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Study on Escalator fall off behavior and structural strength during earthquake

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Abstract

In the 2011 off the Pacific coast of Tohoku Earthquake, escalator fall accidents occurred. The fall accidents occurred to the escalator which was connected the second floor to the third floor of commercial facilities of steel frame buildings. In general, escalators are set on beams of buildings, furthermore one side or both sides of the support are not fixed because of preventing damage to the escalator from the interlaminar deformation of the building. Further, it is called “overlap allowance” where is the overlap between truss support angle and building beam. However the cause of the fall accidents occurred due to that the escalators came off from the beams of the buildings by the great earthquake more than expected. After the escalator accidents, the seismic standard was revised in Japan. Conventional length of overlap allowance was the value that is calculated by multiplying lift of the escalator and interlayer displacement angle of building, 1/100[rad], and add margin of overlap allowance to them. In new standard, the maximum interlayer displacement angle which have to be counted in the building was defined 1/24[rad]. In short, the interlayer displacement angle of buildings was considered more than before. From this, overlap allowance is longer so the possibility of the fall accidents decreases so much. However, the escalator, which is already constructed and difficult to recovery to suit new standard, is thought that an unfixed part of the escalator may collide with a building beam due to the earthquake. Furthermore, the escalator may transform by the collision and affect to the safety of themselves. Accordingly, the dynamic behavior of the escalator with the building beam during earthquakes is investigated and confirmed safety against the revised earthquake resistance standards in this study. In this paper, a three meter lift escalator, which has fallen due to an earthquake, was targeted. The 3/10 scale model based on the three meter lift escalator which the top is not fixed was created. Further, the vibration experiment with the 3/10 scale escalator model was carried out. The behavior of the 3/10 scale escalator model was confirmed during the earthquakes. In addition, the 3/10 scale escalator model and the full scale escalator model were conducted static analysis by Finite Element Method. The load-displacement characteristics were confirmed, the skeleton curves of each escalator model were grasped. Moreover the seismic responce analysis with the lumped mass models in the vibration experiment. The validity of the analysis model was confirmed by comparing the analysis results with the experimental results.

Keywords: Escalator, Quake-resistance standards, Analytical model, Finite element method, Collision, Buckling,

1. Introduction

An escalator is one of the transport equipment that moves people vertically. The escalator is installed in the building and connects the floor and another floor. In general, escalators are not fixed to building beams on one or both sides to prevent damage from deformation. However, in the 2011 off the Pacific coast of Tohoku Earthquake, four fall accidents of escalators occurred. These fall accidents occurred in an escalator installed in a commercial facility of a steel frame building that connected the third floor and the second floor. The cause of the fall accident is that the escalator was removed from the beam of the building more than expected due to a large earthquake. After the escalator accidents, the quake resistance standard was revised in Japan. According to this standard, the layer displacement of buildings to be expected during earthquake is more than before. The layer deformation angle for design before the revision of quake resistance standard was less than 1/100 [rad]. However, the layer deformation angle after the revision of quake resistance standard was 1/40 [rad] in principle, and it was 1/24 [rad] when the structural calculation was not done. As a result, the length required for falling accidents was improved. However, the building may be greatly deformed. Furthermore, the escalator may collide with the supporting part of the building due to the increase of the design interlayer deformation angle. Accordingly, the purpose of this study is the comprehension of the dynamic behavior of escalators during earthquakes considering the collision. In this paper, the characteristics are confirmed by a compression test of a full-scale escalator truss. Based on this, a dynamic experiment is performed with a 3/10 scale escalator truss. Further, a dynamic analysis is performed with the bilinear model.

2. Escalator design policy

The diagrammatic view of the escalator is shown in Fig.1. The escalator consists of steps, handrails, transport equipment parts and a truss which supports these transportation parts. The overlap between the escalator truss and the building prevents the damage of the escalator by the interlayer deformation. As shown in equation (1), (2) and (3), the length of the overlap allowance is determined by escalator technology standard in Japan. Where C is the gap between the beam of the building and the escalator, H is the height, γ is the layer deformation angle of building and 20 [mm] is margin of the overlap allowance.

$$B \geq \Sigma\gamma H + 20 \qquad (\Sigma\gamma H - C \leq 0) \qquad (1)$$

$$B \geq \Sigma\gamma H + 20 \qquad (0 \leq \Sigma\gamma H - C \leq 20) \qquad (2)$$

$$B \geq 2\Sigma\gamma H - C \qquad (20 < \Sigma\gamma H - C) \qquad (3)$$

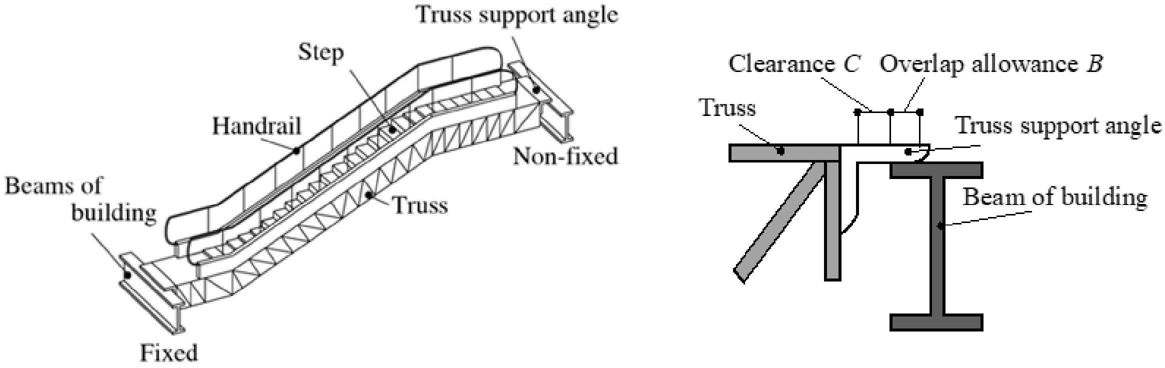

Fig. 1 – Escalator system and the non-fixed side of the escalator

3. Compressive Experiment

3.1 Outline of experiment

As part of the building standards development promotion project in 2014, a compression experiment of the actual sized escalator truss was carried out. The deformation behavior of the escalator truss was confirmed. The escalator truss received a compressive load from the building beam during the earthquake. In the structure of the escalator truss, the buckling will occur when subjected to enforced displacement in the longer direction. The truss members probably deform, furthermore the strength of the truss decreases greatly. Accordingly, the support ability of the deformed truss member is confirmed.

3.2 Experiment model

The specifications of the experiment model are shown in Table 1 and 2. The main material is Japanese Industrial Standard (JIS) SS400. The lift height of the escalator was 3 [m], further the experiment model is similar to a practical machine escalator. The experiment model is shown in Figure 2. The truss was included in the experiment model, without the escalator's internal equipment (such as step, handrail drive unit and so on). The weight of internal equipment was reproduced by hanging the dummy weights.

Table 1 – Parameter of escalator

Height [mm]	Span [mm]	Truss width [mm]	Incline [°]	Main Material	Support
3000	9476	1500	30	JIS SS400 (carbon steel)	Top: Fixed Bottom: Non fixed

Table 2 – Parameter of JIS SS400

Types of symbol	Yield stress [MPa]		Tensile strength [MPa]
	Thickness of steel [mm]		
	t ≦ 16	16 < t ≦ 40	
JIS SS400	245 and over	235 and over	400～510

Fig. 2 – Test body

3.3 Experiment method

The experimental outline is shown in Figure 3. The apex of support angle and the apex of frame were fixed because the escalator truss was prevented from floating up during compression. The bottom part of the escalator truss was constructed to slide in the longer direction because it can be compressed in the longer direction. A load cell, which measure the reaction force, was installed at the bottom end. The experimental process is shown in Table 3. The compression and unloading were given step by step, furthermore the influence by repetition load was confirmed. Finally, enforced displacement was given up to 200 [mm].

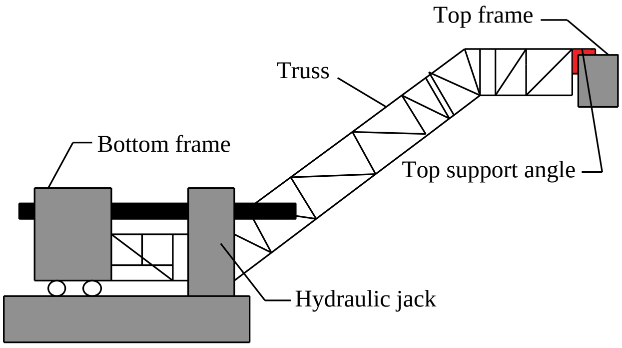

Fig. 3 – Experiment outline

Table 3 – Experiment step

Step1	Press to 40 mm
Step2	Unloading
Step3	Press to 80 mm
Step4	Unloading
Step5	Press to 200 mm
Step6	Unloading

3.4 Experiment result

The appearance of deformation is shown in Figure 4. The relationship between the reaction force of the truss and the enforced displacement is shown in Figure 5. Immediately after the start of compression, the relationship between reaction force and the displacement are linear. After that, the truss member buckled, further the load suddenly decreased. The effect of repetition is negligible at the displacement 40 [mm] and 80 [mm]. The trusses were standing by themselves without falling at the enforced displacement 200mm.

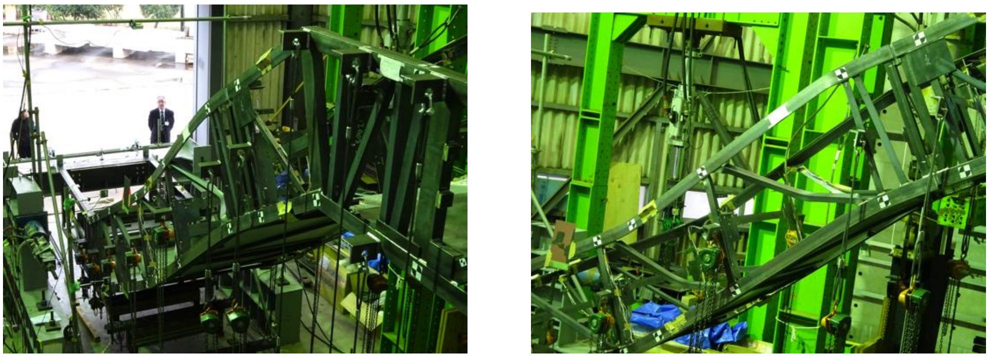

Fig. 4 – Deformation of experiment

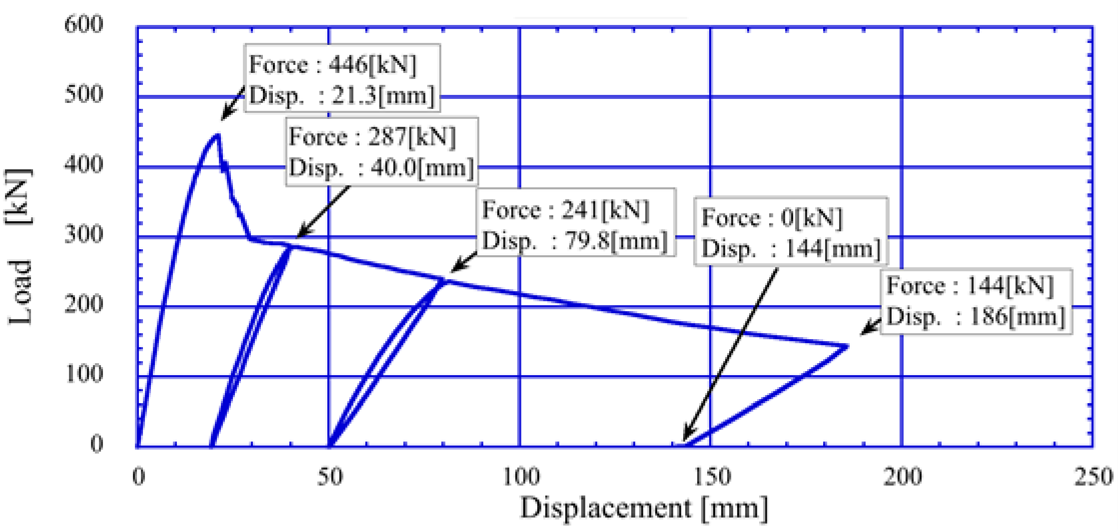

Fig. 5 – Reaction force of compression of experiment

3.5 Analysis model

The elasto-plastic analysis with the finite element method (FEM) was performed. Many escalator trusses are made of welded L-shaped steel. In this analysis model, the material properties of the welded steel are same as that of the base material, further the material properties of a steel are same regardless of the shape of member. The analysis with the bilinear models was performed. This model was analyzed with the yield stress of two case. Incidentally, this model was analyzed with the same plastic factor. The simulation 1 is yield stress of JIS standard. The simulation 2 is yield stress according to experimental result. In the experiment, the weight of the internal equipment was reproduced by hanging weights. On the other hand, the weight of the internal equipment is reproduced by the load in the analysis. The analysis conditions are shown in Table 4 and Table 5.

Table 4 – Parameter of simulation

Truss	Incline	Element	Material property	support method	Load condition
Height : 3000mm Span : 9476mm width : 1500mm	30 °	Solid	Bilinear model Young's modulus:206GPa Plastic factor:1450MPa	Top: X,Y,Z fixed Bottom: Y,Z fixed	(1) Linear pressure (2) X 200mm (3) Unloading

Table 5 – Parameter of yield stress

Case	Yield stress[MPa]
Simulation 1 JIS standerd	245
Simulation 2 adjustment	285

The analysis condition is similar to the experiment condition. The apex end of the escalator truss was fixed. The lower end of the escalator truss receives the enforced loads. The enforced displacement gradually decreases. The load-displacement curve is compared to result of experiment.

3.6 Analytical result

Figure 6 shows the analytical results. The load-displacement curves are shown in Figure 6(a). The solid line is the experiment result, the broken line is the simulation-1, the dashed line is the simulation-2. Figures 6(b) shows the whole. Figures 6(c) shows the side view. Figures 6(d) shows the top view of truss model.

The buckling loads of the analysis results with the JIS standard are smaller than that of the experiment results. The yield stress of the material in the experiment was higher than that in the JIS standard. The load transition after buckling, when the buckling load was adjusted to the experiment result, can be reproduced roughly. The whole truss sank in the experiment. However, the bottom part of the truss deformed intensively in the analysis. The load-displacement curve of the analysis reproduced that of the experiment. Therefore, the analysis with FEM is effective.

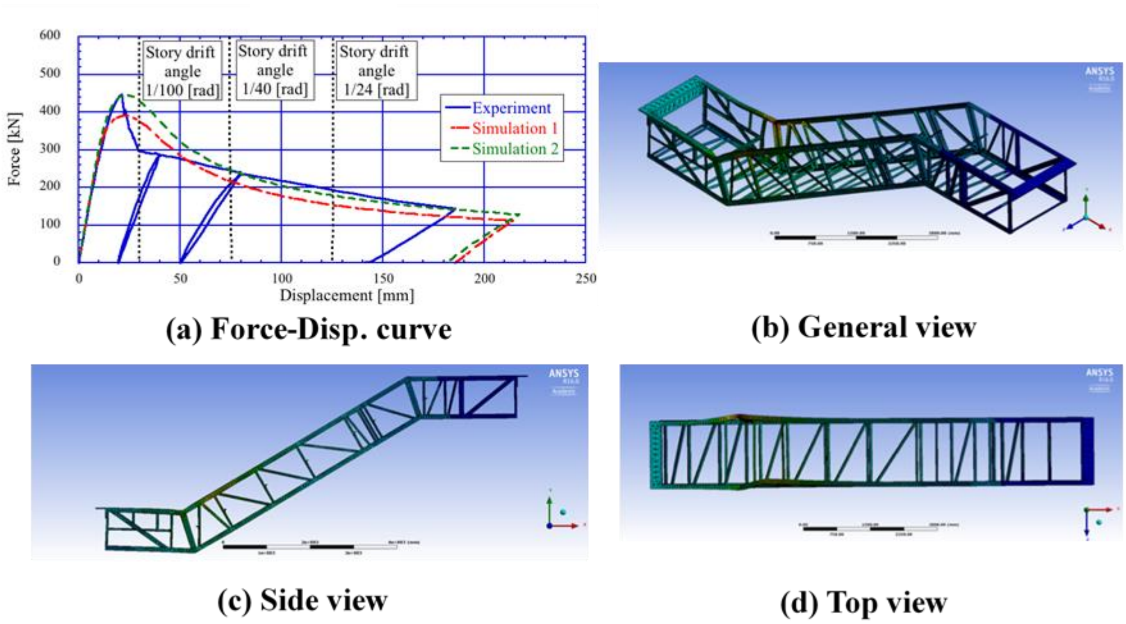

Fig. 6 – Analytical results

4. Vibration Experiment

4.1 Outline of experiment

A vibration experiment with a 3/10 scale model was conducted. In this experiment, the escalator collides with the building model with the seismic waves. The behavior of the escalator including the collision phenomenon is confirmed.

4.1.1 Specimen

The specimen of the vibration experiment is shown in Figure 7. This specimen is composed of an escalator model and buildings model. This model is a 3/10 scale model of a 3 meter lift escalator where a fall accident occurred. The 3/10 scale model of the escalator uses the similarity rules in Table 6. In Table 6, the subscript f indicates the full scale, further the subscript m indicates after the similarity law. The characteristic of the escalator model and the building model is shown in Table 7. The natural frequency of the escalator period is 0.049 sec. The natural frequency of the building model is 0.223 [s].

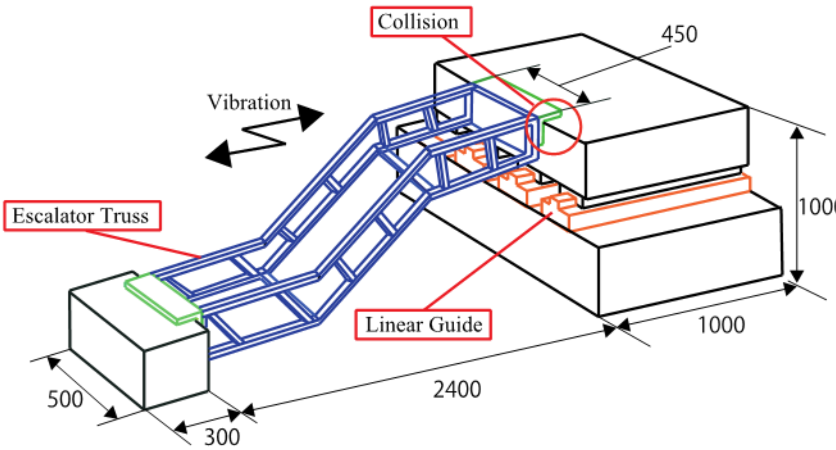

Fig.7 – Schematic of specimen

Table 6 – Parameter of 0.3 scale models

Length	Mass
L_m=0.3L_f	M_m=0.3^3M_f

Table 7 Parameter of 0.3 scale models

Escalator				Building		
Mass	1st stiffness	2nd stiffness	Yield disp.	Mass	1st stiffness	Natural period
m_e [kg]	k_{e1} [N/m]	k_{e2} [N/m]	x_y [m]	m_s [kg]	k_{s1} [N/m]	T_s [s]
400	6.67×10^6	-2.4×10^6	0.0075	2000	1.59×10^6	0.223

4.1.2 Input seismic wave

The input seismic wave is shown in Figure 8. The input seismic waves, which are used in vibration experiments, are scaled by a similarity law with a constant velocity. Accordingly, the acceleration is 3.3 times the observed seismic wave moreover 0.3 times the time. In this paper, 0.3 scale of the JMA Kobe NS 25 kine and 50 kine was used.

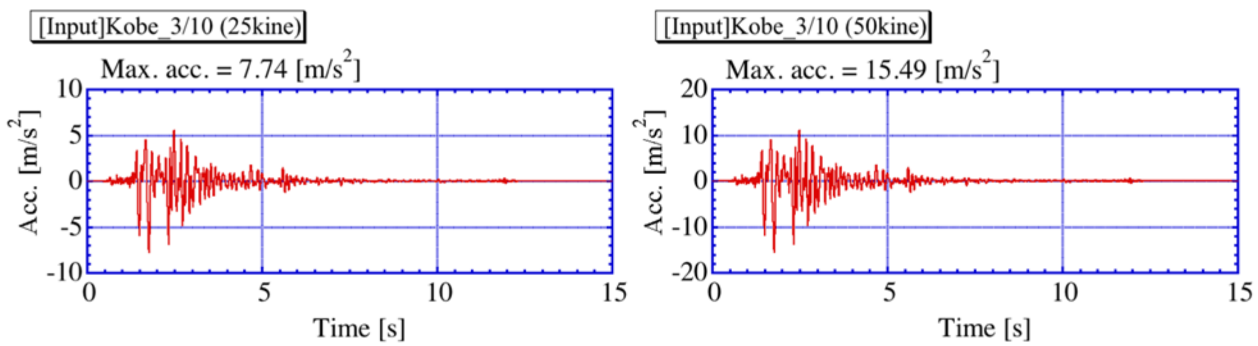

Fig. 8 – Time history wave the JMA Kobe NS 25 kine and 50 kine

4.2 Analytical model

4.2.1 Motion equation in analytical model

In this analysis, the escalator and the building are each one mass models. In order to reproduce the displacement after buckling, the restoring force of the escalator is modeled by a bilinear model. The analytical model image is shown in Figure 9. The characteristics of the escalator trusses and the building is shown in Table 7. In this analysis model, the collision is reproduced by the collision stiffness between the escalator model and the building model. The motion equations are classified into two cases. One is the non-collision case. another is the collision case. In the non-collision case, the motion equations of the escalator model and the building model are the equations (4) and (5). In the collision case, the motion equations are the equations (6) and (7). The transition condition is equation (8). The restoring force characteristic of the escalator model is equation (9) and (10). When the escalator displacement exceeded the yield displacement, the restoring force switches. Here, m is the mass, c is the damping, k is the stiffness, and F is restoring force. Moreover, the subscript e is the escalator, the subscript s is the building, and the subscript c is the collision stiffness.

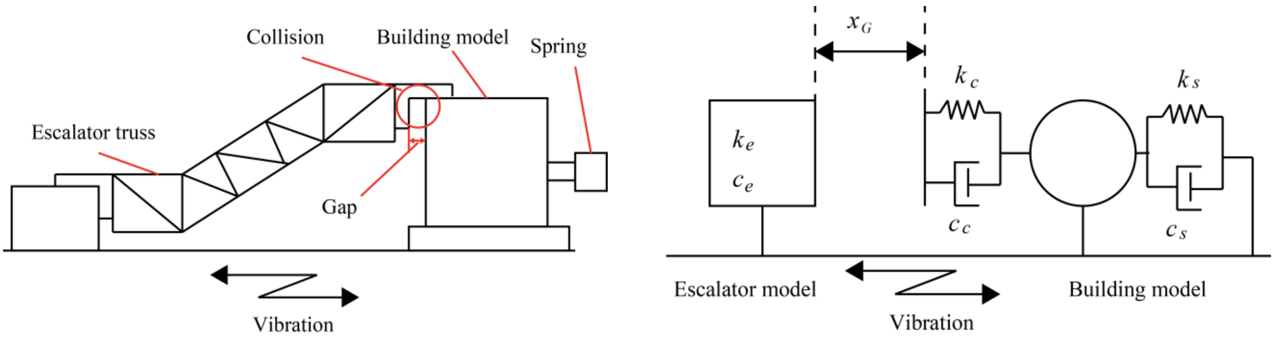

Fig 9 – Analytical model image

Non collision case

Escalator : $$m_e(x_e + z) + c_e x_e + F_e = 0 \quad (4)$$

Building : $$m_s(x_s + z) + c_s x_s + k_s x_s = 0 \quad (5)$$

Collision case

Escalator : $$m_e(x_e + z) + c_e x_e + F_e + k_c(x_e - x_s - x_G) + c_c(x_e - x_s) = 0 \quad (6)$$

Building : $$m_s(x_s + z) + c_s x_s + k_s x_s - k_c(x_e - x_s - x_G) - c_c(x_e - x_s) = 0 \quad (7)$$

Transition condition case

$$x_G > x_e - x_s \quad (8)$$

Restoring force : $$F_{e1} = k_{e1} x_e \quad (9)$$

After yield restoring force : $$F_{e2} = k_{e2} x_e \quad (10)$$

4.3 Results of seismic response experiments and analysis

In the experiment, the acceleration of the shaking table was measured as the input acceleration. The building displacement was measured. Furthermore, the relative displacement between the building and the escalator was measured. In addition, the internal stress of the escalator was measured. The escalator displacement is calculated from the building displacement and the relative displacement. The experimental seismic response is shown in Figure 10. The figure shows the experimental results of the non collision case, the collision case and the buckling case. Additionally, the figure shows the input acceleration, the displacement and the restoring force. In non collision case, the maximum relative displacement is approximately 23 mm. The maximum relative displacement and the maximum building displacement are almost the same. The maximum escalator displacement is less than 1 mm. The escalator displacement is negligible in relative displacement. The relative displacement is mainly the building displacement. Similarly, when a collision occurs, the relative displacement and the building displacement are almost the same. The maximum escalator displacement is approximately 2.5 mm. The escalator displacement of the collision case increased than that of the non collision case. On the other hand, the relative displacement is approximately 25 mm. Regardless of the collision, the relative displacement is mainly the building displacement. In the restoring force characteristics, the deformation does not reach the secondary stiffness. When buckling occurred, the relative displacement exceeded the measurement range. The input wave is more than twice the other two conditions. The building displacement is approximately twice that of the non collision case. The ratchet deformation occurred in the compression direction on the escalator. Accordingly, the ratchet displacement occurred on the relative displacement. When buckling occurs, the relative displacement is a combination of the building displacement and the escalator displacement. The buckling of the escalator is important in assessing relative displacement. The restoring force characteristic reaches the range of secondary stiffness.

The result of the seismic response analysis is shown in Figure 11. The figure shows the experimental results of the non collision case, the collision case and the buckling case. In the non collision case, the maximum relative displacement is approximately 25 mm. the maximum building displacement is approximately 25 mm. The maximum escalator displacement is less than 1 mm. In the analysis, the escalator displacement is negligible in relative displacement. The maximum response value and the waveform trend of the experiment can be reproduced with analysis. However, convergence after the main motion is slow. When collision occurs, the maximum building displacement is approximately 38 mm. The maximum escalator displacement is approximately 3 mm. As in the experiment, the escalator displacement increases than that of the non collision case. The maximum response value and the waveform trend of the experiment can be reproduced with analysis. In addition, the analysis reproduces the restoring force characteristics. In the buckling case, the maximum building displacement is approximately 38 mm. The relative displacement of the analysis is slightly smaller than that of the experimental. However, the waveform trend can be reproduced. The residual escalator displacement is 27 mm. The residual displacement of the relative displacement is 27 mm. The analysis results are the same as the experimental results. In addition, the waveform trend of the analysis can replicate the experiment. The maximum relative displacement in the analysis is approximately 59 mm. The restoring force characteristics of the analysis reproduce the tendency of the restoring force characteristics of the experiment.

Therefore, the behavior of the building and the escalator during earthquakes can be reproduced with a lumped mass model. The behavior of the escalator after buckling can be reproduced with a bilinear model.

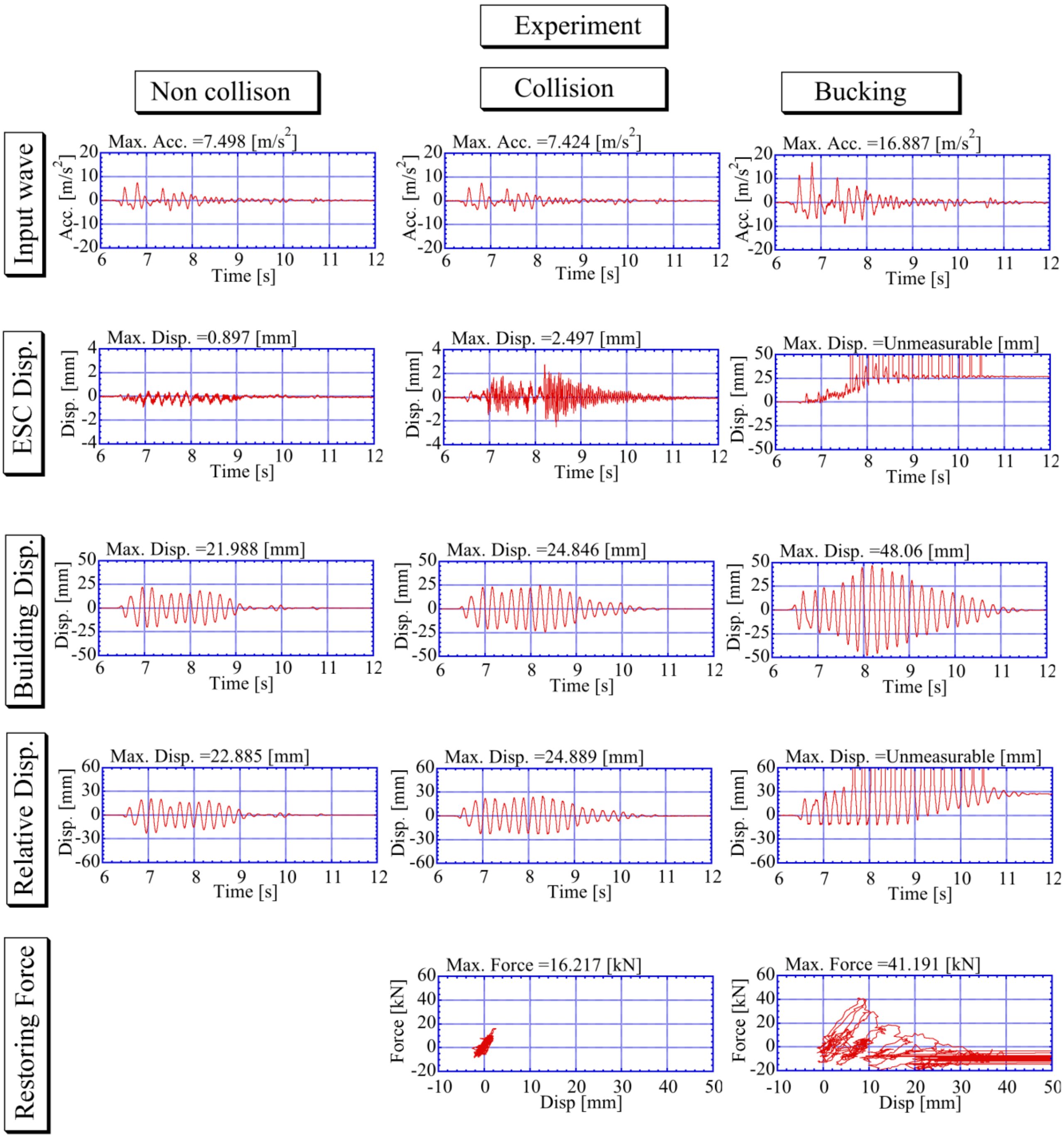

Fig. 10 – Seismic response experiment result

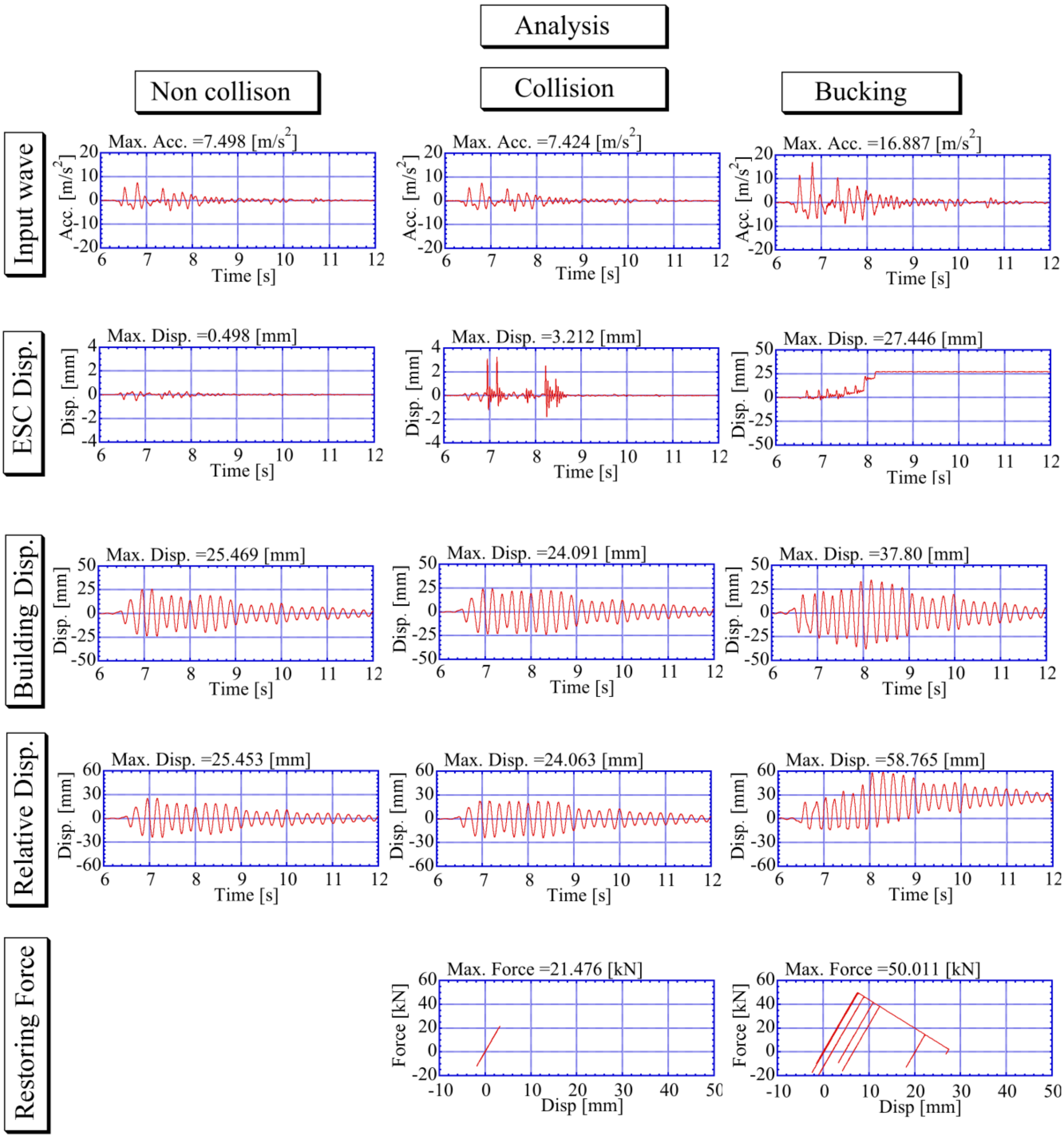

Fig. 11 – Seismic response analysis result

5. Conclusion

In this study, the characteristics of the escalator were confirmed with the escalator compression experiment. Furthermore, the behaviour during the earthquake was confirmed with the vibration experiment with the 3/10 scale model. In addition, an analytical model of the escalator including the collision was constructed. The restoring force characteristics of the vibration experiment were the same as that of the compression experiment. The behavior of the vibration experiment could be reproduced with the analysis model. Furthermore, the restoring force characteristics could be reproduced in the same way. Therefore, the lumped mass model is effective to confirm the behavior of the building and the escalator during earthquakes. In addition, a bilinear model is effective to reproducing the behavior of an escalator after buckling.

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