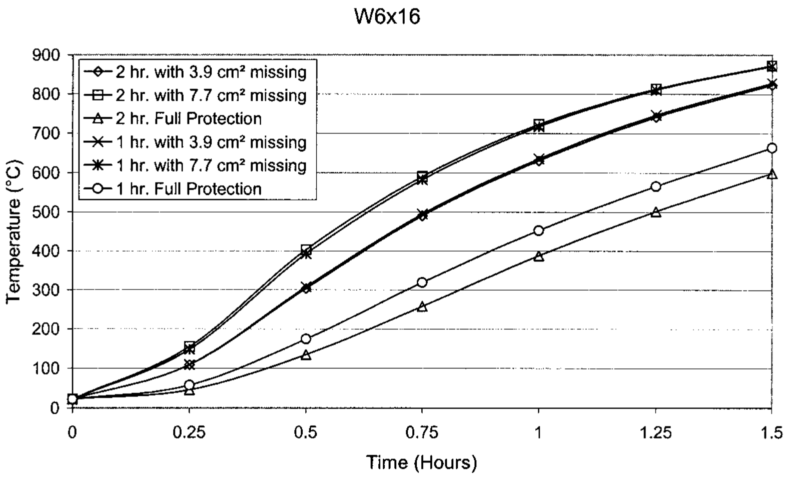

Figure 7. Temperature at exposed flange surface.

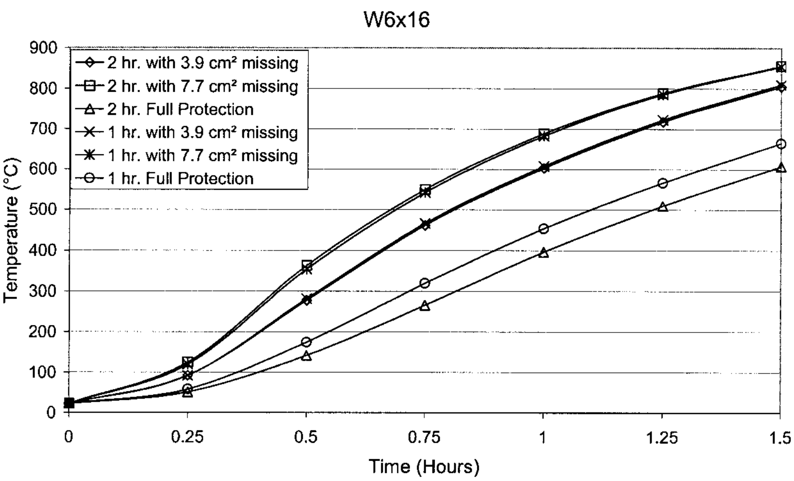

Figure 8. Temperature at exposed web surface.

The results obtained for the web exposure are similar to that for the flange exposure. This would be expected since identical thermal conditions exist at each surface. In practice, the location of the exposure may influence the failure time due to differing thermal conditions at different points on the surface of the column. In terms of the strength of the column for a given exposure, however, the location of the exposure should have little effect, as the temperature profile over the cross section of the column is relatively constant.

In addition to the W6 × 16 column, simulations were also conducted for a much more massive column. The results for two different areas of missing protection are given for a W14 × 233 column, along with the results for the W6 × 16 column, in Figure 9.

Initially, the temperature of the exposed flange surface seems to be primarily a function of the area of missing protection. As the temperature of the protected segments of the column rises, variation between the temperature rise for the different column sizes can be seen. The difference in performance between the larger and smaller columns, however, is not more than a few percent in terms of temperature rise. Also, the temperature of the exposed flange surface for the various levels of protection and column sizes seems to converge for long times.

Similar results are obtained for the web exposure. The temperature rise for the flange exposure is slightly higher than for the web exposure, though the difference would likely be insignificant in practice. Figure 10 illustrates the temperature rise at the exposed web surface for the different column sizes, levels of protection, and areas of missing protection examined.

The results obtained for the web comparison are similar to those obtained for the flange comparison. The temperature rise at the exposed surface seems to primarily be a function of the area of missing protection for times up to 1 h. Some divergence in the temperature rise for the different column sizes is apparent for longer times, but the difference does not seem to be particularly significant.

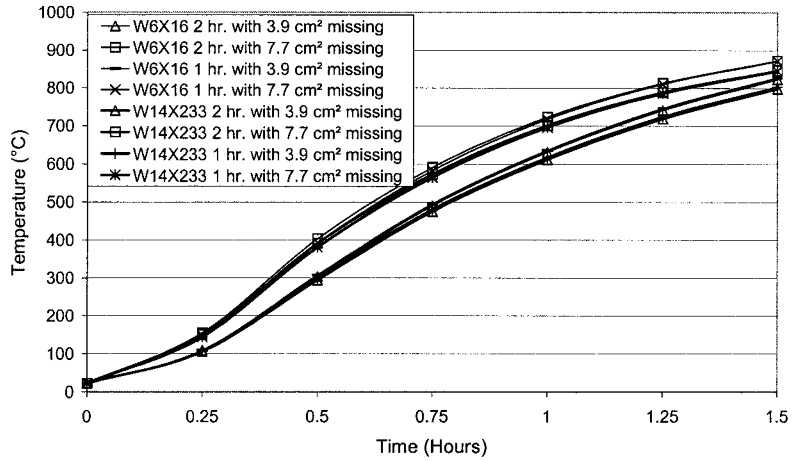

Figure 9. *Comparison of temperatures at exposed flange surface.*

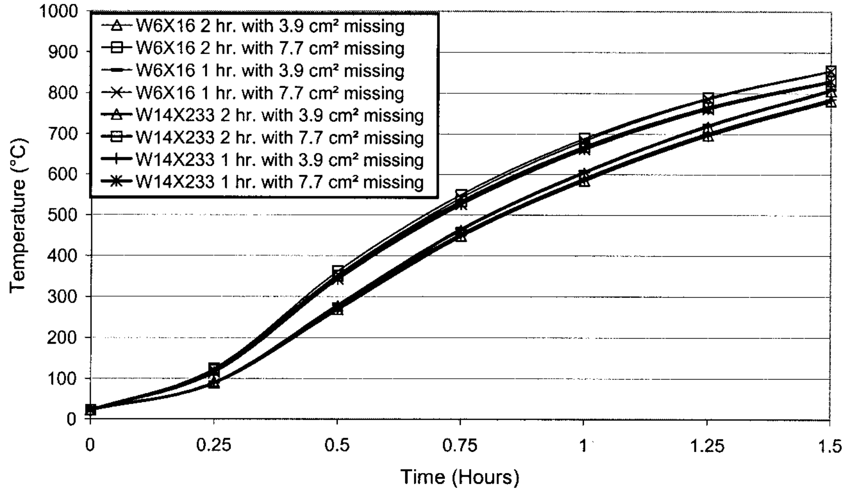

Figure 10. *Comparison of temperature at exposed web surface.*

CONCLUSION

The fire resistance of a column protected with a spray-applied fire resistant material can be severely diminished if even a small portion of the protection is removed. The extent of the reduction in fire resistance for a given exposure will be primarily a function of the area of the missing protection and, to some extent, the size of the column. A greater area of exposure will cause a greater temperature rise in the unprotected cross section. A more massive column will, to some extent, be able to better withstand the removal of protective material due to its increased thermal capacity. For short times, however, the protected portions of each of the column sizes are at similar temperatures. Thus, the column size is relatively insignificant until late in the test.

The results illustrate that the fire resistance of steel columns can be very sensitive to small changes in the degree of protection. The applicability of current evaluation methods for fire resistance seem to be incomplete without an examination of the reliability and level of risk involved with a particular fire protection method. That is, if a particular method of providing fire resistance has a propensity for damage and even small imperfections in the protection cause a significant change in the level of protection provided, then the effectiveness of the protection method is not realistically tested solely by a test of a fully protected column. The evaluation of the level of protection must then be considered in the light of the likely state of the protective material. In any case, vigilance is necessary to ensure that the level of protection characterized by the test method is obtained.

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