## Required Travel Distance and Exit Width for Rooms Determined by Risk-Based Evacuation Safety Design Method

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## ABSTRACT

Introducing fire risk concept in performance-based fire safety design of building is beneficial in many aspects of evacuation safety. In this study, the risk-based evacuation safety design method developed based on fire risk concept was applied to simplify the procedure of performance-based evacuation safety verification of rooms of which the fire risk is relatively low. The critical travel distance to room exit and required exit width derived from this method are found to be dependent on room area but the critical travel distance becomes to be relatively insensitive to room area as the area increase. The particular advantage of this method is that engineers can easily develop the evacuation safety standards for safe room evacuation and designers can check the evacuation safety performance of a large number of rooms in a building efficiently using the developed standards. The comparison of the derived standards for travel distance and exit width with the travel distances and exit widths in actual building rooms revealed that the method in this paper is reasonable and practicable in actual verification practices of evacuation safety of rooms.

**KEYWORDS:** performance based design, evacuation risk in fire, simple verification of room evacuation, standard of evacuation safety design

## NOMENCLATURE LISTING

$A \\ A_p \\ B \\ B_{crit} \\ C_{cas} \\ C_i \\ C_o \\ l \\ l_{crit}$	room area $(m^2)$ parent room area $(m^2)$ exit width $(m)$ required exit width $(m)$ casualty toll per hazardous fire (persons/fire) consequence in scenario <i>i</i> (persons) initial number of occupants (persons) travel distance to room exit $(m)$ critical travel distance $(m)$	$R^{D}_{A}$ t $t_{ASE}$ $t_{RSE}$ $t_{s}$ $t_{start}$ v	design-based acceptable evacuation risk (persons/fire) time (s) critical evacuation time (s) required evacuation time (s) smoke filling time (s) evacuation starting time (s) travel speed of occupants (m/s)
$N$ $q$ $p_{cas}$ $P_{hf}$ $P_{i}$ $Q_{f}$ $R^{D}$	exit flow factor (= 1.5 person/m/s) occupant density (persons/m <sup>2</sup> ) probability of casualty occurrence probability of hazardous fire occurrence (fire/m <sup>2</sup> year) probability of scenario <i>i</i> to occur heat release rate (kW) design-based evacuation risk (person/fire)	Greek $\alpha$ $\alpha_D$ subsc A crit super D	fire growth factor (kW/s <sup>2</sup> ) fire growth factor for design (kW/s <sup>2</sup> ) ripts acceptable critical scripts Design based

## INTRODUCTION

Existing prescriptive building codes place greater emphasis on fire safety provisions (e.g., smoke exhaust systems or fire escape stairs) for larger buildings with a greater number of occupants than for smaller buildings with fewer occupants. This implies that the existing prescriptive codes intend to control the probability of occurrence of severe fire events according the degree of impact of such an event. In other words, the consideration for fire risk control is embedded in the existing prescriptive codes, albeit

implicitly and empirically. In Japan, a performance-based evacuation safety verification method was introduced by the amendment of the Building Standard Law (BSL) in 2000, aiming to provide greater flexibility in building design and clarity in building regulatory systems [1]. However, a serious drawback of the evacuation safety verification method is that it does not consider the fire risk aspect, which is incorporated into the prescriptive provisions in the BSL. The design fires are prescribed, regardless of the size of the space and occupant load, i.e., regardless of the potential consequences. This also means that the stages of evacuation, i.e., (1) room evacuation, (2) floor evacuation, and (3) building evacuation, under the performance-based fire safety design method in the BSL are treated equally in the evacuation safety verification method. However, in a high-rise office building, the safety of staircases, which would be used by all the occupants of the building in the event of a fire, is obviously most important, followed by the safety of common escape routes such as corridors, which would be used by all the occupants of a floor. On the other hand, the importance of room evacuation routes is relatively low considering the occupant load and the probability of a fire occurring in a particular room.

There is tremendous number of rooms in a large building and the rooms are frequently changed with time due to many reasons, e.g., change of tenants, change of business environment. It is necessary to establish an efficient method for verifying the evacuation safety of rooms in order to reduce the workload of building designers and fire safety engineers and thus enable them to devote greater efforts toward floor and the whole building so as to enhance the safety of building evacuation routes and staircases.

Although fire risk assessment methods have been discussed by many researchers [2], they have hardly been applied in real designs of the evacuation safety by now, partly because the concept accepting certain number of casualties as a risk may not fit comfortably in the expressions in a law, and also because the acceptable level of risk is seldom clarified.

To address the abovementioned problems, we have proposed a performance-based (P-B) fire safety design (FSD) method based on risk concept named Risk-based Evacuation Safety Design Method (R-B ESDM), whereby the design fires and scenarios are systematically determined for the verification of evacuation safety of building spaces by using the value of the evacuation risk based on building use and scale [3-7]. In the R-B ESDM, the evacuation risk in the event of a fire in the context of P-B FSD is defined as an expected number of casualties exposed to smoke. If it is verified that no casualty occurs under the design fire selected under this method, the evacuation risk is automatically controlled below the acceptable level. In this paper, the design fires selected on the basis of the R-B ESDM are applied to the evacuation safety of rooms is approved, in terms of required travel distance and exit width. In addition, the conditions for evacuation safety design derived by the R-B ESDM are compared to those of the rooms in an actual office and mercantile occupancy building to determine the practicability with regard to the evacuation safety standards.

## CONCEPT OF RISK-BASED EVACUATION SAFETY DESIGN METHOD

#### **Procedure of Fire Safety Verification**

The purpose of the R-B ESDM is to control the design-based evacuation risk for the object building within the design-based acceptable evacuation risk. The R-B ESDM assumes that evacuation safety verification is conducted according to the usual P-B FSD procedure, as illustrated in Fig. 1. The R-B ESDM is different from the current P-B FSD in that the design fires and scenarios to be checked are systematically selected. The primary components of the R-B ESDM include: (1) acceptable evacuation risk in the context of FSD, (2) design fire with variable fire growth factor, and (3) scenario event tree, established based on the success or failure of the fire safety system. In the R-B ESDM, the design fire growth factor,  $\alpha_D$  is selected by considering the probability density function of the fire growth factor,  $\alpha$ , and the acceptable evacuation risk in each scenario. When no casualty occurs under the design fire,  $Q_f$ , it is verified that the evacuation risk for scenario is below the acceptable value.

$$Q_f = \alpha_D t^2$$

(1)



Fig. 1. Procedure of risk-based evacuation safety design method.

## **Definition of Evacuation Risk**

The evacuation risk in the R-B ESDM is defined as the products of the probability of fire occurrence and the number of casualties exposed to smoke under the fire. According to the concept that the evacuation risk of an arbitrary space of a building is controlled within the acceptable risk,  $R_A$ ,

$$P_{hf}(K)A(K)C_{cas}(K) \le R_A = P_{hf}(DH)A(DH)C_{cas}(DH)$$
<sup>(2)</sup>

We have tried to determine  $R_A$  by using the statistical data. Although there is room for argument regarding the acceptable evacuation risk, we assume the current risk of general dwelling as in Eq. 2. Using Eq. 2, we have proposed the acceptable evacuation risk in the context of the R-B ESDM,  $R_A^D(K)$ , for the arbitrary space. The  $R_A^D$  for arbitrary space K is given as [8]:

$$R_{A}^{D}(K) = 1.1 \times P_{hf}^{*}(K) \times 125 / A(K) \left[ = C_{cas}(DH) \left\{ P_{hf}(DH) / P_{hf}(K) \right\} \left\{ A(DH) / A(K) \right\} \right]$$
(3)

where  $P_{hj}^*$  is the ratio of the probability of the occurrence of a hazardous fire per unit area of the occupancy type of space *K* relative to that of the dwelling. The 125 on the right-hand side in Eq. 3 is the average area and 1.1 is the design-based casualty toll per hazardous fire in the dwelling. Although the casualty toll per hazardous fire obtained from the statistical data is 0.3 persons/hazardous fire, the value is modified to the design-based value, replacing the average occupant density with that prescribed in the P-B evacuation safety design [8]. The ratios of hazardous fire occurrence per floor area of typical building types are obtained by using the national building fire data from the Fire and Disaster Management Agency. Ratios of the occurrence of hazardous fires are shown in Table 1.

Ratio $P_{hf}^{a}$	Theater	Restaurant	Retail Shop	Hotel	Apartment building	Hospital	School	Office	Dwelling
$\frac{P_{hf}(DH)}{P_{hf}(K)}$	1.2	0.5	7.2	3.1	1.5	9.0	9.7	4.1	1.0

Table 1. Ratios of the occurrence of hazardous fire by unit floor area for different occupancies.

<sup>a</sup>*DH* : dwelling; *K* : arbitrary occupancy.

The  $C_{cas}$  of Eq. 2 may be rewritten as the product of the ratio of occupants who fail to evacuate safely, i.e.,  $C_{cas} = p_{cas}C_{\theta}$ . Therefore, by using Eq. 2, the screening room area,  $A_{sc}$ , for which the evacuation risk is obviously lower than the acceptable evacuation risk can be obtained as

$$A_{sc}(K) = \sqrt{\frac{p_{cas}(DH)}{p_{cas}(K)}} \frac{q(DH)}{q(K)} P_{hf}^{*} A(DH) \quad \left[ = 125 \sqrt{\frac{0.14}{p_{cas}(K)}} \frac{0.06}{q(K)} P_{hf}^{*} \right]$$
(4)

where 0.14 is used for  $p_{cas}(DH)$  in dwellings, which was obtained from a past study [8]. There is rarely a case in which all occupants of a fire room die in actual fires, i.e.,  $p_{cas}(K) = 1.0$ . Nevertheless, the extreme example assumes that all occupants fail to evacuate for other occupancies; thus, using the hazardous fire occurrence ratio  $P_{hf}^*$  in Table 2, we can calculate  $A_{sc}$  as shown in the first row of Table 2. The number of occupants is estimated by the occupant density, q, set forth in the BSL for the evacuation safety verification method, which is also shown in Table 2. It may appear that the areas that can be screened out are too small for most occupancies. This is attributable to the extreme assumption that  $p_{cas} = 1.0$ . Usually, the dwelling is the occupancy whose  $p_{cas}$  is the highest. The screening areas calculated by using  $p_{cas}(K) = 0.14$  of the dwelling are also shown in Table 2. In such a room, because the evacuation risk is evidently lower than the acceptable evacuation risk, there is no need for any particular verification of the evacuation safety; it is only necessary to check the room area. Therefore, a room that is larger than  $A_{sc}$  needs to be assessed for evacuation safety.

Occupancy	Theater	Restaurant	Retail Shop	Hotel	Apartment building	Hospital	School	Office	Dwelling
$p_{cas}(K)$	(q=1.5)	(q=0.7)	(q=0.5)	(q=0.16)	(q=0.06)	(q=0.125)	(q=0.7)	(q=0.125)	(q=0.06)
1.0	10	10	43	50	57	97	43	65	47
0.14	28	26	116	134	152	260	114	175	125
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Table 2. Room areas for which the evacuation risk is below the acceptable evacuation risk,  $A_{sc}^{a}$ .

<sup>a</sup>Units:  $A_{sc}$  (m<sup>2</sup>), q (persons/m<sup>2</sup>).

#### Fire Scenario Based on Success or Failure of Fire Protection System

The fire spread for evacuation varies, depending on whether or not the fire protection systems function. However, only the worst cases are considered in P-B FSD. Multiple scenarios considering the success or failure of the equipment for fire protection are evaluated in this method as shown in Fig. 2.



Fig. 2. Scenario event tree constructed based on success or failure of sprinkler system and smoke control system.

Moreover, the design-based evacuation risk,  $R^D$ , is defined as the sum of  $P_i$  and  $C_i$  in the arbitrary fire scenario, *i*, obtained for the event trees developed based on the success or failure of the equipment for fire protection, as shown in Eq. 5:

$$R^D = \sum P_i C_i \tag{5}$$

In the R-B ESDM, safety criteria to verify the evacuation safety in buildings are set at a strict level, such as "not exposed" or "only slightly exposed" to smoke. The purpose of the R-B ESDM is to control  $R^D$  for the object building within the design-based acceptable evacuation risk,  $R_A^D$ , as shown in Eq. 6:

$$R^D \le R^D_A \tag{6}$$

#### **Design Fire Growth Factor**

The fire growth factor,  $\alpha$  [9], is regarded as the probability variable in this paper, because in a real fire, its distribution depends on various factors, e.g., the location, material property, and quantity of the fire source and the manner of ignitions. The design fire growth factor,  $\alpha_D$ , can be obtained by solving Eq. 7, considering the number of occupants in the room,  $C_0$  (= qA), and  $R_A^D$  obtained by Eq. 3:

$$\int_{\alpha_D}^{\infty} f(\alpha) d\alpha = \frac{R_A^D}{C_0} \left( = \frac{R_A^D}{qA} \right)$$
(7)

where  $f(\alpha)$  is the probability density function of  $\alpha$ . The  $\alpha_D$  is dependent upon room area, A, because  $R_A^D/C_0$  is a function of A. In Eq. 7, because the fire equipment is not considered, the probability of the scenario is equal to 1. The concepts of Eq. 7 is explored in some references ([3–5, 9]) and [ANNEX-A]. The  $f(\alpha)$  is modeled as a lognormal distribution, defined as in Eqs. 8–10 based on the distribution of  $\alpha$ , estimated from the statistical data from the fire report of National Fire Defense Agency for fire statistics, as shown in Fig. 3 [9]:

$$f(\alpha) = \frac{1}{\sqrt{2\pi}\zeta\alpha} \exp\left[\frac{-\left\{\log(\alpha) - \lambda\right\}^2}{2\varsigma^2}\right]$$
(8)

$$\lambda = \ln \mu - \frac{1}{2}\varsigma^2 \tag{9}$$

$$\varsigma^2 = \ln\left(1 + \frac{\sigma^2}{\mu^2}\right) \tag{10}$$

where  $\mu$  is mean,  $\sigma$  is standard deviation,  $\lambda$  is mean of logarithmic normal distribution, and  $\zeta$  is standard deviation of logarithmic normal distribution, of which the values are shown for the occupancies of a retail shop and an office.



Fig. 3. Distribution of fire growth factor [9].

Determining  $f(\alpha)$  by inserting  $\mu$  and  $\sigma$  in Fig. 3 into Eqs. 9 and 10, Eq. 7 can be solved for  $\alpha_D$ . The  $\alpha_D$  for the retail shop and the office building is shown as a function of room area in Fig. 4. As Fig. 4 indicates,  $\alpha_D$  becomes large as the area of room increases, because it is assumed that the hazardous fire occurrence probability increases in proportion to the area of the room, and accordingly, the evacuation risk increases.

The starting point of  $\alpha_D$  does not correspond with 0 m<sup>2</sup> in Fig. 4 because the evacuation risk does not exceed the acceptable evacuation risk in small rooms, even if all occupants fail to evacuate.



Fig. 4. Design fire growth factor versus floor area.

# SIMPLE FORMULAS FOR VERIFYING ROOM EVACUATION SAFETY (CRITICAL TRAVEL DISTANCE AND REQUIRED EXIT WIDTH)

#### **Derivation of Basic Formula**

Because virtually no provision for evacuation safety is imposed in usual dwellings, the safety verification of room evacuation should be considerably simplified for small rooms in a building, because the evacuation risk attributable to the occurrence of fire in a small room is often extremely low. For this purpose, we propose a calculation method that explicitly estimates the critical travel distance and the required exit width, which can allow occupants to exit a room without being exposed to smoke under the determined design fire.

The room evacuation safety is verified based on the concept of RSET and ASET, because it is the most familiar among most fire safety engineers. We verify that the evacuation time,  $t_{RSE}$ , is below the critical evacuation time,  $t_{ASE}$ , as shown in Eq. 11:

$$t_{RSE} \le t_{ASE} \tag{11}$$

The  $t_{RSE}$  is determined either by the travel time of the occupant from the remotest location to exits or the time of queuing at exits. Therefore  $t_{RSE}$  is given as follows:

$$t_{RSE} = \max\left(\frac{l}{v}, \frac{qA}{NB}\right)$$

$$(12)$$

$$\frac{Z_{start}}{T_{crit}} \quad t_{s}$$

$$\frac{L}{v} \quad t_{RSE}$$

$$t_{RSE}$$

Fig. 5. Description of  $t_{ASE}$  and  $t_{RSE}$ .

The  $t_{ASE}$  is the difference between the critical evacuation time,  $t_s$ , and the evacuation starting time,  $t_{start}$ , as follows:

$$t_{ASE} = t_s - t_{start} \tag{13}$$

Equation 14 is obtained by substituting Eqs. 12 and 13 into Eq. 11.

$$\max\{l/\nu, qA/(NB)\} \le t_s - t_{start}$$
<sup>(14)</sup>

Here,  $t_s$  and  $t_{start}$  are calculated based on the smoke height. The  $t_{start}$  assumes that occupants start to egress when the smoke layer descends to a certain height ( $Z_{start}$ [= 90 % of the ceiling height m]) [10]. The  $t_s$  is the time when the smoke layer descends to a height that is hazardous to occupants ( $Z_{crit}$ [=1.8 m]). Both  $t_{start}$  and  $t_s$  are calculated by using a generally used smoke filling formula for a time-squared fire. Applying the fire given by Eq. 1, we obtain [5, 11, 12]:

$$t_{start} = \left\{ \frac{5}{2} \cdot \frac{x_s \rho_s A_p}{C_m \alpha_D^{1/3}} \left( \frac{1}{Z_{start}^{2/3}} - \frac{1}{H^{2/3}} \right) \right\}^{3/5}$$
(15)

$$t_{s} = \left\{ \frac{5}{2} \cdot \frac{x_{s} \rho_{s} A_{p}}{C_{m} \alpha_{D}^{1/3}} \left( \frac{1}{Z_{crit}^{2/3}} - \frac{1}{H^{2/3}} \right) \right\}$$
(16)

where *H* is room ceiling height (m),  $\rho_s$  is smoke layer density (= 1.0 kg/m<sup>3</sup>),  $x_s$  is the adjustment coefficient of smoke layer density, and  $C_m$  is the coefficient of the plume flow rate equation (kg/kJ<sup>1/3</sup>/m<sup>5/3</sup>/s<sup>2/3</sup>).

Moreover, in actual office rooms, many rooms are often arranged within a tenant area for various purposes, e.g., meeting rooms and executive office rooms. In the event of fire, the occupants in such a room have to evacuate through the room that connects to a corridor with an exit. Here, let us call the room connecting to the corridor the "parent room" (Fig. 6). In this case, the conditions of a tenant area for evacuation safety are calculated by substituting the area of a parent room (m<sup>2</sup>),  $A_p$ , in Eqs. 15 and 16, when a fire occurs in a parent room.

When simple calculation formulas are used to estimate  $t_s$ , the density of the smoke layer is often assumed as constant (1.0 kg/m<sup>3</sup>) and the distance from the virtual point heat source is neglected. However, in a room with a large floor area, smoke filling takes considerable time, during which the temperature of the smoke layer may rise considerably because of the increase of the heat release rate with time so that the change of smoke density becomes no longer negligible. Therefore, we introduce the adjustment coefficient of smoke layer density,  $x_s$ , in Eqs. 15 and 16, which is calculated as shown in ANNEX-B.



Fig. 6. Definition of smoke filling an area.

From Eq. 14, two critical conditions for safe evacuation can be derived: (1) critical travel distance to the room exit and (2) required exit width, as described in the following.

(1) Critical travel distance,  $l_{crit}$ 

Invoking the travel time from the remotest position to the exit,  $l/v \le t_s - t_{start}$ ,

the critical travel distance,  $l_{crit}$ , is expressed as

$$l_{crit} = (t_s - t_{start})v \tag{17}$$

Therefore,  $l_{crit}$  is obtained by substituting Eqs. 15 and 16 into Eq. 17 as

$$l_{crit} = \left(\frac{5}{2C_m}\right)^{3/5} \left\{ \left(\frac{1}{Z_{crit}^{2/3}} - \frac{1}{H^{2/3}}\right)^{3/5} - \left(\frac{1}{Z_{start}^{2/3}} - \frac{1}{H^{2/3}}\right)^{3/5} \right\} \left\{ \frac{\left(x_s \rho_s A_p\right)^{3/5}}{\alpha_D^{1/5}} \right\} v$$

$$= 8.1 \left\{ \left(\frac{1}{Z_{crit}^{2/3}} - \frac{1}{H^{2/3}}\right)^{3/5} - \left(\frac{1}{Z_{start}^{2/3}} - \frac{1}{H^{2/3}}\right)^{3/5} \right\} \left\{ \frac{\left(x_s \rho_s A_p\right)^{3/5}}{\alpha_D^{1/5}} \right\} v = M K_1 A_p^{3/5}$$
(18)

where M and  $K_l$  are given by Eqs. 19 and 20, respectively, as follow:

$$M = 8.1 \left\{ \left( \frac{1}{Z_{crit}^{2/3}} - \frac{1}{H^{2/3}} \right)^{3/5} - \left( \frac{1}{Z_{start}^{2/3}} - \frac{1}{H^{2/3}} \right)^{3/5} \right\}$$
(19)

$$K_{l} = v \frac{(x_{s} \rho_{s})^{3/5}}{\alpha_{D}^{1/5}}$$
(20)

(2) Required exit width,  $B_{crit}$ 

Invoking queuing time at the exit,  $B_{crit}$  is also calculated as follows:

$$B_{crit} = \frac{qA}{N(t_s - t_{start})}$$
(21)

$$B_{crit} = \frac{qA}{NM} \frac{\alpha_D^{1/5}}{(x_s \rho_s A_p)^{3/5}} = \frac{K_B}{M} \frac{A}{A_p^{3/5}}$$
(22)

where  $K_B$  is given by Eq. 23 and M is given by Eq. 19:

$$K_{B} = \frac{q \alpha_{D}^{1/5}}{N(x_{s} \rho_{s})^{3/5}}$$
(23)

when a room is not divided, Eqs. 18 and 22 can be transformed as follows:

$$l_{crit} = MK_l A^{3/5}, \ B_{crit} = \frac{K_B}{M} A^{2/5}$$
 (24)

# CALCULATION RESULTS OF CRITICAL TRAVEL DISTANCE AND REQUIRED EXIT WIDTH

The critical travel distance and the required exit width in the room obtained by this verification method are compared with those from the provision of the BSL.

In the BSL, there is no standard for restricting  $l_{crit}$  and  $B_{crit}$  in a room, although there is a limitation of maximum travel distance from the exit to the outdoors or to the evacuation stair. However, the limit value is constant, indifferent to room area. For example, the travel distance to the stairs in a retail shop is restricted to 40 m when a principal structure involves semi-fireproof construction or the interior finish material is inflammable and to 50 m when the interior finishing material is nonflammable. On the other hand, the exit width to the stairs must be 0.27 m or more per 100 m<sup>2</sup> of area on each floor above ground level in the case of retail shops.

Figure 7 shows the relation of  $l_{crit}$  and A of a retail shop and an office for the cases in which the ceiling heights are 2.4 m and 3.0 m; the calculations were made by Eq. 24 using v = 1.0 m/s for a retail shop and v = 1.3 m/s for an office room. Moreover, the travel distance limits to the escape stairs (40 and 50 m) prescribed in the BSL provision are shown in Fig. 7.

The limits of the travel distances in the BSL vary with the fire rating of the structure and lining, but are constant, indifferent to the area of the room. Fig. 7 shows that the calculation results of critical travel distance with this method tend to be approximately constant for the area at 500 m<sup>2</sup> or more. In the retail shop, the  $l_{crit}$  for H = 2.4 m of the BSL does not meet the  $l_{crit}$  derived from this method, as shown in Fig. 7(a). In the office building, the  $l_{crit}$  for room ceiling height H = 2.4 m is comparable to the  $l_{crit}$  of BSL, 50 m for A = 500 m<sup>2</sup> or more.



Fig. 7. Comparison of critical travel distance between this method and the BSL.

Figure 8 shows the relation of exit width,  $B_{crit}$ , calculated by Eq. 24 as a function of the room area, A, in which N = 1.5 persons/m/s is used. Figure 8(a) shows the required exit widths for the rooms of the retail shop, with ceiling height H = 2.4 and 3.0 m. The widths of exits to the evacuation stairs prescribed in the BSL, 0.27 m/100 m<sup>2</sup>, are also shown in Fig. 8(a). The  $B_{crit}$  required in the provisions of the BSL is the smallest among the required exit widths in Fig. 8(a), so the demand of the BSL is much looser than the  $B_{crit}$ derived by this method. If we convert the  $B_{crit}$  in Fig. 8(a) to the required exit width per occupant by using the occupant density given in the evacuation safety verification method of the BSL, 0.5 person/ $m^2$ , the values become approximately 1.9, 1.0, and 0.54 cm per person for H = 2.4 m, H = 3.0 m, and the BSL provision, respectively. Because similar codes in many countries require approximately 0.8-1.0 cm/person, the calculated required exit width for H=3.0 m, 1.0 cm/person, is approximately equivalent to the international average, and the width prescribed by the BSL may be too small, if the occupant density, 0.5 person/ $m^2$ , is not an overestimation. Figure 8(b) shows the required exit width for office rooms with ceiling height H = 2.4 and 3.0 m. If the values are again converted to the widths per person, the values are approximately 0.8 and 1.6 cm per person for the ceiling heights H = 2.4 and 3.0 m. The 0.8 cm/person for H = 2.4 is equivalent to the international average. From the previously shown comparisons of the critical travel distances and required exit widths, it may be suggested that the maximum travel distance in the BSL should be less restrictive and that the required exit width in the BSL should be more demanding.



Fig. 8. Relation between required exit width and room area.

#### Comparison of Conditions between This Method and Actual Buildings

Figures 9 and 10 show comparisons of the conditions for this method and those in actual buildings where the fire safety designs have been evaluated by the current evacuation safety verification method of the BSL. The number of rooms investigated in actual buildings includes 273 retail shops and 81 offices for the area, the travel distance, the exit width, and the ratio of the parent room,  $A_p$ , to A. The percentages that the ratio of the parent room is less than 0.5 are 1.1 % in retail shops and 30.9 % in office rooms; thus, office rooms are used by dividing the parent room to make many annexed rooms. In this comparison, the rooms with typical ceiling height are considered, i.e., 2.8 and 3.5 m for retail shops and 2.6 and 3.0 m for office rooms. However,  $l_{crit}$  and  $B_{crit}$  are not considered in the ratio of the parent room.







Fig. 10. Comparison between  $B_{crit}$  of this method and exit width of actual buildings.

In both occupancies, the travel distances of actual buildings tend to increase for relatively small room areas and to be constant from approximately 500 m<sup>2</sup>, just like the  $l_{crit}$  of this method. However, the  $l_{crit}$  calculated in this study is larger than the actual travel distances. This is why the actual travel distances are decided by the restriction of travel distance to the stair, based on the provision in BSL. Moreover,  $l_{crit}$  is not considered about the ratio of the parent room.

In actual retail shops, the trend that the exit width is proportional to A is shown in Fig. 10(a). The exit widths of actual retail shops tend to be close to the  $B_{crit}$ , except for some small rooms, whereas there are only small numbers of rooms that do not satisfy  $B_{crit}$ . The lower limit of  $B_{crit}$  is regarded as the BLT. On the other hand, the exit widths of actual office rooms are much wider than the required exit width,  $B_{crit}$ , and scatter widely, as shown in Fig. 10(b).

As shown in Figs. 9 and 10, the overall tendencies of travel distances and exit widths in rooms of actual building are that they can reasonably clear the proposed levels based on the method in this paper. This implies that the proposed critical travel distance and required exit width can be accepted without pains to the owners, users, or designers. Considering that the function of any standards for the fire safety of buildings is to reject extraordinarily unsafe building features, the proposed method for critical travel distance and required exit is assessed to be reasonable.

## CONCLUSION

We proposed a method for calculating the critical travel distance and required exit width to evacuate without exposing occupants to smoke in a room based on the R-B ESDM. The effects of the difference between building occupancy and the ceiling height of the room were assessed. The standards for evacuation safety design using this method were compared with the prescriptive provisions of the BSL. In addition, the travel distance to exits and exit widths of the rooms in the actual buildings designed by using the evacuation safety verification method were compared with the proposed standards. Accordingly, the following results were obtained.

- Because the design fire growth factors are determined according to the evacuation risk reflecting room area, reasonable standards can be derived for critical travel distances to exits and required exit widths.
- The critical travel distance according to this method depends on room area, but becomes relatively insensitive when the room area is 500m<sup>2</sup> or larger. On the other hand, the required exit width is proportional to room area, as in the case of the BSL provision.
- Compared with the BSL, the critical travel distance in this method tends to be easier, whereas the required exit width is more severe.
- The ceiling height has a significant effect on the critical travel distance and the required exit width in this method.
- It is possible to develop simple verification standards for the evacuation safety of rooms by using this method so that verification of the evacuation safety of rooms can be efficiently conducted, including when the layout of a room is changed from the original.

Finally, this method can be applied when a sprinkler system is taken into account for evacuation safety, although this paper only dealt with non-sprinkler situations.

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## ANNEX-A:

The conceptual distribution of the fire growth factor,  $\alpha$ , and between the number of casualties and  $\alpha$ , is also illustrated on the left-hand side of Fig. A1. Here,  $\alpha$  is described as a stochastic variable. To determine the shape of distribution for  $\alpha$ , an analysis was performed, Deguchi [9], which was modeled as logarithmic normal distribution. Although no occupant will be injured during a small  $\alpha$ , casualties will begin to occur at the instant of a certain level,  $\alpha_D$ . Although it is though that casualties actually increase gradually under  $\alpha_D$  or more, the shape of the distribution for C ( $\alpha$ ) is unknown. It is assumed that all occupants ( $C = C_0$ ) cannot

evacuate safely at  $\alpha_D$  or more, because the maximum number of casualties is  $C_0$ . Hence, the evacuation risk can be represented as a function of the fire growth factor. The threshold value of  $\alpha_D$  that satisfies Eq. 6 can be obtained by solving Eq. 7.



Fig. A1. Conceptual relation among  $f(\alpha)$ ,  $C(\alpha)$ , and  $\alpha$ .

# ANNEX-B: CALCULATION METHOD FOR ADJUSTMENT COEFFICIENT OF SMOKE LAYER DENSITY

The simple prediction equations for smoke filling time for  $t^2$  fire, Eqs. 15 and 16, are provided as practical fire safety engineering tools [10, 11]. In this study, the smoke layer density of Eqs. 15 and 16 are slightly modified to take into account of the change of smoke layer densities and the distance of virtual point heat source due to the increase of HRR during smoke filling in terms of the adjustment coefficient of smoke layer density,  $x_s$ , determined by the calculation method shown below. The calculation procedure is as follows [14]:

#### (Step 1) Calculate heat release rate of design fire and representative length of fire source

$$Q_f(t) = \alpha_D t^2 \tag{b1}$$

$$D(t) = \sqrt{Q_f(t)/q''}$$
 (b2)

where  $Q_f$  is heat release rate of design fire (kW), t is the time (s) (dt = 1),  $\alpha_D$  is fire growth coefficient of design fire (kW/s<sup>2</sup>), D is representative length of fire source (m) and q'' is fire release rate per unit floor area (kW/m<sup>2</sup>)

#### (Step 2) Calculate virtual point of heat source distance and flow rate of fire plume

$$z_0(t) = 1.02D(t) - 0.083Q_f(t)^{2/5}$$
(b3)

$$m_p(t) = C_m Q_f(t)^{1/3} \left\{ Z(t-1) + z_0(t) \right\}^{5/3}$$
(b4)

where  $z_0$  is virtual point of heat source distance (m),  $m_p$  is flow rate of fire plume (kg/s),  $C_m$  is plume coefficient (=0.076 kg/kJ<sup>1/3</sup>/m<sup>5/3</sup>/s<sup>2/3</sup>) and Z is smoke layer height (m)

#### (Step 3) Calculate wall area which is exposed to smoke layer

$$A_{w}(t) = A + L_{w}\{H - Z(t-1)\}$$
(b5)

where  $A_w$  is wall surface area which is exposed to smoke layer (m<sup>2</sup>), A is floor area (m<sup>2</sup>),  $L_w$  is perimeter of wall (=4 $\sqrt{A}$ ) (m) and H is ceiling height (m)

(Step 4) Calculate smoke layer temperature, smoke layer density and smoke layer height

$$T_{s}(t) = T_{s}(t-1) + \frac{Q_{f}(t) - c_{p}m_{p}(t)(T_{s}(t-1) - T_{0}) - h_{k}A_{w}(t)(T_{s}(t-1) - T_{0})}{c_{p}\rho_{s}(t-1)A(H - Z(t-1))}\Delta t$$
(b6)

$$\rho_s(t) = 353/T_s(t) \tag{b7}$$

$$Z(t) = Z(t-1) - \frac{1}{A} \left[ \frac{Q_f(t) - h_k A_w(t) (T_s(t) - T_0)}{c_p \rho_0 T_0} + \frac{m_p(t)}{\rho_0} \right] \Delta t$$
(b8)

where  $T_s$  is smoke layer temperature (K),  $T_0$  is ambient temperature (=293 K),  $h_k$  is effective heat transfer (=0.015 kJ/K.m<sup>2</sup>),  $\rho_s$  is smoke layer density (kg/m<sup>3</sup>) and  $\rho_0$  is ambient density (kg/m<sup>3</sup>)

#### (Step 5) Calculate available safe evacuation time by computer model, from Step1 to Step 4

$$t_{ASE(com)} = t_{(Z=Z_{ot})} - t_{(Z=Z_{stat})}$$
(b9)

where  $t_{ASE(com)}$  is available safe evacuation time calculated by computer model,  $t_{(Z=Hlim)}$  is smoke filling time to the critical smoke layer height,  $Z_{crit}$  (=1.8m), and  $t_{(Z=Zstart)}$  is smoke filling time to the smoke layer height at which occupants start to evacuate,  $Z_{start}$ (=0.9H)

#### (Step 6) Calculate adjustment coefficient of smoke layer density

The adjustment coefficient of smoke layer density  $x_s$  is obtained by equating the ASET,  $t_{ASE}$  by simple calculation formula and the precise computation above and solving the equation for  $x_s$ , i.e.:

$$x_{s} = \frac{2}{5} \cdot \frac{C_{m} \alpha_{D}^{1/3}}{\rho_{s} A} \cdot \left[ \frac{t_{ASE(com)}}{\left( 1/Z_{crit}^{2/3} - 1/H^{2/3} \right)^{3/5} - \left( 1/Z_{start}^{2/3} - 1/H^{2/3} \right)^{3/5}} \right]^{5/3}$$
(b10)

The results are shown in below Fig. B1 for retail shop and office occupancy with different ceiling heights. As seen in Fig. B1, the adjustment coefficient of smoke layer density  $x_s$ , decreases as room area increases but  $x_s$  is not affected by the difference in ceiling height.

This is an unexpected but very convenient feature for use in evacuation safety design practice. This interesting result is suspected to be attributed to the balance of the mass and heat that are accumulated in the smoke layer until the layer descend to the critical height (=1.8m) but we need further investigation for clearer understanding.



Fig. B1. Adjustment coefficient of smoke layer density.

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