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

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Abstract

The effect of the loss of fire protection material on the thermal response of steel columns is examined. A three-dimensional finite element heat transfer analysis is conducted to simulate the heating conditions associated with 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. 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 thermal response of the column regardless of the protection thickness. The area of the missing protection seems to be the primary factor in the temperature rise 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.

Introduction

The standard test for the fire resistance of structural members, ASTM E119, describes a furnace test of structural members, with endpoint criteria specified by temperatures within the member [1], i.e. 538°C at a single point and an average temperature of 649 °C. 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 for 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 accordance with the listing of the spray applied product. However, 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 protection material is missing. Using the temperature endpoint criteria noted in ASTM E119, the differences in temperature rise are noted. It is impractical to perform an analysis of every possible case of missing protection. Thus, an attempt is 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, practicing engineers can apply the methodology described in this paper for a specific case. The three-dimensional analysis of a single member is extremely time consuming. The number of elements that need to be input into the model are on the order of 100 for a two-dimensional analysis, while a three-dimensional analysis requires thousands of elements. Defining each of the elements and 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, such would be useful in performance-based analyses of fire resistance and to assess the appropriateness of the single point temperature criterion included in ASTM E119.

Previous Work

Tomecek and Milke provided a two-dimensional analysis of the impact of missing fire protection material on the temperature rise on steel columns using FIRES-T3 [4,5]. 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 percent loss of protection resulted in a 15 percent reduction in the time to reach the thermal endpoint criteria for a one-hour rated W10X49 column and a 40 percent reduction in the time for a two-hour rated W10X49 column. An important observation was that the reduction in time was not nearly as severe for a more massive column. For instance, a W14X233 column showed only a 15 percent reduction in time with the loss of 4 percent of protection during a two-hour exposure. This is appreciably less than that experienced with the W10X49 column. Thus, the massiveness of the column appears to be an important factor in assessing the temperature rise of the column for missing protection as well as for a completely protected 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 E-119.

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. The governing partial differential equation is:

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

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

A three-dimensional grid is created for the assembly, with nodes assigned to spatial coordinates and the nodes grouped into elements. Heat transfer properties are assigned to each of the elements, depending on the composition and location of the element. Convective and radiative heat transfer conditions to the column are described the environment of the ASTM E119 furnace. Convection is modeled using Eq. (2) [5]:

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

where q is the rate of heat transfer (W), C is the convection constant, 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 Eq. (3) [5]:

$$q = \sigma F A \left(\alpha_s \varepsilon_f T_f^4 - \varepsilon_s T_s^4 \right) \qquad (3)$$

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 in the model are provided in Table 1.

Table 1. Convective and Radiative Heat Transfer Properties

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

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. A portion of the column mesh is shown in Fig. 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.

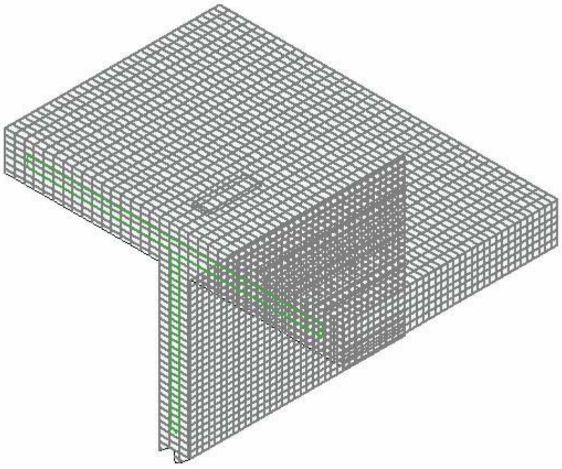

Fig. 1. Mesh Representation of the Structural Column

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 UL X738 [2]. The material properties used in the analysis are presented in Table 2.

Table 2. Material Properties

	Conductivity (W/m-°C)	Specific Heat (kJ/kg-°C)	Density (kg/m^3)
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	

An initial estimate of the necessary protection thickness was done based on the correlation developed by Lie and Stanzak resulting from a one-dimensional heat transfer analysis [6]. The form of the correlation is:

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

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

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

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 UL X738 [2], based upon extensive test data gathered by UL.

The thickness is determined using Eq. (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.

Table 3. Baseline Column Assembly Designs

	Thickness of Protection Material	
Column Shape	1 hour	2 hour
W6X16	22.9 mm	45.7 mm
W14X233	7.9 mm	15.7 mm

Milke [7] and Gandhi [8] applied FIRES-T3 to analyze the heat transfer in steel column assemblies subjected to the ASTM E-119 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 one example, Fig. 2 illustrates a comparison of the predicted average steel temperature versus that obtained from measurements for one column assembly. Gandhi found the time for the steel to reach the endpoint temperatures determined by FIRES-T3 was within approximately 6 percent of those determined from tests conducted at UL.

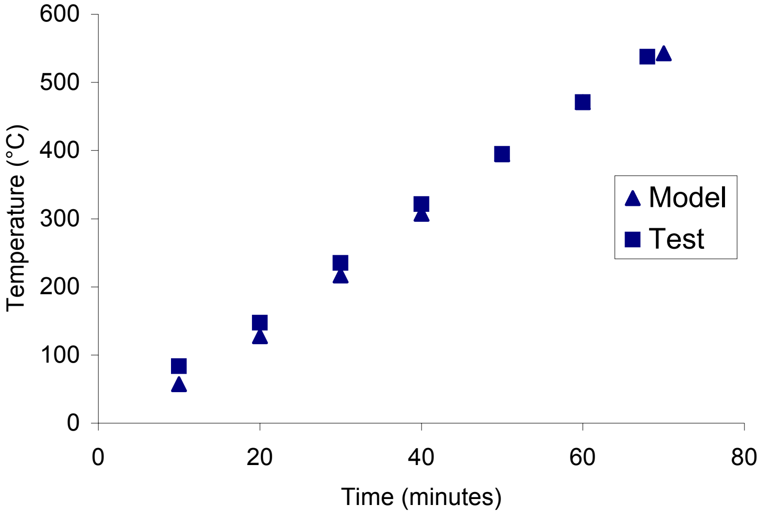

Fig. 2. Average Temperature of W10x49 Steel Column with 19 mm of Protection

Results

The depth of the thermal penetration is 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 is irrelevant. Alternatively, if an elevated temperature at the surface is preserved, then the single point criterion at the flange surface is relevant. Further, if the temperature distribution over the cross-section is uniform, then a two-dimensional analysis of the problem can, using a length and a radial dimension (i.e. distance from the centroid), rather than three-dimensional analysis.

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

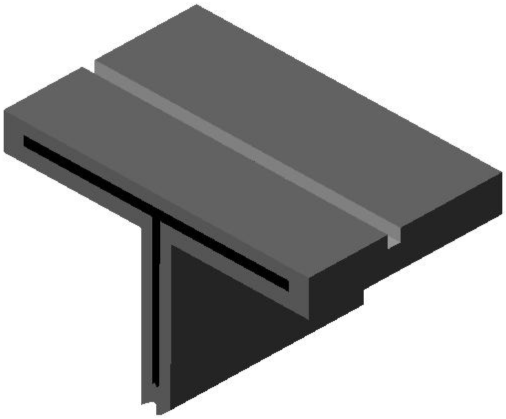

Fig. 3. Diagram of Half of Steel Column with Missing Protection on Flange

Fig. 4 illustrates the exposed section on the web of the column as a result of removal of a rectangular section of protection material. 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.

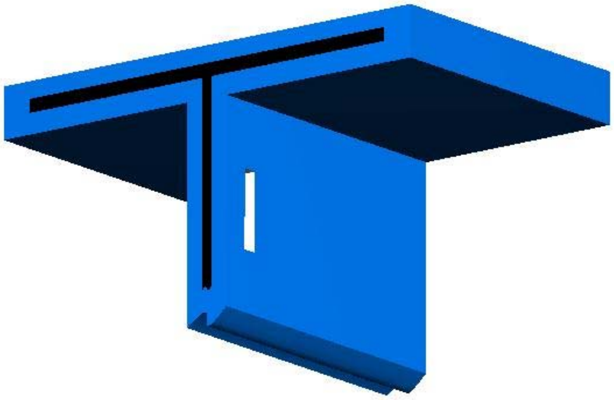

Fig. 4. Diagram of Half of Steel Column with Missing Protection on Web

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 Fig. 5 at the elevation of the missing protection for a W6X16 column with 2 hours of protection. A section of protective material 7.7 cm^2 in area is removed from the flange of the column. The profile is taken normal to the exposed surface.

Fig. 5 shows a relatively uniform profile for the temperature distribution over the column cross-section. This is consistent with the results of Tomecek and Milke where the reduction in fire resistance of a partially protected column is 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.

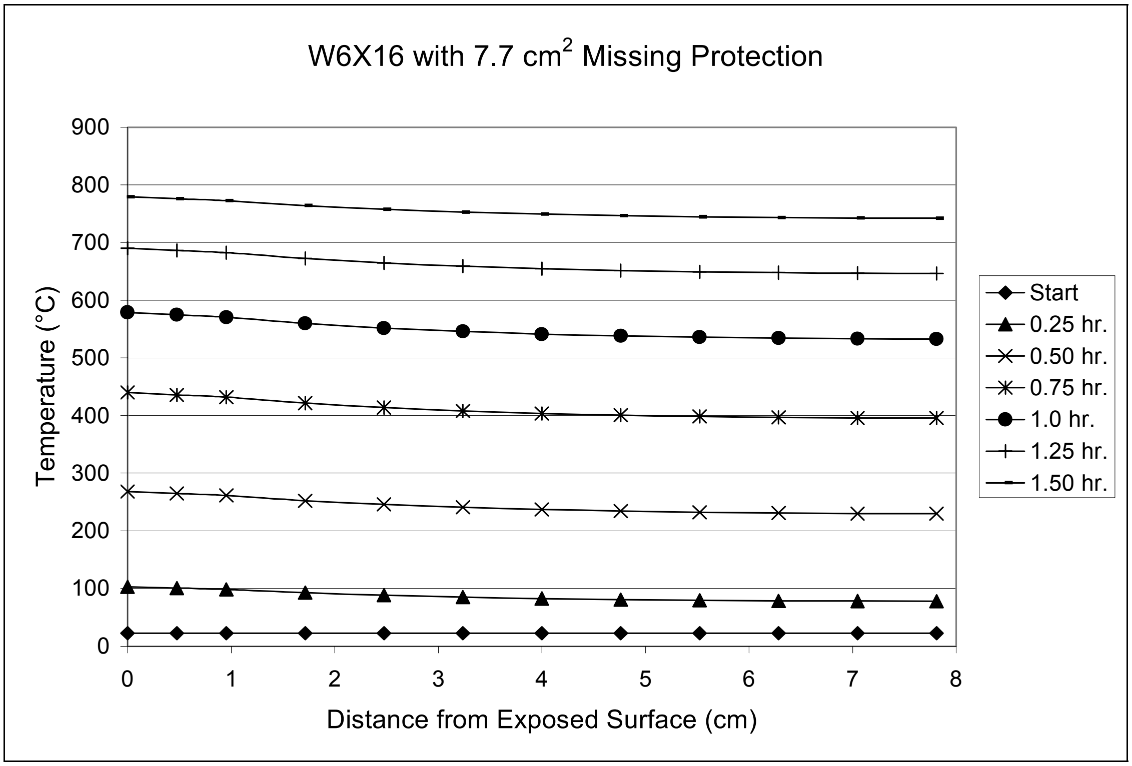

Fig. 5. Temperature Profile Perpendicular to the Flange

The temperature profile over the length of the column on the flange containing the missing protection is illustrated in Fig. 6. The entire length of the column is not represented because the temperature rise at the exposed section of the column is not significantly influenced by the temperature rise at distances more than 20 cm from the exposure.

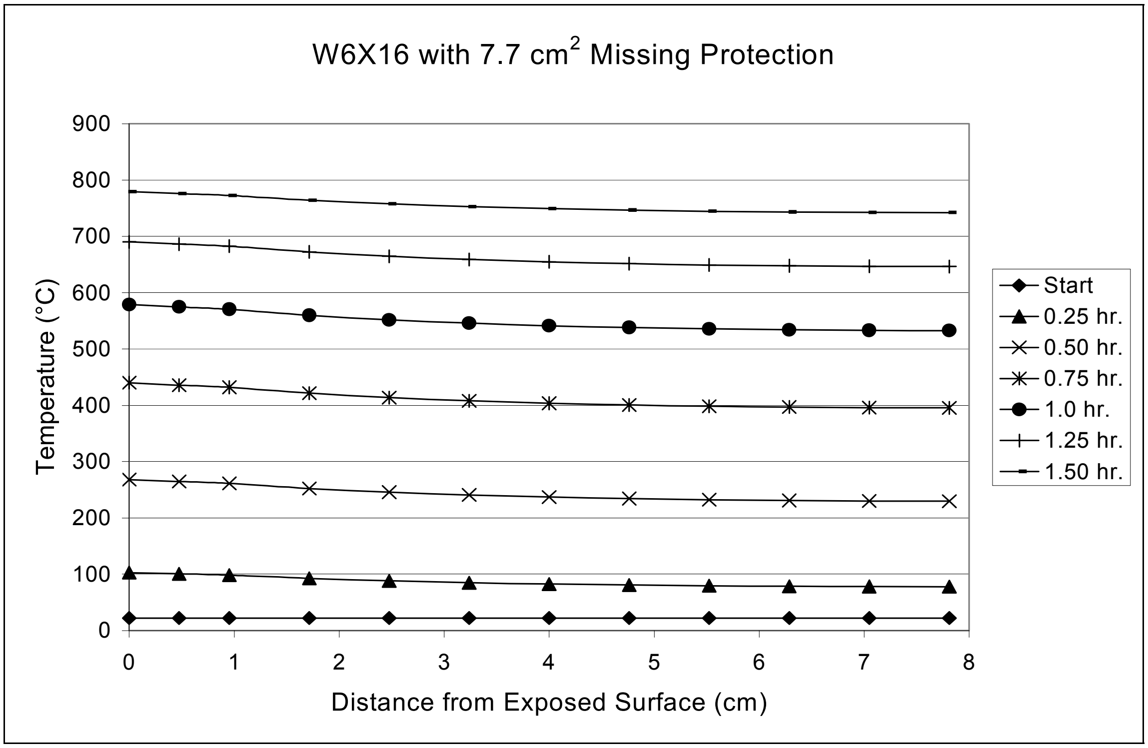

Fig. 6. Temperature Profile Over the Column Length

The temperature rise at the surface of the column where the protection is missing provides a failure criteria 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 Fig. 7 along with the fully protected columns for a W6X16 column.

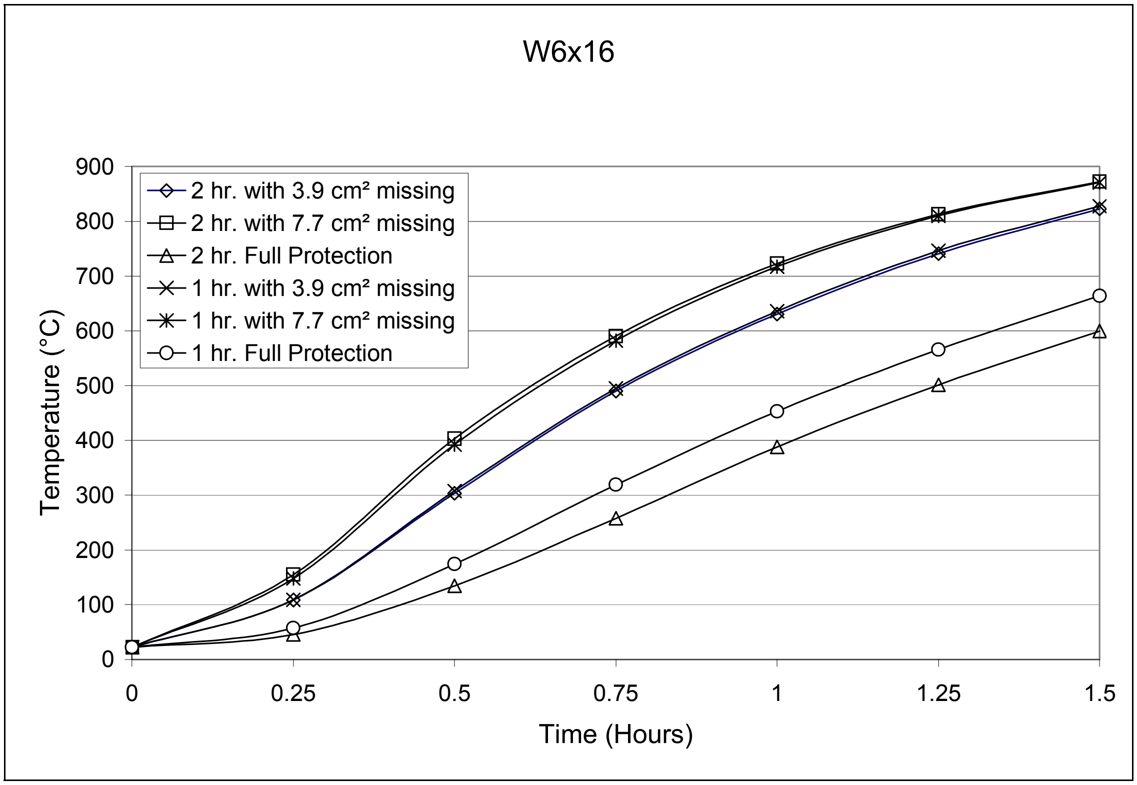

Fig. 7. Temperature at Exposed Flange Surface

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 hours for the one-hour design with 7.7 cm^2 of missing protection area, representing a 40 percent reduction in fire resistance for the 1-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 is also plotted in Fig. 8 as a function of time for missing protection on the web of the column.

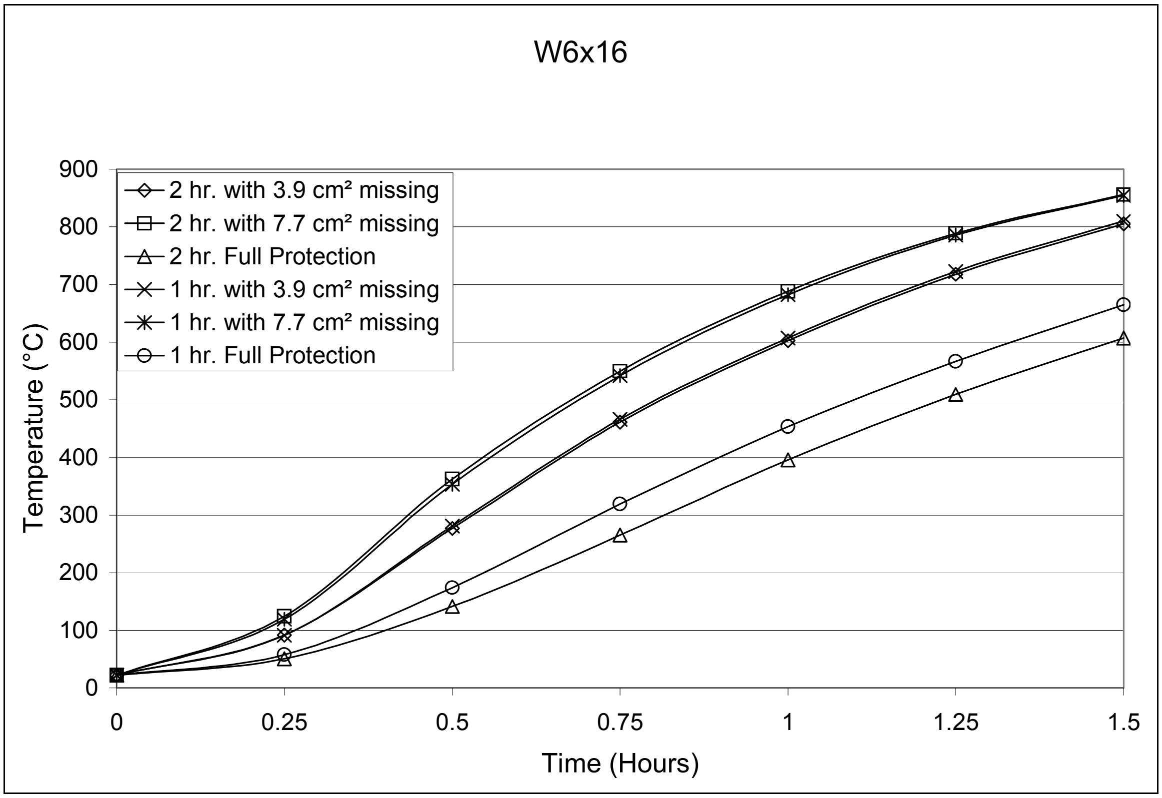

Fig. 8. Temperature at Exposed Web Surface

The results obtained for the web exposure are similar to those for the flange exposure, as expected because the identical thermal conditions exist at each surface. In practice, the location of the exposure may influence the time to reach thermal endpoint limits due to differing thermal conditions at different points on the surface of the column.

In addition to the W6x16 column, simulations were also conducted for a W14x233 column. A comparison of the results for the two columns are presented in Fig. 9.

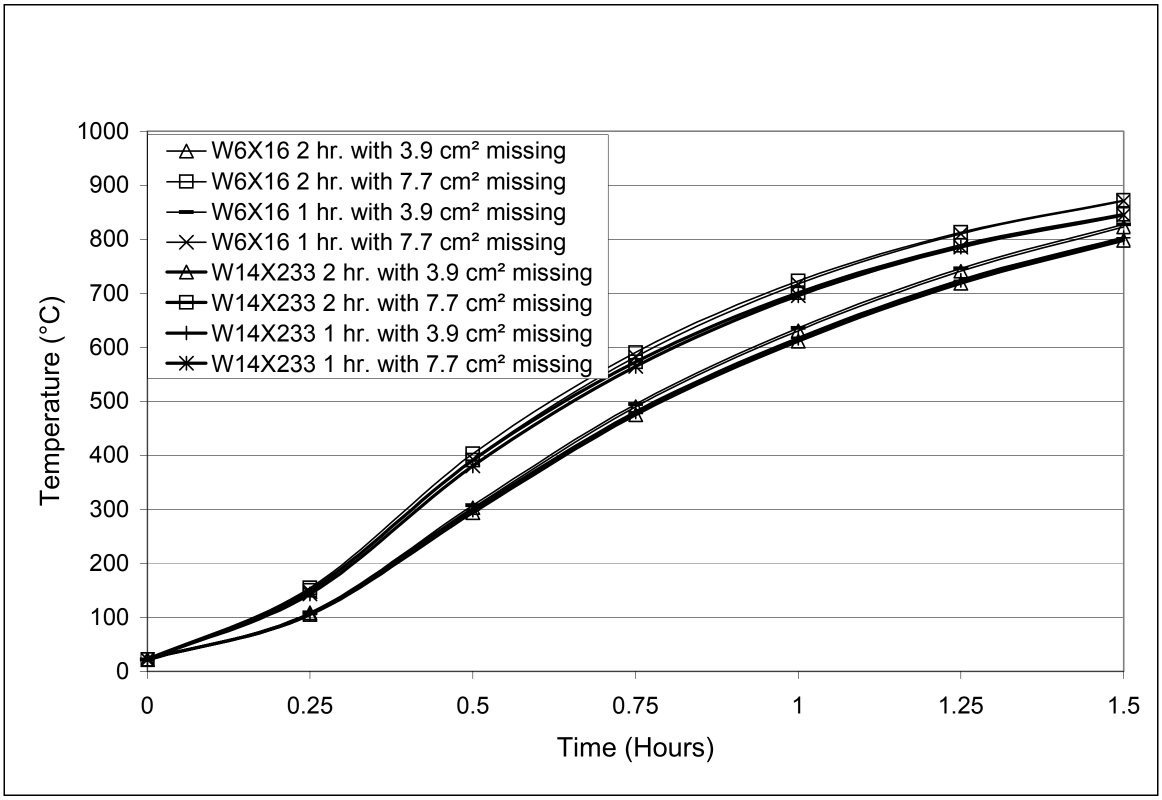

Fig. 9. Comparison of Temperatures at Exposed Flange Surface

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. However, the difference in temperature rise between the larger and smaller column is minimal and converges with increasing time.

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. Fig. 10 illustrates the temperature rise at the exposed web surface for the different column sizes, levels of protection, and areas of missing protection examined.

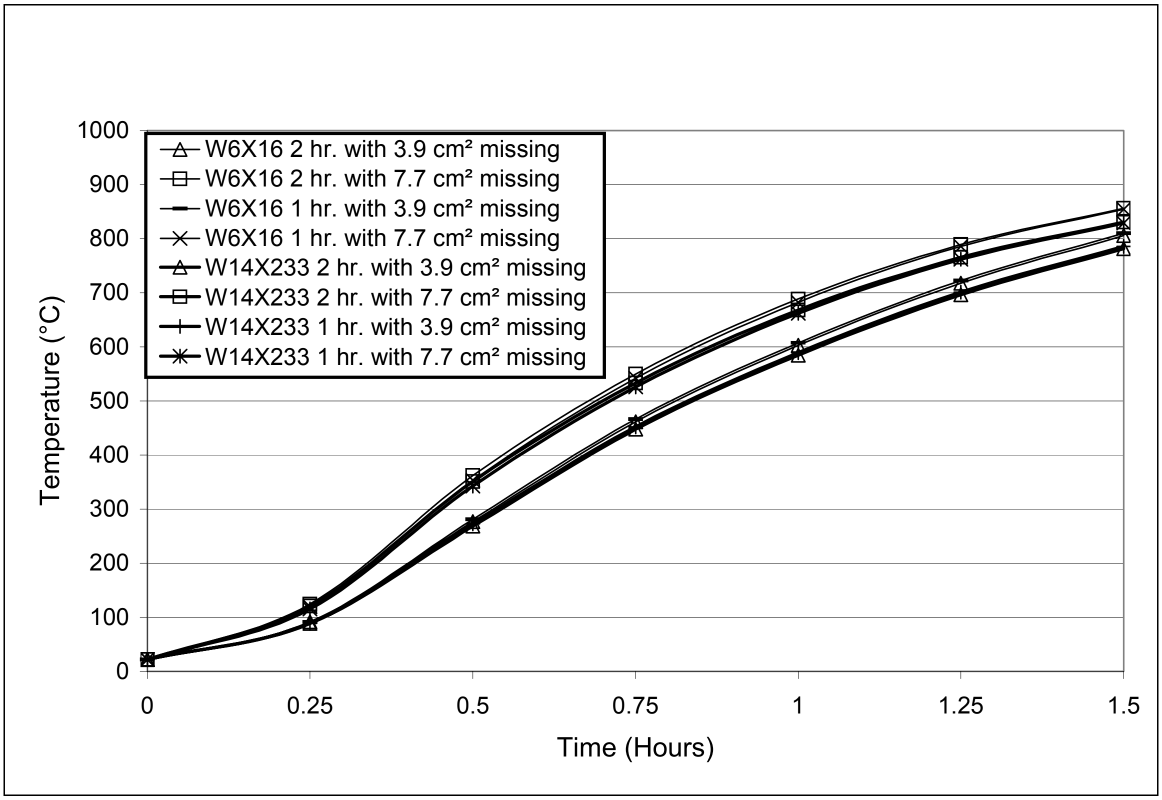

Fig. 10. Comparison of Temperature at Exposed Web Surface

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 be primarily a function of the area of missing protection for times up to 1 hour. Some divergence in the temperature rise for the different column sizes is apparent for longer times, but the difference is insignificant.

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. 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 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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