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Performance Based Fire Engineering in Japan

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Abstract

This paper explains the Japanese present situations relevant to the fire resistance performance. Performance-based fire provisions was introduced in 1998 for the first time when the Building Standard Law was amended. However, performance-based fire resistance design had been used since long before the official introduction of performance-based provisions. A Comprehensive Technology Development Project of Ministry of Construction from 1982 to 1986 established a technical basis for performance-based fire safety engineering in Japan. A system of calculation methods for fire resistance verification was prescribed in the Ministry Notification in 2000 utilizing the results of this project as a background. This method, referred to as the Fire Resistance Verification Method (FRVM), is the standard method to verify the fire resistance performance of principal building parts such as columns, beams, and walls of steel, concrete, or wood structured buildings. For tall buildings, however, more advanced method for performance verification is often necessary because new building materials or structural systems are often used for these buildings. An example project of tall building owned by a major newspaper company is presented in this paper. Advanced thermal deformation analysis is executed to secure the fire resistance of the building.

Keywords: Fire resistance, Performance-based, Code requirements, Steel building, High-rise, Thermal deformation

1. Introduction

In Japan, performance based fire engineering has evolved since long before the official introduction of Performance Provisions of Building Standard Law (BSL), in 1998 law amendment. Experimental and theoretical researches were intensely carried out through 1982 to 1986 in the Comprehensive Technology Development Project of Ministry of Construction. Technical methods developed by this Project established technical basis for the performance-based fire safety design of buildings. In the late 1980’s to 1990’s, many buildings using new and advanced construction materials/methods but not comply with the prescriptive requirements of the Building Standard Law were designed and evaluated its fire safety performance by using the technical methods developed by the Project. In this period, however, the verification to the Law requirements was based on the Article 38 of the BSL, which was deleted in the 1998 Law Amendment. Minister of Construction could approve the equivalent ‘effect’ of the buildings that used new construction materials or new construction methods to ordinary buildings that comply with the provisions in other part of the BSL than Article 38. Practically, compliance with the BSL was judged by the evaluation committee in the Building Center of Japan (BCJ). The committee was composed of mostly professors in the relevant field. As there was no clear definition of the performance objectives and requirements in the BSL, the rationality of the committee was often subjected to discussion.

In the late 1990’s, worldwide trends to shift building regulations from conventional prescriptive provisions to performance-based provisions generated discussion among Japanese building experts. Then, in 1998, the BSL was amended to performance-based regulation system. For fire resistance of buildings, the performance objective and its criteria was described to some extent and a new performance verification method, the FRVM, was introduced in May 2000. One year before that, the Architectural Institute of Japan (AIJ) had published “Recommendation for Fire Resistant Design of Steel Structures” in 1999. This Recommendation summarized the state-of-art methods to verify the fire resistance performance of steel buildings and guidelines to use these methods. The calculation methods for steel members in the FRVM largely owed to the AIJ Recommendation.

2. Code Requirement for Fire Resistance

Building regulation in Japan has the feature that Building Standard Law is applicable to all the buildings built in Japan. BSL provides various regulatory standards with a hierarchy system of the Law, Enforcement Order, Enforcement Regulation and Notifications by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT, the former Ministry of Construction). The objectives of the

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regulation are mainly described in the Law. Technical standards to achieve the objectives are provided in the Enforcement Order. Detailed various provisions including prescriptive ones are given in Notifications to supplement the Enforcement Order. The last major revision of the BSL was done in 1998 to shift the provisions from prescriptive regulation to performance-based one.

The fire regulations consist of provisions both for structural fire resistance and the evacuation safety of buildings. In either case, performance verification methods, such as the fire resistance verification method (FRVM), and the verification methods for floor evacuation safety and building evacuation safety, are prescribed besides purely prescriptive provisions.

In BSL, required fire resistance of a building depends on the building occupation, scale of building and fire zoning of the site. For example, in the Fire Protection Zone such as urban center where the highest level fire safety is required, a building which has three or more stories or whose total floor area exceeds 100 m^2 is obliged to be the fire-resistive building. Fire-resistive buildings are defined in BSL as buildings which have "principal building parts" (namely, those walls, columns, beams, roofs, and stairways which are important from the viewpoint of fire prevention) of fire-resistive construction, or constructed using a method that has been confirmed (using the FRVM, etc.) to be capable of withstanding effect of flame and heat until the end of a fire, and fire doors in portions liable to catch fire, in order to prevent destruction or the spread of fire until the end of a normal fire. As most tall buildings are built in urban area, they are generally required to be fire-resistive buildings.

3. Three Approaches for Fire Resistance Verification

If a building is required by BSL to be a fire-resistive building, the designer of the building needs to verify the fire resistance of the building to conform to the BSL by one of three approaches. These approaches are referred to as Route A, Route B and Route C. Route A is a conventional prescriptive approach, which is to use fire-rated constructions for all principal building parts. The required fire resistance time depends on building part and its location in the building as shown in Table 1. Route B is a performance approach. In this approach, however, only verification methods prescribed in the Notification No. 1433 of the Ministry of Construction / May 31, 2000 are allowed to use. If one wants to use some other methods than those in the Notification, one needs to get an Approval by the Minister of Construction. The Minister issues an Approval based on the results of performance, in this case fire resistance, evaluation conducted by one of the Designated Performance Evaluation Bodies.

In the BSL, a building design is required to receive 'building confirmation' from a building official or by Designated Confirmation and Inspection Body before the construction of the building begins. As shown in Fig. 1, in Route A or Route B approaches, one can apply directly for building confirmation. On the other hand, in Route C approach, there are intermediate steps for Minister Approval before application for building confirmation. In general, these intermediate steps take more than 2 months.

4. Applicability and Features of the Fire Resistance Verification Method (FRVM)

As mentioned in the previous section, a systematic calculation method of fire resistance was established under the BSL in 2000. This method is referred to as the Fire Resistance Verification Method (FRVM). The FRVM is applicable to steel, reinforced concrete and wood structured buildings. The flowchart of the method for enclosure fires is shown in Fig. 1. The calculation method of expected indoor fire is common to all types of structures. The fire temperature is express by the following equation.

$$T_f(t)=\alpha t^{1/6}+20 \ (0\le t\le t_f) \tag{1}$$

Where, α (°C·min.$^{1/6}$) represents the severity of the fire, and t_f (min.) is the duration of the fire.

Methodologies used to determine retained fire resistance time of structural elements are not necessarily the same among structural types. Features of each verification method are:

Table 1. Required fire resistance time

Parts of buildings \ Stories of buildings		Uppermost story, and second to fourth stories from the uppermost story	Fifth to fourteenth stories from the uppermost story	Fifteenth story or more from the uppermost story
Walls	Partition walls (Load bearing)	1 hour	2 hours	2 hours
	Exterior walls (Load bearing)	1 hour	2 hours	2 hours
Columns		1 hour	2 hours	3 hours
Floors		1 hour	2 hours	2 hours
Beams		1 hour	2 hours	3 hours
Roofs			30 minutes	
Stairs			30 minutes	

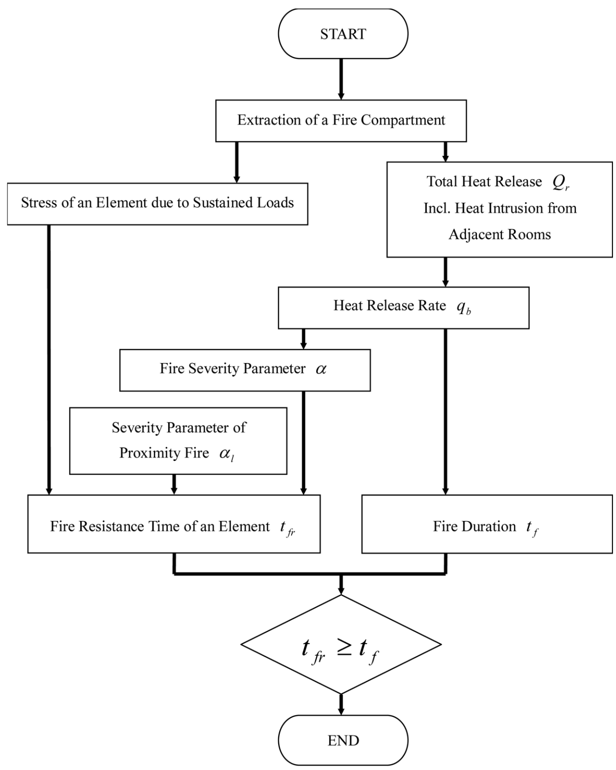


Figure 1. Flowchart of the Fire Resistance Verification Method in the BSLJ.

Steel
- Applicable only to columns and beams of moment resisting steel frames.
- Applicable to unprotected members and members protected with sprayed rockwool or calcium silicate boards.
- Only for loadbearing capacity verification.

Reinforced Concrete
- Applicable to columns, beams, walls, slabs and roofs.
- Applicable only to ordinary concrete or Class 1 light weight concrete.
- Design strength of concrete not exceeding 60 MPa.
- Minimum thickness of cover concrete to steel bar is 3 cm (2 cm for floor slab).
- Loadbearing capacity, insulation and integrity can be verified.

Wood
- Applicable only to columns and beams.
- Minimum section size not less than 20 cm.
- Only for loadbearing capacity verification.

As for example, the calculation method of retained fire resistance time for protected steel columns is briefly described below. The critical member temperature, T_{cr} (°C), of a column is calculated by the following equation.

$$T_{cr}=\min\{T_B, T_{LB}, T_{DP}, 550\} \qquad (2)$$

In this equation,
T_B : Maximum temperature for overall buckling (°C),
T_{LB} : Maximum temperature for local buckling (°C),
T_{DP} : Maximum temperature for thermal deformation (°C),
550 : Limiting temperature for joint stability (°C).

Maximum temperature for overall buckling, T_B (°C), is calculated by Eq. (3a) or (3b) depending on the slenderness of the column.

For $\lambda < 0.1$:

$$T_B=700-375p \qquad (3a)$$

and for $0.1 \leq \lambda \leq 1$:

$$T_B=\max\left\{700-375p-55.8(p+30p^2)(\lambda-0.1),\ 500\sqrt{1-\frac{p(1+0.267\lambda^2)}{1-0.24\lambda^2}}\right\} \qquad (3b)$$

Where, p is the axial force ratio defined by $p = P/FA_c$. P (N) is the axial force, A_c (mm^2) is the cross-sectional area, and F (N/mm^2) is the design strength of the steel. Effective slenderness ratio is:

$$\lambda=\frac{l_e/i}{3.14\sqrt{E/F}} \qquad (4)$$

Where l_e (mm) is the length of the column, i (mm) is the radius of inertia of the steel cross-section, and E (N/mm^2) is the elastic modulus of steel at normal temperature.

Maximum temperature for local buckling, T_{LB} (°C), is

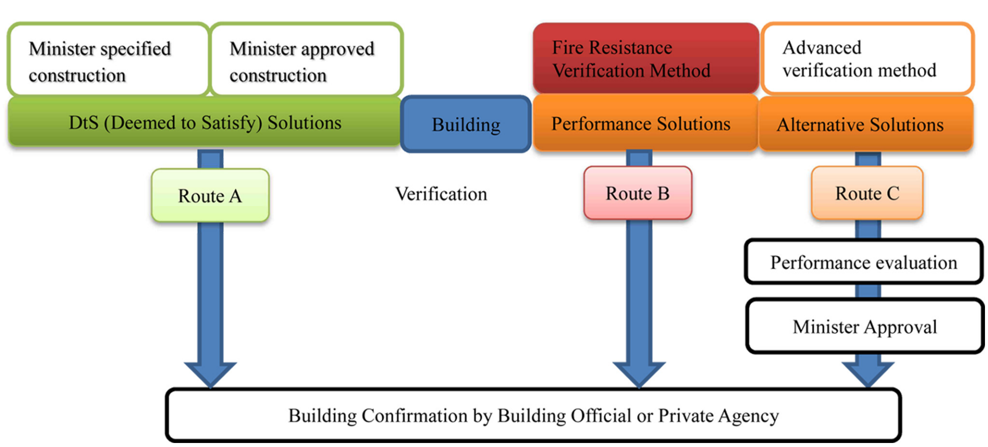


Figure 2. Three routes for compliance with free resistance provision of BSLJ.

calculated by the following equation.

$$T_{LB}=700-\frac{375p}{\min(R_{LBO},0.75)} \tag{5}$$

Where R_{LBO} is a function of the width to thickness ratios of the cross-section as shown in Table 5.

Maximum temperature for thermal deformation, T_{DP} (°C), is determined as a function of the floor area S (m^2).

$$T_{DP}=20+\frac{18000}{\sqrt{S}} \tag{6}$$

Thus, for an enclosure fire with the fire severity parameter α (°C·min.$^{1/6}$), the retained fire resistance time of a protected steel column exposed to the enclosure fire, t_{fr} (min.), is calculated by the following equation.

$$t_{fr}=\max\left\{\begin{array}{l}\dfrac{9866}{\alpha^{3/2}}\left\{\dfrac{2}{h}\left\{\dfrac{1}{\log_e\{h^{1/6}(T_{cr}-20)/1250\}}\right\}^2+\dfrac{a_w}{(H_i/A_i)^2}\right\}\\ \left(\dfrac{T_{cr}-20}{\alpha}\right)^6\end{array}\right. \tag{7}$$

For protected steel sections the temperature rise parameter of the sections, h, is calculated by the following equation.

$$h=\frac{\phi K_0(H_s/A_s)}{\left\{1+\dfrac{\phi R}{H_i/A_i}\right\}\left\{1+\dfrac{\phi H_s/A_s}{2H_i/A_i}C\right\}} \tag{8}$$

Where H_s and H_i are the heated perimeter of the steel and the covering material, and A_s and A_i are the cross-sectional areas of the steel and the covering material, respectively. $\phi=H_i/H_s$ is the heated perimeter ratio. $C=\rho_i c_i/\rho_s c_s$ represents the heat capacity ratio. Because the variability of C at elevated temperatures is relatively small, C is calculated using material properties at normal temperature. The basic temperature rise rate, K_0 (m/min.), thermal resistance coefficient, R, and temperature rise delay time coefficient, a_w, were determined by regression analyses of fire resistance test data and given in Tables 3a and 3b.

Similar but different set of equations are given for other types of principal building parts to calculated the retained fire resistance time against enclosure fire. Thus, if the calculated retained fire resistance time of each principal building part is equal to or greater than the duration of the fire for the room whose interior is faced by the principal part, the building is regarded as fire-resistive building.

5. Project Example: Nakanoshima Festival Tower – Fire Resistance Design of Steel Frames

5.1. Outline of the building

The main occupancy of the tall building is office use and the building is owned by a major newspaper company. Figure 3 shows the appearance of the building which is located at the heart of Osaka, one of the largest cities in

Table 2. Determination of R_{LBO}

Section Shape	R_{LBO}
H-shaped cross-section (Wide flange)	$\min\left\{\dfrac{7}{0.72\dfrac{B_f}{t_f}+0.11\dfrac{B_w}{t_w}},21\dfrac{t_w}{B_w}\right\}$
Hollow square or cross-section (limited to hot-formed or weld built-up members)	$21\dfrac{t}{B}$
Hollow square or cross-section (limited to cold-formed members)	$17\dfrac{t}{B}$
Cylindrical hollow cross-section	$\dfrac{35.6}{D/t_{cy}+10.6}$

B_f, B_w, t_f, t_w, B, t, D and t_{cy} are measured in mm.

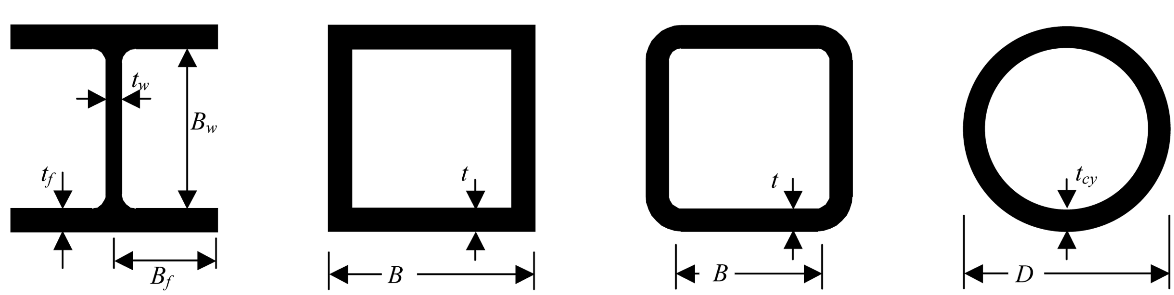


Table 3a. Parameters related to temperature rise of steel columns

Fire protection	Steel corss-section	a_w	K_0 (m/min)	R	C
Sprayed rock wool (thickness not less than 25 mm)	H-shaped steel	22,000	0.00089	310	0.081
	Square steel pipe or cylindrical steel pipe	19,600	0.00116	390	0.081
Fiber reinforced calcium silicate boards (thickness not less than 20 mm)	H-shaped steel	28,300	0.00089	815	0.136
	Square steel pipe or cylindrical steel pipe	32,000	0.00116	700	0.136

Table 3b. Parameters related to temperature rise of steel beams

Fire protection	Steel corss-section	a_w	K_0 (m/min)	R	C
Sprayed rock wool (thickness not less than 25 mm)	H-shaped steel	26,000	0.00067	235	0.081
	Square steel pipe or cylindrical steel pipe	22,000	0.00089	310	0.081
Fiber reinforced calcium silicate boards (thickness not less than 20 mm)	H-shaped steel	20,300	0.00067	365	0.136
	Square steel pipe or cylindrical steel pipe	28,300	0.00089	815	0.136

Figure 3. Nakanoshima Festival Tower.

Japan. The head office function of the company requires advanced information integration capability, so this building is equipped with such advanced functionality. In addition to these functions, several other facilities are also contained within the building. The predecessor of the building contained the world-class concert hall named ‘Festival Hall.’ Therefore, this building has a theater that reproduced the well-known concert hall at the lower part of the building. Table 4 shows the overview of the building, and Figs. 4 and 5 illustrate the typical plan and vertical section of the building, respectively.

Table 4. Building overview

Site area	8,150.09 m^2
Building area	5,725.26 m^2
Floor area	145,602.26 m^2
Floor count	39 (+3 basement floors)
Architectural height	198.958 m

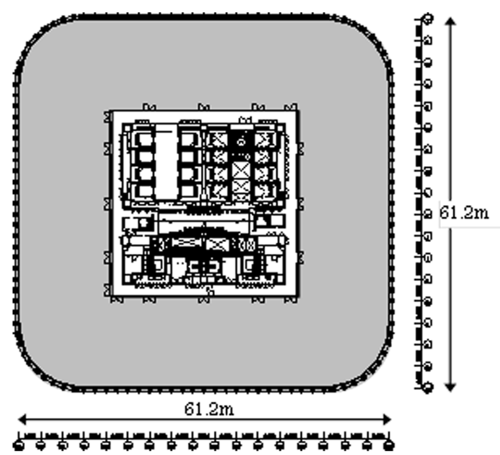


Figure 4. Typical floor plan.

In order to ensure a high earthquake resistance performance, a seismic isolation system is located at the mid height of the building. The lower part below the isolation system is reinforced concrete and steel encased reinforced concrete structure, and the upper part is steel moment resistance frame structure.

5.2. Fire resistance design

The building is required to be a fire-resistive building by the BSL. Thus, it was necessary to verify the fire resistance to comply with the requirements in the BSL. Unfortunately, the structure of the building is outside the scope of the prescribed FRVM (Route-B method) in the following respects:

・Use of unapproved base isolation material,

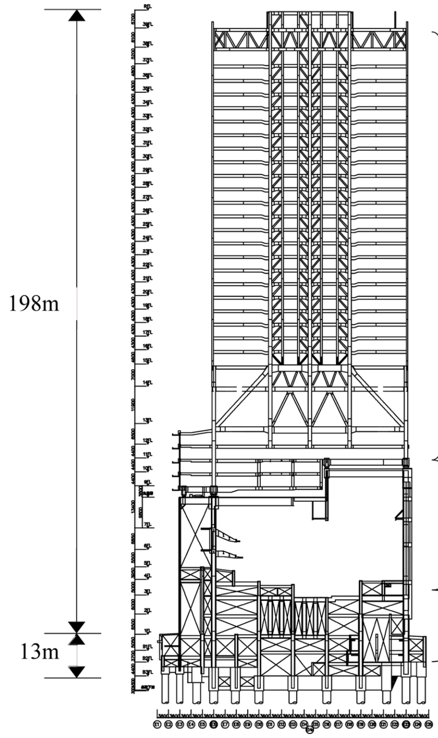


Figure 5. Vertical section.

- Use of steel not conforming to JIS standard,
- Use of truss structure,
- Use of concrete filled tubular steel columns, and
- Use of unprotected steel members which are designed against special fire source.

Thus advanced fire resistance verification was necessary to get the Minister Approval.

Several different design approaches were taken for this building depending on the material and members of interest. Fire resistance was secured both by controlling the amount of fire source and taking appropriate distance between the fire source and structural member, because significant decrease in strength due to temperature rise was expected for members such as base isolation material and unprotected steel. High temperature properties of steels not conforming to JIS standard were examined by coupon tests at elevated temperatures. The same calculation methods in the FRVM were also used for the fire resistance verification of the members consist of these materials by confirming the equivalence of JIS non-conforming steels to JIS conforming steel by the test results.

For the truss frame, because each member was relatively highly constrained at the member ends, the thickness of fire protection was determined to limit the temperature rise of the member so that any member did not buckle due to the thermal stress. Under this condition, the higher temperature strength of truss member was determined by the similar calculation method used in the FRVM. This design approach, that the strength at elevated temperature of members is determined by the similar or same calculation methods as prescribed in FRVM, has become the mainstream in fire resistance design practice in Japan. On the other hand, FRVM does not provide any methods to directly verify the structural stability of building against thermal deformation, for example excessive column inclination due to thermal elongation of beams. In FRVM, the maximum temperature for column and beam members due to the thermal deformation of beams is determined by Eq. (6). This equation is derived based on the following considerations. Square root of the floor area of fire room S is the equivalent length of a hypothetical beam in the room. Because the beam is constrained by adjacent members, it is assumed that the thermal expansion of the beam is 80% of its unconstrained thermal expansion. Assuming the height of story is 4.0 m, the beam expands toward one side from the center as in Fig. 6, thermal expansion coefficient of steel is 12×10^{-6} K^{-1}, and the limiting drift angle of the column is 0.02 rad, one will get Eq. (6). Thus the equation may give unsafe value if , for example, the aspect ratio of the room plan is not close to unity, or if the story height is lower than 4.0 m.

The fire compartment in the typical floor plan of the building is torus-shape as illustrated in Fig. 4. The plan has the shape of about 61 m square and the total floor area is about 3,700 m^2. The floor area of the fire compartment is about 2,800 m^2. Thus the hypothetical length of the beam, $\sqrt{S}$, in Eq. (6) is about 53 m, which is shorter than the actual length of the beam. This means that the thermal deformation of the frame can be underestimated if Eq. (6) is used. So, the thermal stress analysis of the typical floor was carried out to confirm that the deformation of the members due to thermal expansion will not be excessive at fire occasion.

5.3. Analysis model

In general thermal analysis model, members such as columns, beams and floor slabs are modeled by the shell or solid elements, because these elements can handle the temperature variation within the cross-section of a member. For concrete members, the temperature may vary significantly within the cross-section, the modeling by shell or solid elements is essential for precise analyses. However, the modeling by these elements requires a larger number of nodes and elements, and consumes a longer time for computation. Thus it is not efficient if the temperature distribution within the cross-section of member can be negligible. For steel members, temperature variation within the cross-section is relatively small. It can be conservative for thermal deformation analysis even if the

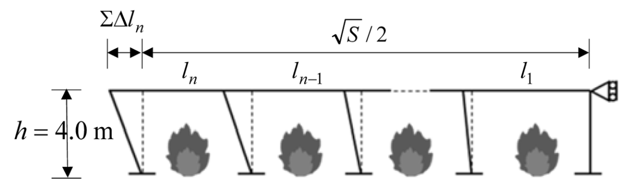


Figure 6. Schematic diagram of thermal deformation.

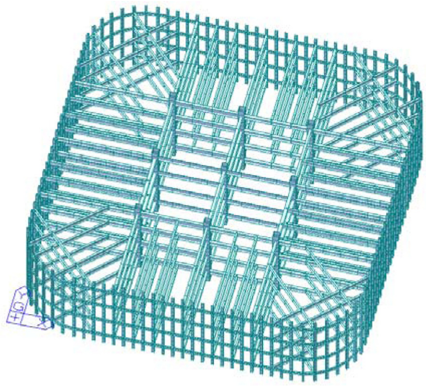


Figure 7. 3D frame model by beam elements.

uniform temperature within cross-section is assumed and the maximum temperature of the steel cross-section obtained as a result of heat transfer analysis is used for the uniform temperature.

Thus a three-dimensional model by beam elements as in Fig. 7 was constructed for the thermal deformation analysis of the typical story of the building. Each beam element had three equally distributed intermediate nodes as shown in Fig. 8. All beams within the story of the fire compartment and just above and below stories were modeled. All columns in these three stories were also modeled and columns projecting to upper and lower stories were modeled as half height column. The lower ends of the half height columns were pin supported and the upper ends of the half height columns were vertically roller supported as illustrated in Fig. 9. The effect of floor slabs and sub-beams was not considered in this analysis. The general purpose finite element analysis program NASTRAN was used for the analysis to consider the temperature-dependent nonlinear properties of steel members.

5.3.1. Load for analysis

Dead and live loads of above stories were applied as column axial loads at the top nodes of the model. Floor

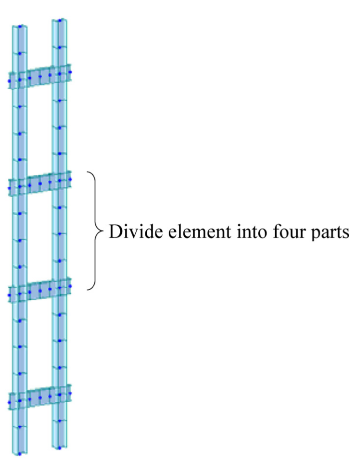


Figure 8. Beam elements in detail.

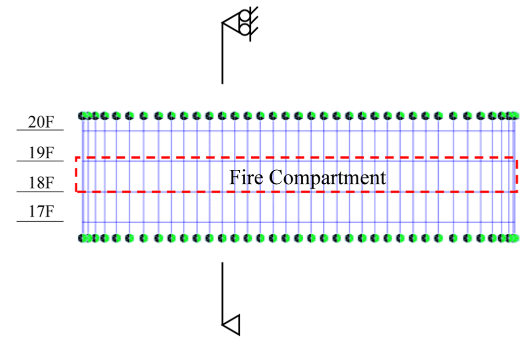


Figure 9. Boundary conditions and fire compartment.

loads were applied as distributed beam load at each floor level.

The fire compartment was heated by the ISO 834 standard fire temperature curve. The duration of fire was determined by the calculation method prescribed in the FRVM and converted to the equivalent fire duration time to that of standard fire. The equivalent fire concept is widely used in fire resistance design in Japan. In this concept, two fires are recognized equivalent if the time integrals of fire temperature above 400°C are identical. Then, the temperature of member facing to the fire compartment was analyzed by transient heat transfer analysis until the equivalent fire time to obtain the maximum temperature of each member. In the thermal deformation analysis of the 3D frame model, temperatures of each member were increased linearly from normal temperature (20°C) to the maximum temperature obtained by the heat transfer analysis of the member. The linear incremental temperature of members was adopted because it was well known from many fire resistance tests that the temperature of protected steel members tended to rise almost linearly. As an example, Fig. 10 shows the temperature curves of wide flange beam section under the ISO 834 heating condition.

5.3.2. Material properties at elevated temperatures

There exist several stress-strain curves for steel at elevated temperature. Two curves are generally used in fire resistance analysis in Japan. One is the curve defined by

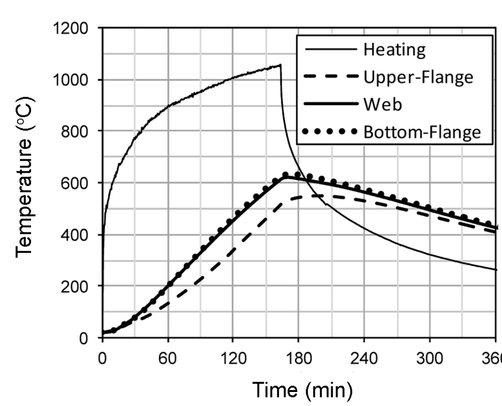


Figure 10. Fire test of protected steel wide flange.

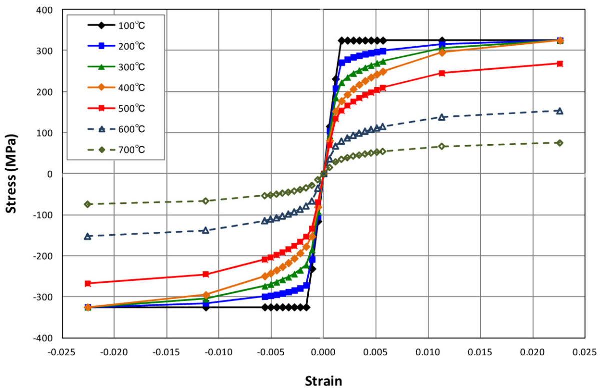


Figure 11. Stress-strain curve at elevated temperatures by Eurocode 4.

Eurocode 4 as in Fig. 11 and the other one is that proposed by the AIJ Recommendation. The Eurocode 4 curve was used for the analysis.

5.4. Results of analysis and design criteria

Figs. 12 and 13 show the results of the deformation analysis. It is clearly observed from Fig. 12 that the tubular outmost frame deformed symmetrically to outward. The beams spanning 18 m between the core frame and the outmost frame sagged largely in the midportion. The drift of column was determined as the difference of horizontal displacements at the top and bottom of a column. As each node had two horizontal components of displacement, a vector composition was considered to determine the horizontal displacement of each node. The length of a column was defined by the distance between upper and lower beam-column joint nodes. Thus the drift angle of column was 0.185 (1/54) as shown in Fig. 13. The drift satisfied the design criteria of less than 0.2 (1/50).

The sag of beam has the effect to pull back the horizontal displacement of connecting column. The sagging of beam can be reduced if the composite effect of floor slab and beam exists. In this frame model analysis, because floor slabs were not modeled, the sag of beams could be overestimated. On the other hand, higher temperature of

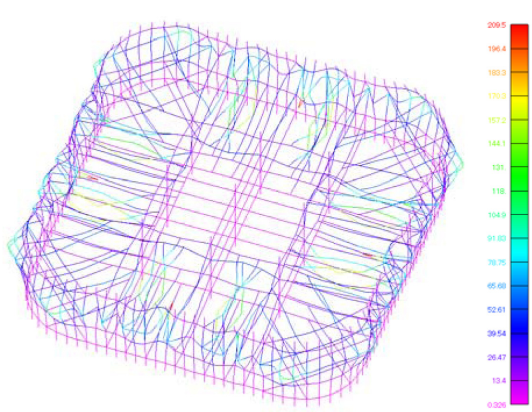
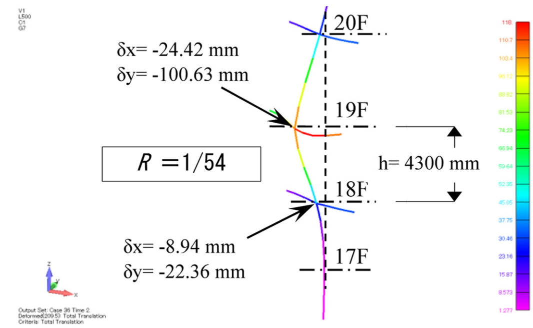


Figure 12. Thermal deformation of 3D frame model.



Displacement is magnified by 30.

Figure 13. Deformation of the outmost columns.

steel was assumed and effect of floor slabs and sub-beams to suppress the thermal expansion of the main beam was ignored. These points together with sufficient safety factor in other analytical conditions balanced out to appropriately estimate the drift of columns.

6. Concluding Remarks

In the fire resistance design of Japan, the strength of members in fire is generally verified by using the calculation methods prescribed in the Fire Resistance Verification Method (FRVM), which is stipulated in the Ministry Notification under the Building Standard Law of Japan. An advanced analysis of thermal deformation of frame is necessary if the deformation has significant negative effect on the stability of the frame depending on the characteristics of building structure. In this case, however, it is commonly accepted to model only the part of building to perform thermal deformation analysis for the efficiency of the analysis. Proper treatment of key parameters, such as temperature of members, material properties at elevated temperature, boundary conditions of model frame, is very important for the appropriate performance verification. Comprehensive knowledge on fire phenomena and structural response to fires are required to designers and experts to evaluate the design.

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