SiF 2022– The 12th International Conference on Structures in Fire
The Hong Kong Polytechnic University, Nov 30 - Dec 2, 2022

DETERMINING SFRM THERMAL PROPERTIES THROUGH FIRE TESTS ON I-BEAM SECTIONS

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ABSTRACT

Steel structural members exhibit lower fire resistance due to high thermal conductivity, low specific heat, and faster degradation of strength and elastic modulus of steel material with temperature. These structural members are often applied with spray-applied fire-resistive materials (SFRM) to delay temperature rise in the cross-section. This paper investigates the temperature-dependent thermal properties of gypsum-based Cafco 300 and cement-based Cafco Mandolite CP2 fire protection materials through fire furnace tests of protected beam members under constant loading. These properties are crucial for computational heat transfer models, which are utilized to evaluate the fire resistance of protected steel sections. A total of 3 fire furnace tests are conducted under 3-sided standard fire exposure. The average temperature of steel sections from the experiments are compared against the steel section temperature calculated by Eurocode method for steel profiles insulated by fire protection material. Nonlinear regression and random sampling methods are employed to minimize the residual sum of squares between the experimental and numerical temperature results. The results show that the temperature-dependent conductivity of SFRMs ranged from 0.08 W/(m˚C) to 0.25 W/(m˚C) with increasing temperature. The specific heat did not have a significant effect on the section temperature development and therefore kept temperature-independent at 1100 J/(kg˚C). The experimental results are closely captured by using the estimated temperature-dependent SFRM conductivity curves.

Keywords: SFRM; insulation; heat transfer; thermal properties; fire tests

1 INTRODUCTION

Steel structural members exhibit lower fire resistance due to high thermal conductivity, low specific heat, and faster degradation of strength and elastic modulus of steel material with temperature [1]. These structural members are often applied with spray-applied fire-resistive materials (SFRM) to delay temperature rise in the cross-section [2]. SFRMs are typically composed of mineral wool, quartz, perlite and vermiculite along with a binding agent such as cement or gypsum.

Fire resistive materials are currently qualified and certified based on lab-scale fire tests such as those described in the ASTM E119 Standard Test Methods for Fire Tests of Building Construction and Materials [3]. However, these ratings have no quantitative relationship to the actual performance of a SFRM in an actual fire other than the standard fire [4]. To evaluate steel temperatures under fire conditions that differ from the standard fire, thermal analysis can be performed, but such analysis requires knowledge of the thermal material properties of SFRMs [5]. Computational heat transfer models offer the potential to bridge the gap between laboratory testing and field performance. However, these models depend critically on having accurate values for the thermo-physical properties of the SFRM as a function of temperature, to be

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used as inputs along with the system geometry and fire and heat transfer boundary conditions [3]. The thermal performance of gypsum- and cement-based SFRMs were previously studied and there were no consensus on the temperature-dependent specific heat values but the sensitivity analyses shown negligible effect on the steel section temperatures. In addition, the moisture level greatly affected the density measurements at elevated temperatures [6].

This paper investigates the temperature-dependent conductivity of gypsum-based *Cafco 300* and cement-based *Cafco Mandolite CP2* fire protection materials through fire furnace tests of protected beam members under constant loading. The beam members are utilized as part of a 59-story tall steel-concrete building project. The I-beam steel sections in the interior are covered with gypsum-based SFRM and the beams on the exterior connecting steel columns are covered with cement-based SFRM for fire protection. The SFRM thermal properties are estimated by comparing the average temperature of steel sections from the experiments against the temperatures calculated by Eurocode method for steel profiles insulated by fire protection material [7]. Nonlinear regression and random sampling methods are employed to minimize the residual sum of squares between the experimental and numerical temperature results.

2 PROBLEM DESCRIPTION

2.1 Furnace tests

A total of 3 fire furnace tests are conducted under standard fire exposure. In the fire tests, simply supported 4 m long IPE 270, HEM 360 and HEB 360 I-beam sections are exposed to Standard (ISO-834) fire on 3 sides for 120 minutes. All beam sections are loaded with 0.3 utilization ratio (moment capacity) after SFRM application to reflect realistic conditions. IPE 270 and HEM 360 sections are protected with *Cafco 300* and HEB 360 section is protected with *Cafco Mandolite CP2*. The insulation thicknesses are estimated to maintain below the mandated critical temperature of 750℃ for 120 minutes standard fire exposure. Accordingly, IPE 270 and HEB 360 sections are protected with 23mm and 10mm Cafco 300, respectively. HEB 360 section is protected with 11mm Cafco Mandolite CP2. The average section temperature is obtained by 9 thermocouples placed on the bottom flange, web and top flange of I-beam sections at 3 different beam lengths as illustrated in Figure 1. The section factors for IPE 270, HEM 360 and HEB 360 are 197 $1/m$, 51 $1/m$ and 86 $1/m$, respectively.

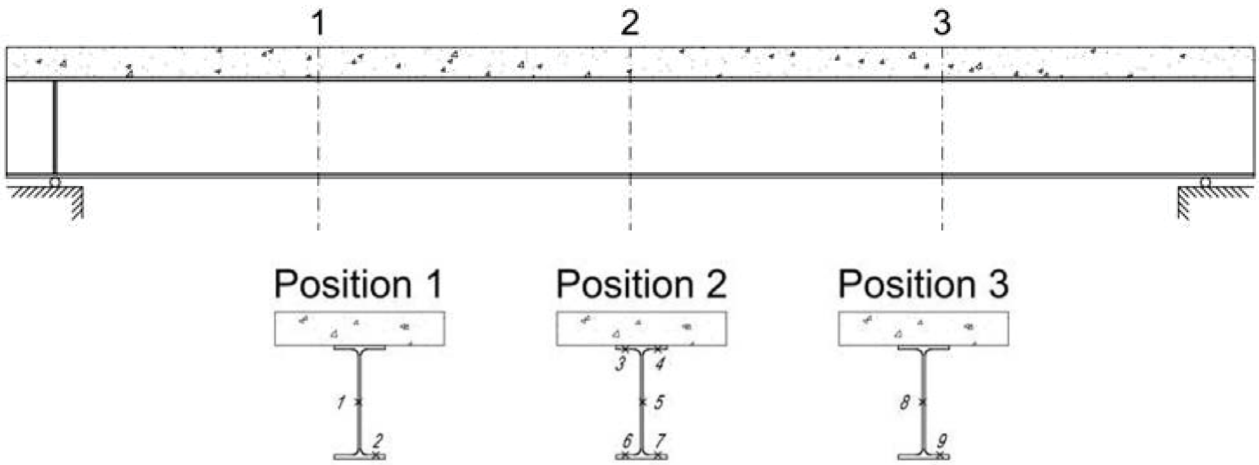


Figure 1. A total of 9 thermo-couple locations within the beam cross section at various lengths for the fire tests.

(a) IPE 270 - 23mm Cafco 300

(b) HEM 360 - 10mm Cafco 300

(c) HEB 360 - 11mm Cafco Mandolite CP2

Figure 2. SFRM applied loaded steel sections after the standard fire exposure.

Before the experiments are conducted, the moisture level of *Cafco 300* and *Cafco Mandolite CP2* are measured between 3-7% during the fire experiments. The post-fire conditions of the insulated beam members are shown in Figure 2. IPE 270 beam member experienced excessive deformations at midspan and therefore the fire test was terminated prematurely at 90 minutes. HEB 360 beam member experienced delamination of the insulation at midspan at around 100 minutes as seen in Figure 2c. Therefore, the thermocouples 5, 6 and 7 of HEB 360 are excluded from the average section temperature readings. Figure 3 plots the average section temperatures of the three profiles. As expected, the temperature development of all sections are fairly similar. This is because the insulation thicknesses are purposefully calculated to keep the section temperature below the mandated critical temperature of 750 °C.

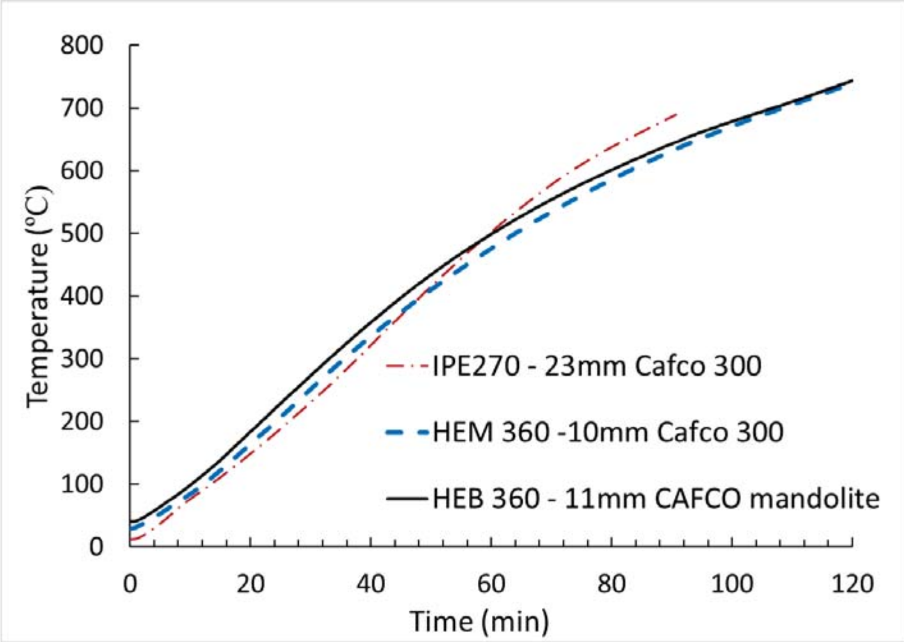


Figure 3. Furnace test results of IPE 270, HEM 360 and HEB 360 steel sections with SFRM under standard fire exposure of 90-120 minutes.

2.2 Heat transfer analyses

Eurocode 3 Part 1-2 provides Eq. 1 for the estimation of uniformly insulated steel cross section temperature. This equation is derived from a condensed one-dimensional (1-D) heat transfer model based on the lumped heat capacity method assuming a uniform temperature within the steel section. Here; T_f is the fire temperature, $\frac{A_p}{V}$ is the section factor and k, ρ, c are density, temperature-dependent conductivity, and temperature-dependent specific heat of the steel material according to Eurocode 3 [7]. For the insulation (SFRM) materials; k_i, ρ_i, c_i, d_i are defined as conductivity, density, specific heat and thickness. The equation to calculate the average section temperatures for IPE 270, HEM 360 and HEB 360 profiles is formulated using Excel spreadsheet. The maximum time increment is taken as 30 seconds.

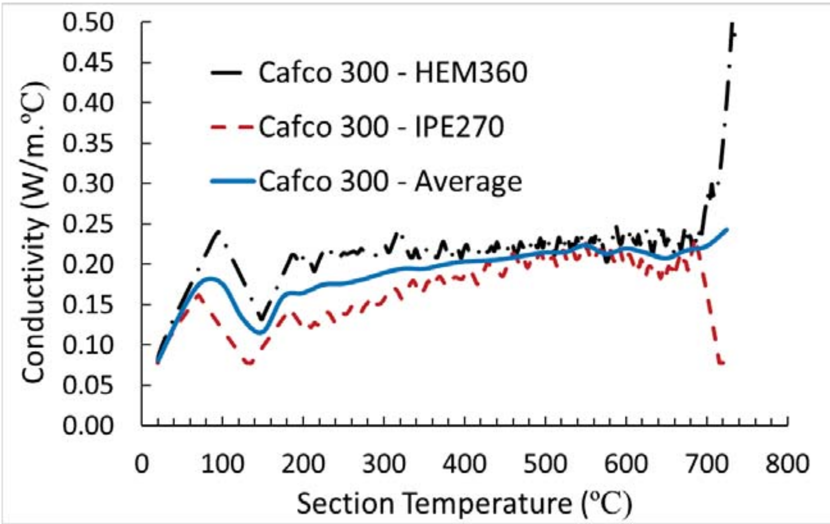
$$\Delta T = \frac{A_p}{V}\,\frac{k_i/d_i}{\rho\, c}\,\frac{T_f - T}{1+\phi/3}\,\Delta t - \left(e^{\frac{\phi}{10}} - 1\right)\Delta T_f \qquad where \quad \phi = \frac{A_p}{V}\,\frac{c_i\,\rho_i\,d_i}{c\,\rho} \qquad \text{Eq. 1}$$

The density of *Cafco 300* and *Cafco Mandolite CP2*, which is highly dependent on the moisture level, is taken constant as 315 kg/m^3 and 365 kg/m^3, respectively. As suggested by NIST [4], SFRM specific heat at room temperature is kept constant throughout the fire duration as c_i values of typical SFRM's typically vary only about ± 20% from a mean value. In addition, the variation of SFRM specific heat does not significantly change the average section temperature obtained by Eq. 1 since the SFRM thermal mass is usually minor compared to that of the steel section [8].

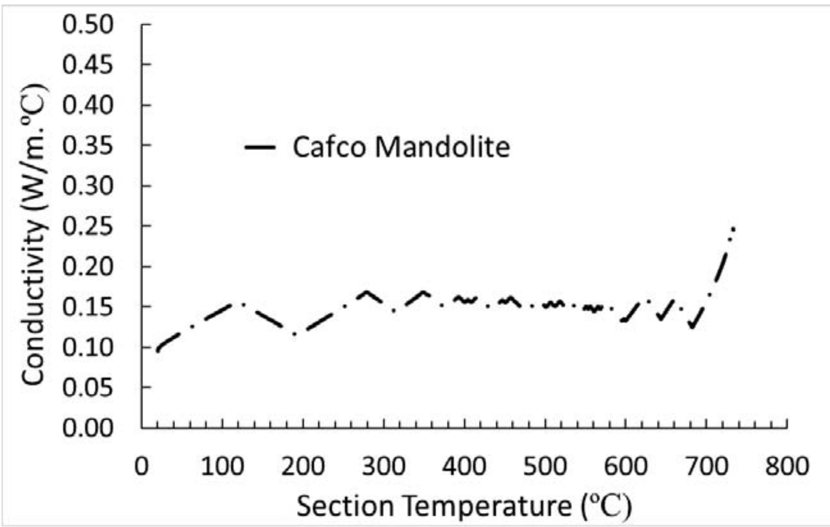
The SFRM conductivity, however, greatly affects the steel section temperatures. The manufacture reports of SFRMs provide the room temperature conductivities 0.078 $\frac{W}{m\,°C}$ and 0.095 $\frac{W}{m\,°C}$ of *Cafco 300* and *Cafco Mandolite CP2*, respectively. The temperature range is limited to 800 °C since reliable data on thermal properties of SFRMs at temperatures over 800 °C are not available in the literature due to the limitations of testing techniques.

Several methodologies are streamlined in Excel to estimate SFRMs temperature-dependent conductivity. First, the random sampling method determined to make the first guess of the conductivity range of both

SFRMs from 20 °C to 800 °C at each time increment. The lower limits are taken as the room temperature conductivity values supplied by the manufacturer. The upper limit for both SFRM conductivity is taken as 0.50 $W/_{m\,°C}$ in accordance to data available in the literature. This value is six times of the initial conductivity of *Cafco 300* and *Cafco Mandolite CP2* at room temperature. The upper range closely aligns with NIST investigations on the thermal performance of fire resistive materials [8]. Next, Excel macros are used to randomly select 10000 samples of SFRM conductivity value (with upper and lower limits) at each time increment (i.e. 30 seconds) and compare the section temperature residuals between the three experiments and numerical results. At each increment, the conductivity with the minimum squared-residual is stored and the conductivity for the next time increment is evaluated. Figure 4a-b show the discrete conductivity values of *Cafco* 300 and *Cafco Mandolite CP2*, respectively. It is observed that the graphs are not smooth as expected but the section temperatures obtained from the numerical analysis almost exactly capture the experimental results. In addition, Figure 4a shows that *Cafco 300* conductivity results are slightly different for IPE 270 (thick insulation-small cross-section) and HEM 360 (thin insulation - heavy cross-section). This is attributed to the uncertainties in temperature readings during the furnace tests. It is decided to take the average of the two results in Figure 4a to represent *Cafco 300* temperature-dependent conductivity.



(a)



(b)

Figure 4. Discrete conductivity curve for (a) *Cafco 300* and (b) *Cafco Mandolite CP2 obtained from the random sampling method.*

Nonlinear regression method is performed to fit the discrete conductivity values of both *Cafco 300* and *Cafco Mandolite CP2* to a smooth logarithmic function (see Eq. 2). SFRM conductivity asymptotically approaches to a constant value towards 800 ℃. The coefficients of the logarithm are shown in Table 1. SFRM conductivity values are plotted in Figure 5. Table 2 lists the thermal properties of SFRMs. It is clear that *Cafco Mandolite CP2* varies much less at elevated temperatures compared to *Cafco 300*.

$$k_i\ (T) = A\ln\ (T) + B \qquad \text{Eq. 2}$$

Table 1. Coefficients for the logarithmic representation of thermal conductivity of SFRMs.

Coefficients	***A***	***B***
Cafco 300	0.0371	-0.0211
Cafco Mandolite CP2	0.015	0.0623

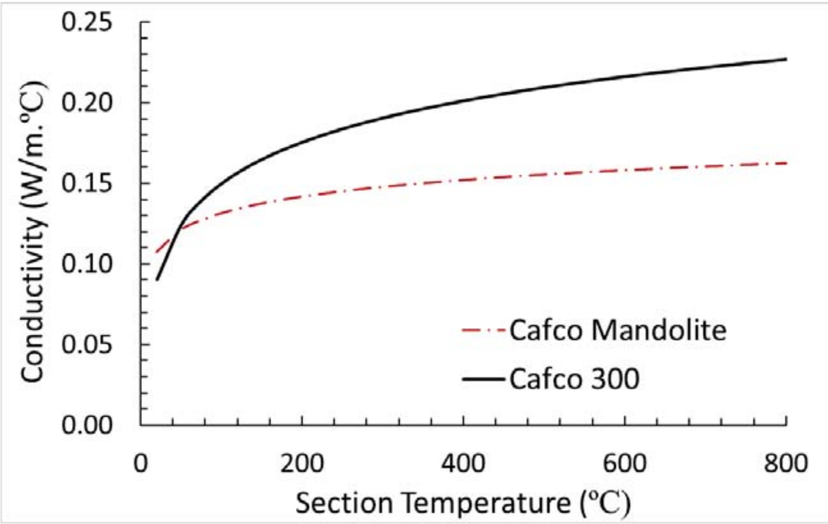


Figure 5. Temperature-dependent conductivity curves for *Cafco 300* and *Cafco Mandolite CP2 obtained from nonlinear regression method.*

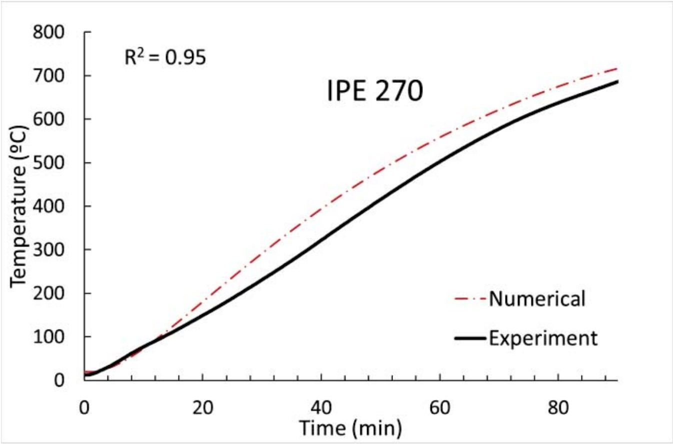
Table 2. Thermal Properties of *SFRMs.*

Thermal Properties	**Density** ρ_i kg/m^3	**Specific heat,** c_i J/(kg°C)	**Conductivity,** k_i W/(m°C)								
Temperature (℃)	20-800	20-800	20	100	200	300	400	500	600	700	800
Cafco 300	310	1100	0.078	0.150	0.175	0.191	0.201	0.209	0.216	0.222	0.227
Cafco Mandolite CP2	365	1100	0.095	0.131	0.142	0.148	0.152	0.156	0.158	0.161	0.163

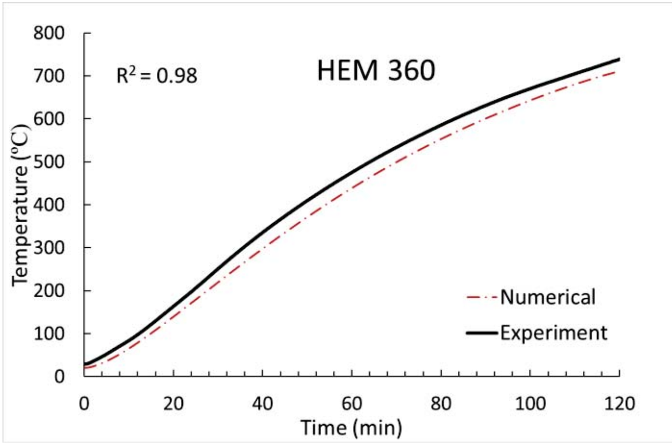
3 RESULTS

Using the temperature-dependent conductivity of SFRMs as shown in Figure 5, the average section temperatures estimated by Eq. 1 closely followed the temperatures from the furnace tests. Figure 6a-c show the section temperature comparison between the numerical and experimental results. The performance of good-fit to the experimental results is measured by the coefficient of determination (i.e. R-squared) method. R-squared method determines the proportion of variance in the dependent variable that can be explained by the independent variable by calculating the residual sum of squares between the experimental and numerical section temperatures as in Eq. 4. Here, y_i is the experimental temperature, $\bar{y}$ is the mean experimental temperature and $\check{y}_i$ is the numerical (i.e. predicted) value. For all the tests, R^2 is above 95, which indicates a very close fit to the experimental results.

$$R^2 = 1 - \frac{(y_i - \check{y}_i)^2}{(y_i - \bar{y})^2} \qquad \text{Eq. 4}$$



(a)



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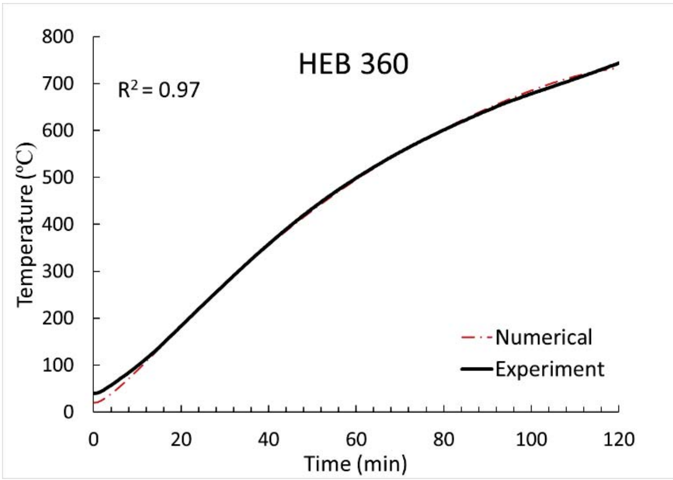

(c)

Figure 6. Average steel section temperature results from the experiments and numerical analyses and the estimated R^2 correlation.

4 CONCLUSIONS

This paper investigates the temperature-dependent conductivity of gypsum-based *Cafco 300* and cement-based *Cafco Mandolite CP2* fire protection materials through fire furnace tests of protected beam members under constant loading. A novel methodology is proposed in reverse calculating SFRM conductivity values from the experimental results. The methodology combines random sampling and nonlinear regression and can be applied to more experimental data of SFRM protected steel sections available in the literature. The study provides a database for the thermal properties of gypsum-based *Cafco 300* and cement-based *Cafco Mandolite CP2* to be utilized in numerical heat transfer simulations. It is found that the variability of the SFRM conductivity greatly changes the steel section temperatures. By utilizing random sampling method, it is determined that temperature-dependent SFRM conductivity can be represented by the logarithmic function. The R-squared method confirms the close match of the numerical results with the section temperatures from the furnace tests with R^2 above 95%.

ACKNOWLEDGMENT

The author would like to acknowledge Efectis Fire Laboratories for the carefully instrumented fire furnace tests and graduate student Ahmet Alperen Orgev for his support in numerical analysis. The author also acknowledge Bogazici University Scientific Research Projects BAP: 7122P, which provided the funding for this study.

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