SELECTION OF DESIGN FIRES IN EVACUATION SAFETY DESIGNS OF BUILDINGS BASED ON FIRE RISK CONCEPT

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ABSTRACT

It is necessary for sound development of performance-based fire safety design method of building to incorporate fire risk aspect into the method. Design fire scenarios and acceptable safety criteria in P-B fire safety design play the role to control fire risk of buildings within an acceptable level. However, the relationship between the fire risk and the design fires in current P-B fire safety design method has not been clarified. In this paper, an attempt was made to develop a methodology for appropriately selecting design fire for evacuation safety designs. Determination of acceptable safety criteria and selection of growth rate coefficient of heat release rate of design fire in evacuation safety designs are considered.

KEYWORDS: Risk-based fire safety design, Acceptable risk, Design fire, Fire growth coefficient

INTRODUCTION

In Japan, performance-based codes and verification methods for evacuation safety and were introduced by the amendment of the Building Standard Law in 2000 with the intention to provide more flexibility and clarity in regulatory building control system and they are now increasingly used in fire safety designs of actual buildings [1]. The verification method defines design fires and safety criteria based on which evacuation safety is verified. However, it has not incorporated fire risk concept so sometimes causes silly fire safety design practices. For example, safety of a staircase, which is vital for a large number of occupants, is treated with the same level of attention as safety of a small room with several occupants. Fire safety engineers are spending much more time for verification of small room evacuation safety than more important fire floor or whole building evacuation.

Even though implicitly, fire risk concept is prudently incorporated in existing prescriptive fire safety codes. Small facilities with insignificant occupants are imposed only light requirements or no requirement at all while requirements for large buildings are very rigorous. It is quite natural that the greater the potential consequence of an event the securer measures are taken to minimize the probability of the event to occur. Introduction of ‘design fires and safety criteria’ into P-B fire safety codes can greatly contribute to rational fire safety designs. But it is vital for sound design practices to incorporate fire risk concept into P-B fire safety codes.

EVACUATION SAFETY DESIGN AND SAFETY VERIFICATION

In this paper, we focus on the risk-based evacuation safety design of building in fire. The evacuation safety measures that are dealt with by building designers and engineers may be broadly classified into three categories by their functions, i.e. those for fire control, for smoke control and for evacuation support. Their interests are almost focused on how less expensively and quickly as well as safe effectively design these measures always considering the compromise with the needs of owners who wish to make most of the building. Needless to say, it can be a choice, and probably a good choice for them, not to provide any of such measures at all as long as the safety verification is cleared.

Fig. 1 shows usual procedure of evacuation safety verification. Under prescribed design fire conditions, behaviors of fire and occupants are predicted using appropriate calculation methods to compare with safety criteria. It will be readily understood that the more rigorous the design fire conditions the higher the fire safety level will be. But higher level of safety can seldom be attained without claiming more cost. So a certain compromise need be sought between safety level and cost. Essential role of the design fire and acceptable safety criteria in the P-B safety design method is to control fire risk of buildings within an acceptable level.

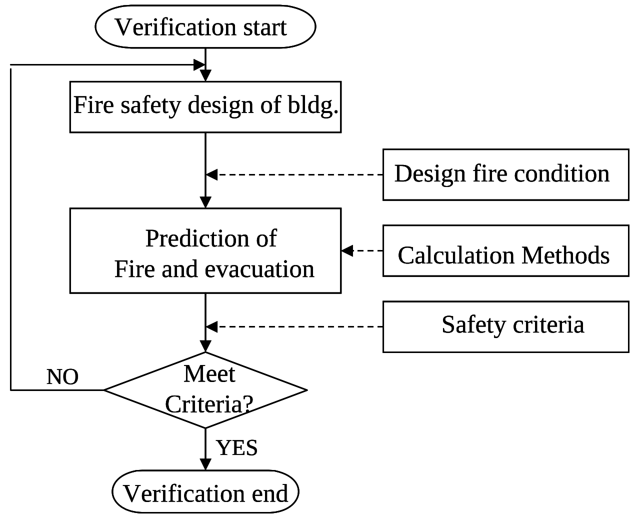

FIGURE 1. Procedure of fire safety verification

EVENT TREE OF DESIGN FIRE SCENARIOS

Event-tree is a useful tool to analyze and clarify the events involved in fire. An event tree of fire scenarios associated with evacuation from the room of origin is shown in Fig. 1, where we find the fire scenarios to be considered in the evacuation safety design are as many as 21 cases in all. Although this seems complicated, since it is up to the design if sprinkler or smoke exhaust system is equipped, actual fire scenarios for a specific building can become simpler.

The objective of developing the event tree as in Fig. 1 is to clarify the scenarios involved in evacuation safety design to control evacuation risk under an acceptable level. With the objective in mind, the definitions and qualitative analyses were made as follows:

Growing fire: Fire incidence rate differs with use and size of building. Statistically, a significant portion of fires is put out at early stage by building occupants, fire brigade etc. Although these factors need be taken into account in actual fire risk, fire safety designs are carried out on the premise that fires grow.

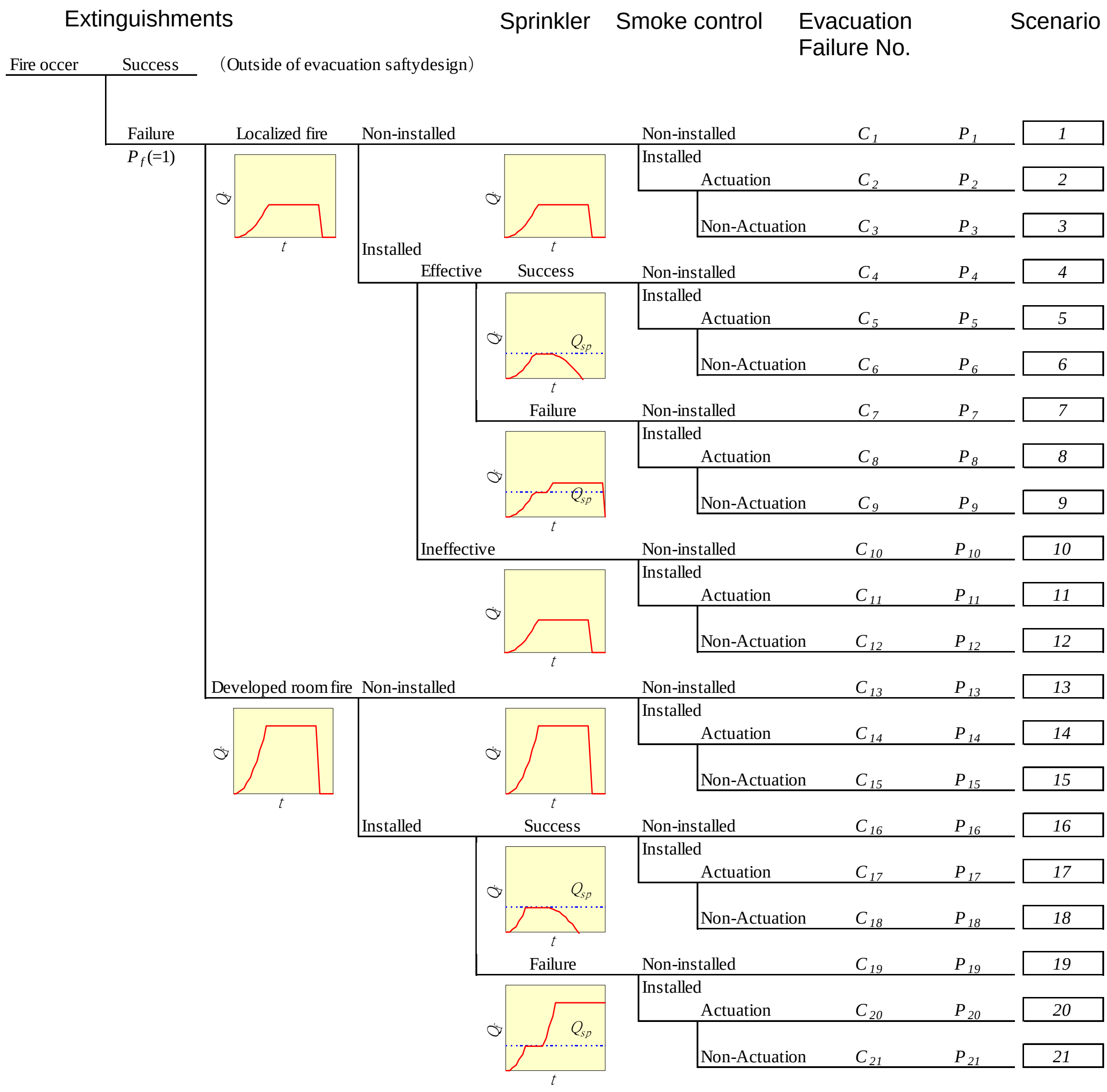

FIGURE 2. Event tree of fire scenarios in the evacuation from the room of origin

The growing fires are classified into "localized fire" and "developed room fire". In either type of fire, the heat release rate is assumed to increase proportionally to time-square in the beginning and then levels off after having reached the maximum value. The control factors of the maximum heat release rate are different.

Localized fire: Fire that occurs in a space with limited fire load density, such as in a lobby, a hall etc. The maximum heat release rate is controlled by property and dimension of burning item.
Developed room fire: Fire that occurs in a space with significant fire load density, such as in office, living room etc. The maximum heat release rate is controlled by fuel load and ventilation factor of fire room.
Fire control by Sprinkler system: Sprinkler system operates when sprinkler head has reached its actuation temperature. The minimal heat release rate that is able to actuate sprinkler head, Q_{sp}, can be estimated using established formulas [2]. Unless heat release rate of fire exceeds Q_{sp} sprinkler system will not operate. Here, as illustrated in Fig. 3, the heat release rates of fire sources are classified as follows:

Effective: Heat release rate of fire source, Q_f, grows to exceed Q_{sp}, so is potential to activate sprinkler system. In this category, there are two subcategories:
Success: Sprinkler system succeeds to suppress fire heat release rate below Q_{sp}.
Failure: Sprinkler system fails to suppress fire to allow its heat release rate to increase beyond Q_{sp} by malfunction or insufficient performance.
Ineffective: Heat release rate of fire source, Q_f, does not reach Q_{sp}, so is not potential to activate sprinkler system. Note that smoke hazard may be caused even by this size of fire.

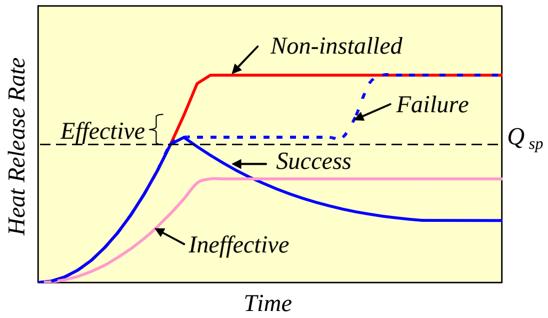

FIGURE 3. Fire source heat release rate with sprinkler system installed

Smoke control: Smoke control is a means to mitigate smoke hazards to occupants' evacuation. However, the degree of the hazard mitigation depends on fire size and capability of smoke exhaust system, which is then up to its design. Then, the conditions of a smoke exhaust system are simply classified into "actuation" and "non-actuation", i.e.
Actuation: Smoke exhaust system operates normally.
Non-actuation: Smoke exhaust system does not operate due to some fault of a system.
Number of evacuation failures *C*: Number of evacuation failures, C, is the number of occupants who are exposed to untenable smoke or heat in the evacuation from fire.
Probability of each fire scenario *P*: The probability of each fire scenario to occur, P_i, is calculated from relevant branch probabilities, which involve the reliabilities of sprinkler system, smoke exhaust system and means of escape.

RISK-BASED EVALUATION OF EVACUATION SAFETY PERFORMENCE

According to the event tree in Fig. 2, safety level of an evacuation safety plan is assessed by the risk of evacuation failure, R, given by:

$$R = \sum P_i C_i \qquad [1]$$

where P_i and C_i are the probability and the consequence of scenario i, or more concretely, the number of occupants who fail to evacuate safely. As already mentioned, evacuation safety verification is made on the premise that a fire breaks out and grows. Hence the summation Σ in Eqn. [1] is taken with respect of the events under growing fire only. Since all the scenarios under the premise are covered by the event tree

$$\sum P_i = 1 \qquad [2]$$

For an evacuation safety plan to be acceptable, the R must be below acceptable risk, R_A, i.e.

$$R = \sum P_i C_i < R_A \qquad [3]$$

In general, consequence C_i has to be calculated under the specific condition of scenario i. However, if the worst scenario and its evacuation failure number, C_{max}, can be identified, Eqn. [1] turns out to be as follows:

$$R = \sum C_i P_i \leq C_{\max} \sum P_i = C_{\max} < R_A \quad [4]$$

In other words, if $C_{max} < R_A$, no other scenarios need to be checked. Furthermore, if the initial number of occupants, C_0, is smaller than R_A,

$$R < C_{\max} \leq C_0 < R_A \quad [5]$$

Therefore, Eqn. [1] is always satisfied so that evacuation safety plan itself is not necessary.

ACCEPTABLE RISK FOR EVACUATION IN FIRE

In order to implement the risk-based fire safety design method, the value of the acceptable risk, R_A, need to be specified. As already mentioned, acceptable fire risk is a societal compromise between fire safety and cost. However, nowhere we can find explicit statement of the acceptable risk level so we cannot help but seek for it in indirect sources. The candidate sources will be the existing fire safety provisions and public attitude to the current fire loss.

Definition of Evacuation Failure

When we discuss the risk in the context of evacuation safety designs of buildings, it is necessary to define what the failure of evacuation is. Table 1 shows the casualty rates, persons/fire, according to casualty levels and building sizes by 'Major fires' from fire statistic of mixed use buildings in Tokyo from 2001 to 2005 [4]. In the table, 'Major fire' means the fire that developed beyond the possibility of early stage extinguishments.

The casualty level in Table 1 ranges from slight to death. A question here is which level of injury should be deemed as the evacuation failure? This is related to the safety criteria used in fire safety verification. In Japan, the criteria are such that smoke layer interface is 1.8m or higher or that '(temperature rise)^2 - time' exposure is less than 10^4 K^2s etc.[5] In other words, the violation of such criteria dose not immediately mean death of an occupant but rather corresponds to slight injury or interruption of smooth escape due to exposure to smoke.

TABLE 1. Injury rate of building fires in mixed use buildings [5]

Fire Size	Building Size Floor Area A[㎡]	Injury Rate [person/fire] Slight	Middle	Serious	Death	Total
Major Fire	A≦150	0.38	0.17	0.08	0.00	**0.63**
	150＜A≦300	0.28	0.16	0.01	0.08	**0.54**
	300＜A≦500	0.34	0.08	0.07	0.04	**0.54**
	500＜A≦1000	0.36	0.07	0.05	0.03	**0.52**
	1000＜A≦1500	0.36	0.08	0.04	0.03	**0.51**
	1500＜A≦3000	0.37	0.12	0.05	0.05	**0.59**
	3000＜A≦6000	0.39	0.12	0.05	0.10	**0.66**
	6000＜A	0.33	0.08	0.05	0.05	**0.50**
	Average	0.35	0.10	0.05	0.05	**0.55**

Acceptable Evacuation Risk in the Context of Evacuation Safety Design Verification

If the current level of the fire casualties for buildings of mixed use is societal acceptance, it follows from the above definition of evacuation failure that the total casualty rate, i.e. 0.55 person/(major fire) is the most appropriate as the acceptable risk in the context of evacuation safety verification.

However, dwellings perhaps provide more persuasive basis for the acceptable evacuation risk since almost no provisions is imposed for evacuation safety. Although about 1,300 persons are killed every year by fires in dwellings in Japan [6], the probability of a specific person to be killed by the fire is estimated to be only once per 100,000 years.

From fire statistics, the number of casualties by dwelling fires is about 5 times of the number of fatality [6], so the total casualties including deaths are about 1,300 x 6 = 7,800. On the other hand, the failure rate of early stage extinguishments of the 19,000 dwelling fires per year appears to be 40 to 55% [7], i.e. the number of major fires is estimated to be 19,000 x (0.45-0.6) = 8,550-10,400. So roughly, the casualty rate may be converted to 0.8 person/(major fire), although a certain portion of casualties may be caused by minor fires as well.

Such concrete values of risk are hardly available for a variety type of building uses, except the two occupancy types in the above. Table 2 shows the data of fires in several typical occupancies, which are the average of the years 2001-2003 [6]. The average areas were calculated from the data of buildings constructed in 1996 [8]. The number of facilities, except dwelling house, is from Fire Service White Book 2004, in which facilities smaller than 150 m^2 are excluded [7] so a certain degree of errors are expected in the numbers of fires per facility. The numbers for dwelling house are those of independent houses and dwelling units in apartment buildings. Unfortunately, data for injury were not found at this moment.

TABLE 2. Fatality rate per fire for several building uses (*: number of household units)

Type of occupancy	Number of facilities	Average area (m^2)	Number of fires/ year	Number of fires/facility (x 10^{-3})	Number of deaths per year	Deaths /fire (x 10^{-2})
Dwelling house	45,258,400*	93	19,093	0.42	1280	6.70
Restaurant, Bar	87,328	243	667	7.63	3.67	0.55
Shop, Market	142,356	616	500	3.51	4.00	0.80
Hospital, Clinic	61,586	1005	154	2.50	0.33	0.22
Hotel, Inn	75,458	942	180	2.39	3.67	2.03
Amusement	18,058	936	145	8.05	0.33	0.23
School	131,448	1131	393	2.99	1.33	0.34
Ware house	323,701	324	753	2.33	4.00	0.53
Office building	405,729	426	844	2.08	9.33	1.11
Mixed use	581,310	-	3,778	6.49	96.3	2.55

SCREENING FOR SELECTION OF SAFETY DESIGN TARGETS

Not all the buildings but only particularly important ones are objects of usual P-B fire safety designs/verifications. Dwelling houses are usually out of its interests although its death rate per fire is extremely high relative to other type buildings. For consistency of fire risk, evacuation safety verification could be waived for buildings or spaces under certain size.

In the context of P-B evacuation safety design/verification, the evacuation failure risk, R_{evac}, can be expressed as:

$$R_{evac} = \left(P_{mf} A_{spc}\right) \times P_{inj} \times C_0 \qquad [6]$$

where P_{mf} is the incidence rate of major fire per area, P_{inj} is the probability to be injured by a major fire, A_{spc} and C_0 are the area of space and the number of occupants to be potentially involved in the major fire. Note here that fire incidence rate is assumed to depend not only on type of use but also on size of building or space.

If taking dwelling houses, H, as the standard, the risk of different type of building, K, must be

$$R_{evac}(K) \leq R_{evac}(H) \qquad [7]$$

that is

$$P_{mf}(K) A_{spc}(K) \times P_{inj}(K) \times C_0(K) \leq P_{mf}(H) A_{spc}(H) \times P_{inj}(H) \times C_0(H) \qquad [8]$$

From the preceding discussion, for dwelling houses as the standard

$$P_{inj}(H) \times C_0(H) = 0.8 \text{ person/(major fire)} \qquad [9]$$

in real fires.

The average number of family member in Japan is 2.4 persons, from the census [9], so on statistic base C_0(H) = 2.4 person so that P_{inj} (H) would be 0.8/2.4 = 1/3 (person/major fire)/person if family members were always fully loaded in the event of a major fire. In reality, major fires do not always occur when all the family members happen to be in their house. For example, in the extreme case of arson fires, which comprise about 30% of fires in recent years, nobody might happen to be in the house. There is no statistics data available for such information but of course the range of the value is 0 - 2.4 so simply mean value, 1.2, is employed here. Then it follows that P_{inj} (H) = 0.8/1.2 = 2/3 (person/major fire)/person.

In P-B fire safety designs, the number of occupants is normally set by area assuming fully loaded condition. The number will be conservatively set at 5-6 persons for a house with average area. Here we arbitrarily adopt C_0(H) = 6 person. So using C_0(H) = 6 in Eqn.(8) and A_{spc}(H) = 100 m^2 , in addition, for convenience we obtain

$$C_0(K) \leq 6 \times \left(\frac{100}{A_{spc}(K)}\right)\left(\frac{P_{mf}(H)}{P_{mf}(K)}\right)\left(\frac{P_{inj}(H)}{P_{inj}(K)}\right) \qquad [10]$$

that is, any space, K, in which number of occupants satisfy Eqn. [10] need not subject to P-B fire safety design. Incidentally, the acceptable risk on design base can be calculated as:

$$P_{inj}(H) \times C_0(H) = \frac{2}{3} \times 6 = 4 \quad \text{person/(major fire)} \qquad [11]$$

This could be used in Eqn. [10] to slightly change the formula but Eqn. [10] as it is will be more convenient as shown below.

The number of occupants are often prescribed using occupant density, p [person/m^2] or occupant factor, F (=1/p) [m^2/person], so that C_0(K) = p A_{spc}(K)= A_{spc}(H)/F, in which case Eqn. [10] is rearranged as

$$A_{spc}(K) \le \frac{24.5}{\sqrt{p}} \times \sqrt{\left(\frac{P_{mf}(H)}{P_{mf}(K)}\right)\left(\frac{P_{inj}(H)}{P_{inj}(K)}\right)} = 24.5\sqrt{F} \times \sqrt{\left(\frac{P_{mf}(H)}{P_{mf}(K)}\right)\left(\frac{P_{inj}(H)}{P_{inj}(K)}\right)} \qquad [12]$$

i.e., any space whose area satisfy Eqn. [10] does not need safety verification. (See **Example 1**)

Eqn. [12] implies that the maximum space area of any type of occupancy for which safety verification is waived can be obtained if the ratios of incidence rate, P_{mf}(H)/P_{mf}(K)**,** and injury probabilities, P_{mf}(H)/P_{mf}(K), are known for every type of occupancy. Unfortunately, however, sufficient data are not available so some of them have to be substituted by approximate ones. Table 3 is the results of such a trial. Although the premise of P-B fire safety design is violated in some points such as that not all fires are major ones, casualty is replaced by fatality and the condition of fire provisions applied is neglected, the values may not be so ridiculously distant from true values.

TABLE 3. Fatality rate per fire for several building uses

Type of occupancy	Average area (m^2) (*1)	Number of fires/facility ($x10^{-3}$) (*1)	Number of fires/100m^2 ($x10^{-3}$) (*1)	P_{mf}(H) / P_{mf}(K) (*1)	Deaths /fire ($x10^{-2}$) (*2)	P_{inj}(H) / P_{inj} (K) (*2)
Dwelling house	93	0.42	0.45	1.0	6.70	1.
Restaurant, Bar	243	7.63	3.14	0.14	0.55	12.2
Shop, Market	616	3.51	0.57	0.79	0.80	8.4
Hospital, Clinic	1,005	2.50	0.25	1.8	0.22	30.5
Hotel, Inn	942	2.39	0.25	1.8	2.03	3.35
Amusement	936	8.05	0.86	0.52	0.23	29.1
School	1131	2.99	0.26	1.73	0.34	19.7
Ware house	324	2.33	0.72	0.63	0.53	12.6
Office building	426	2.08	0.49	0.92	1.11	6.04
Mixed use	(1,000)*3	6.49	(0.65) *3	(1.44) *3	2.55	2.63

(*1: Minor fires are included, *2: Casualty data not available, *3: Area data not available)

SELECTION OF DESIGN FIRES IN EVACUATION SAFETY DESIGNS

Acceptable Evacuation Risk in Evacuation Safety Verification

Once it has been decided through screening that evacuation safety verification is required, it must be proved that the evacuation failure risk of the space is lower than the acceptable risk. The risk is the conditional risk in the context of evacuation safety verification. According to Eqns. [8] and [11], the risk of a space of type of occupancy K, R_D(K), is given by:

$$\begin{aligned} R_D(K) &= P_{inj}(K)\times C_0(K) \le \frac{P_{mf}(H)A_{spc}(H)}{P_{mf}(K)A_{spc}(K)} \times \{P_{inj}(H)\times C_0(H)\} \\ &= 4\times\left(\frac{P_{mf}(H)}{P_{mf}(K)}\right)\left(\frac{100}{A_{spc}(K)}\right) \end{aligned} \qquad [13]$$

The right hand side of the last row is the concrete value of the acceptable evacuation failure risk. The ratio P_{mf}(H)/P_{mf}(K) is found in Table 4.(See **Example 2**)

Fire Growth Coefficient

The early stage of fire growth is expressed in terms of heat release rate, Q_f, as:

$$Q_f = \alpha t^2 \tag{13}$$

where t is the time from ignition and α is the growth coefficient.

Since evacuation occurs at relatively early stage, result of safety verification is strongly dependent upon the value of α. The value of α is considered to vary depending on type and amount of fuels so is probabilistic in general, with high probability for small α and low probability for large α. In realistic fire situations, the probability density function of α, $F(\alpha)$, may be Poisson type as shown by dashed line in Fig. 4, but here we adopt an exponential distribution for convenience of calculation as:

$$F(\alpha) = \lambda e^{-\lambda\alpha} \tag{14}$$

where parameter λ is given using the mean value $\overline{\alpha}$ as:

$$\lambda = 1/\overline{\alpha} \tag{15}$$

The mean value of fire growth coefficient $\overline{\alpha}$ is considered to depend on use of space since types and characteristics of live combustible items in a space reflect use of space. $\overline{\alpha}$ is considered to be an important parameter to characterize fire hazard level of building spaces.

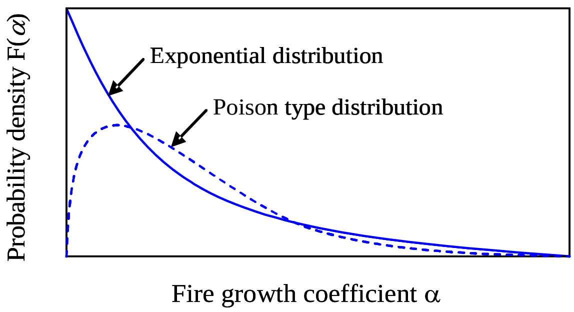

FIGURE 4. Conceptual probability density function of α

Fire Growth Rate Coefficient α and Evacuation Failure C(α)

While safety of evacuation is easily assured for small α, it is hard for large α. Fig. 5 illustrates the conceptual relationship between α and the number of occupants, C(α), who fail to evacuate safely under $Q = \alpha t^2$. Up to a certain level of α, $C(\alpha)$ will be zero but becomes greater with the increase of α. The $C(\alpha)$ eventually reaches C_0, the total number of occupants. Here, we define the α at which C(α) starts to rise as the critical fire growth rate coefficient, α_c.

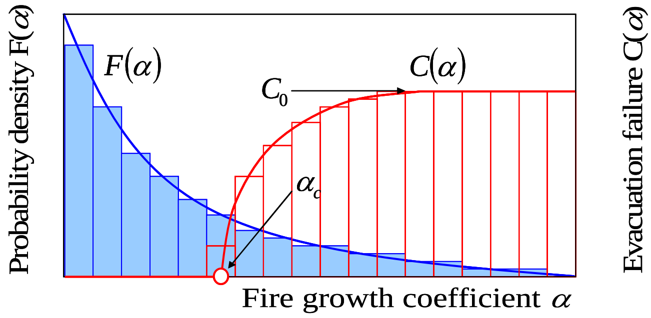

FIGURE 5. Fire growth coefficient α and C(α)

Evacuation Failure Risk and Fire Growth Rate in Case with Single Scenario

Let's consider the case of a fire growing to be developed room fire in a space with no sprinkler nor smoke control system, which corresponds to Scenario 13 in Fig. 2. In this case, the probability of the event in the context of evacuation safety design is unity, i.e. P_{13}=1, but fire growth rate is still probabilistic. Hence, the evacuation failure risk R is calculated as:

$$R = P_{13}C_{13} = C_{13} = \int_0^{\infty} F(\alpha)C(\alpha)d\alpha \qquad [16]$$

Noting that C(α) = 0 for $\alpha < \alpha_c$, the right hand side of Eqn. [16] can be written as:

$$\begin{aligned}\int_0^{\infty} F(\alpha)C(\alpha)d\alpha &= \int_0^{\alpha_C} F(\alpha)C(\alpha)d\alpha + \int_{\alpha_C}^{\infty} F(\alpha)C(\alpha)d\alpha \\ &= \int_{\alpha_C}^{\infty} F(\alpha)C(\alpha)d\alpha\end{aligned} \qquad [17]$$

The concrete function C(α) for $\alpha > \alpha_c$ is dependent of many factors such as room dimensions so not readily known but since

$$\int_{\alpha_C}^{\infty} F(\alpha)C(\alpha)d\alpha < C_0 \int_{\alpha_C}^{\infty} F(\alpha)d\alpha \qquad [18]$$

and, from the assumed probability density distribution of Eqn. [14],

$$\int_{\alpha_C}^{\infty} F(\alpha)d\alpha = \int_{\alpha_C}^{\infty} \lambda e^{-\lambda\alpha} d\alpha = e^{-\lambda\alpha_C} = e^{-\alpha_C/\bar{\alpha}} \qquad [19]$$

the evacuation failure risk R is:

$$R < C_0 e^{-\alpha_C/\bar{\alpha}} \qquad [20]$$

Therefore, if the following relationship is satisfied, R is conservatively $R < R_A$.

$$C_0 e^{-\alpha_C/\bar{\alpha}} < R_A \qquad [21]$$

Eqn. [21] can be solved for α_c as:

$$\alpha_C > \bar{\alpha} \ln \frac{C_0}{R_A} \tag{22}$$

The important implication of Eqns. [20] to [22] is that the evacuation failure risk R is conservatively verified to be below the acceptable risk, R_A, if the number of occupants who cannot evacuate safely is made zero under the design fire as follows: (See **Example 3**)

$$Q_f = \alpha_D t^2 \quad \text{where} \quad \alpha_D = \bar{\alpha} \ln \frac{C_0}{R_A} \tag{23}$$

Evacuation Failure Risk and Fire Growth Rate in Case with Two Scenarios

As another simple example let's consider the case with smoke control system. The other conditions are assumed as the same as the above. This case corresponds to Scenarios 14 and 15 in the event tree in Fig. 2. Scenario 14 is when the smoke control system normally operates and Scenario 15 is when it fails due to some trouble. Fig. 6 shows the conceptual relationship between fire growth coefficient, α, and evacuation failure, $C(\alpha)$**,** for these scenarios. Evacuation safety in Scenario 14 can be assured for wider range of α, than in Scenario 15 since the smoke control system mitigates smoke hazard.

The goal in the case is to satisfy

$$R = P_{14} C_{14} + P_{15} C_{15} < R_A \tag{24}$$

Hence, it follows that some freedom exists to attain this goal. We may be able to set partial acceptable risks for each of the scenarios, $R_{A(14)}$ and $R_{A(14)}$, arbitrarily as:

$$P_{14} C_{14} < R_{A(14)}, \quad P_{15} C_{15} < R_{A(15)} \tag{25}$$

provided that

$$R_{A(14)} + R_{A(15)} \leq R_A \tag{26}$$

The design fire for each of the two scenarios can be calculated as:

$$\alpha_{D(14)} = \bar{\alpha} \ln \frac{P_{14} C_0}{R_{A(14)}} \quad \text{(for Scenario 14: smoke control normally work)} \tag{27a}$$

and

$$\alpha_{D(15)} = \bar{\alpha} \ln \frac{P_{15} C_0}{R_{A(15)}} \quad \text{(for Scenario 15: smoke control system fails to work)} \tag{27b}$$

Needless to say, the evacuation failure risk $R < R_A$ is conservatively verified if the evacuation failure in each scenario is made zero under the respective design fire (See **Example 4**).

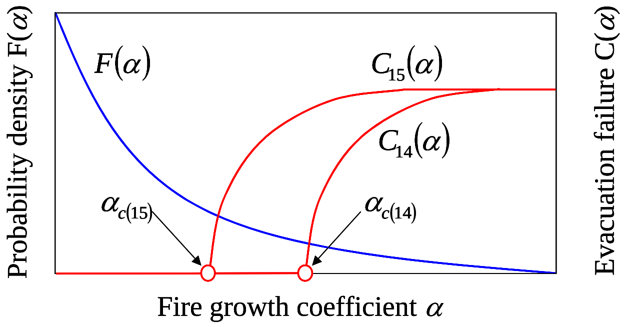

FIGURE 6. α and C(α) for case with two scenarios

Evacuation Failure Risk and Fire Growth Rate in Case with Multiple Scenarios

For the cases with multiple scenarios also, the partial acceptable risk can be arbitrarily chosen to satisfy the following conditions.

$$P_i C_i < R_{A(i)}, \quad \sum R_{A(i)} \le R_A \qquad [28]$$

and the design fire for each scenarios can be determined using the fire growth coefficient given by the equation as follows: (See **Example 5**)

$$\alpha_{D(i)} = \bar{\alpha} \ln \frac{P_i C_0}{R_{A(i)}} \qquad [29]$$

CONCLUDING REMARKS

In this paper, design fire scenarios and acceptable risk, R_A, for performance-based evacuation safety design were developed. Acceptable evacuation failure risk in the context of evacuation safety verification was sought from fire statistics available. Using the results, the method for screening building spaces without need of P-B evacuation safety verification was proposed.

For spaces for which evacuation safety verification is required, a methodology to determine the fire growth coefficient of design fire was developed. If evacuation failure is made zero under this design fire, acceptable level of safety can be conservatively assured.

EXAMPLES

Example 1: For shops, markets etc. with occupant factor F = 2 m^2/person, the maximum area for which evacuation safety verification, A_{MAX}, is calculated as:

$$A_{MAX} = 24.5\sqrt{2} \times \sqrt{0.79 \times 8.4} = 89 \ \text{m}^2$$

and for office with occupant factor F = 8 m^2/person,

$$A_{MAX} = 24.5\sqrt{8} \times \sqrt{0.92 \times 6.04} = 165 \ \text{m}^2$$

Example 2: Acceptable evacuation failure risk in the context of evacuation safety design for an office with 400 m^2 of area is calculated as:

$$R_A = 4 \times 0.92 \times (100/400) = 0.92 \text{ person/(major fire)}$$

Example 3: If mean fire growth coefficient for office occupancy is $\bar{\alpha} = 0.025$, the fire growth coefficient of the design fire for an office with 50 occupants, C_0 = 50, and 400 m^2 of area (Refer to Example 2) is calculated as:

$$\alpha_D = \bar{\alpha} \ln \frac{C_0}{R_A} = 0.025 \times \ln \frac{50}{0.92} = 0.10 \text{ kW/s}^2$$

Example 4: Considering the case where a smoke control system is equipped in the office room of Example 3 and P_{14} = 0.9 and P_{15} = 0.1 are assumed to be known, and if $R_{A(14)}$ = 0.5 and $R_{A(15)}$ = 0.4 is arbitrarily chosen (note $R_{A(14)}$+ $R_{A(15}$ < 0.92),

$$\alpha_{D(14)} = 0.025 \times \ln \frac{0.9 \times 50}{0.5} = 0.112 \text{ and } \alpha_{D(15)} = 0.025 \times \ln \frac{0.1 \times 50}{0.4} = 0.063$$

and if $R_{A(14)}$ = 0.2 and $R_{A(15)}$ = 0.7 is chosen

$$\alpha_{D(14)} = 0.025 \times \ln \frac{0.9 \times 50}{0.2} = 0.135 \text{ and } \alpha_{D(15)} = 0.025 \times \ln \frac{0.1 \times 50}{0.7} = 0.049$$

That is, if a smoke control system can cope with severer fire condition, verification for the case the system fails to activate can be made under less severe fire condition.

Examples 5: Considering the case where sprinkler system and smoke control systems are installed with other conditions the same as in Example 4. The corresponding scenarios are 17, 18, 20 and 21 in Fig. 2. If it is assumed that success and failure probabilities of the sprinkler system be 0.8 and 0.2, respectively, and that activation and non-activation probabilities of the smoke control system be 0.9 and 0.1, the corresponding event probabilities are calculated as follows:

$$P_{17} = 0.8 \times 0.9 = 0.72, \quad P_{18} = 0.8 \times 0.1 = 0.08$$
$$P_{20} = 0.2 \times 0.9 = 0.18, \quad P_{21} = 0.2 \times 0.1 = 0.02$$

Taking into account of that maximum fire size is controlled by the effect of sprinkler in Scenarios 17 and 18, we may arbitrarily set the partial acceptable risk for each event within the limit of $\Sigma R_{A(i)}$< 0.92, for example,

$$R_{A(17)} = 0, \quad R_{A(18)} = 0, \quad R_{A(20)} = 0.5, \quad R_{A(21)} = 0.4$$

Note that $R_{A(17)}$ = $R_{A(18)}$ = 0 means that fire growth coefficients for Scenario 17 and 18 are infinity so the verification must be made with the maximum heat release rate. (note that the maximum heat release rate is suppressed by sprinkler effect). In Scenario 20 and 21, some effect to suppress fire may be expected despite of the failure of suppression but it is conservative to neglect the effect, then the design fires are calculated as:

$$\alpha_{D(20)} = 0.025 \times \ln \frac{0.18 \times 50}{0.5} = 0.072 \text{ and } \alpha_{D(21)} = 0.025 \times \ln \frac{0.02 \times 50}{0.4} = 0.023$$

The lower values of α_D relative to the values in Example 4 are due to the effect of sprinkler.

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