A Study on Seismic Response Analysis in Consideration of Non-linear Restoring Force Characteristics of Escalator Truss Structure

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Abstract. In the Great East Japan Earthquake, fall accidents of four escalators occurred. In one of these accidents, the escalator that linked the third floor from second floor dropped. This occurred in the commercial facilities of the low-rise, steel-frame building. In general, escalators are usually installed in buildings with one side of them in fixed connection and the other side in free condition. In contrast, they might be installed both sides in the non-fixed style in order to mitigate undesirable excessive deflections induced in the truss-like structures of escalators. However, an escalator truss might break off from the building beams, due to excessive lateral deformations induced in the storey-layers. In a new public notice about the reinforcement of the falling off prevention structure of the escalator after these accidents, a new and improved structure was determined: 1, The structure must include enough overlap allowance, 2, The structure must take backup measures to ensure enough overlap allowance for the escalator truss to not come off from the beam of building, and so it is less likely to drop. During these accidents, it was also considered that a non-fixed part might collide with the beam of building by larger deflections than expected; this collision might cause excessive compressive force and residual displacement. It is necessary to clarify the seismic behavior of the escalator to prevent such an accident. From the above-mentioned background, the object of this research is to construct an analytical model to clarify the seismic response behavior using the non-linear restoring force characteristic of the escalator truss model. In this paper, the multi-linear model is built based on the load-displacement. In addition, the seismic response analysis of an escalator installed in the building is performed using the multi-linear model and the bi-linear model. As result, the bi-linear model is acceptable to evaluate the seismic response.

1 INTRODUCTION

Escalators are one of the most important vertical transportation measures to connect storey-layers in buildings. During severe earthquakes, escalators are not only shaken by themselves, but withstand lateral relative deflections induced in the structures or buildings installing them. Therefore, escalators are usually installed in the buildings with one side of them in fixed connection and the other side in free condition or utilized both sides in the non-fixed style in order to mitigate undesirable excessive deflections induced in the truss-like structures of escalators. However, in the Great East Japan Earthquake, fall accidents of four escalators occurred in the three locations [1] [2]. Escalator truss might come off from the building beams, because excessive lateral deformations were induced in the storey-layers with more than assumption where the accidents happened.

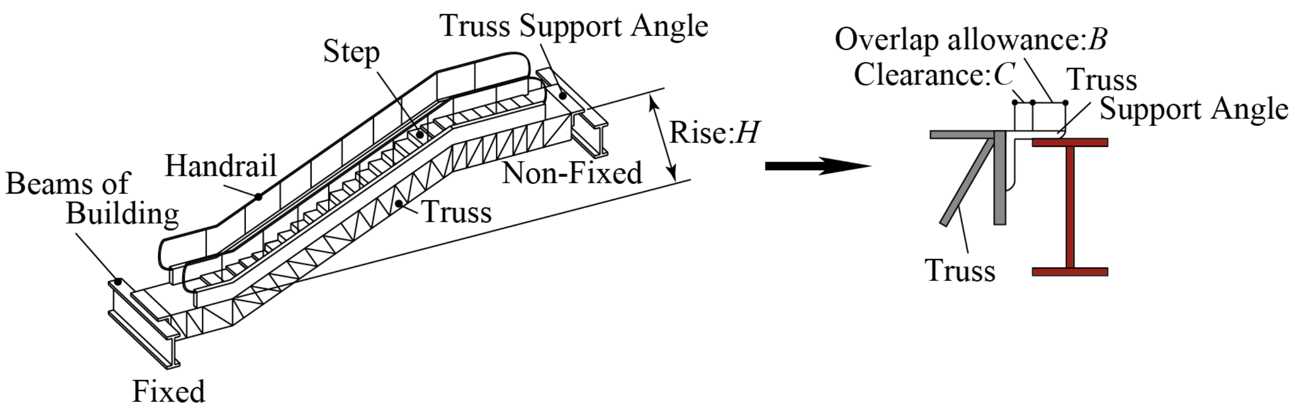
During these accidents, it was also considered that a non-fixed part might collide with the beam of building by larger deflections than expected occurred in the sliding parts; this collision might cause excessive compressive force and residual displacement in the escalator truss might be caused. It is necessary to clarify the seismic behavior of the escalator to prevent such an accident. From the above-mentioned background, the object of this research is to construct an analytical model to clarify the seismic response behavior using the non-linear restoring force characteristic of the escalator truss model. In this paper, the restoring force characteristic model is built based on the load-displacement. In addition, the seismic response analysis of an escalator installed in the building is performed using the restoring force characteristic and the Bi linear model.

2 STRUCTURE OF ESCALATOR

The general view of the escalator and the enlarged picture of the non-fixed side are shown in (a) and (b) of Figure 1. Escalators are comprised of steps, handrails and electric motors, with the escalator truss supporting them. An escalator truss is a structural element supporting live load and its own weight. Angle steels are used mainly. The frame combined by angle steels is coupled by welding. Therefore, each element receives the axial force of compression or tensile. Escalators are usually installed in the buildings with one side of them in fixed connection and the other side in free condition or utilized both sides in the non-fixed style in order to mitigate undesirable excessive deflections induced in the truss like structures of escalators. The length of that escalator truss hangs to the building beams is called overlap allowance. As shown in equation (1) and (2), the length of the overlap allowance is determined by escalator technology standard in Japan [3]. Where C is the gap between the beam of the building and the escalator, H is the rise, γ is the layer deformation angle of building, and 20 [mm] is margin of the overlap allowance.

$$B \geq \sum \gamma \cdot H + 20 \qquad (C > \gamma \cdot H) \tag{1}$$

$$B \geq 2\sum \gamma \cdot H + 20 \qquad (C \leq \gamma \cdot H) \tag{2}$$



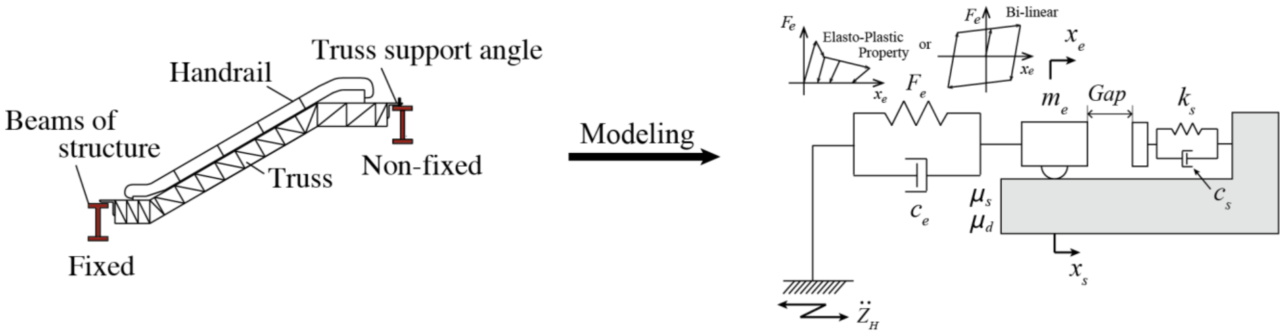
(a) Escalator System (b) Enlarged Picture

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

3 ANALYTICAL MODEL

3.1 Analytical model of escalator

In this study, the target escalator is a bottom end fixation - upper and non-fixation type escalator. Focus on the slide friction that is caused between the building beams and the escalator, the simple escalator model of one mass system was built [5]. The dynamic behavior of the escalator truss members is regarded as a spring element, and the damping of the support member is considered. Therefore, the damping force, the friction force, the inertial force and the restoring force act on the escalator. Figure 2 shows the escalator analytical model. In Figure 2: m_e is the mass of the escalator, F_e is the stiffness escalator truss, c_e is the damping coefficient of the escalator truss, μ_s is the static friction coefficient of the escalator truss, μ_d is the dynamic friction coefficient of the escalator truss, x_e is the displacement of the escalator, k_s is the stiffness of the building beam, c_s is the damping coefficient of the building beam, x_s is the displacement of the building, $\ddot{z}_H$ is the acceleration of the bottom end fixation department floor of the escalator. Table 1 shows parameter of escalator. The escalator used in this analysis shall have a mass of 8000[kg] and a head of 6.0[m]. The 1st stiffness k_1 of the escalator truss is calculated using FEM analysis, and the damping ratio ζ_e is 1[%]. In this study, a general escalator installed in the commercial facilities is intended for. In addition, the dynamic friction coefficient and the static friction coefficient is equal in this analysis, and their values are set to 0.25 as the friction coefficient of the typical steel. The behavior of the escalator shall not come under an influence of a building.



(a) Escalator System (b) Escalator Analysis Model

Figure 2 Analytical model of escalator

Table 1 Parameter of escalator

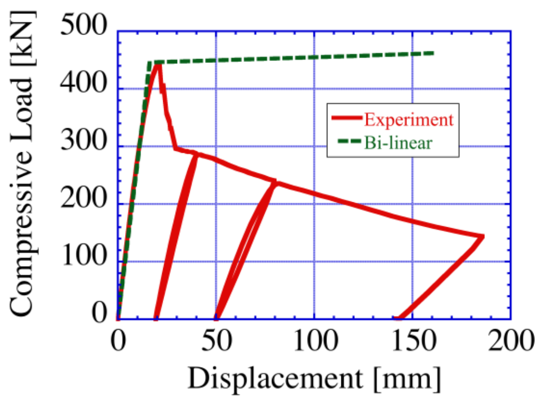
Mass of Escalator m_e [kg]	1st stiffness k_1 [N/m]	Damping ratio ζ_e [%]	Friction Coefficient μ_s , μ_d	*Gap* [m]
8000	2.75×10^7	1	0.25	0.03

3.2 Restoring force characteristics of escalator

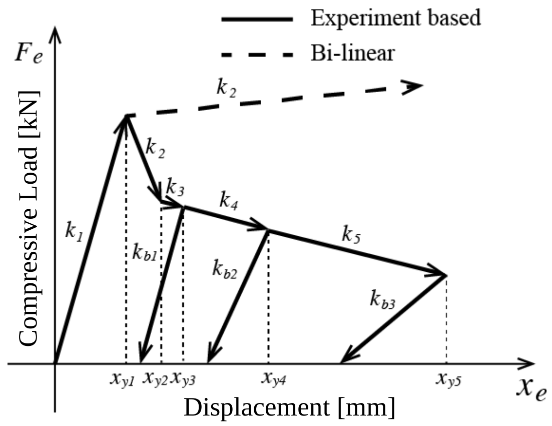
In the past this study, bi-linear model has been used as the restoring force characteristics of the escalator truss. The compression experiment using the size of the original escalator truss was conducted in 2014, so the restoring force characteristics of the escalator truss were provided.

Figure 3 (a) shows the load-displacement curve obtained in the experiment, and (b) shows the result of linear approximation.

It is necessary to revise an escalator analysis model to consider the restoring force characteristics obtained the experiment. Therefore, the restoring force characteristics model of the escalator truss is built by being similar by plural straight lines with the load-displacement curve that the experiment provided. In this paper, the restoring force characteristic obtained from experimental values is called “multi-linear model”.



(a) Load-displacement curve of the experiment value and bi-linear model



(b) Linear approximation of the experiment value and bi-linear model

Figure 3 Elasto-plastic properties of the escalator truss in the compression experiment using the size of the original escalator and Bi-linear model

Table 2 Parameter of Escalator Truss Stiffness

	Bi-linear	**Experiment based**
1st stiffness **k_1 [N/m]**	2.75×10^{7}	2.75×10^{7}
2nd stiffness **k_2 [N/m]**	1.10×10^{5}	-2.70×10^{7}
3rd stiffness **k_3 [N/m]**	-	-9.70×10^{5}
4th stiffness **k_4 [N/m]**	-	-9.70×10^{5}
5th stiffness **k_5 [N/m]**	-	-9.70×10^{5}

3.3 Equation of motion in analytical model of escalator

The three equations of motion are devised, in consideration of influence by the slide friction and the collision to occur between an escalator and the building beams. Equation (3) shows the case that sliding does not occur. Equation (4) shows the case that sliding occurs. Equation (5) shows the case that collision with the construction beams occurs. In addition, Equation (6)~(9) show the switching condition of Case 1, Case 2, and Case 3.

(Case 1) when sliding does not occur

$$\ddot{x}_e = \ddot{x}_s \qquad \dot{x}_e = \dot{x}_s \qquad x_e - x_s = const \tag{3}$$

(Case 2) when sliding occurs

$$m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) = -m_e\ddot{z}_H \tag{4}$$

(Case 3) when collision with construction beams occurs

$$m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) + k_s\{(x_e - x_s) - Gap\} + c_s(\dot{x}_e - \dot{x}_s) = -m_e\ddot{z}_H \tag{5}$$

Switching condition

Case 1→Case 2

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| > \mu_s \frac{1}{2} m_e g \tag{6}$$

Case 1→Case 3

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| > \mu_s \frac{1}{2} m_e g \ \text{ and } \ x_e - x_s \geq Gap \tag{7}$$

Case 2→Case 1

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| \leq \mu_d \frac{1}{2} m_e g \ \text{ and } \ \dot{x}_e = \dot{x}_s \tag{8}$$

Case 2→Case 3

$$x_e - x_s \geq Gap \tag{9}$$

Case 3→Case 1

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| \leq \mu_d \frac{1}{2} m_e g \ \text{ and } \ \dot{x}_e = \dot{x}_s \ \text{ and } \ x_e - x_s < Gap \tag{10}$$

Case 3→Case 2

$$x_e - x_s < Gap \tag{11}$$

3.4 Analytical model of building

In this study, it is assumed that the escalator is installed in the three-story steel-frame building, the response of each layer is input into an escalator analysis model. In addition, it is assumed that the restoring force characteristic of the building is tri-linear in consideration of the elastic-plastic deformation. The primary natural period is 0.74[s], and the structural damping of the building is 2[%].

Figure 4 shows the modeling building. In Figure 4, m_{si} is the mass, c_{si} is the damping coefficient, k_{si} is the 1st stiffness, Q_{si1} is the 1st yield load, Q_{si2} is the 2nd yield load, α_{si1} is 2nd stiffness degradation ratio, α_{si2} is 3rd stiffness degradation ratio, $\ddot{z}_H$ is the horizontal seismic acceleration.

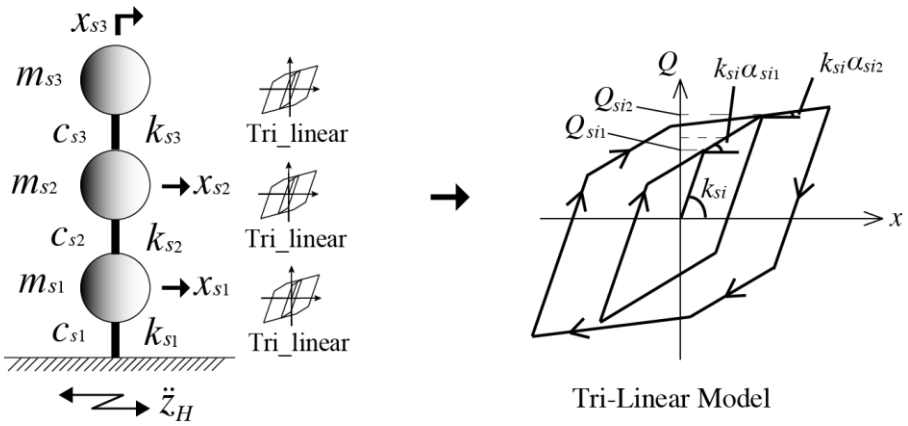


Figure 4 Analytical model of building

Table 3 Parameter of building

Layer	Height [m]	Mass m_{s1} [kg]	1st Stiffness k_{s1} [m]	1st Yield Disp. x_{s1} [m]	1st Stiffness Degradation Ratio α_{si1}	2nd Yield Disp. x_{s2} [m]	2nd Stiffness Degradation Ratio α_{si2}
3	5.5	11.22×10^{6}	3.48×10^{9}	1.20×10^{-2}	0.130	5.0×10^{-2}	0.020
2	5.5	9.20×10^{6}	3.68×10^{9}	1.55×10^{-2}	0.145	6.4×10^{-2}	0.042
1	6.5	9.70×10^{6}	3.83×10^{9}	1.80×10^{-2}	0.212	6.0×10^{-2}	0.056

4 SEISMIC RESPONSE ANALYSIS

4.1 Input seismic wave

In this analysis, the seismic wave is inputted into the analysis model of the building. The seismic response analysis of the escalator is performed by inputting the analysis results of each layer into the analytical model of the escalator. By the seismic response analysis, the changes of the seismic behavior are confirmed by the difference in the restoring force characteristics of the escalator.

Figure 5 shows the response spectrum and the time history wave of the input seismic wave. In this paper, the K-NET Sendai NS Original wave observed at Sendai in the Grate East Japan Earthquake was used. This seismic wave was obtained from Strong-motion Seismograph Network of National Research Institute for Earth Science and Disaster Prevention (K-NET); the observation point is MYG013 [4]. From the response spectrum of Figure 5, a natural period excels in the amplitude of the seismic wave near 0.6~0.7 seconds.

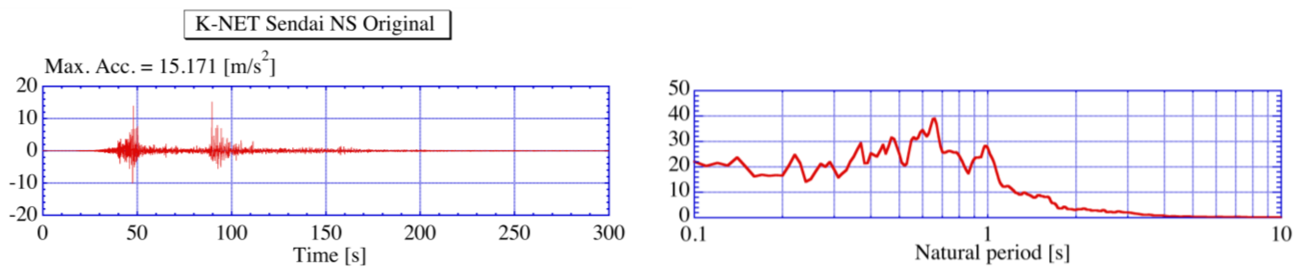


Figure 5 Input seismic waves, and response spectrum (damping ratio 5[%])

4.2 Results of seismic response analysis of building

Figure 6 shows the results of the seismic response of analysis of the building; they are the vibration mode, the maximum acceleration of each floor, the maximum layer displacement, and the maximum layer deformation angle from the left. Focus on the maximum acceleration of each floor, it is clear that the acceleration of the building does not greatly amplify, for increase of acceleration of the seismic wave. It is considered that the seismic energy is absorbed for the elastic-plastic deformation of the building. In addition, it is clear that the floor of the largest layer deformation angle was between the second floor and the third floor. Therefore, there is the high risk that the escalator is installed between the second floor and the third floor falls down.

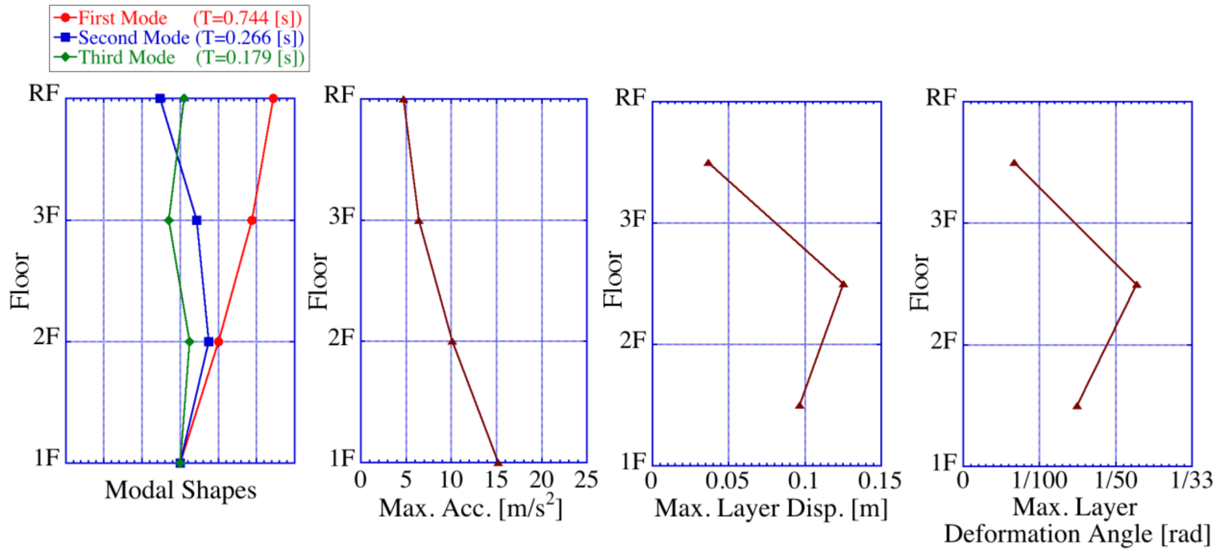


Figure 6 Vibration mode and response values of each floor

4.3 Results of seismic response analysis of escalator

Figure 7 shows the results of the seismic response analysis of the escalators; they are installed on the 2nd through 3rd floors, in case of bi-linear model and multi-linear model obtained from experiment results. Figure 7 expresses the acceleration, the slide displacement, the displacement, the restoring force, and the case (state of the escalator in the sliding and the collision). When the condition of the escalator shifted to Case 3, the acceleration of the escalator shows a big value, it expresses that the escalator replied intensely when the escalator and the building beams collide.

Figure 8 shows the maximum response values of the displacement and the slide displacement of the escalator in such floor. As a result, the response of the escalator installed between the second floor and the third floor showed the biggest value. It is thought that this is because the residual displacement that a building gives to an escalator grows big so that the displacement of the building is big.

As shown in the restoring force of the escalator, plastic deformation occurs to the escalator, and it is able to confirm that that residual displacement is remained. In the bi-linear model and the multi-linear model obtained from experiment results, the big difference by the difference in restoring force characteristics was not seen in the maximum deformation. Therefore, it is supposed that there is little influence to give the seismic behavior of the escalator. When the seismic behavior of the escalator is considered, it is able to be supposed to be bi-linear model.

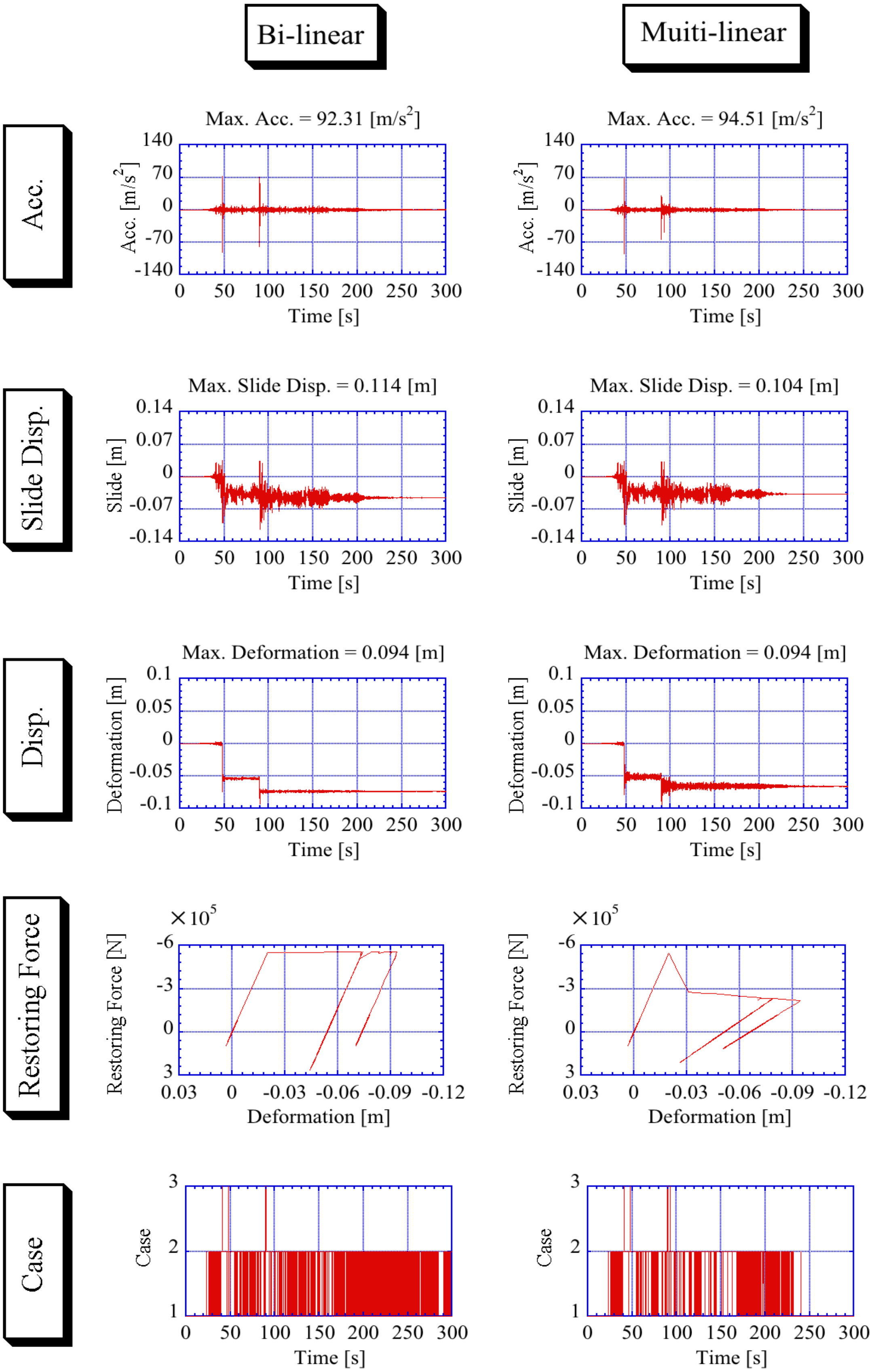


Figure 7 Seismic Response Analysis of Escalator installed between 2nd floor and 3rd floor

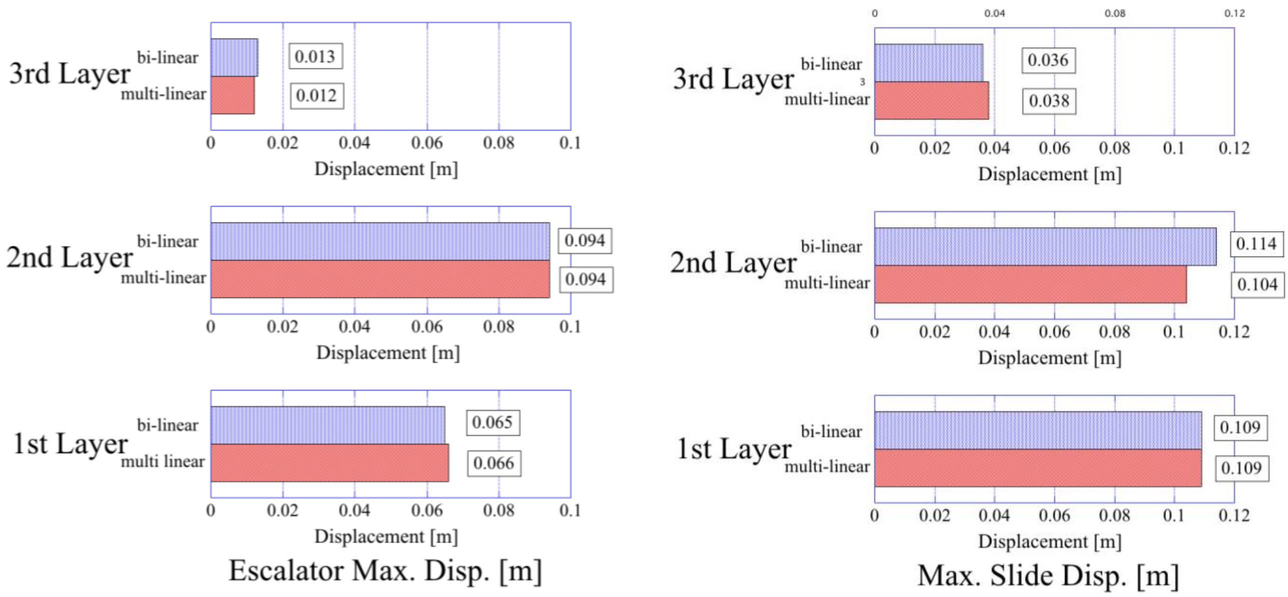


Figure 8 Max. Response values of displacement and slide displacement

5 CONCLUSION

In this paper, the analytical model of escalator was built, that was considered that slide friction and collision caused between escalators and building beams, and elasto-plastic property of the escalator truss obtained by the compression experiment. In addition, the analytical model of building was built, that was similar to the building that fall accidents of escalators occurred in the 2011 Great East Japan Earthquake. Seismic response analysis was performed using 2 kinds of the restoring force characteristics, and the seismic behavior of the escalator was examined. In Bi-linear model and the restoring force characteristics obtained by the experiment, the big difference by the difference in restoring force characteristic was not seen. Therefore, it is thought that the seismic behavior of escalator is evaluated integrally with restoring force characteristics of Bi-linear model in consideration of material properties. In both restoring force characteristics, it is thought that the maximum displacement of the escalator is more likely to depend on forced displacement to receive from a building.

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BIOGRAPHICAL DETAILS

Miss Asami Ishii received a master's degree in mechanical engineering from Tokyo Denki University, Tokyo Japan, 2006. She is now a doctoral course student of Tokyo Denki University. Her research interest includes seismic behavior of escalator and seismic behavior of lift ropes.

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and currently a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MILIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MILIT. In addition, he has been a chair of the ISO TC178 Japanese committee.