to estimate the quantity of heat release and mineral assemblaces crystal [10, 11].

ACKNOWLEDGEMENTS

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An Extraporation Method of Steel Column Temperature Rise under Fire Resistance Tests by Using Parameter Estimation Technique

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ABSTRACT

To derive design diagrams of insulated steel columns, a methodology was proposed to extrapolate the temperature rise of specific steel column assembly under fire resistance test to those differing in cross sectional area of steel. Having a set of steel column temperature measurement, the thermal conductance between fire resistance furnace and steel was estimated by the technique of parameter estimation. Then, using the estimated thermal conductance, temperature rise of steel columns with arbitrate cross sectional area was calculated while keeping the construction of insulation unchanged. The results were compared with fire resistance test results that were conducted separately. The agreement was good or conservative if the cross sectional area were larger than the reference cross sectional shape. Thus it was shown that the methodology is feasible to develop design diagrams for insulated steel columns. A practical chart and simple design formula was produced for columns insulated by calcium silicate boards.

Key words: fire resistance tests, steel columns, fire resistance insulation, parameter estimation ,extrapolation, design diagram

INTRODUCTION

To prevent the structural frame from collapse during fire, fire resistance is essential to the members of structural frame. In case of steel frame, mechanical properties such as elastic modulus and the yield strength are decreased as the steel temperature rises, which results in buckling of columns and excessive deflection of beams. Therefor it is necessary to put thermal insulation on steel members in order to keep the temperature rise below critical value.

For the purpose of evaluating the construction of insulation, fire resistance test by furnace[1,2] is applied for most cases. As a practical procedure, so-called *standard* size columns or beams are selected. The insulation is constructed upon standard columns and/or beams. Then the assembly is subjected to standard fire to see if the steel temperature is below the critical temperature (350°C for the present Japan's procedure) during prescribed time. The evaluation by fire resistance test is an explicit way in which important physical and chemical behavior could be included. Examples of such phenomena are chemical reaction in the material, thermal cracks, fallout, spalling and so on.

However single test result gives little information on how the result can be extrapolated to realistic situations. Typical and practically important question is "How the fire resistance time varies if the same construction is applied to steels with different cross sectional shape?". From the physical point of view, the temperature rise of steel depends not only on the insulation construction, but also on the heat capacity on the steel. Optimal combination of steel size and insulation construction (typically the thickness of insulation material) may exist in order to obtain necessary fire resistance time. If we try to know the optimum combination, we would have to carry out quite a lot of fire resistance tests, which is impractical considering the cost and time for fire tests.

One of the feasible approach is to extrapolate the measured steel temperature of *standard* size columns into arbitrate size of steel with the help of analytical methods. When we calculate the steel temperature in a straightforward way, numerical methods such as lumped heat capacity model[3], one-dimensional finite difference method[4] and finite element method[5] are adopted. To follow this approach, we should have all the construction details and material properties, which is rarely possible in practical applications. To overcome this problem, inverse analysis method was adopted in this paper. Having one time-temperature history of steel during fire test, the material property (thermal conductance) of insulation material was estimated using measured temperature. The value should be regarded as an "effective" value that includes the effect of cracks and so on. After having the thermal conductance, the temperature rise of arbitrate cross sectional shape could be calculated in a straightforward way to extrapolate the test result into different size of steel with identical construction of insulation.

THEORY

The principle for extrapolation is quite general to be appreciable to any structural and separating members insulated by reactive and/or non-reactive materials. However, we limit our interest to H-sectioned columns insulated by lightweight non-reactive materials for simplicity. Considering the current Japanese practice on the fire resistance test of insulated steel columns, we assume that one or two sets of time - steel temperature history is available for *standard* column (H-300x300x10x15*). The extrapolation to different cross sectional shape is main point of discussion.

---

* H-sectioned, outer length 300mm by 300mm, web thickness 10mm, flange width 15mm

Lumped Body Approximation

To describe the temperature rise of steel, the construction was approximated by the lumped body as shown in FIGURE 1. The H-sectioned steel and the insulation material were approximated by two flat plates that has the same cross sectional area per unit heated perimeter of insulation material. Using the nominal thickness of the insulation materials, the heated perimeter l, and the cross sectional area A_i, are expressed by

$$l = 2(a+b) + 8d_i, \tag{1}$$

$$A_i = 2d_i(a+b) + 4d_i^2. \tag{2}$$

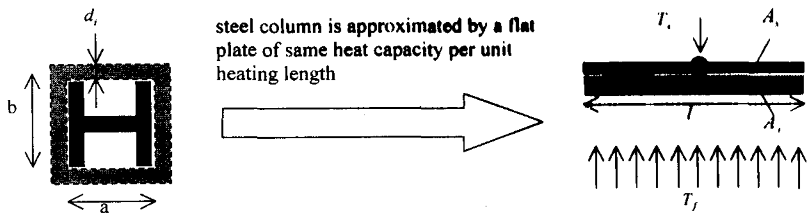

FIGURE 1 Lumped Body Approximation

Further, we assume that the temperature profile in the insulation material is close to linear. Under these assumptions, the temperature rise of steel could be described by

$$(\rho_i c_i A_i + \rho_s c_s A_s)\frac{dT_s}{dt} = kl(T_f - T_s), \tag{3}$$

without considerable loss of accuracy[3], where T_s is the representative (average) steel temperature [K], ρ_i is the density [kg/m^3] and c_i is the specific heat of insulation material [J/kg.K], ρ_s and c_s are those of the steel column, $T_f(t)$ is the fire gas temperature (standard time - temperature curve),

$$T_f(t) = T_0 + 345\log_{10}(8t/60+1). \tag{4}$$

Selection of Unknown Parameter(s)

The governing equation (3) has several material properties. Among them, the heat conductance between fire gas and steel was selected as an unknown parameter to be estimated. Using thermal conductivity and thickness, it could be written nominally as

$$k = 1/(1/h + d_i/\lambda_i) \tag{5}$$

where the first term of the denominator $(1/h)$ is the thermal resistance of the turbulent boundary layer between fire gas and outer surface of insulation material. Second term (d_i / λ_i) denotes the thermal resistance across insulation material. To compare the relative importance of these two terms, we assume that the overall heat transfer coefficient is more than 50[W/m.K] and that the thermal conductivity of insulation material is in the order of 0.1[W/m.K]. If the thickness of the material is more than 20mm, d_i / λ_i(=0.2) is sufficiently larger than $1/h$(=0.02). Thus it is reasonable to treat the thermal conductance k as a specific parameter that is intrinsic to insulation material and construction.

Specific Heat and Density

The remaining parameters are the specific heat and density of steel and insulation material. Theoretically it is possible to estimate these parameters at the same time with thermal conductance. In most of the practice, however, it is easy to get accurate values for these two parameters by consulting the data books and/or product specification. Thus they were excluded from the group of unknown parameters. In reality, the specific heat of the lightweight inorganic material are around 920[kJ/kg.K] with 20% of scatter. Even if we use this value, it is unlikely that we lose correct estimate of thermal conductance except for the very early stage of heating in case of lightweight insulation materials.

Evaporation of Contained Water

At around 100°C, contained water in the insulation materials evaporates. Due to the latent heat of evaporation, temperature rise is delayed. To take this beneficial effect into account, the specific heat of insulation material is increased. Namely we have

$$c_i(T) = c_{i0} + c_w w(T) - L_w dw(T)/dt, \qquad (6)$$

where c_{io} is the specific heat [kJ/kg.K] of oven dry condition, c_w is the sensible heat capacity of water (=4.18[kJ/kg,K]), L_w is the latent heat of water evaporation (=2260[kJ/kg.K]).

The symbol $w(T)$ denotes the water content [kg/kg] at temperature T. The evaporation of water is a complicated process. However, it was simplified that the evaporation takes place at the temperature range between $T_e - \delta$ (=80℃) and $T_e + \delta$ (=120℃). Peak of evaporation takes place at T_e(=100°C). The following two equations gives the approximated function for the rate of evaporation per unit temperature rise and remaining water content at specified temperature,

$$\frac{dw(T)}{dT} = \frac{w_o}{\delta^2}\begin{cases}(T_e - \delta) - T & (T_e - \delta < T \le T_e)\\ T - (T_e + \delta) & (T_e < T < T_e + \delta)\end{cases}, \qquad (7)$$

$$w(T) = \frac{w_0^2}{2\delta^2}\begin{cases}2\delta^2 - T^2 + 2(T_e - \delta)T - (T_e - \delta)^2 & (T_e - \delta < T < T_e)\\ T^2 - 2(T_e + \delta)T + (T_e + \delta)^2 & (T_e < T < T_e + \delta)\end{cases}, \qquad (8)$$

where w_0(=0.05) is the water content at initial condition [kg/kg]. The functional form is

illustrated in FIGURE 2 and FIGURE 3.

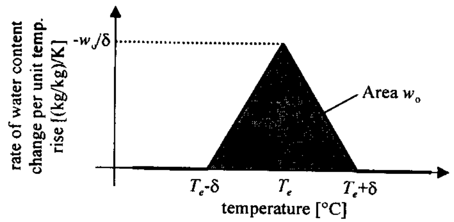

FIGURE 2 Rate of Water Content Change per Unit Temperature Rise

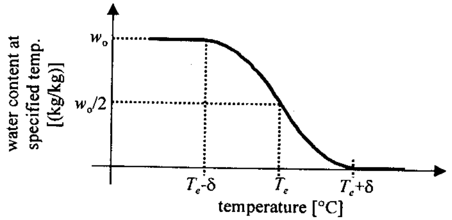

FIGURE 3 Water Content at Specified Temperature

Equation for Thermal Conductance

As described above, the thermal conductance k is the single parameter that have to be estimated. Considering that the steel temperature is measured at constant time interval Δt as is a common fire test procedure, the governing equation (1) is approximated by backward finite difference equation as

$$(\rho_i c_i^{j-1} A_i + \rho_s c_s A_s)\frac{T_s^j - T_s^{j-1}}{\Delta t} = k^{j-1} l \, (T_f^{j-1} - T_s^{j-1}), \qquad (9)$$

where the superscript j on temperature T_s and T_f denotes the j-th temperature measurement, the superscript j on the specific heat c_i means that the value is to be evaluated by the steel temperature at j-th measurement of T_s. Rearranging the terms, we get

$$k^{j-1} = \frac{(T_s^j - T_s^{j-1})(\rho_i c_i^{j-1} A_i + \rho_s c_s A_s)}{l \Delta t (T_f^{j-1} - T_s^{j-1})}. \qquad (10)$$

By substituting the measured steel and furnace temperatures $\{T_s^0, T_s^1, T_s^2, \ldots\}$, $\{T_f^0, T_f^1, T_f^2, \ldots\}$ into equation (10), the thermal conductance $\{k^0, k^1, k^2, \ldots\}$ can be calculated as a function of time. After arranging the thermal conductance versus corresponding steel temperature, we get the thermal conductance as a function of steel temperature.

Once the functional form of the thermal conductance is established, it is possible to calculate the temperature rise of steel that differs in cross sectional area A_s and heated perimeter l, as long as the construction of the insulation is deemed identical.

EXPERIMENTAL VERIFICATION

In order to verify the accuracy of extrapolation, a series of fire resistance tests were analyzed. In the test series, eight fire resistance tests were carried out for various cross sectional shape of steel column insulated by 40mm- thick calcium silicate board[6]. Among the test data, one test data (H-300x300x10x15) was selected to estimate the thermal conductance. After we got the thermal conductance, the calculations were carried out for the other cross sectional shapes. The calculated results were compared with test data to discuss whether the extrapolation is feasible.

Test Series

The cross sectional shape of the tested columns is shown in FIGURE 4. All the specimens have the same construction of insulation. The difference is the cross sectional area A_s and the heated perimeter l. The ratio of cross sectional area over heated perimeter of insulation (effective thickness of steel) varies in the range of 0.0114 to 0.0051 [m]. Initial water continent of insulation was approximately 5.0% by weight. The column was 3m long, whose top and bottom ends were supported by pin.

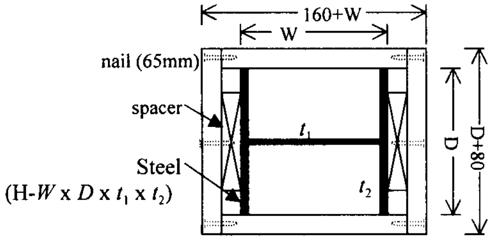

FIGURE 4 Cross Sectional Shape of Tested Steel Columns (Unit in mm)

TABLE 1 summarizes the testing conditions. As this test series were carried out mainly to investigate the mechanical load bearing capacity of steel, the load ratio was varied in some of the tests. Among the tests, we selected the test C to estimate the thermal conductance because the load ratio is most close to unity among the tests which is the common procedure of fire test. Using the estimated thermal conductance, we calculated the steel temperature that correspond with tests A, F, G and H. Then the results were compared with measurements.

TABLE 1 Testing Conditions

Test	Steel size	cross sectional area of steel [m²]	Heated perimeter l [m]	load ratio φ[-]*	critical time [s]
A	H-400×400×13×21	0.02194	1.92	0.62	337
B	H-300×300×10×15	0.01232	1.52	0.62	274
C	H-300×300×10×15(**)	[illegible]	[illegible]	1.14	207
D	H-300×300×10×15	0.01232	1.52	1.20	182
E	H-300×300×10×15	0.01197	1.52	1.37	126
F	H-250×250×9×14	0.00924	1.32	0.59	249
G	H-200×200×8×12	0.00635	1.12	1.20	175
H	H-100×100×6×8	0.00216	0.42	1.55	144

* applied load / allowable maximum load at normal temperature[7] ** reference

Estimation of the Thermal Conductance

FIGURE 5 shows the result of steel temperature measurement at Test C (reference) together with Test B, D and E where the same column was tested under different load ratio. The data shows that the time to critical condition (collapse) is greatly affected by load ratio. Even more, the temperature rise seems to be slightly accelerated as the load ratio is increased. This may be attributed to that large axial force increases the crack and fallout of insulation material. However the degree is not so obvious, thus it is enough to select the data in the sufficiently loaded condition in practical application. This is why we selected the test C as reference, where the column is loaded to full load-bearing capacity.

Using the test data C, the thermal conductance of insulation was estimated by equation (9). The result is expressed as a function of steel temperature in FIGURE 6. At the beginning of the heating and at the temperature range of water evaporation ($T_v \pm \delta$), there are some numerical scatter of the results. However, numerical scatter is reduced in the temperature range above 200°C. The following function was fit to the estimated thermal conductance for the calculation to extrapolate the steel temperature of different cross sectional shape.

$$k = \begin{cases} 3.2 & (20 \le T_s < 130) \\ 0.00533T_s + 2.42 & (130 \le T_s < 280), \\ 4.0 & (280 \le T_s \le 500) \end{cases} \qquad (11)$$

which is shown by bold line in FIGURE 6.

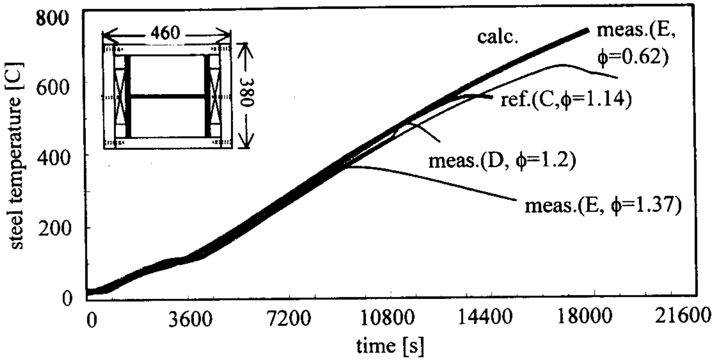

FIGURE 5 Temperature Rise of Standard Columns (H-300x300x10x15, Test B, C (reference), D, E and Calculated Results)

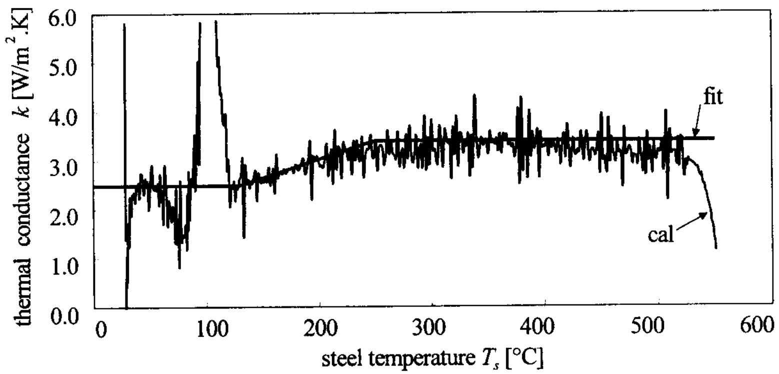

FIGURE 6 Estimated Thermal Conductance and Fitting Tri- Linear Function

Extrapolation to Different Cross Sectional Shape of Steel

Using equation (11) in the governing equation (1), the steel temperature rise for the specimens in test A (H-400×400×13×21), F (H-250×250×9×14), G(H-200×200×8×12), H(H-100×100×8×6) were calculated and compared with the measurements. The results are shown in FIGURE 7 to FIGURE 10. In case of Test A (FIGURE 7), the extrapolated temperature is slightly higher than the measurement. Thus it seems that the method is feasible to derive conservative estimate of the critical time of the column. In case of Tests F, G and H, the extrapolation gives almost the same or slightly low temperature. Thus it gives the realistic or optimistic estimate. The difference in the tendency could be attributed to the relative size of the column between reference and extrapolated size. In the Test A, the column size is larger than the reference, while in the other tests, the columns are smaller than the reference. If the cross sectional shape of the column is small, the distortion may be increased even at the same temperature, which increases the degree of crack and fallout of insulation materials.

To examine the overall tendency, all the results are plotted in FIGURE 11. The time to critical condition in tests are plotted against the time to critical temperature in extrapolated time-temperature history. As was anticipated, the extrapolation is optimistic if the time to critical temperature is large, which implies that the degree of crack and fallout is small. Thus it is safe to conclude that the extrapolation is only possible only to the direction to prolong the time to critical temperature due to the increase in the cross sectional area of steel.

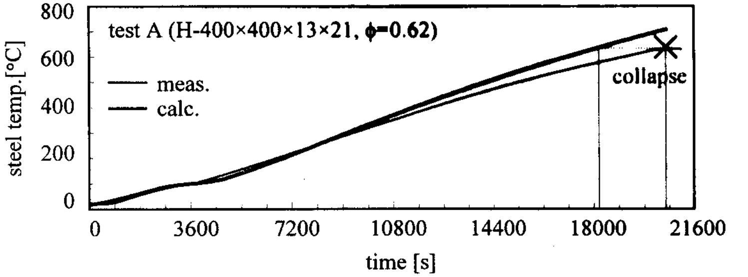

FIGURE 7 the Comparison of the Steel Temperature Rise between Measurement and Extrapolation (Test A : H-400×400×13×21)

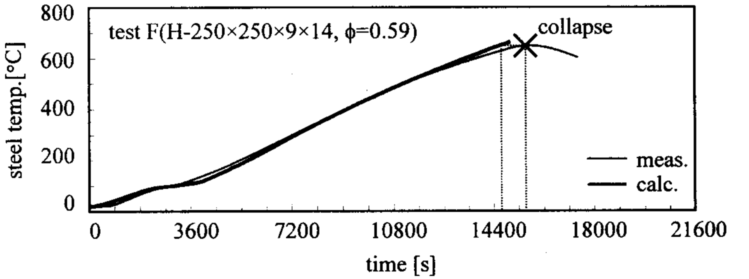

FIGURE 8 the Comparison of the Steel Temperature Rise between Measurement and Extrapolation (Test F : H-250×250×9×14)

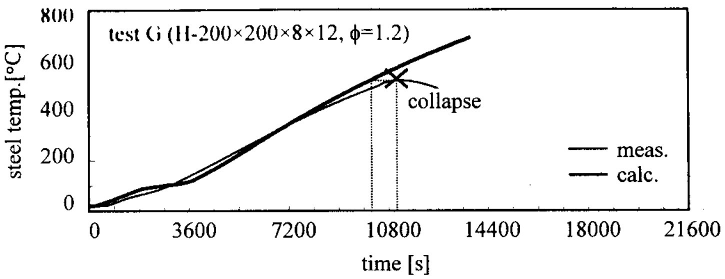

FIGURE 9 the Comparison of the Steel Temperature Rise between Measurement and Extrapolation (Test G : H-200 × 200 × 8 × 12)

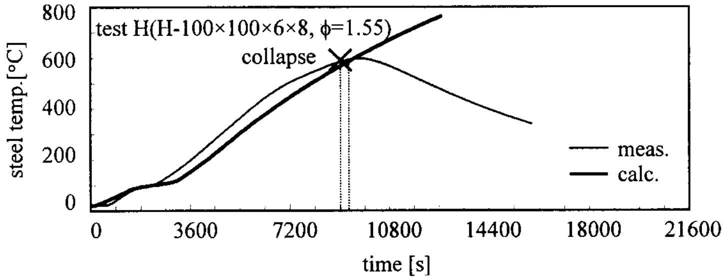

FIGURE 10 the Comparison of the Steel Temperature Rise between Measurement and Extrapolation (Test H : H-100 × 100 × 6 × 8)

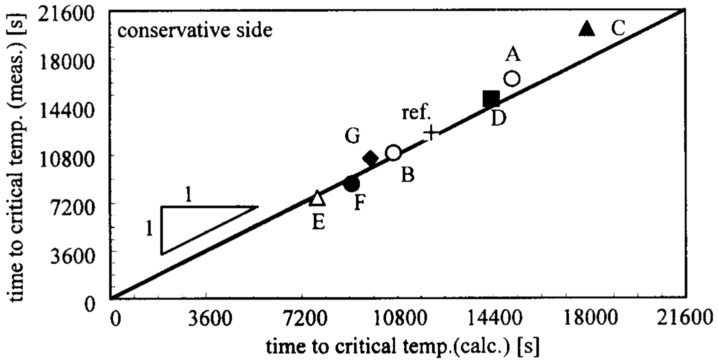

FIGURE 11 Comparison of Time to Critical Temperature between Measurements and Extrapolation

(normally 30mm from surface) is *very roughly* the same if the time temperature area is the same between actual (design) fire and standard fire as shown in FIGURE 1. He adjusted the threshold temperature to 400 or 500°C depending on the critical temperature for steel bars. His method has been extended to other cases such as the evaluation of unexposed surface temperature of separation element by changing the threshold temperature to 260°C, which is not derived from physical understanding of phenomena, but just a critical temperature for insulation failure.

For steel structures, Law[5], Pettersson et al[6] made a similar definition independently. Their definition of equivalent duration is the time to maximum steel temperature attained in specific actual fire as shown in FIGURE 2. Their main effort is to correlate the equivalent fire duration with building design parameters[7].

$$t_{eq} = f(w, A_F, A_T, A_w\sqrt{H_w}, \cdots) . \tag{1}$$

An example of this approach is shown in Annex E of Eurocode[8] draft.

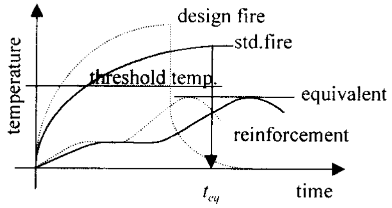

FIGURE 1 Kawagoe's Definition of Equivalent Fire Duration

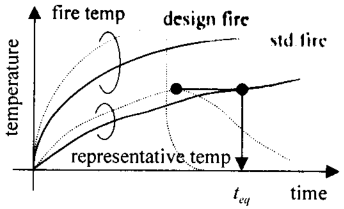

FIGURE 2 Law's Definition of Equivalent Fire Duration

However, as a coarse approximation, the thermal behavior of "any" building element could be correlated with the total amount of absorbed heat during fire. If the total amount of absorbed heat is identical, the temperature of the element would be roughly the same provided that the difference of temperature distribution in the element is negligible. Also it is expected that the thermal breaking of materials might be correlated with total amount of heat provided that energy for breaking is a property intrinsic to specific materials of construction. Kawagoe's formula for time-temperature area was derived through empirical correlation. However it can be interpreted as a rough approximation of a total amount of heat to the element in question. This approach can be extended if we find a way to calculate the total amount of absorbed heat for arbitrate fire severity.

In this paper, an approximate formula is proposed to correlate the total amount of absorbed heat during actual (design) fires and standard fires. Then a simple formula for equivalent fire exposure was derived. The schematic idea is shown in FIGURE 3. Similar approach has been proposed by Harmathy and Mehaffy[9], however, the present approach intends to derive a simple formula.

NOMENCLATURE

Alphabets

A_i	cross sectional area of insulation	[m^2]
A_s	cross sectional area of steel	[m^2]
c_i	specific heat of insulation	[J/kg.K]
c_{i0}	specific heat of insulation at oven dry (=920)	[J/kg.K]
c_{i0}	specific heat of water (4180)	[J/kg.K]
c_s	specific heat of steel	[J/kg.K]
d_i	insulation thickness	[m]
h	heat transfer coefficient	[W/m^2.K]
k	thermal conductance	[W/m^2.K]
l	heated perimeter	[m]
l/A_s	section factor	[m^{-1}]
L_w	latent heat of evaporation	[J/kg]
t	time	[s]
T_e	evaporation temperature (=100℃)	[°C]
T_f	fire temperature	[°C]
T_s	steel temperature	[°C]
T_0	initial temperature	
$w(T)$	water content of insulation	[kg/kg]
w_0	initial water content of insulation material (=0.05)	[kg/kg]

Greek Symbols

δ	evaporation temp. width	[°C]
λ_i	thermal conductivity of insulation	[W/m.K]
ρ_i	density of insulation material	[kg/m^3]
ρ_s	density of steel	[kg/m^3]

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Equivalent Fire Duration Based on Time- Heat Flux Area

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ABSTRACT

A simple formula was proposed to calculate the equivalent fire exposure based on time- heat flux area. Given a fire severity and duration of design fires, the heat flux absorbed by building element was described by an analytical formula for heat conduction in a semi-infinite medium. Using the formula, the time to give the same amount of heat to building elements under design fires and under standard (ISO 834 fire) is derived. Assuming that the behavior of building element is identical if the total amount of heat is equivalent, then the formula can be used as a representation of equivalent fire duration for structural fire resistance design. Numerical examinations and several experimental results show that the assumption holds fairly well for practical range of application.

Key words: equivalent fire duration, ISO 834 fire, design fires, actual fire, severity

INTRODUCTION

In the fire resistance tests of building construction[1,2,3], standard time- temperature curve is adopted in order to classify building elements into fire resistance ratings. The standard time-temperature curve is one of the representatives of actual fires. However, the actual fires differ considerably from the standard fire depending on fuel load density, internal surface area of compartment boundary and ventilation parameter. Thus various formula have been proposed in order to correlate the behavior of specific building element under actual fires with that under standard fire.

Kawagoe[4] made extensive calculations and experiments for reinforced concrete elements. After his results, he concluded that the maximum temperature of reinforcing steel bar