Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 910

EVALUATION OF SEISMIC DAMAGE RISK OF ELEVATOR ROPE IN HIGH-RISE BUILDING BASED ON CCQC METHOD

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ABSTRACT

To solve the problem of elevator rope sway in a high-rise building, the seismic damage risk of a building and suspension rope are examined using the Complex Complete Quadratic Combination method. A building site was assumed at Sinjuku, Tokyo in Japan and possible earthquake source zones were considered in Chuetsu, Niigata and the northwest of Chiba. The following findings were obtained: For the 100-, 150- and 250-meter-high buildings, the damage risk of the rope was high when an elevator car or a counterweight was in a lower floor because the rope was long to cause resonance. However, for the 50-, 100- and 200-meter-high buildings, the damage probability was the highest when in a layer other than the bottom. The distribution of the probability of rope damage varies considerably depending on the building height.

Introduction

An elevator set up in a high-rise building causes a problem of elevator rope sway. Due to the 2004 Niigata-ken Chuetsu earthquake, main (suspension) rope of an elevator in a high-rise building oscillated to tangle around hoistway components although the building was located about 200 km far away from the epicenter. Elevator rope in a high-rise building is so long that the natural period of a rope sway mode is close to that of a building sway mode and the resonance risk would increase. In addition, long period seismic wave, which a large magnitude earthquake often brings about, reaches a very far place.

To consider this problem, it is necessary to understand the relation between responses of a building and rope. The authors' research group studies on this issue based on time history analysis with input ground motion of some seismic records (Mitsui and Kohiyama 2007). However, a finite element model of the rope requires not a small number of degrees of freedom to obtain a reliable result and it takes very long time to conduct a Monte Carlo simulation for risk analysis. In other past studies on rope sway, the number of input waves is also limited, and there is no study to evaluate the seismic damage risk stochastically in consideration of the probability of earthquake occurrence. Therefore, it is desired to evaluate the seismic damage risk by using a time efficient method and to plan measures for safety.

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In this study, the response of a building-elevator system was examined using the CCQC (Complex Complete Quadratic Combination) method, which is proposed by Zhou et al. (2004). The CCQC method expands the CQC (Complete Quadratic Combination) method (Wilson et al. 1981) to deal with a non-proportional damping system, which has complex eigenvectors. A building site was assumed in Tokyo, Japan and possible earthquakes were considered in the Chuetsu District, Niigata Prefecture and the northwest of Chiba Prefecture. The response was modeled by the lognormal distribution, and the damage probabilities of the rope were obtained considering the probability distribution of the earthquake magnitude and the seismic event occurrence, etc.

Models Used in the Study

Building Models

This study focuses on a traction-type elevator, which has rope, on a high-rise building. A driving machine and a car are attached to the top floor of a building and hoistway, respectively, via a spring and a damper (Fig. 1). Five models of high-rise buildings are generated, in which mass points of floors are connected with linear elastic shear springs. Table 1 shows the models and the model names correspond to the height of the building, e.g. Model H50 stands for the height of the building is 50 meters. Story stiffness distribution is determined based on A_i distribution of the Building Standard Law of Japan and the fundamental periods as well as damping factors of the models are shown in the Table 1. Note that these values are assumed considering practical design.

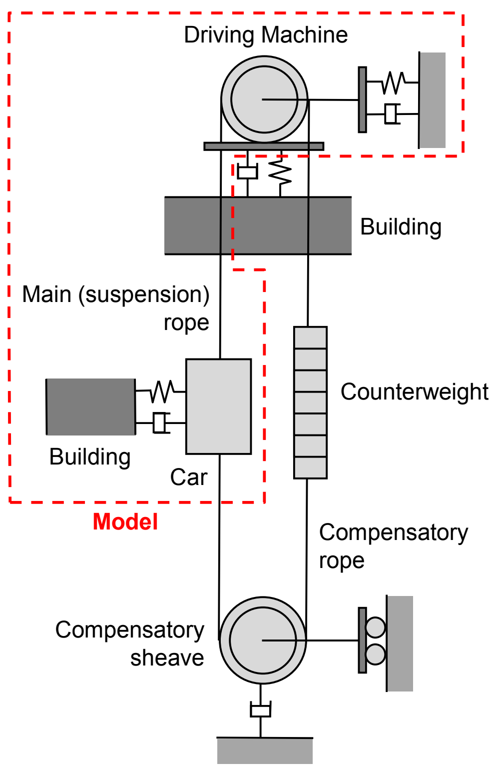


Figure 1. Components of a traction-type elevator system and the modeled part.

Table 1. Parameters of building models.

Model	Building height	Number of stories	Fundamental period	Damping factor
H50	50 m	15	1.0 s	0.03
H100	100 m	30	2.5 s	0.03
H150	150 m	45	3.7 s	0.03
H200	200 m	50	4.3 s	0.03
H250	250 m	60	5.8 s	0.01

Rope Models

Elevator rope is modeled by 30 finite elements divided with equal length. Note that Kimura et al. (2008) clarifies that the number of element should be equal to or more than 20 to obtain accurate rope response. In this study, only suspension rope is focused for simplicity, and governor rope and compensation rope under a car are omitted in the models. The seismic damage risk of the omitted rope can be easily evaluated by elaborating the models. The linear density and the damping factor are 1.7 kg/m and 0.002, respectively. Regarding the position of the elevator car, all the cases of the car position is considered, i.e. the car is located at each mass height.

Earthquake Models

Considering recent damage to elevator systems, the site of a building is assumed at Shinjuku, Tokyo in Japan, and two earthquake source zone, Sources 1 and 2 are assumed as shown in Table 2. These parameters are given based on the data in NIED (2009). The bounded Gutenberg-Richter (G-R) recurrence relationship is used with the minimum and the maximum magnitude shown in Table 2. The magnitude is discretized with the interval of 0.1 in the risk evaluation.

Table 2. Assumed earthquake source zone.

Source	District	Focal depth	Epicentral distance	Magnitude	Occurrence probability	
					30 years	50 years
Source 1	Chuetsu District, Niigata Prefecture	13 km	190 km	6.5 to 8.2	0.05	0.08
Source 2	North-western region of Chiba Prefecture	60 km	40 km	6.7 to 7.2	0.7	0.9

Ground Motion Models

Earthquake ground motions are generated based on empirical spectrum attenuation formulae; response spectrum proposed by Uchiyama and Midorikawa (2006) and acceleration spectrum proposed by Zama (2000) are employed for short period range (0.08-5.0 s) and long period range (2-20 s), respectively. For the overwrapping range, a larger spectrum is adopted.

To simulate the non-stationary amplitude change, the Jennings-type envelope function is used and the Fourier phase spectrum is determined so that the phase deference spectrum fits the envelope shape. For each source and each discretized magnitude, 100 ground motions are generated. The site is assumed on the engineering base rock, and no amplification due to surface soil is considered.

Structural Response Models

For each source and each discretized magnitude, two structural responses, which are random variables, are modeled by the lognormal distributions: (1) the maximum relative displacement between the rope and the building and (2) the maximum interstory drift angle. The lognormal distribution is evaluated based on the results of seismic response analyses with the above-mentioned 100 input waves.

Evaluation of Seismic Damage Risk

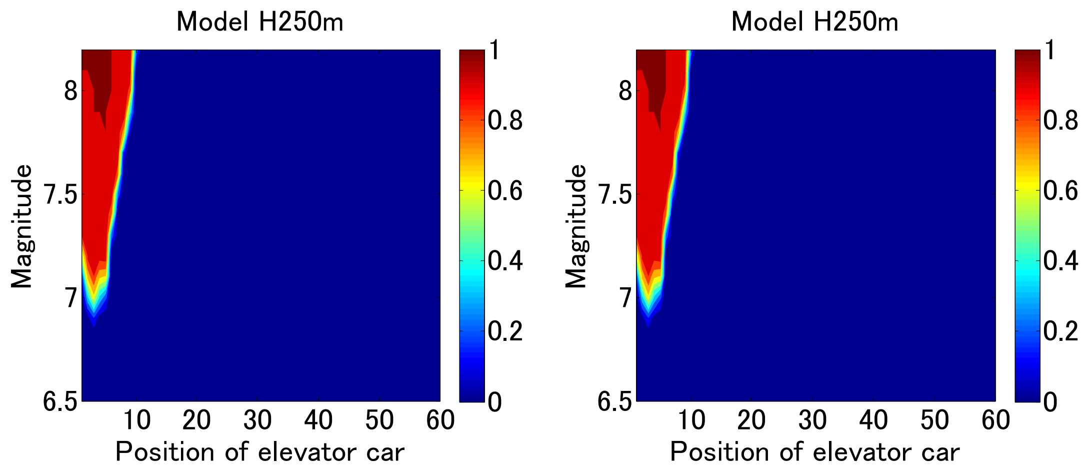
The probability of the seismic damage is evaluated based on (1) the probability of earthquake occurrence at each source for a given duration of time (Table 1), (2) the conditional probability that a magnitude is M given the occurrence of earthquake at each source (the bounded G-R relation), and (3) the conditional probability of damage of building and rope given the occurrence of a magnitude M earthquake (the lognormal model based on the results of seismic response analyses).

With respect to thresholds to determine the occurrence of damage, the maximum interstory drift angle of 1/200 rad is used for building damage, and the maximum relative displacement between rope and elevator of 0.1, 0.2, and 0.3 m for rope damage. Note that rope of counterweight and that of governor would interfere with a car when the relative displacement exceeds 0.3 m.

In the seismic response analyses, we modified the CCQC method (Zhou et al. 2004) based on Igusa et al. (1984) to calculate a relative displacement from complex modes properly. The building-elevator system used in this study has non-classical damping and phase difference exists between a mass point of the building and a node of finite element of the rope in the eigenmodes. The maximum response $|y(t)|_{\max}$ is estimated as follows:

$$|y(t)|_{\max} \approx \left[\sum_{n=1}^{N_{\text{mode}}} \sum_{m=1}^{N_{\text{mode}}} \left(\rho_{nm}^{DD} A_n A_m + 2\rho_{nm}^{DV} B_n A_m \omega_n + \rho_{nm}^{VV} B_n B_m \omega_n \omega_m \right) {}_n S_D \, {}_m S_D \right]^{1/2} \tag{1}$$

where N_{mode} is the number of modes considered in the estimation; in this study, $N_{\text{mode}} = 15$ is adopted based on the convergence analysis (Fig. 2). The variables ρ_{nm}^{DD}, ρ_{nm}^{DV}, and ρ_{nm}^{VV} are correlation coefficients between nth and mth displacement modes, nth displacement and mth velocity modes, and nth and mth velocity modes, respectively; A_n and B_n are modal participation factors of displacement and velocity, respectively; ${}_nS_D$ is the spectral displacement at the nth natural circular frequency, ω_n.



(a) All modes considered (b) Up to 15 modes

Figure 2. Damage occurrence risk of the rope given the earthquake occurrence in Source 1. The building model is H250 and the damage threshold of the rope is 0.3 m.

Risk of Building Damage

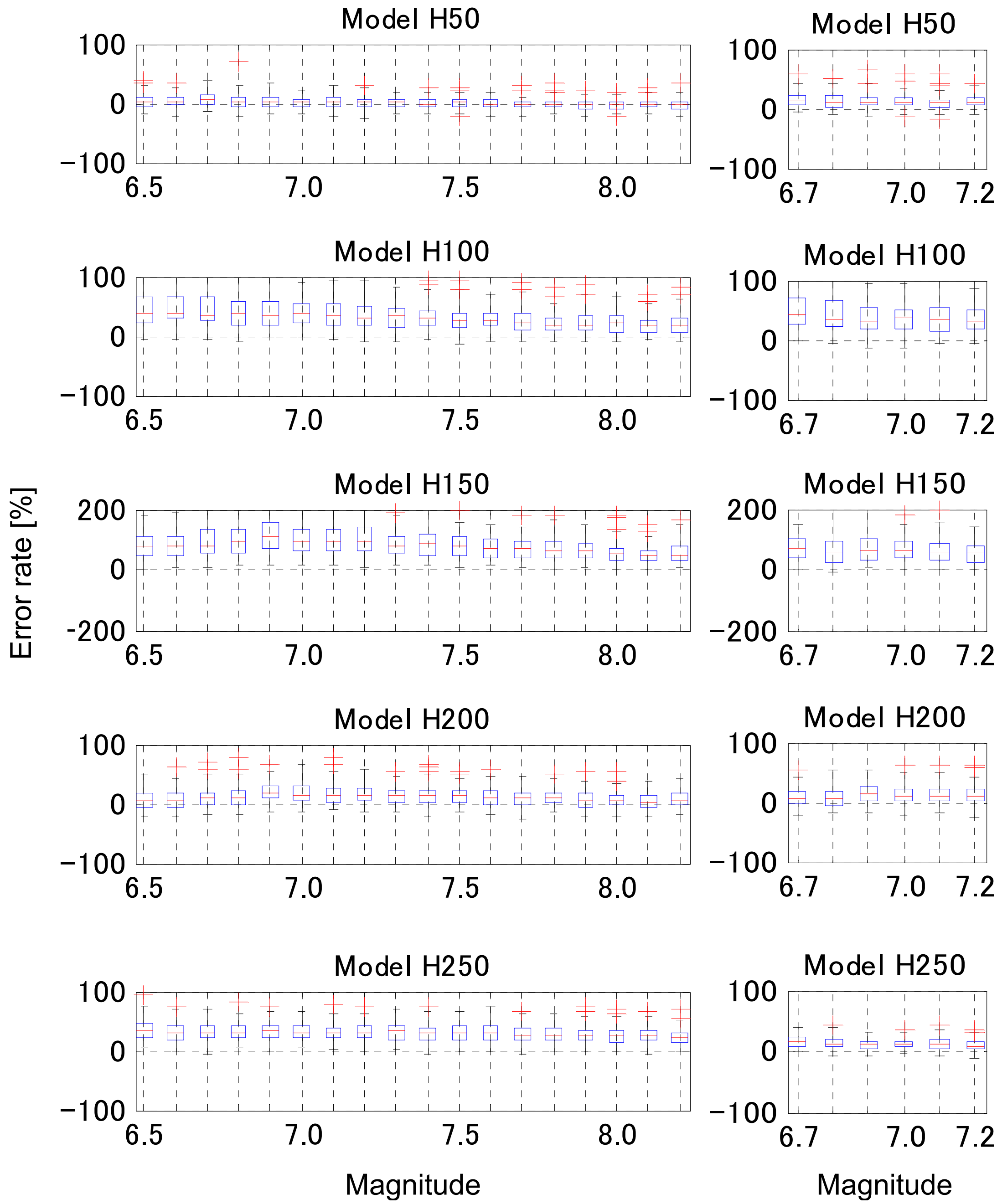
First, the assumption of linear elastic response is verified. The maximum interstory drift angles calculated by time-history analyses are less than 1/150 rad for all the cases, and the assumption can be considered to be admissible.

Fig. 3 shows the error rate of the modified CCQC method to the time-history analysis with respect to the maximum relative displacement between rope and a building. Good accuracy is observed for the cases of Models H50, H200 and H250 for both Sources 1 and 2. However, the error rates are relatively large for the other cases arguably because the response tends to be small.

Table 2 shows the probability of damage occurrence of the building. The building damage occurs in the case of a large magnitude earthquake in Source 1, while the probability of damage occurrence is nearly zero for all the building models in the case of Source 2. It is clarified that the higher the building is, the larger probability of damage occurrence it has.

Table 2. Probability of building damage.

Model	**Probability of damage occurrence of the building**			
	Source 1		**Source 2**	
	30 years	**50 years**	**30 years**	**50 years**
H50	≈ 0	≈ 0	7.00×10^{-1}	8.99×10^{-1}
H100	1.12×10^{-4}	1.79×10^{-4}	3.12×10^{-2}	4.01×10^{-2}
H150	5.08×10^{-8}	8.12×10^{-8}	1.53×10^{-9}	1.97×10^{-9}
H200	1.27×10^{-5}	2.04×10^{-5}	≈ 0	≈ 0
H250	1.89×10^{-5}	3.02×10^{-5}	≈ 0	≈ 0



(a) Source 1 (b) Source 2

Figure 3. Error rate of the modified CCQC method to time-history analysis with respect to the maximum relative displacement between rope and a building. The horizontal axis corresponds to magnitude of the earthquake and there are 100 simulated ground motions for each magnitude. A blue box, a red bar and whiskers stand for the 25th-to-75th percentiles, the median and the range of non-outliers, respectively. Outliers are plotted with red cross markers.

Risk of Rope Damage

Fig. 4 shows the probability of rope damage given the earthquake occurrence in each source, in which the building model is H250 and the damage threshold of the rope is 0.3 m. The probability of damage increases when the elevator car is located in a lower floor, because the length of rope becomes long and the natural period of rope comes close to that of the building. Source 1 results in larger probability of rope damage. This is because Source 1 has larger upper limit of the magnitude and yields long period waves, which excite the rope vibration.

Fig. 5 shows the probability of rope damage within 50 years for the building model H250, in which both Sources 1 and 2 are considered. The length of the suspension rope of a counterweight can be obtained by the building height minus the length of rope of a car, approximately. Fig. 6 shows the probabilities of damage of both ropes within 50 years. Generally, the risk of rope damage reduces when a car is located in the middle of the building height. However, for the building model H100, the floors near the middle height cause larger risk of damage. The distribution of the probability of rope damage varies considerably depending on the building height.

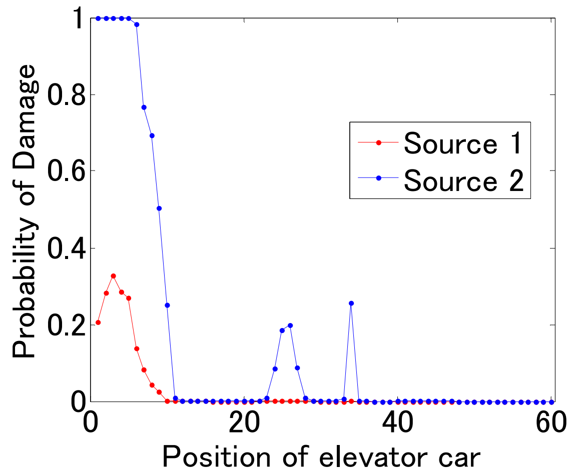


Figure 4. Probability of rope damage given the earthquake occurrence in each source. The building model is H250 and the damage threshold of the rope is 0.3 m.

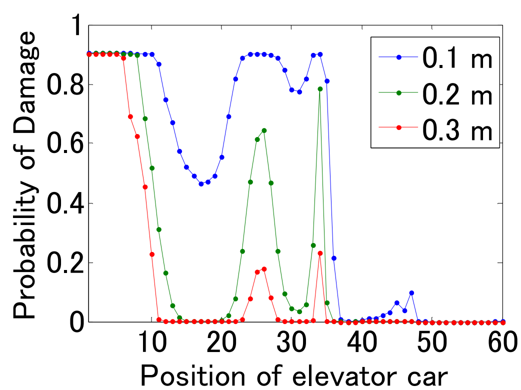
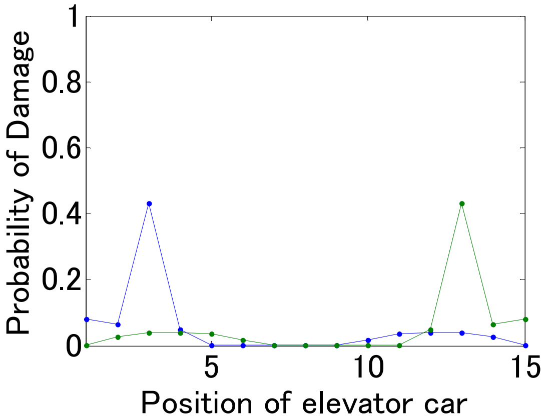
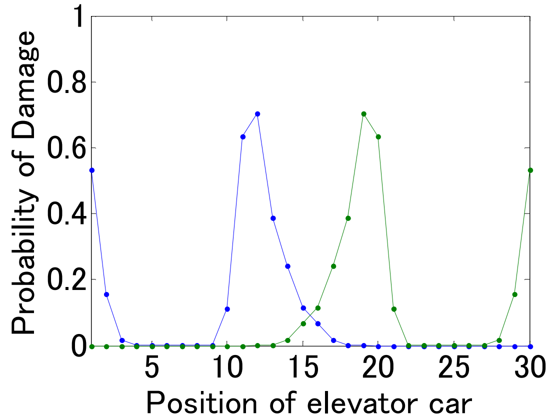


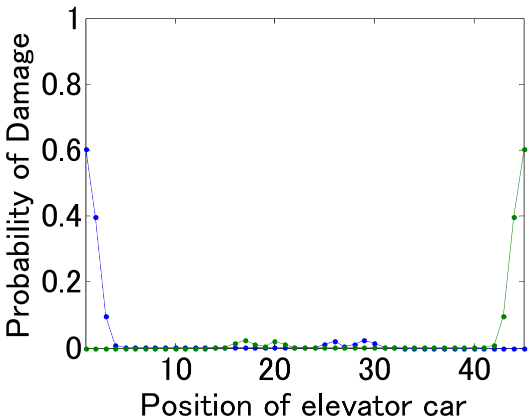
Figure 5. Probability of rope damage within 50 years for the building model H250.



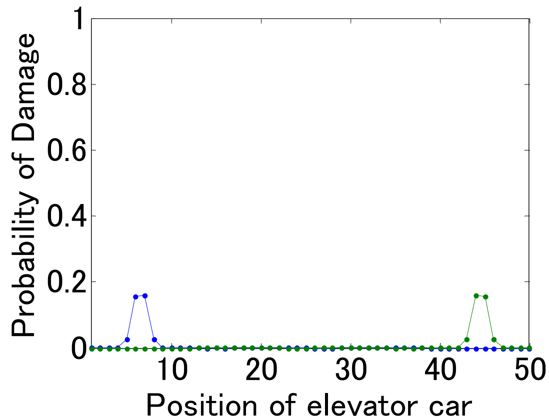
(a) Model H50



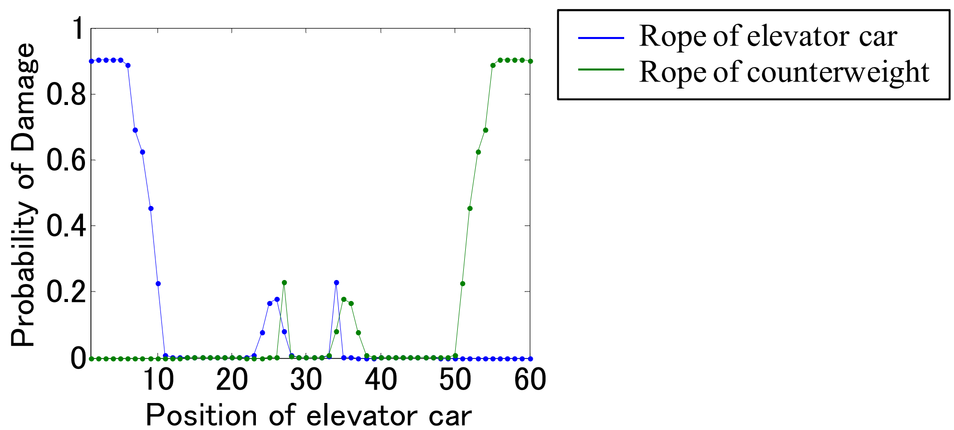
(b) Model H100



(c) Model H150



(d) Model H200



(e) Model H250

Figure 6. Probability of rope damage within 50 years considering both suspension ropes of a car and a counterweight. The building model is H250 and the damage threshold is 0.3 m.

Conclusions

To solve the problem of elevator rope sway in a high-rise building, the response of a building-elevator system was examined using the Complex Complete Quadratic Combination method (Zhou et al. 2004). The method was slightly modified based on Igusa et al. (1984) to calculate a relative displacement from complex modes properly. A building site was assumed at Sinjuku, Tokyo in Japan and possible earthquake source zones were considered in the Chuetsu District, Niigata Prefecture and the northwest of Chiba Prefecture. The response was modeled by the lognormal distribution, and the damage probabilities of the building and the rope were obtained considering the probability distribution of the earthquake magnitude and the seismic event occurrence, etc. As a result, the following findings were obtained:

- For the building models with height 100 m, 150 m and 250 m, the probability of rope damage was high when a car or a counterweight was in a lower layer because the rope was long to cause resonance.

- For the building models with height 50 m, 100 m and 200 m, the damage probability was the highest when an elevator car or a counterweight was in a layer other than the bottom. The distribution of the probability of rope damage varies considerably depending on the building height.

- It is clarified that damage risk of a building-elevator system can be evaluated and safer car position can be sought based on the method used in this study. If few people use the elevator such as in nighttime, it is recommended to move and park the car at the lower risk positions.

In the study, suspension ropes of a car and a counterweight was focused. However, actual elevator system has other ropes, such as governor rope compensation rope. Hence, the lower risk positions should be evaluated considering damage risk of all the ropes in practice.

Acknowledgments

This study was supported by research grant of TOSTEM Foundation for Construction Materials Industry Promotion. The authors acknowledge the financial support.

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