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]

REFERENCES

1. International Standardization Organization, ISO/TR834, Fire Resistance Test-Elements of Construction
2. Ministry of Construction, Notification No. 2999, Fire Resistance Test of Elements of Building Construction, 1969
3. Petersson, O., Magnusson, S., E., Thor,J., Fire Engineering Design of Steel Structures, Lund Institute of Technology, 1976
4 The Building Center of Japan, Total Fire Safety Design Method of Building, Series 4, Fire Resistance Design, pp52- 63, 1989 (in Japanese)
5. (for example) Yagawa, M., Finite Element Methods in Fluid Flow and Heat Conduction, Baifukan, 1983 (in Japanese)
6 Annual report of MOC project, "Development of Fire Testing and Evaluation System of Materials and Construction (Structural Fire Resistance Design Sub Committee)", 1998 (in Japanese)
7. Architectural Institute of Japan, Design Standard for Steel Structures, 1973
8. JIS G 3192-1990, Dimensions, mass and permissible variations of hot rolled steel sections
9. Hiroyuki SUZUKI, "Ultimate Temperatures of Steel Frames Subject to Fire", transactions of AIJ, No.477, pp147-156, and "Recommendation for Fire Resistant Design of Steel Structures", Architectural Institute of Japan, 1998 (in Japanese)

Equivalent Fire Duration Based on Time- Heat Flux Area

KAZUNORI HARADA
Department of Architecture and Environmental Design, Kyoto University
Yoshida-honmachi, Sakyo, Kyoto 606-8501, Japan

RYO KOGURE, KEN MATSUYAMA and TAKAO WAKAMATSU
Department of Architecture, Science University of Tokyo
Yamasaki 2641, Noda, Chiba 278-8510, Japan

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

Simplified Design Formula

Through the examination above it is possible to extend the time to critical condition in accordance with the increase in the cross sectional area of steel. Using the extrapolation method above, calculation were carried out for various cross sectional area of steel. Among the specifications in JIS G 3192[8], twelve cross sectional shapes were selected. The ratio l/A_s ranges in 33~330. Also calculated is the infinitesimally small steel ($l/A_s \to \infty$) for the purpose of comparison. The results are shown in FIGURE 12.

As the failure temperature of steel columns differ by the load ratio in the range of from 350°C and 600°C, the time to reach these temperature was read from the diagram, and correlated by

$$t_{cr}/(T_{cr} - T_0) = 1490/(l/A_s) + 14.5 \quad (12)$$

where T_{cr} is the critical (buckling) temperature of steel as a function of load ratio[9].

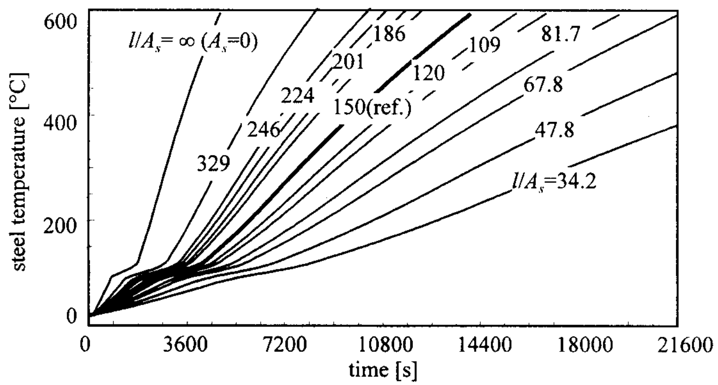


FIGURE 12 Design Diagram for Various Cross Sectional Area of Steel Insulated by Calcium Silicate Board (40mm)

SUMMARY

A methodology was proposed to extrapolate the steel temperature of steel columns insulated by lightweight passive materials. To make use of the parameter estimation technique, the heat transfer in the column was described by a lumped body approximation. Then the unknown parameter, the thermal conductance, was estimated by a fire test data for standard construction. The obtained thermal conductance was used to calculate the temperature rise of steel columns that are insulated in the same way but differ in cross sectional shape of steel. The calculated values are compared with measurement to get fair or conservative agreement. Using the extrapolation technique a simple design formula was developed for various size of steel insulated by 40mm thick calcium silicate board.

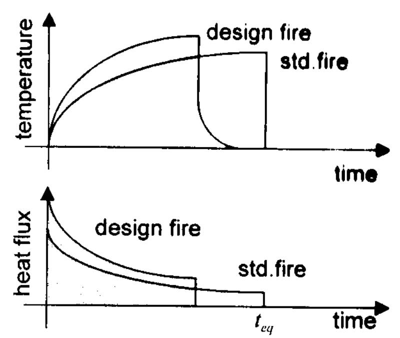


Figure 3 Equivalent Fire Duration Based on the Equivalency in Time- Heat Flux Area

THEORY

Compartment Fire Temperature

Before we discuss the equivalent fire duration, we limit our interest to fully developed compartment fires. There are many proposals for predicting compartment fire temperatures. Among them, we adopted the following set of formula proposed by McCerffry at al[10] and extended by Matsuyama et al[11].

Compartment fire could be classified by using the burning type factor, which relates to air supply rate per unit fuel surface area (see nomenclature for symbols),

$$\chi = A_w\sqrt{H_w} / A_{fuel}, \quad (2)$$

where the fuel surface area can be calculated by[12]

$$A_{fuel} = \phi(wA_F) = 0.54w^{-2/3} \times wA_F = 0.54w^{1/3}A_F, \quad (3)$$

given the fuel load density as a characteristic value for building use.

<u>Ventilation Controlled fires</u>: ($\chi \le 0.07$)

The compartment fire temperature and duration would be

$$T_f - T_\infty = 3.0T_\infty\left(A_w\sqrt{H_w} / A_T\sqrt{\lambda\rho c}\right)^{1/3} t^{1/6}, \quad (4)$$

$$t_D = wA_F / 0.1A_w\sqrt{H_w}. \quad (5)$$

<u>Fuel Surface Controlled Fires:</u> ($\chi > 0.07$)

McCerffery's formula is applied with empirical heat release rate formula developed by Ohmiya *et al*[11].

$$T_f - T_\infty = 0.022 T_\infty \frac{Q^{2/3}}{(A_T \sqrt{\lambda\rho c} A_w \sqrt{H_w})^{1/3}} t^{1/6}, \quad (6)$$

$$t_D = 16000 w A_F / Q, \quad (7)$$

$$Q / A_{fuel} = \begin{cases} 112 & (\chi \le 0.1) \\ 192\chi \exp(-11\chi) + 48 & (0.1 \le \chi) \end{cases}. \quad (8)$$

Standard Fire:

The standard fire temperature in ISO 834 can be approximated by

$$T_{f,ISO} - T_\infty = 345 \log_{10}(8t/60+1) \approx 230 t^{1/6} \quad (9)$$

without considerable loss of accuracy.

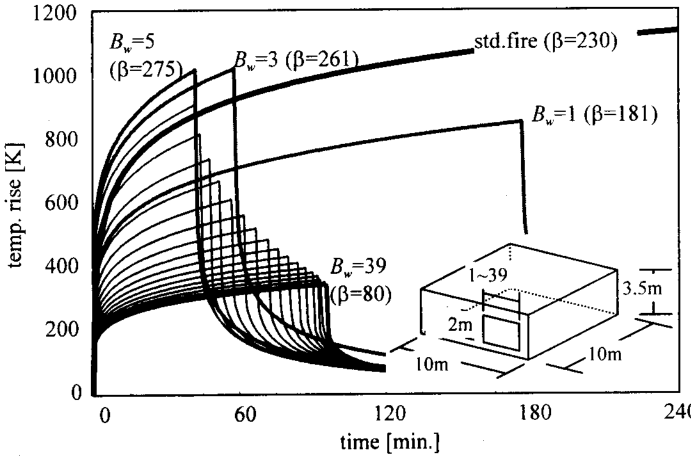


Figure 4 Compartment Fire Temperature in Comparison with Standard Fire (w=30kg/m^2, A_{room}=100m^2, H_{room}=3.5m, B_w=1~39m, H_w=2m)

General Expression for Compartment Fires

All the fires defined by equations (4), (6) and (9) are expressed by (1/6) power of time. Thus it is possible to write

$$T_f - T_\infty = \beta t^{1/6}, \quad (10)$$

in a general expression using the fire severity coefficient β [K/s$^{1/6}$]. As an example, fire temperature curves are shown in FIGURE 4 for a single compartment with 100 m^2 floor area, ceiling height 3.5 m, fuel load density 30 kg/m^2 of floor area. The opening height was fixed to 2 m, while the opening width was changed in the range of 1 (representative for storage room) to 39 m (representative for open type structures). The corresponding fire severity coefficient ranges from 80 to 275.

Heat Flux Absorbed by Building Elements

Most fire effects are transient. Thus we could approximate most of the building elements by semi- infinite body with respect to heat conduction. If the absorbed heat flux is constant over time, an analytical expression is possible for surface temperature rise,

$$T_s - T_\infty = \frac{2q}{\sqrt{\pi}} \sqrt{\frac{t}{\lambda\rho c}}. \quad (11)$$

Rearranging the terms, we get,

$$q = \frac{\sqrt{\pi}}{2} \sqrt{\frac{\lambda\rho c}{t}} (T_s - T_\infty). \quad (12)$$

Approximating that surface temperature is close to the fire temperature, we obtain

$$q \approx \frac{\sqrt{\pi}}{2} \sqrt{\frac{\lambda\rho c}{t}} (T_f - T_\infty) \approx \frac{\sqrt{\pi}}{2} \sqrt{\frac{\lambda\rho c}{t}} \beta t^{1/6} \quad (13)$$

Integrating equation (13) over fire duration, we get the total amount of heat absorbed by the surface as

$$E(t) = \int_0^{t_D} q(t) dt = \frac{3\sqrt{\pi}}{4} \sqrt{\lambda\rho c}\, \beta t^{2/3}. \quad (14)$$

Equivalent Fire Duration

Let the fire severity coefficient be $\beta_{(design)}$ and fire duration and $t_{D(design)}$ for specific design fire. Then the time-flux area will be

$$E_{(design)} = \frac{3\sqrt{\pi}}{4} \sqrt{\lambda\rho c}\, \beta_{(design)} t_{D(design)}^{2/3}. \quad (15)$$

For standard fire, same relationship holds for the heating period up to t_{eq}.

$$E(t_{eq}) = \frac{3\sqrt{\pi}}{4}\sqrt{\lambda\rho c} \times 230 t_{eq}^{2/3}, \tag{16}$$

Equating equation (15) and (16), we obtain,

$$t_{eq} = \left(\frac{\beta_{(design)}}{230}\right)^{3/2} t_{D(design)}. \tag{17}$$

VERIFICATION BY NUMERICAL ANALYSIS

Methods

For the fires described by $\beta t^{1/6}$, heat flux is not constant over time. In a precise manner, the heat flux would be given by a convolution integral of fire temperature and impulse response of building element. Thus the validity of equation (13) and (17) were checked against numerical calculations of heat conduction.

We selected a 100mm thick concrete wall (thermally thick wall) and a 20mm thick calcium silicate board (thermally thin wall). For both of them, the wall temperature and absorbed heat flux were calculated for the design fire temperatures shown in FIGURE 4 and for the standard fire. Namely, the equation of heat conduction

$$\rho c \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T(x,t)}{\partial x}\right), \tag{18}$$

was solved by finite difference method as shown in FIGURE 5. The boundary conditions at $x = 0$ and $x = L$ are, respectively,

$$-\lambda \frac{\partial T(0,t)}{\partial x} = h_c(T_f - T(0,t)) + \varepsilon_{eff}\sigma(T_f^4 - T^4(0,t)\}, \tag{19}$$

$$\lambda \frac{\partial T(L,t)}{\partial x} = h_c(T_\infty - T(0,t)) + \varepsilon_{eff}\sigma(T_\infty^4 - T^4(0,t)\}. \tag{20}$$

Based on the calculated temperature profile, time- heat flux area was calculated by

$$E_{(design)} = \int_0^{t_D} q(t)dt = \int_0^{t_D} [h_c(T_f - T(0,t)) + \varepsilon_{eff}\sigma(T_f^4 - T^4(0,t))]dt \tag{21}$$

for design fires. For the standard fire, the same formula was applied to calculate the heating duration to apply the same time- heat flux area.

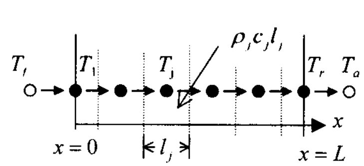


Figure 5 One-dimensional wall heat conduction

Results

As an example, the results for B_w=1 (β=181[K/s$^{1/6}$], t_D=1060[s]) is shown in FIGURE 6. The time-flux area for the design fire temperature was 156.6 [MJ/m^2]. Using the calculated time- flux relationship for the standard fire, the time to the same time-flux area was found to be 120 minutes. On the other hand, equation (17) yields,

$$t_{eq} = \left(\frac{181}{230}\right)^{3/2} \times 177 = 123, \tag{22}$$

which is very close to numerical results.

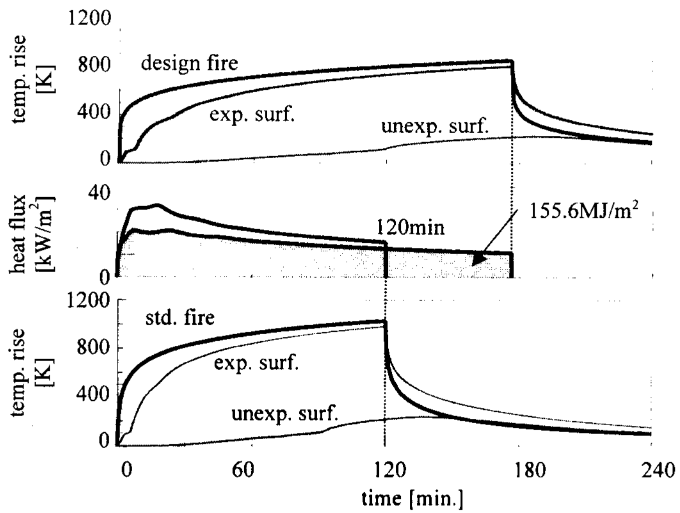


FIGURE 6 Calculation of Equivalent Fire Duration Based on Time-Flux area (Concrete 100mm)

Similar analysis was carried out for all the design fire temperatures shown in Figure 4 both for concrete and for calcium silicate board. The results are shown in Figure 7. As to thermally thick wall (concrete), the agreement is very good between numerical results and simple formula (17). As to the thermally thin walls (calcium silicate board), the agreement is not so good as that of thermally thick walls. Simple formula tends to give smaller values. But this tendency is only for mild (small β) fires, where the problem of fire resistance is not serious. Thus it is possible to conclude that the simple formula (17) is accurate enough to calculate the equivalent fire duration for the fires described by $\beta t^{1/6}$.

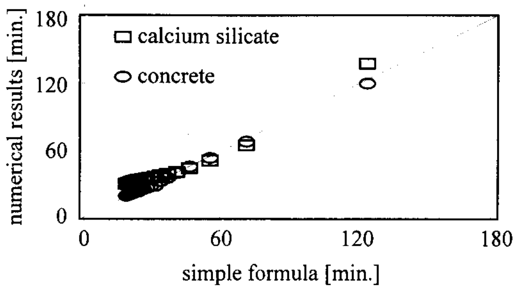


FIGURE 7 Comparison of equivalent fire duration calculated by simple formula (17) with precise calculation

Wall Temperature Rise

The calculated temperature rise of the unexposed surface is summarized in FIGURE 8. As is shown in FIGURE 8a), the temperature rise greatly depends on fire severity. In FIGURE 8b), the same data are plotted versus the equivalent time $t_{eq} = (\beta / 230)^{3/2} t$. The scatter during the fire period can be greatly reduced. Thus it is reasonable to scale the "real" time in accordance with equivalent time $t_{eq} = (\beta / 230)^{3/2} t$ at least in the period of heating.

In FIGURE 9, maximum surface temperature for design fires are compared with those for standard fires at equivalent duration. FIGURE 9a) shows the temperature at the end of fire. In case of concrete, agreement is good for severe fires. For mild and short fires, the temperature at equivalent fire duration is very low because of the large heat capacity of concrete, which delays the heat propagation to unexposed surface. However, this type of error is not a significant problem for practical fire resistance design. In case of calcium silicate board, the agreement is poor. The temperature for standard fire is higher than the design fires for most of the cases. This side of error is always conservative. Thus the present method is acceptable as a design tool. FIGURE 9b) shows the maximum temperature including the post fire period. In case of concrete, the agreement is much better. As to the calcium silicate board, the results are still poor but conservative.

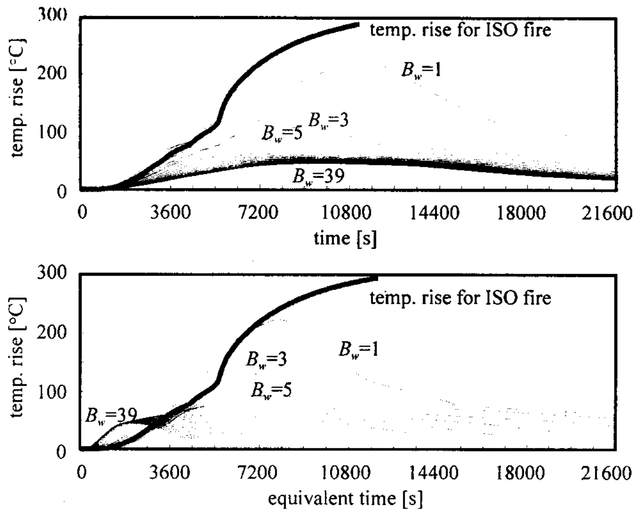
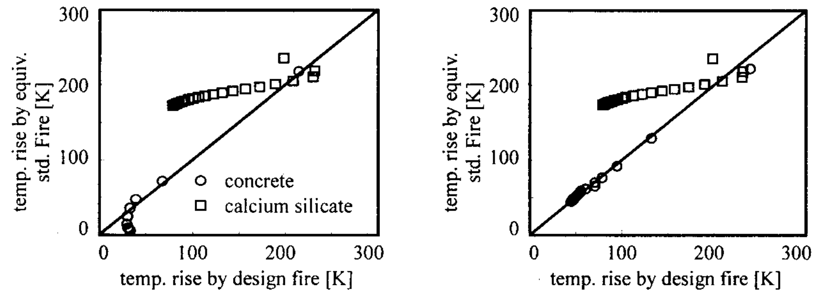


FIGURE 8 Unexposed surface temperature of Concrete Wall (100mm) heated by $\beta t^{1/6}$-fires and ISO 834 fire.



a) at the end of fire b) maximum temperature (incl. post fire)

FIGURE 9 Comparison of temperature of unexposed surface

EXPERIMENTAL SURVEY

To investigate the appropriateness of the present method, a survey was carried out to check the accuracy of proposed formula against existing fire test data.

Thermally Thick Case

As a representative for thermally thick construction, fire test data on concrete slab[14] was analyzed. In Figure 10, three fire test data for concrete floors are plotted. The difference between the three tests is the furnace temperature, which was altered to 90, 100 and 110% of the standard time- temperature curve. The difference in temperature rise in the three tests is greatly reduced by plotting versus equivalent time, $t_{eq} = (\beta / 230)^{3/2} t$ instead of actual time.

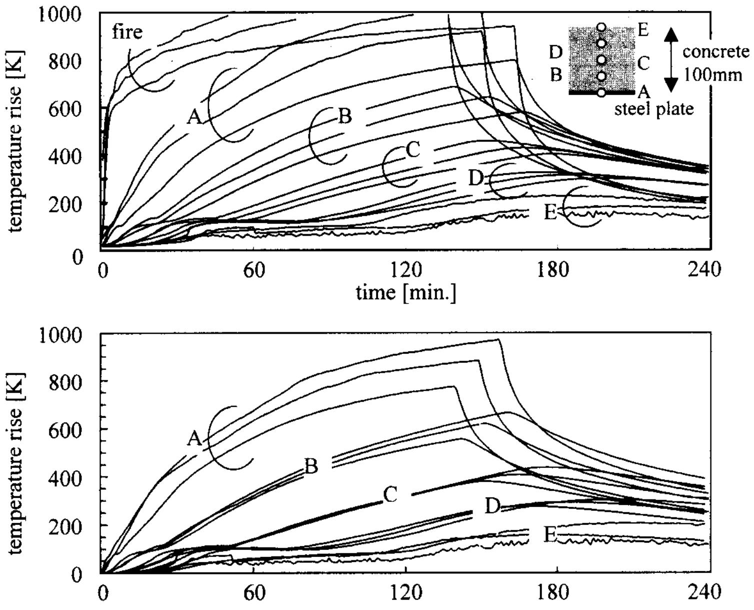


FIGURE 10 Test results of 100mm thick concrete floor covered by a steel plate.

Thermally Thin Case:

Figure 11 shows the three test results of four thermally thin wall specimens, heated by standard fires (44 and 54 minutes) and 80% of standard fire for 72 minutes[15]. Similar to thermally thick slabs, the difference of temperature rise during heating period was reduced by using the equivalent time. However, the maximum temperature does not agree well as was predicted theoretically in FIGURE 9.

Figure 12 shows the test results[16] of gypsum board (12mm +12mm). The time to integrity failure was measured at 33, 45 and 57 minutes, for 80, 100 and 120% of the standard fire. By using equation (17), those times are converted to 41 and 43 minutes, which are sufficiently close to the time under standard fire (45 minutes).

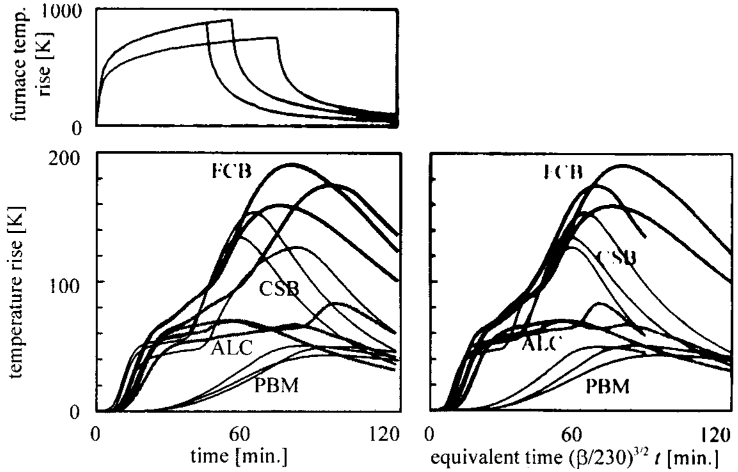


Figure 11 Test results of FCB (fiber cement board, L=50mm, w=3.23%-wt.), ALC (Autoclaved Lightweight Concrete, 50mm, 14.5%), CSB (Calcium Silicate Board, 40mm, 3.85%) and PBM (Plastic Beads Mortar, 70mm, 15.4%)

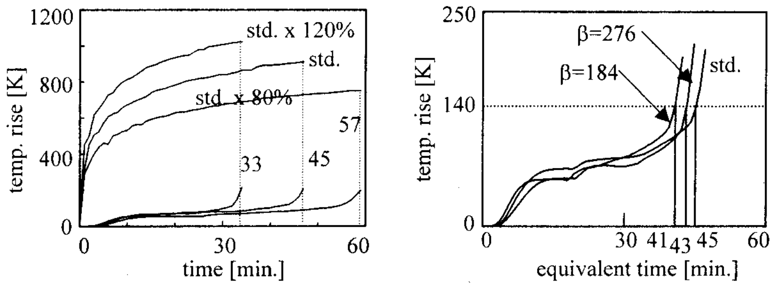


Figure 12 Test results of gypsum plaster boards (12mm x 2)

CONCLUSIONS

A simple formula for equivalent fire duration was proposed based on the equivalency in time-heat flux area, not by time- temperature area. The accuracy of the formula was checked against numerical calculations of the heat flux history for thermally thin and thick walls. A survey of existing experimental data was carried out to investigate the applicability of the proposed formula. In summary the formula gives reasonable results for temperature during heating period. As to the cooling period (post - fire), the temperature can not be predicted accurately, but conservative results can be obtained.

NOMENCLATURE

Alphabets					
A_t	internal surface area	[m²]	t_D	fire duration	[s]
A_F	floor area	[m²]	h_c	convective factor	[W/m².K]
A_W	window area	[m²]	L	wall thickness	[m]
A_{fuel}	fuel surface area	[m²]	$T(x,t)$	temp. of building element	[K]
c	specific heat	[kJ/kg.K]	T_f	fire temperature	[K]
E	time- heat flux area	[kJ/m²]	T_∞	ambient temperature	[K]
H_W	window height	[m]	Greek letters		
w	fuel load density per unit floor area (wood equivalent)	[kg/m²]	ε_{eff}	effective emmisivity	[-]
$A_W\sqrt{H_W}$	ventilation factor	[m$^{5/2}$]	ϕ	surface area coeff.	[m²/kg]
q	heat flux	[kW/m²]	λ	thermal conductivity	[kW/m.K]
Q	heat release rate	[kW]	ρ	density	[kg/m³]
t	time	[s]	$\sqrt{\lambda\rho c}$	thermal inertia	[kJ/s$^{1/2}$.m².K]
t_{eq}	equivalent time	[s]	β	fire severity coeff.	[K/s$^{1/6}$]
			σ	Stefan-Boltzman const.	[W/m²K⁴]

REFERENCES

1. Ministry of Construction, Notification No. 2999, 1969
2. ISO/TR834, Fire Resistance Test-Elements of Construction
3. American Society of Testing Materials, ASTM E119
4. Kawagoe, K., Sekine, T., Estimation of Fire Temperature - time Curves, BRI Occasional Report No.11(1963) and 17(1964)
5. Law, M., "A Relationship between Fire Grading and Building Design Components", Joint Fire Research Organization Fire Research Note, No. 877, 1971
6. Magnusson, S., E., Thelandersson, S., "Temperature - Time Curves for the Complete Process of Fire Development", Acta Polytechnica Scandinavia, Ci65, 1970
7. Law, M., "A Review of Formulae for T- Equivalent", Fire Safety Science (proc. 5th IAFSS, Melbourne), pp. 985- 996, 1997
8. Draft European Prestandard, Eurocode 1 - Basis of Design and Actions on Structures - Part 2-2: Actions on Atructures - Actions on Structures Exposed to Fire, Feb., 1995
9. Harmathy, T., Z., Mehaffy, J. R., "Post Flashover Compartment Fires", Fire and Materials, Vol. 7(2), 1983
10. McCaffery, B., J., Quintiere, J., G., Harkleroad, M., F., "Estimating Room Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations", Fire Technology, Vol. 17(2), pp.98- 119, 1981
11. Matsuyama, K., Fujita, T., Kaneko, H., Ohmiya, Y., Tanaka, Y., Wakamatsu, T., "Simple Predictive Method for Room Fire Behavior", Fire Science and Technology, Vol. 18(1), pp. 23-32, 1998
12. Aburano et al., Transactions of AIJ, No.483, 1996 (in Japanese)
13 Ohmiya, Y., Sato, M., Tanaka, T., Wakamatsu, T., Transactions of AIJ, No. 469, pp.149- 158 and No. 472, pp. 169- 176, 1995 (in Japanese)
14 Harada, K., Terai, T., "Numerical Simulations of Fire Test of Concrete Slab", Fire Safety Science, (Proc. second Int. Symp. on Fire Safety Science, Tokyo), pp. 707- 717, 1988
15. Annual report of MoC project, "Development of Fire Testing and Evaluation System of Materials and Construction (Structural Fire Resistance Design Sub Committee)", 1996 (in Japanese)
16. Unpublished Data

LARGE SCALE EXPERIMENTS