Outline of the Fire Resistance Verification Method in the Building Standard Law of Japan

by

Mamoru Kohno[1]

ABSTRACT

Fire resistance of buildings is one of major issues in the building standard. In the Building Standard Law of Japan, fire provisions state the requirements for fire resistance and evacuation safety. The approach conventionally used for the compliance with the requirements for the fire resistance is use of fire-resistive constructions for principal building parts without taking the detailed fire conditions expected to occur inside the building.

The Fire Resistance Verification Method was introduced in May, 2000 as an alternative to the conventional fire-resistive construction approach. Duration and intensity of fires predicted to occur inside a building is evaluated and the fire performance of principal building parts against the fires is verified in the FRVM.

Fire resistance requirements in the Building Standard Law of Japan are briefly introduced and outline of the FRVM is explained through the verification process of protected steel columns.

KEYWORDS: Building Standard Law of Japan, Fire Provision, Fire Resistance, Performance Verification

1. INTRODUCTION

Most of building codes or building standards contains structural and fire safety provisions as its major components. In structural design process, the performance of a structure or portions of a structure is checked mostly based on calculation methods, e.g. the allowable stress design, the limit states design, etc. In the fire safety arena, however, fire resistance design has been such that a designer chose appropriate fire-rated constructions from catalogues or lists to comply with requirements specified in the regulation. Though fire resistance is linked to the behavior of structures, the approach used in ordinary design process has been quite different from those used for seismic or wind resistance design.

Technical bases for analysis of structural behavior under fire conditions have been developed by many researchers. Advanced designers have utilized the state-of-the-art method in the technical bases for the fire resistance design of building for quite long time. In Japan, however, only a designated technical committee could review such an advanced design and it took long time to get the required Ministerial approval for the building design till May, 2000.

In the 1998-2000 revision of the Building Standard Law of Japan (BSL), the fire resistance verification method (FRVM) was enacted. The FRVM contains prescriptive verification methods of fire performance of steel, reinforced concrete and wooden structural members taking parametric fires into account. This enabled ordinary engineers to evaluate the fire performance of structures under respective fire condition of the buildings. The process is similar to the cases of wind and seismic design of buildings.

2. REQUIREMENTS FOR FIRE RESISTANCE

The BSL requires a building to be fire-resistive according to its occupancy, size (i.e. number of story, height or floor area) and location. In the BSL the fire-resistive buildings are prescribed as the buildings that conform to the following criteria (*Article 2(9-2)*):

(a) Buildings whose principal parts come under either (1) or (2) below.

[1] Head, Fire Standards Division, Building Department, National Institute for Land and Infrastructure Management (NILIM), Tsukuba 305-0802, Japan

(1) Those which are of fire-resistive construction.

(2) Those which conform to technical criteria specified by Cabinet Order concerning the performances mentioned below (in the case of principal building parts other than exterior walls, only the performance mentioned in (i)): *Order Article 108-3.*

(i) Those which can withstand the heat of a fire predicted to occur inside the building according to the construction, building equipment, and use of the said building until the end of the said fire.

(ii) Those which can withstand the heat of a normal fire occurring in the area surrounding the said building until the end of the said fire.

(b) Building which have fire doors or other opening protective assembly specified by Cabinet Order at such openings in exterior walls liable to catch fire. *Order Articles 109 and 109-2.*

Conventional method to comply with the fire resistance requirements is of course (a)(1). In the BSL the fire-resistive construction is prescribed as follows (*Article 2(7)*):
Fire-resistive construction: The type of construction for walls, columns, floors and other parts of a building which conforms to technical criteria specified by Cabinet Order concerning fire-resistive performance* such as reinforced concrete structure and brick structure and which uses structural methods established by the Minister of Land, Infrastructure and Transport or which is proved by the Minister.
*(performance required for the said building parts to prevent a normal fire from causing both the collapse of the building and the spread of fire until the end of the said normal fire) *Order Article 107*

The performance required for each of the principal building parts are shown in Table 1. Required fire resistance time of each building part varies depending on the number of story where the part is used. Table 2 shows the details.

This approach for compliance with the fire resistance requirements is easy to apply and has been used for long time. Real fires occurring in buildings, however, are not identical with the nominal fire, e.g. fire defined in the ISO 834 or ASTM E 119. Generally, the fire-resistive constructions, or fire-rated constructions in more general term, are tested only against the standard fire temperature curve. Real performance of the fire-resistive constructions under general fire conditions is not clear though it is believed to be conservative.

The FRVM is an alternative approach to the conventional fire-resistive construction method.

3. THE FRVM FOR STEEL MEMBERS

The FRVM verify the performances pertaining to (a) (2) above and prescribe practical methods of calculation. The FRVM is provided in Article 108-3 of the Enforcement Order of the BSL and in Notification No. 1433 (2000) issued by the Ministry of Infrastructure, Land and Transport (MLIT).

Under the FRVM as they pertain to (a) (2) (i) above, the intensity and duration of fires occurring within enclosed spaces are predicted; On the other hand, pertaining to (a) (2) (ii) above, external fires are prescribed (in practical terms, 30 or 60 minutes of the ISO 834 standard fire temperature curve). It is verified that principal building parts, e.g. columns, beams, walls or other parts can resist (or can sustain to maintain the required performance) to the intensity and duration of enclosure or neighboring fires.

3.1 Flow of Verification Method

The FRVM prescribes verification methods of fire performance for steel, reinforced concrete and wooden structural members. All verification methods are structured so as to verify that “the retained fire resistance time” is longer than or equal to “the duration of the fire” at the final verification stage.

An outline of the FRVM for verifying the performance of columns and beams of steel-structure buildings pertaining to (a) (2) (i) above is introduced below. As shown in Fig. 1, the verification flow is divided into two parts—prediction of enclosure fires and calculation of the performance to be achieved by columns and beams in resisting the enclosure fires.

3.2 Duration and Temperature Rise Coefficient of Enclosure Fires

The first step in structural design is to make assumptions regarding actions that will affect the structural system (frames, members, etc.). In the case of fire resistance design, the first step is, of course, to make assumptions regarding the effect of fire-induced calorific heat on the structural system. Fires can in practice occur in a variety of building spaces and will be influenced by the indoor combustibles and ventilation, as well as the endoergic conditions and other factors of the walls, ceilings, floors and other structures. Even only with regard to combustibles, it is not easy to adopt a refined fire model that takes into account the size, location and material properties of combustibles in detail.

Therefore, fires are uniformly expressed by Equation (1) in the FRVM.

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

where

T_f : fire temperature (ºC)

t : time lapse after fire outbreak (min.)

t_f : fire duration (min.)

α : fire temperature rise coefficient (ºC/min.$^{1/6}$)

The fire duration, t_f (min.), is found by Equation (2) in which the calorific value of combustible materials in the room, Q_r (MJ), is divided by the heat release rate, q_b (MW).

$$t_f = Q_r / (60\, q_b) \qquad (2)$$

The calorific value of combustible materials in the room takes into account the effects of combustibles stored inside a room, interior finishes, fire spreading to adjoining rooms and other factors. The calorific value of combustibles stored inside a room is given in Table 3 by room category. Interior and other finishes are calculated according to the actual conditions of the rooms. The effects of adjoining rooms are valued at 0~15% of the total calorific value of these rooms (rate depends on the degree of fire resistance provided by the intervening walls); the resulting value is added to the calorific value of the room in question.

The heat release rate, q_b (MW), is calculated according to the surface area of combustibles and the ventilating conditions of the room. The fire temperature rise coefficient, α (ºC/min.$^{1/6}$), on the other hand, is a parameter for expressing the intensity of a fire and is found by Equation (3). This equation calculates the balance between heat released by combustibles and heat losses resulting from perimeter wall areas (walls, floors and ceilings) and openings.

$$\alpha = 1280 \left(\frac{q_b}{\sqrt{\sum A_C I_h} \sqrt{f_{op}}} \right)^{2/3} \qquad (3)$$

where

A_C : area of perimeter wall area (m^2)

I_h : thermal inertia (kW・s$^{1/2}$/m^2・K)

$f_{op} = \max\left\{ \sum A_{op} \sqrt{H_{op}}, A_r \sqrt{H_r} / 70 \right\}$

A_{op}, H_{op} : area (m^2) and height (m) of opening, respectively

A_r, H_r : floor area (m^2) and floor height (m), respectively

Meanwhile, the standard fire temperature curve of ISO834 conforms closely with the curve when the fire temperature rise coefficient is set at $\alpha = 460$ in Equation (1).

3.3 Retained Fire Resistance Time of Steel Members against Enclosure Fires

As shown in Table 1, load carrying capacity to enclosure fires is required for columns and beams—the principal structural parts of steel-structure buildings. Accordingly, the maximum fire duration—i.e. the period during which the principal structural parts of steel-structure buildings retain their load carrying capacity against heat produced by enclosure fires as expressed by Equation (1)—is defined as the retained fire-resistance time against enclosure fires.

In order to find the retained fire resistance time against enclosure fires, the first factor to be determined is the critical member temperature T_{cr} (°C), which is the critical temperature below which members retain their load carrying capacity. Following this, calculation is made of the fire duration, which is the time required for structural members to reach the critical member temperature in a fire having the fire temperature rise coefficient, α, determined in the previous section. The fire duration thus calculated becomes the retained fire-resistance time against enclosure fires.

For example, in the case of structural steel columns, the critical member temperature, T_{cr} (°C), is given by Equation (4).

$$T_{cr} = \min(T_B, T_{LB}, T_{DP}, 550) \qquad (4)$$

where

T_B: maximum temperature for overall buckling of the column (°C)

T_{LB}: maximum temperature for local buckling of the column (°C)

T_{DP} : maximum temperature for thermal deformation of the column (°C)

550: temperature to guarantee the soundness of joints (°C)

Under the FRVM, equations are given for calculating T_B and T_{LB} according to the geometrical and loading conditions of the columns. Further, because T_{DP} is a factor in guaranteeing that excess inter-story drift due to elongation of beams at elevated temperatures does not occur, the equation for calculating this factor in accordance with the geometrical conditions of the rooms is also given.

In cases where the structural steel columns are provided with fire-protective covering and possess the critical member temperature found by Equation (4), the retained fire-resistance time against enclosure fires is, basically, determined by Equation (5).

$$t_{fr} = \frac{9866}{\alpha^{3/2}}\left\{\frac{2}{h}\left\{\frac{1}{\ln\{h^{1/6}(T_{cr}-20)/1250\}}\right\}^2 + \frac{a_w}{(H_i/A_i)^2}\right\} \qquad (5)$$

where

h : member temperature rise coefficient

H_i : heated perimeter of the covering material (m)

A_i : cross-sectional area of the covering material (m^2)

a_w : temperature rise delay time coefficient stipulated in Table 4

The member temperature rise coefficient, h, is calculated by the following equation.

$$h = \frac{\phi K_0 (H_s / A_s)}{\left\{1+\frac{\phi R}{H_i / A_i}\right\}\left\{1+\frac{\phi C (H_s / A_s)}{2(H_i / A_i)}\right\}} \qquad (6)$$

where

ϕ : heated perimeter ratio calculated by $\phi = H_i / H_s$

H_s : heated perimeter of the member (m)

K_0 : basic temperature rise rate stipulated in the following table (m/min.)

Steel category	Basic temperature rise rate
H-shaped steel	0.00089
Rectangular or cylindrical steel pipe	0.00116

A_s : cross-sectional area of the member (m^2)

R : coefficient of thermal resistance in Table 4

C : heat capacity ratio in the following table

Fire protective covering category	Heat capacity ratio
Sprayed rock wool	0.081
Fiber reinforced calcium silicate boards	0.136

Parameters a_w, K_0 and R are determined from a regression analyses based on a variety of heating tests for steel members with fire-protective coverings. The second term in Equation (5) expresses the delay in temperature rise due to the evaporation of water included in the fire-protective covering.

The FRVM also provides equations for structural steel beams that calculate the retained fire-resistance time against enclosure fires having systems similar to that mentioned above for structural steel columns.

3.4 Application of Fire-resistant Steel, Stainless Steel and other High-performance Steel Materials

Current FRVM provides calculation methods that take into account only reductions in the yield strength and elastic coefficient of ordinary steel at elevated temperatures. Accordingly, even when fire-resistant steel and stainless steel having superior properties at elevated temperature than ordinary steel are to be applied, their correspondingly higher performance properties cannot be assessed. To remedy this situation, examinations to improve the current FRVM are underway.

4. CONCLUSIONS

Outline of the FRVM in the BSL is explained through the verification process of protected steel columns. The FRVM is an alternative to the conventional fire-rated construction approach. The verification process is similar to that of wind or seismic design in that the actions and response of structures are evaluated according to particular conditions of the buildings.

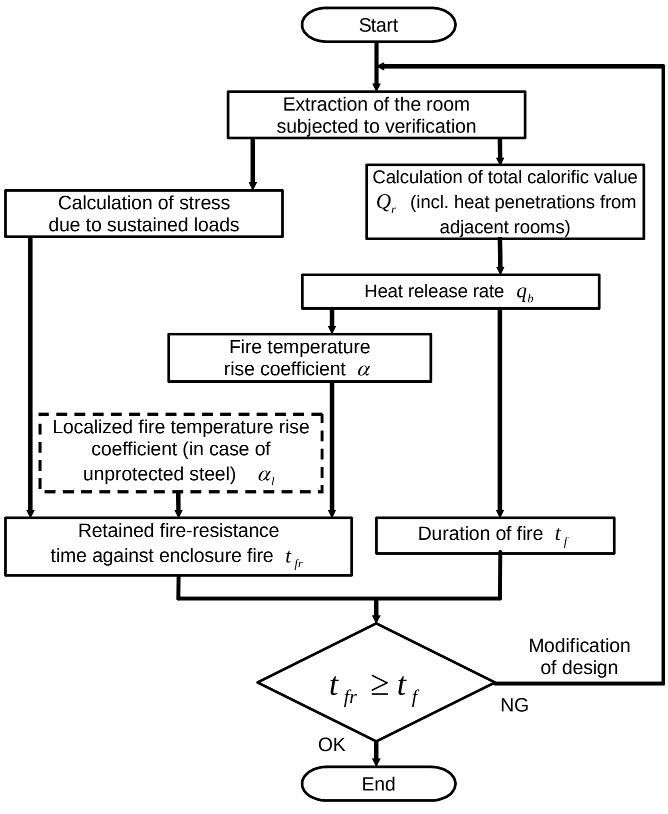

Fig.1 Verification Flow of Steel Members for Enclosure Fire under the FRVM

Table 1 Fire Resistance Required for Principal Structural Parts

Required performance	Principal structural parts						
	Exterior wall	Partition wall	Column	Beam	Floor	Stair	Roof
Enclosure fire:							
Load-carrying capacity	R*	R*	R	R	R	R	R
Insulation	--	R	--	--	R	--	--
Integrity	R	--	--	--	--	--	R
Exterior fire:							
Load-carrying capacity	R*	--	--	--	--	--	--
Insulation	R	--	--	--	--	--	--

R: Required, R*: Required in the case of bearing wall, --: Not required

Table 2 Required Fire Resistance Time for Fire-resistive Constructions

Load-carrying capacity:				
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 (limited to bearing walls)	1 hour	2 hours	2 hours
	External walls (limited to bearing walls)	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		
Insulation:				
Walls and Floors		1 hour		
Parts other than parts liable to catch fire of external walls that are non-bearing walls		30 minutes		
Integrity:				
External walls		1 hour		
Roofs and parts other than parts liable to catch fire of external walls that are non-bearing walls		30 minutes		

Table 3 Calorific Value per Unit Floor Area of Combustibles Stored inside a Room

<table>
<tr><th></th><th colspan="3">Room category</th><th>Calorific value (MJ/ m^2)</th></tr>
<tr><td rowspan="2">(1)</td><td colspan="3">Habitable room of a dwelling</td><td>720</td></tr>
<tr><td colspan="3">Bedroom or sickroom in a building other than a dwelling</td><td>240</td></tr>
<tr><td rowspan="2">(2)</td><td colspan="3">Office or other room similar thereto</td><td>560</td></tr>
<tr><td colspan="3">Conference room or other room similar thereto</td><td>160</td></tr>
<tr><td rowspan="3">(3)</td><td colspan="3">Classroom</td><td>400</td></tr>
<tr><td colspan="3">Arena or other room similar thereto in a gymnasium</td><td>80</td></tr>
<tr><td colspan="3">Exhibition room or other room similar thereto in a museum or art gallery</td><td>240</td></tr>
<tr><td rowspan="4">(4)</td><td rowspan="2">Salesroom in a department store, store engaged in commodity sales, or other similar thereto</td><td colspan="2">Salesroom selling books or furniture or other room similar thereto</td><td>960</td></tr>
<tr><td colspan="2">Other parts</td><td>480</td></tr>
<tr><td rowspan="2">Dining facility or other dining rooms</td><td colspan="2">Simple dining room</td><td>240</td></tr>
<tr><td colspan="2">Other dining room</td><td>480</td></tr>
<tr><td rowspan="3">(5)</td><td rowspan="3">Theater, movie theater, entertainment hall, grand-stand, public hall, assembly hall, or other room provided for use similar thereto</td><td rowspan="2">Seating space</td><td>Immovable seating</td><td>400</td></tr>
<tr><td>Other seating</td><td>480</td></tr>
<tr><td colspan="2">Stage area</td><td>240</td></tr>
<tr><td rowspan="2">(6)</td><td rowspan="2">Parking garage or automobile repair shop</td><td colspan="2">Parking space or other part similar thereto</td><td>240</td></tr>
<tr><td colspan="2">Automobile passageway or other part similar thereto</td><td>32</td></tr>
<tr><td rowspan="3">(7)</td><td colspan="3">Corridor, stairway, or other passageway</td><td>32</td></tr>
<tr><td rowspan="2">Vestibule, lobby, or other part similar thereto</td><td colspan="2">Those in a building provided for use as a theater, movie theater, entertainment hall, grand-stand, public hall, assembly hall, or other use similar thereto, or as department store, store engaged in commodity sales, or other use similar thereto</td><td>160</td></tr>
<tr><td colspan="2">Others</td><td>80</td></tr>
<tr><td>(8)</td><td colspan="3">Machine rooms of elevators or other equipment</td><td>160</td></tr>
<tr><td>(9)</td><td colspan="3">Rooftop plaza or balcony</td><td>80</td></tr>
<tr><td>(10)</td><td colspan="3">Storage or other room used to store objects</td><td>2,000</td></tr>
</table>

Table 4 Temperature Rise Delay Time and Thermal Resistance Coefficients

<table>
<tr><th>Fire protective covering category</th><th>Steel category</th><th>Temperature rise delay time coefficient</th><th>Thermal resistance coefficient</th></tr>
<tr><td rowspan="2">Sprayed rock wool (excluding the spray-applied to metal lath method for H-shaped steel)</td><td>H-shaped steel</td><td>22,000</td><td>310</td></tr>
<tr><td>Square steel pipe or cylindrical steel pipe</td><td>19,600</td><td>390</td></tr>
<tr><td rowspan="2">Fiber reinforced calcium silicate boards (limited to this made by membrane enclosure)</td><td>H-shaped steel</td><td>28,300</td><td>815</td></tr>
<tr><td>Square steel pipe or cylindrical steel pipe</td><td>32,000</td><td>700</td></tr>
</table>