Fundamental Study on Rope Damage Reduction Using Intermediate Transfer Floor of High Rise Buildings

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Abstract. Lifts are essential for means of vertical transportation. In recent years, high rise buildings have become higher, leading to higher lifts and longer lift ropes. High-rise buildings have a longer natural period than conventional buildings. As lift ropes become longer, the natural period of the lift ropes become longer as well, and get closer to the natural period of the building. Consequently, the lift ropes are hooked to the equipment in hoistway when the lift ropes vibrate by an external force, such as a strong wind and earthquake. Secondary damage such as containment of passengers and lift service stop may occur. It has become a problem. For example, The 2011 off the Pacific coast of Tohoku Earthquake, 2215 cases such as catch and damage of lift ropes have been reported. However, operations of lifts after earthquakes are required. Therefore, this study constructs an analytical method capable comprehensive analysis. We aim to build a method to prevent catching by vibration reduction measures of the lift ropes. In this report, we examine the effectiveness of lifts using intermediate transfer floors for damage reduction of ropes. In the analysis, the maximum displacement of the main rope and compensation rope was examined when the lift travel is divided into two and four. The calculated results of the analysis confirmed that dividing the lift travel reduces the response of the main rope. On the other hand, the response of compensation rope was reduced by finely dividing the travel. It was confirmed that dividing the lift travel is effective for reducing the response of the rope.

1 INTRODUCTION

Earthquakes occur frequently in Japan, which causes various damage to lifts. Therefore, lifts require various seismic countermeasures, including reinforcement of seismic structure as part of their buildings. Another countermeasures is a vibration problem of the lift ropes. In recent years, numbers of high-rise buildings are increasing in urban areas with the development of building technology. Lifts installed in buildings use long objects such as main rope, compensating rope and cables. Due to the high-rise of buildings, the natural period of these long objects is prolonged. Since the natural period of the high-rise building is long, and as the long ropes and cables object becomes larger, the natural periods of the building and the long object approach and resonate due to disturbances such as long-period ground motions and wind. The rope collide with the hoistway by swaying. As a result, the lift ropes catch on the protrusions in the hoistway, causing damage to the rope and the confinement of passengers. In Japan, the evacuation staircase is said to be effective as an evacuation method when lifts stop. However, it is difficult to use the evacuation staircase in high-rise buildings. Moreover, there are many more people in high-rise buildings. If those people evacuate all at once, they are likely to cause confusion and congestion. In recent years, temporary evacuation areas on the middle floors of high-rise buildings are set up during disasters such as earthquakes and fires. In China, it is obliged to establish an "intermediate evacuation floor" that people can stay safely for a long time during disasters. At that time, evacuation methods using lifts are an attractive option. Therefore, lifts that can be operated at the time of disaster are required.

Therefore, in this research we aim to design lifts that can be operated even after earthquakes. In our previous research, it has been confirmed that the displacement of the rope is a small issue for lifts with low lift travel [1,2,3,4]. Also, I focused on the intermediate evacuation floor that is the evacuation method at the time of a disaster. In this report, we examine effectiveness of lifts using intermediate transfer floors for damage reduction of ropes.

2 ANALYTICAL MODEL

Construction of analytical method of traction type lifts is often used for high-rise buildings. Figure 1 shows the dividing model and analytical model. Model A shows a lift where only long travel is installed. Model B shows that the lift travel is divided into two, so as to divide the building height equally; the model has two lifts installed. Model C is a case that four lifts are installed, and the lifts are labeled as the first, second, third, and fourth from the top. In the analysis, the main rope is measured from the top end along the rope. In contrast, the compensation rope is measured along the rope from the bottom end.

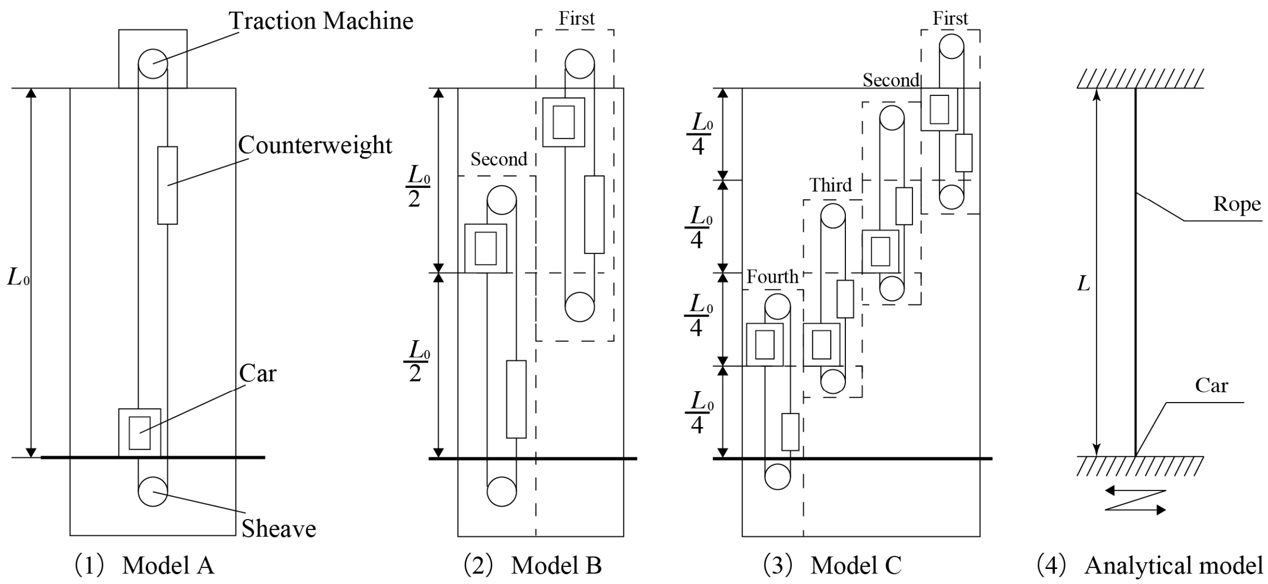

Figure 1. The dividing model and analytical model

2.1 Lift Ropes Model

The equation of motion of lift ropes as strings is as shown in Eq. (1).

$$\rho A\frac{\partial^2 u}{\partial t^2}+C\frac{\partial u}{\partial t}-\frac{\partial}{\partial z}\left(T(z)\frac{\partial u}{\partial z}\right)=0 \tag{1}$$

Where, ρA is a linear density of rope, C is a damping coefficient of rope, $T(z)$ is the tension considering the weight of the rope. u is the horizontal displacement of the rope, t is a time, z is position of elements except traction machine side. Eq. (1) is only valid when the lift is stationary. Eq. (1) is transformed to Eq. (2) by difference approximation [5,6].

$$\left(1+\frac{C\Delta t}{2\rho A}\right)u_{j+1}^{i}=2\left(1-\frac{T(z)\Delta t^{2}}{\rho A\Delta z^{2}}\right)u_{j}^{i}+\frac{\Delta t^{2}}{\Delta z^{2}}\left(\frac{T(z)}{\rho A}-g\frac{\Delta z}{2}\right)u_{j}^{i+1}+\frac{\Delta t^{2}}{\Delta z^{2}}\left(\frac{T(z)}{\rho A}+g\frac{\Delta z}{2}\right)u_{j}^{i-1}+\left(-1+\frac{C\Delta t}{\rho A}\right)u_{j-1}^{i} \tag{2}$$

Where, Δt is time step, Δz is length step, i is time coordinates, j is space coordinates, g is gravitation acceleration. Figure 2 shows a lattice point of the difference method.

2.2 Building Model

Figure 3 shows an analytical model of building. The structure in which a lift is set has been modeled as single-mass system. The equation of motion of structure is as shown in Eq. (3).

$$m\ddot{x}+c\dot{x}+kx=-m\ddot{z}_{H} \tag{3}$$

Where, m is a mass of structure, c is a damping coefficient of structure, k is a stuffiness of structure.
The natural period of structure is calculated using Eq. (4) [7].

$$T_{H}=0.025\times H \tag{4}$$

Where, T_H is a natural period of structure, H is a height of structure. Also, the vibration mode shape of the building is not straight but curved. Therefore, the shakes of the building are calculated using a correction coefficient for correcting the vibration mode. The correction equations used for the correction coefficients are shown in Eq. (5) and (6).

$$w=\alpha_{1}\times h+\alpha_{2}\times h^{2}+\alpha_{3}\times h^{3} \tag{5}$$

$$h=\frac{H_{position}}{H_{top}} \tag{6}$$

Where, w is vibration mode of building, $H_{position}$ is position of building, H_{top} is height of the top of the building, $\alpha_1=1.138$, $\alpha_2=0.5743$, $\alpha_3=-0.7083$. α were calculated by the Stodola method. The response value at the top of the building is calculated from Eq. (3). The response value of each building height is calculated by multiplying the response value obtained from Eq. (3) by the correction coefficient of each building height obtained from Eq. (5) and (6). The top and bottom of the rope vibrate synchronously with the building. Therefore, the response value obtained by the above method is input to the top and bottom of the rope.

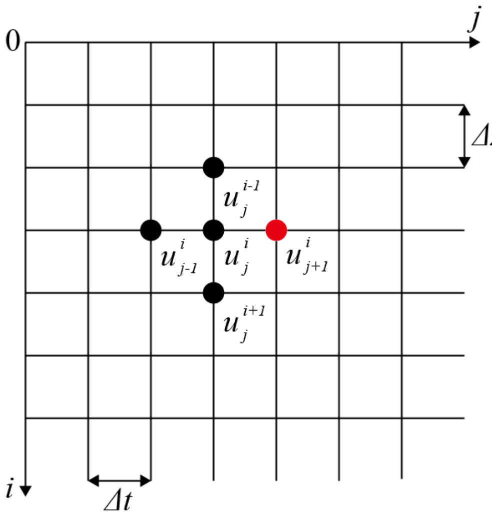

Figure 2. Lattice point

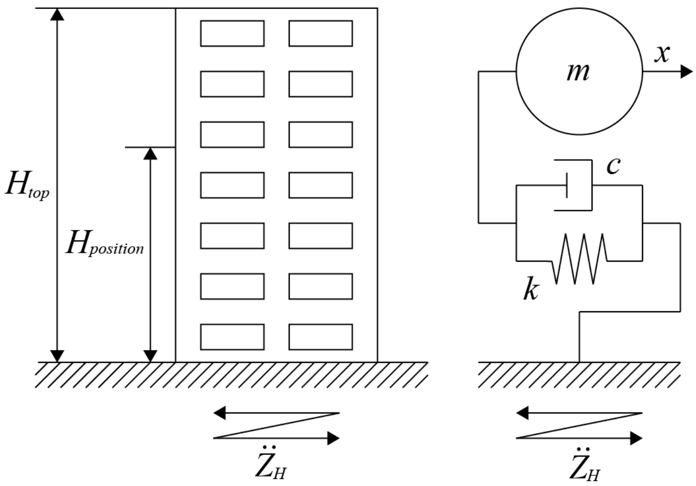

Figure 3. Structure model

3 ANALYTICAL CONDITION

3.1 Specifications of Structure and Lifts

We conduct seismic response analysis that was performed by using the derived equations in Section 2. Table 1 shows parameters of structure used for the analysis. Tables 2 to 4 show the parameters of each lift used for the analysis. Building height where the lift is installed is 240 [m]. The rope length used for the analysis was determined taking into consideration the height of car and sheave, hoisting machine and so on. The gap was determined by considering the actual lift dimensions.

Table 1. Specifications of building

Building height [m]	240
Natural period of buildings [s]	6
Damping ratio of buildings	0.02

Table 2. Specifications of model A

Roping		2:1
Car mass [kg]		2350
Counterweight mass [kg]		3450
Compensating sheave mass [kg]		554
Main rope	Number of ropes	6
	Linear density [kg/m]	0.494
	Length(Car side) [m]	3~238
	Length(Counterweight side) [m]	3~238
	Damping ratio	0.002
	Gap (cage side) [m]	0.8
	Gap (counterweight side) [m]	0.2
Compensating rope	Number of ropes	6
	Linear density [kg/m]	0.704
	Length(Car side) [m]	3~236
	Length(Counterweight side) [m]	3~235
	Damping ratio	0.02
	Gap (cage side) [m]	0.8
	Gap (counterweight side) [m]	0.4

Table 3. Specifications of model B

		First	Second
Roping		2:1	2:1
Car mass [kg]		2220	2220
Counterweight mass [kg]		3170	3180
Compensating sheave mass [kg]		167	167
Main rope	Number of ropes	5	5
	Linear density [kg/m]	0.494	0.494
	Length(Car side) [m]	3~118	3~124
	Length(Counterweight side) [m]	3~118	3~124
	Damping ratio	0.002	0.002
	Gap (cage side) [m]	0.8	0.8
	Gap (counterweight side) [m]	0.2	0.2
Compensating rope	Number of ropes	4	4
	Linear density [kg/m]	0.704	0.704
	Length(Car side) [m]	3~116	3~121
	Length(Counterweight side) [m]	3~115	3~121
	Damping ratio	0.02	0.02
	Gap (cage side) [m]	0.8	0.8
	Gap (counterweight side) [m]	0.4	0.4

Table 4. Specifications of model C

		First	Second	Third	Fourth
Roping		2:1	2:1	2:1	2:1
Car mass [kg]		2220	2220	2220	2220
Counterweight mass [kg]		3070	3080	3080	3080
Compensating sheave mass [kg]		167	167	167	167
Main rope	Number of ropes	4	4	4	4
	Linear density [kg/m]	0.494	0.494	0.494	0.494
	Length(Car side) [m]	3~58	3~63	3~63	3~63
	Length(Counterweight side) [m]	3~58	3~63	3~63	3~63
	Damping ratio	0.002	0.002	0.002	0.002
	Gap (cage side) [m]	0.8	0.8	0.8	0.8
	Gap (counterweight side) [m]	0.2	0.2	0.2	0.2
Compensating rope	Number of ropes	3	3	3	3
	Linear density [kg/m]	0.704	0.704	0.704	0.704
	Length(Car side) [m]	3~55	3~61	3~61	3~61
	Length(Counterweight side) [m]	3~55	3~61	3~61	3~61
	Damping ratio	0.02	0.02	0.02	0.02
	Gap (cage side) [m]	0.8	0.8	0.8	0.8
	Gap (counterweight side) [m]	0.4	0.4	0.4	0.4

3.2 Input Earthquake Wave and Specifications of Analysis

Figure 4 shows the input earthquake wave that was observed in 2011, when the earthquake at Shinjuku, (North-South Direction)[8] took place off the Pacific coast of Tohoku. Due to this earthquake, a large amount of lift damage was confirmed. Table 5 shows analysis time, time step and length step.

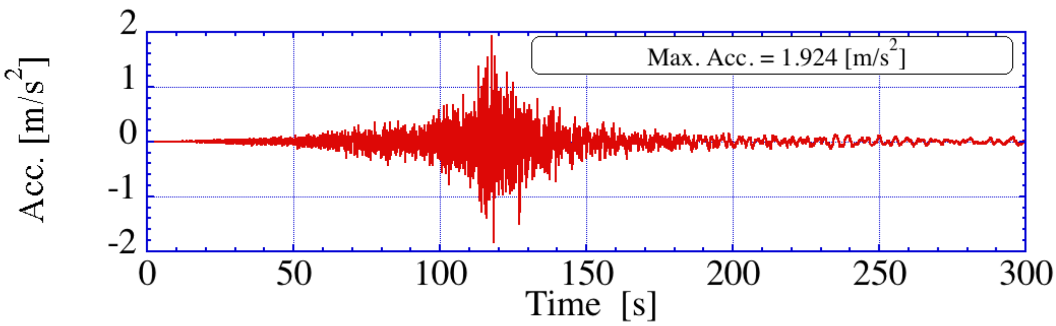

Figure 4. Input wave, The 2011 off the Pacific coast of Tohoku Earthquake at Shinjuku North-South Direction

Table 5. Specifications of Analysis

Analysis time [s]	600
Time step [s]	0.005
Length step [m]	1

4 RESULTS AND CONSIDERATIONS

Figures 5-10 show seismic response analysis results of the lift ropes. Figures 5-7 show the maximum displacement of each rope length of main rope. Figures 8-10 show the maximum displacement of each rope length of compensation rope.

From figure 5, the maximum displacement of the rope increases in proportion to the length of the rope. This is because the natural period becomes longer as the rope becomes longer, and it is close to the natural period of the building. Also, it can be confirmed that the displacement of the rope of the counterweight side is smaller than that of the car side. This is because the mass of the counterweight is larger than the mass of the car, and the natural period is short.

From figure 6, the maximum displacement on the car side and the counterweight side is smaller than model A's result. This is because dividing the lift travel has shortened the maximum rope length, and the natural period of the rope is no longer close to the natural period of the building. However, both the car side and the counterweight side can confirm that the maximum displacement of the rope is larger than the contact distance. And it can be confirmed that the displacement of the upper lift is larger than that of the lower lift. This is because the vibration amount of the rope depends on the amount of vibration applied to the top and bottom of the rope. It is considered that the displacement of the upper lift becomes larger because the amount of vibration of the upper lift is larger than that of the lower lift.

From figure 7, the maximum displacement on the car side and the counterweight side is smaller than the results of Model A and Model B. On the cage side, it can be confirmed that the maximum displacement of the rope is smaller than the contact distance. However, on the counterweight side, it can be confirmed that the maximum displacement of the rope reaches the contact distance. This is because the distance between the rope and the hoistway is smaller on the side of the counterweight.

From figure 8, the car side and the counterweight, the maximum displacement is obtained when the rope length is around 100 [m]. After that, the displacement is decreasing, and it can be confirmed that the displacement increases in the vicinity of 240 [m]. It is thought that this is because the compensating rope has lower tension than the main rope and its natural period is long. In the vicinity of 100 [m], it is considered that the first natural period of the rope is close to the natural period of the building. And in the vicinity of 240 [m], it is considered that the second natural period is close. Also, the length of the rope with the maximum displacement is changing. It is thought that this is because the number of ropes and rope length changed and the natural period changed.

From figure 9, the maximum displacement of the car side and the counterweight side is larger in the upper lift than the result of model A. This is because the vibration amount of the rope depends on the amount of vibration applied to the top and bottom of the rope. By dividing the lift, the amount of vibration input to the lower part of the compensating rope of the upper lift became larger than that of model A. Therefore, the displacement increased in the upper lift compared to the result of model A.

From figure 10, the maximum displacement on the car side and the counterweight side is smaller than the result of model A. This is because the rope length became shorter as the number of divisions increases, and the natural period of the rope and the natural period of the building no longer come close to each other.

From the above results, dividing the lift travel is effective for suppressing the displacement of the main rope. For the compensation rope, it is considered that displacement can be suppressed by increasing the number of divisions of the lift travel. Therefore, it is considered that dividing the lift travel leads to an improvement in the safety of the lift.

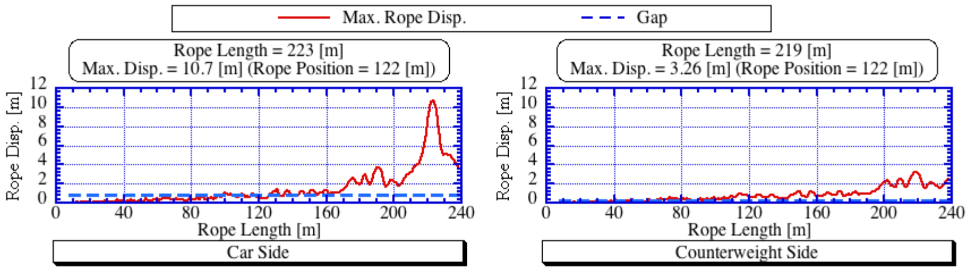

Figure 5. Numerical result of model A of main rope

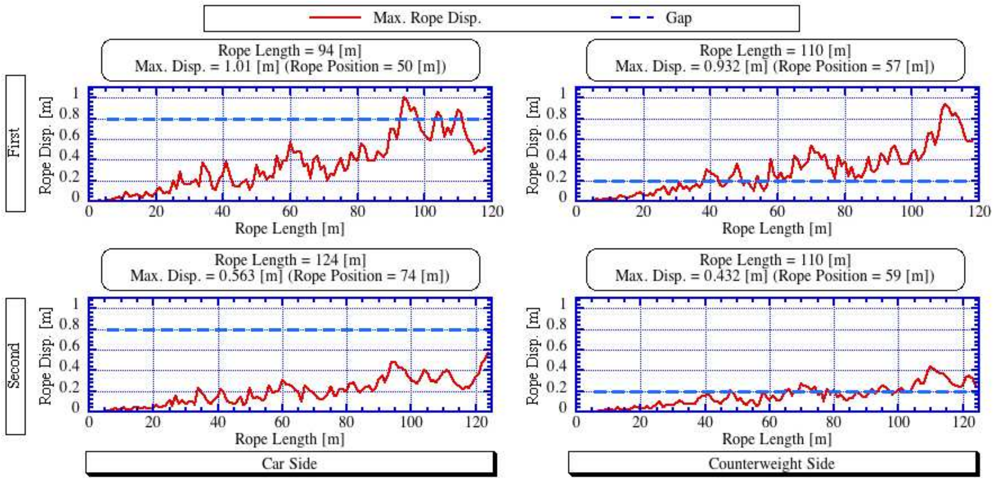

Figure 6. Numerical result of model B of main rope

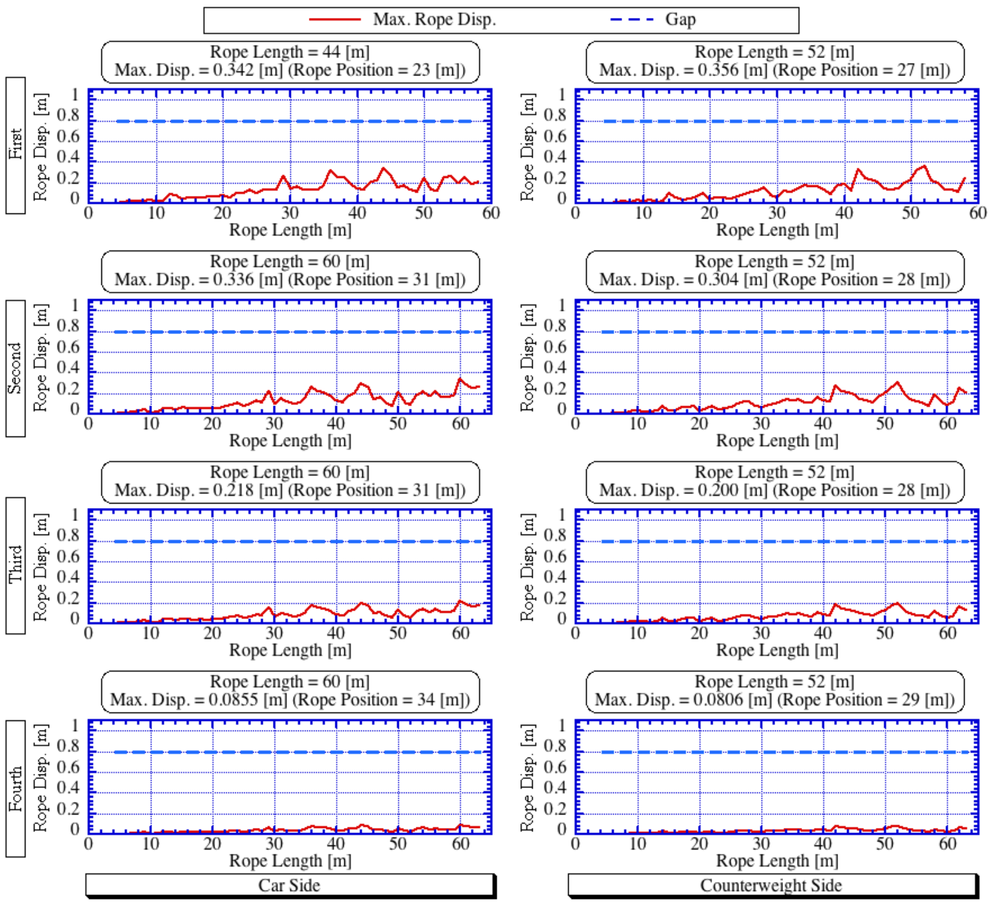

Figure 7. Numerical result of model C of main rope

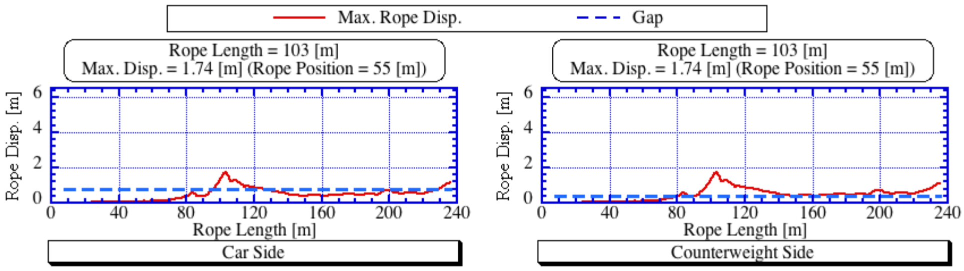

Figure 8. Numerical result of model A of compensation rope

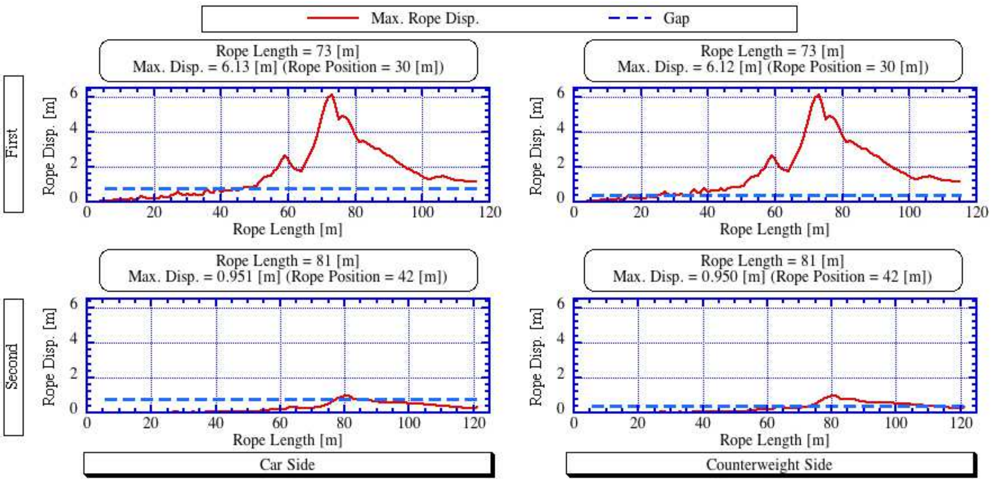

Figure 9. Numerical result of model B of compensation rope

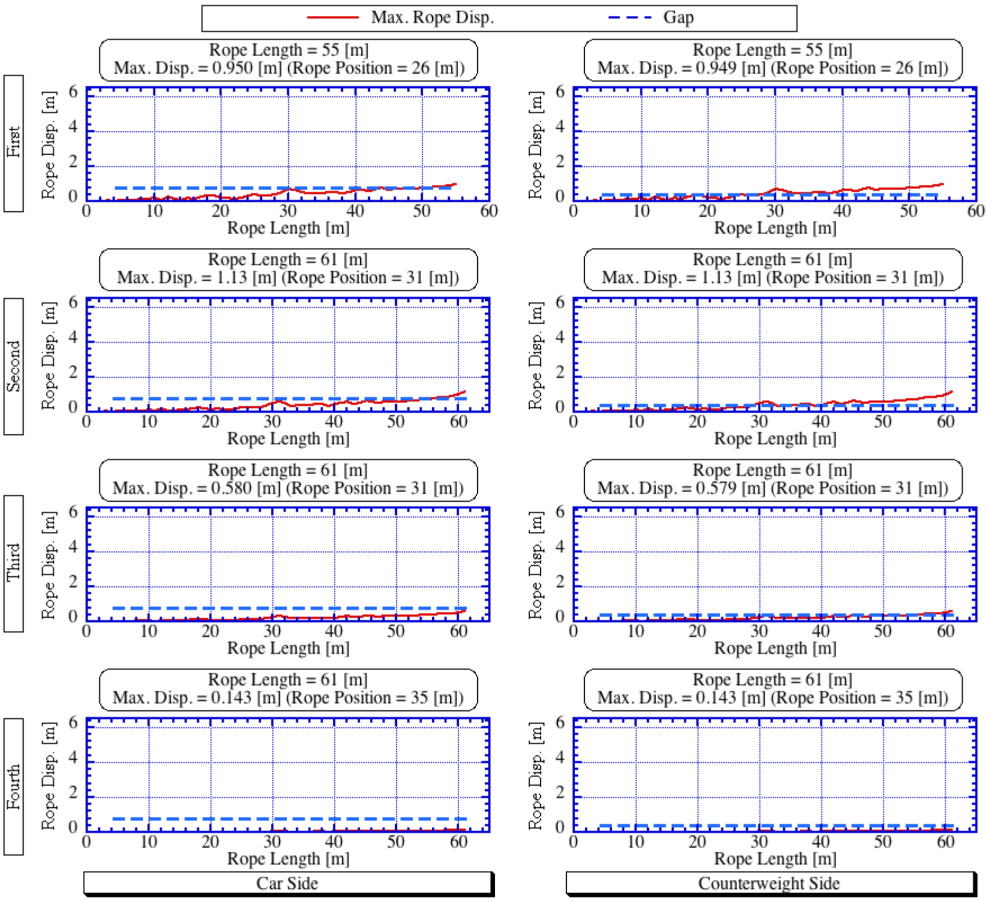

Figure 10. Numerical result of model C of compensation rope

5 CONCLUSIONS

In this report, we examined effectiveness of lifts using intermediate transfer floors for damage reduction of ropes. In the analysis, the maximum displacement of the main rope and compensation rope was examined when the lift travel is divided into two and four. As a result of the analysis, it was confirmed that displacement of the main rope could be suppressed by dividing the lift travel. And in the compensation rope, it was confirmed that displacement could be suppressed by increasing the number of divisions of the lift travel. Therefore, it is considered that dividing the lift travel can reduce damage of the lift rope. Analysis confirmed that this method is extremely useful for disaster prevention. Also, when dividing the lift travel, we confirmed that the displacement of the upper lift is larger than the lower lift. In the future, we will consider how to divide the upper lift shorter and the lower lift longer. Furthermore, We will consider the optimum division method and division number.

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BIOGRAPHICAL DETAILS

Hiroya Tanaka is master's course student in mechanical engineering of Tokyo Denki University. He researches vibration suppression of lift rope.

Miss Asami Ishii was received 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.

Kazuhiro Tanaka, has been in Toshiba Elevator since 1995, is in charge of development for elevator system and representative of quality expert in development dept. He has developed many special elevators especially hi-rise one like applied in tall tower. He is also chairperson of expert committee of machine technology in Japan Elevator Association since 2016.

Yoichi Ogawa entered Toshiba elevator in 2013.He belongs to the Development Dept. and is engaged in the development of cage mainly.