Seismic Performance of Passenger Elevators in Taiwan

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ABSTRACT

In 1999 there were two major earthquakes, the 921 and 1022 earthquakes, near large population areas in Taiwan. In addition to the structural damage produced, much equipment was also damaged. Among the damaged equipment that strongly influenced building operations after the quake was the elevator. This research conducted a field investigation in Chia-Yi city, where both earthquakes registered strong ground motion. Elevator service personnel were interviewed and the elevator damage data was analyzed. The onsite investigation revealed that current design and construction practices made elevators vulnerable in earthquakes. CW derailment constituted the largest percentage of damage. Fouling of governor ropes was the second most frequent damage type. This research examined the causes of these damage types and proposed several measures to improve the seismic capacity of elevators.

INTRODUCTION

Problems with insufficient elevator seismic capacity were noticed in the USA right after the 1964 Alaska earthquake [1]. Countermeasures to improve elevator safety in earthquakes were proposed but little was adopted. Until the 1971 San Fernando earthquake, in Northern Los Angeles, 1,000 of the 9,000 elevators in the area sustained damage and 700 counterweights (CW) were thrown out of the guide rails. People began to realize the seriousness of this problem and started to propose improved techniques and related elevator code modifications for public buildings. In the 1987 Whittier Narrows earthquake, the first major earthquake after the 1971 San Fernando earthquake, the operation and performance of earthquake protection devices, although the expectations were not fully met, did significantly reduced damage and the potential for injury [2]. In the following two major earthquakes, the 1989 Loma Prieta earthquake and the 1995 Northridge earthquake, the mandated US code changes to hospital elevator systems for the post 1973 era were generally responsible for the excellent performance of these elevator systems [3].

Research work on the seismic behavior of elevators was scarce and most of them concentrated on the dynamics of the CW. Some try to investigate from the system identification approach [4], and some try to simulate the time history response of the CW by using finite element approach [5]. However, experimental data to verify their accuracy was insufficient.

There were two major earthquakes in Taiwan in 1999, the 921 Chi-Chi (M_L = 7.3) and 1022 Min-Shong (M_L = 6.4) earthquake. Extensive damage to elevators in the disaster region was reported. Post earthquake operation of many important organizations was hindered by the limited accessibility to the upper floors in their buildings. In hospitals, the vertical transportation of patients to and from the appropriate stories was delayed. The burden on post earthquake rescue work was greatly increased because of this problem.

Chia-Yi city has a population of 260,000 and is about 55km away from the 921 epicenter and 10km from the 1022 epicenter, Fig. 1. This city was chosen for this study on elevator damage because the city is large enough to have an ensemble of elevators and the ground motions were not big enough to create great structural damage. The elevator performance in Chia-Yi city under earthquake conditions may therefore be considered free from serious structural damage interference. This study analyzed the elevator damage data in Chia-Yi city and investigated possible causes of the damage.

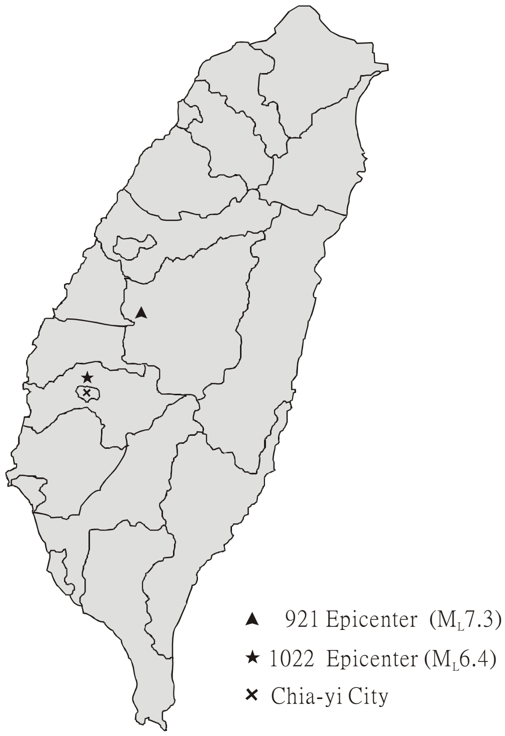


Fig. 1 Geographical relation between Chia-yi city and the epicenters

PERFORMANCE OF PASSENGER ELEVATORS IN EARTHQUAKES

Survey was sent to five major elevator service companies and onsite visits to the damaged elevators were conducted during the four months following the 921 earthquake. The maintenance crew managers were interviewed during most of these visits. Their opinions and impressions of the damaged elevators were carefully reviewed and the common comments were chosen as part of the text in this research. An evaluation questionnaire regarding the various damage patterns was collected from the five major elevator maintenance companies in the city. The final statistics for the eight major damage types is shown in Table 1.

Table 1 Major elevator damage statistical patterns

Damage Patterns	% of total damage in the 921 earthquake	% of total damage in the 1022 earthquake
1. Damage to CW shoes	7.9	7.7
2. Damage to CW rail	1.4	2.8
3. CW cage derail	40.2	66.3
4. Control cable damage	5.2	0.0
5. Governor rope entanglement	18.2	7.7
6. Speed governor damage	2.1	1.1
7. Damage to the extrusions in the hoistway	8.6	4.2
8. Compensating chain damage	2.1	0.0
Total elevator damage number	291	285

The estimated total number of elevators in Chia-Yi city is about 1,600. According to Table 1, close to 20% of these elevators sustained some kind of damage in the 921 and 1022 earthquakes. Among the reported elevator damage, CW derailment and governor rope entanglements were the two most frequent damage patterns in both earthquakes.

Building addresses of damaged elevators were requested from the elevator companies. Because of business considerations, the elevator companies were only willing to release a portion of these addresses. Therefore only 56 address for the 921 earthquake and 62 for the 1022 earthquake were collected. These buildings were visited in order to understand their fundamental period. Assuming that all of the structural types are rigid RC frames, as this is the dominant building structural type in this city, the fundamental periods of these buildings can be estimated using Eq. (1).

$$T = 0.070\ h_n^{3/4} \quad (1)$$

where T is the fundamental period of the building in seconds and h_n is the roof height from the street in meters [6].

Fundamental period distributions for these buildings are shown in Fig. 2. It is observed that there are three major peaks in the damaged building periods. The damage percentages from high to low were 0.71, 1.05, and 0.92 second. Each of these periods corresponds to a 7-, 12-, and 10-story building. Comparing to Fig. 3, these buildings' fundamental frequencies all fall within the peak frequency ranges of both earthquakes. Confirmation from the elevator companies agreed that these three building heights constituted most of the damaged elevators.

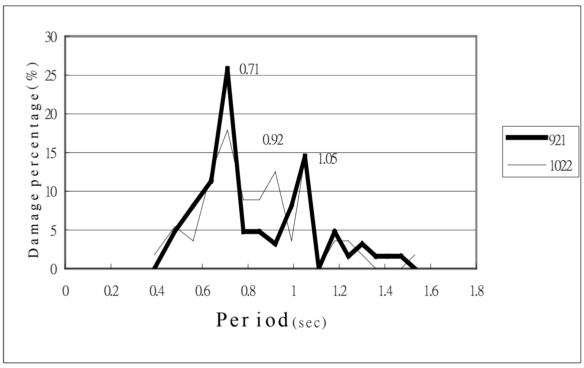


Fig. 2 Building fundamental period distribution with damaged elevators

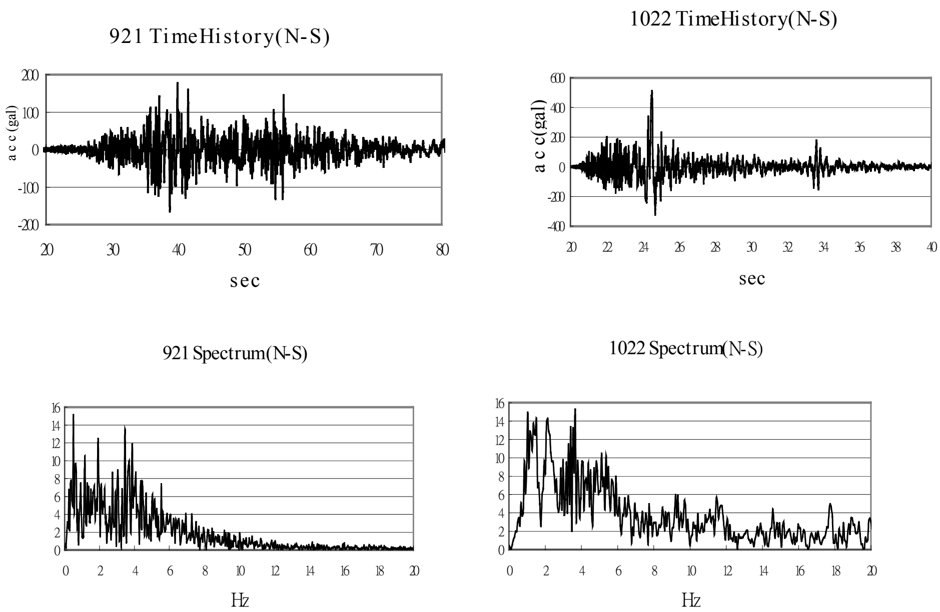


Fig. 3 Time history and Fourier spectrum of station CH047 in two earthquakes

Most of Chia-Yi city's buildings are below 20 stories. The tallest building is 21-story. City building regulation limits building height in residential area to 21 meters and business area to 36 meters. Building height also can not be greater than 1.5 times the street width plus 6 meters. Exceptions could be granted if several provisions were met. Therefore these regulations made most of the buildings are either 7- or 12-story high inside the urban planning zone. This is part of the reason that most of the damaged elevators belonged to a few particular building heights.

ANALYSIS OF ELEVATOR DAMAGE DATA

The recorded ground motion by the Central Weather Bureau (CWB) in Chia-Yi city is shown in Table 2. It is noticed that the PGA values are quite different for both earthquakes inside the city boundary. The 921 earthquake produced smaller PGA than the 1022 earthquake. However, the number of damaged elevators in both earthquakes was almost the same. Two reasons might have attributed to this phenomenon:

1. A lot of the elevator damage in the 921 quake was contributed by the reoccupation of elevators after the quake before a maintenance crew could have arrived and made an inspection. Therefore small problems such as the fouling of cables, compensating chain, and governor

Table 2 Peak ground acceleration in the Chia-Yi city (gal)

Stations	921 earthquake		1022 earthquake	
	NS	EW	NS	EW
CHY	145	NA	314	430
CHY003	74	54	114	134
CHY009	NA	NA	188	327
CHY046	186	142	257	308
CHY047	177	165	510	352

ropes were aggravated into major damage once the car was moved. In the 1022 earthquake, people learned their lessons from the 921 earthquake and would not use the elevators until they received maintenance crews' approval. Therefore the small problems described above were easily resolved and did not result in a damage. This is reflected in Table 2, in which most of the damage types related to fouling cables in the 1022 were reduced. Only those damage patterns related to CW pounding, which was directly related to earthquake intensity, increased.

2. Some of the damaged elevators in the 921 earthquake were not routinely maintained by any elevator company. After the 921 earthquake, renewed elevator maintenance has increased the strength of these elevators. As a consequence, they performed better in the following 1022 earthquake.

In Table 1, two types of damage related to the CW guide rail, type 2 and 3, increased significantly. This indicated the increased PGA in the 1022 earthquake was a direct consequence of the damage to the CW guide rail. However, the number of damaged elevators was not directly proportional to the PGA increase. This could be related to the large high frequency contents in the 1022 earthquake comparing to the 921 quake, as shown in Fig. 3. The frequency components above 10Hz is richer in the 1022 data. The flexible CW system has a low natural frequency [4] and was not greatly magnified by the high PGA values rooted in the high frequency contents in the 1022 earthquake.

PGA contour maps from the recorded 921 and 1022 earthquake in Chia-Yi city were generated from Table 2. The location of buildings, which suffered various types of elevator damage, was identified on the same map for comparison, as shown in Fig. 5 and Fig. 6 for both earthquakes. Because 921 quake had a smaller PGA in all stations than the 1022 quake, the smallest PGA to produce different types of elevator damage can be identified by analyzing the 921 contour map in Fig. 5. In the 921 quake, the EW PGA was smaller than the NS PGA in every station was. Therefore by interpolating the NS PGA in Fig. 5., the smallest PGA to generate CW derailment was estimated to near 75 gal. The same analysis approach indicated that the smallest PGA started to generate governor rope damage was approximately 115 gal.

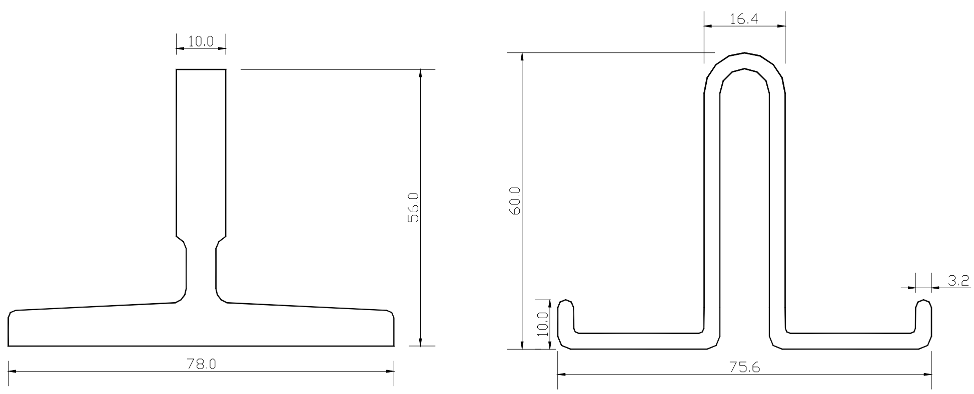
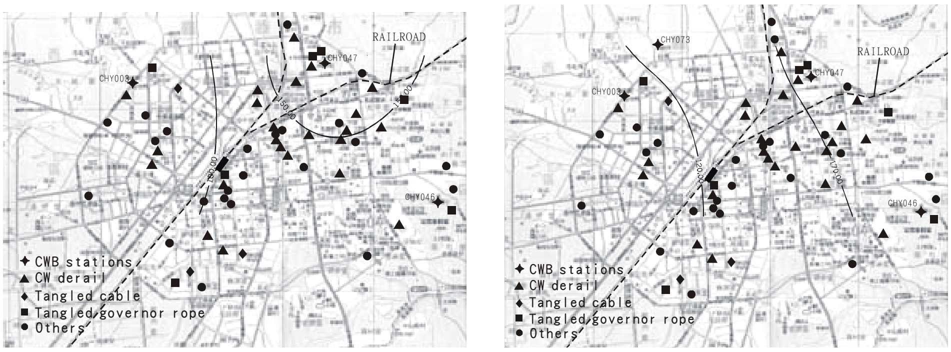
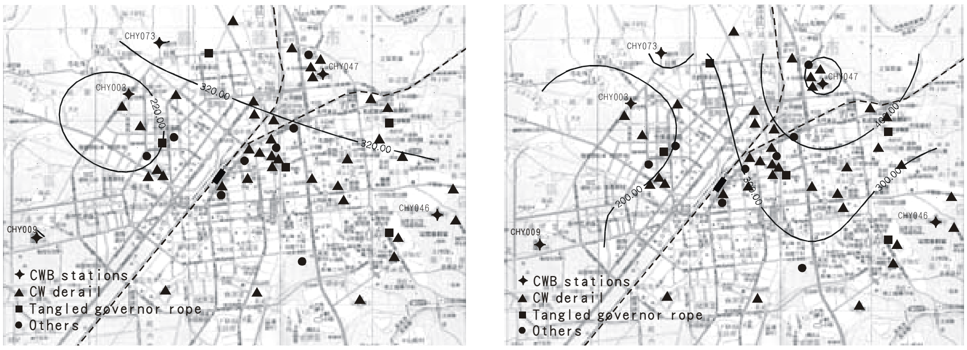


Fig. 4 CW rail size comparison



E-W N-S

Fig. 5 PGA contour map and the damaged elevators in the 921 earthquake



E-W N-S

Fig. 6 PGA contour map and the damaged elevators in the 1022 earthquake

MAJOR DAMAGE MECHANISMS OF ELEVATORS

According to Table 1 and the discussion in the last section, it was noticed that several major components necessary for maintaining elevator functions were vulnerable to earthquake attacks. The reasons for this vulnerability and the damage mechanisms are discussed below based on investigations and discussions with elevator engineers from various maintenance companies. Figure 7 depicts most of the critical items in an elevator hoistway.

CW Cage Derailment

At least two hospitals experienced such damage in the 921 quake and the derailed CW cage hit the car and deformed part of the cab. Fortunately no one was injured because it happened at night. Most of the CW cage derailments took place on the 5kg/m guide rail. There were two mechanisms for this derailment:

1. The in-plane vibration of the CW cage resulted in pounding with guide rails and deformed the rail. As a result, the cage was released from its tracks to swing freely in the hoistway. Damage of this mechanism made up roughly 60% of the CW derailments. When this happened, the deformed rail and sometimes the rail brackets would need replacement before the elevator could return to service. The installation of new rails and rail realignment might take several days to complete.

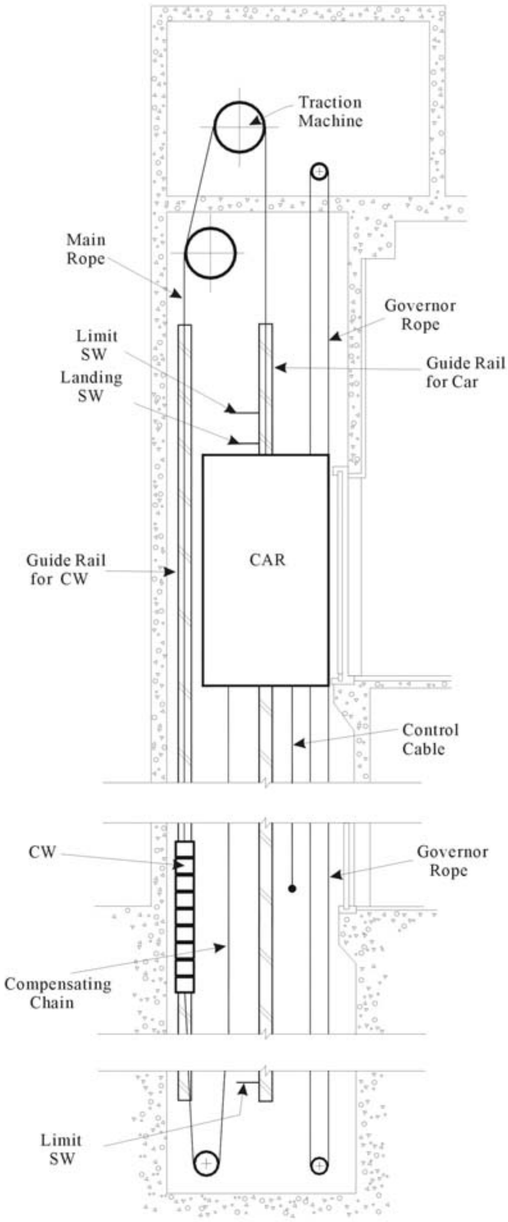


Fig. 7 Vulnerable elevator components

2. The out-of-plane inertia force pushed the CW cages against the rail surface and forced the guide shoe to rotate along its connection end. Because only two bolts were used to tighten a shoe, one on each side, the shoe acted like a semi-rigid connection. When the pushing created large shoe rotation, derailment could take place. Damage of this mechanism made up approximately 40% of the CW derailments. If the rails were not bent into permanent deformation, the repair work could be finished in about one hour. Otherwise rail replacement would be necessary and it took several days to finish. Major problems with CW derailment involved the rail cross section. The most commonly used CW guide rail for low-rise residential buildings has been the 5kg/m rail type, see Fig. 4, which is made of a steel plate formed rail. This rail type constituted 95% of the derailment cases. Usually when the load requirement for a higher capacity railed is needed, the next level up is the 8kg/m rail, which is made from hot-rolled T section steel. The 5kg/m rail is much weaker than the solid hot-rolled section in terms of stiffness and strength. Also, the alignment at the 5kg/m rail junctions is usually poor, therefore a larger tolerance at the guide shoes is required. The enlarged distance also increases the possibility of derailment in earthquakes.

CW Block Detachment from the CW Cage

The CW blocks inside a CW cage are made of solid iron plates to produce the needed weight for car balance. Traditionally all weight blocks had two drilled holes and a tie rod was inserted through each hole to tie all the blocks to the cage. The ends of the tie rod were threaded and tightened with lock nuts to compress all of the blocks together. However, the competitive market has driven this practice out of most of the cheap apartment and office elevators in the past decades. Common practices today utilize an iron bar on top of the weight blocks to tighten the top weight blocks only.

According to the damage survey, most of the detached blocks were originally situated at the mid-height of the cages. The cages were pounded by the CW blocks at the middle during the earthquake and deformed so greatly that the iron blocks could escape from the cage. This failure mechanism could be attributed to the less tightening force in the middle portion of the CW cage due to the new practice. Because the locking action from the top bar provided little constraint on weight blocks below, and the vertical acceleration from the earthquake motion decreased the frictional effect in preventing the middle blocks from moving freely. If the traditional through block tie rods had been used, all of the blocks would have behaved as one unit. The blocks would not have escaped from the CW cage to pose a serious threat to passengers. According to experience in these two earthquakes, no CW block detachment occurred to elevators with the traditional through block tightening method.

Fouling of Control Cables and Governor Ropes

Control cables and governor ropes are long free-swinging items in the hoistway. They easily foul together or entangle onto extruded elements in the hoistway such as guide rails or landing switches in earthquakes.

This alone would not cause serious damage unless the car continued to move or the car moved after the restoration of electricity. Then the tangled wires or cables might be torn apart and created a major failure. This actually happened to many elevators in the aftermath of the 921 earthquakes and resulted in many torn cables and governor ropes.

The shapes of the control cable seemed to play a very important role in reducing the vibration of the control cables. The round cable had a higher damage ratio than a flat cable for almost any elevator company that used both types of cable according to company internal statistics.

Damage to Landing Switch (SW) and Limit SW

Landing SW and limit SW are elements that extend out into the hoistway to control the car landing at the right floor or to prevent a car from travelling over the top or bottom of the hoistway. To achieve this goal, these extended arms are designed to signal the location of the cab. These extended arms could easily come into contact with the car in an earthquake and be distorted or knocked out of the correct position. Hence the car could not recognize the correct location to stop. Another possible cause of this damage was the tangled cables or governor ropes pulled and deformed these extended members.

Control Panel Failure

Elevator control panels exhibited two types of failure:

1. IC board failure due to electric pulse

There were several reports of IC boards burned out, which shut down the elevators and prevented them from restarting. Discussions with elevator maintenance crews concluded that the unstable voltage from the emergency generator could have caused this. When the normal electricity supply was terminated in the earthquake, the emergency generator was started to supply the needed electricity. However, within the first minute, the electrical current was unstable and a high voltage current might have burned some of the delicate IC circuit boards. If the elevator were programmed to delay the restart time until the voltage became stable, the IC boards would not have the burn-down problem.

2. Overturned cabinet

Control cabinets were usually buried into a concrete pad above the floor surface. If some kind of anchorage were introduced at the initial installation stage, the control cabinets were usually safe from earthquakes. However, there were several incidences of overturned cabinets because the cabinets were not fixed into the foundation pad. In one case, stacked bricks were found under an overturned control cabinet suggesting they were used to level the cabinet and became a weak link at the base during the earthquake.

Inadequate Seismic Code Provision

The major design code for passenger elevators in Taiwan in the past 17 years is the CNS 10594 [7]. In its earthquake design section, a horizontal load of 20% self weight is assigned. Compared to the 1998 building code in Taiwan [6], the peak ground acceleration for building structural design in central Taiwan ranged from 0.23G to 0.33G. The earthquake design force for elevators has been obviously under-estimated. If the floor amplification factor [8] at the upper floor is taken into account, which could increase up to a factor of 4 at the roof [9], the earthquake load in the CNS 10594 code is far less than what is prescribed in building codes for equipment.

This under-designed seismic capacity was reflected in the large number of CW cage derailment and upper limit SW pounding damage from the 921 earthquake. Because many elevator systems in buildings were programmed so that the passenger car had to wait at the first floor when not in operation. Therefore, many CW cages were at the top floor when earthquake struck on the night of 921. Consequently most of the CW damage took place at the highest story in the building.

CONCLUSIONS

This paper analyzed elevator damage data from the 921 and 1022 earthquakes in 1999 within the city boundary of Chia-Yi city. By conducting interviews with the elevator maintenance crews and performing on site visits, the major elevator damage patterns were determined. Through statistical analysis, the incipient damage levels were discussed. The following are some of the major conclusions:

1. The insufficient seismic design force provision in the CNS standards should be updated to improve the overall seismic capacity of elevators in Taiwan.
2. The smallest PGA to initiate CW derailment and governor rope fouling were found to start from 75 and 115 gal according to the statistics from the two earthquakes. These values should be useful for the installation of seismic switches to set up the appropriate triggering value.
3. CW blocks detachment from CW cages should be considered as the most dangerous damage type to human lives. The proposed counter measures such as: through block tie rods, seismic switches, and other

effective means to prevent this failure should be adopted by the elevator safety agency.

4. Other measures to increase overall elevator safety should be sought to increase the seismic capacity of elevators, especially in buildings with special missions after a major earthquake such as hospitals.

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