EFFICIENCY OF FURNITURE OVERTURNING PROTECTION DEVICES DURING EARTHQUAKES - AN EXPERIMENTAL AND NUMERICAL STUDY –

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ABSTRACT: For disaster reduction, it is important that people have the ability to clearly imagine what will happen around them as time goes after the hazard occurrence considering regional natural and social characteristics and other conditions related to the season, weather, day of the week, and time of the day when the event occurs, among others. Also, understanding the effects of countermeasures is essential. In this study, we aim at improving the people's capacity to imagine disasters and to understand effects of specific countermeasures for disaster reduction. At first, we analyze the effect of furniture overturning prevention devices and evaluate its efficiency through shaking table tests. Then, we try to promote people's risk awareness by showing animations prepared by numerical simulations of furniture's dynamic behavior when an earthquake occurs. Finally, we promote people's recognition of disaster countermeasures by discussing the furniture overturning ratio decline when prevention devices are installed.

Key Words: earthquake damage, overturning of furniture by earthquake, disaster imagination capability, shaking table test, numerical simulation, overturning protection device

INTRODUCTION

In order to implement efficient disaster prevention measures, it is very important and indispensable for the general public to take proper countermeasures by themselves. Unfortunately, even after the 1995 Kobe earthquake, real countermeasures are not well implemented. Furthermore, the priority of securing the safety of structures and living spaces, although extremely high, is not recognized. One of the main reasons why proper countermeasures are not implemented well is the lack of disaster imagination capacity of the people.

In this study, shaking table tests with solid wooden blocks emulating commonly used furniture and furniture itself were performed to help increasing people's imagination capacity and to evaluate/show the efficiency of available overturning protection devices. Potential risks, strengths and weaknesses of each protection system were identified. Based on these observations, the best ways to protect furniture against overturning were suggested. The overturning ratios for each device, i.e. the percentage of cases in which the furniture fixed with a particular device overturned, were determined. Through numerical simulations, the risk reduction in a typical house room attained by the installation of overturning prevention devices was evaluated.

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SHAKING TABLE EXPERIMENTS

To simulate the dynamic behavior of furniture during earthquakes and evaluate the efficiency of overturning protection devices, shaking table experiments using solid wooden blocks and real furniture were carried out. The former were useful to determine key parameters to consider in the latter and also in the numerical simulation.

Shaking table experiments using solid wooden blocks

These tests were carried out on a 1.5m by 1.5m shaking table. The geometrical characteristics of the wooden blocks are listed in Table 1. The specimen A-1 was a single block whereas the specimen A-2 consisted of two blocks one over the other. A total of 38 ground motions were applied with amplitude and frequency varying from 100 to 1,400 Gals and 0.5 to 3.5 Hz, respectively. The Japanese Meteorological Agency Intensity (JMAI) for each motion was calculated. Several types of overturning protection devices available in the market, such as steel L-shape, stopper, gel mat, pole, honeycomb board box, and chain/belt, were evaluated. In the case of steel L-shape and chain/belts, relatively small screws were used considering the relation between the sizes of wooden blocks and real scale furniture. Stoppers and gel mats were also scaled down. The tests were carried out considering that the blocks were standing against a fixed wall.

Table 1. Characteristics of the wooden blocks used in shaking table tests

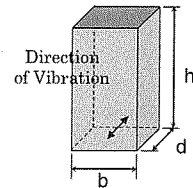| Block	Size			V [cm³]	m [kg]	d/h
	h [cm]	b [cm]	d [cm]			
A-1	75	37.5	22.5	63,281	41.55	0.3
A-2	50	25	15	18,750	11.20	0.3

Figure 1 shows the overturning critical intensity level. Above it, the furniture overturned and below it, it remained standing up. This figure shows the results for the case in which the floor surface was smooth, i.e. flooring finishing, and the wall was strong enough. Tests were also carried out over *tatami* (traditional Japanese flooring mat) and using a, relatively weak, gypsum wall.

Results of shaking table tests using real furniture

As the next step, shaking table tests using real furniture were performed to further assess the efficiency of overturning protection devices. Real scale furniture (180cm by 59cm by 39cm) available in the market was used for these tests. Their self weight was 24.5kg and 60kg to account for its contents while in use were added. The shaking table dimensions were 4.0m by 4.0m.

Two strong ground motions were used: 1995 Hyogo-ken Nambu Earthquake (Kobe Earthquake) recorded at the Kobe Maritime Observation station and the 2004 Niigata-ken Chuetsu Earthquake recorded at K-NET Ojiya station. The former was scaled to obtain input motions with JMAI 5+, 6- and 6+. Two floor surfaces were considered: flooring and *tatami*, and two overturning protection devices, chain and poles, which were found to be the most efficient in the previous set of tests. As in the previous case, the furniture was considered to be standing against walls.

To propose a better installation of overturning protection devices, several tests were done changing the inclination angle of chains/belts or pasting a wooden veneer on top of the poles as shown in Figure 2.
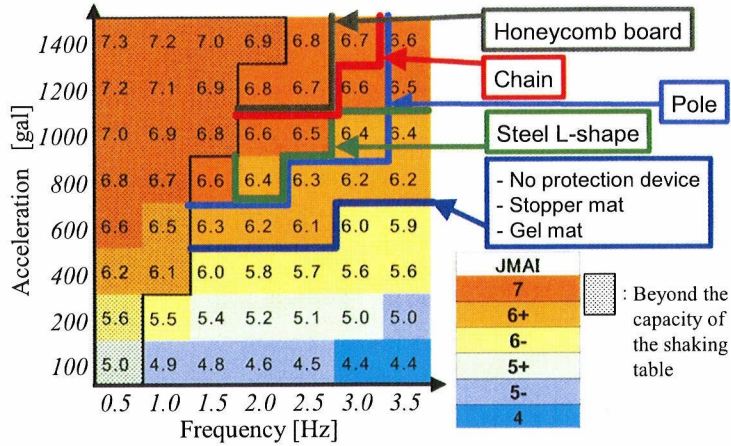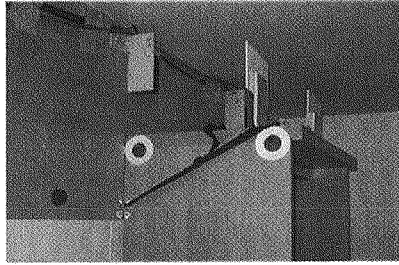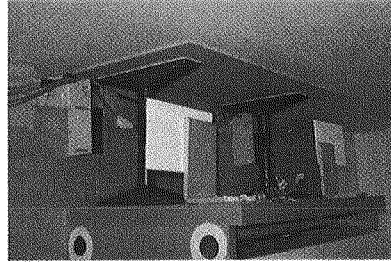
(a) Block A-1
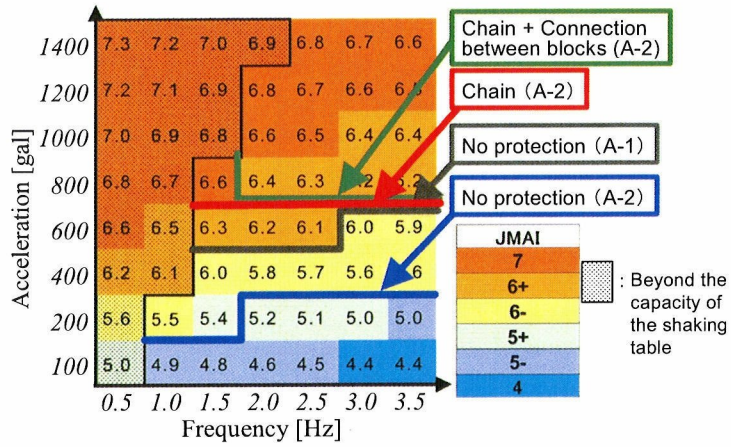
(b) Block A-2

Figure 1. Overturning criteria obtained from shaking table tests
(Floor surface: flooring, wall surface: strong timber)

Table 2. Strong ground motions characteristics

Earthquake	Station	PGA [Gal]			JMAI
		X-dir	Y-dir	Z-dir	
Hyogo-ken Nambu	Kobe Marine Observation	818	617	332	6+
		491	370	119	6-
		276	208	112	5+
Niigata-ken Chuetsu	K-NET Ojiya	1310	1110	781	7

(a) Belt (30° downwards)   (b) Pole with wooden veneer

Figure 2.   Most efficient installation method
proposed for overturning prevention devices

A summary of all results is shown in Table 3. It is very common to use belts/chains oriented 30 to 60° upwards. However, it was found that it is more efficient to use them 30° downwards because in this way, the vertical component of the belt/chain tension prevents uplift, and therefore, sliding and overturning are avoided.

Table 3. Summary of experimental results

		Hyogo-ken Nambu Eq.			Niigata-ken Chuetsu Eq.
		5+	6-	6+	7
No protection	Flooring	⊗	●	-	-
	Tatami	⊗	●	-	-
Belt	30° Upwards	⊗	⊗	⊗	-
	30° Downwards	○	○	◉	◉
	60° Upwards	-	-	◉	-
Pole	Without veneer	○	○	○	●
	With veneer	-	-	-	⊗

● : Overturning
◉ : Damage to contents
⊗ : Exhibits displacement
○ : No displacement
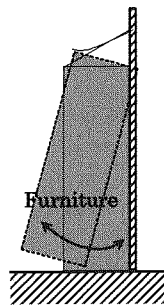
Figure 3.   Furniture movement observed during shaking
when chain/belts are used upwards

If the downward angle is increased, as depicted in Figure 4, the efficiency of the belt/chain decreases because the same horizontal inertial force has to be resisted by an increasing tension on the belt/chain. This large force eventually leads to the belt/chain connection failure. Based on these observations, it was concluded that 30° is the optimum inclination.
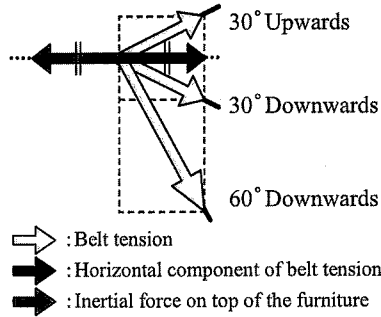
Figure 4. Restraining mechanism of chain/belt

When poles are used as protection devices, usually two poles, which shake independently, are used. The system performance can be greatly improved if both poles work together. This can be achieved by installing a wooden veneer between the poles and the ceiling. This measure guaranties not only that both poles will work together but also avoids the ceiling local damage at the points where poles are installed. With this system, furniture could stand the severe Niigata-ken Chuetsu Earthquake strong ground motion, which was not possible without it.

SAFETY EVALUATION OF LIVING SPACES

In order to evaluate the safety of living spaces simulations using 3-Dimensional Extended Distinct Element Method (3D-EDEM) were carried out. The simulation accuracy was previously evaluated using the results obtained from the shaking table tests. Figure 5 shows the comparison of the experimental and numerical results. It is clear that the simulation captured well the behavior observed during the experiments.
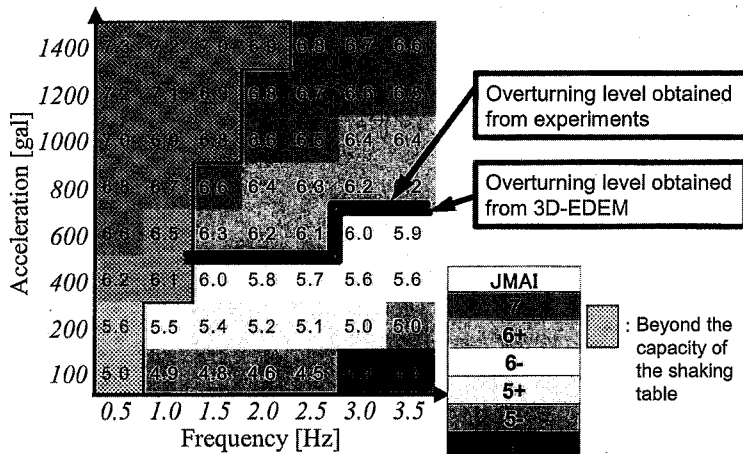
Figure 5. Comparison of numerical simulation and experimental results

Study of the living space
The target living space was an $87m^2$ model room located at different stories of a 20-story building, as shown in Figure 6. Three types of furniture were considered, from B-1 to B-3, with the characteristics shown in Table 4. The furniture distribution is depicted in Figure 6. The elements in gray represent

stable bodies which were not expected to overturn and therefore were not a matter of consideration for this study.

Table 4. Characteristics of the furniture considered for the simulations

	h [cm]	d [cm]	b [cm]	d/h	m [kg]	ρ [kg/cm3]
B-1	180	54	90	0.3	200	2.29E-04
B-2	180	36	90	0.2	133.3	2.29E-04
B-3	135	54	90	0.4	150	2.29E-04

Input motion calculation using a multi-degree freedom system

In order to obtain the input motion to the model room, a multi-degree freedom system was excited with past strong ground motions having a wide range of predominant periods as shown in Table 5. Eleven strong ground motions obtained from K-NET were used and the responses at floors 1, 5, 10, 15, and 20 were determined and used as input to the model room.
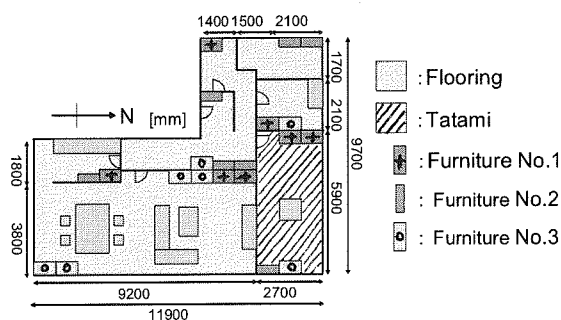
Figure 6. Layout of the living space considered for the study

Table 5. Input motions used for the living space safety evaluation

Date	Name of Earthquake	Observation Station	Magnitude	Focal Depth [km]	JMAI	Predominant Period [sec]
1/17/1995	Hyogoken-Nanbu	Kobe Marine Observatory	7.3	16	6.40	0.71
10/6/2000	Tottoriken-Seibu	Yuki	7.3	11	5.06	0.29
3/24/2001	Geiyo	Yuki	6.4	51	5.71	0.46
12/2/2001	Iwateken-Nairiku-Nanbu	Daitoh	6.4	122	4.49	0.11
5/26/2003	Miyagiken-Hokubu	Oga	7.0	71	6.20	0.37
9/26/2003	Tokachioki	Hiroo	8.0	42	6.07	0.27
9/26/2003	Tokachioki	Tomakomai	8.0	42	4.49	4.50
9/5/2004	Kiihanto-Nantooki	Hakusan	7.4	44	4.69	0.18
9/5/2004	Kiihanto-Nantooki	Sakai	7.4	44	3.76	6.40
10/23/2004	Niigataken-Chuetsu	Ojiya	6.8	13	6.73	0.60
3/20/2005	Fukuokaken-Seihooki	Hirado	7.0	9	5.09	0.46

Figure 7 shows the obtained floor responses in terms of seismic intensity calculated using the JMA definition. Based on the original definition of JMA, the maximum seismic intensity is 7. However, in order to have a clearer picture of this parameter in the upper range, it was divided in three sub-ranges: 7- for intensities from 6.5 to 6.9, 7+ for intensities from 7.0 to 7.4 and 7++ for intensities above 7.5.

Calculation of furniture overturning ratio

Three cases were simulated: Case A: No overturning protection devices provided; Case B: chains/belts were set in all furniture, Case C: honeycomb boards were used in high furniture (B-1 and B-2) and chains/belts were installed in low furniture (B-3). Some results obtained by 3D-EDEM are displayed

in Figure 8. These images were prepared using virtual reality technology. This tool allows the user to freely move inside the virtual space and therefore verify the effect of using overturning prevention devices by himself/herself.
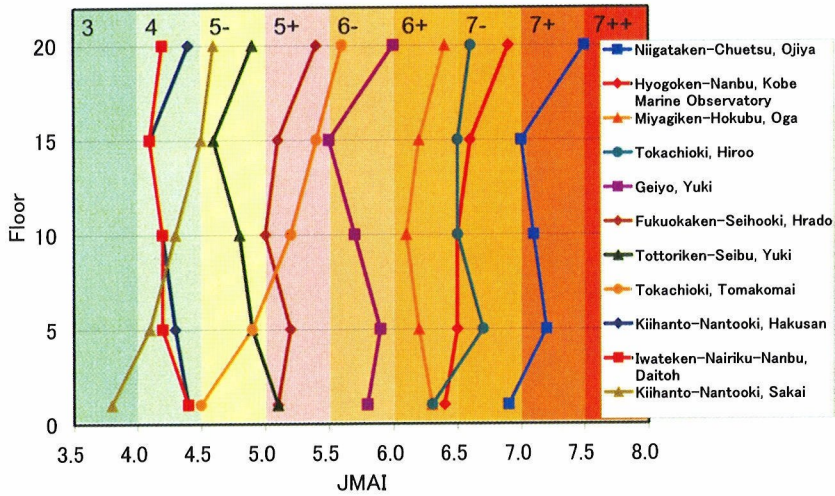

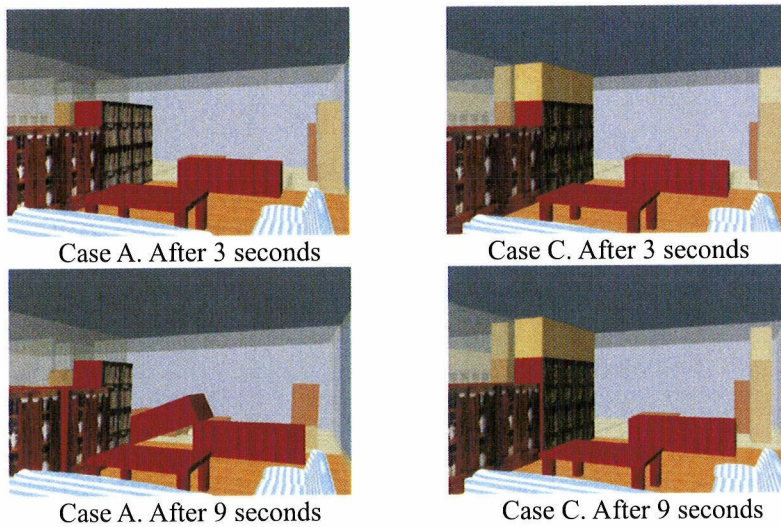**Figure 7**.   Floor response in terms of JMA seismic intensity

Figure 8.   Floor response in terms of seismic intensity

Figure 9 shows the overturning ratio versus input motion intensity for the three cases considered. In Case A, risk increases rapidly for shakes with JMAI 7+ or more. In Case B, the protection devices were damaged themselves for high JMAI and therefore lost effectiveness. In Case C, the lowest overturning ratios were obtained even for high intensity shakes.

Evaluation of the safety of living spaces based upon the furniture overturning ratio
The overturning ratio in the living spaces where people spend most of their time should be decreased as much as possible. The rooms where they sleep should be given particular attention because it has been observed that when an earthquake occurs while people are sleeping, their response is not considered good. The results of this study, however, showed that even with the best performance of the protection devices currently available in the market, overturning ratio could not be decreased below 17.5% and 33.3% in case of shakes with JMAI 7+ and 7++, respectively. In order to further decrease this percentage, it is proposed to install building vibration control systems, to develop more efficient protection devices, and to establish some regulation by which only built-in furniture can be used in high rise buildings.
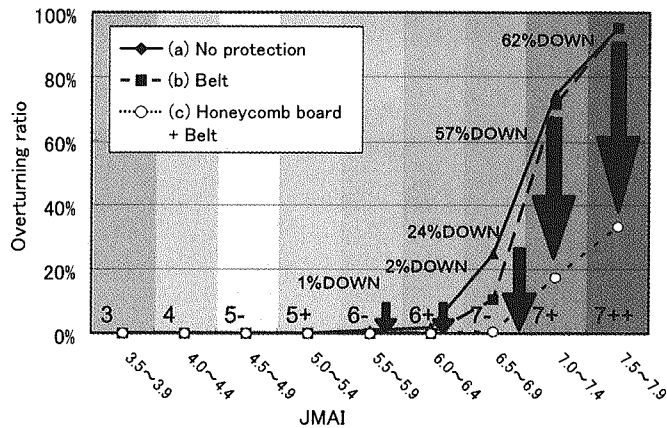
Figure 9.   Overturning ratio versus JMA seismic intensity
for each case considered

CONCLUDING REMARKS AND FUTURE ISSUE

In the first part of this study, shaking table tests to evaluate the efficiency of existing overturning protection devices were performed with solid wooden blocks and furniture. After the last series of tests, the best way to install the overturning protection devices available in the market was proposed.
To evaluate the safety of the living space, 3D-EDEM numerical simulations combined with virtual reality applications were carried out. The accuracy of the simulations was verified with the obtained experimental data. Based upon the results for a 20-story building case, it was concluded that it was very difficult to avoid overturning using protection devices currently available in the market for shakes JMAI 7+ and 7++, which are experienced in the upper stories. Therefore, three possible solutions were suggested: to decrease the structural response using building vibration control systems including bas isolation system, to develop more efficient overturning prevention systems, or to use only built-in type of storing spaces so that potential overturning objects are not used at all. The present study can be very useful to further study these options.

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