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A CONSIDERATION ON REQUIRED NUMBER OF EXITS IN A ROOM
A Study on the Safety Performance of Exit Provisions Part 1

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ABSTRACT

It is commonly believed that it is important for safe evacuation in building fire to arrange two or more escape routes in different directions. The various provisions are prescribed in building and fire codes of many countries to realize this concept in buildings. The requirement of two or more exits from a room is one of such provisions. However, the way for requiring two or more exits is significantly different from one country to another, and the level of safety assured by the provisions is not clear. In this paper, the meaning of the requirement of two or more exits is considered from the view point of the expected number of occupants unable to escape and a criterion for required exits is proposed as an alternative to the existing provisions. The proposed criterion is basically the same as the existing provisions in terms of the average level of safety assured, but allows to assess the effect of the number of exits on safety more explicitly.

1. INTRODUCTION

It is commonly believed that it is important for safe evacuation in building fire to arrange two or more escape routes in different directions. The requirement of two or more exits for a space having floor area or number of occupants exceeding certain limits, which is found in building or fire codes in many countries, is one of the evidences of the belief. This, needless to say, intends to assure alternative exits should one of the exits be blocked by the influence of fire.

It would be absolutely desirable from the viewpoint of pure safety to provide two ore more exits in every space. In reality, however, it is not always easy to achieve the ideal arrangement of exits because of the constraints raised by building economy, everyday convenience and so forth. Fire is a relatively rare danger. Even though safety is undeniably the first priority for building planning, it is understandable that reluctance exists in sacrificing the benefit or the convenience in time of normal use. It is by such consideration that only one exit is allowed for relatively small space.

In this study, the meaning of the concept and the provisions of two or more exits are reviewed from the viewpoint of safety performance. The final goal is to contribute to the establishment of more rational design of means of escape in buildings.

2. REQUIREMENTS OF TWO OR MORE EXITS IN THE EXISTING REGULATIONS

The provisions concerning the requirements of two or more means of escape in the building codes of several countries are summarized in Table 1[1]. Usually, two or more means of escape are required when story or height of a building, or area or number of occupants of a room exceeds a certain limit. Incidentally, the legal principle in the U.S. and the U.K. codes seem to

TABLE 1 Minimum Number of Means of Escape

	Australia	France	Japan	U.K.	U.S.
General	2 exits for story a) >6 stories or >25 m height Hospital, Assembly, School b) >6 stories or >25 m height c) ward floor d) preschool e) primary or secondary school & >=2 stories f) any story >50 Ps.	for story or part of story 1) =<19Ps. 1 2) =<50 Ps. 1+sub 3) =<100 Ps. 2 or 1+sub 4)=<500 Ps. 2 5) >500 Ps. +1 per 500 Ps. sub: sub–exit	2 exits for story a) >5th floor b) on 3–5th floor & S >200 m^2 c) on 2nd floor & S >400 m^2 d) story for Assembly or Shop e) ward floor & S>100 m^2 f) Hotel : floor with sleeping rooms & S>200 m^2 g) Apartment & S>200 m^2	for story or part of story 1) =< 500 Ps. 2 2) =<1000 Ps. 3 3) =<2000 Ps. 4 4) =<4000 Ps. 5 5) =<7000 Ps. 6 6) =<11000 Ps. 7 7) =<16000 Ps. 8 8) >16000 Ps +1 per 5000 Ps.	for story or part of story 1) =< 500 Ps. 2 2) =<1000 Ps. 3 3)>1000 Ps. 4 2 exit access doors for a room School a)>50Ps. or S>93m^2 Hospital b) sleeping room S>93 m^2 c) others S>230 m^2 Hotel d) S>185 m^2
Single Means of Escape		Apartment single stairs a) combinations of stairs and corridors opened to the air or with smoke control b) stairs with smoke control	Assembly exits door for auditorium 1) =<250 Ps. 2 2) =<500 Ps. 3 3) =<1000 Ps. 4 4) =<2000 Ps. 5 5) >2000 Ps. 6	Apartment a) top floor <11m, =<4 stories, door–exit < 4.5m Others c) top floor <11m, =<50 Ps. d) room =< 50 Ps. e) story =<50 Ps.	Assembly a) balcony =<50 Ps. Hotel, Apartment b) =< 4 stories, =<4 living units per story, sprinklered Office c)room/area<100Ps. – outside < 30m d) =<3 stories, each story < 30Ps., – outside <30 m

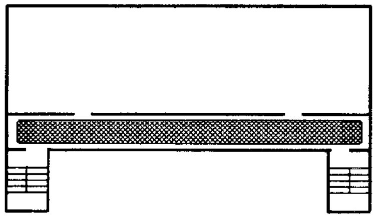
Ps.: persons, S: room area

require two or more for every space. But since this requirement is exempted for small rooms, the practical effects on the building planning is the same as the other codes. In average, 50 seems to be the threshold number of the occupants allowed in the rooms having only one exit.

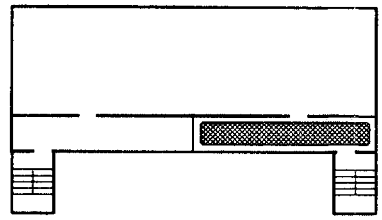
In many countries, providing only two exits is not sufficient but the number of required exits must increase with the number of occupants. As can be seen in Table 1, the required number of exits for a large number of occupants significantly differs in different countries. Which provision is the most rational from the viewpoint of safety? Is it enough to provide only two exits whatever the number of occupants may be or is it necessary to increase the number of exits with the increase of occupants? Should it be necessary, how many exits for how many occupants? A clear account has not been given to these crucial questions.

3. THE OBJECTIVE OF REQUIREMENT OF TWO OR MORE EXITS

The objective of the requirement of two or more exits for rooms is considered to assure alternative exit/exits even when an exit happens to be blocked by fire.[2] Two possibilities are conceivable as the scenarios that an exit is made impassable by fire: one is that a hazardous fire occurs at an area adjacent to a door way inside the room as illustrated by Figure 1a; and the other is that a fire occurs somewhere outside the room and an exit is made impassable by the effect of the fire such as the smoke propagating to the corridor connected to the room.



a. two or more exits are blocked by smoke



b. smoke partitioning of a corridor

FIGURE 1 A fire occurs somewhere outside the room and an exit is made impassable by the effect of the fire

The scenario that is assumed in the requirement of two or more exits for rooms is considered to be the former, i.e. an inside fire adjacent to a door way. In case of the latter scenario, the other exits along the corridor will be made impassable too when an exit is blocked by smoke, so if the intent of the requirement is to prevent this scenario some additional provisions such as smoke partitioning of the corridor, as illustrated in Figure 1b, have to go along with. Such codes are not found, however.

4. THE EXPECTED NUMBER OF OCCUPANTS UNABLE TO ESCAPE FROM A ROOM

4.1 Probability that an Exit is Blocked by Fire

It is when a fire beaks out in a room, grows to be a hazardous size and the fire happens to be in the area adjacent to the exit that occupants are unable to escape through a doorway. The probability of such an event to take place is expressed as:

$$P = p1 \cdot p2 \cdot p3 \qquad (1)$$

where *p1*: probability of fire occurrence in the room
p2: probability that the fire develops to be a hazardous fire
p3: probability that the fire is located in the area that impede the escape through an exit

Let's call the probability *P* as Exit obstruction probability. The probabilities *p1* and *p2* may be evaluated if detailed fire incidents data are available. These probabilities must be very small for the rooms accommodating many occupants such as theaters and offices since it is hard to believe that the ignition and growth of fire are overlooked in front of many awake people. But some concern may remain in the rooms used for sales, exhibition and special amusement etc.

It is not easy to estimate probability *p3*. Normally, little combustible is expected in the vicinity of a doorway since it is usually used as a passage area. From this point of view the probability of fire occurrence is suspected to be lower than other place in the room. But it might be higher if arsons have to be taken into account. Since no means is available for estimating the probability distribution of fire occurrence in a room, it is assumed here that the probability *p3* is uniform within a room.

4.2 Rooms Having Only One Exit

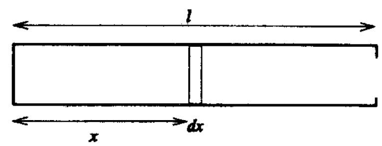


FIGURE 2 Long and narrow rooms having only one exit

(1) Long and narrow rooms

For the first step, let's imagine a very narrow room as shown in Figure 2 . In such a room, if a fire occurs at a point, the escape of the occupants located at the inner part of the room will be blocked. The expected number of occupants unable to escape E is calculated as

$$E=\int_0^l\left(Q\frac{x}{l}\right)p1\cdot p2\left(\frac{dx}{l}\right)=\frac{Q}{2}p1\cdot p2 \qquad (2)$$

where Q: number of occupants in the room
l: length of the room (m)
x: distance of fire from exit (m)

(2) Ordinary rooms

In ordinary rooms, the occupants are able to make a round the fire to make a way to the exit as shown in Figure 3a. It is only when the fire occurs in the vicinity of the exit that the escape is impeded. Let a be the area that a fire therein impedes the escape through the exit. From the assumption of uniform probability distribution of fire occurrence within the room,

$$p3=\frac{a}{A} \qquad (3)$$

where A: floor area of the room

Not only the source of physical danger such as flames and heat radiation, but also psychological fear may need be taken into account in assessing area a. If such is the case, area a may not necessarily be small but involves somewhat large area around the exit.

The expected number of occupants unable to escape E in this case is given as

$$E=Q\cdot P=Q\cdot p1\cdot p2\cdot\frac{a}{A} \qquad (4)$$

Although the absolute value cannot be known, area a is considered to be determined by the

a. occupants are able to make a round the fire to make a way to the exit

b. area that a fire therein impedes the escape through the exit.

FIGURE 3 Ordinary rooms having only one exit definition of the size of hazardous fire and independent from room floor area A, so $p3 \propto A^{-1}$. On the other hand, usually $Q \propto A$. Hence $E \propto p1 \cdot p2$, that is, if $p1$ and $p2$ are the same regardless the floor area A, the expected number of occupants unable to escape E becomes independent from A.

If the expected number E is independent from the area, it follows that there is no reason to require more than one exit for sizable room. Therefore, it is suspected that $p1 \propto A$ is implicitly assumed in the existing regulations, in which case $E \propto A$.

4.3 Rooms Having Two or More Exits

Two exits are supposed to be sufficient if all the occupants are able to escape through the other exit when one exit is blocked by a fire, as long as the two exits is adequately separated so that the two exits are not simultaneously involved in the influence of a fire. However, in many countries, more than two exits are required for the rooms accommodating a large number of occupants, as shown in Table 1. This is partly because care has been paid to prevent the danger due to excessive queuing in front of a doorway. But it may be taken into consideration to mitigate the direct hazard from smoke or fire. This possibility is investigated in the following.

(1) When "available escape time" = "escape time"

If a fire occurs in a room, a smoke layer which develops under the ceiling gradually descends to make the room untenable after a while. Available escape time t_A is defined here as the time from the start of escape to when such untenable condition reaches. Engineering methods usable to predict t_A are now available, although we do not refer to them here.

On the other hand, escape time t_E is defined as the time from the start to the completion of the escape. When the escape time t_E is controlled by the width of doorway, it is calculated by

$$t_E = \frac{Q}{NB} \qquad (5)$$

where B: total width of the exits(m)
N: doorway egress flow rate(person/m sec)

Now, suppose there are n exits in a room, and let the width of each exits be $B_1, B_2, \ldots, B_k, \ldots, B_n$, respectively, and that the total width of the exits be exactly enough to evacuate the room within the available escape time t_A.

When a fire occurs in the vicinity of door k, the number of occupants unable to escape within the available escape time t_A is $(B_k/B)Q$. Hence, if the probability $p3(=a/A)$ is the same for any door, the expected number of occupants unable to escape E is given as

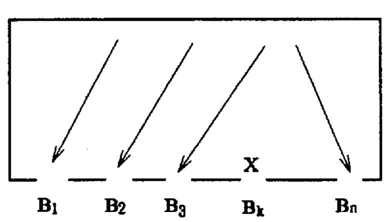


FIGURE 4 A fire occurs in the vicinity of door k

$$E=\sum_{k=1}^{n}\left(\frac{B_k}{B}\right)QP=\frac{\sum_{k=1}^{n}(B_k)}{B}QP=QP \tag{6}$$

that is, when the total width of exits B is exactly enough to evacuate the room the available escape time, the expected number of occupants unable to escape E is constant regardless the number of the exits. Hence, it follows that increase of number of exits does not increase the safety of the escape, although it may increase the conditional safety when a fire has occurred at an exit.

(2) When "available escape time" > "escape time"

Usually, the total width of exits is determined more to prevent excessive queuing at the exits than to evacuate the room within the available escape time. As a result, escape time t_E is more or less shorter than available escape time t_A. In other words,

$$Q=NBt_E<NBt_A \tag{7}$$

Let B_A be the width that is necessary for evacuating the room exactly within the available escape time, that is

$$Q=NB_At_A \tag{8}$$

Then the width given as follows

$$B_\alpha=B-B_A \tag{9}$$

can be considered as the surplus of the width.

The number of the occupants manage to escape Q' when exit k is blocked by fire is given as

$$Q_k'=N(B-B_k)t_A \tag{10}$$

provided that Q' cannot be larger than Q.

From Eqns.(9) and (10), the number of the occupants unable to escape is

$$\begin{aligned}Q-Q_k'&=NB_At_A-N(B-B_k)t_A=N\{B_A-(B-B_k)\}t_A\\&=N(B_k-B_\alpha)t_A\end{aligned} \tag{11}$$

provided that $Q-Q'=0$ when $B_k-B_\alpha<0$, since the number of the occupants unable to escape cannot be negative.

Hence, the total expected number of occupants unable to escape E is calculated by taking the summation of Eqn.(11) multiplied by P for all the exits of the room, that is,

$$E=\sum_{k=1}^{n}(Q-Q_k')P=\sum_{k=1}^{n(B_k-B_\alpha\geq 0)}N(B_k-B_\alpha)t_AP \tag{12}$$

provided that the summation is only taken for $B_k-B_\alpha>0$.

Needless to say, $E=0$ when $B_k-B_\alpha>0$ for any k, in other words, whichever exit may be blocked by a fire, all the occupants are expected to be able to escape when extra width of the exits is larger than the width of any exit.

5. AN ALTERNATIVE RULE TO EXISTING TWO OR MORE EXITS REQUIREMENTS

5.1 Proposed Criterion

Applying Eqn.(12) for n=1, a room with a single exit, we obtain

$$E = N(B - B_{\alpha})t_A P = NB_A t_A P = QP \qquad (13)$$

Therefore, Eqn.(12) can be applied consistently for any number of exits.

The absolute value of P in Eqn.(12) is not known, although suspected to be trivial, so there is no way to calculate the absolute value of the expected value E. However, because the exit codes in many countries require two or more exits for a room accommodating more than 50 occupants and having no sleeping facilities, as shown in Table 1, the requirement of the codes is interpreted as

$$E = QP < 50P^{*} \qquad (14)$$

where P^{*} is the exit obstruction probability for the typical space the character of which is such that one exit is deemed to be acceptable up to 50 occupants by many of the exit codes.

This limit on the expected value for the reference room having one exit may be extended to more generic rooms with arbitrary number of exits and various character, namely,

$$E = \sum_{k=1}^{n(B_k - B_{\alpha} \geq 0)} N\left(B_k - B_{\alpha}\right)t_A \overline{P} \leq Q_{ref} \qquad (15)$$

where $\overline{P} = P/P^{*}$ and $Q_{ref} = 50$

Eqn.(15) can be used as the criterion equitable to any room in terms of the acceptable level of safety. The character of a specific room associated with fire risk can be taken into account by $\overline{P}$, which is the relative exit obstruction probability reference to P^{*}. For example, if probability of fire occurrence $p1$ of the room is twice larger than the reference room, it follows that $\overline{P} = 2$ through Eqn.(1) provided that the other conditions are the same; if the initial fire growth rate of the combustible contents in the room is likely to be larger than the contents in the reference room, P will become somewhat large through the increase of the value of $p2$.

Note, however, that for such a space that the probability of fire occurrence is in proportion to the floor area, $P \propto A^{0}$ since $p3 \propto A^{-1}$ while $p1 \propto A$. In other words, floor area is not the factor which affects $\overline{P}$.

5.2 Sample Applications

The following examples illustrate how the arrangement of exits from a room is assessed based on the above criterion can be used for the assessment . Let the number of occupant Q=1,000, the available egress time t_A= 120 sec, and the relative exit obstruction probability $\overline{P} = 1$. Note that the exit width that is necessary for evacuating the room exactly within the available escape time B_A is calculated as

$$B_A = \frac{Q}{Nt_A} = \frac{1000}{1.5\times120} = 5.56(m)$$

(1) In case the widths of exits are the same

Suppose that the room has four exits and the width of each exit is 1.9m. The total width of the exits is 4×1.9m=7.6m. The surplus of the exit width B_α is

$$B_\alpha = B - B_A = 7.6 - 5.56 = 2.04(m) \quad > 1.9(m)$$

Hence, the expected number of occupants unable to escape $E=0$, so needless to say the criterion of Eqn.(15) is satisfied, in the case of this room.

(2) In case the widths of exits are different

Suppose that the room has four exits with different widths: two with 2.4m width each and the other two with 1.4m width each. The total width is 2×2.4+2×1.4=7.6, that is, the same as (1). In this case, the expected value becomes as

$$E = \sum_{k=1}^{n(B_k - B_\alpha \geq 0)} N\left(B_k - B_\alpha\right)t_A \overline{P} = 2\times1.5\times(2.4-2.04)\times120\times1 = 129.6 > 50$$

that is, the criterion of Eqn.(15) is not satisfied by such unbalanced arrangement of exits.

(3) In case the number of exits is increased

Let's consider the case that the room has five exits and the width of each exit is 1.4m. The total width of the exits is 5×1.4m=7.0m. The surplus of the exit width B_α in this case is

$$B_\alpha = B - B_A = 7.0 - 5.56 = 1.44(m) \quad > 1.4(m)$$

Hence, again E=0. This implies that in some cases the criterion may be met by less total width if number of exits is increased.

5.3 Consideration on Required Number of Exits

As we have seen before, the required number of exits increases with number of occupants in the exit codes of many countries. Now let's study how many exits are required to satisfy the criterion given by Eqn.(15). Here we assume that every exit has the same width for simplicity, i.e.

$$B_k = \frac{B}{n} \qquad (16)$$

Let the surplus rate of exit α be

$$\alpha = \frac{B_\alpha}{B_A} \qquad (17)$$

then total exit width can be expressed as

$$B = B_A + B_\alpha = (1+\alpha)B_A \qquad (18)$$

Firstly, using Eqns.(16) – (19) to the condition that E=0 when $B_k - B_\alpha < 0$ yields the number of exits which never generates the occupants unable to escape as

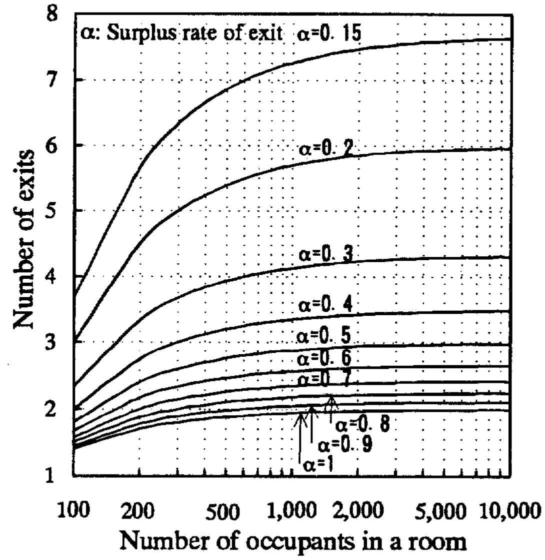


FIGURE 5 Required number of exits based on number of occupants in a room and exit surplus rate

$$n \geq \frac{1+\alpha}{\alpha} \qquad (19)$$

Next, substituting Eqns.(16) –(19) into Eqn.(15) gives

$$n \geq \frac{(1+\alpha)-\frac{Q_{ref}}{Q\overline{P}}}{\alpha} \qquad (20)$$

Eqn.(20) indicate that required number of exits is governed by number of occupants and exit surplus rate. This relationship is shown in Figure 5. The smaller the exit surplus rate, the larger the required number of exits and vice versa. Specifically, when the surplus rate equal 1, namely, when the exit width is twice as large as B_A, number of the exit can be only two.

When the surplus rate is the same, the number of required exits increases with the number of occupants , but the rate of increase is relatively small for the increase of number of occupants, and furthermore asymptotically approaches to the value given by Eqn.(19). Note, however, that the total width of exits has to increase in order to get the occupants escape within the available escape time. Hence, it is considered that the required number of exits for large occupant load tends to be satisfied without difficulty if the width of each exit is only normal.

6. CONCLUSIONS

The requirement of two or more exits of a room was discussed from the view point of the expected number of occupants unable to escape and a criterion for required exits is proposed as an alternative to the existing provisions. The proposed criterion is basically the same as the existing provisions in terms of the average level of safety assured, but allows to assess the effect of the number of exits on evacuation safety more explicitly.

Also, the relationship between number of occupants and the required number of exits was discussed based on the criterion. The required number of exits depend not only on the number of occupants but also on surplus width of exits.

NOMENCLATURE

A	Room floor area (m^2)
B	Total exit width (m)
B_k	Width of exit k (m)
B_{α}	The surplus of exit width (m)
B_A	The exit width that is necessary for evacuating the room exactly within the available escape time (m)
E	Expected number of occupants unable to escape
N	Doorway egress flow rate (person/m sec)
$p1$	Probability of fire occurrence in the room
$p2$	Probability that the fire develops to be a hazardous fire
$p3$	Probability that the fire is located in the area that impede the escape through an exit
P	Exit obstruction probability
P^*	Reference exit obstruction probability
$\overline{P}$	Relative exit obstruction probability reference to P^*
Q	Number of occupant of a room
Q'_k	The number of the occupants manage to escape when exit k is blocked by fire
t_E	Egress time (s)
t_A	Available egress time (s)
α	Surplus rate of exit

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Discussion

Akihiko Hokugo: Fifty people is the figure set forth by the regulation. Could you please elaborate on that. Do you think that is the appropriate level?

Ichiro Hagiwara: The requirements for an evacuation route vary depending on the country. In Australia, it is determined by the number of floors and the height of the building. However, in buildings for special use, there are special requirements, such as if there are people working and one floor exceeds more than fifty, then a minimum of two evacuation exits are required. And not only in Australia, but on France and England, fifty is the minimum required for two evacuation exits. In the United States, as is shown here, in case of an assembly hall, if the building has a balcony, if the number of people there is less than fifty, then only one exit is required. In other words, if the number exceeds fifty, they are required to have two exits. So it seems that in a lot of major countries, it seems that this number fifty is used as the standard to divide one versus two exits. However, there is no clear cut explanation as to why fifty is used for that purpose. Nonetheless, in order to have consistency with the current existing codes, we used fifty in our study.