# Fundamental Study on Rope Vibration Suppression by Middle Transfer Floor using Risk Information

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**Abstract.** Lifts are essential for means of vertical transportation. Recently, the lifts installed in the high-rise buildings are long travel, thus the lift ropes are becoming longer. The natural period of the high-rise buildings is longer than that of the conventional buildings [1] and in addition to the lift rope becoming longer, the natural period of the lift ropes has also become longer. Accordingly, the natural period of the lift ropes gets closer to the that of the building. Consequently, the lift ropes might be hooked to the equipment of wall when the lift ropes vibrate by an external force, such as a strong wind or an earthquake. Furthermore, secondary accidents such as containment of passengers and lift service stop may occur. In the 2011 Great East Japan Earthquake, over 2000 problems such as the catch and the damage of lift ropes were reported [2]. Operation of lifts after earthquakes is required for the security of the refuge course. Accordingly, the analytical method for comparative evaluation is investigated in this study. Furthermore, a method to prevent a catch by vibration reduction of the lift ropes is investigated. In the previous research, it was confirmed that the division of the lift stroke is effective for reducing the response of the rope. When the lift stroke was equally divided, the displacement of the upper lift became larger than that of the other lift and so the effectiveness of the division ratio of lift stroke was examined in this report. The catching of the lift rope using differential analysis and risk assessment was investigated and as the result, the displacement of the upper lift was decreased by the apposite division ratio. The probability of catching rope of the upper lift is reduced. Furthermore, it was confirmed that the risk of the catching rope reduces in probabilistic risk assessment.

## 1 INTRODUCTION

Earthquakes occur frequently in Japan, which causes various damages to lifts. Accordingly, lifts require various seismic countermeasures including reinforcement of seismic structure as part of buildings. One of the problems is the vibration of the lift ropes. In recent years, the number of high-rise buildings is increasing in the urban areas with the development of building technology. Lifts installed in the buildings use the long components such as main rope, compensating rope and cables. Due to the increased height of the buildings, the natural period of these long objects is prolonged. Accordingly, the natural periods of the building and these long objects approach each other and resonate due to disturbances such as long-period ground motions and wind. The rope collides with the hoistway by swaying and 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 evacuate high-rise buildings with the evacuation staircase. Moreover, there are many people in high-rise buildings. If those people evacuate all at once, they are likely to cause confusion and congestion. In recent years, evacuation refuges, that people can temporarily evacuate to on the middle floors of high-rise buildings during disasters such as earthquakes and fire, have been set up. In China, they often have an "intermediate evacuation floor" that people can stay safely for long periods during disasters. At current, the evacuation methods using lifts are attracting attention. Accordingly, lifts that can be operated at the time of disaster are required.

Therefore, lifts that can be operated even after earthquakes are investigated in this study. In the previous study, it was confirmed that the division of the lift travel is effective for reducing the response of the rope. When the lift travel was equally divided, the displacement of the upper lift became larger than that of the other lift. Accordingly, the effectiveness of the division ratio of lift travel was examined in this report.

## 2 ANALYTICAL MODEL

Construction of analytical method of traction type lifts is often used for high-rise buildings. Fig.1 shows the dividing model and analytical model. Model A is the case where one tall lift is installed alone. Model B is the case that the lift travel is divided into two, with two lifts installed. In this paper, three patterns for model B were examined, with the division ratios of 1:1, 1:2, and 1:3. In the analysis, the main rope is measured along the rope from the top end. On the other hand, the compensation rope is measured along the rope from the bottom end.

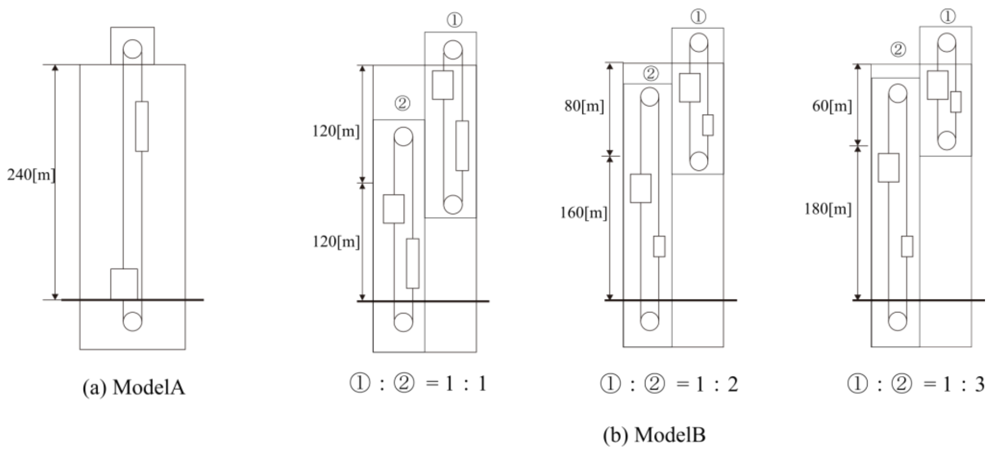


**Figure 1: The dividing model and analytical model**

### 2.1 Lift Ropes Model

The equation of motion of lift ropes as strings is 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, $\rho A$ 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 time, $z$ is position of elements except traction machine side. Eq.1 is valid when the lift is stationary. Eq.1 is transformed to Eq.2 by the difference approximation method. [3,4].

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

Where, $\Delta t$ is time step, $\Delta z$ is length step, $i$ is time coordinates, $j$ is space coordinates, $g$ is gravitational acceleration. Fig.2 shows a lattice point of the difference method.

## 2.2 Building Model

Fig. 3 shows an analytical model of a building. The building is modeled as a 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 the mass of the building, $c$ is the damping coefficient of the building, $k$ is the stiffness of the building, $\ddot{z}_{H}$ is the acceleration of input wave.
The natural period of building is calculated using Eq.4 [4].

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

Where, $T_H$ is the natural period of building and $H$ is the height of building. The vibration mode shape of the building is not straight but curved. Accordingly, the vibration behavior of the position of the building is calculated using a correction coefficient, which is corrected by 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 the vibration mode of building, $H_{position}$ is the position of the building, $H_{top}$ is the height of the top of the building, $\alpha_1$ = 1.138, $\alpha_2$ = 0.5743 and $\alpha_3$ = -0.7083. $\alpha_{1,2,3}$ were calculated by the Stodola method. The response at the top of the building is calculated from Eq.3. The response of each building height is calculated by multiplying the response 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. Accordingly, the response obtained by the above method is the input to the top and bottom of the rope.

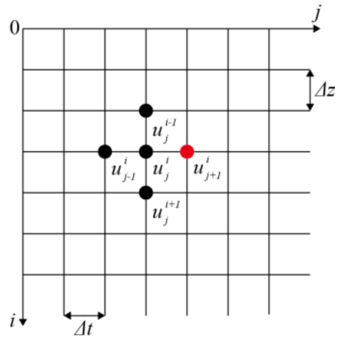


**Figure 2: Lattice point**

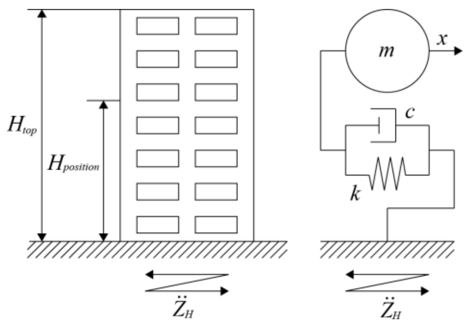


**Figure 3: Structure model**

# 3 ANALYTICAL CONDITION

## 3.1 Specifications of Building and Lifts

The seismic response analysis was conducted by the derived equations in Section 2. Table 1 shows the parameters of the building. Tables 2 to 3 show the parameters of each lift. Building height where the lift is installed is 240 m. The rope length was determined taking into consideration the height of car and sheave, hoisting machine and so on. The gap was determined in consideration of 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 |
| Cage mass [kg] | | 2350 |
| Counterweight mass [kg] | | 3450 |
| Compensating sheave mass [kg] | | 554 |
| Gap (cage side) [m] | | 0.8 |
| Gap (counterweight side) [m] | | 0.2 |
| Main rope | Linear density [kg/m] | 0.494 |
| | Length(Cage side) [m] | 3~238 |
| | Length(Counterweight side) [m] | 3~238 |
| | Damping ratio | 0.002 |
| Compensating rope | Linear density [kg/m] | 0.704 |
| | Length(Cage side) [m] | 3~236 |
| | Length(Counterweight side) [m] | 3~235 |
| | Damping ratio | 0.02 |

**Table 3: Specifications of model B**

| Division ratio | | 1:1 | | 1:2 | | 1:3 | |
|---|---|---|---|---|---|---|---|
| Lift number | | First | Second | First | Second | First | Second |
| Roping | | 2:1 | 2:1 | 2:1 | 2:1 | 2:1 | 2:1 |
| Cage mass [kg] | | 2220 | 2220 | 2220 | 2220 | 2220 | 2220 |
| Counterweight mass [kg] | | 3170 | 3180 | 3090 | 3220 | 3090 | 3220 |
| Compensating sheave mass [kg] | | 167 | 167 | 167 | 167 | 167 | 167 |
| Gap (cage side) [m] | | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Gap (counterweight side) [m] | | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Main rope | Linear density [kg/m] | 0.494 | 0.494 | 0.494 | 0.494 | 0.494 | 0.494 |
| | Length(Cage side) [m] | 3~118 | 3~124 | 3~78 | 3~164 | 3~58 | 3~184 |
| | Length(Counterweight side) [m] | 3~118 | 3~124 | 3~78 | 3~164 | 3~58 | 3~184 |
| | Damping ratio | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| Compensating rope | Linear density [kg/m] | 0.704 | 0.704 | 0.704 | 0.704 | 0.704 | 0.704 |
| | Length(Cage side) [m] | 3~116 | 3~121 | 3~76 | 3~161 | 3~56 | 3~181 |
| | Length(Counterweight side) [m] | 3~115 | 3~121 | 3~75 | 3~162 | 3~55 | 3~182 |
| | Damping ratio | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |

### 3.2 Input Earthquake Wave and Specifications of Analysis

Fig.4 shows an input earthquake wave, which was observed in 2011 off the Pacific coast in the Tohoku Earthquake at Shinjuku North-South Direction [5]. Due to this earthquake a large number of lifts were confirmed damaged. Table 4 shows analysis time, time step and length step.

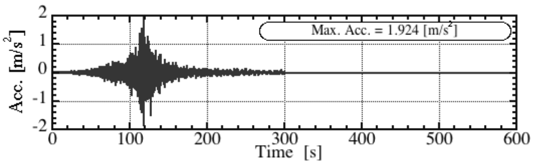


**Figure 4: Input wave**

**Table 4: Specifications of Analysis**

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

## 4 PROBABILISTIC RISK ASSESSMENT

Probabilistic risk assessment is a method to quantitatively evaluate the frequency of occurrence and the effect of the occurrence of an accident that may occur. In this report, the risk of the rope catch is evaluated. The evaluation formula for the fragility curve is as shown in Eq. 7 [6]. In this report, it is assumed that probability distribution of various elements of the fragility curve is a log-normal distribution, as a method to make the failure probability curve simply. Assuming that the probability distribution of various elements of the fragility curve is log-normal, Eq. 7 can be applied to various phenomena.

$$P_f\left(Z_m(s)\right)=\phi\left[\frac{\left(Z_m(s)/A_m\right)+\beta_u\phi^{-1}(Q)}{\beta_r}\right] \tag{7}$$

Where, $P_f$ is the failure probability, $Z_m(s)$ is the velocity of the earthquake, $Am$ is the median of the index due to catch of the rope, $\beta_u$ is a logarithmic standard deviation representing epistemic uncertainty, $\beta_r$ is the logarithmic standard deviation representing accidental uncertainty, $\phi(\cdot)$ is standard normal distribution, $\phi^{-1}(\cdot)$ is the inverse function of $\phi(\cdot)$ and $Q$ is the non-exceeding probability of failure probability considering epistemic uncertainty. When making a fragility curve based on Eq.7, it is necessary to experimentally determine the median and the uncertainty of the index caused by the catching rope. In this report, as a basic examination of probabilistic risk assessment, if displacement occurs up to 0.8 m in car side and up to 0.2 m in counterweight side, the rope will not be caught at 99% probability. Uncertainty such as error in rope analysis, error due to principle of occurrence of the catch and effects of dividing lift stroke are assumed to be constants. In this report, $\beta r$ and $\beta u$ are evaluated as 0.1. Moreover, in this report, evaluations are made by a 95% reliability curve which is high reliability.

## 5 RESULTS AND CONSIDERATION

### 5.1 Rope Analysis

Fig. 5-8 show seismic response analysis results of the lift ropes. Fig.5 shows the maximum displacement of each rope length of the main rope and the compensation rope in the model A. Fig. 6-8 show the maximum displacement of each rope length of the main rope and the compensation rope of the model B.

From Fig.5, the maximum displacement of main rope increases in proportion to the length of the rope. The natural period becomes longer as the rope becomes longer. As the result, the natural period of the main rope is close to the natural period of the building. Also, the maximum displacement of compensation rope is obtained when the rope length is around 100 m. After that, the displacement is decreasing, and the displacement increases in the vicinity of 240 m. Because the compensation rope has lower tension than the main rope, the natural period of the compensation rope is longer than of the main rope. In the vicinity of 100 m, it is considered that the first natural period of the compensation rope is close to the natural period of the building.

From Fig.6, the displacement of the upper lift in both the main rope and the compensation rope is larger than the displacement of the lower lift. The displacement of the rope is considered to depend on the amount of vibration at the top and the bottom of the rope. Since the vibration input of the upper lift is larger than that of the lower lift, the displacement of the upper lift is considered to be large.

From Fig.7, when the division ratio changes from 1:1 to 1:2, the displacement of the upper lift decreased. The vibration input of the upper lift is larger than that of the lower lift. The displacement is decreased by changing the division ratio and shortening the lift stroke. Also, when the division ratio changes from 1:1 to 1:2, the displacement of the lower lift increased. The vibration input of the lower lift is smaller than that of the upper lift. The displacement was increased by changing the division ratio and lengthening the lift stroke.

From Fig.8, the displacement decreases in the upper lift and increases in the lower lift compared to the cases where the division ratios are 1:1 and 1:2. As in the case of a 1:2 ratio, this is considered to be caused by a change in the division ratio.

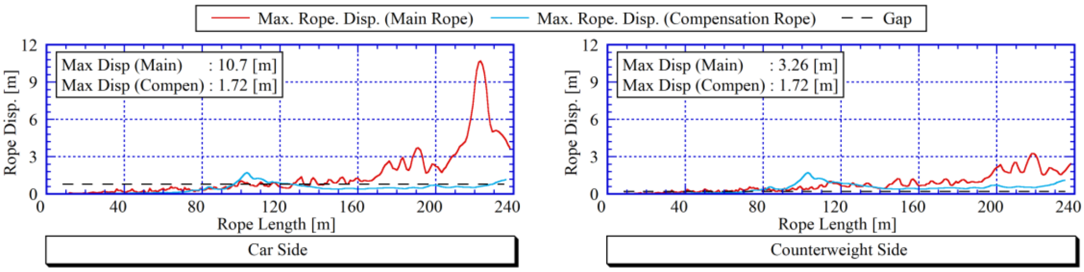


**Figure 5: Numerical result of model A**

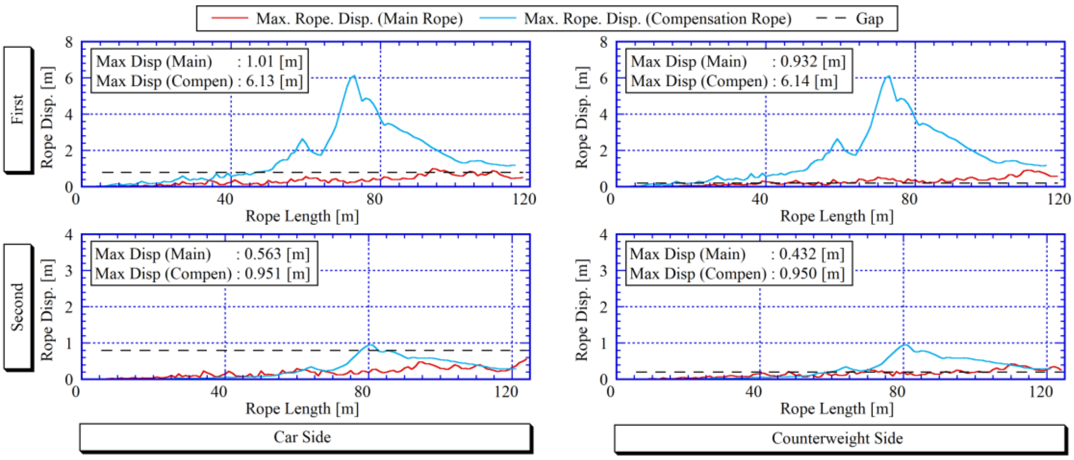


**Figure 6: Numerical result of model B (1:1)**

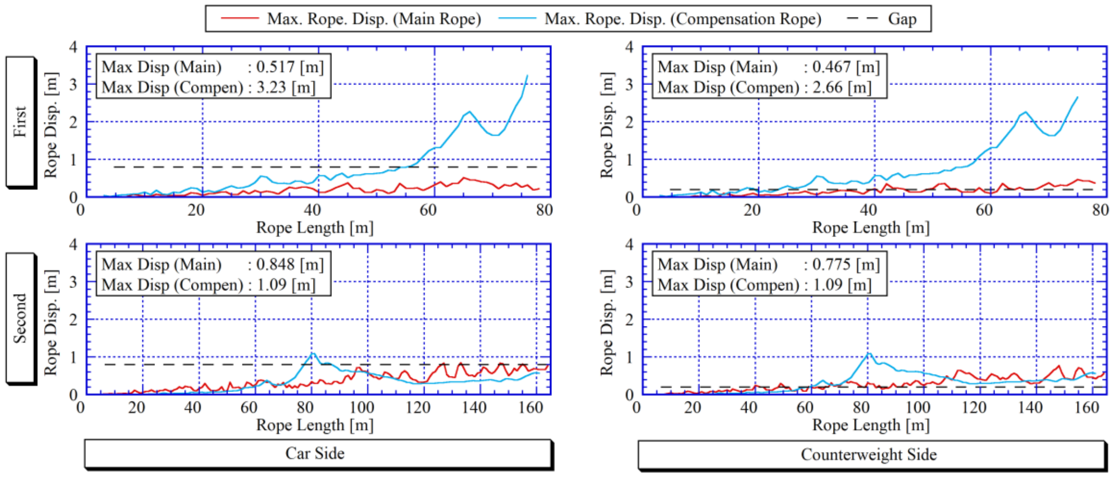


**Figure 7: Numerical result of model B (1:2)**

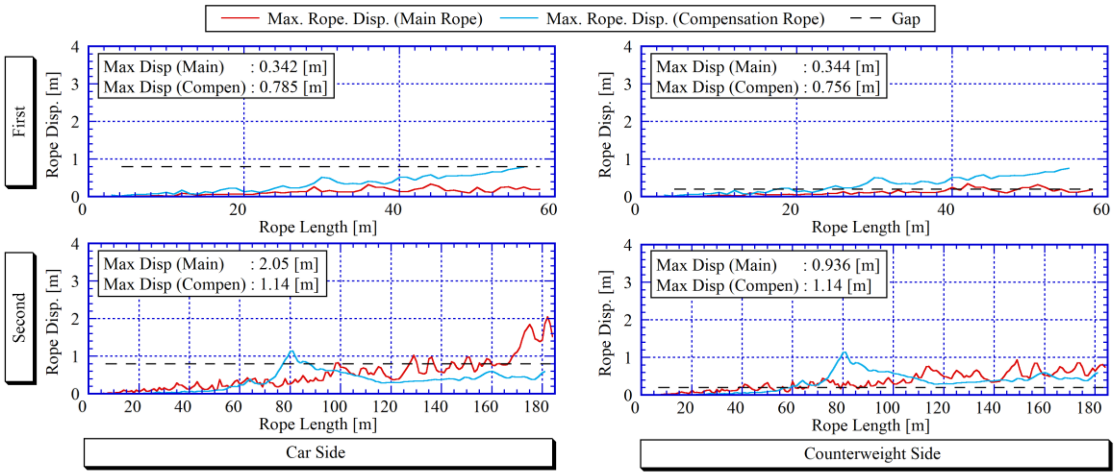


**Figure 8: Numerical result of model B (1:3)**

## 5.2 Probabilistic Risk Assessment

Fig. 9-12 show the fragility curves for each lift. Fig. 9-10 show the fragility curves for main rope and compensation rope of model A. Fig. 11-12 show the fragility curves for main rope and compensation rope of model B. The HCLPF values for each lift are shown in Table 5. The HCLPF value, which guarantees the performance of the equipment mainly used in the nuclear field, is the value of 5% failure probability in the 95% reliability curve.

From Fig. 9-10 and Table 5, the main rope and the compensation rope in Model A have a high probability of catching rope, even by small input seismic waves.

From Fig. 11-12 and Table 5, the probability of the catching rope was lower in model B than in model A because by dividing lift stroke, the displacement of the lift rope decreased. When the division ratio is 1:1, the probability of the catching rope is larger in the upper lift than in the lower lift because the upper lift vibrates more than the lower lift, the displacement of the upper lift becomes large. Division ratio changes from 1:1 to 1:2 or 1:3, and the lift stroke of the upper lift shortens. Therefore, the probability of catching rope also decreases. On the contrary, lower lift increases the probability of the catching rope because the lift stroke becomes longer.

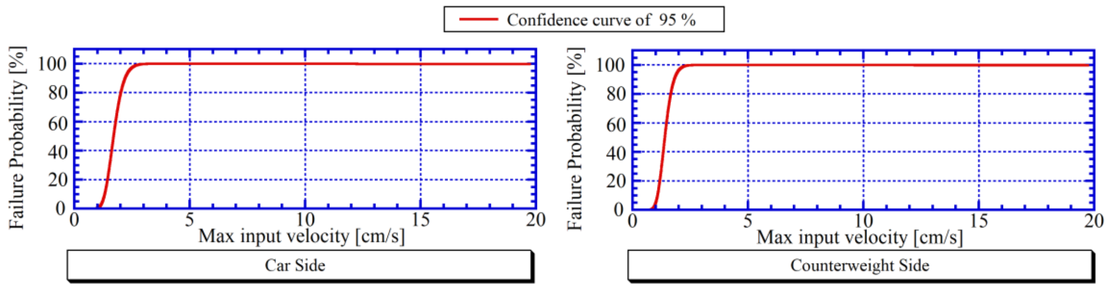


**Figure 9: Fragility curve of model A of main rope**

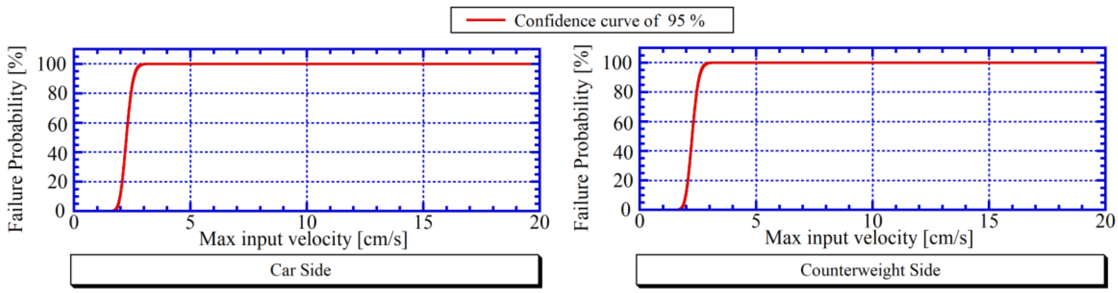


**Figure 10: Fragility curve of model A of compensation rope**

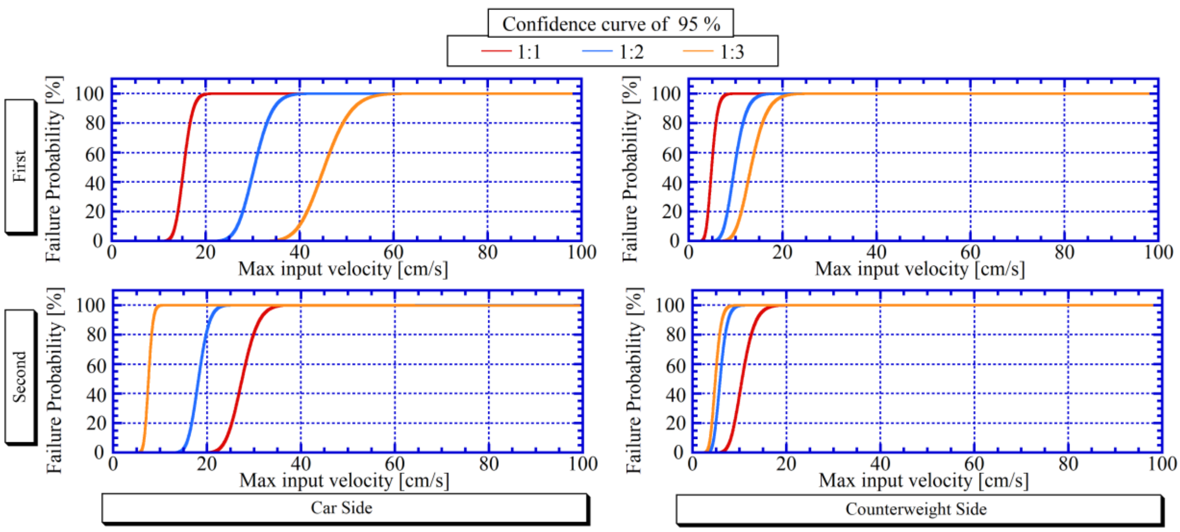


**Figure 11: Fragility curve of model B of main rope**

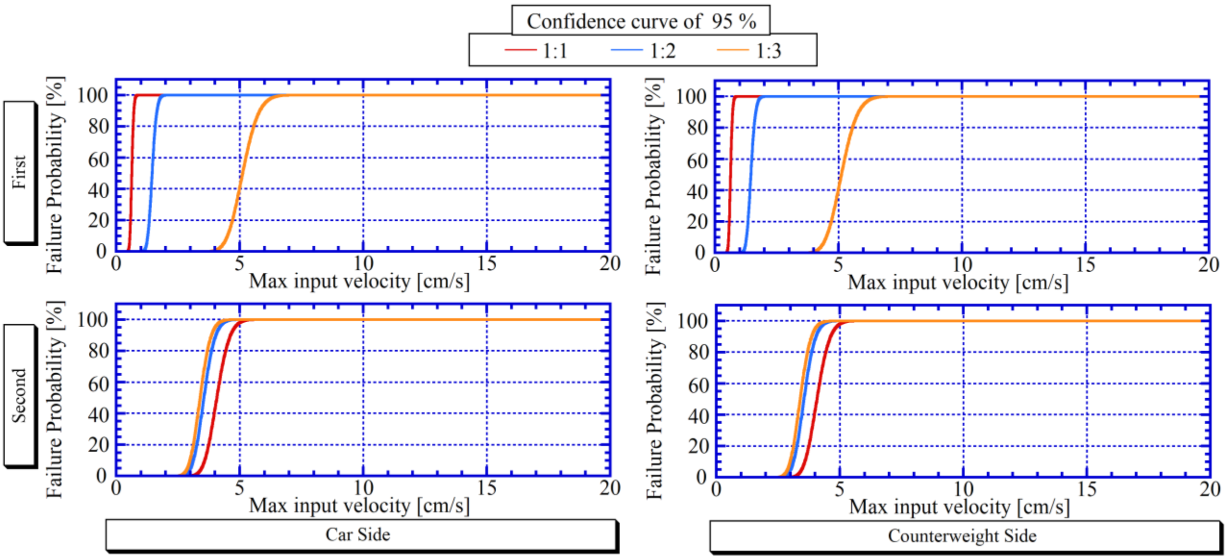


**Figure 12: Fragility curve of model B of compensation rope**

**Table 5: HCLPF Value of each lift**

| | Division ratio | Lift Number | HCLPF [cm/s] | | | |
|---|---|---|---|---|---|---|
| | | | Main Rope | | Compensation Rope | |
| | | | Car side | Counterweight side | Car side | Counterweight side |
| Model A | | | 1.23 | 1.01 | 7.63 | 1.91 |
| Model B | 1:1 | First | 13.0 | 3.52 | 2.14 | 0.536 |
| | | Second | 23.3 | 7.59 | 13.8 | 3.45 |
| | 1:2 | First | 25.7 | 7.02 | 4.06 | 1.23 |
| | | Second | 15.4 | 4.23 | 12.0 | 3.01 |
| | 1:3 | First | 38.4 | 9.53 | 16.7 | 4.34 |
| | | Second | 6.40 | 3.50 | 11.5 | 2.88 |

## 6 CONCLUSIONS

In this paper, as a vibration reduction method of lift rope in a high-rise building, the effectiveness of installing multiple lifts by dividing the lift travel and the effectiveness of changing the division ratio of the lifting travel were evaluated using the maximum displacement of rope and the fragility curve. As the result, the occurrence probability of displacement and the probability of catching rope of the upper lift decreased, by changing the division ratio of the going lift travel, and displacement and the probability of catching rope of the lower lift increased. By appropriately setting the division ratio in consideration of the vibration behavior and the length of the rope, the probability of the rope catch can be suppressed. Therefore, the safety of the lift can be improved during and after seismic events including long period earthquakes.

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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 high-rise ones applied in tall towers. He is also chairperson of expert committee of machine technology in Japan Elevator Association since 2016.

Tomohiro Shiki entered Toshiba elevator in 2011. He belongs to the Development Dept. and is engaged in the development of cage mainly.

Associate Professor Shigeki Okamura has been in Toyama Prefectural University since 2018. Previously, he had been in the research institute and manufacturing. He has been engaged in engineering research and development of seismic isolation systems and the seismic evaluation method for the important facilities, such as, nuclear power plant/components. In addition, he had been engaged in seismic design of nuclear power plant/components.