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A NEW DESIGN APPROACH FOR STEEL STRUCTURES EXPOSED TO FIRES

by

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SUMMARY

There is a need to develop an analytical methodology for the design of steel framed structures exposed to fire to provide design engineers with an approach which will achieve a known level of performance. An important step in this process is the development of a simple technique for determining the thermal impact of a fire.

Such a technique is presented in this paper for insulated steel structures. This approach involves a new technique to determine a post-flashover fire's time-temperature history. Based on this, a method is presented for determining the peak temperature in an exposed steel beam, as well as a means to determine an equivalent fire endurance rating based on the ASTM E119 Standard Fire Test. This work is an extension of the existing applications of the Normalized Heat Load Concept.

INTRODUCTION

Simple techniques have been developed to enable engineers to design concrete and masonry structures for fire. One technique was developed by Harmathy and Mehaffey[1] using the concept of the Normalized Heat Load to determine the fire's impact.

This paper develops an analogous approach for the design of steel structures.

BACKGROUND

Fire severity has often been defined in terms of the area under the standard furnace time-temperature curve[2]. In order to better describe a fire's severity, Harmathy has defined the Normalized Heat Load, H[3]. The Normalized Heat Load accounts for the total incident heat flux absorbed by the boundary of a fire compartment, "normalized" to account for differing thermal properties by dividing the average heat flux by the thermal inertia[4]. This results in Equation 1[1]:

$$H = \frac{\bar{q}\,\tau}{\sqrt{k\rho c}} \qquad (1)$$

In order to use Equation 1 in practical engineering applications, an expression for H in terms of simply measured quantities would be useful. Harmathy has developed such an expression:

$$H = \frac{\left(11.0\,\delta + 1.6\right) M_f}{A_t \sqrt{k\rho c} + 935\sqrt{\phi\, M_f}} \times 10^6 \qquad (2)$$

Equation 2 was derived based on the following set of assumptions:

1. The fire is ventilation controlled, therefore the rate of burning may be assumed to be constant for a given ventilation parameter, ϕ. In terms of ϕ the rate of burning is described by Equation 3.

$$\dot{m}_f = 0.0236\,\phi \qquad (3)$$

where

$$\phi = A_o\, \rho_{air} \sqrt{gh} \qquad (4)$$

2. The maximum temperature reached within a boundary modeled as a semi-infinite solid constructed using typical materials, is practically independent of the heat flux—time exposure history, but is dependent on the total heat flux absorbed by the boundary.

3. The expression for the percentage of combustion which occurs within the compart-

ment is given by:

$$\delta = 1 \; or \; \delta = 0.79 \sqrt{h^3/\phi} \qquad (5)$$

whichever is less.

4. The fuel is considered to be cellulosic. The burning rate is assumed to be constant and equal to the maximum burning rate possible for cellulosic fuels under ventilation controlled conditions.

5. Radiative heat transfer from the compartment (primarily through the openings) is ignored.

6. The fire is assumed to be well mixed and therefore homogeneous throughout the compartment.

7. The airflow into the compartment is described by:

$$\dot{m}_{air} = 0.138\,\phi - 0.53\,\dot{m}_f \qquad (6)$$

Once H is determined from Equation 2, three different design approaches are available. The first is to use Equation 1 to calculate the average heat flux, $\bar{q}$, to a structural element, such as a concrete column or a heavily insulated structural steel beam. This result may then be used to calculate the time to failure of the element. Limitations of this approach are that the element must be thermally thick and that situations where the maximum fire gas temperature is a critical parameter are not accounted for.

Another approach is to combine Equation 2 with an expression which relates H with an equivalent fire endurance time τ_e. Harmathy has shown that to endure a fire with severity characterized by H, a structural element must have a fire endurance rating τ_e given by Equation 7.

$$\tau_e = 0.11 + 0.16 \times 10^{-4}\,H + 0.13 \times 10^{-9}\,H^2 \qquad (7)$$

A third approach suitable for lightly insulated or unprotected steel structures has been developed by Barnett but will not be addressed in this paper[5].

Using Normalized Heat Load for Design

Harmathy and Mehaffey[1] have developed a design procedure using the Normalized Heat Load approach and fire endurance time: H as calculated in Equation 2 is substituted into Equation 7.

Another approach is to develop a technique to predict the fire gas' time-temperature curve and use that to predict the temperature distribution in the structure. This has the advantage of accounting for the actual peak heat flux and fire gas temperature. Also, the results may be used to calculate an equivalent Normalized Heat Load which may be used to predict a fire endurance time, thus utilizing the best feature of the Normalized Heat Load approach. Finally, if the fire gas time-temperature curve can be predicted without some of the limitations used in the development of Equation 2, greater accuracy may be expected.

A New Approach

It is proposed that the time-temperature history of a room fire may be described by Equation 8.

$$T_f = a + bt + ce^{td} \qquad (8)$$

The form of Equation 8 has been chosen to account for the post-flashover fire development excluding the decay period. This is necessary to develop conservative design criteria[6].

The coefficients in Equation 8, a, b, c, and d, are based on the fire room's thermal inertia, openings as represented by the modified opening factor, ϕ', and the total bounding area of the walls and ceiling, A_T. The modified opening factor is given by Equation 9. This is similar to the modified opening factor suggested by Pettersson, *et al*[7].

$$\phi' = \frac{A_o \sqrt{h}}{A_T} \qquad (9)$$

The coefficients were determined by first using a post-flashover computer model COMPF2[8] to predict the time-temperature relationship for different room fires. The coefficients were then determined by fitting the computer generated time-temperature data to the function of Equation 8. The advantage of this approach is that it results in a simple technique for predicting a room fire's time-temperature history, yet

Table 1. Thermal Properties of Firebrick (R26), Gypsum Wallboard (R27)

Case	Density ρ (kg/m^3)	Conductivity k (W/mK)	Specific Heat c (J/kgK)	Thermal Inertia $\sqrt{k\rho c}$ (J/m^{2}K$\sqrt{s}$)
R26	800	0.134	1053	335.9
R27	680	0.27	3000	742.2

retains the accuracy implicit in the use of the computer model COMPF2.

The Prediction of the Coefficients for the Room Time-Temperature Equation

COMPF2 was used to model a wide range of openings with opening factors, ϕ', ranging from 3.297×10^{-3} to 3.973×10^{-2}. The actual opening dimensions ranged from opening heights of 0.2 m to 2.0 m and opening widths from 0.7 m to 1.2 m. The total wall plus ceiling surface area, A_T, was 37 m^2. One hundred twenty different openings were modeled. For each of these cases many different boundaries were also modeled[6]. The thermal properties of two of the boundaries are listed in Table 1. They represent area weighted plaster and firebrick (R26), and gypsum wallboard (R27). The burning rate was fixed at that specified by Equation 3 for the entire 5000 second simulation.

The results of the COMPF2 simulations were used to determine the values of the coefficients as functions of the modified opening factor. These functional relationships may be approximated as 4th degree polynomials ($C_0 + C_1\phi' + C_2\phi'^2 + C_3\phi'^3 + C_4\phi'^4$) with correlation coefficients greater than 0.9. Tables 2 and 3 list the values of the 4th degree polynomial's coefficients for each case presented.

Discussion of the Results

Equation 8 was used to predict the post-flashover time-temperature curves for two room fire tests. The experiments were conducted at the National Research Council of Canada (NRCC). The dimensions were 2.4 m by 3.6 m with a 2.4 m ceiling height and a single window opening 1.2 m high by 0.72 m wide[9]. The fuel consisted of four wood cribs with a total mass of 133.4kg. The only difference between the two rooms was the wall insulation. Room 1 had walls lined with ordinary brick $\sqrt{k\rho c} = 805$. Room 2 had walls lined with firebrick $\sqrt{k\rho c} = 335.9$. The predicted room temperatures compared to those measured are shown in Figure 1. The results are encouraging because the trends are as expected. The predicted temperatures are higher than actual, but within about fifteen percent of the experimental results when the decay period is ignored.

Equivalent Fire Endurance Time

Equation 8 may be combined with the concept of the Normalized Heat Load to determine an equivalent fire endurance time. The equivalent fire endurance time is the duration of a standard ASTM E119 furnace test fire of the same severity (normalized heat load) as the actual

Table 2:
Coefficients for determining constants *a*, *b*, *c* and *d* for Boundary R26, $\sqrt{k\rho c}$ = 335.9 J/m^2 K $\sqrt{s}$

	a	*b*
C_0	2.95082×10^{2}	4.4091×10^{-2}
C_1	1.04690×10^{5}	6.11806×10^{1}
C_2	-4.63283×10^{6}	-6.59089×10^{2}
C_3	9.76151×10^{7}	2.20611×10^{4}
C_4	-7.79824×10^{8}	-2.43327×10^{5}

	c	*d*
C_0	-1.6735×10^{2}	-4.66048×10^{-2}
C_1	-5.71183×10^{4}	8.18691×10^{0}
C_2	2.82367×10^{6}	-5.73592×10^{2}
C_3	-7.08650×10^{7}	1.61009×10^{5}
C_4	6.74086×10^{8}	-1.64905×10^{5}

Table 3:
Coefficients for determining constants *a*, *b*, *c* and *d* (for Boundary R27, $\sqrt{k\rho c}$ = 742.2 J/m^2 K $\sqrt{s}$

	a	*b*
C_0	3.44529×10^{2}	5.41979×10^{-2}
C_1	7.34368×10^{4}	3.17188×10^{0}
C_2	-2.38688×10^{6}	-2.61708×10^{2}
C_3	3.49327×10^{7}	6.30069×10^{3}
C_4	-1.61510×10^{8}	-5.08584×10^{4}

	c	*d*
C_0	-2.05981×10^{2}	-6.28181×10^{-2}
C_1	-3.62649×10^{4}	8.86131×10^{0}
C_2	1.09108×10^{6}	-5.51805×10^{2}
C_3	-1.61442×10^{7}	1.30634×10^{5}
C_4	9.18618×10^{7}	-1.11091×10^{5}

compartment fire. The use of Equation 7 as a means for calculating the equivalent fire endurance time for reinforced concrete and prestressed concrete structures has been described by Harmathy and Mehaffey[1]. The method may be extended to insulated steel beams as follows. Consider the following expression:

$$\frac{q}{\sqrt{k\rho c}} = \frac{1}{\sqrt{\pi\tau}}\left(T_s - T_a\right) \qquad (10)$$

This is an expression for the Normalized Heat Flux (the LHS of the equation) to a semi-infinite solid whose surface is suddenly jumped to a temperature T_s and held at that temperature for time τ[10]. Harmathy[3] found that the maximum temperature at a distance x from the surface may be approximated by Equation 11.

$$\frac{\bar{q}\,\tau}{\rho c x\left(T_{max} - T_a\right)} \cong 2.3 \qquad (11)$$

In theory, the use of Equation 11 is limited to the conditions where Equation 12 applies.

$$0.69 < F_o \leq 1.5625 \qquad (12)$$

F_o is the Fourier number, where $F_o = \alpha\tau/x^2$. For many applications, this limitation on the Fourier number is not too severe. For reinforced concrete beams Harmathy[3] has noted that the distance specified by Equation 12 for typical fire exposures is the depth where the reinforcing steel is located. This is a critical depth as the typical failure mode for reinforced concrete beams is failure of the reinforcing steel due to excessive heating. More recently, Harmathy and Mehaffey[11] have developed the formalism for concrete columns as well as beams.

For steel beams, the analogous question is to *ask if the "critical" depth fits within the criteria* specified by Equation 12. This question was answered by analyzing steel beams protected by a common insulation material, vermiculite plaster (k = 0.25, ρ = 660.0, c = 2700.0 and α = 1.40 × 10^{-7}). Figure 2 illustrates the minimum insulation thickness consistent with Equation 12 compared to the actual thickness required for beams exposed to the ASTM E119 furnace fire exposure test. The actual thicknesses illustrated are based on listings in the Underwriters Laboratories Fire Resistance Directory[12]. The points shown are for the average thicknesses

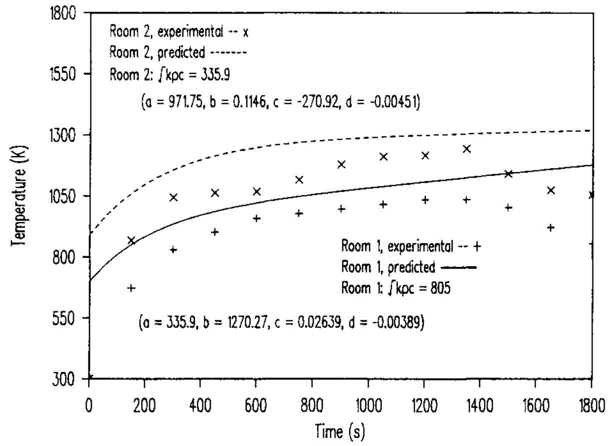

Figure 1. Predicted vs. experimental fire temperature.

required for 1, 1.5, 2 and 3 hour ratings for both "restrained" and "unrestrained" beams. Examining Figure 2 shows that the insulation thickness criteria of Equation 12 is reasonable for the beams illustrated.

In order to determine the equivalent time, the Normalized Heat flux of the LHS of Equation 10 must be converted into a Normalized Heat Load, H'. The prime indicates that this Normalized Heat Load is for real, or natural fires, as compared to H used in Equation 7 which represents the Normalized Heat Load in a furnace. If it is assumed that the surface temperature is the same as the fire gas temperature, then H' may be determined by substituting the average fire temperature, $\overline{T_f}$, for T_s on the RHS of Equation 10 and then integrating from time zero to time τ. The average fire gas temperature may be found from Equation 8 and is:

$$\overline{T_f} = \frac{1}{\tau}\left(a\,\tau + 0.5\,b\,\tau^2 + \frac{c e^{\tau d}}{d} - \frac{c}{d}\right) \qquad (13)$$

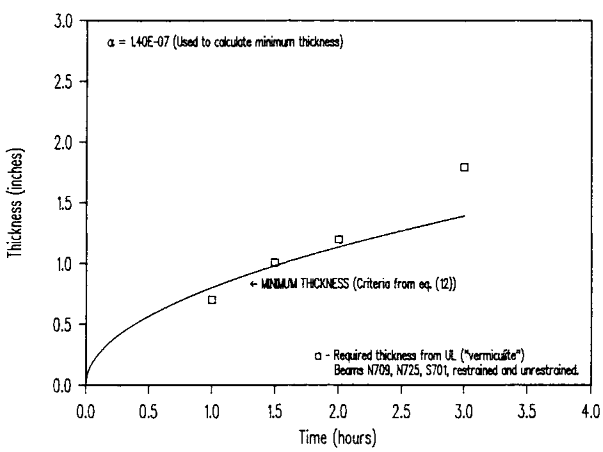

Figure 2. Required insulation thickness.

The value of τ in Equation 13 is the maximum fire exposure time. This may be a specified time, or calculated using Equation 14.

$$\tau = \frac{M_f}{\dot{m}_f} \qquad (14)$$

Substituting Equation 13 into Equation 10 and solving for the Normalized Heat load yields Equation 15 which is an expression for the Normalized Heat Load in a natural fire, H'.

$$H' = \frac{2\left(\overline{T}_f - T_a\right)\sqrt{\tau}}{\sqrt{\pi}} \qquad (15)$$

After H' is calculated using Equation 15, the equivalent fire endurance time may be determined by substituting H' for H in Equation 7. Alternatively, if the steel's time temperature history in the furnace is known, the equivalent time may be found by comparing the time needed to reach a critical temperature in the furnace exposure with the time needed to reach the same critical temperature in the natural fire exposure.

An alternative approach requires the calculation of the maximum steel temperature due to the natural fire exposure. The maximum temperature may be found by substituting Equation 1 into Equation 11 and rearranging:

$$T_{max} = T_a + \frac{\sqrt{k\rho c}\, H'}{2.3\, \rho c\, x} \qquad (16)$$

If it is assumed that the steel's heat capacity is negligible compared to that of the insulation and that the steel's temperature is uniform throughout the cross-section, then Equation 16 may be used to determine the maximum temperature of an insulated steel beam. The use of Equation 16 was checked by comparing its prediction of T_{max} with that predicted by a finite element model. The finite element model used was TASEF-2[13]. TASEF-2 is a two-dimensional finite element model which uses an explicit forward difference time integration scheme. The model is capable of accounting for temperature dependent thermal properties including the specific heat, density and conductivity. In addition, a broad spectrum of boundary conditions may be modeled.

For the purpose of this study, TASEF-2 results were compared with those from Equation 16 for a one-dimensional analysis of a steel plate insulated with vermiculite plaster. The steel was 0.0338 meters thick. This is the maximum one-half flange thickness for a standard wide-flange beam. Two thicknesses of vermiculite insulation were analyzed, 0.01 meters and 0.02 meters. The results are illustrated in Figures 3 and 4, respectively. These figures are plots of the maximum steel temperature versus the fire's duration. Because the time corresponding to the maximum steel temperature was greater than the fire's duration, τ, the TASEF-2 analysis required multiple computer simulations. For each simulation, the fire exposure was continued for a time period equal to the fire's duration, τ. At time τ, the boundary condition was changed to a non-fire exposure equal to an assumed ambient temperature of 25°C. The TASEF-2 simulations were then continued for a 2-hour simulation time period. The maximum steel temperature was then noted.

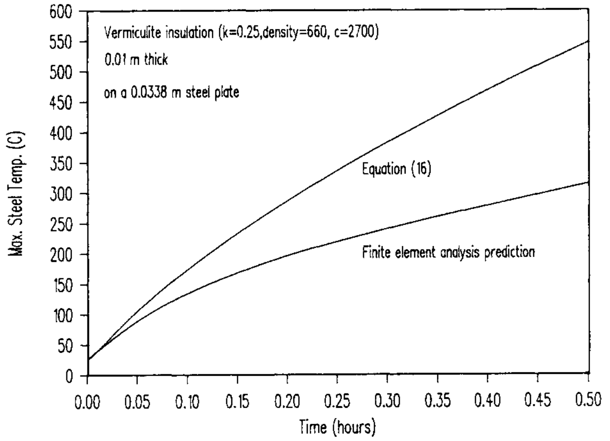

Figure 3. Steel temperature prediction; 0.01 m insulation.

For the case of the 0.01 m thick insulation, the use of Equation 16 greatly overpredicts the steel's temperature. This is primarily because the use of

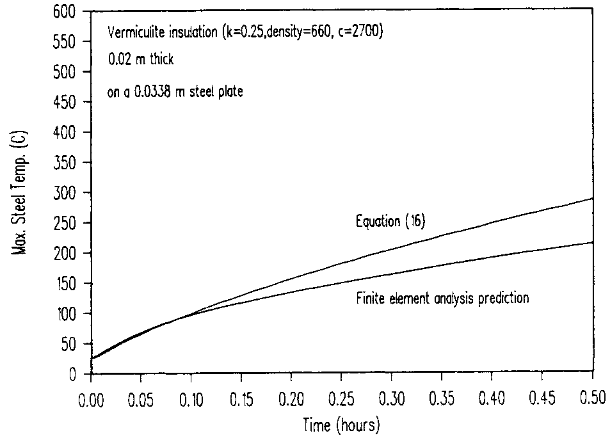

Figure 4. Steel temperature prediction; 0.02 m insulation.

Equation 16 does not account for the heat capacity of the steel. In addition, the temperature predicted is the maximum temperature of the insulation at a depth x, where x is equal to the thickness of the insulation. Because the steel plate modeled is equal to the maximum one-half flange thickness of a beam likely to be found in practice, and the 0.01 m thick vermiculite is a very light insulation, the situation modeled is a severe test of this proposed design method.

A Design Example

One approach to the design of steel structural elements for fire loading is the use of the concept of a critical temperature. The critical temperature is the maximum temperature allowed in a structural element, such as a beam. It is usually based on the value of the steel member's temperature where the yield strength is reduced to sixty percent of the room temperature strength. Therefore, for A36 steel (a common structural steel), a critical temperature of about 773 K is often used.

The Design of a Steel Beam in an Office Occupancy

The following is an application of the design method for an office occupancy. The room that the beam is being designed for is 3 m x 4 m, with a 2.36 m ceiling height. Two geometries are to be considered, one with a window 0.6 m wide, 1.0 m high, the other with a window 0.6 m wide, but 2.0 m high. The cellulosic fuel load was determined to be 20 kg of fuel per square meter of floor area. If this were not known, values of fuel loadings for typical occupancies are available from a number of sources, the most comprehensive of which is in Appendix A of the CIB Design Guide: Structural Fire Safety[14]. Two types of boundary construction are to be considered:

- Type I consists of brick and plaster construction with thermal properties equal to that of R26, Table 1.
- Type II consists of a gypsum wallboard boundary with properties equal to that of R27, Table 1.

The size of the steel beam is W360 x 32.9 (W14 x 22 in U.S. Customary Units) and is to be protected with a coating of vermiculite plaster insulation. Two insulation thicknesses are to be determined, one which will protect the beam for 1800 s, the other is to be adequate for the maximum fire duration time based on the total fuel load in the room.

The Solution

1. Calculate basic geometric variables and the basic parameters:
   (a) $A_T = 3 \cdot 4 + 2 \cdot 2.36 \cdot (3 + 4) = 45.0\ m^2$
   (b) $A_o = 0.6 \cdot 1.0 = 0.6\ m^2$ (for $h = 1.0$ m)
   $A_o = 0.6 \cdot 2.0 = 1.2\ m^2$ (for $h = 2.0$ m)
   (c) from Equation 9:
   $\phi' = 0.6\sqrt{1.0}/45.0 = 0.0133\ m^{0.5}$ (for $h = 1.0$ m)
   $\phi' = 1.2\sqrt{2.0}/45.0 = 0.0377\ m^{0.5}$ (for $h = 2.0$ m)
   (d) $M_f = 20\ kg/m^2 \cdot (3 \cdot 4) = 240$ kg
   (e) from Equation 3 and Equation 4:
   $$\dot{m}_f = 0.0236 \cdot 1.206\sqrt{9.81 \cdot 1.0}$$
   $= 0.05349$ kg/s (for $h = 1.0$ m)
   $$\dot{m}_f = 0.0236 \cdot 1.206\sqrt{9.81 \cdot 2.0}$$
   $= 0.15128$ kg/s (for $h = 2.0$ m)
   (f) from Equation 14:
   $$\tau = \frac{M_f}{\dot{m}_f} = \frac{240}{0.05349} = 4487\text{s (for } h = 1.0 \text{ m)}$$
   $$\tau = \frac{M_f}{\dot{m}_f} = \frac{240}{0.15128} = 1586\text{s (for } h = 2.0 \text{ m)}$$
2. Calculate the room fire. This is done by using ϕ' and the data from Tables 2 and 3 to determine the coefficients for use in Equation 8. The coefficients are used to predict the average fire temperature, T_f, during the fire duration using Equation 13. The Normalized Heat Load, H', for the natural fire may now be calculated using Equation 15.
3. Determine the required insulation thickness:
   (a) Rearranging Equation 16 to determine the insulation thickness yields:
   $$x_{(required)} = \frac{\sqrt{k\rho c}\ H'}{2.3\,\rho c\left(T_{max} - T_a\right)}$$
   (b) For vermiculite insulation, $k = 0.25$, $\rho = 660.0$, $c = 2700.0$, setting $T_a = 300$ K, and $T_{max} = 773$ K, results in:
   $$x_{(required)} = 3.445 \times 10^{-7}\ H' \qquad (17)$$

The Answer to the Problem:

For the Type I boundary construction: from

Table 2, the following values were calculated:

a = 1078.365 b = 0.053177
c = –575.815 d = –0.00648

Using these values yields:

	Window Ht. 1.0 m		Window Ht. 2.0 m
	Duration 1800 s	Duration 4487 s (τ_{max})	Duration 1586 s (τ_{max})
$\bar{T}_f$	1029 K	1059 K	1298 K
H'	34,900	57,369	44,847
$x_{required}$	0.012 m	0.020 m	0.015 m

For the Type II boundary construction: From Table 3, the following values were calculated:

a = 981.5356 b = 0.063133
c = –533.396 d = –0.0153

Using these values yields:

	Window Ht. 1.0 m		Window Ht. 2.0 m
	Duration 1800 s	Duration 4487 s (t_{max})	Duration 1586 s (t_{max})
$\bar{T}_f$	962 K	974 K	1263 K
H'	31,692	50,944	43,275
$x_{required}$	0.011 m	0.018 m	0.015 m

CONCLUSION

A new technique to simplify the design process for steel structures exposed to fires has been presented. The process is an extension of the application of Harmathy's and Mehaffey's Normalized Heat Load approach for the design of concrete structures to insulated steel structures.

The technique is simple and is meant for use by design engineers; without the need for elaborate computer models.

NOMENCLATURE

A_o	Opening area (m^2)
A_t	Inner surface area of the boundary (m^2)
A_T	Inner surface area of the boundary, less floor area (m^2)
a	Coefficient for the natural fire approximation
b	Coefficient for the natural fire approximation
$C_o...C_4$	Coefficients for determining the a, b, c, d coefficients
c	Specific heat (unsubscripted: of the boundary) (J/kg K) Also, coefficient for the natural fire approximation.
d	Coefficient for the natural fire approximation
F_o	Fourier Number
g	Acceleration due to gravity (m/s^2)
H	Normalized heat load ($K\sqrt{s}$)
H'	Normalized heat load for a natural fire ($K\sqrt{s}$)
h	Opening height (m)
k	Thermal conductivity (W/m K)
M_f	Mass of the fuel (kg)
$\dot{m}_f$	Rate of mass loss of the fuel (kg/s)
$\dot{m}_{air}$	Air flow into the compartment (kg/s)
q	Heat flux absorbed by the compartment boundaries during the fire's duration (W/m^2)
$\bar{q}$	Average heat flux absorbed by the compartment boundaries during the fire's duration (W/m^2)
T_a	Ambient air temperature (K)
T_f	Fire gas temperature (K)
T_{max}	Maximum temperature (K)
T_s	Surface temperature (K)
$\bar{T}_f$	Average fire gas temperature (K)
t	Time (s)
x	Distance normal to the surface (m)
α	Thermal diffusivity (m^2/s)
δ	Percent of energy released within the compartment
ρ	Density (kg/m^3)
ρ_{air}	Density of air (kg/m^3)
τ	Fire duration (s)
τ_e	Fire endurance rating (hours)
ϕ	Ventilation parameter (kg/s)
ϕ'	Area compensated ventilation parameter ($\sqrt{m}$)
$\sqrt{k\rho c}$	Thermal inertia (unsubscripted: of the boundary) ($J/m^2K\sqrt{s}$)

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