Study on the Concept of Using Lifts and Escalators in Evacuation Routes Using Fragility Assessment

(Damage Analysis and Pedestrian Simulation)

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Keywords: Safety Evacuation, Escalator, Fragility assessment, Seismic response analysis

Abstract. In Japan, seismic safety design has been used for buildings on the ground surface and for important facilities and equipment. However, few studies have been conducted on maintaining system functionality during earthquakes, considering buildings and equipment within buildings as a single system. Lifts and escalators, which are normally used as flow lines, cannot be used in evacuation routes in the event of fire or disaster. In this study, a pedestrian simulation is carried out on the assumption of escalators after the revision of seismic standards reported in a previous paper, taking into account damage occurring to equipment related to the selection of evacuation routes, and the concept of an appropriate evacuation route is examined. This paper analyses the effectiveness of the use of escalators and elevators for rapid evacuation using pedestrian simulation in a high-rise building. As a result, it was confirmed that, in the analyzed building model used in this study, the use of escalators and elevators is effective in reducing the evacuation time by about 70 seconds for every 10 stories, compared to the time when evacuating by staircases.

1 INTRODUCTION

In Japan, seismic design has been adopted for buildings on the ground surface and important mechanical structures [1]. However, few studies have examined the maintenance of system functionality during earthquakes by considering the building and machinery within the building as a single system. For example, during strong earthquakes, not only the building itself is damaged, but also various piping, electrical cables, air conditioning equipment, elevators, and other mechanical elements within the building that maintain the function of the building system are often damaged, resulting in the failure of the building's function [2]. In addition, the impact of such damage on evacuation routes can be significant. Elevators and escalators, which are always used for human flow, cannot be used in evacuation routes. In the event of a disaster, lifts and escalators are designed to quickly move to the nearest floor and unload passengers, and escalators may stop suddenly when an abnormality is detected, such as in the event of an earthquake. In any case, the escalators are not yet ready to be utilized as evacuation routes.

This study examines the concept of appropriate evacuation routes based on pedestrian simulations considering damage events to mechanical structures related to the selection of evacuation routes, assuming the escalators after the revision of the seismic design standards reported in the previous paper [3]. In this paper, pedestrian simulations in a 40-story high-rise building are conducted to quantitatively evaluate the time required to complete evacuation and to analyse the effectiveness of using escalators and elevators for rapid evacuation.

2 DAMAGE PROBABILITY FROM FRAGILITY ASSESSMENT OF MECHANICAL STRUCTURES

2.1 Fragility assessment

In this study, the fragility assessment of equipment and machinery is carried out using an assessment method based on the realistic bearing capacity and realistic response of the object [4], [5]. The target equipment is modelled and the fragility evaluation indices are selected to produce a fragility curve that represents the damage probability of the equipment. The fragility curve is obtained using the probability density function of the capacity and response [6]. The probability density function is a normal distribution that includes uncertainty and can be expressed as follows, where μ is the mean of the data and σ is the standard deviation.

$$f_c\left(x\right)=\frac{1}{\sqrt{2\pi\sigma}}e^{\left[\frac{(x-\mu)^2}{2\sigma^2}\right]} \tag{1}$$

$$f_{Ra}\left(x_R\right)=\frac{1}{\sqrt{2\pi\sigma}}e^{\left[\frac{(x_R-\mu')^2}{2\sigma^2}\right]} \tag{2}$$

The fragility for an optional value of H due to the response of the rating index is a cumulative distribution function that represents the conditional damage probability that the probability density function $f_c(x)$ of the realistic capacity exceeds the probability density function $f_{Ra}(x_R)$ of the realistic response. It is expressed as follows.

$$F\left(\alpha\right)=\int_0^{\infty} f_{R\alpha}\left(H,x_R\right)\left(\int_0^{x_R} f_c\left(x\right)dx\right)dx_R \tag{3}$$

2.2 Damage mode

The fragility curve derived from the probability density function represents the probability of the occurrence of one damage mode. In real mechanical structures, damage occurs continuously in response to external inputs. If the occurrence or non-occurrence of only one damage state is analyzed, the hazards caused by other damage states and damage caused by other factors are not taken into account sufficiently. Therefore, this study focuses on damage modes, which divide the damage modes of mechanical structures into different phases. The damage mode is a classification of a specific damage mode in the response, and the damage probability represents the corresponding conditional probability.

2.3 Examples of fragility curves

In this example, suspended ceilings are considered [7], [8]. Suspended ceilings have a large installation area, so damage such as falling off may cause serious damage. In past major earthquakes, extremely critical situations due to falling ceiling panels have frequently been observed. Because of this risk, damage assessment is carried out under the stresses generated by the seismic response. Here, a ceiling with a mass of more than 2 kg/m2 is considered, as shown in Fig. 1. The suspension structure of a ceiling basically consists of suspension bolts with embedded inserts, bracing material between the pitches of the suspension bolts, and clips fixing the lower frame and ceiling plate. In the analysis, the mass part of the suspended ceiling is modelled as a one-degree-of-freedom vibration system. The capacity of the ceiling plate support clips is then investigated from the response of the mass section of the suspended ceiling. The damage mode settings for suspended ceilings are shown in Table 1. Mode 2 is set in consideration of the plastic deformation of the member due to the load test of the clip. Mode 3 is based on the acceleration at which rupture of the suspended ceiling is confirmed, and

Mode 4 is based on the capacity of the member. The calculated fragility curve is shown in Fig. 2. Based on the fragility curves, the damage probability of a suspended ceiling with a suspension length of 800 mm, a pitch of 900 mm between suspension bolts and a unit mass of 22 kg can be summarized for each clip, as an example, from the time history response of the building using one degree of freedom model due to each seismic wave. Table 2 summarizes the damage probabilities for each clip. Other fragility assessment factors considered in the study include suspension bolts and suspended equipment such as air-conditioning.

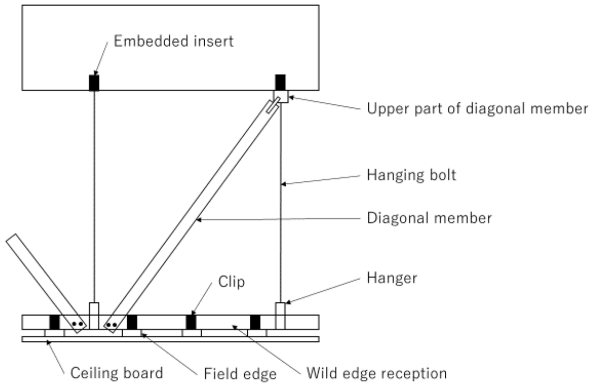


Figure 1 Typical suspended ceiling configurations

Table 1 Damage mode of suspended ceiling

Damage mode	Damaged condition
Mode1	No damage
Mode2	Plastic deformation of metal clips
Mode3	Partially dropped out
Mode4	All dropped out

Table 2 Seismic wave and Clip damage mode

Seismic wave	Max resp. Acc. [m/s^2]	Max resp disp [m]	Stress [N]	Damage mode value	Damage probability [%]
El Centro NS	3.84	0.0395	485	2.51	75.0
JMA Kobe NS	7.86	0.121	994	3.02	96.3

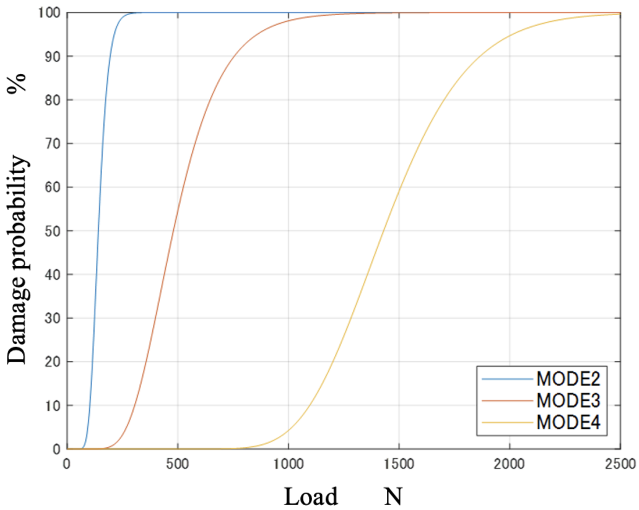


Figure 2 Fragility curve of clip

4 INFLUENCE COEFFICIENT AND SIMULATION OF A PEDESTRIAN

4.1 Influence coefficient from pedestrian simulation

In general, public facilities and buildings used by many people have defined evacuation routes, but not all of them may be passable in a disaster. Various damaged or dropped equipment in buildings may cause the evacuation route to be blocked. Generalizing the detour routes for evacuating pedestrians to obstacles and understanding the trends of detours according to the size of the obstacle and the degree of path occupancy can contribute to improving evacuation safety from the stage of designing the layout of equipment.

In this study, diversion routes against obstacles are considered from pedestrian simulations, and the influence of obstacles on evacuation routes is calculated as an influence coefficient. In the simulation, one pedestrian is assumed to proceed along the evacuation route while bypassing obstacles. Obstacles are placed on the evacuation routes divided into a grid with different occupancy rates for different degrees of damage. Basically, pedestrians go straight ahead, and if there is an obstacle in their path, they bypass it to the left or right. The distance from the start point to the end point is calculated. In this simulation, a 1/6th scaled evacuation route with a passageway of 2.5m wide and 10m long, divided into 15 × 60 cells, is used. The diversion behaviour of the pedestrian is assumed to be to a greater extent than the actual size to avoid the obstacle. A weight of 50 % passability is added around the proximity of the obstacle. The influence coefficient is determined from the simulation results and the ratio of straight-ahead time without obstacles.

$$e = 1 - \frac{v_e}{v_0} = 1 - \frac{x/t_e}{x/t_0} = 1 - \frac{t_0}{t_e} \tag{4}$$

In here, v_e: walking speed in each damage mode, v_0: walking speed without obstacles, t_e: required evacuation time for each damage mode, t_0: required evacuation time without obstacles. An obstacle is defined as e=0, and no passage at all is defined as e=1. For the walking speed during evacuation, the average walking speed of all generations of men and women, 1.18 [m/s] [9], is used from the average walking speed of men and women by age group. In this paper, it is assumed that healthy persons evacuate by walking.

4.2 Simulation with a suspended ceiling as an obstacle

The evacuation routes for each damage mode assuming a ceiling fall are shown in Fig.3. The ceiling panel is 1.8×0.9 m. Several patterns of evacuation routes are derived from the simulation. Four examples are shown here. From the simulation results, the bypass patterns for each damage mode are shown in Fig. 4. The walking times and calculated impact coefficients for each damage mode are summarized in Table 3.

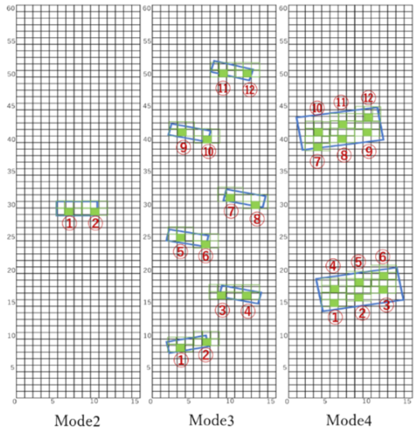
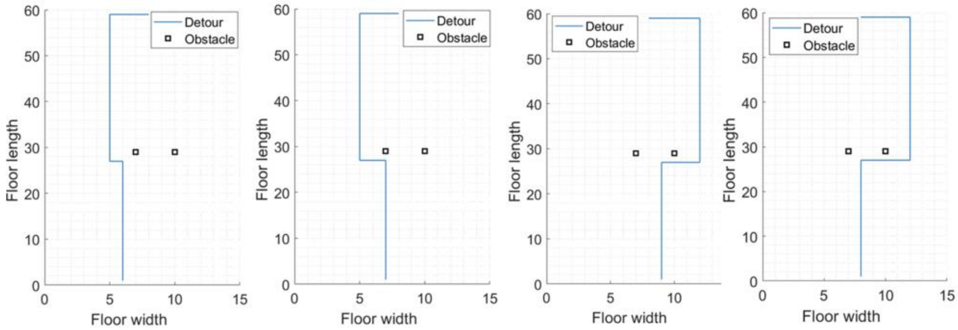
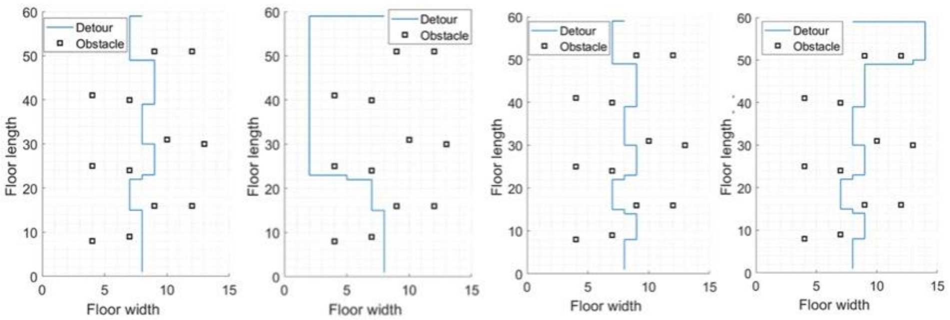


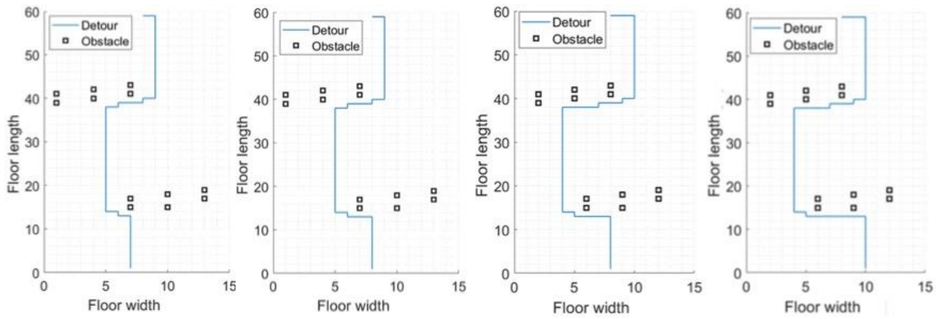
Figure 3 Example of a study of falling ceiling panels into an escape route.



(a) Mode2 simulation results of ceiling



(b) Mode3 simulation results of ceiling



(c) Mode4 simulation results of ceiling

Figure 4 Simulation of evacuation with falling ceiling panels

Table 3 Walking time and Influence coefficient

Damage mode	Min. walking time [s]	Max. walking time [s]	Min. Influence coefficient	Max. Influence coefficient
Mode2	8.47	8.89	0.231	0.267
Mode3	9.32	9.83	0.301	0.337
Mode4	9.15	10.17	0.288	0.359

5 PEDESTRIAN SIMULATION IN A HIGH-RISE BUILDING

5.1 High-rise building for simulation

In high-rise buildings, the seismic response differs between the low-rise, mid-rise and high-rise floors, which may result in various types of damage to the installed equipment. Therefore, a comprehensive understanding of the effects of the seismic response is required. In addition, evacuation simulation in high-rise buildings makes it possible to ascertain evacuation assumptions for different building heights and structures.

In this study, the evacuation situation is simulated by pedestrian simulation on each floor of a high-rise building, and the time required for evacuation is investigated from the results. A 40-storey office building is assumed as a high-rise building. The building model is shown in Fig. 5. The height of the target building is assumed to be 160 [m] and 4 [m] per storey. The dimensions of each floor are set to 40 x 40 [m].

The floor map for each floor is the same for each of the 10 floors as shown in Fig. 6. As the diagram shows, each floor has two staircases, an escalator, and an elevator. A total of 100 evacuees are assumed for each floor and a total of 4000 evacuees are considered in the building for the pedestrian simulation.

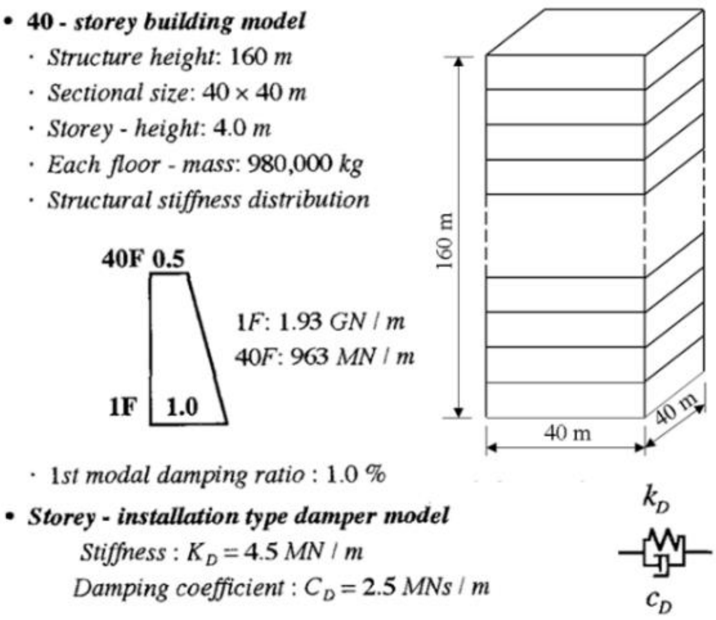


Figure 5 High-rise building model used for Pedestrian simulation

Figure 6 Floor map for each of the 10 floors

The equations of motion of the building model are expressed by the following equations:

$$\boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{C}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} = -\boldsymbol{M}\ddot{\boldsymbol{Z}}_H. \tag{5}$$

Here, the mass matrix, damping matrix and stiffness matrix are as follows:

$$\boldsymbol{M} = \begin{bmatrix} m_1 & 0 & \cdots & \cdots & 0 \\ & m_2 & 0 & \cdots & 0 \\ & & \ddots & & \vdots \\ & & & m_{39} & 0 \\ & & & & m_{40} \end{bmatrix} \qquad \boldsymbol{C} = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & \cdots & 0 \\ & c_2 + c_3 & -c_3 & \cdots & 0 \\ & & \ddots & & \vdots \\ & & & c_{39} + c_{40} & -c_{40} \\ & & & & c_{40} \end{bmatrix}$$

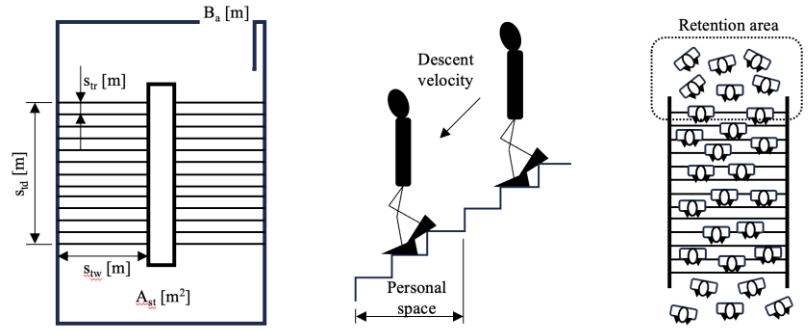
$$\boldsymbol{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & \cdots & 0 \\ & k_2 + k_3 & -k_3 & \cdots & 0 \\ & & \ddots & & \vdots \\ & & & k_{39} + k_{40} & -k_{40} \\ & & & & k_{N40} \end{bmatrix}$$

5.2 Pedestrian simulation method using a high-rise building

5.2.1 Examination of evacuation method by staircase

In this pedestrian simulation, the cells divided into a floor map grid are numbered, and the simulation is performed by moving to a cell with a smaller number than the current cell. If there is a person or obstacle in the cell to be moved to, the algorithm waits, or acquires the number of the diagonal cell and can move if the number is smaller than the current cell and there is no person in the cell. The walking speed is 1.0 m/s and the time is calculated from the number of steps required for evacuation. The evacuation of a high-rise building involves a large percentage of time for staircase evacuation, including escalators if available. Therefore, the staircase movements shown in Fig. 7(a) are considered in detail and the time required for evacuation is calculated. In the case of stair descent by evacuees, the number of persons who can be evacuated within a certain time is calculated. Furthermore, the delay time due to stagnation propagation is assigned as a variation of the evacuation time using a model for the occurrence of stagnation phenomena as shown in Fig. 7(c) caused by human congestion at staircase entrances and in staircase rooms.

In order to establish these calculation models and to obtain the stair specifications and the behaviour of pedestrians when descending stairs, field measurements are carried out and a realistic evacuation time is calculated based on the measured data [10]. The calculation model outputting the throughput for evacuation from the staircase is calculated on the basis of references [11]. Here, the specifications of the staircase (stair width and length, door width, landing area, etc.), pedestrian specifications (step height, walking speed, number of parallels, etc.) and the retention specifications that occur near the entrance (retention area, retention density, etc.) are set. Based on the setting of the various parameters, the occurrence time and the transition (flow rate) of the number of people in the three states of stagnation, start of stair descent and end of stair descent are calculated.



(a) (b) (c)

Figure 7 Analytical parameters for the use of stairs during evacuation

The performance of the staircases used in the simulation in a given time period is considered. As an example, the performance of staircases and people, and the resulting evacuation time model cases are shown in Table 4. For the generation of delay times due to stagnant propagation in stairwells in high-rise buildings, the walking conditions in the stairwells are differentiated between flow and stagnant conditions. The parameters of the stagnation in stairwells are based on statistics: the density of the flow state is 1.66 /m^2, the stagnation density is about 4.0/m^2, and 5.5/m^2 is a complete stop. The confluence ratio of the passage and staircase descent communities is 0.66~0.69. The example dimensions of the staircase landing are a landing length of 4.5m, landing width of 2.1m, and landing area of 9.45m^2. The calculated results are shown in Table 5.

The results show that the maximum floor evacuation time without stairwell stagnation is 52s, the maximum delay time due to stagnation propagation is 52s and the maximum floor evacuation time due to delay time is approximately 85s. These results show that the floor evacuation time is approximately in the range of 58-100s when stairwell retention

Table 4 Stairs and walker specs

Target	Measured value
Stairs entrance width [B_a]	1.2 [m]
Stair width [s_{tw}]	2.22[m]
Stairs walking distance [s_{td}]	13.91 [m]
Length of one staircase [s_{tr}]	0.294 [m]
Stairs travel time [Est]	19.3[s]
Max. number of people in parallel [Pmax]	3
Congestion end time [N]	67.3 [s]
Width space [Cs]	0.6~0.9[m]
Vertical space [Cv]	3[step]

Table 5 Delay time by retention

Max. delay time [s]	Min. floor evacuation time[s]	Max. floor evacuation time [s]
52.1	51.9	84.7

5.2.2 Examination of evacuation method by escalators

In Japan, the use of elevators for evacuation and escalators during disasters has not yet been authorized, but this paper examines the possibility of improving the efficiency of evacuation routes by using escalators and stairs together when evacuating a large number of people from upper floors during an earthquake [12]. In many commercial buildings, escalators are located in the centre of the floor and evacuation stairways are located at the end of the floor, far from the centre. In such structures, the use of escalators for evacuation could greatly improve safety and evacuation time efficiency. Escalator travel during evacuation is assumed to be accompanied by walking. In this case, the speed of the escalator is 0.5 m/s and the speed of movement during stair walking is 0.6 m/s, which together are treated as 1.1 m/s. The length of the escalator is assumed to be 8 m. As the building in question is a 40-storey building, the number of escalators is 39 x 2. The calculation of the time required to complete the evacuation by escalator can be expressed by the following equation.

$$\frac{l \times n}{v} + t_t \times 2 \times (c - 1) \quad (6)$$

In here, l: escalator length, n: number of escalators, v: travel speed, t_t: time per step, c: number of people in line.

5.2.3 Examination of evacuation method by lifts

In high-rise buildings, few elevators move through all levels, and the floors on which they operate are often defined [13]. In this study, the elevators are set up so that they stop every ten floors and the doors open and close. The specifications of the elevator handled in this study are shown in Table 6. This elevator specification is commonly used for general purposes.

Table 6 Elevator specifications

Service floor	1 to 40	
Capacity [people]	22	
Rated speed [m/s]	5.0	
Acceleration and deceleration [m/s^2]	±0.7	
Door width [m]	1.1	
Door opening and closing time [s]	1.5	
Flow coefficient [people/m/s]	【Ride】1.07	【Alighting】1.22

5.2.4 Pedestrian simulation result in a high-rise building

Using the above condition set-up, an evacuation simulation is carried out for a 40-storey high-rise building. The results are shown in Fig.8. The figure graphically shows the time to complete evacuation for each evacuation method used, in relation to the inputs to the building in question. The results show that as the seismic input increases, the time to complete the evacuation increases due to the progression of damaged equipment and the increase in obstacles to the evacuation route. It can also be confirmed that the use of multiple means of evacuation allows for a faster and safer evacuation. The time saved by using only the staircase versus using all evacuation routes is about 300 seconds. It can also be confirmed that escalators contribute to faster evacuation than elevators.

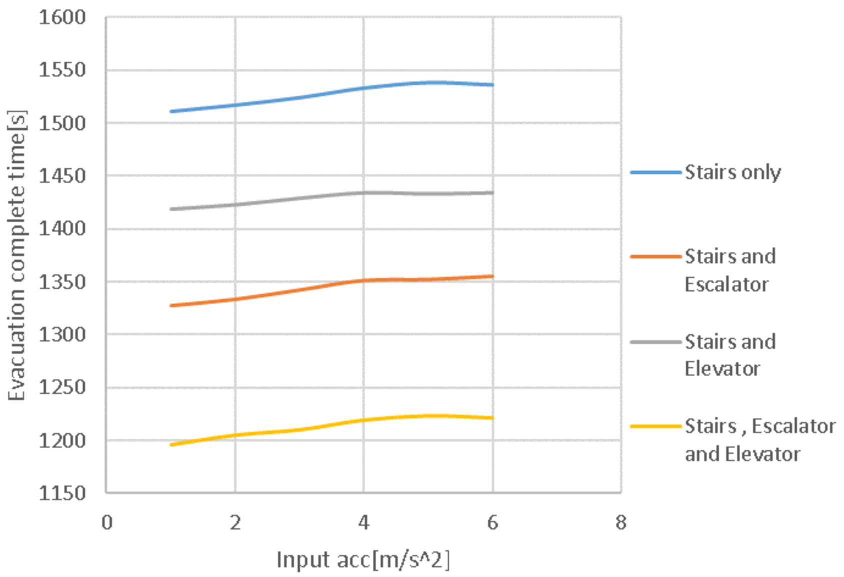


Figure 8 Pedestrian simulation result in high-rise building

6 CONCLUSIONS

Damage to equipment in buildings during an earthquake under seismic loads due to building response was investigated, and evacuation routes were evaluated, taking into account the probability of damage. In this paper, impact coefficients representing the degree of impact on the pathway at the time of damage were calculated from pedestrian simulations, from each damage mode defined for the damage state of the mechanical structures. An analytical model was also developed to calculate the evacuation capacity of stairways, focusing on stairways as an existing means of evacuation. Furthermore, pedestrian simulation in multi-storey buildings in a time history response analysis of a high-rise building was carried out to quantitatively confirm the time required to complete evacuation in relation to the input earthquake level. Furthermore, pedestrian simulation in multi-storey buildings in a time history response analysis of a high-rise building was carried out to quantitatively confirm the time required to complete evacuation in relation to the input earthquake level. The effectiveness of using escalators and elevators together as evacuation means to speed up evacuation was confirmed. As a result, it was confirmed that a time reduction of about 300 seconds was achieved compared to a staircase evacuation. Based on the concept of using escalators and elevators in combination with stairs, it was confirmed that a time reduction effect of about 70 seconds could be achieved for every 10 levels. The pedestrian simulation constructed to determine evacuation times can be set up for group travel, but does not apply psychological states and interactions between people, so reflecting these effects in the simulation would contribute to improving the accuracy of actual evacuation route time estimation.

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BIOGRAPHICAL DETAILS

Ryusei Nakajima is a master's course student in mechanical engineering at Tokyo Denki University. He researches safe evacuation routes including mechanical structures.

Prof. Osamu Furuya is Professor at Tokyo Denki University. Recently, his main research object is the research and development of vibration reduction for various structures and seismic safety for important facilities.