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Comments by the Author of the Introductory Report

Remarques de l'auteur du rapport introductif

Bemerkungen des Verfassers des Einführungsberichtes

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Thermal Effects of Fire in Building

The Introductry Report of Subtheme III (a) "Thermal Effects of Fires in Buildings" written by us has been issued in 1975.

Four Preliminary Reports have been presented to the Subtheme III (a) and issued before the Congress.

In the first paper "Théorie des Equivalences" by Mr.E.Absi and M.Borensztein, CEBTP, France, the calculation method to predict the temperature-time field and the thermal stress in a concrete structural element are described and some calculation results are shown.

In the second paper "Détermination par la method des éléments fines des evolutions de temperature pour les structure soumises à l'incendie" by Mr.J.C.Dotreppe and M.Hogge, Universite de Liege, Belgique, the detail of a calculation method to predict the temperature-time field in a structural element is described and an experimental result is compared with the calculated one.

In the third paper "Application of a Limit State Concept to the Performance of a Structure under Fire Conditions" by Mr.H.L. Malhotra, Fire Research Station, U.K., a new concept considered some limit state to the performance of a structure, based on the semi-probablistic approach is described.

In the fourth paper "A Differentiated Approach to Structural Fire Engineering Design" by professor O. Pettersson, Lund University, Sweden, a pure engineering design method for fire resistance of building structure which has been legally available in Sweden is described.

These four papers are connected each other and I will explain as one story mixing with our introductry report.

As Mr.Malhotra describes in his paper, "the standard temperature-time curve" for the standard fire test of building structural elements was established, and the simple relationship between the fire load density and the necessary duration of fire exposure along the standard temperature-time curve was derived by Dr.S.H.Ingberg about 60 years ago.

Then the concept of the fire resistance design for building structure was established.

That concept was to subdivide the building effectivelly into "fire resisting compartments," and the building regulations and codes designated the fire duration required, depending on the occupancies and the height or the size of building and also the fire resisting capacity of structural element was determined by the results of the full scale standard fire test.

In many countries except Sweden and France, this traditional design method has been still used legally and the International Standard Fire Test Method by ISO has recently been agreed.

Over the last fifteen years the fire research has been advanced remarkably, and the people intend to use the engineering method for fire resisting design apart from the traditional way.

The first country in which a new engineering method was permitted to use legally was Sweden. Professor Pettersson describes in his paper that it is necessary to define the following four items to establish an engineering design system.

a) the fire load characteristics,
b) the gas temperature-time curve of the fire compartment as a function of the fire load density, the ventilation characteristics of the fire compartment,
c) the temperature time field, and
d) the structural behaviour and minimum load bearing capacity of the fire exposed structure for a complete process of fire development.

Our introductry report has been described along these items. Now I explain some detail of each one.

a) The survey of the fire load of several occupancies has been done in several countries. But the fire load characteristics is slightly different for each country, because the structure and the use of building are different. Therefore it is necessary to determine the fire load density in each country, whatever the survey of fire load takes much labour and time.

The explanation of fire load density has many ways, depending on the purpose, as follows,

$$\frac{\text{equivalent weight of wood (Kg)}}{\text{unit floor area (m}^2\text{)}} \quad \text{(traditional)}$$

$$\frac{\text{potential heat content (Mj)}}{\text{unit floor area (m}^2\text{)}} \quad \text{(ISO)}$$

$$\frac{\text{effective heat content (Mj)}}{\text{unit interior surface area (m}^2\text{)}} \quad \text{(Sweden)}$$

$$\frac{\text{effective heat content (Mj)}}{\text{unit window area (m}^2\text{)}}$$

b) The gas temperature-time curve of a given compartment can be predicted roughly by the calculation of heat balance equation inside compartment, in which the heat release of fire load inside compartment.

In Sweden the calculated gas temperature time curve of a given compartment is taken as the heat load to the fire exposed structure, ignored "the standard temperature-time curve."

In Japan and other countries, the equivalent fire duration along the standard temperature-time curve, which temperature time area over the critical temperature of steel is same as the calculated one, is wanted to use as the heat load.

The result of the international corporative study of CIB W-14, in which eight laboratories were joined to test the model compartment fires, concluded that an experimental formula ($t_f = kL/\sqrt{A_W A_T}$) as shown in Malhotra's paper could be available to use for the estimation of fire duration alon the standard temperature time curve.

c) The temperature rise of steel member protected by the fire cover is not only depend on the thickness and the thermal properties of fire cover but also the heat capacity of steel member itself. It is not rational to determine only the thickness of covering material as usual designation in the codes and regulation.

In Sweden the thickness of fire cover is determined by the calculation of the heat conduction of each element exposed by each thermal load. Therefore a lot of tables and figures have been prepared, some of which are shown in Pettersson's paper.
In France the calculation method is applied legally in the concrete structural design since December 1975, which method is described in Adam's paper in subtheme III (c).

Because the theory of heat conduction has already been established, a lot of studies has been made for the prediction of temperature time field of structural elements exposed by fire.

In preliminary reports in this subtheme, Mr.Absi and Borensztein describe the calculation method used by the theory of equivalences and show some calculated results of concrete structural elements briefly. And Mr.Dotreppe and Hogge describe the detail of calculation method using the finite element one and compare an experimental result obtained from the heating of a block of concrete 18cm X 18cm with the calculated one.

In fact, in the calculation of heat balance equation in a compartment, the calculation of temperature time field of enclosed structual element is necessary. If a big computer could be used, the temperature time field could be calculated in the same time so that it is not necessary to divide b) and c).

Instead the theoretical calculation can be possible to any section of structual elements, the effect of spalling of concrete and of cracks of materials are rather difficult to insert the calculation and also the thermal properties of materials under the high temperature and the mechanism of moisture migration inside material under the high temperature are not well known, which are the problems to be solved.

d) The structual behaviour and the load bearing capacity of the fire exposed structure are the main themes of IABSE and especially in subtheme III (b) and III (c). In this subtheme III (a), Mr.Absi and Borensztein describe the calculation method of the thermal stress and the deformation used by the theory of equivalences, but the discussion of these problems is left to III (b)and(c).

For the systematize of the engineering design method based on from a) to b), many ways can be chosen. Now we look at the Swedish system as an example.

At the first, the rate of burning and the rate of heat release in a given compartment are calculated from the fire load density, the size and the geometry of compartment and the ventilation characteristics. Then the gas temperature time curve is calculated which is assumed as the heat load.

Input this heat load to the structural element, the temperature-time field inside it is calculated.

From this temperature-time field and the restraint forces, moments, thermal stress and the reduction of mechanical properties in the structual element, the load carring capacity Rd is calculated.

Leaving these calculated results, the load effect at fire condition Sd is calculated separately.

If Sd is greater than Rd, the proposed structure is modified and recalculation is made until to obtain the satisfaction of Sd<Rd.

In Japan, tall apartment buildings of a big project was designed their fire resistance used by a similar engineering method, but it was specially permitted, not available to use any building.

Finally, the new concept of the limit state approach in fire by Mr.Malhotra is introduced. He divides the limit state into two, one is the limit state of stability which means the structural load carring capacity under fire based on the probablistic approach and another is the limit state of integrity which means the capacities of barrier of the compartmentation.

A similar probablistic analysis for steel structure is presented by Dr.S.E.Magnusson in subtheme III (b).

These studies based on the probablistic approach are only started, but the re-consideration of fire safety will become an important research subject in the fire engineering field because it would be the important basic concept of engineering design.

Numerical Calculation of the Temperature Distribution in Hot Gas Plume from a Window

Calcul numérique de la distribution des températures dans une colonne de gaz chaud s'échappant d'une fenêtre

Numerische Berechnung der Temperaturverteilung in einer aus einem Fenster ausströmenden Heissluftsäule

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1. INTRODUCTION

In order to prevent the fire spread to upstairs through broaken windows in a building, it is necessary to provide a fireproof spandrel between the windows. The estimation of its necessary height was once studied by YOKOI*[1], who conducted both dimensional analysis and small scale experiments on the behavior of the hot gas plume ejected from a window to find that the temperature distribution along its trajectory would be estimated by the normalized temperature Θ which is defined as

$$\Theta \equiv \Delta\theta r_0^{5/3} / \sqrt[3]{Q^2 \theta_0 / C_p^2 \rho^2 g} \qquad (1)$$

where $\Delta\theta$: excess temperature of the trajectory(°C), Q: released energy rate from window(kcal/sec), θ_0: temperature of ambient air(°K), C_p: specific heat of air at constant pressure(kcal/kg°K) r_0: equivalent radius of window(m) and ρ: density of hot gas(kg/m^3). Fig.1 summarizes the results of the small scale experiments for various geometries of window. This simple method gives good results for many cases, but when the refractoriness of a spandrel or the interaction between the spandrel and the plume is discussed, it will be also necessary to predict the temperature dis-

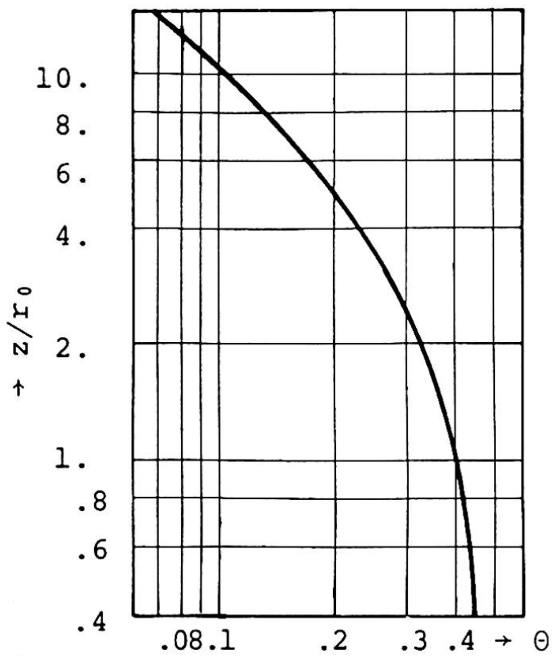

Fig.1 TEMPERATURE DISTRIBUTION ALONG THE TRAJECTORY OF HOT GAS PLUME*[1]

tribution in hot gas plume,especially near the spandrel above the window.

In this paper,we introduce the calculation method by the finite difference approximation of the governing differential equations on the behavior of hot gas plume and then show a calculation result **with** an experimental one carried out under the almost similar condition to the one for the numerical calculation.

2. GOVERNING EQUATIONS

The governing equations of a thermally expanding or contracting turbulent motion of gas are the following set of 6*2.

EQUATION OF MOMENTUM:

$$\frac{\partial \overline{\rho u}_i}{\partial t} + \frac{\partial \overline{\rho u}_i \overline{u}_j}{\partial x_j} \simeq -\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\{\overline{\sigma}_{ij} + K(\frac{\partial \overline{\rho u}_i}{\partial x_j} + \frac{\partial \overline{\rho u}_j}{\partial x_i})\} - \delta_{i3}\overline{\rho}g \qquad (2)$$

where u:velocity(m/sec), P:pressure(kgm/sec^{2}m^2), σ:viscosity stress(kgm/sec^{2}m^2), K:eddy **coe**fficient(m^2/sec), i or j:tensor mark and δ:KRONECKER delta. Overbarred quantities denote the time-smoothed variables. The time-smoothed velocity is given by

$$\overline{u}_i \simeq \frac{\overline{\rho u}_i + K(\frac{\partial \overline{\rho}}{\partial x})_i}{\overline{\rho}} \qquad (3)$$

EQUATION OF CONTINUITY:

As the time-smoothed density is obtained from the equation of state in our calculation scheme,the equation of continuity should be transformed to the POISSON type equation for $\overline{P}$. This equation is obtained by substituting the equation of momentum into the **na**tural form of continuity equation $\partial\overline{\rho}/\partial t + (\partial\overline{\rho u}/\partial x)i = 0$.

$$\frac{\partial^2 \overline{P}}{\partial x_i^2} \simeq \frac{\partial^2 \overline{\rho}}{\partial t^2} + \frac{\partial^2}{\partial x_i \partial x_j}\{\overline{\sigma}_{ij} + K(\frac{\partial \overline{\rho u}_i}{\partial x_j} + \frac{\partial \overline{\rho u}_j}{\partial x_i}) - \overline{\rho u}_i \overline{u}_j\} - g\frac{\partial \overline{\rho}}{\partial x_3} \qquad (4)$$

CONSERVATION EQUATION OF ENERGY:

$$\overline{\rho}\frac{\partial \overline{h}}{\partial t} + \frac{\partial \overline{\rho u}_i \overline{h}}{\partial x_i} \simeq \frac{\partial}{\partial x_i}(\kappa\frac{\partial \overline{T}}{\partial x_i} + K\frac{\partial \overline{h}}{\partial x_i}) + \overline{Q} + h\frac{\partial \overline{\rho u}_i}{\partial x_i} \qquad (5)$$

where h:enthalpy of air(kcal/kg), κ:thermal conductivity(kcal/sec m) and Q:generation rate of heat(kcal/secm^3). The dissipation of kinetic energy is ignored for its minor role in the conservation of energy.

DEFINITION OF EDDY COEFFICIENT:

PRANDTL's dimensional relationship is applied to the modeling of eddy coefficient. In this model,eddy **coefficient is given by**

$$K \simeq \sqrt{q}\ell \qquad (6)$$

where the mixing length 'ℓ' may be determined geometrically and the turbulent energy is given from the conservation equation for it.

$$\frac{\partial \overline{\rho q}}{\partial t} + \frac{\partial \overline{\rho u}_i \overline{q}}{\partial x_i} \simeq \frac{\partial}{\partial x_i}(\overline{\rho}K\frac{\partial \overline{q}}{\partial x_i} + \mu\frac{\partial \overline{q}}{\partial x_i}) + K\frac{\partial \overline{\rho}}{\partial x_3}g - \overline{\rho\varepsilon} + K(\frac{\partial \overline{\rho u}_i}{\partial x_j} + \frac{\partial \overline{\rho u}_j}{\partial x_i})\frac{\partial \overline{u}_j}{\partial x_i} \qquad (7)$$

where μ:dynamic viscosity(kg/secm) and ε:turbulent energy decay rate(m^2/sec^3).

EQUATION OF STATE:

The change or variation of the pressure in fire is usually so small that the equation of state may be approximated correctly by

$$\bar{\rho} \simeq \frac{P_0}{R\bar{T}} \qquad (8)$$

where P_0:referential pressure(kgm/sec^{2}m^2), R:gas constant and T: absolute temperature of air(°K).

3. OUTLINE OF THE CALCULATION METHOD

The governing equations above introduced are of course so complicated for an analytical solution that we solve them simultaneously in a numerical manner. However,because we do not have enough space to describe everything about the calculation method, we present the outline of the finite difference calculation method which is detailed in REF.2.

In our numerical code,the unsteady equations (2),(3) and (7) are transformed into explicit finite difference equations, whilst the POISSON type equation for the pressure (4) is solved by an iterative method such as Over-Relaxation method. For the finite difference calculation of the spacially differentiated terms,the Cell Model in which the physical variables are arranged by the way as shown in Fig.2 is used. A stable marching of the unsteady calculation is achieved only when the finite increment of time satisfies the following criterion which is known as COURANT-FRIEDRICHS-LEWY condition.

$$\Delta t < \frac{1}{\left(\sum_{i}^{3} |\bar{u}_i/\Delta x_i|\right)_{max}} \qquad (9)$$

Then,the finite difference equations for (2)∿(8) are solved unsteadily by the procedure as shown in Fig.3.

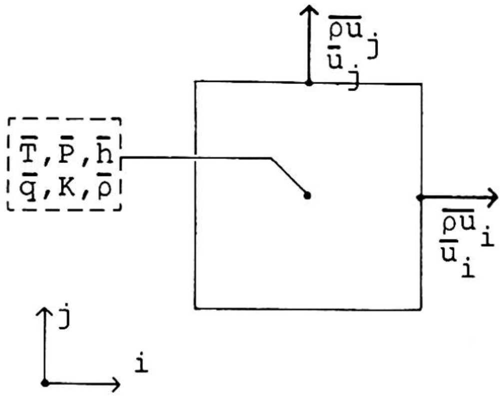

Fig.2 GRID ARRANGEMENT IN CELL MODEL

4. CALCULATION OF THE TEMPERATURE DISTRIBUTION IN HOT GAS PLUME

Now,we apply the calculation method above introduced to the estimation of the temperature distribution of a hot gas plume ejected from a broaken window.

It was suggested by YOKOI*[1] on the basis of the results of his small scale experiments that the hot gas plume from a wide opening would close to the wall or spandrel above it to be a possible cause of the fire spread to upstairs. This phenomenon which may be interpreted by the COANDA effect was also observed in the full scale experiment conducted recently by KAWAGOE et al*[3]. Such a phenomenon seems to be represented pertinently in a two-dimensional calculation,because we may conceptually replace a wide opening by a two-dimensional one without bringing any serious problem.

In this paper,we make a numerical calculation of the hot gas plume under the conditions which are determined according to KAWA-

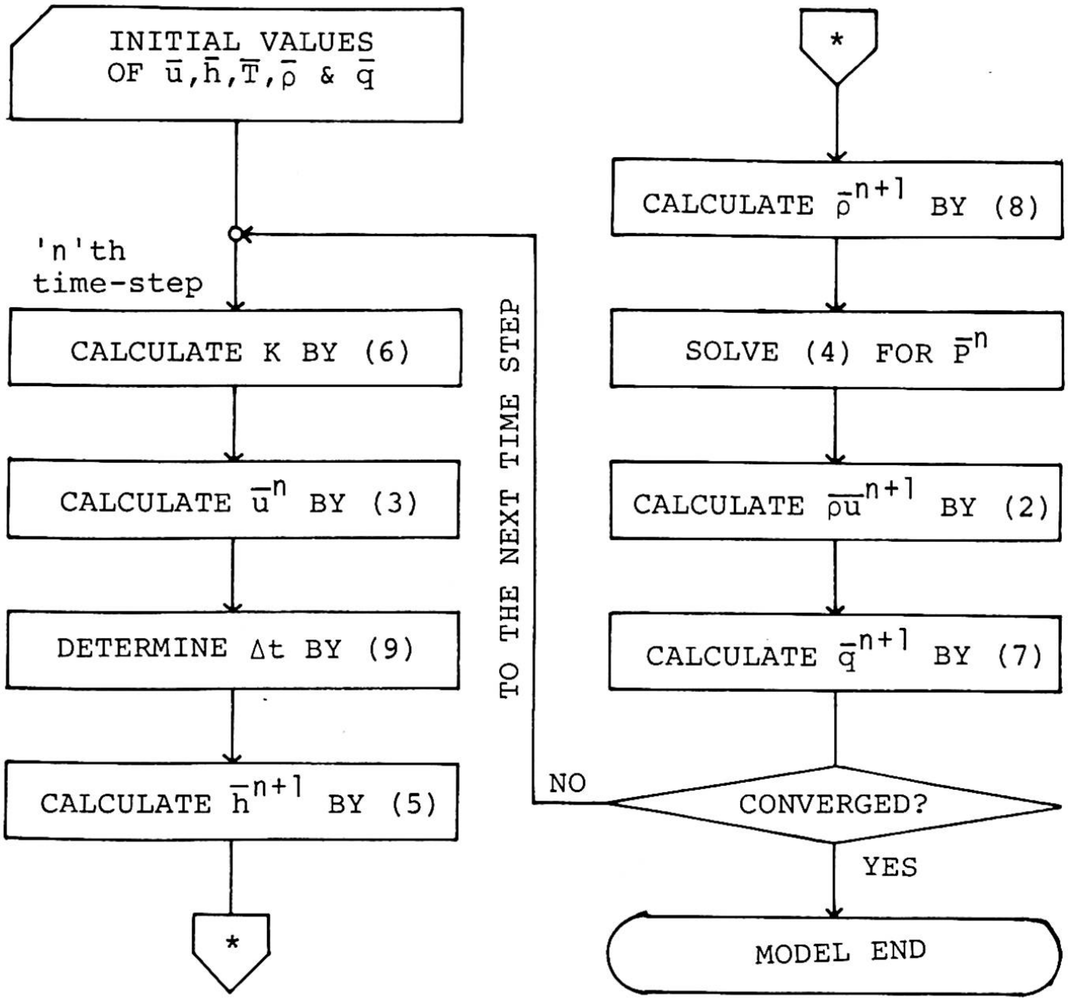

Fig.3 OUTLINE OF THE UNSTEADY CALCULATION PROCEDURE

GOE's experiment as shown in Tab.1 and then compare the calculation result with the experimental one. Among these conditions for the calculation,the height of neutral plane and the distribution of the mixing length are determined empirically and the spouting velocity is estimated by YOKOI's equation.

Tab.1 CONDITIONS FOR THE NUMERICAL CALCULATION

TEMPERATURE OF HOT GAS PLUME AT OPENING	900°C
TEMPERATURE IN UPSTAIRS ROOM	100°C
TEMPERATURE OF AMBIENT AIR	30°C
MASS FLUX RATE OF PLUME AT OPENING	$\rho U = \sqrt{2gh''(\rho_0-\rho)}$ ρ_0:density of ambient air h":height from neutral plane
MIXING LENGTH	$\ell = 0.4y$, $\ell_{max} = 0.2H$ y:distance from boundary H:height of building

In Fig.4 are superimposed the calculated isotherms on the temperature field generated from the experiment. Although the discrepancy between the calculated and experimental distributions near the opening of the fire compartment is considerably great, the phenomenon above mentioned which may be a cause of the fire spread to upstairs is represented pertinently in the calculation result.

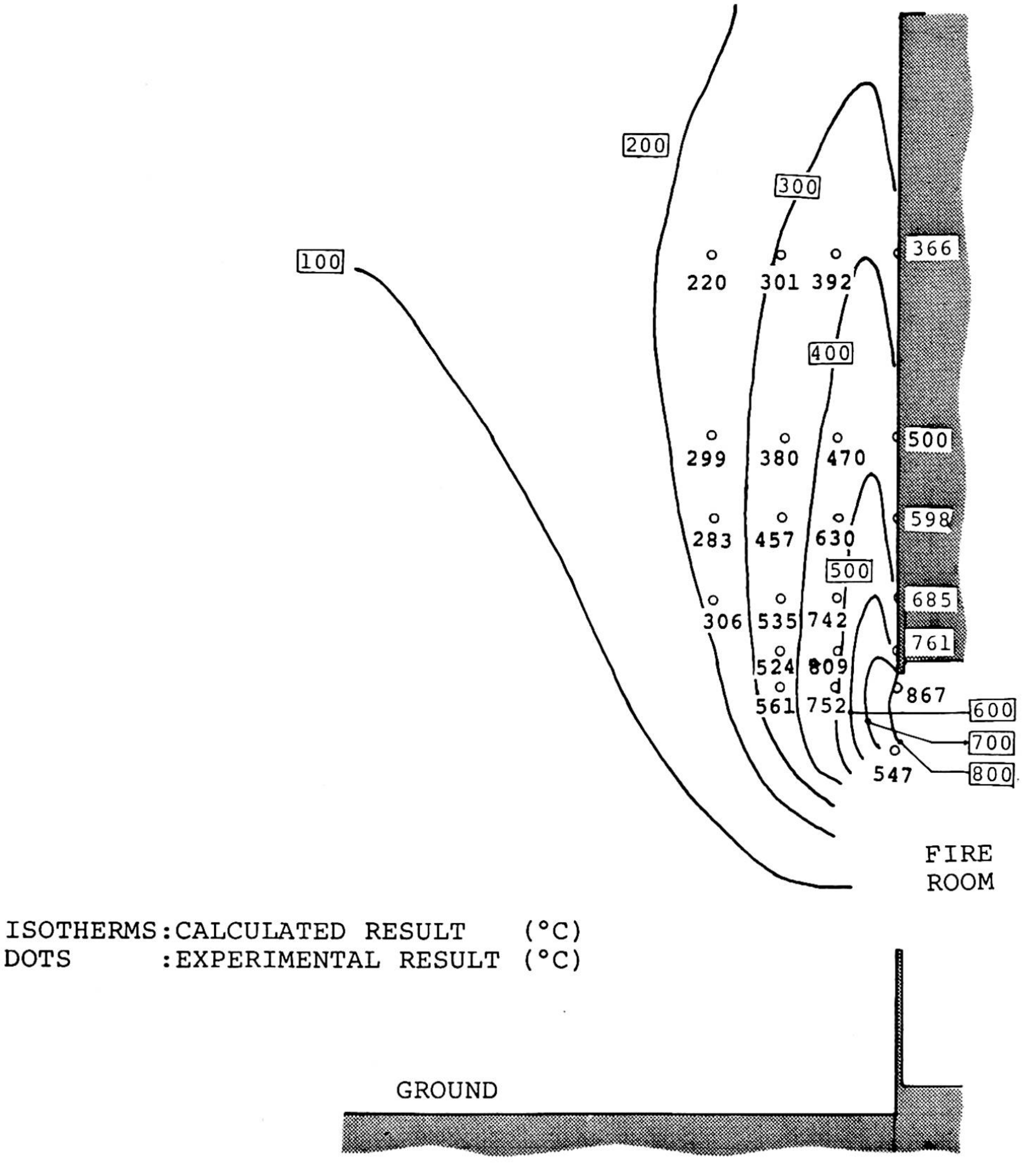

Fig.4 TEMPERATURE DISTRIBUTION IN HOT GAS PLUME FROM A WINDOW (COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS)

5. CONCLUSIONS

The temperature distribution in two-dimensional hot gas plume was calculated as an application of the prediction method. The use of a large EDPS will permit also a three-dimensional calculation, because the calculation method for the three-dimensional case does not differ basically from the one for the two-dimensional case which is introduced in this paper. Though some problems such as the calculation of the flame radiation are left as future subjects,we can utilize such a calculated temperature distribution for designing the height or refractoriness of a spandrel from the view point of fire safety.

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SUMMARY

This paper presents a method for the numerical calculation of the temperature distribution in a hot gas plume from a window. The calculation is given for a two-dimensional window and also compared with experimental results. Calculation and experiments show a good agreement.

RESUME

Cet article présente une méthode numérique pour calculer la distribution des températures dans une colonne de gaz chaud s'échappant d'une fenêtre. Le calcul est présenté pour une fenêtre à deux dimensions et est aussi comparé avec des résultats expérimentaux. La concordance entre le calcul et l'expérience est bonne.

ZUSAMMENFASSUNG

Der Autor beschreibt ein numerisches Verfahren zur Berechnung der Temperaturverteilung in einer aus einem Fenster ausströmenden Heissluftsäule. Die Berechnung wird für ein zweidimensionales Fenster vorgelegt und mit Versuchsergebnissen verglichen. Die Uebereinstimmung zwischen Berechnung und Versuch ist gut.

Design of Tall Apartment Buildings for Fire Resistance

Conception de bâtiments d'habitation hauts en vue de leur résistance à l'incendie

Entwurf von hohen Wohnhäusern in bezug auf Brandeinwirkungen

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The existing Japanese building codes for fireproof constructions prescribe the fire endurance of the individual structural elements, such as beams, columns, floors and so on, without concerning the fire properties and structural features of buildings. Buildings have been designed against fire according to these codes. However, researches on the fire properties in compartments and the behaviour of steel structures under fire have recently been carried out and made the design of fireproof constructions possible by engineering methods.

This paper discusses the method and the results of the fireproofing design of the Ashiyahama Housing Project currently under construction. The Ashiyahama Housing project consists of many multistoried buildings as shown in Photo 1 and the dwellings totaled 3384.

The fireproofing design system used on this project is illustrated in Fig.1, and the following procedure was applied:

1) Fire compartments were allocated as shown in Fig. 2.

2) Fire loads were estimated from the quantity and the quality of the combustible materials for individual fire compartments.

3) Using a monograph, the equivalent fire duration time of dwelling unit was obtained from the fire load, floor factor, temperature factor and others. The equivalent fire duration time of public floor was determined by taking into account the fire load and burning phenomenon in the open space.

4) If the fire was not to spread to the adjoining fire compartments, then advance to the next step.

5) Using a computer program, allowable temperature of the steel frame was calculated from dead load, live load, thermal expansion and deterioration of steel members at elevated temperature. Shown as example, Fig.3 represents the joint displacement according to only thermal expansion and Fig.4 shows the distribution of bending moment that is due to the ordinary design load and the thermal expansion.

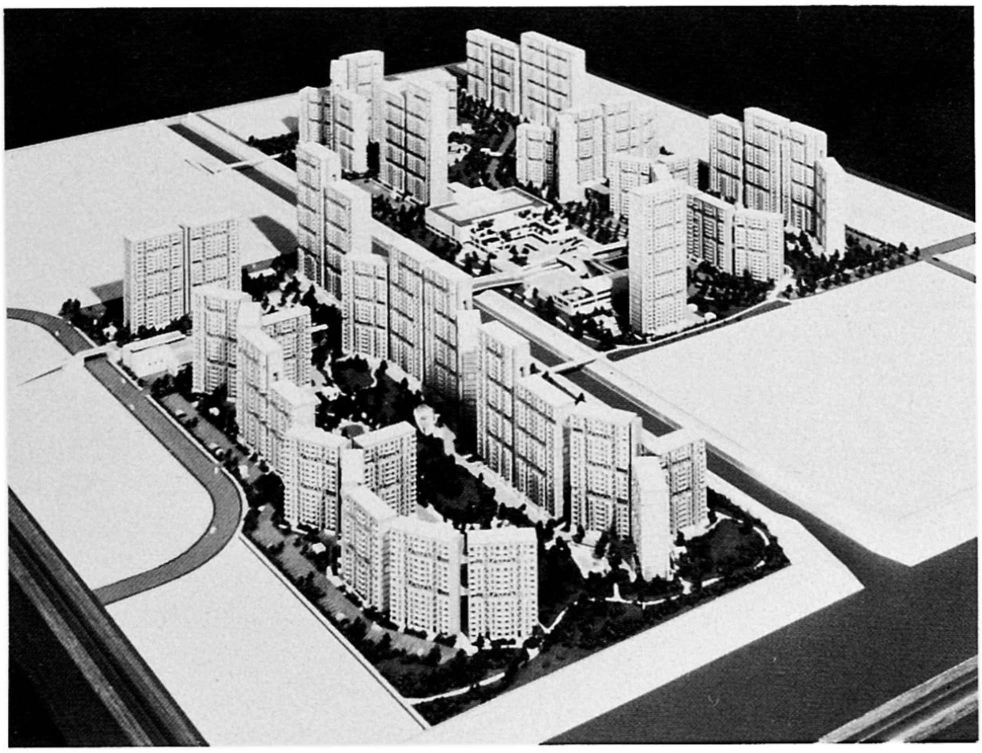

Photo 1: The bird's-eye view of the Ashiyahama Housing Project.(model)

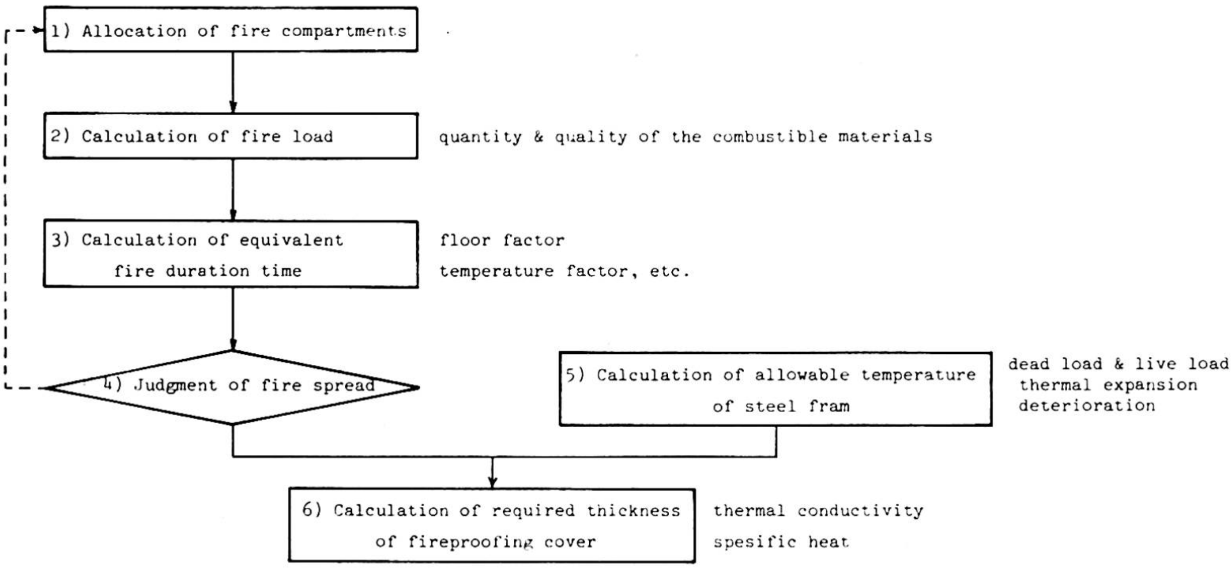

Fig. 1: The fire proofing design system

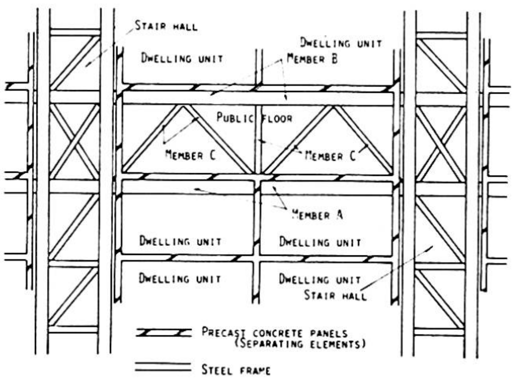

Fig. 2: The fire compartment and steel frame

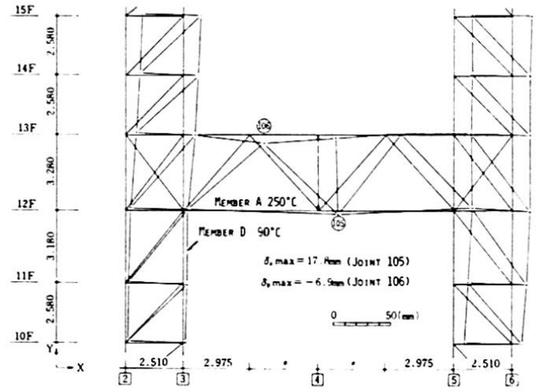

Fig. 3: Joint displacement according to only thermal expansion

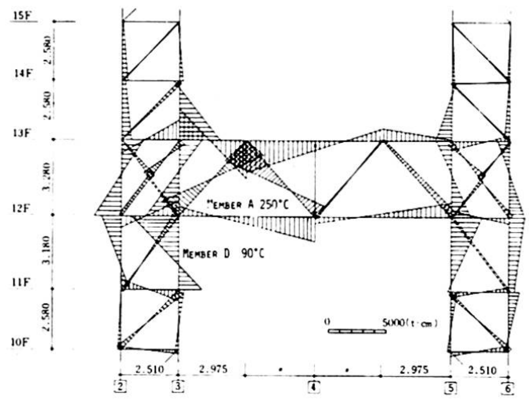

Fig. 4: Distribution of bending moment according to the ordinary design load and the thermal expansion

Fire compartments	Fire load (Kg/m²)	Equivalent fire duration time (min.)	steel members in compartment	allowable temperature of steel members (°C)	Required thickness of fireproofing cover* (mm)
Dwelling unit	60	90	A	250	45
Public floor	15	30	B	200	15
			C	100	15**
Stair hall	0		others		0

* Sprayed asbeston.

** This value was determined by taking into account the heating condition and birning phenomenon in the open space.

Table 1: Results of the fireproofing design

6) The need for some fireproofing cover was realized by which the temperature rise of steel member could be kept below the allowable temperature after heating for equivalent fire duration time along the standard time-temperature curve. The required thicknesses of the fireproofing cover for members named A, B and C were calculated. It was found that other members did not require fireproofing cover.

These results are tabulated in Table 1.

Adopting the fireproofing design in this project despite the current building codes, structural safety against fire was secured and economical design was established.

The fireproofing design system adopted in this project can be applied, without modification, to such design of other buildings.

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SUMMARY

This paper discusses the method and results of the fireproofing design for the Ashiyahama Housing Project currently under construction. By adopting the fireproofing design in this project, without restriction of the existing Japanese building codes for fireproofing construction, the structural safety against fire was secured and economical design was satisfied.

RESUME

Cette étude discute la méthode et les résultats du calcul et de la conception du quartier d'habitation d'Ashiyahama en vue de la résistance à l'incendie. L'adoption de cette méthode qui n'est pas en contradiction avec la réglementation actuelle japonaise en la matière a permis d'assurer la sécurité structurale contre l'incendie et de réaliser un projet économique.

ZUSAMMENFASSUNG

Dieser Artikel erörtert die Methoden und Ergebnisse des Entwurfs in bezug auf Brandeinwirkungen für das derzeitig im Bau stehende Ashiyahama Wohnbauprojekt. Die für dieses Projekt herangezogene Methode gewährleistet einen ausreichenden Brandschutz, ist zudem wirtschaftlich und entspricht in allen Punkten den bestehenden japanischen Vorschriften für brandsichere Bauten.