Study on Evacuation Route in Case of Disaster Considering the Fragility of Mechanical Structures

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Abstract. To improve the evacuation safety of multi-story buildings by escalator, escalator fragility curves were calculated using a probabilistic risk assessment. In order to calculate the damage probability of the escalator and mechanical structure in each story, the time history response analysis of the three storey building model was calculated. A floor model was constructed from graph theory, and a simulation to find a safe evacuation route. The change in the possibility of using the escalator during evacuation due to the revision of the seismic code of the escalator was compared with the old Japanese code in each floor of the building.

1 INTRODUCTION

In the earthquake disaster, many industrial facilities suffered frequent equipment damage and their functions stopped. It also led to secondary damage such as breaking of the evacuation route due to falling or scattering of equipment. The seismic code for escalators was revised because of the fall accident of the escalator body in the Great East Japan Earthquake on March 11, 2011. Since the standard was set to make the interstorey drift angle of buildings in the event of an earthquake larger than before, the shortage of the length of the escalator, which is considered to be the main cause of the fall accident, has been improved.

However, the evacuation plan at the time of a disaster is still in accordance with the old seismic standard, and the use of escalators is not stipulated, and it is recommended to avoid using it during evacuation [1]. In many commercial facilities, there is only an escalator in the center of the floor, and the evacuation exit is located far from the center. In such a structure, using an escalator for evacuation can greatly improve safety and efficiency. Therefore, the feasibility of an evacuation plan including an escalator will be examined as a new proposal based on the new standard.

In this research, the durability and the risk (or safety) on the evacuation route were examined by applying the probabilistic risk assessment to the design parameters of escalator and mechanical structures related to evacuation route. The safety of the escalator will be examined by simulating the search for a safe evacuation route in a multi-story building in consideration of the danger of mechanical structures.

2 RISK ASSESSMENT

2.1 Escalator structure

As shown in Fig.1, the escalator mainly consists of transportation equipment such as steps and handrails, and an escalator truss that supports the transportation equipment. L-shaped support members are attached to both ends of the escalator, and the support members are hung on the building beam and one or both ends are not fixed. Therefore, a supporting method is adopted in which the non-fixed part of the escalator slips during an earthquake and the forced displacement due to the interstorey drift of the building is released [2][3].

In this research, the escalator with fixed lower end and non-fixed upper end, which has the same support method as the escalator in which a fall accident occurs, is targeted. The escalator with fixed lower end and non-fixed upper end is an escalator installed with the supporting member at the lower end of the escalator truss fixed to the building beam and the supporting member at the upper end sliding on the building beam. The part where the support member attached to the escalator truss and the building beam overlap is called the Overlap allowance.

A new standard defines a structure with a low risk of the escalator falling off due to an earthquake or other vibration after the escalator fall accident (Japan Building Equipment/Elevator Center, Japan Elevator Association, 2016). As shown in Table 1, the standard value of the interstorey drift angle before design was 1/100 [rad] or less before revision, whereas the revised standard value was 1/40 [rad], When structural calculation is not performed, it is over 1/24 [rad] [4]. Three standards, 1/100[rad], 1/40[rad], 1/24[rad], are set as Old standard, New standard1, New standard2 in the table. Since the interstorey drift angle is greatly increased, the overlap allowance of escalator increases, and there is a margin for the slide displacement to escape the forced displacement due to the building.

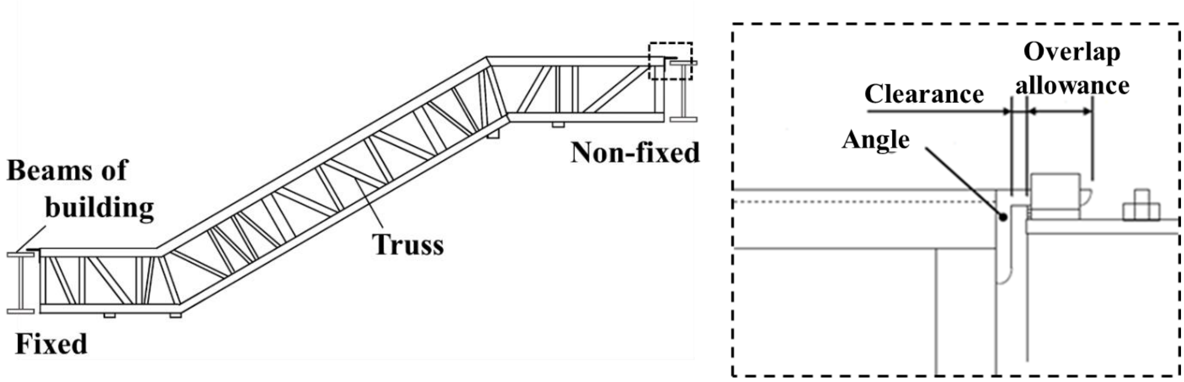


Figure 1 Escalator system and the non-fixed side of the escalator

Table 1 Interstorey drift angle and overlap allowance of the escalator

	Design for the Interstorey drift angle [rad]	Clearance [m]	Overlap allowance [m]
Old standard	1/100	0.03	0.080
New standard 1	1/40		0.245
New standard 2	1/24		0.428

2.2 Escalator Fragility curve

In this research, damage evaluation of mechanical structures is performed by a method based on realistic proof strength and realistic response. Model an object to be evaluated, select damage evaluation index, and create a fragility curve that represents the damage probability [5]. The fragility curve is obtained by using the probability density function of proof stress and response. The probability density function is a normal distribution that includes variations in consideration of uncertainty. Letting the average of the data be μ and the standard deviation be σ. From these parameters, the probability density function of realistic strength and realistic response is calculated by the following equation (1) (2).

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

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

The fragility for an arbitrary value H according to the evaluation index is a cumulative distribution function representing the conditional damage probability, in which the probability density function $f_c(x)$ of the realistic strength exceeds the probability density function $f_{Ra}(x_R)$ of the realistic response. It is calculated from equation (3).

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

The cause of the escalator's fall is considered to be that the escalator fell off the building beam because the non-fixed part of the building slipped a lot due to the unexpected interstorey drift of the building caused by the earthquake motion. Therefore, the three Design for the interstorey drift angle in Table 1 are used as evaluation indices as standard for the possibility of escalator falling. As shown in Fig.2, assuming an escalator with each as a standard for evacuation safety, the probability density distribution is calculated from the statistics based on the slide allowance and the drift angle.

The fragility curve is calculated as shown in Fig.3 from the probability density distribution. The fragility curve that can determine the damage probability of each mechanical structure during vibration is a weight that represents the traffic risk on the evacuation route. If it exceeds the standard value, it is judged that there is a risk for lifting and lowering, so 80-90% is given as a weight. In addition, the 50% reliability curve is applied in consideration of aging deterioration and uncertainty of the structure.

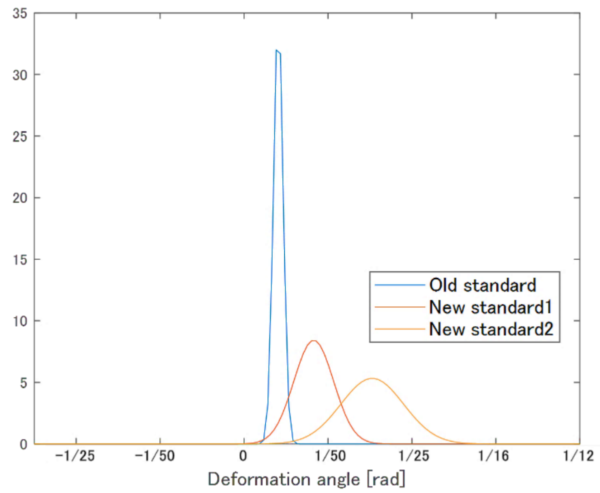


Figure 2 Probability density distribution of escalator

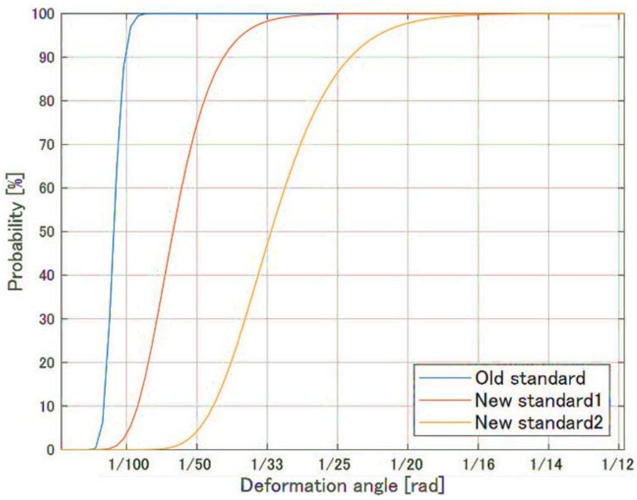
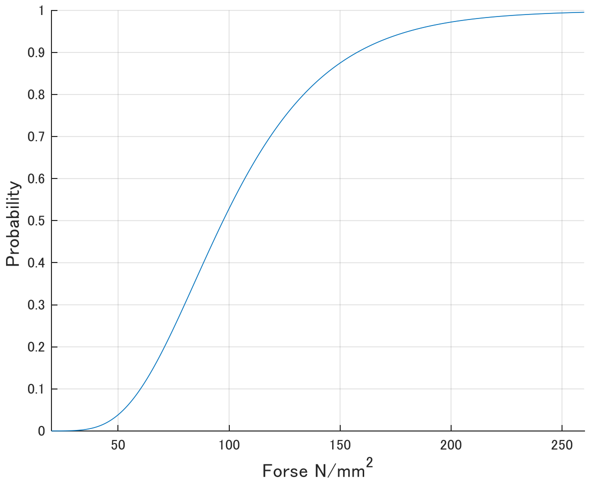


Figure 3 Fragility curve of escalator

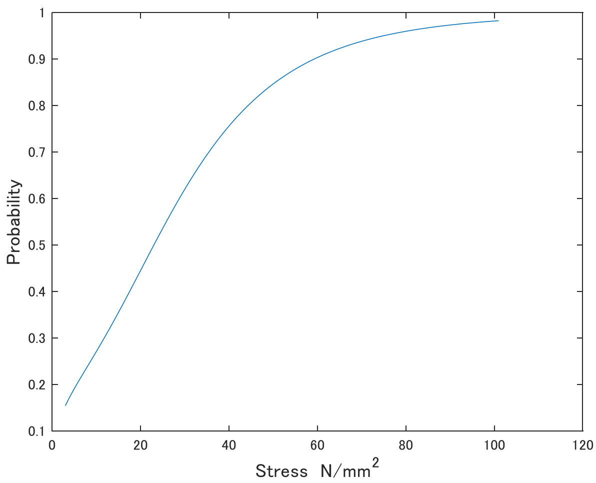
2.3 Other Mechanical structure Fragility curves

At commercial facilities and terminal stations, there are plate glasses, suspended information boards, electronic bulletin boards, and piping. In this research, damage evaluation is shown as these mechanical structures that can be obstacles on the evacuation route.

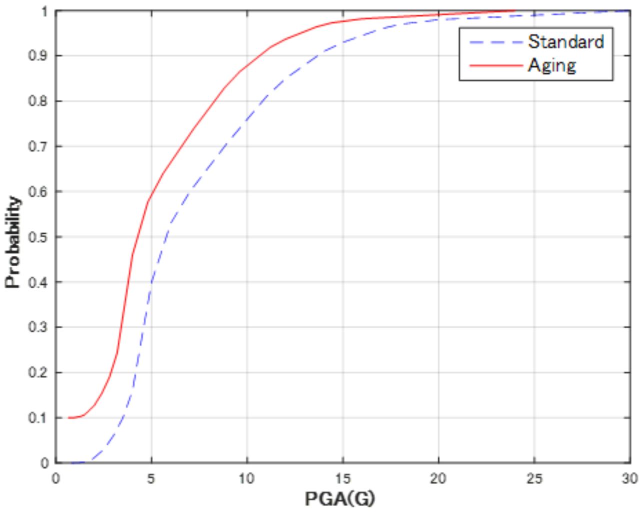
In plate glass, many small cracks exist on the surface, and stress concentration due to external force is thought to occur at the crack tip. When stress is continuously applied, the crack grows deep and leads to fracture. Destruction occurs at the practical strength of plate glass of about 49 to 98 [N/mm^2] [6]. Therefore, the calculation was performed when the horizontal axis of the fragility curve in Fig.4 (a) was stress. In a ceiling-mounted structure, it plays the role of holding the hanging bolt (pole) so that it will not fall. Suspension bolt damage is caused by cracks gradually progressing and cross-sectional areas decreasing due to repeated vibration and load [7]. Therefore, as shown in Fig.4 (b), calculation was performed with the horizontal axis of the fragility curve as the stress. As for piping, the structural integrity of the piping used in nuclear facilities has been confirmed [8]. In this research, it is assumed that the structure is used for general building structures, Fig.4 (c) shows the results of piping examination.



(a) Plate glass



(b) Hanging bolt



(c) Piping

Figure 4 Mechanical structure Fragility curves

3 SIMULATION MODEL

3.1 Response analysis using Building model

A time history response analysis of a multi-story building is performed to select the damage state, damage probability, and search conditions for mechanical structures for evacuation route search. The analytical model of the building is assumed to be a steel-framed three-story commercial facility in which the escalator falls. Fig. 5 shows the analytical model of the building model. In Fig.5, m_{si} is the mass, c_{si} is the damping coefficient, k_{si} is the initial stiffness, and $\ddot{z}_H$ is the ground acceleration. The input ground motion was the K-NET Sendai NS Original wave observed in Sendai City, Miyagi Prefecture during the Tohoku-Pacific Ocean Earthquake [9].

The maximum values of each response are shown in Fig.6. From the maximum interstorey drift angle results, the design interstorey drift angle 1/100 [rad] used in the old standard for calculating the margin is exceeded in the first layer. In the second layer, it can be confirmed that the value is close to 1/40 [rad] of the new standard.

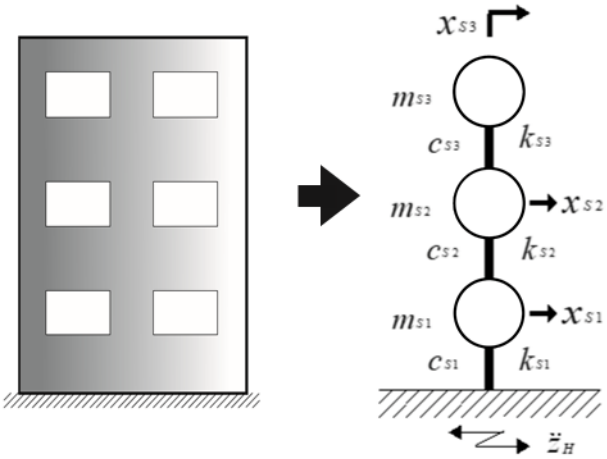


Figure 5 Analytical model of building

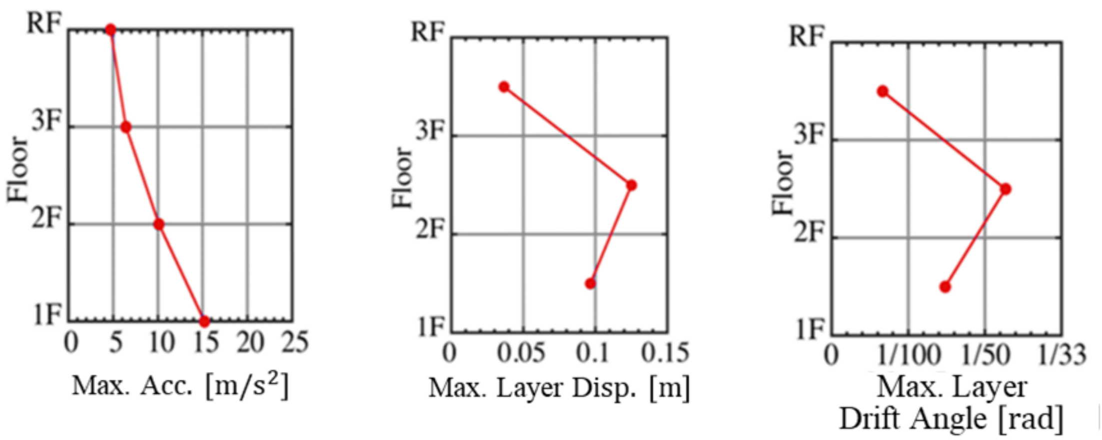


Figure 6 Response values of each layer

3.2 Evacuation route search Simulation model

The evacuation route is evaluated by modeling the floor in the facility using graph theory. This is a method of modeling a phenomenon using points (nodes) dividing a route and line segments (edges) connecting the points, and analyzing its properties and structure.

As a weight, the impassability rate (damage probability × influence coefficient) is given to the edge, and the Dijkstra method is applied in which the route with the lowest total probability is the shortest [10]. The floor model has a simple structure with a staircase and an escalator in the center as an evacuation exit. Figure 7 shows a floor model of the inside of the facility, and Fig.8 shows a network model showing the floor with nodes and edges. It can be confirmed that the escalator located in the center can handle evacuation from both directions toward the center.

The evacuation route is searched from the shortest route. The damage probability is calculated by applying each maximum response value of the 3rd floor building due to the input seismic wave to the fragility curve of the mechanical structure. The impassable rate is calculated from the damage probability and the degree of influence on the passage. In order to compare the evacuation safety of the escalator according to the old standard and the new standard, search between 2F-1F and between 2F-3F with large response values.

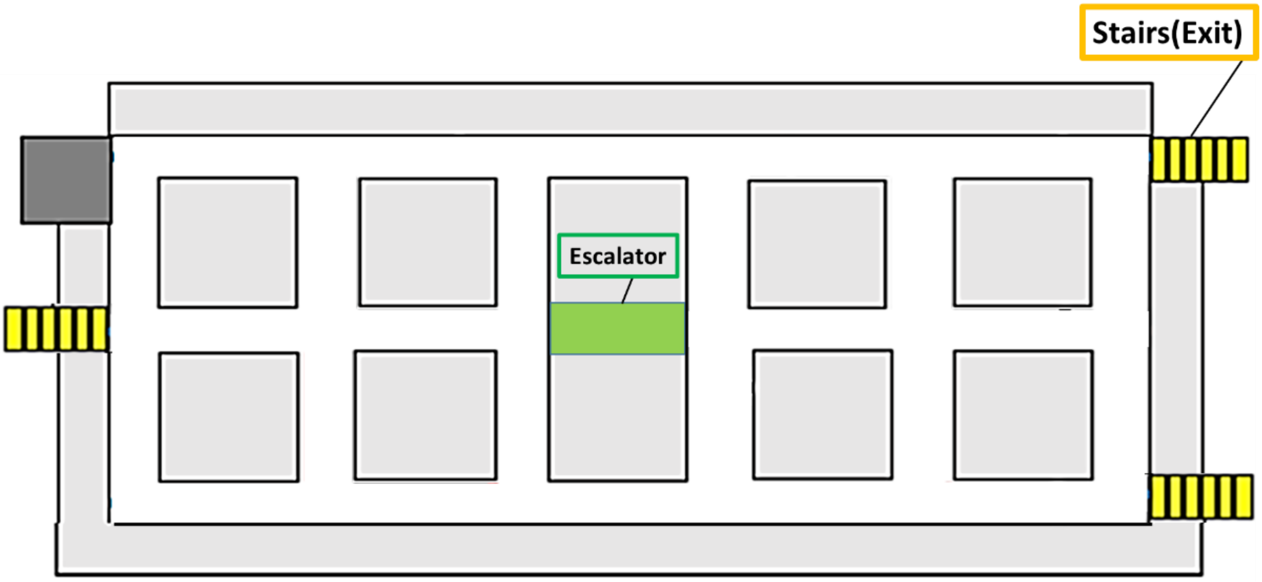


Figure 7 Floor model

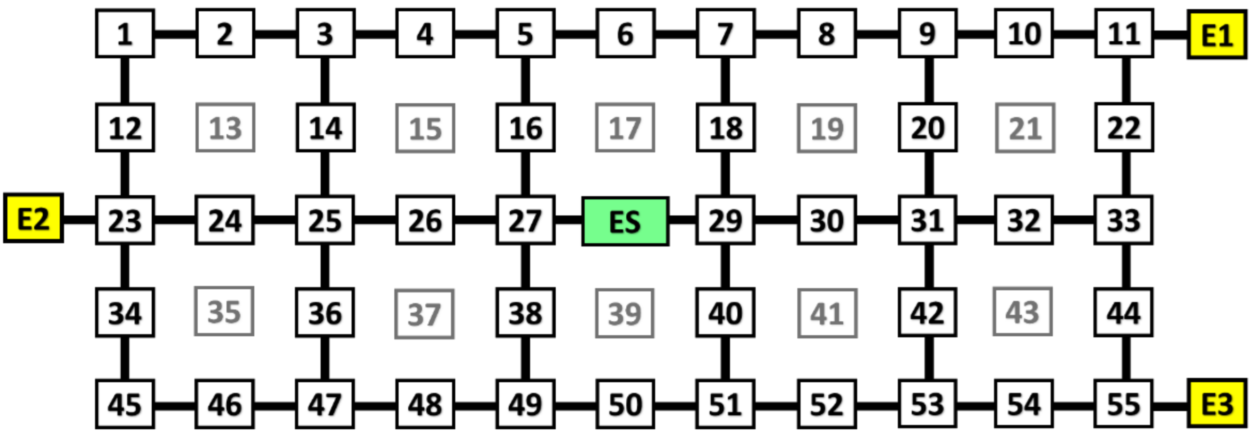


Figure 8 Network model of floor

4 EVACUTION ROUTE

4.1 Evacuation route focusing on Escalator

The safety of the escalator will be examined according to each standard in order to use it as the exit of the evacuation route. By using the inside of a facility with no obstacles as a model, the performance as an exit is evaluated from the evacuation distance and the risk of escalator. Since there are no obstacles, the safe evacuation route in this model is the shortest route.

Table 2 shows the damage probability of the escalator based on the maximum response value of each layer. At each node, the evacuation probability is calculated by simulating four routes leading to the exit. Probability of evacuation is the probability that the route will reach the exit, and specifies a passable level of 70% or higher. Table 3 shows the maximum evacuation probability for each level when using the escalator for each standard. In the old standard, all are about 20%, so there is a great risk and it is considered impossible to pass. Focusing on New standard 1, the evacuation probability was improved compared with the Old standard, 3F-2F was 33.6%, and 2F-1F was significantly improved at 76.0%. 2F-1F is a value exceeding 70% of the passable level. In New standard 2, the evacuation probability is significantly improved compared to other standards, 92.0% for 3F-2F and 97.6% for 2F-1F. This is a value far exceeding 70% of the passable level in both cases.

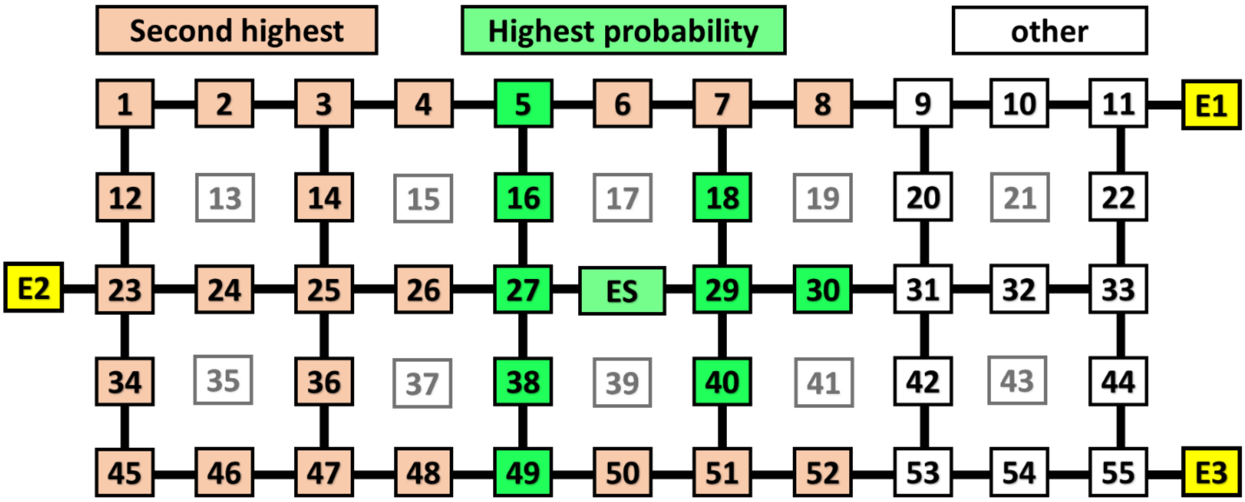
Figure 9 shows the evacuation probability of the shortest route from the escalator of New standard 2 to the exit. It can be seen that the central area (green) has the highest evacuation probability compared to other exits. Even at points away from the center, there are many areas (orange) that show the second highest evacuation probability. Due to the presence of mechanical structures, the second highest route may result in the safest route. In this way, even considering the danger of the escalator, it can be seen that the New standard 2 can function sufficiently as an exit. Especially in the central part of the floor where the stairway exit is not near, the escalator is considered to be effective in the efficiency and safety of evacuation behavior.

Table 2 Damage probability of escalator

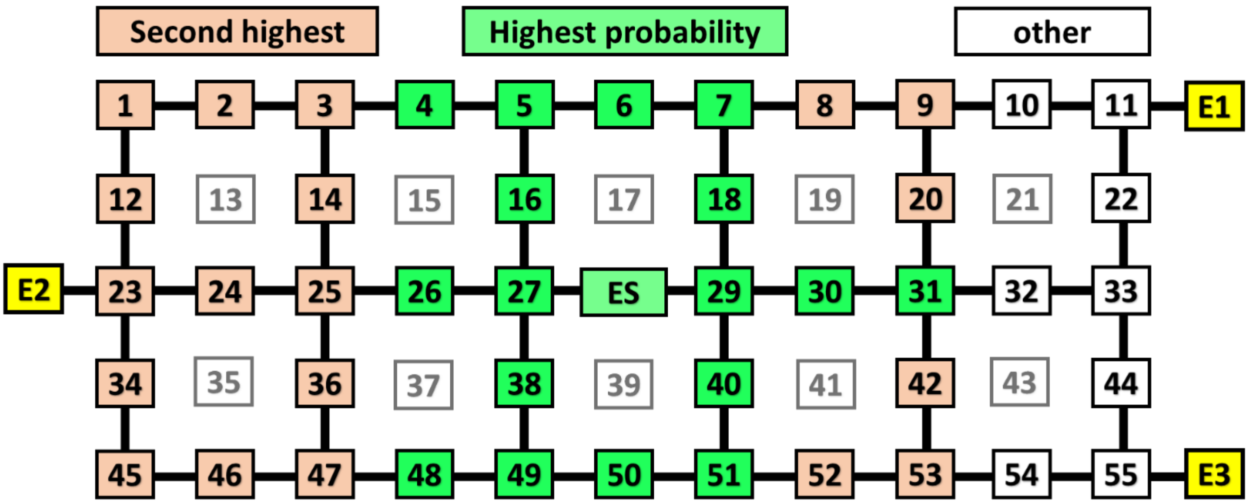
Mechanical structure		3F-2F Damage Probability [%]	2F-1F Damage Probability [%]
Escalator	Old standard	99	99
	New standard1	83	30
	New standard2	10	3

Table 3 Escalator maximum evacuation probability

	3F-2F Probability of evacuation [%]	2F-1F Probability of evacuation [%]
Old standard	20.8	20.8
New standard1	33.6	76.0
New standard2	92.0	97.6



(a) 3F-2F nodes



(b) 2F-1F nodes

Figure 9 Nodes with higher escalator probability than other exits

4.2 Evacuation route including mechanical structures

Search for safe evacuation routes under more realistic conditions with mechanical structures inside the facility. A safe route is a route with the highest probability of passage. As shown in Fig.10, the floor model has mechanical structures related to the evacuation route and stairs and escalators.

The search results of the route from node 9 to each exit node are shown below. Figure 11 shows the result of illustrating the evacuation route on the floor. Node 9 is close to both the escalator and E1. This is the place where the escalator can be used as the exit with the second highest evacuation probability depending on the conditions. Table 5 shows each Route with the node number indicating the safest route from the initial position (initial node) to each exit. Table 6 shows the probability of each standard of Route4, which is an evacuation route using an escalator.

As a general tendency, it was confirmed that a route is taken to avoid a structure with a high probability of damage. The layout of the structures is unified, and the evacuation routes do not change by floor due to the balance between impassability and distance. By following the route with the highest evacuation probability, determine the appropriate evacuation route for each floor.

Focusing on Route 4 which uses an escalator, it is impossible to pass because the old standard is about 10% in each case. In New standard 1, which is a general standard, the value is close to 70% of the passable level in 2F-1F. In the new standard 2 which is a strict standard, both are passable levels. It can be confirmed that 3F-2F is the safest route next to Route3, and 2F-1F is the safest route. From these results, it is considered that the escalator based on New standard2, which is the standard when no structural calculation is performed, can make a great contribution to the efficiency and safety of evacuation behavior even in facilities with mechanical structures.

Table 4 Damage probability of mechanical structure

Mechanical structure		3F-2F Damage Probability [%]	2F-1F Damage Probability [%]
Escalator	Old standard	99	99
	New standard1	83	30
	New standard2	10	3
Glass		90	80
Pole		14	20
Plumbing		92	75

Table 5 Evacuation route of simulation result

	Route	3F-2F Evacuation probability [%]	2F-1F Evacuation probability [%]	Length of the route
Route 1	9-20-31-32-33-22-11-E1	80.86	77.39	7
Route 2	9-8-7-6-5-16-27-38-49-48-47-36-25-24-23-E2	68.13	63.15	15
Route 3	9-20-31-42-53-54-55-E3	82.80	80.70	7
Route4	9-8-7-18-29- ES	-	-	5

Table 6 Escalator evacuation probability

	3F-2F Evacuation probability [%]	2F-1F Evacuation probability [%]
Old standard	18.30	17.70
New standard1	29.60	67.00
New standard2	82.10	87.00

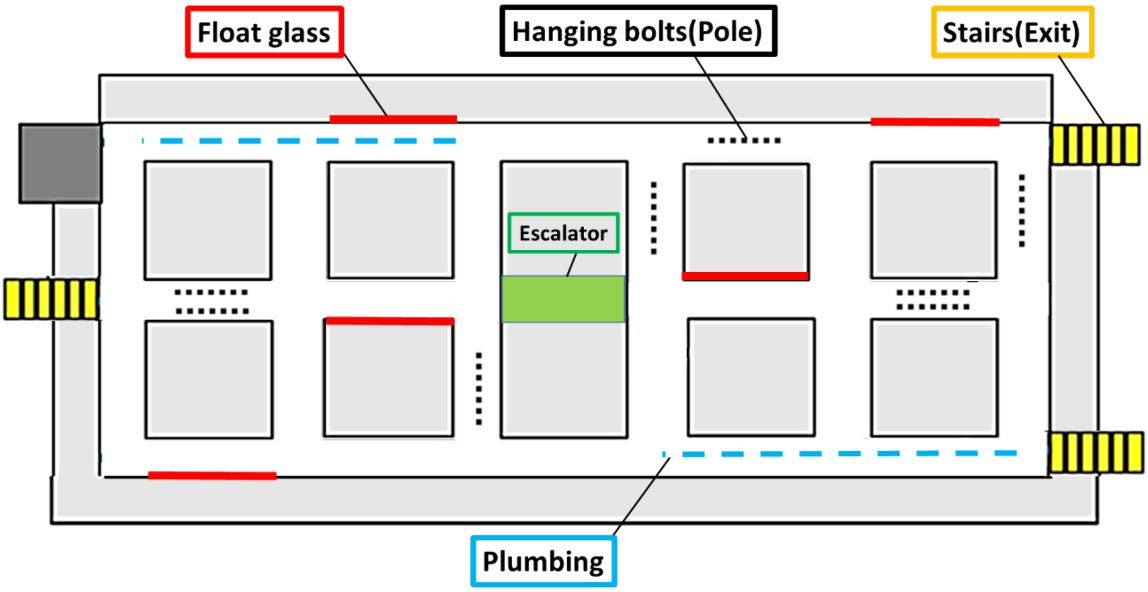


Figure 10 Floor model with mechanical structure

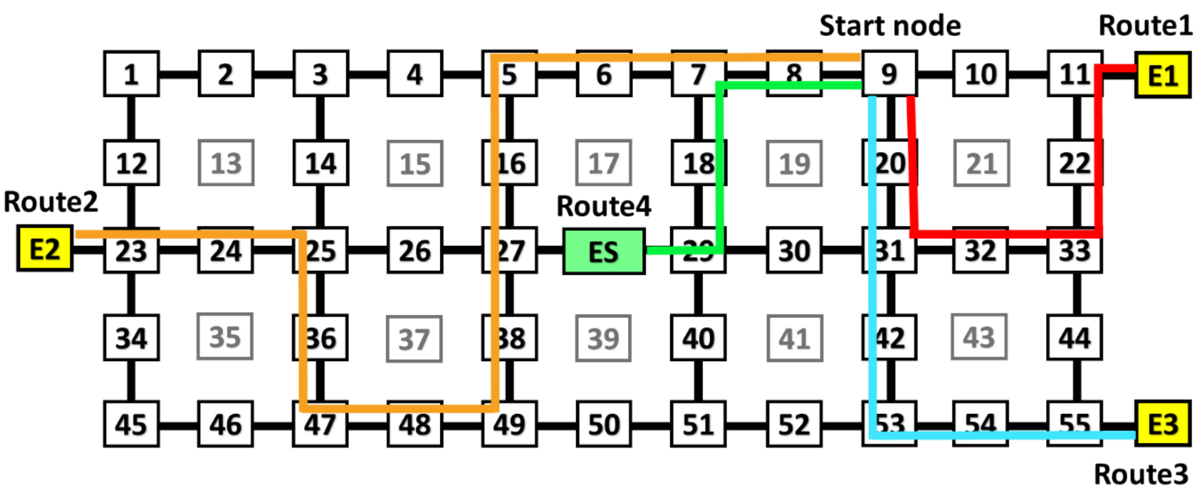


Figure 11 The evacuation route on the floor

5 CONCLUSION

In this study, to examine the use of escalators in evacuation planning, a fragility curve was calculated from a probabilistic risk assessment focusing on the falling event. The possibility of the escalator falling was calculated from the maximum response value of the multi-story building. The search for an evacuation route considering the risk of falling was simulated by applying the Dijkstra method to the route with the maximum Passable probability.

From these results, it is conceivable that the escalator will not be able to utilize New standard 1 as an evacuation route in the event of a large-scale earthquake, but it will have sufficient function as an exit at New standard 2 level.

As a future development, we will analyze the escalator slide displacement during an earthquake and make a more accurate evaluation. In addition, it is considered that the fluctuation of probability due to other conditions such as the passage of time and population density will increase. Therefore, considering the degree of influence of the structure on the passage, we plan to study the influence coefficient under a specific damage condition.

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CREDITS

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BIOGRAPHICAL DETAILS

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