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A RISK-BASED TRANSLATION OF FIRE RESISTANCE REQUIREMENT

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INTRODUCTION

It is quite common in fire safety codes of buildings that the higher or the larger the building, and the larger the number of occupants, the more strict the provisions applied. This, of course, intends to reduce the probability and the potential size of fire loss. Although the consistency of the principle and the attainable level of the prescriptive provisions of the existing codes is questionable, the favorable interpretation of their intention will be expressed in a scientific term as "to control fire risk under a certain level", that is, letting R be the fire risk, P_L be the probability of fire loss occurrence, S_L be the potential size of the loss, and R_a be the acceptable fire risk,

$$R = P_L S_L \leq R_a \qquad (1)$$

By so considering, many provisions can be interpreted in a rational manner. For example, the fire resistance requirements on principal structural members intends to control the fire risk by lowering P_L; compartmentation and shaft sealing by limiting S_L as well as to lowering P_L; provisions for safe escape routes are not imposed, or at least very lightly if any, for small buildings such as family dwellings because the potential size of life is so small.

Currently, attempts are being made for developing performance-based fire safety design systems in many countries[1]. It will be important to reflect the fire risk concept, which obviously exists in the current codes albeit implicitly, on the new performance-based system for its rational structuring. In this paper, conversion of the fire resistance requirements in the Building Standard Law to a risk-based performance-based standard is discussed.

1. PERFORMANCE-BASED STANDARDS AND ACCEPTANCE OF FIRE RISK

It is becoming to be a common understanding that a performance-based standard is given in terms of a design fire and a safety criterion. The design fire will be standardized as the fire whose heat release rate $\dot{Q}$ initially grows proportionally to square of time t, i.e. $\dot{Q} = \alpha t^2$, and later on stays constant at maximum value controlled by ventilation condition etc., as illustrated in FIGURE 1. The duration of the maximum heat release period is approximately proportional to fire load, hence to fire load density w in a specific fire compartment.

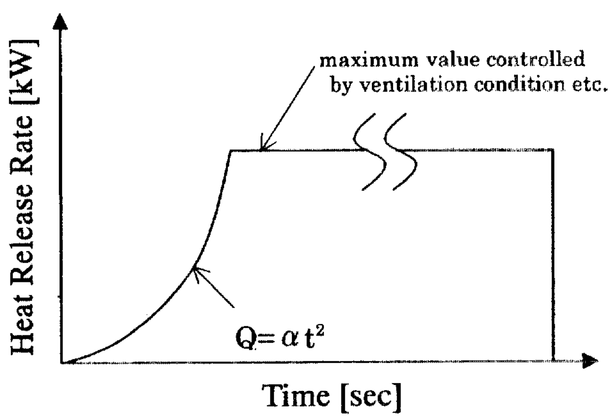
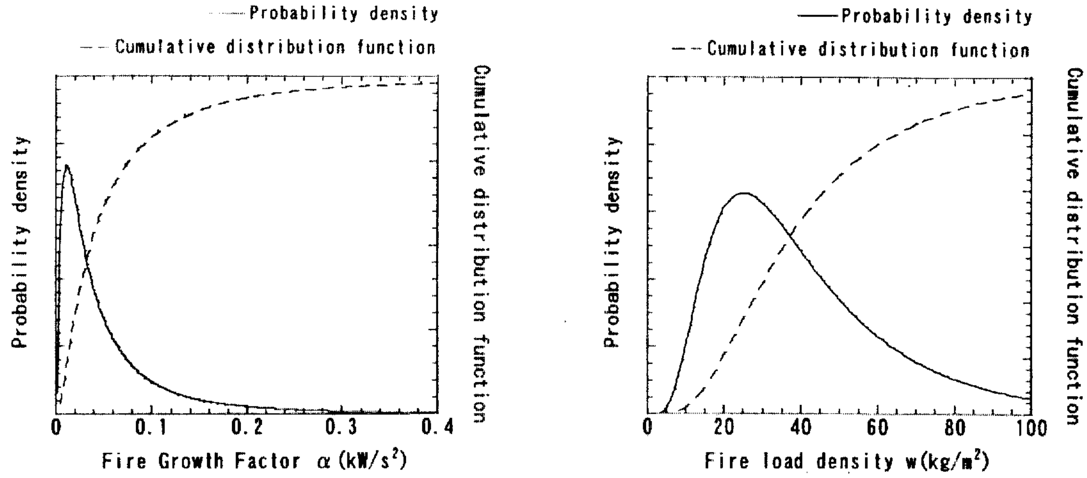


FIGURE 1 Design Fire in a Performance-based Design System

The fire growth factor α [kW/s²] affects the smoke filling in the early stage of fire, hence important for the assessment of evacuation safety and the fire load density w [kg/m²] is related to fire duration, so important for the evaluation of structural stability of load bearing members and prevention of fire spread by fire walls. Both of these are not fixed values but vary as are illustrated in FIGURE 2 by the conceptual probability density distribution. Therefore, it is necessary to choose a certain appropriate value as the standard for designs taking to specifically determine a design fire. Once the design fire is defined, measures will be taken so as to assure the safety of a building under this premise. If the conditions of a fire occurred happens to be severer than those of the design fire the safety measures may fail. Generally speaking, the higher the standard values, the lower the failure probability is supposed to be but the higher the cost of the safety measures will be at the same time, therefore a compromise is necessary. Deciding the standard values implies the acceptance of a certain level of fire risk.



(a) Fire growth factor α

(b) Fire load density *w*

FIGURE 2 Conceptual Probability Distribution of α and *w*

2. FIRE RISK RELATED TO FULLY DEVELOPED FIRE

It is considered to be rational to determine the values of α and *w*, which specify the design fire, based on the acceptable fire risk, however, their probability distributions are needed to do so. In this paper, only the fire risk in which fire load density is involved since an extent of the statistical data are available based on field fire load survey.

2.1 Acceptable Failure Probability

The fire in which fire load density becomes to be an issue is such a fire that whole combustibles in the room are involved in the fire, in other words, a fully developed fire. Structural stability and integrity of compartment wall and so forth are discussed usually assuming fully developed conditions of fire. In this case, it is when a fire breaks out, it grows to be a fully developed fire, fire brigades fail to suppress it and the measures to cope with the fire fails that the fire loss occurs. Hence the fire loss occurrence P_L in Eqn.(1) can be written as

$$P_L = P_{fire} P_{FO} P_{\sup} P_{fail} \qquad (2)$$

where P_{fires} the fire occurrence probability, P_{FO} is the probability that a fire grows to be a fully developed fire, P_{sup} is the probability that fire brigades fail to suppress the fully developed fire and P_{fail} is the failure probability of the safety measure.

Note that in the performance-based standard where a standard value of fire load density w_0 is given the maximum value of P_{fail}, i.e. the acceptable failure probability, is the same as the probability that fire load density exceeds the standard value w_0.

2.2 Examples of Fire Risks Related to Fully Developed Fire

(1) Fire wall performance

The example illustrated in FIGIRE 3 denotes two rooms, room 1 and room 2, separated by a fire wall with a certain level of performance to prevent fire spread across the wall. In other words, this wall can prevent fire spread provided that fire load density does not exceed a certain standard value of fire load w_0. Let A_1 and A_2 be the floor areas of room1 and room 2, respectively.

Considering that the fire occurrence probability in room 1 is proportional to the area and the life time, the probability $P_{1,fire}$ is expressed as

$$P_{1,fire} = p_f A_1 Y_L \tag{3}$$

where p_f is the fire occurrence probability per unit area and per year and Y_L is the life year of the room.

Further letting q be the value of room 2 per unit area, the fire risk of room 2 due to the fire from room 1 R_{12} is given as

$$R_{12} = (p_f A_1 Y_L) P_{FO} P_{sup} P_{fail} (q A_2) \tag{4}$$

Hence, if the acceptable fire risk should be the same regardless the areas of the rooms, the failure probability of the fire wall P_{fail} needs to be

$$P_{fail} \leq \frac{R_a}{p_f P_{FO} q P_{sup} Y_L A_1 A_2} \tag{5}$$

Incidentally, the fire risk of room 1 due to the fire in room R_{21} becomes the same as Eqn.(5) if the conditions of the two rooms are identical, i.e. p_f, P_{FO}, P_{sup}, Y_L and q are the same. In other words, the performance of the fire wall can be the same against the heat exposure from either surface.

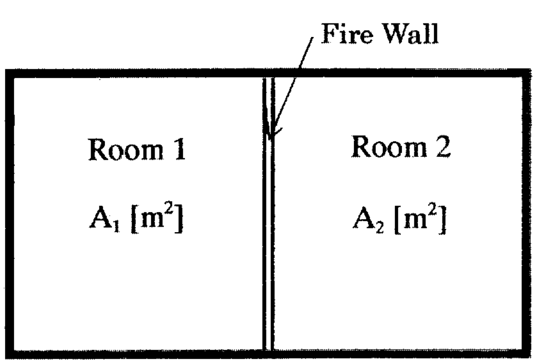


FIGURE 3 Two Rooms Separated by a Fire Wall with a Certain Level of Fire Stop Performance

(2) Stability of structural members

Here we discuss the issue of fire resistance requirements with building height. A multiple story building having the same floor area A_{FLR} on every story, as illustrated in FIGURE 4 is considered for simplicity.

It is assumed here that all the floors above the fire floor have to be abandoned if a principal structural member on the fire floor collapsed, although there may be a room for dispute on this point. Then, letting N be the number of floors above the fire floor, the fire risk due to the fire R_N can be given as

$$R_N = (p_f A_{FLR} Y_L) P_{FO} P_{\sup} P_{fail} (N q A_{FLR}) \qquad (6)$$

Since R_N must be smaller than the acceptable fire risk R_a, the failure probability of the structural member needs to be

$$P_{fail} \le \frac{R_a}{p_f P_{FO} P_{\sup} q Y_L N A_{FLR}^2} \qquad (7)$$

that is, the failure probability of the structural member on a floor should be inversely proportional to the number of floors above the floors and the square of the floor area.

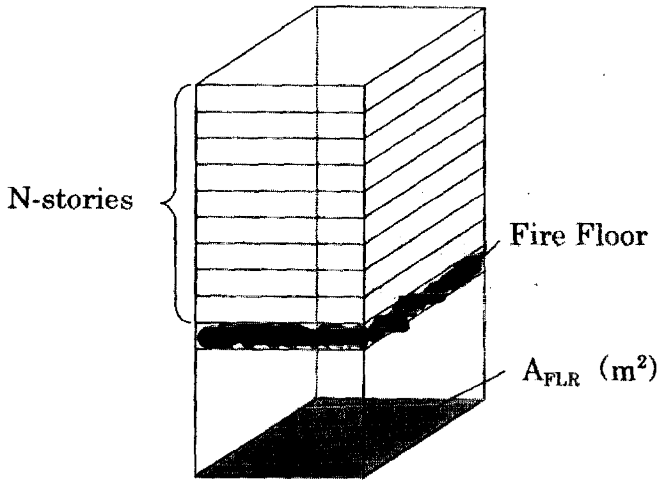


FIGURE 4 A Multiple Story Building with a Certain Level of Fire Resistance

3. CONVERSION OF REQUIRED FIRE RESISTANCE TIME TO FIRE LOAD DENSITY

3.1 Acceptable Structural Failure Probability as a Function of Building Condition

The discussion here is focused on the structural stability, although similar arguments may be possible regarding the fire wall performance.

If it is allowed to insist that the acceptable failure probability of structures should be the same regardless the number of floors above the fire floor and the floor area, the following relationship holds between two arbitrary buildings:

$$p_f P_{FO} P_{\sup} q Y_L N A_{FLR\}}^2 P_{fail} = \overline{p_f P_{FO} P_{\sup} q Y_L N A_{FLR\}}^2 P_{fail}} \qquad (8)$$

hence

$$P_{fail} = \left(\frac{\overline{p_f}}{p_f}\right)\left(\frac{\overline{P_{FO}}}{P_{FO}}\right)\left(\frac{\overline{P_{\sup}}}{P_{\sup}}\right)\left(\frac{\overline{q}}{q}\right)\left(\frac{\overline{Y_L}}{Y_L}\right)\left(\frac{\overline{N}}{N}\right)\left(\frac{\overline{A_{FLR}}}{A_{FlR}}\right)^2 \overline{P_{fail}} \qquad (9)$$

Therefore, if the conditions in the right hand side of Eqn.(8) can be specified by choosing a reference building, the acceptable failure probability of an arbitrary building P_{fail} can be determined from Eqn.(9) as a function of the conditions of the building. Naturally, such a reference building should be selected from the buildings for which fire resistance time is prescribed in the existing codes. The Building Standards Law, Japan, requires fire resistance time from 1 hour to 3 hours according to the number of stories, but virtually no indications on the other conditions such as those exhibited by the parameters in Eqn.(9), except the number of stories N. Therefore, several conditions of the reference building need be presumed taking into account the actual state of buildings. However, as is suggested by Eqn.(9), it is not always necessary to know the absolute values of these parameters but enough to know the values relative to the reference conditions. If there is no solid reason to make difference, it may be allowed to assume

$$\left(\frac{\overline{p_f}}{p_f}\right)=1,\quad \left(\frac{\overline{P_{FO}}}{P_{FO}}\right)=1,\quad \left(\frac{\overline{P_{\sup}}}{P_{\sup}}\right)=1,\quad \left(\frac{\overline{q}}{q}\right)=1,\quad \left(\frac{\overline{Y_L}}{Y_L}\right)=1 \qquad (10)$$

until some facts have been found regarding these parameters.

Incidentally, it has been reported from fire incidence statistics that the probability of flashover of sprinklered rooms is 1/4 - 1/5 of that of unsprinklered rooms[2]. Therefore, if a room happens to be sprinklered, it may be appropriate to estimate as $\overline{P_{FO}} / P_{FO} = 4 - 5$.

3.2 Acceptable Failure Probability for Reference Condition ($\overline{P_{fail}}$)

(1) Fire load density and fire duration

Although it is rational to consider that structural failure probability is the probability that fire load density exceeds the standard value of the density, the structural failure criteria in the existing codes are prescribed in terms of fire duration. Accordingly, the presumption of the acceptable failure probability for reference condition has to begin with the relationship between the fire load density and the fire resistance time.

Usually, the duration of a fully developed fire t_D is assessed as follows

$$t_D = \frac{W}{m_b} = \frac{w A_{FLR}}{0.1 A_W \sqrt{H_W}} \qquad (11)$$

where W and m_b are the total fire load and the burning rate, respectively, and $A_W\sqrt{H_W}$ is the ventilation factor of the compartment.

Eqn.(11) can be rewritten as

$$t_D = \Omega \cdot w \qquad (12)$$

where Ω is the coefficient defined by

$$\Omega \equiv \frac{A_{FLR}}{0.1A_W\sqrt{H_W}} = 10\left(\frac{A_T}{A_W\sqrt{H_W}}\right)\left(\frac{A_{FLR}}{A_T}\right) \qquad (13)$$

where A_T is the total boundary surface area of the compartment.

The values in the two ( )s in Eqn.(13) , i.e. the so-called temperature factor and the ratio of the floor area to the total surface area, respectively, depend on the design of the space and affect on the temperature and the duration of the fire. The Building Standards Law do not explicitly describe anything on such conditions of buildings but simply states that the required fire resistance time is the tome until which the structural member has to endure against the exposure to the "usual fire". The "usual fire" considered in the Law seems to be nothing but the fire resistance test condition prescribed in JIS 1304. In this test, the temperature rises to 925℃, hence about 900℃ rise from from room temperature.

On the other hand, it is known that the temperature rise of fully developed compartment fires can be given as[3], [4]

$$\frac{\Delta T_F}{T_\infty} = 3.0\left(\frac{A_W\sqrt{H_W}}{A_T}\right)^{1/3}\left(\frac{t}{k\rho c}\right)^{1/3} \qquad (14)$$

The dependence of the temperature rise in fire resistance tests is known to be close to that of this equation. It is clear that the fire temperature rise depends on thermal properties of boundary wall as well as temperature factor of a compartment. Assuming that normal concrete are considered as the typical wall material in building codes, $t/k\rho c \approx 0.3t$ is used in Eqn.(14). Substituting the temperature rise condition of the above mentioned JIS 1304 fire test, the temperature factor corresponding to the fire resistance tests can be obtained as

$$\frac{A_W\sqrt{H_W}}{A_T} \approx \left(\frac{\Delta T_F/T_\infty}{3.0}\right)^3 \frac{1}{(0.3t)^{1/2}} \approx \left(\frac{900/300}{3.0}\right)^3 \frac{1}{(0.3\times 3600)^{1/2}} \approx \frac{1}{33} \approx 0.03 \qquad (15)$$

that is, what the Building Standards Law call "usual fire" is interpreted as the fires in the rooms whose temperature factor is around 0.03, which is well in a realistic range of its values of actual buildings.

The value of another factor in Eqn.(13), i.e. the ratio of floor area to total boundary surface area A_{FLR}/A_T varies with the size of rooms. However, the estimation of the values for the rooms having

3m of the ceiling height and the floor area of 100 - 1500 m^2 reveals that this value is roughly in the relatively narrow range as follows

$$\frac{A_{FLR}}{A_t} = 0.3 - 0.42 \qquad (16)$$

Although the exact room conditions considered in the building code is not clear, the average value is simply employed here. Then the value of Ω in Eqn.(12) is estimated as

$$\Omega = 10 \times 33 \times 0.36 \approx 119 \qquad (17)$$

(2) Probability density distribution of fire duration

The fire load density w varies considerably depending on the manner of use of rooms. Its probability density distribution might be regard as a normal (Gausian) distribution, but here it is assumed that it is a log-normal distribution, that is, ln w follows the normal distribution $[\mu_{\ln w}, \sigma_{\ln w}]$ defined as follows[5], [6]:

$$\psi(\ln w) = \frac{1}{\sqrt{2\pi}\sigma_{\ln w}} \exp\left\{-\frac{(\ln w - \mu_{\ln w})^2}{2\sigma^2_{\ln w}}\right\} \qquad (18)$$

In this equation, letting μ_w and σ_w be the mean and standard deviation of fire load density w, $\mu_{\ln w}$ and $\sigma_{\ln w}$ in Eqn.(18) are given as follows:

$$\mu_{\ln w} = \ln\left\{\mu_w / \sqrt{1 + (\sigma_w / \mu_w)^2}\right\} \qquad (18\text{-}2)$$

$$\sigma_{\ln w} = \sqrt{\ln\left\{1 + (\sigma_w / \mu_w)^2\right\}} \qquad (18\text{-}3)$$

Noting that taking logarithm of Eqn.(13) yields

$$\ln t_D = \ln \Omega + \ln w (\approx 4.78 + \ln w) \qquad (19)$$

it is obvious that ln t_D follows to the distribution of Eqn.(18) shifted to the right by $\ln \Omega$, i.e. the normal distribution $[\mu_{\ln w} + \ln \Omega, \sigma_{\ln w}] \equiv [\mu_{\ln t_D}, \sigma_{\ln t_D}]$. Incidentally, the standard deviation of the distribution of ln t_D is the same as that of ln w. Further, by normalizing the fire duration t_D as

$$\tau = \frac{\ln t_D - \mu_{\ln t_D}}{\sigma_{\ln t_D}} \qquad (20)$$

τ follows the standard normal distribution [0,1], that is

$$\phi(\tau) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\tau^2}{2}\right) \qquad (21)$$

(3) Calculation of the failure probability

It is clear from the above discussion that if fire load density follows a log-normal distribution and if structural members collapse when fire duration exceeds the prescribed fire resistance time t_X, the failure probability of the structural members can be obtained by following the procedure (i) -(iii) as shown in the below:

(i) The mean $\mu_{\ln t_D}$ and the standard deviation $\sigma_{\ln t_D}$ of log-normal distribution of fire duration

Letting μ_w and σ_w be the mean and the standard deviation of fire load density w,

$$\mu_{\ln t_D}\left(=\mu_{\ln w}+\ln\Omega\right)=\ln\frac{\mu_w}{\sqrt{1+\left(\frac{\sigma_w}{\mu_w}\right)^2}}+\ln\Omega \qquad (22)$$

$$\sigma_{\ln t_D}\left(=\sigma_{\ln w}\right)=\sqrt{\ln\left\{1+\left(\frac{\sigma_w}{\mu_w}\right)^2\right\}} \qquad (23)$$

(ii) The normalized fire resistance time t_X

Using $\mu_{\ln t_D}$ and $\sigma_{\ln t_D}$ calculated in the above, and letting t_X be the prescribed fire resistance time,

$$\tau_X=\frac{\ln t_X-\mu_{\ln t_D}}{\sigma_{\ln t_D}} \qquad (24)$$

(iii) The failure probability of the structural member $\overline{P_{fail}(t_X)}$

Letting t_X be the prescribed fire resistance time, the failure probability $\overline{P_{fail}(t_X)}$ is given as

$$\overline{P_{fail}(t_X)}=\int_{\tau_X}^{\infty}\phi(\tau)d\tau\left\{=\Phi(\tau_X)\right\} \qquad (25)$$

(4) The failure probability for the prescribed fire resistance time

According to the above described procedure, attempts were made to seek for the failure probability for the fire resistance time prescribed in the Building Standard Law. Two cases were considered regarding the mean and the standard deviation of the fire load density, i.e., (μ_w =30, σ_w =10) and (μ_w=40, σ_w =20). These values are not exactly based on the existing fire load survey but not unrealistically far from the survey data for office buildings[7]. The calculated results of the failure probability estimated for 1, 2 and 3 hours of fire resistance rating are shown in TABLE 1.

According to TABLE 1, the failure probability for one and two hour rated structures are considerably high, despite that we hardly encounter the collapse of the buildings to which such requirements are imposed. The primary cause is considered to be the combination of the factors as follows although many other may be conceivable.

(a) Significant safety allowance is involved in the specifications and the fire resistance test criteria for one and two hour rated structures.

(b) Even though the failure probability is high, the probability of actual collapse, which is the product of several probabilities indicated in Eqn.(2), is low enough so that the collapse of buildings does not take place as frequent as to be perceived in everyday life. Particularly, fires are extinguished well before all the combustibles have been consumed thanks to the intervention of fire brigades.

(c) In structural designs of buildings, safety factors are considered in both the design load and the safety criteria for structural materials. As a result, the structural members are far less loaded than their loading capacity.

TABLE 1 The Failure Probability of Structures Rated to 1, 2 and 3 Hours Fire Resistance

	μ_w=30, σ_w=10	μ_w=40, σ_w=20
P_{fail}(1h=3600)	0.43	0.64
P_{fail}(2h=7200)	0.01	0.13
P_{fail}(3h=10800)	0.0002	0.02

As for cause (c), FIGURE 5 shows the results of the survey conducted by Building Contractor's Society of Japan for the ratio of the loading in the designs to the allowable loading to steel columns of the buildings[8]. According to FIGURE 5, the most frequent loading ratio is only 0.2 and more than 95% of columns are covered in the range less than 0.4. As shown in TABLE 2, the failure probabilities for structures with such small loading ratio are extremely low.

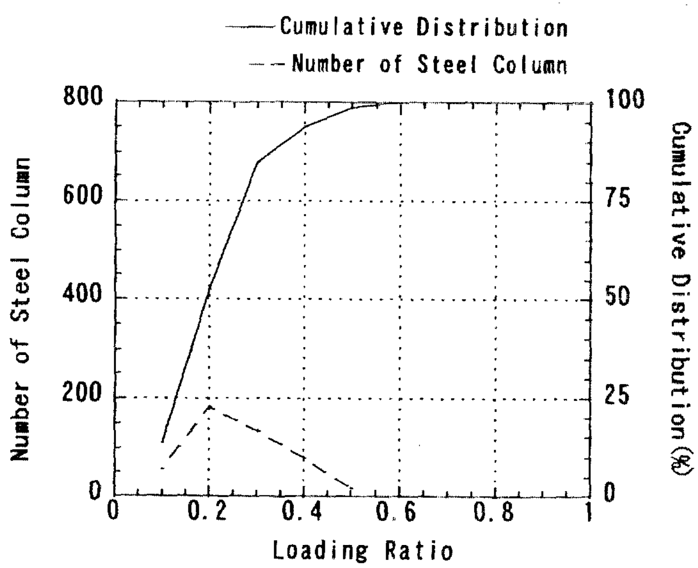


FIGURE 5 The Loading Ratio in the Structural Designs of Steel Columns

TABLE 2 The Failure Probability of the Structures with Different Loading Ratios

Roading Ratio	μ_w=30, σ_w=10	μ_w=40, σ_w=20
0.2	4.52×10^{-8}	7.15×10^{-4}
0.4	2.31×10^{-7}	1.44×10^{-3}
0.6	7.12×10^{-7}	2.34×10^{-3}
0.8	2.28×10^{-6}	3.84×10^{-3}
1	1.39×10^{-5}	8.30×10^{-3}

3.3 Fire Resistance Requirement Based on Acceptable Failure Probability

In view of controlling the fire risk of buildings under an acceptable level, it is most rational to determine the design fire load density corresponding to the acceptable failure probability, taking into account the various factors suggested in Eqn.(9), and to provide necessary safety measures based on the prediction of fire behavior under the design fire load density.

(1) Code equivalent performance-based fire resistance standard

The failure probability of the structures complying to the current provisions are not necessarily low as seen in the above. However, considering that the collapses of buildings are rare thanks to the many other factors involved, the probability can be said appropriate as the acceptable failure probability under the condition at which such factors are disregarded.

In the current Building Standards Law, there is as large as one-hour gap between 4 and 5 story, and between 14 and 15 story. However, the acceptable failure probability of structures should change continuously with number of story from the viewpoint of the fire risk expressed by Eqn.(9). In order to use Eqn.(9) to determine the acceptable failure probability of arbitrary buildings, it is sufficient to define only one reference building. FIGURE 6 demonstrates how the acceptable failure probabilities change with number of stories when a building with 5, 10 and 14 stories, which are in the range of two-hour fire resistance rating in the code, are selected as the candidates of the reference buildings. It was assumed that the area of a floor of the reference building is the same within this range of stories so number of stories is the only variable. The reason that the candidate reference buildings are selected only in this range of floor is that the fire resistance requirements for 4-stories or less is somewhat complicated and that there is no height limit for 15-stories or more in the code, hence it is difficult to specify the number of stories of the reference building.

The acceptable failure probabilities based on Eqn.(9) and the reference buildings can be compared with those based on fire resistance requirements. Needless to say, it is unavoidable that there is some difference between the failure probabilities based on the present method and the building code. However, some of the difference may be justified: According to the present method, the failure probability for low rise buildings is significantly high, but this correspond to that there is little fire resistance requirements for low-rise small buildings in the code as well, so accordingly they are not expected to endure severe fires; Where the number of stories is high, the failure probability for the code is lower than the acceptable failure probability based on the present method, but this can be explained from Eqn.(9) if higher buildings tend to have larger floor area.

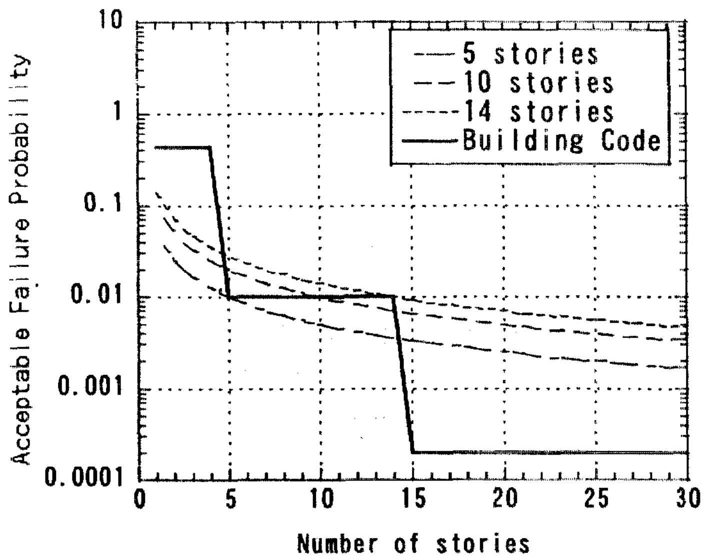


FIGURE 6 The Acceptable Failure Probability with Number of Stories

(2) Determination of design fire load density

As discussed in the above, once the reference building is specified along with its acceptable failure probability, the acceptable failure probability P_{fail} for an arbitrary building can be readily calculated from Eqn.(9) as a function of various conditions of the building. The probability P_{fail} can be converted to the design fire load density for use in the fire safety design as follows:

The normalized fire duration τ_X for P_{fail} can be obtained from Eqn.(25) as

$$\tau_X = \Phi^{-1}(P_{fail}) \tag{26}$$

then, the fire duration t_X can be obtained from Eqn.(24) as

$$\ln t_X = \mu_{\ln t_D} + \Phi^{-1}(P_{fail})\sigma_{\ln t_D} \tag{27}$$

Using Eqns.(22) and (23) to Eqn.(27) to yield more explicit form of t_X

$$t_X = \frac{\mu_w \Omega}{\sqrt{1+\left(\frac{\sigma_w}{\mu_w}\right)^2}} \exp\left[\Phi^{-1}(P_{fail})\sqrt{\ln\left\{1+\left(\frac{\sigma_w}{\mu_w}\right)^2\right\}}\right] \tag{28}$$

Hence, further using Eqn.(13) yields

$$w_X = \frac{t_X}{\Omega} = \frac{\mu_w}{\sqrt{1+\left(\frac{\sigma_w}{\mu_w}\right)^2}} \exp\left[\Phi^{-1}\left(P_{fail}\right)\sqrt{\ln\left\{1+\left(\frac{\sigma_w}{\mu_w}\right)^2\right\}}\right] \qquad (29)$$

That is, the design fire load density can be determined only from the mean and the standard deviation of fire load density, i.e. μ_w and σ_w, and the acceptable failure probability P_{fail}, indifferent of Ω, i.e., the ventilation factor and the floor area.

It should be noted that the values of μ_w and σ_w in Eqn.(29) are different from those used to estimate the failure probability of the reference building. These values usually differ depending on the type of use of the space, so the smaller the fire load density, the smaller the design fire load density can be even though the acceptable failure probability P_{fail} is the same.

CONCLUDING REMARKS

Fire behavior heavily depends on the various conditions of the space and the fire load, hence the impact of fire to a building differ from one building to another. Evidently, it is irrational to impose the same fire safety provisions neglecting such difference in building conditions. This is the very reason that attempts are being made worldwide for developing a performance-based design system, in which the safety measures are provided based on the prediction of fire behavior under a certain design fire condition. However, the fire growth factor α and the fire load density w, which constitute the design fires, vary in a wide range so choice of the values for design remains to be an important issue.

On the other hand, it is apparent that the fire safety provisions in the current building codes have been made taking into the fire risk, albeit empirically. In fact, the control of fire risk is considered to be the very essence of the fire safety provisions. In this paper, particularly focusing on the issue of structural fire resistance requirements, an idea to determine the design fire load density at such a value as to make the acceptable fire risk constant for any building. If a different measure of fire loss is considered the conclusion may be slightly different but it seem to be clear that some sort of principle is necessary to define the design fires in a performance-based design system.

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