EFFICIENCY OF FURNITURE OVERTURNING PROTECTION DEVICES DURING EARTHQUAKES

- A EXPERIMENTAL AND NUMERICAL STUDY -

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ABSTRACT :

To reduce earthquake damage in the future, it is very important that each of us take proper countermeasures on our own initiative. After the 1995 Kobe Earthquake, strengthening houses and attachment of furniture to prevent its overturning were identified as the main issues. Reportedly, these problems have not been properly addressed yet. One of the principal causes for this is that many people do not have disaster prevention consciousness and ability to prepare against earthquakes. In this study, we aim at improving the people's capacity to imagine disasters so that they implement specific disaster countermeasures. At first, we analyze the effect of furniture overturning prevention devices and evaluate its efficiency through shaking table tests. The effectiveness of the devices is discussed based on the ground motion intensity which they can withstand, their installation easiness, whether their performance depends on external factors such as wall and floor characteristics, and so on. Then, we try to promote people's danger and risk awareness by showing animations obtained by numerical simulations of furniture's dynamic behavior when an earthquake occurs, especially focusing on a particular house space, the living room. For this purpose, advanced visualization software is used so that people can feel as if they were at their own rooms during a shake. Finally, we promote people's recognition of disaster countermeasures by discussing the furniture overturning ratio decline when prevention devices are installed.

KEYWORDS: furniture, overturning protection devices, overturning, numerical simulation, shaking table experiment

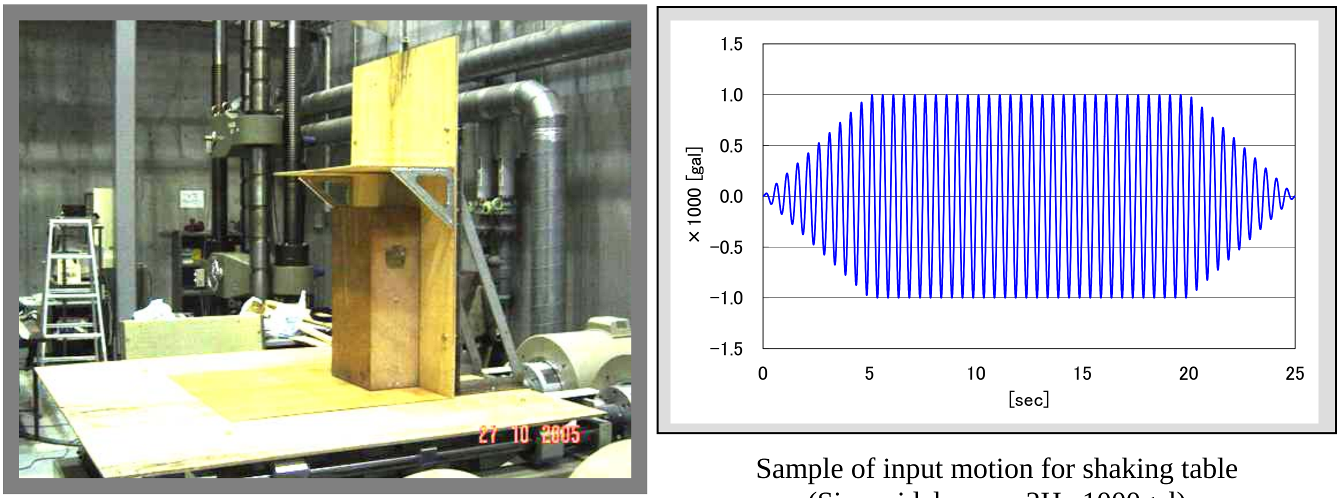
1. INTRODUCTION

To reduce earthquake damage in the future, it is very important that each of us take countermeasures on our own initiative. After the 1995 Kobe Earthquake, strengthening houses and attachment of furniture to prevent its overturning were identified as the main issues. Reportedly, these problems have not been properly addressed yet. One of the principal causes for this is that many people do not have disaster prevention consciousness and ability to prepare against earthquakes.

In this study, we aim at improving the people's capacity to imagine disasters so that they implement specific disaster countermeasures. At first, we analyze the effect of furniture overturning prevention devices and evaluate its efficiency through shaking table tests. The effectiveness of the devices is discussed based on the ground motion intensity which they can withstand, their installation easiness, whether their performance depends on external factors such as wall and floor characteristics, and so on. Then, we try to promote people's danger and risk awareness by showing animations obtained by numerical simulations of furniture's dynamic behavior when an earthquake occurs, especially focusing on a particular house space, the living room. For this purpose, advanced visualization software is used so that people can feel as if they were at their own rooms during a shake. Finally, we promote people's recognition of disaster countermeasures by discussing the furniture overturning ratio decline when prevention devices are installed.

2. SHAKING TABLE EXPERIMENTS

To simulate the dynamic behavior of furniture during earthquakes and evaluate the efficiency of overturning protection devices, shaking table experiments (Figure 1) 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.



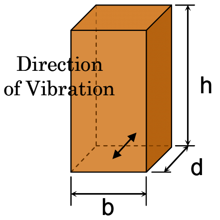
Scene of shaking table experiment

Sample of input motion for shaking table
(Sinusoidal wave: 2Hz,1000gal)

Figure 1 Scene of shaking table experiment and one sample of input motion

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

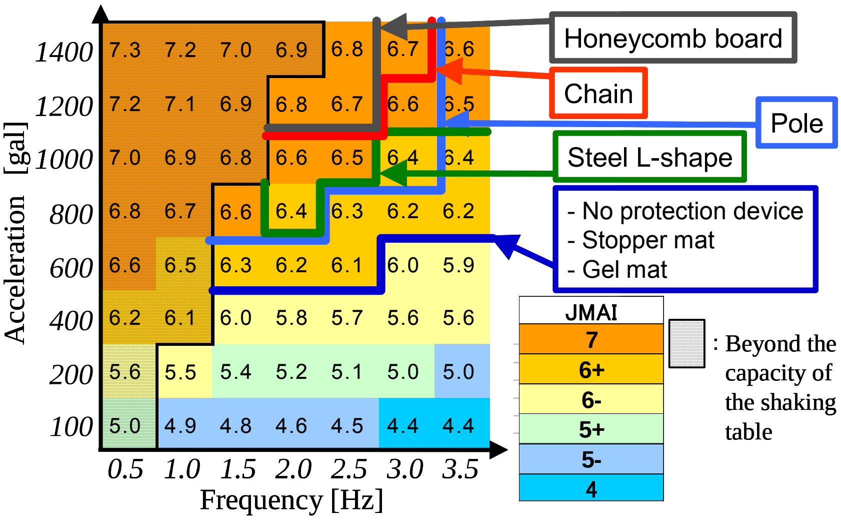
Block	Size			V [cm^3]	m [kg]	d/h
	h [cm]	b [cm]	d [cm]			
A-1	75	37.5	22.5	63,281	41.55	0.3
A-2	50	25	15	18,750	11.20	0.3



2.1 Shaking table experiments using solid wooden blocks

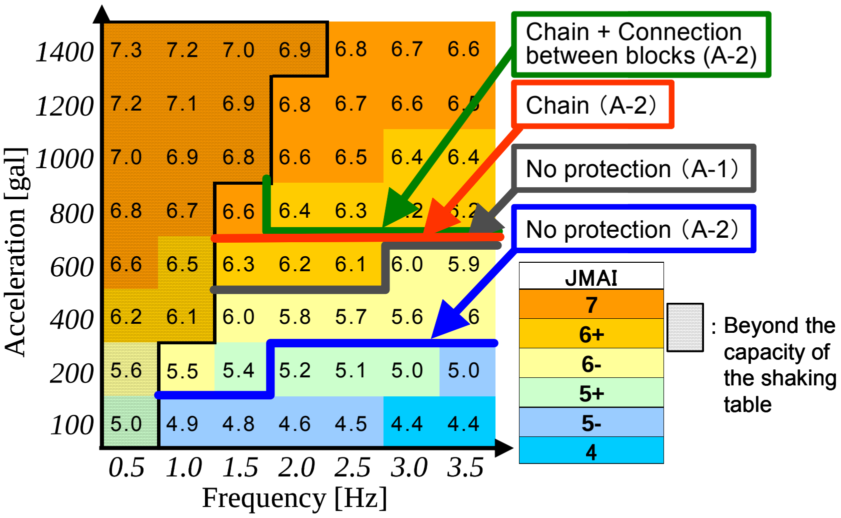
These tests were carried out on a 1.5m by 1.5m shaking table. The geometrical characteristics of the wooden blocks are listed in Table 1. The specimen A-1 was a single block whereas the specimen A-2 consisted of two blocks one over the other. A total of 38 ground motions were applied with amplitude and frequency varying from 100 to 1,400 Gals and 0.5 to 3.5 Hz, respectively (Figure 1). The Japanese Meteorological Agency Seismic 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, 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 as shown in Figure 1.

Figure 2 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 relatively strong. Tests were also carried out over tatami (traditional Japanese flooring mat) and using a, relatively weak, gypsum wall.



Acceleration [gal] \ Frequency [Hz]	0.5	1.0	1.5	2.0	2.5	3.0	3.5
1400	7.3	7.2	7.0	6.9	6.8	6.7	6.6
1200	7.2	7.1	6.9	6.8	6.7	6.6	6.5
1000	7.0	6.9	6.8	6.6	6.5	6.4	6.4
800	6.8	6.7	6.6	6.4	6.3	6.2	6.2
600	6.6	6.5	6.3	6.2	6.1	6.0	5.9
400	6.2	6.1	6.0	5.8	5.7	5.6	5.6
200	5.6	5.5	5.4	5.2	5.1	5.0	5.0
100	5.0	4.9	4.8	4.6	4.5	4.4	4.4

(a) Block A-1



Acceleration [gal] \ Frequency [Hz]	0.5	1.0	1.5	2.0	2.5	3.0	3.5
1400	7.3	7.2	7.0	6.9	6.8	6.7	6.6
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1000	7.0	6.9	6.8	6.6	6.5	6.4	6.4
800	6.8	6.7	6.6	6.4	6.3	2	.2
600	6.6	6.5	6.3	6.2	6.1	6.0	5.9
400	6.2	6.1	6.0	5.8	5.7	5.6	6
200	5.6	5.5	5.4	5.2	5.1	5.0	5.0
100	5.0	4.9	4.8	4.6	4.5	4.4	4.4

(b) Block A-2

Figure 2 Overturning criteria obtained from shaking table tests
(Floor surface: flooring, wall surface: strong timber)

2.2 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.

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

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.


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

Figure 3 Most efficient installation method
proposed for overturning prevention devices

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 3.

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

If the downward angle is increased, as depicted in Figure 5, 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.

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.

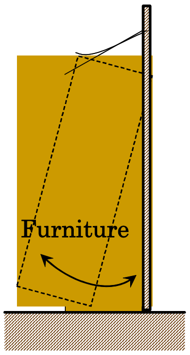


Figure 4 Furniture movement observed during shaking
when chain/belts are used upwards

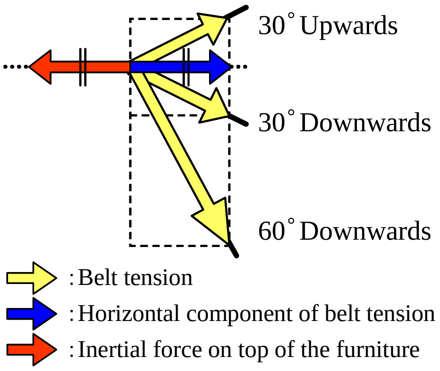
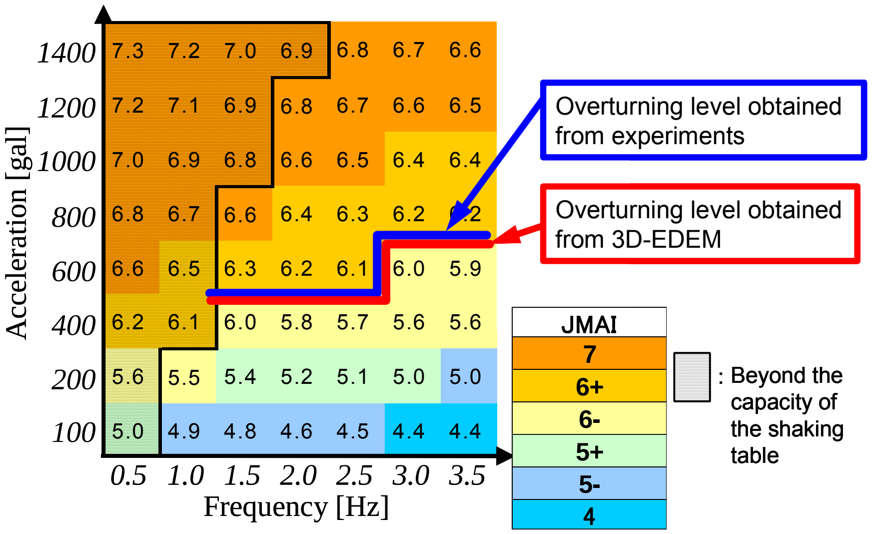


Figure 5 Restraining mechanism of chain/belt

3. 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 6 shows the comparison of the experimental and numerical results. It is clear that the simulation captured well the behavior observed during the experiments.



	0.5	1.0	1.5	2.0	2.5	3.0	3.5
1400	7.3	7.2	7.0	6.9	6.8	6.7	6.6
1200	7.2	7.1	6.9	6.8	6.7	6.6	6.5
1000	7.0	6.9	6.8	6.6	6.5	6.4	6.4
800	6.8	6.7	6.6	6.4	6.3	6.2	6.2
600	6.6	6.5	6.3	6.2	6.1	6.0	5.9
400	6.2	6.1	6.0	5.8	5.7	5.6	5.6
200	5.6	5.5	5.4	5.2	5.1	5.0	5.0
100	5.0	4.9	4.8	4.6	4.5	4.4	4.4

Figure 6 Comparison of numerical simulation and experimental results

3.1 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 7. 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 7. 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

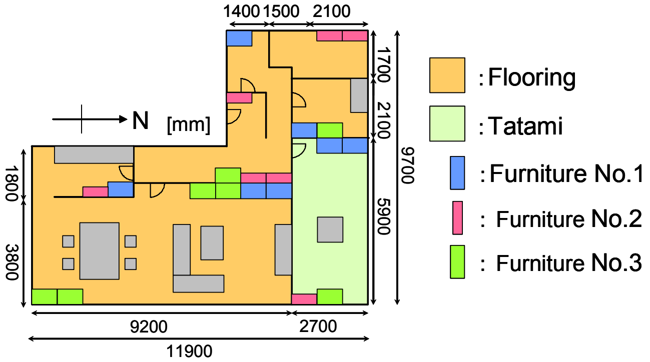


Figure 7 Layout of the living space considered for the study

3.2 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.

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 8 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.

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 9. 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 10 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.

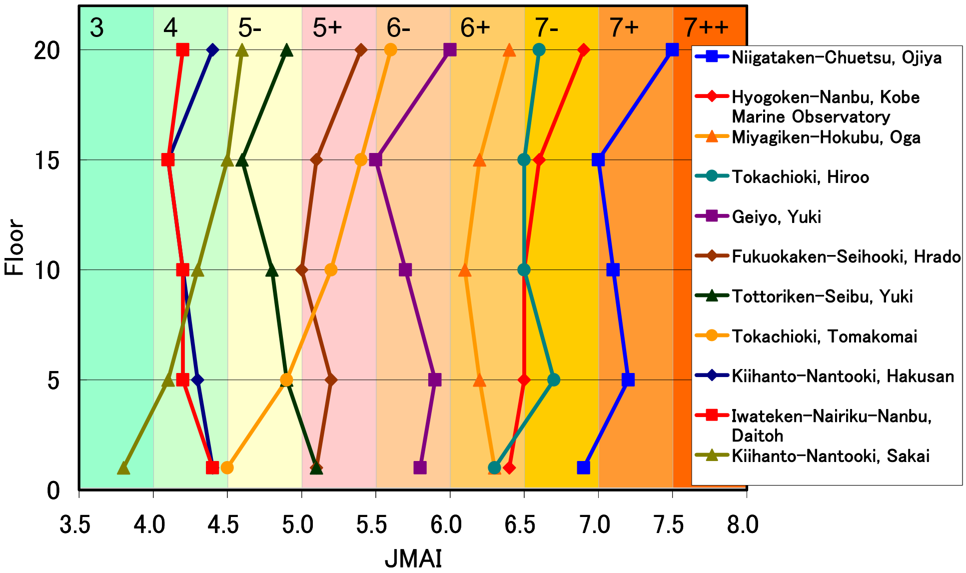
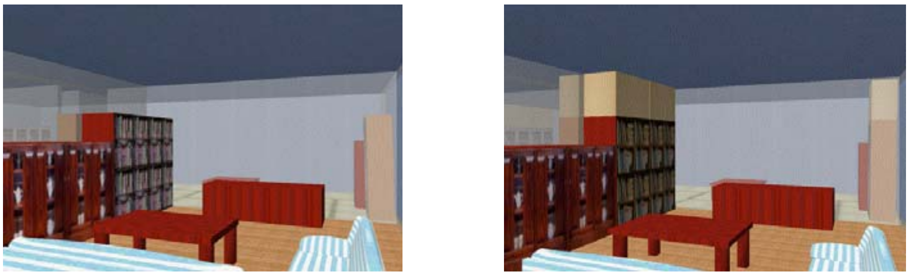
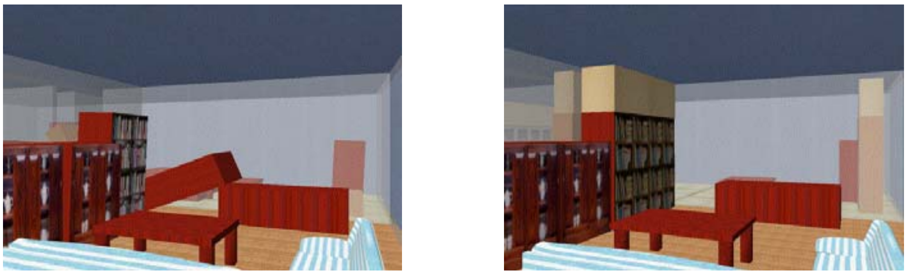


Figure 8 Floor response in terms of seismic intensity



Case A. After 3 seconds   Case C. After 3 seconds



Case A. After 9 seconds   Case C. After 9 seconds

Figure 9 Floor response in terms of seismic intensity

3.4 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 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 use more efficient protection devices, and to establish some regulation by which only built-in furniture can be used in high rise buildings.

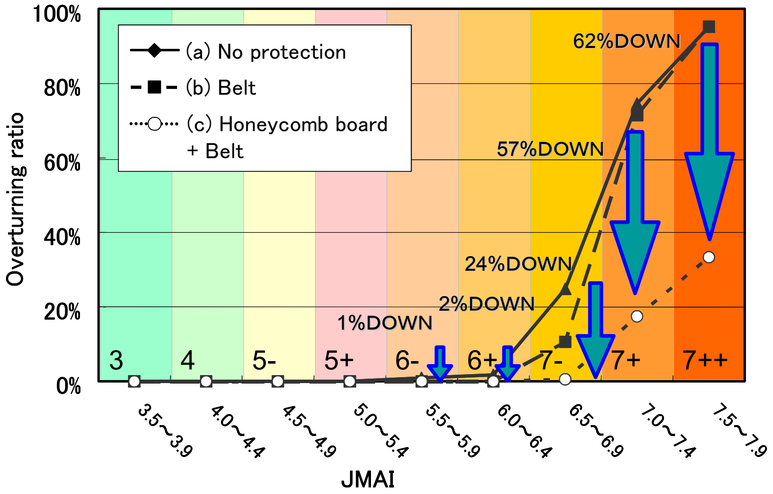


Figure 10 Overturning ratio versus seismic intensity
for each case considered

4.CONCLUDING REMARKS AND FUTURE ISSUES

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, to use 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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