Integration of Fire Risk Concept into Performance-Based Evacuation Safety Design of Buildings

TAKEYOSHI TANAKA
Disaster Prevention Research Institute, Kyoto University
Gokasho, Uji, Kyoto 611-0011, Japan

ABSTRACT

The integration of the fire risk concept in performance-based fire safety design of buildings is beneficial in many aspects of fire safety. In this paper, a Risk-Based Evacuation Safety Design Method is proposed for rational evacuation safety design as an important area of fire safety design. While the goal of this method is to control the evacuation risk in fire within an acceptable level, the evacuation safety verification in this method can be conducted according to the deterministic procedure in usual performance-based fire safety design. The particular advantage of this method is that design fires and scenarios in the performance-based design of a building are identified in a systematic manner. The practicability of this method in performance-based designs of actual buildings is demonstrated by case studies for realistic buildings.

KEYWORDS: performance-based design, fire risk, acceptable risk, design fire, fire growth factor, event tree.

NOMENCLATURE LISTING

A	area (m^2)	R	evacuation risk (persons)
B	width (m)	t	time (s)
C_i	consequence in scenario i	z	along edge (m)
C_0	initial number of occupants (persons)	**Greek**	
H	height (m)	α_D	fire growth coefficient of design fire
l_{max}	maximum travel distance to exit (m)	**subscripts**	
P_i	probability of scenario i to occur	$_a$	acceptable
p_{cas}	probability of casualty occurrence	$_C$	corridor, ceiling
p_{hf}	probability of hazardous fire occurrence	$_D$	design, door
$\dot{Q}$	heat release rate of fire source (kW)	$_R$	room
q_0	occupant density (persons/m^2)	$_{sp}$	sprinkler

INTRODUCTION

Fire safety design practices for buildings worldwide are now shifting from complying with prescriptive building/fire regulations to performance-based fire safety design (P-B FSD), where various computer models and calculation methods are extensively used. No doubt, the rapid development in fire models in recent decades is among the contributors to this trend. It is blessing for fire research community that the results of fire research are extensively used, but a concern is that P-B FSD sometimes seems to be taken too simplistically as only the matter of calculations, e.g. available safe egress time (ASET) and required safe egress time (RSET) calculations.

Another factor that has made P-B FSD popular is the complexity and multiplicity of the existing prescriptive building/fire provisions. However, the prescriptive requirements are at least based on the lessons learnt from serious fire accidents in the past. For example, evacuation safety provisions started out with fire ladders carried by fire brigades and, as serious fire casualties occurred in buildings with increased height and size, expanded to built-in escape stairs, smoke-proof stairs, fire detection systems, fire suppression systems, smoke control systems and so on. It is true that such provisions were rather empirically made without solid scientific bases so that they need be rationalized but it should be duly recognized that building safety from fire at present is maintained thanks to these provisions.

Although fire safety of a building involves many fire safety systems, e.g. sprinklers, smoke control and structural fire resistance, none of them are perfect. It is the performance attained by the combination of

these systems that provide adequate safety. A question is whether the current simplified P-B FSD practices, e.g. ASET–RSET calculation, can adequately evaluate the fire safety performance attained by such systems.

From another point of view, fire is already a rare event. According to the national fire statistics of Japan, the annual fire occurrence rate of dwelling fires is 0.4 per 1,000 household, i.e. the frequency of fire occurrence for a particular household is only once per 2,500 years. Moreover, most of these events are small fires. Serious fires that involve a whole room or house are only 10-20 % of fire occurrences. The annual number of fatalities from fire is about 1,200 in Japan, which is only 1/100,000 of the population per year. For example, if a person were reborn 1,000 times to live for 100 years life each, the person would expect to die by fire only once. People in a city may hear of fire incidences frequently, but this is just because a tremendous number of buildings exist in their city. This may be the cause of the recognition gap in the necessity of fire safety systems between a building owner, who only has to care about the safety of their particular building, and a building authority, who has to care for all of the buildings in the community in their charge. Another cause of the recognition gap is that there is no objective metric that is sharable by both sides to assess the level of fire safety of a building. In the age of P-B FSD, a quantitatively defined fire risk may help to reduce the gap. In fact, fire risk consideration is incorporated in the conventional prescriptive provisions in the manner that the larger and taller a building is the more severe the requirements imposed, even though they are empirical and not always consistent. On the other hand, the fire risk issue is not sufficiently taken into account in the P-B FSD practices at present.

Consider a 10 storey building with 10 identical rooms on each floor. Even though the probability of fire occurrence in a room is negligible, the probability increases by 10 times for a floor and the number of occupants affected by the fire increases by 10 times as well. For the whole building, both the probability and the number of occupant involved are 100 times larger than those for a room, i.e., the potential fire risks to the occupants with regard to floor and building evacuations are 100 and 10,000 times larger relative to room evacuation, respectively. This example may help to explain why the levels of rigorousness of the prescriptive building/fire provisions are different amongst rooms, floors and buildings.

Although the integration of fire risk concept into P-B FSD is necessary in every aspect of fire safety, this paper focuses on the evacuation issue. The author names the methodology presented here as the Risk-Based Evacuation Safety Design Method (R-B ESDM).

BACKGROUND

The Risk-Based Evacuation Safety Design Method (R-B ESDM) that author and co-workers have proposed is a methodology to select design fires and scenarios for P-B FSD [1-5]. In this methodology, evacuation risk is conservatively controlled below an acceptable risk level if it is verified that no casualty occurs under the design fires and scenarios generated by this method. This study was motivated mainly by the current state of P-B FSD practices and the studies concerning fire risk assessment.

Performance-based Fire Safety Design (P-B FSD)

In Japan, an attempt to develop a P-B FSD began during the 5 year Ministry of Construction (MOC) project called *Development of Fire Safety Design Method of Building*, conducted from 1982 through to 1986. This project was motivated by the frustration of the building community with the heavy burden of fire safety measures imposed by the regulations. The project was assisted by the contact with advanced fire science and technologies through the UJNR panel on fire research and safety, which had started in the late 1970s. The project was actually conducted by the Building Research Institute (BRI) with the help of researchers from construction industries and universities. In this project, the fire safety provisions in the Building Standards Law (the BSL) and related documents were analyzed to identify the fire safety objectives and fundamental requirements underlying the provisions, design fires and safety criteria [6–8] and fire models, e.g. BRI2, and calculation methods were developed [9,10]. This design method was favorably accepted in the building community in Japan and resulted in an impressive increase in the number of building using P-B FSD.

It is well known that P-B FSD has been promoted in many countries such as the USA, Australia, New Zealand, Canada, the Nordic Countries, UK, Hong Kong [11,12]. Also international bodies e.g. SFPE, ISO/TC92 and CIB/W14 are engaged in the activities concerning P-B FSD.

The actual P-B FSD practices differ in detail among countries depending on legal, traditional, cultural and technological conditions. However, the basic procedure of P-B FSD is thought to be the same: in case of evacuation safety design, (1) an evacuation safety plan of a specific project is presented, (2) evacuation behavior and smoke behavior are predicted under prescribed design fire conditions, (3) the results are checked against prescribed safety criteria to verify the compliance to safety requirements, and improvements to the plan are made if it failed to comply. Usually, this procedure is deterministic, which is almost critical for P-B FSD practices to avoid too heavy burden in conducting the designs. However, for ensuring the necessary level of fire safety by such a relatively small number of checks, it is critical to adequately select the design fires and scenarios.

Fire Risk Assessment

Attempts to construct a P-B FSD method based on fire risk assessment methods have been made from the early stages of P-B FSD development. In the Fire Safety and Engineering Project by The Warren Centre at The University of Sydney, DRAM (a demonstration risk assessment model) was developed to calculate expected risk to life and fire cost expectation as a basis for cost-effective design solutions [13]. This type of methodology was developed most actively in Australia and Canada [14,15].

Concerning fire risk assessment methodologies, ample studies exist in many countries, such the USA, Sweden, and the UK. Several national and international bodies, e.g. SFPE, NFPA and ISO, have developed and published guidance documents for fire risk assessment [16–19]. The procedure of the risk assessment is not exactly the same among the documents but the essence of the procedure may be summarized as: (1) identify objectives and goals, (2) identify related hazards, (3) construct an event tree concerning the hazards, (4) estimate the probability of each event, (5) estimate the consequence for each event, (6) calculate the risk for each event and (7) evaluate if the total risk is at an acceptable level.

This procedure appears to be rational in a theoretical sense but may be too difficult for practicing fire safety engineers to implement in the fire risk assessment of actual buildings. Engineers may encounter such questions as: how can they determine an appropriate goal in terms of acceptable risk criteria?; how can they identify the relevant hazards?; how can they construct the event tree properly?; where can they obtain appropriate values of event probabilities?; what are the proper design fires for estimating the consequence?; how can they manage a large event tree? etc. For the risk assessment to be practicable in realistic targets, some more breaking-down will be necessary for every step in the procedure.

Analysis of Fire Statistics Data

For fire risk assessment, various statistical data from the real world are precious. For example, statistics of fire load density in real building spaces is useful to evaluate how much residual risk remains when a building is designed under a given fire load density. Efforts to establish databases for fire risk assessment are going on, by which it has been found that the frequency histograms of fire load density and fire growth factor in natural fires are both fitted to log-normal distribution [20,21]. While the frequency distribution of fire load density is most important in the risk assessment involving structural stability in fire and fire spread across fire compartment boundaries, the frequency distribution of fire growth rate is important for the assessment of evacuation risk.

Although such results of existing investigations are precious, the specific values may be different among countries reflecting various regional conditions, e.g. living customs and cultural traditions. So it is desirable that such data are collected in each country if relevant sources are available. In conjunction with the development of R-B ESDM, analyses of national fire report data for annual fire occurrence rate per unit floor area, casualty rate per fire, fire growth factor distribution etc. for different occupancies is ongoing [3].

RISK-BASED EVACUATION METHOD FRAMEWORK

The expected users of R-B ESDM are fire safety engineers who have enough expertise in manipulating fire models and calculation methods in the compliance verification of fire safety design of buildings, once the conditions for calculations are given. If it is verified that no occupant fails to evacuate safely under the design fires and scenarios provided by R-B ESDM, the evacuation risk of a building space is conservatively proved to be within an acceptable level.

Risk-based Evacuation Safety Design Method

R-B ESDM assumes that evacuation safety verification is conducted according to the usual P-B FSD procedure. Some notable features of the current P-B FSD are: (1) the design fires are always hazardous fires, in other words insignificant fires, e.g. smoldering fires, self extinguishing fires, are disregarded; (2) the occupant load is determined based on a fully loaded condition; and (3) the safety criteria are set at strict levels, e.g. 'not exposed' or 'only slightly exposed' to smoke. Such P-B FSD practices are understandable considering that the aim of P-B FSD is mostly to adequately design fire safety systems, e.g. sprinkler system, smoke control system, fire compartment, evacuation route, which are vital only when severe conditions for evacuation occur. Strict safety criteria are set partly because it is virtually impossible to predict evacuation behavior under threatening fire environments and partly because it is not reasonable for fire safety design to allow too hazardous circumstances to occur.

On the other hand, R-B ESDM is different from ordinary P-B FSD in that the design fires and scenarios to be checked are systematically selected. The concept of the function of the R-B ESDM is illustrated in Fig. 1. The main components of R-B ESDM are: (1) an acceptable evacuation risk in the context of FSD, (2) a design fire with a variable fire growth factor, and (3) establishment of a scenario event tree based on the success/fail of the fire safety system.

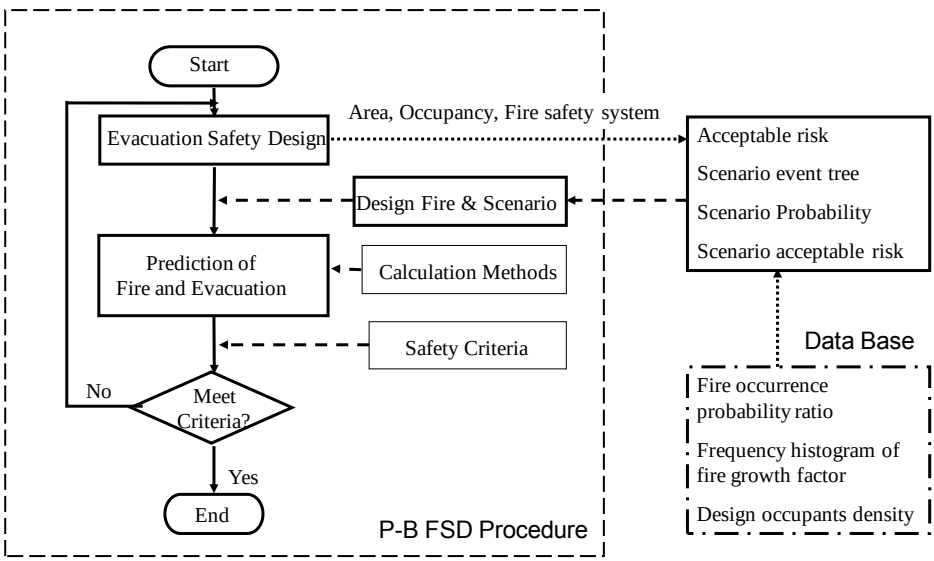

Fig 1. Outline of Risk-Based Evacuation Safety Design Method.

Evacuation Risk in Fire

Although the word 'risk' may be used in a broad meaning, the evacuation risk, *R*, in R-B ESDM is defined as the expected number of casualties in a fire condition, i.e.:

$$R = PC \tag{1}$$

where *P* is the probability of the fire condition to occur and *C* is the number of casualties during the fire.

The fire occurrence probability, *P*, differs depending on the target space to be considered. In the case of an apartment building, the probability of fire occurrence in the building is supposed to be almost in proportion to the number of dwelling units. Although it is not clear if the same tendency holds for any type of space, the fire occurrence probability is assumed to be proportional to the floor area of a space, *A*, i.e.

$$P = p_{hf} A \tag{2}$$

where p_{hf} is fire occurrence probability per unit area, which is presumed to depend on the characteristics of a space, e.g. occupancy type.

The casualties caused under a fire condition may be rewritten as

$$C = p_{cas} C_0 \tag{3}$$

where C_0 is the number of occupants in the space at the time of the fire and p_{cas} is the proportion of occupants who fail to evacuate safely. The proportion p_{cas} is supposed to be dependent on the characteristics of a space, e.g. occupancy type and design of the space, as well as the fire condition.

Using Eqs. 2 and 3, Eq. 1 is rewritten as

$$R = (p_{hf} A)(p_{cas} C_0) \tag{4}$$

Acceptable Evacuation Risk in the Context of Fire Safety Design

Existing building/fire regulations are generally more restrictive for larger buildings. Although their provisions may be empirical and not always be consistent, it will be reasonable to consider that the underlying intent is to control fire risk below a certain acceptable level irrespective of the size and occupancy of building. That is, in the case of evacuation risk,

$$R = (p_{hf} A)(p_{cas} C_0) \le R_a (= \text{costant}) \tag{5}$$

This implies that the larger the building space and occupant load, the smaller the chance of a casualty must be. Thus, the function of building/fire provisions can be translated as the reduction or control of the value of p_{cas}. While A and C_0 are the conditions from specific designs, the characteristics of an occupancy is taken into account through the fire occurrence probability, p_{hf}, and the casualty probability, p_{cas}. For example, if sleeping or handicapped persons are expected in a building, more measures will be necessary to attain the same value of p_{cas}.

The next issue is to find the value of R_a in Eq. 5. Although code equivalency is a candidate approach to determining the value, this will be a difficult task considering the complexity and multiplicity of the existing building/fire codes. Another candidate is to use fire statistics. In the past, many serious fires have occurred that have sometimes claimed hundreds of lives and thereby invoked grave societal concern. However, due to the various fire safety measures imposed on buildings, the annual life loss in developed countries seems to have stabilized and the general feeling is that no additional measures are affordable for a further reduction in fire casualties. This indicates that our societies accept the current level of fire losses.

Note, however, that the level of fire risk acceptance differ more or less among different societies since the level is determined by a compromise between the safety level and the cost required to attain the safety level. It is up to a particular society to determine the level to choose. In this paper, the evacuation risk obtained from dwelling fire statistics in Japan is adopted. The main reason is that the most numerous and stable data are available from fire statistics, but it is also taken into account that virtually no evacuation safety provisions are applied to dwellings. While provisions for evacuation differ depending on the size and occupancy of building, the consistency in view of the safety level among them is debatable, which may cause difficulty in deciding which class of building should be chosen to obtain the acceptable risk.

Adopting the evacuation risk for dwelling houses as the acceptable risk, an arbitrary space is needed to satisfy the following equation:

$$R(\mathrm{K}) \equiv p_{hf}(\mathrm{K}) A(\mathrm{K}) p_{cas}(\mathrm{K}) C_0(\mathrm{K}) \le R_a \equiv p_{hf}(\mathrm{H}) A(\mathrm{H}) p_{cas}(\mathrm{H}) C_0(\mathrm{H}) \tag{6}$$

where K and H are indicators of the arbitrary space and a dwelling house, respectively.

From Eq. 6, we have the following formula:

$$p_{cas}(\mathrm{K})C_0(\mathrm{K}) \le p_{cas}(\mathrm{H})C_0(\mathrm{H})\left\{\frac{p_{hf}(\mathrm{H})}{p_{hf}(\mathrm{K})}\right\}\left\{\frac{A(\mathrm{H})}{A(\mathrm{K})}\right\} \tag{7}$$

Recall that P-B FSD is always conducted assuming hazardous fires. The left-hand side of Eq. 7 is the evacuation risk under the condition that a hazardous fire has occurred, R^D (K), i.e. the conditional evacuation risk in the context of P-B FSD. Likewise, the right-hand side of Eq. 7 is the acceptable risk in the context of P-B FSD.

The average casualty per hazardous fire in dwelling houses, p_{cas}(H), was found to be 0.15 [3]. Using the occupant density factor for a dwelling prescribed in the Building Standards Law of Japan, 1 person/16 m^2, and the average floor area of dwelling houses, 125 m^2, in addition to p_{cas}(H) = 0.15 in Eq. 7, the acceptable evacuation risk in the context of P-B FSD for arbitrary space K is given as

$$R_a^D(\mathrm{K}) = 1.2\left\{\frac{p_{hf}(\mathrm{H})}{p_{hf}(\mathrm{K})}\right\}\left\{\frac{125}{A(\mathrm{K})}\right\} \tag{8}$$

In order to calculate $R_a^D(\mathrm{K})$, the ratio of hazardous fire occurrence probability per unit area of the occupancy type of space K relative to that of dwelling house is necessary. Analyses of annual occurrence rates of hazardous fires and building statistics were conducted to establish the ratios for different occupancy types. The results are shown in Table 1 [3]. Note that casualty includes slight injury as well as fatality and serious injury in accordance with the level of safety criteria in P-B FSD.

Note, however, that even though the acceptable evacuation risk has been established as Eq. 8, it will be more or less necessary to make an adjustment later to avoid an excessively large gap to occur between the new method and the current practices.

Table 1. Ratios of 'hazardous fire occurrence per unit floor area' for different occupancy types [3].

Ratio	Dwelling	Apartment	Shop	Hotel	Restaurant	Hospital	Office	Theatre	School
$\frac{p_{hf}(\mathrm{H})}{p_{hf}(\mathrm{K})}$	1	1.5	7.2	3.1	0.5	9.0	4.1	1.2	9.7

Event Tree Based on Success/Fail Scenarios of Fire Safety Systems

The environmental conditions for evacuation in a fire differs drastically as to whether the fire safety systems, e.g. sprinkler, smoke control, fire door, function as expected or not. However, it will make such a fire safety system meaningless if only the worst cases are considered in P-B FSD. Although none of these safety systems are perfect, the overall reliability can be elevated by the redundancy of these sub-systems. A rational safety verification method should be able to duly evaluate the benefits of the fire safety systems.

For this purpose, it is useful to construct a scenario event tree based on the success/failure of the fire safety systems involved in the evacuation as exemplified for a fire room evacuation in Fig. 2. An advantage of this tree is that the probabilities of the scenarios can be calculated using the success/failure probability of each safety system. Even though it is still not very easy to acquire accurate data on the probability, some data will be available from several sources e.g. fire reports, maintenance records, etc. In addition, it is considered to be a part of P-B FSD to design reliable safety systems.

Letting N be the number of scenarios involved in the evacuation of a space, the goal of the R-B ESDM is to attain the following condition:

$$\sum_{i=1}^{N} R^D(i) = \sum_{i=1}^{N} P_i C_i \le R_a^D \tag{9}$$

where $R^D(i)$, P_i and C_i are the evacuation risk, probability and casualties of an arbitrary scenario i, respectively. Incidentally, from the premise of P-B FSD that a hazardous fire has occurred, P_i satisfies

$$\sum_{i=1}^{N} P_i = 1 \qquad (10).$$

The acceptable evacuation risk for the space, R_a^D, can be allocated to each scenario arbitrarily:

$$P_i C_i = R_a^D(i) \qquad (11)$$

provided that the following condition is met.

$$\sum_{i=1}^{N} R_a^D(i) \le R_a^D \qquad (12)$$

where $R_a^D(i)$ is the partial acceptable evacuation risk allocated to scenario i.

Mathematically, there is freedom to satisfy Eq. 12 since N scenario risks exist against a sole constraint, which may offer P-B FSD some chance of trade-off. In the actual P-B FSD practices, however, technical and economical aspects can be additional restraints for the allocation of the partial acceptable risks.

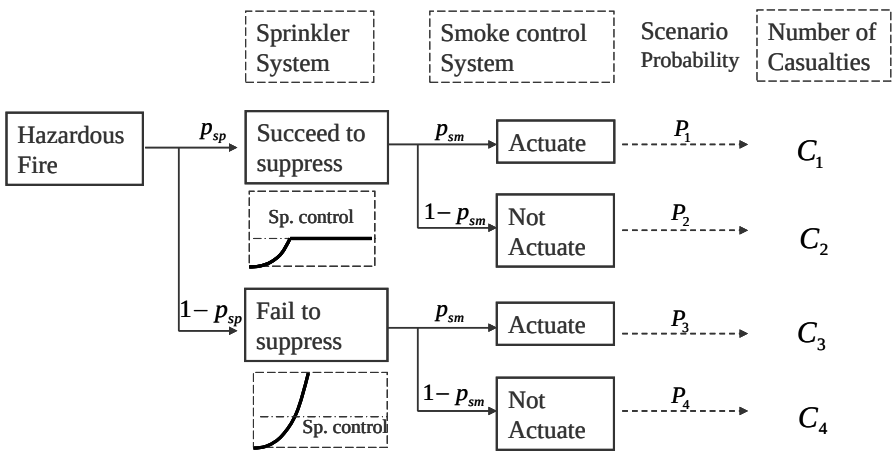

Fig. 2. Scenario event tree constructed based on success/failure of fire safety systems.

Design Fire

The design fires widely used in P-B FSD are as shown in Fig. 3. At the initial stage, the heat release rate (HRR) of fire sources increases with time-squared (t^2 fire) until it reaches the maximum HRR, which is controlled either by the ventilation condition, the fuel condition or sprinkler activation. In terms of a mathematical formula, the HRR of the design fires is expressed as

$$\dot{Q} = \min\left(\alpha t^2, \dot{Q}_{\max}\right) \qquad (13)$$

where $\dot{Q}, \dot{Q}_{\max}, \alpha, t$ are the HRR of fire, the maximum HRR, fire growth factor and time, respectively.

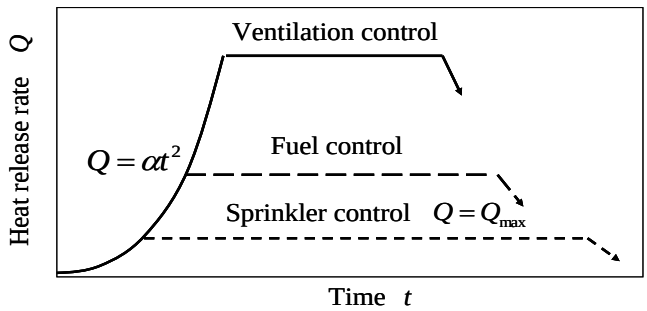

Fig. 3. Heat release rate of design fires.

The maximum HRR is assumed to be constant and estimated using relevant calculation methods although, in reality, it varies more or less depending on the various conditions involved. On the other hand, the fire growth factor α in real fires is probabilistic in nature. It greatly varies depending on the item ignited, the ignition source, etc. that happen to be involved in a fire. According to the similar analyses by Holborn et al. [21] made of the national fire report data for burn area and fire brigade operation time, the frequency histogram of α in any of the occupancies investigated is fits well to a log-normal distribution shown by solid lines in Fig. 4, where HRR per unit floor area, q, was estimated based on design fire load densities.

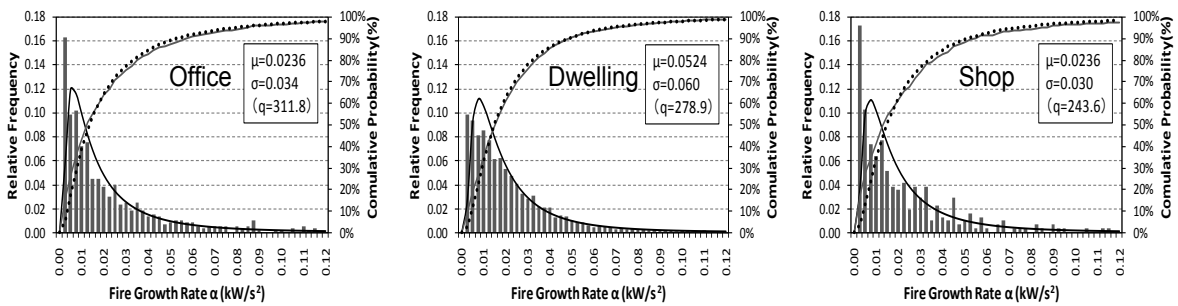

Fig. 4. Histograms of fire growth factors obtained from fire report data in Japan.

Incidentally, the sprinkler controlled HRR does not necessarily mean that a sprinkler system cannot completely extinguish a fire when actuated, but means that all the fires of which the HRR is too small to actuate a sprinkler, including fires extinguished by sprinklers, will be covered under this limit. Therefore, the sprinkler controlled HRR here is a very conservative design fire.

Design Fire for Conservative Evacuation Safety Verification

According to the above discussion, the evacuation safety of a target space has to be verified by satisfying Eq. 11 one by one. In Eq. 11, P_i is determined as the probability of scenario i occurring but the expectation of casualties, C_i, has to be calculated considering the fire condition, or fire growth factor in this particular design method. The faster a fire develops, the more casualties will be caused. The fire growth rate is stochastic, according to distributions as illustrated in Fig. 4. Hence, considering the number of casualties is a function of fire growth factor, α, the expectation of casualties, C_i, can be given as

$$C_i = \int_0^\infty f(\alpha) C(\alpha) d\alpha \tag{14}$$

where $f(\alpha)$ is the probability density function of the fire growth factor, α and $C(\alpha)$ is the casualties for α. Eq. 14 holds for any scenario, i.e. regardless of i.

The conceptual relationship between α and $C(\alpha)$ is illustrated in Fig. 5. When the fire growth factor, α, is very small, i.e. a fire grows very slowly, then no occupant will be injured. It will be only when the fire growth factor exceeds a certain level that casualties during evacuation begin to be caused. In other words, letting α_D be the threshold of α up to which casualties are zero, Eq. 14 can be written as

$$C_i = \int_0^{\alpha_D} f(\alpha)C(\alpha)d\alpha + \int_{\alpha_D}^{\infty} f(\alpha)C(\alpha)d\alpha = \int_{\alpha_D}^{\infty} f(\alpha)C(\alpha)d\alpha \tag{15}$$

The dependence of casualties on the fire growth factor varies according to many factors, e.g. space conditions, occupant state. In other words, the shape of $C(\alpha)$ is generally not known for $\alpha > \alpha_D$. However, since $C(\alpha)$ cannot exceed the initial number of occupants, C_0,

$$C_i = \int_{\alpha_D}^{\infty} f(\alpha)C(\alpha)d\alpha \le C_0 \int_{\alpha_D}^{\infty} f(\alpha)d\alpha \tag{16}$$

Using Eq. 16, Eq. 11 can be rewritten as

$$P_i C_i \le P_i C_0 \int_{\alpha_D}^{\infty} f(\alpha)d\alpha \le R_a^D(i) \tag{17}$$

This implies that the threshold value of fire growth factor, α_D, that conservatively satisfies Eq. 11 can be obtained by solving

$$\int_{\alpha_D}^{\infty} f(\alpha)d\alpha = \frac{R_a^D(i)}{P_i C_0} \text{ (or } \int_0^{\alpha_D} f(\alpha)d\alpha = 1 - \frac{R_a^D(i)}{P_i C_0}\text{)} \tag{18}$$

That is, the evacuation safety for scenario i can be conservatively verified if no casualty is found to be caused under the design fire:

$$\dot{Q} = \min\left(\alpha_D t^2, \dot{Q}_{\max}\right) \tag{19}$$

Note that no verification is required if $R_a^D(i)/P_i C_0 \ge 1$ since α_D = 0, i.e. the risk is already below the acceptable risk for scenario i, and that the verification must be made under the constant fire with maximum HRR if $R_a^D(i) = 0$ since $\alpha_D = \infty$. However, the maximum HRR is limited in the case of a sprinkler controlled fire, so verification will be relatively easy. Incidentally, since there is no actual fire with infinite an fire growth factor, the condition of $\alpha_D = \infty$ may be eased to the level of an ultra-fast fire, for example.

Note also that the above derivation of design fire may sometimes be too conservative. Particularly, Eq. 16 will be too restrictive for sprinkler controlled fire since it is unrealistic that nobody can survive when the maximum HRR is suppressed to a low level even though the fire growth is extremely fast.

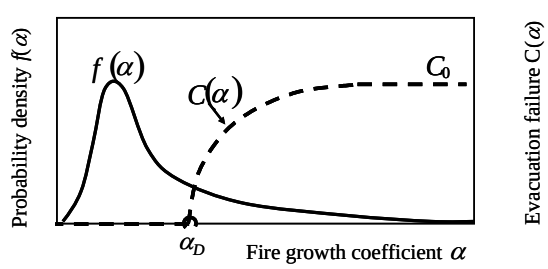

Fig. 5. Conceptual relationship among $f(\alpha)$, $C(\alpha)$ and α.

Evacuation Safety Verification Procedure

Based on the discussions above, the procedure of R-B ESDM is summarized as follows:

1. Calculate the acceptable evacuation risk for the target space, R_a^D , using Eq. 8,
2. Construct the scenario event tree based on success/failure of the fire safety system involved in the evacuation safety of the target space,
3. Calculate the provability of each scenario to occur, P_i, using success/failure probabilities of the fire safety systems involved,
4. Allocate a partial acceptable evacuation risk to each scenario, $R_a^D(i)$, within the limitation of Eq. 12,
5. Verify that no casualty occurs under the conditions and design fire corresponding to each scenario:
   - if $R_a^D(i)/P_iC_0 \geq 1$: no particular verification is necessary,
   - if $R_a^D(i)/P_iC_0 \leq 1$: verify that no casualty occurs under the design fire given by Eq. 19,
   - if $R_a^D(i) = 0$: verify that no casualty occurs under the design fire with the maximum HRR.

PRACTICABILITY OF THE RISK-BASED VERIFICATION METOD

Since R-B ESDM is intended to contribute to rational and efficient P-B FSD of actual buildings, some example applications are presented to demonstrate the practicability of the method in P-B FSD.

Conditions for Exempting Verification of Fire Room Evacuation

As virtually no provisions are imposed on dwelling houses, the safety verification of room evacuation should be exempted for small rooms in a building since the evacuation risk due to the fire occurrence in a small room is often extremely low. For efficient P-B FSD practices, the conditions to exempt the verification of room evacuation safety are discussed in terms of evacuation risk.

Space without Sprinkler System

Consider first the case of spaces with no sprinkler system, where the existing scenario is only one as illustrated in Fig. 6a. Since the acceptable risk depends on space area, it is better to go back to the basic concept of R-B ESDM that any space, K, has to satisfy

$$p_{hf}(K)A(K)p_{cas}(K)C_0(K) \leq p_{hf}(H)A(H)p_{cas}(H)C_0(H) \qquad (20).$$

Using the design occupant density, q_0, Eq. 20 is rewritten as

$$p_{hf}(K)A(K)p_{cas}(K)\{q_0(K)A(K)\} \leq p_{hf}(H)A(H)p_{cas}(H)\{q_0(H)A(H)\} \qquad (21)$$

From Eq. 21, the condition of floor area that satisfies Eq. 20 can be obtained as

$$A(K) \leq \sqrt{\frac{p_{hf}(H)}{p_{hf}(K)} \cdot \frac{p_{cas}(H)}{p_{cas}(K)} \cdot \frac{q_0(H)}{q_0(K)}}A(H) \qquad (22)$$

The problem to calculate the precise value of A(K) for an arbitrary occupancy using Eq. 22 is that p_{cas}(K) is virtually unknown mainly because hardly any data are available for the number of occupants who happened to be in the building when a fire occurred. However, it is conservative to assume that p_{cas}(K) = p_{cas}(H) since no other building is used more freely from restrictions by persons with a variety of physical and mental conditions than dwelling houses. Then, Eq. 22 becomes as

$$A(K) \le \sqrt{\frac{p_{hf}(H)}{p_{hf}(K)} \cdot \frac{q_0(H)}{q_0(K)}} A(H) \tag{23}$$

where the ratio of hazardous fire occurrence and design occupants density are only necessary.

Space with Sprinkler System

When a space is equipped with a sprinkler system, two scenarios can take place according to the success or failure of the sprinkler, as illustrated in Fig. 6b. From Eq. 9, the goal of R-B ESDM in this case is:

$$\sum_{i=1}^{2} P_i C_i = P_1 C_1 + P_2 C_2 \le R_a^D \quad (24).$$

The allocation of the acceptable risk is arbitrary but the following will be a simple and practical allocation

$$P_1 C_1 = p_{sp} C_1 = 0, \quad P_2 C_2 = (1 - p_{sp}) C_2 = R_a^D \tag{25}$$

From the second equation of Eq. 25, we have

$$(1 - p_{sp}) p_{cas}(K) \{q_0(K) A(K)\} \le \frac{p_{hf}(H) A(H)}{p_{hf}(K) A(K)} p_{cas}(H) \{q_0(H) A(H)\} \tag{26}$$

That is, again assuming p_{cas}(K) = p_{cas}(H), we have

$$A(K) \le \sqrt{\frac{1}{1 - p_{sp}} \cdot \frac{p_{hf}(H)}{p_{hf}(K)} \cdot \frac{q_0(H)}{q_0(K)}} A(H) \tag{27}$$

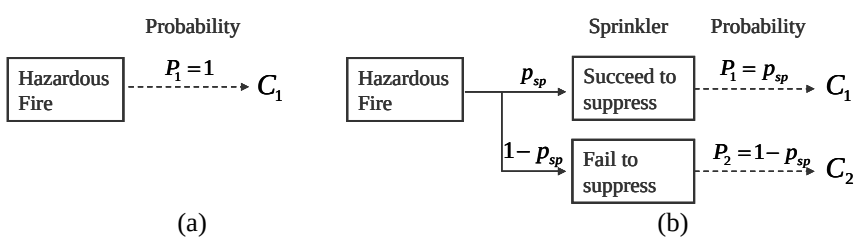

Fig. 6. Scenarios for rooms: (a) without sprinkler system; (b) with sprinkler system.

The floor area limit for exemption of the evacuation safety verification for different occupancies can be obtained by using the values in Table 1 in Eq. 27. The results are shown in Table 2 along with the results using Eq. 23. In Table 2, the sprinkler success probability is tentatively set at three values to examine the difference. Considering the usual size of rooms, a sprinkler will not be necessary for many occupancy types. Although the area limits for a restaurant and a theatre seem to be too small, this is because the occupants' state during the use of these facilities are disregarded and assumed to be the same as dwellings. Considering the occupants' state, a much larger area will be allowed, which is true for other occupancy types as well. Note also that the results in Table 2 only hold for the issue of room evacuation. A sprinkler system can be needed from the view point of floor and building evacuations.

Table 2. Floor area limit for exemption of verification of evacuation safety.

Occupancy type	Occupant density	p_0(H)/p_0(K)	p_{hf}(H)/p_{hf}(K)	Limit of A(K) for verification exemption (m^2)			
				No. sprinkler	p_{sp} = 0.85	p_{sp} = 0.9	p_{sp} = 0.95
Dwelling	0.06	1.0	1.0	125	279	395	560
Apartment	0.06	1.0	1.5	153	342	484	684
Shop	0.50	0.12	7.2	116	259	367	519
Hotel	0.16	0.375	3.1	135	301	427	603
Restaurant	0.70	0.086	0.5	26	58	82	116
Hospital	0.13	0.46	9.0	254	568	803	1136
Office	0.125	0.48	4.1	177	395	560	792
Theatre	1.50	0.04	0.22	27	60	85	121
School	0.70	0.086	9.7	114	255	360	510

Coming back to Eq. 25, not only the second but the first equation must be satisfied to take advantage of sprinkler system in extending the limit of exempted area, A(K). Allocating the acceptable risk to zero means that evacuation safety must be verified under a constant maximum HRR. An example of verification of room evacuation is shown below for an office room. Using conservatively approximated values: H_R = 2.5 m, H_D = 2.0 m, ρ_{smoke} = 1.0 kg/m^3, C_w = 0.08 and $Q_{max(sp)}$ = 300 kW and letting $z_{start} = 0.9H_R$ and $z_{crit} = H_D$ in Eq. A2, Eqs. A1 and A2 shown in the Annex, the ASET is calculated to be

$$t_{ASE} \approx 0.128A \tag{28}$$

Comparing this with RSET given by Eq. A1,

$$\frac{l_{\max}}{v} \le 0.128A, \quad \frac{q_0 A}{1.5B} \le 0.128A \tag{29}$$

where l_{max}, v and B are the maximum travel distance to an exit (m), the travel velocity (m/s) and the exit door width (m), respectively, and q_0 = 0.125 (persons/m^2) for office room is used.

This will not be inflexible restrictions for room designs to meet at all conditions. In actual office rooms, however, many rooms are often arranged within a tenant area as illustrated by Room 3 in Fig. 7, in which case occupants have to make egress through the room connecting to corridor. Let us call the room the 'parent room'. A conservative way to deal with such a case is to conservatively approximate that the smoke filling takes place only in the 'parent room'. Then the area A on the right-hand side of Eq. 28 has to be replaced with parent room area, A_p, and Eq. 29 can be transformed to:

$$\frac{l_{\max}}{v} \le 0.128A_p, \quad \frac{A_p}{A} \ge \frac{q_0}{0.128 \cdot 1.5B} \approx \frac{0.66}{B} \tag{30}$$

Therefore the restriction of l_{max} is in proportion to A_p. On the other hand, the ratio of the 'parent room' area to total room area is dependent on the exit door width, e.g. roughly 80 % for one door of 0.8 m width and 40 % for two doors of the same width. In conclusion, the two restrictions in Eq. 30 and the area limit in Table 2 are the conditions to exempt evacuation verification for an office room, although the precise number may change slightly depending on room geometry, critical smoke layer height, etc. Such a somewhat loose restriction as this will be beneficial considering the frequent changes in room layout in office buildings.

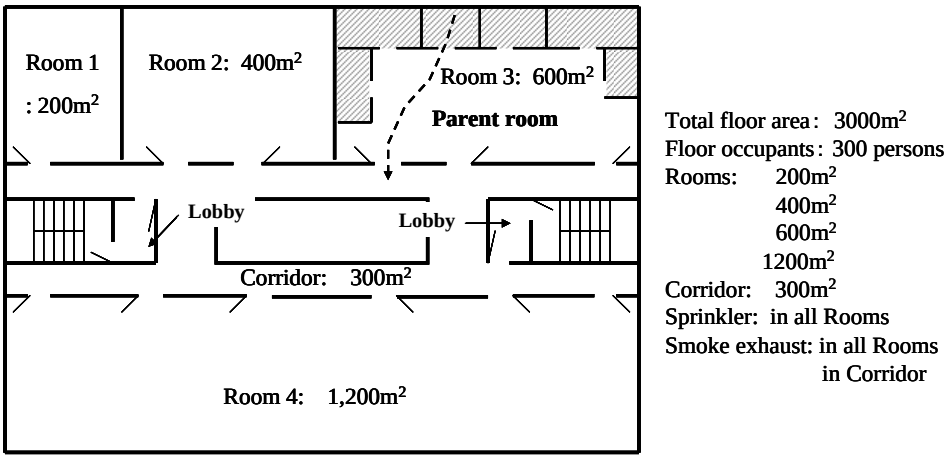

Fig. 7. Example floor and room layout of office building.

Conditions to be Satisfied by Rooms not Exempted of Evacuation Verification

Do not misunderstand that rooms are not allowed unless meeting the conditions in the previous discussion. Any room is allowed as long as the evacuation safety is verified, for which a variety of methods will be available. In any event, the scenario for which $R_a^D(i)/P_iC_0 \le 1$ is involved when evacuation verification is not exempted so it is necessary to determine the value of α_D using Eq. 18. Once α_D is determined, the smoke filling with a t^2 fire can be calculated using appropriate calculation methods, e.g. Eqs. A3 and A4 in the Annex. Using the same values as in deriving Eq. 28, the ASET is obtained as

$$t_{ASE} \approx \frac{0.68}{\alpha_D^{1/5}} A_p^{3/5} \tag{31}$$

Hence, the restrictions imposed on the room with no sprinkler are

$$\frac{l_{\max}}{v} \le \frac{0.68}{\alpha_D^{1/5}} A_p^{3/5}, \quad \frac{A_p}{A} \ge \left(\frac{\alpha_D^{1/5}}{0.68 \cdot 1.5}\right)^{5/3} \frac{A^{2/3}}{B^{5/3}} \tag{32}$$

where $P_i = 1$ is used in Eq. 18 to calculate α_D for a room without sprinkler.

If the acceptable risk is totally allocated to the sprinkler success scenario, in case of a room with a sprinkler, $P_i = 1\text{-}p_{sp}$ is used to calculate α_D and the conditions in Eq. 30 need be satisfied as well as Eq. 32. Since α_D is dependent upon room area, it is a bit difficult to have straightforward insight into the effect of the restrictions given by Eq. 32 on realistic room designs but it is useful to notice that the value of $\alpha_D^{1/5}$ is not so sensitive to the change in α_D.

Fire Floor Evacuation

In the event that a fire occurs in a room on a floor, the evacuation safety needs be considered for all of the occupants on the floor. Since any room on a floor has a possibility of fire occurrence, occupants on a floor are subjected to the risk due to fires originated from all rooms. The issue in floor evacuation is how to adequately handle such risks caused by the multiple origins.

Acceptable Evacuation Risk for Fire Floor Evacuation

Consider an office building. In general, multiple rooms with different floor areas and uses are arranged on a floor. Letting n be the number of rooms on a floor, R-B ESDM requires:

$$\sum_{k=1}^{n} p_{hf}(k)A(k)R_{a(r\bullet f)}^{D}(k) \le 1.2\, p_{hf}(H)A(H) \tag{33}$$

where $R_{a(r\bullet f)}^{D}(k)$ is the acceptable evacuation risk to all floor occupants due to the fire in room *k*.

There is freedom in determining the values of the acceptable risk in Eq. 33. They can be determined arbitrarily as long as Eq. 33 is satisfied. A possibility is to set the voluntary constraint as

$$p_{hf}(1)A(1)R_{a(r\bullet f)}^{D}(1) = \cdots = p_{hf}(k)A(k)R_{a(r\bullet f)}^{D}(k) = \cdots = p_{hf}(n)A(n)R_{a(r\bullet f)}^{D}(n) \qquad (34).$$

Using Eq. 34 in Eq. 33 yields

$$R_{a(r\bullet f)}^{D}(k) = \frac{1.2}{n}\left\{\frac{p_{hf}(H)}{p_{hf}(k)}\right\}\left\{\frac{A(H)}{A(k)}\right\} \tag{35}$$

This appears to be sound in many occupancy types since it follows that the higher the fire occurrence probability the more rigorous safety measures are required. However, an inconvenience when this method is applied to office buildings is that the value of the acceptable evacuation risk is dependent on the number of rooms. In office buildings, the layout and size of rooms are usually renewed when tenants change. It will be inconvenient that the acceptable risk for all the rooms on a floor needs be re-calculated even if such changes are minor. To minimize frequent modification to the fire safety system due to the change of the acceptable risk, it is a practical possibility to set

$$R_{a(r\bullet f)}^{D}(1) = \cdots = R_{a(r\bullet f)}^{D}(k) = \cdots = R_{a(r\bullet f)}^{D}(n) \tag{36}$$

Then using this in Eq. 33,

$$R_{a(r\bullet f)}^{D}(k) \le 1.2\frac{p_{hf}(H)A(H)}{\sum_{k=1}^{n} p_{hf}(k)A(k)} \tag{37}$$

Note that this value is the same for any room on the floor.

Example of Floor Evacuation Safety Verification

Let us examine the practicability of R-B ESDM in floor evacuation safety verification based on the procedure presented above taking the example of the office floor as shown in Fig. 7. This floor has 4 rooms with different floor areas and a corridor. The total floor occupant load is 300 persons and the floor has two exits to staircase with 1 m width each. The fire safety systems equipped are the sprinkler in the rooms and mechanical smoke exhaust in the rooms and the corridor. The dimensions of the rooms and the corridor, and the actuation probabilities of the fire safety systems assumed in the case study are shown in Table 3.

According to the R-B ESDM procedure, the first step is to calculate the acceptable evacuation risk. In this particular case it is the acceptable evacuation risk to all of the floor occupants due to a fire in each room. If the method by Eq. 37 is adopted, the acceptable risk allocated to each room of fire origin is the same, which is given as

$$R_{a(r\bullet f)}^{D}(k)=1.2\cdot\frac{p_{hf}(H)}{p_{hf}(k)}\cdot\frac{A(H)}{\sum_{k=1}^{4}A(k)}=1.2\cdot 4.1\cdot\frac{125}{2400}=0.25625 \tag{38}$$

where use was made of the value for an office in Table 1 for $p_{hf}(\mathrm{H})/p_{hf}(k)$.

Table 3. Dimensions and features of the floor.

	Floor Area (m^2)	Ceiling height (m)	Occupant number (persons)	Door to corridor			Actuation probability		
				Number	Width (m)	Height (m)	Sprinkler	Smoke exhaust	Door (each)
Room 1	200	2.8	25	1	1.0	2.1	0.9	0.9	0.9
Room 2	400		50	2					
Room 3	600		75	3					
Room 4	1200		150	6					
Corridor	300	2.6	N/A	N/A			N/A	0.9	N/A

The second step is to construct the scenario event tree for the fire in each room. Since there are 4 rooms on the floor, 4 trees need be constructed. Here, only the tree for 1,200 m^2 is shown in Fig. 8. The calculation of the scenario probabilities are made for the third step and the results are also shown in Fig. 8. Note that number of open doors affects the required capacity of smoke exhaust in the corridor, so the probability of door closure is calculated according to the number of closed doors.

The fourth step is to allocate the acceptable evacuation risk to each scenario. In this process, the expertise of fire safety engineers is vital. How much acceptable risk should be allocated to each scenario is dependent upon the specific conditions of the fire safety systems in the scenarios. There is no fixed rule but general strategy will be as follows:

- Allocate $R_a^D(i)=P_iC_0$ for scenarios for which it is extremely difficult to consider the measures to assure safety. Although the total values of the acceptable risks for these scenarios need to be well covered within the total acceptable risk, such a scenario takes place when many of the fire safety systems have failed so the scenario probability, P_i, is usually very low, i.e. such scenarios are not likely to happen, as long as the reliability of each system is reasonably high.
- Allocate $R_a^D(i)=0$ or small values for scenarios for which the conditions of fire safety systems are favorable, e.g. a sprinkler is successful, the doors to corridor are closed. The probabilities of such scenarios are generally high so it is often necessary to allocate zero. Even though the maximum HRR has to be set for the design fire in such a scenario, it will be reasonable to deal with the hazards to the corridor during sprinkler control or door closure by means of evacuation.
- For the remaining scenarios, allocate $R_a^D(i)$ considering the conditions of the fire safety systems in the scenarios. The larger the value of $R_a^D(i)/P_iC_0$ the smaller the value of fire growth factor α_D so it is wise to allocate the smaller values for scenarios in which more fire safety systems are available.

Be mindful in allocating the acceptable risks as above that the sum does not exceed the value given by Eq. 39. An example of the allocation is also shown in Fig. 8.

The last step is to verify that no occupant fails to evacuate safely from one scenario to another under the corresponding design fire and success/failure conditions of the fire safety systems. The details of the calculation methods used in the verification are omitted here but only simple calculation methods were used to estimate the floor evacuation time, smoke filling in corridor, etc.

Design fire scenario				Probability P_i	Allocated Ra	*Scenario NO.*	Design fire
Sprinkler	Smoke exhaust (@Room)	Door to Corridor	Smoke exhaust (@ Corridor)				
○Success	○Actuate	○Close	○Actuate	P_1	R_{A1}	F01	
0.9	0.9	0.531441	0.9	0.387	0		
			×Fail	P_2	R_{A2}	F02	
			0.1	0.0430	0		
		×Open>=2	○Actuate	P_3	R_{A3}	F03	
		0.468559	0.9	0.3416	0		
			×Fail	P_4	R_{A4}	F04	
			0.1	0.0380	0		
	×Fail	○Close	○Actuate	P_1	R_{A1}	F05	
	0.1	0.531441	0.9	0.043	0		
			×Fail	P_2	R_{A2}	F06	
			0.1	0.0048	0		
		×Open>=2	○Actuate	P_3	R_{A3}	F07	
		0.468559	0.9	0.0380	0		
			×Fail	P_4	R_{A4}	F08	$\alpha=\infty$ Qmax=391
			0.1	0.0042	0		
×Fail	○Actuate	○Close	○Actuate	P_1	R_{A1}	F09	
0.1	0.9	0.531441	0.9	0.043	0		
			×Fail	P_2	R_{A2}	F10	
			0.1	0.0048	0		
		△Open=1	○Actuate	P_3	R_{A3}	F11-1	$\alpha=\infty$ Qmax=4565
		0.354294	0.9	0.0287	0		
			×Fail	P_4	R_{A4}	F12-1	$\alpha=\infty$ Qmax=4565
			0.1	0.0032	0		
		▲Open=2	○Actuate	P_3	R_{A3}	F11-2	$\alpha=\infty$ Qmax=9130
		0.098415	0.9	0.0080	0		
			×Fail	P_4	R_{A4}	F12-2	No verification necessary
			0.1	0.0009	0.042795		
		×Open>=3	○Actuate	P_3	R_{A3}	F11-3	$\alpha=0.0267$ Qmax=27389
		0.01585	0.9	0.0013	0.0998		
			×Fail	P_4	R_{A4}	F12-3	No verification necessary
			0.1	0.0001	0.042795		
	×Fail	○Close	○Actuate	P_1	R_{A1}	F13	
	0.1	0.531441	0.9	0.005	0		
			×Fail	P_2	R_{A2}	F14	
			0.1	0.0005	0		
		△Open=1	○Actuate	P_3	R_{A3}	F15-1	$\alpha=\infty$ Qmax=4565
		0.354294	0.9	0.0032	0		
			×Fail	P_4	R_{A4}	F16-1	$\alpha=\infty$ Qmax=4565
			0.1	0.0004	0		
		▲Open=2	○Actuate	P_3	R_{A3}	F15-2	$\alpha=\infty$ Qmax=9130
		0.098415	0.9	0.0009	0		
			×Fail	P_4	R_{A4}	F16-2	No verification necessary
			0.1	0.0001	0.0295245		
		×Open>=3	○Actuate	P_3	R_{A3}	F15-3	No verification necessary
		0.01585	0.9	0.0001	0.042795		
			×Fail	P_4	R_{A4}	F16-3	No verification necessary
			0.1	0.0000	0.004755		
					ΣR_{Aj}	R_A	
					0.2625 ≦	0.2625	

Fig. 8. Condition of fire safety systems, scenario probability, allocated acceptable risk and design fire.

Although the scenarios in the event tree in Fig. 8 might seem too numerous, the actual number of scenarios to be verified can be reduced significantly since the verification for the most disadvantageous condition is enough for all the scenarios with the same design fire, such as that with the same constant maximum HRR. Thus the verifications for scenarios for F01- F07 can be exempted once F08 is verified. The verifications of extremely rare scenarios in which most of the fire safety systems simultaneously fail can be also exempted by allocating the acceptable risks corresponding to the scenario probabilities within the limit of the total acceptable risk available to the room. Although this treatment might sound cunning, the relevance will be understood considering the fact that multiple reliable safety systems are required to make use of this treatment. It is a part of FSD to design a reliable fire safety system with adequate redundancy. Among the 24 scenarios, calculations were actually needed for 6 scenarios. It was found that the total smoke exhaust rate required for the room and corridor in Scenario F11-3, 916 m^3/min is about the same as the rate required by the Building Standard Law in Japan. The results of the verification are summarized in Table 4.

Table 4. Summary of the verification results.

Scenario number	Scenario probability P_i	Allocated $R_a^D(i)$	Design fire		RSET t_{SET} (s)	HRR at t_{SET} (kW)	Smoke layer height at t_{SET}	Smoke exhaust rate (m^3/min)	
			a_D	Q_{max}				room	corridor
F08	0.00422	0	-	391	540	391	2.02	-	-
F12-1	0.00319	0	-	4,565	287	4,565	1.89	277	-
F11-2	0.001284	0	-	9,130	246	9,130	(1.72)	477	277
F12-2	0.0009	0.042795	Calculations for verification exempted						
F11-3	0.00128	0.0998	0.0267	-	451	5,418	(1.77)	516	400
F12-3	0.00014	0.042795	Calculations for verification exempted						
F16-1	0.00035	0	-	4,565	287	4,565	1.89	-	-
F15-2	0.00089	0	-	9,130	246	9,130	(1.72)	-	299
F16-2	0.00010	0.0295245	Calculations for verification exempted						
F15-3	0.00010	0.042795							
F16-3	0.00014	0.042795							

CONCLUSION

The concept and methodology of R-B ESDM was proposed to construct the framework for objectively providing design fires and scenarios to P-B FSD. The main factors of this method are acceptable evacuation risk, probabilistic distribution of fire growth factor, scenario event tree based on the success/failure of fire safety systems and the allocation of acceptable risk to scenarios in the event tree. The practicability of R-B ESDM in P-B FSD was demonstrated by example applications to realistic building situations. It is thought that R-B ESDM also help recognize the meaning of the redundancy of fire safety systems in evacuation safety during fire.

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ANNEX: SIMPLE CALCULATION FORMULAE FOR ROOM EVACUATION

In P-B FSD practices, it is necessary to verify the safety for all the critical scenarios in fire. The verifications are not always necessary to be very accurate but enough to be on the safer side. Since a considerable number of scenarios are involved, simple calculation methods are valuable to efficiently conduct the verification work. Also, the advantage of simple calculation formulas in FSD practices is that their parameters can allow fire safety engineers to draw quick insights on what happens when conditions in a building are changed. In this paper, only simple calculation methods were used for the floor evacuation case study too, here only the formulas used for room evacuation are listed due to the page limitation.

Although the concept of RSET and ASET is not always convenient, the room evacuation safety is verified based on this concept since it is most familiar among most of fire safety engineers. The calculations of RSET and ASET are relatively easy when smoke control is neglected.

Required Safe Evacuation Time

If room evacuation starts simultaneously, the evacuation time is nearly determined either by the travel time of the occupants at the remotest location from exits or the time of termination of the queue at exits.

$$t_{RSE} = \max\left(\frac{l_{\max}}{v}, \frac{q_0 A}{1.5B}\right) \tag{A1}$$

where l_{max} = maximum travel distance to exit (m), v = travel velocity of occupants (m/s), q_0 = occupant load density (person/m^2), A= room floor area (m^2), B = exit door width (m).

Available Safe Evacuation Time

Here, taking the smoke layer height as the measure for the hazard level of the fire environment, it is assumed that occupants start to evacuate when smoke layer descends to a certain height [10].

- for fire source with HRR = $\dot{Q}_{\max}$

$$t_{ASE} = \frac{3}{2}\frac{\rho_{smoke}}{C_m \dot{Q}_{\max}^{1/3}}\left(\frac{1}{z_{crit}^{2/3}} - \frac{1}{z_{start}^{2/3}}\right)A \tag{A2}$$

- for fire source with HRR = $\alpha_D t^2$

$$t_{ASE} = t_{crit} - t_{start} \tag{A3}$$

where

$$\begin{aligned} t_{start} &= \left\{\frac{5}{2}\cdot\frac{\rho_{smoke}}{C_m \alpha_D^{1/5}}\left(\frac{1}{z_{start}^{2/3}} - \frac{1}{H_R^{2/3}}\right)\right\}^{3/5} A^{3/5} \\ t_{crit} &= \left\{\frac{5}{2}\cdot\frac{\rho_{smoke}}{C_m \alpha_D^{1/5}}\left(\frac{1}{z_{crit}^{2/3}} - \frac{1}{H_R^{2/3}}\right)\right\}^{3/5} A^{3/5} \end{aligned} \tag{A4}$$

and z_{start} = smoke layer height when occupants start to evacuate (m), z_{crit} = critical smoke layer height (m), H_R = room ceiling height (m), ρ_{smoke} = smoke layer density (kg/m^3) and C_m = coefficient of plume flow rate equation.

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