An Examination of Feasibility of Elevator Evacuation Based on Risk Assessment

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ABSTRACT

In Japan, occupants should usually escape by stairways, not by elevator cars in case of a building fire. However, it is reported that occupants used elevator cars for evacuation in several major fires such as the Hiroshima Motomachi High-rise Apartments Fire that occurred on October 28, 1996 in Japan. Moreover, the demand for evacuation by elevator cars has been growing especially after the WTC collapse on September 11, 2001.

In this context, we developed an elevator evacuation model to simulate evacuation completion time by multiple elevator cars. Moreover, we conducted case studies with this model to examine merits and demerits of evacuation by elevator cars in consideration of the influence of smoke. Main parameters are vertical travel time and waiting time for elevator cars. As a result, we found that elevator evacuation might be more effective than stairways evacuation under certain conditions such as a 57-story high-rise building with 32 elevator cars and 2 stairways based on an existing high-rise building in Japan.

KEYWORDS: elevator evacuation model, feasibility, probability, fire scenario

INTRODUCTION

In Japan, we have a regulation to install an emergency elevator car in a building depending on its size in height or in floor area. An emergency elevator car should be located with a fire proof and smoke proof vestibule, and the vestibule has fire protection systems such as smoke control systems. The emergency elevator cars are mainly used by firefighters for access to the floor of fire or the floor below. On the other hand, regular elevator cars are set under control by emergency operators in case of fire, so as not to allow occupants to use those elevator cars. In case of a building fire, occupants are told to escape by stairways, not by elevator cars.

However, the demand for elevator evacuation has been growing recently. Therefore, we developed a simplified model to simulate evacuation time assuming the utilization of multiple regular elevator cars in order to examine the viability of this sort of evacuation strategy. Although we have examined the efficiency of elevator evacuation and the influence of the input parameters in our past studies [1,2], these studies did not consider the effectiveness of fire protection systems or the influence of smoke.

In this paper, therefore, we present the results of case studies that were carried out to look into the feasibility under the influence of smoke by using the elevator evacuation model and two-layer-zone smoke model [3] according to fire scenarios.

OUTLINE OF RISK ASSESSMENT IN CONSIDERATION OF ELEVATOR EVACUATION

Figure 1 presents the process of the risk assessment, with which we carried out to check the feasibility of elevator evacuation. Here, we propose an "evacuation safety index," which is defined as the ratio of the number of successful evacuees to overall occupants in a whole building. The evacuation safety index is calculated in Eq. 1.

P_k (number of occupants unable to escape) is calculated by comparing time between an a smoke flow time on the floor in fire of a case study building and an evacuation completion time of overall occupants in a whole building.

$$E_{safe} = 1 - E_{out} = 1 - \sum_{i=2}^{n}\left(F_i \sum_{k=1}^{s}(Q_k R_k)\right) = 1 - \sum_{i=2}^{n}\left(F_i \sum_{k=1}^{s}\left(Q_k \frac{P_k}{P_{occupants}}\right)\right) \quad (1)$$

E_{safe} expected number of occupants enabled to escape,
E_{out} expected number of occupants unable to escape,
F_i probability of a fire on floor i,
Q_k probability of a fire scenario k,
R_k ratio of the number of occupants influenced by smoke under scenario k,
n number of floors in a building,
s number of fire scenarios,
P_k number of occupants unable to escape under scenario k (persons),
$P_{occupants}$ number of whole occupants in a building (persons).

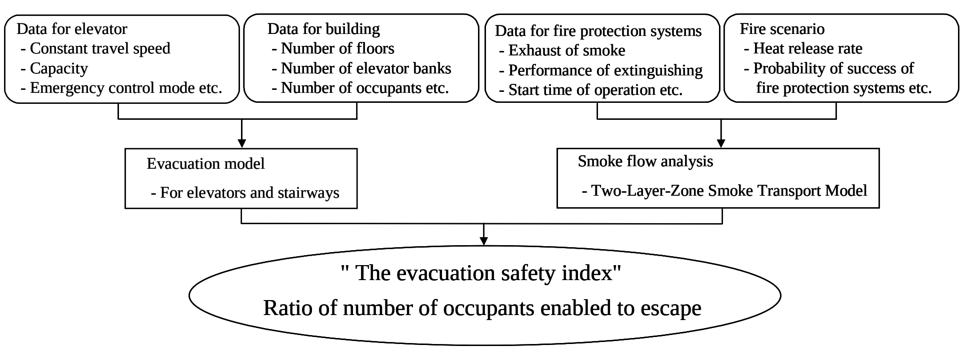

Fig. 1. The process of this study.

The risk assessment of elevator evacuation in consideration of the influence of smoke is conducted by using the datasets of elevator cars, fire protection systems, and fire scenarios described later in chapter of case study. The fire protection systems include extinguishers, sprinkler system, and so on. The behavior of smoke is analyzed using the two-layer-zone smoke transport model [3] according to the fire scenarios.

MODELS OF EVACUATION BY ELEVATOR CARS AND BY STAIRWAYS

Outline of Elevator Evacuation Model

The outline of the elevator evacuation model is summarized as follows. We applied this model to a high-rise model building and examined the feasibility of elevator evacuation.

- The model simultaneously calculates evacuation completion time by up to eight elevator cars in the same bank.
- Evacuation completion time is sum of vertical movement time and time of taking an elevator car and getting off an elevator car as shown in Eq. 2.
- All elevator cars start from the first floor, and move up directly to the highest floor in each bank.
- Once an elevator car is filled with occupants, it descends directly to the first floor.
- After the occupants reach the first floor, an elevator car moves up directly to the highest floor where there are any occupants waiting for an elevator car.
- An elevator car will continue to service for evacuation until all the occupants complete evacuation from the building.

$$T_{EV} = \sum_{i=1}^{m} (T_{i\_move} + T_{i\_occupants} + T_{i\_door}) \tag{2}$$

T_{EV}	evacuation completion time by elevator cars (s),
m	number of times of round trip (times),
T_{i_move}	time of movement by an elevator car (s),
$T_{i\_occupants}$	time of taking an elevator car and getting off an elevator car (s),
T_{i_door}	time of opening and closing of door (s).

Elevator Evacuation Model

The models for the multiple-elevator and stairway evacuation are outlined hereafter. To calculate the elevator travel time, we should consider the stages of elevator movement such as “stop,” “acceleration,” “constant velocity,” and “deceleration.” Figure 2 schematizes these stages.

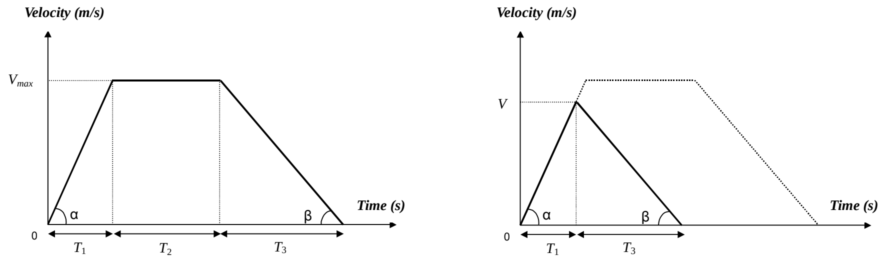

Fig. 2. Schematic diagram for calculating elevator travel time.
(Left: stage of the constant velocity, Right: no
stage of the constant velocity).

We have three patterns of elevator movement to represent travel time of elevator cars.

Pattern 1: If the stage of constant velocity is included, total travel time is represented by:

$$T_{i\_move} = T_1 + T_2 + T_3 = \frac{V_{max}}{\alpha} + \frac{\left(L - \frac{V_{max}^2}{2\alpha} - \frac{V_{max}^2}{2\beta} \right)}{V_{max}} + \frac{V_{max}}{\beta} \tag{3}$$

Pattern 2: If the elevator decreases its velocity just after reaching the constant velocity:

$$T_{i\_move} = T_1 + T_3 = \frac{V_{max}}{\alpha} + \frac{V_{max}}{\beta} \tag{4}$$

Pattern 3: If the elevator decreases its velocity before reaching the constant velocity:

$$T_{i\_move} = T_1 + T_3 = \left(\frac{1}{\alpha} + \frac{1}{\beta} \right) \sqrt{\frac{L}{\frac{1}{2\alpha} + \frac{1}{2\beta}}} \tag{5}$$

L	vertical distance for the elevator movement (m),		
α	elevator acceleration (m/s^2),	β	elevator deceleration (m/s^2),
V_{max}	maximum elevator velocity (m/s),	T_1	acceleration time (s),
T_2	constant velocity time (s),	T_3	deceleration time (s).

Stairway Evacuation Model

Based on the assumption that occupants use two stairways that are described in Section of Setting Parameters of Evacuation Model, the starting time of occupants' action is the same for every floor. Equation 6 calculates the evacuation time by two stairways.

$$T_{str} = \frac{L_h}{V_h} + \frac{L_s}{V_s} + max\left(\frac{P_{str}}{(N_{str} \cdot W_{str})}, \frac{P_{str}}{(N_{Exit} \cdot W_{Exit})} \right) \tag{6}$$

T_{str} evacuation completion time by stairways (s),
L_h maximum horizontal distance (50 m),
V_h horizontal walking speed (1.0 m/s),
L_s maximum vertical distance (m), V_s vertical walking speed (0.25 m/s),
P_{str} number of occupants by stairways (persons),
N_{str} effective flow rate in stairways on the first floor (1.3 persons/m/s),
N_{Exit} effective flow rate at the door of the first floor (1.5 persons/m/s),
W_{str} available stairways width (1.2 m), W_{Exit} available door width (1.08 m).

CASE STUDY

Purpose of Case Study

The main target of this study is to calculate an "evacuation safety index." The following subjects are examined.

- The waiting time of elevator cars by occupants is examined.
- The vertical travel times by elevator cars and by stairways are compared, and the ratio of vertical travel time is examined.
- The number of occupants enabled to escape by elevator cars and by stairways in consideration of influence of smoke as well as fire protection systems is examined.

Model Building for Case Study

The model is a 57-story high-rise building with a center-core system, based on an existing high-rise building in Japan. The floor configuration and the elevation of the model for case studies are shown in Fig. 3. The specifics of this building follow:

- The first (ground) floor is an entrance lobby used as a safety floor, and other floors are used for offices.
- A typical floor area per story is 2629 m^2 including an office area of 1680 m^2.
- The height of story is 3.65 m and except for the first floor of 7.0 m.
- This building is divided in four elevator banks shown in Fig. 3.
- The elevator cars in each bank have the same performance and capacity.
- Two emergency elevator cars are used by firefighters but not used for evacuation by occupants.

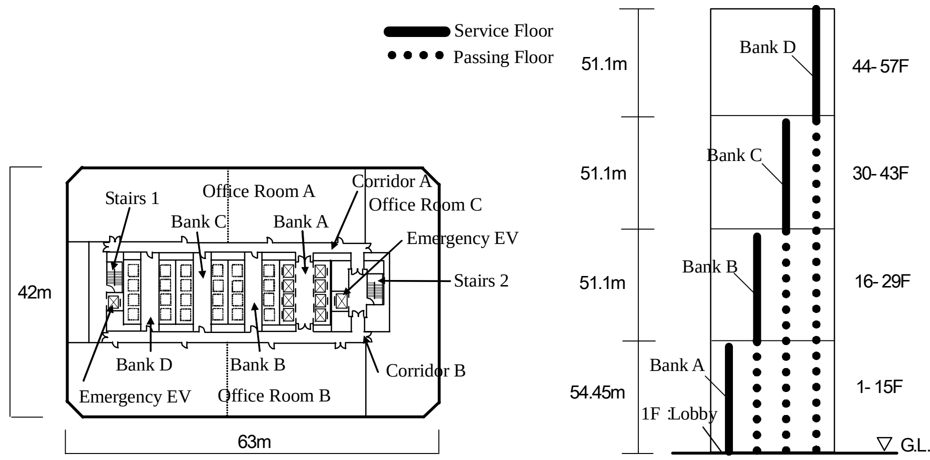

Fig. 3. Floor plan and elevation for case study.

Setting Parameters of Evacuation Model

The starting time of occupants' action is the same time (283 seconds from outbreak of fire) for every floor based on a method of Notification of the Ministry of Land, Infrastructure and Transport in accordance with the Building Standard Low of Japan. Table 1 shows the performance of the elevator cars used for an elevator evacuation model. The eight elevator cars in each bank are assumed to have the same performance.

Table 1. Conditions of elevator in each bank.

	Unit	**Bank A**	**Bank B**	**Bank C**	**Bank D**
Service floor	floors	1 ~ 15	1,16 ~ 29	1,30 ~ 43	1,44 ~ 57
Number of elevator cars [n]	-	8	8	8	8
Capacity	persons	22	22	22	22
Constant travel speed [V_{max}]	m/s	4	5	6	7
Acceleration [α]	m/s^2	0.7	0.7	0.7	0.7
Deceleration [β]	m/s^2	-0.7	-0.7	-0.7	-0.7
Door width	m	1.1	1.1	1.1	1.1
Occupant load on each bank	persons	2940	2940	2940	2940

Stairways 1 and 2 used in the stairways evacuation model have the same specifics as shown in Table 2. The influence of congestion in a stairway is considered by reducing the flow factor from 1.5 persons/s/m to 1.3 persons/s/m.

Table 2. Conditions by stairways.

	Unit	Stairway 1	Stairway 2
Width of stairways [W_{str}]	m	1.2	1.2
Available width of an exit door [W_{Exit}]	m	1.08	1.08
Flow factor of stairways [N_{str}]	persons/s/m	1.3	1.3
Flow factor of an exit door [N_{Exit}]	persons/s/m	1.5	1.5
Vertical walking speed [V_s]	m/s	0.25	0.25
Occupant load on each stairways [P_{str}]	persons	5880	5880

Condition of Fire Protection Systems

We assumed that fire scenarios had 16 patterns in consideration of success or failure of fire protection systems as shown in Fig. 4. We identified four fire protection systems such as use of extinguisher, activation of sprinkler, compartmentation by a fire door, and operating of smoke control system. The probability of success of fire protection systems is assumed as follows [4,5].

- Extinguisher: 0.996.
- Sprinkler system: 0.97.
- Compartmentation by fire door: 0.70.
- Smoke control system: 0.95.

The weight per story for the probability of fire is assumed the same from the second floor up to the 57th floor: 1/56 (1/story).

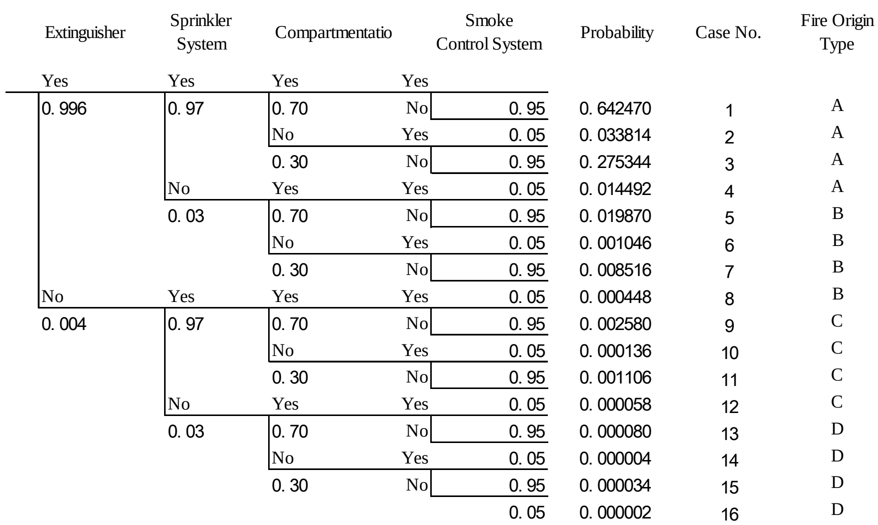

Fig. 4. Fire scenario and probability.

The activation time of an extinguisher is assumed to be 63 seconds that is the sum of the starting time of evacuation in the office room (43 seconds) and the time of preparation of extinguishers by an occupant (20 seconds). Total duration of extinguishers activation is assumed to be 112 seconds based on the performance of a typical extinguisher (14 seconds) multiplied by the number of extinguishers of 8, as specified by the Fire Service Law of Japan.

The activation time of sprinkler is assumed 89 seconds based on the temperature and the velocity of smoke at the ceiling of the fire room calculated by Alpert [6].

The smoke control system is assumed present in the office rooms, corridors, and vestibules except for the elevator lobby. Exhaust of smoke is assumed 1 $m^3/min/m^2$ in office rooms and corridors, and 4 $m^3/min/m^2$ in vestibules according to the Building Standard Law. The activation time of smoke control system is assumed 116 seconds in office rooms, and 210 seconds in corridors and vestibules based on the smoke flow.

The compartmentation is formed by fire doors located at the corridors' interfaces to the office, the elevator lobby, and the vestibule. In calculating the smoke flow by the two-layer-zone smoke transport model [3], a fire door was assumed to open when the compartmentation was failed. The leakage of a fire door was assumed to be 0.2 times of the surface area of each door when the compartmentation was formed successfully.

Conditions of Fire Origin

The heat release rate in this case study is assumed to follow α t-squared design fire, before fire protection systems start to be active. The heat release rate after sprinkler activation is reduced based on Eq. 7 [7]. On the other hand, the effect of an extinguisher is assumed relatively small, and the heat release rate grows again after the fire-extinguishing agent is used up. The patterns of heat release rate are summarized in Fig. 5.

$$Q = Q_{sp} e^{(-0.0023\Delta t)} \tag{7}$$

Q_{sp} the heat release rate at sprinkler activation (kW),
Δt the time after sprinkler activation (s).

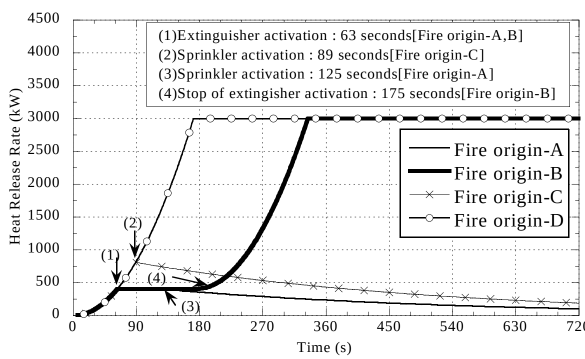

Fig. 5. Heat release rate of fire origins.

RESULTS OF CASE STUDY

Characteristics of Elevator Evacuation

Before calculating an "evacuation safety index," we examine the characteristics of elevator evacuation such as the evacuation completion time, the waiting time of elevator cars, and the vertical travel time. The results are shown in Fig. 6 to 8. Figure 6 shows that the evacuation completion time by elevator cars is shorter than the time needed evacuation by stairways. Moreover, Fig. 7 shows that the time to start taking elevator cars varies widely from 22 seconds to 1640 seconds. However, there was very little difference between time to start taking elevator cars and time to complete taking elevator cars on the same floor. Furthermore, Fig. 8 shows the ratio of vertical travel time by an elevator car and by a stairway (by stairs / by elevator cars). The ratio of vertical travel time became higher for evacuation from higher stories. It should be noted that the vertical evacuation time used for calculating this ratio does not include waiting time in the elevator hall.

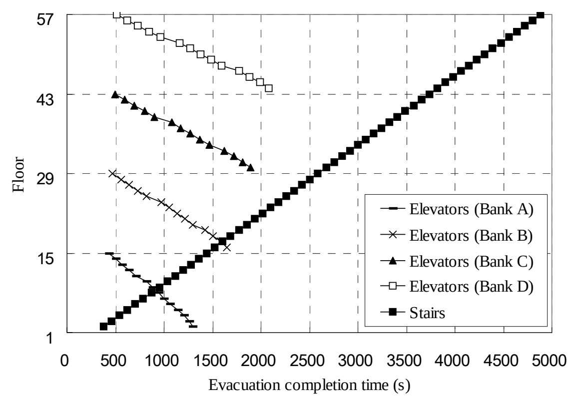

Fig. 6. Comparison of the evacuation completion time.

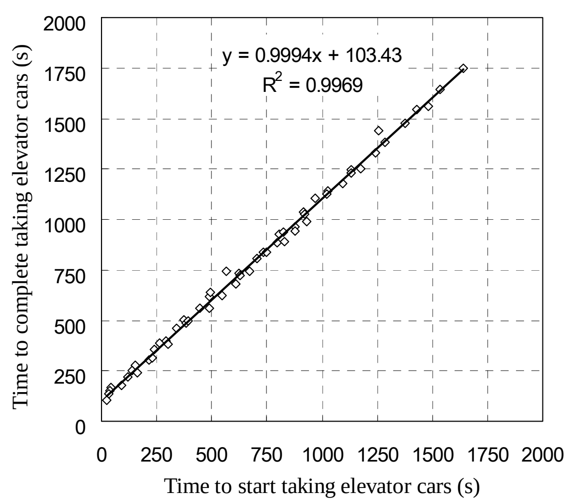

Fig. 7. Comparison between time to start taking and time to complete taking elevator cars.

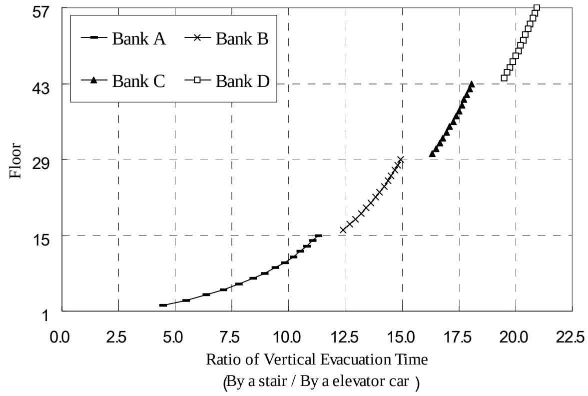

Fig. 8. Ratio of vertical travel time by an elevator car and by a stairway.

Therefore, it might be effective to use elevator cars mainly for evacuation at upper floors in the high-rise building. Moreover, it is necessary to move elevator cars to the most congested story continuously so that the evacuation waiting time by elevator cars may become shorter.

The Influence of the Probability of Success of Fire Protection Systems

The indices are calculated in order to produce an "evacuation safety index" such as shown by Eq. 1. The indices are "failure ratio of evacuation index" and "failure number of evacuees index." The "failure ratio of evacuation index" is defined as expected number of occupants unable to escape according to fire scenarios, and the "failure number of evacuees index" is defined as the number of occupants unable to escape according to fire scenarios. These indices are shown in Fig. 9. As a result, the following became clear.

- The "failure number of evacuees index" by elevator cars and by stairways was zero in case of success of smoke control system (case of an odd number).
- When three or four of fire protection systems failed, a "failure number of evacuees index" was larger than the other cases (Cases 8, 12, 14, and 16).
- The "failure ratio of evacuation index" of Case 2 was higher than other cases. Case 2 is the case of the failure of smoke control system operation and the success of other fire protection systems.

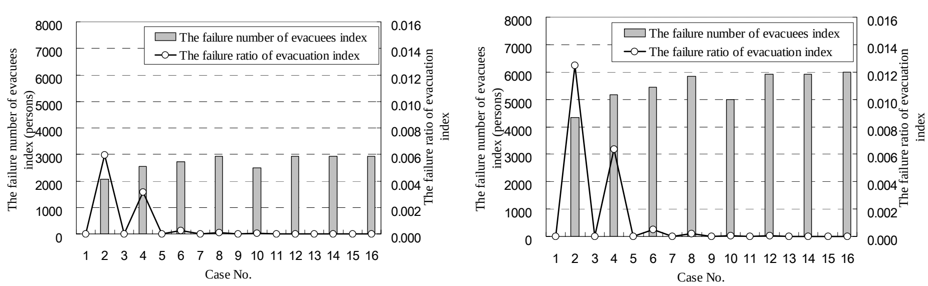

Fig. 9. The calculation result for each case (Left: by elevator cars, Right: by stairways).

Calculating an "Evacuation Safety Index"

The values of E_{safe}, E_{out}, and P_k are shown below. E_{safe} for the elevator evacuation was higher than the index for the stairway evacuation, and E_{out} and P_k for the elevator evacuation were smaller than the index for the stairway evacuation.

$$\begin{aligned} &E_{safe\_elv} = 0.9905 \\ &E_{out\_elv} = 1 - E_{safe\_elv} = 0.0095 \\ &P_{k\_elv} = E_{out\_elv} P_{occupants} = 0.0095 * 11760 = 112(\ persons\ ) \end{aligned} \tag{8}$$

$$\begin{aligned} &E_{safe\_stair} = 0.9803 \\ &E_{out\_stair} = 1 - E_{safe\_stair} = 0.0197 \\ &P_{k\_stair} = E_{out\_stair} P_{occupants} = 0.0197 * 11760 = 231(\ persons\ ) \end{aligned} \tag{9}$$

CONCLUSIONS

We conducted fire risk assessment by using an elevator evacuation model for multiple elevator cars in a typical high-rise building to examine merits and demerits of evacuation by elevator in consideration of the influence of smoke. The results of case studies are summarized as follows.

- The evacuation completion time by elevators evacuation is shorter than the time by stairways evacuation. Moreover, the effectiveness of elevator evacuation compared to stairways evacuation appears especially large for upper floors. However, the waiting time varies widely from 22 seconds to 1640 seconds. Therefore, in order to escape by elevator cars effectively, elevator cars should be used mainly for evacuation from the upper part of a building. Moreover, it is necessary to move elevator cars to the congested floors continuously so that the evacuation waiting time by elevator cars become shorter.
- In order to decrease "failure number of evacuees index," the operation of fire protection systems such as sprinkler systems, compartmentation, and smoke control systems are necessary. Especially, the effect of smoke control systems is more significant than that of other fire protection systems in this case study. To assure safer evacuation using regular elevator cars, it is necessary to keep smoke control for lobbies of regular elevator cars.
- The E_{safe} for elevator cars was larger than the index of stairways. The difference of the index was seemingly small, because the probability of number of occupants unable to escape was small. However, E_{out} for stairways is twice index for elevator cars, and the difference of number of occupants unable to escape is 119 persons.

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