

SIMPLE PREDICTION METHOD OF FURNITURE DAMAGES DURING EARHQUAKES

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SUMMARY

The authors have conducted shaking table tests for full-sized furniture generally provided in offices, hospitals and apartments. The test results showed that there was a significant correlation between floor excitation amplitudes and furniture damages. Also, the test results proved that seismically isolated buildings exhibited noticeable performance to protect indoor furniture from serious earthquakes. While, response vibration of a building floor to a certain ground motion requires the construction of adequate model for time history analysis. The paper introduces a method to estimate maximum response values of a general building by providing only the number of stories, story height, major structural material, ground motion intensity, and a little additional information. By combining the shaking table test results and this response evaluation method, the authors propose a simple prediction method is further coded to a visual aided computer program, thus not only structural engineers, but also architects, owners and inhabitants can easily grasp the seismic safety of their furniture subjected to earthquake excitations.

INTRODUCTION

Following the 1995 Kobe Earthquake, demands for the improvement in seismic safety of indoor furniture is growing, in addition to structural safety. There used to be a general understanding that seismic isolation can protect the furniture as well as the structure. This trend is observed from the statistic that the number of seismically isolated buildings has increased dramatically since the disaster. Figure 1 shows the chronological increase of the number of seismically isolated buildings in Japan. However, previous studies on overturning of rigid bodies report that the lower the excitation frequency is, the smaller the critical acceleration of overturning becomes. It means that furniture placed inside seismically isolated buildings may not always be safe only because the seismic response acceleration is much reduced.

Several shaking table tests and analytical studies were undertaken to investigate the relationship between floor excitation amplitudes and furniture damages [1]-[6]. But behaviors of furniture inside seismically isolated buildings were not studied except in report [3] which contained shaking table tests of reduced

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scale model of a rigid body. Thus, the authors conducted shaking table tests for actual furniture generally provided in offices, hospitals and apartments, especially to investigate the behaviors of furniture placed inside the seismically isolated buildings.



Figure 1 Chronological increase of seismically isolated buildings in Japan

SHAKING TABLE TESTS

Outline of the Tests

Typical office room, hospital room and dining room in apartments were assembled on a large-sized shaking table in turns. Figure 2 shows the furniture arrangement in each room type. Excitations of the shaking table were as follows.

a. Sin waves (mono-axial)

frequency: 0.25Hz - 3.0Hz, Amplitude: max.50gal - 600gal

b. Sweep waves (mono-axial)

frequency: upward from 0.3 to 5.0Hz and downward from 5.0 to 0.3Hz

c. Random waves (tri-axial)

(Floor response waves to earthquakes calculated for the models of existing buildings) For the case of office and hospital:

Input ground motions: El Centro 1940, Hachinohe 1968, JMA Kobe 1995

Models of buildings: 4 seismically isolated buildings and 1 conventional building For the case of apartment:

Input ground motions: El Centro 1940, Hachinohe 1968, JMA Kobe 1995

Models of buildings: 6 seismically isolated buildings and 1 conventional building

Approximately 40 to 50 tests were carried out for each room type by changing the table excitation. Accelerometers were set on tops and bottoms of major furniture and response vibrations were recorded. Also, the furniture behaviors in every test case were eyed and videotaped, finally classified into each of four levels of damages as defined in Table 1.

Damage Level	Condition of furniture / contents		
D1 : No Damage	furniture : no movement	contents : small movement / rattle	
D2 : Slight Damage	furniture : small movement / rattle	contents : movement / rattle	
D3 : Serious Damage	furniture : movement / rattle	contents : overturning / falling down	
D4 : Extreme Damage	furniture : overturning		

Table 1 Classification of furniture damages



Figure 2 Furniture arrangements in the shaking table test

Test Results

Figure 3 and 4 show the relationships between the excitation amplitudes of the shaking table and the furniture damages in case of sin wave excitations. The difference between the two figures indicates that the friction between the furniture and the floor apparently affected the furniture damages. The furniture placed on slippery floor, finished with plastic or wood, hardly overturned except for "Unstably placed" ones. Also as seen from Figure 3 and 4, there was an apparent characteristic that the furniture damages were categorized in five groups, according to the shapes and the supports of the furniture as shown in Table 2. Where, aspect ratio is the height divided by the depth of the furniture.

Also, the two red-colored lines in each figure show the critical acceleration and velocity level to estimate the overturning of representative furniture by following equations for rigid body [2]:

$$A = \frac{B}{H}g....(1)$$

$$V = 10\frac{B}{\sqrt{H}}...(2)$$

where, A and V are the critical acceleration and velocity of the floor, g is the gravity acceleration, B and H are the depth and the height of the rigid body. The sin wave excitation results almost followed these equations. In detail, equation (1) roughly corresponded with the test results in case that excitation frequency was 1Hz or lower, while equation (2) corresponded with the results of frequency higher than 1Hz.

On the other hand, the random wave excitations did not follow the sin wave results. It is evident from that maximum values of random waves occur only one time, while that of sin waves appear in cycles. The random excitation results were found to be fitted to the sin wave results by reducing maximum values of the floor amplitudes 0.8 times.

Table 2	Classification	of furniture	by the shape	s and the supports
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Shapes / Supports	Furniture examples
Unstably placed	Computer monitor, Plant pot, Vase
Aspect Ratio 4 or more	Cabinet, Locker, Bookshelf, Cupboard (Tall)
Aspect Ratio around 3	Cabinet, Locker, Bookshelf, Cupboard
Aspect Ratio 2 or less	Desk, Table, Chair, Bed
With Casters	Chair, Wheelchair



Figure 3 Relationships between the excitation amplitudes and the furniture damages (fricative floors)



Figure 4 Relationships between the excitation amplitudes and the furniture damages (slippery floors)

Figure 5 shows the random excitation test results. Above results indicate that the floor excitation exceeding 250gal (=200/0.8) could possibly make unstably placed or tall (aspect ratio 5 or more) furniture to overturn. But no furniture in the seismically isolated buildings overturned in the tests, even in the case subjected to the excitation by severe earthquakes. This means that the seismically isolated buildings have enough capability to protect indoor furniture from severe earthquake disasters, since the response acceleration of appropriately designed and constructed buildings with the seismic isolation hardly exceed 250gal even in extremely severe earthquakes.





Floor excitation intensities X:165gal, Y:150gal, Z:420gal

Floor excitation intensities X:165gal, Y:150gal, Z:420gal

Floor excitation intensities X:150gal, Y:123gal, Z:332gal

Figure 5 Examples of the random excitation results

Proposal of Evaluation Guidelines for Furniture Damages

Considering the test results, the authors propose evaluation guidelines for furniture damages during earthquakes (Figure 6 for fricative floors and 7 for slippery floors, respectively). Taking the maximum response acceleration for the horizontal axis and the maximum response velocity for the vertical axis at the floor of the building in consideration, the cross-point of the two values shows one of the four levels of the classified furniture damages.

Using the guidelines needs caution that the area larger than 800gal and 80kine had never been investigated in the shaking table tests and thus the states of furniture in this area are extrapolated.



Figure 6 Evaluation guidelines for furniture damages (fricative floors)



Figure 7 Evaluation guidelines for furniture damages (slippery floors)

SEISMIC RESPONSE OF BUILDING

Proposed evaluation guidelines enable to predict furniture damages, by estimating the maximum floor response of the building in consideration. In this section, a simplified estimation method for ordinary buildings subjected to code stipulated ground motions is briefly described. This method utilizes and modifies the response evaluation method stipulated in the Article of Enforcement Order under Building Standard Law, Japan, revised in year 2000.

Statistically, the first natural period of a general building can be estimated as follows:

 $T_P = 1.2T_E$(4) where, T_P (sec.) is the first natural period of the building with plastic hinges. Equation (4) is based on the assumption that the story drift ratio and the stiffness ratio to the elastic limit are 1.6 and 0.2 respectively,

subjected to the "Extremely rare earthquake" (Figure 9). However, in case of a seismically isolated building, the superstructure should remain elastic regardless of the ground motion intensities, thus the first natural period T_I is estimated as follows:

$$T_{\rm I} = \sqrt{T_{\rm E}^{\ 2} + T_{\rm iso}^{\ 2}}$$
(5)

where, T_{iso} is the natural period calculated from the equivalent stiffness of isolation interface and total mass of superstructure.

Maximum response acceleration at the top floor (the N^{th} floor) of the building is calculated by the multiplication of the response spectrum value (Figure 8) and four other factors shown in Table 3.

Gs is the amplification factor by subsurface ground layer above engineering bedrock, which are defined as shown in Table 4. Bd_N is the response amplification factor at the top floor of the building, and estimated from the first mode shape:





Figure 8 Response spectra of the ground motions stipulated in the Building Standard Law



Figure 9 Skeleton curve and response values of the assumed structure

where, p and q are also shown in Table 4, Mu_d and bd_N are calculated by equation (7) and (8):

$$Mu_{d} = \left(\sum_{i=1}^{N} m_{i} \cdot \delta d_{i}\right)^{2} / \sum_{i=1}^{N} m_{i} \cdot \delta d_{i}^{2} \dots (7)$$

$$bd_{N} = 1 + \left(\frac{1}{\sqrt{N}} - \frac{1}{N^{2}}\right) \cdot \frac{2\beta NH}{1 + 3\beta NH} \cdot N \dots \text{(for conventional buildings)}.....(8-1)$$

$$bd_N = 1 + N/250...(for seismically isolated buildings)....(8-2)$$

where, m_i is the mass of the ith floor and assumed to be equal for all floors in the method proposed herein. Also, δd_i is the deformation of the ith floor and defined as follows.

$$\delta d_i = i \dots (\text{for conventional buildings}) \dots (9-1)$$

$$\delta d_i = 1 + i/100 \dots$$
 (for seismically isolated buildings).....(9-2)

 Mu_d and bd_N represent the equivalent mass and the participation function at the Nth floor for the first mode, respectively.

Damping reduction factor Fh is described as follows:

where, h_{eq} is the damping factor of the structure, and defined as $h_{eq} = 0.05$ for elastic condition, while $h_{eq} = \Delta W / \pi W \approx 0.17$ for plastic condition (Figure 9). While h_{eq} of the seismically isolated buildings will be around 0.15 to 0.25.

Z is the seismic zone category factor in Japan and varies between 0.7 and 1.0.

Finally, maximum response velocity at the Nth floor is calculated as follows:

 Table 3
 Maximum response acceleration of the building

Building Period	to the "Rare earthquake"	to the "Extremely rare earthquake"
T<0.16	$A_{max} = (64 + 600T) \cdot Bd_N \cdot Fh \cdot Z \cdot Gs$	$A_{max} = (320 + 3000T) \cdot Bd_{N} \cdot Fh \cdot Z \cdot Gs$
$0.16 \le T < 0.64$	$A_{max} = 160 \cdot Bd_N \cdot Fh \cdot Z \cdot Gs$	$A_{max} = 800 \cdot Bd_{N} \cdot Fh \cdot Z \cdot Gs$
$0.64 \le T$	$A_{\text{max}} = (102.4 / T) \cdot Bd_{N} \cdot Fh \cdot Z \cdot Gs$	$A_{max} = (512 / T) \cdot Bd_N \cdot Fh \cdot Z \cdot Gs$

Table 4 Ground amplification factor Gs and factor p,q

Stiff Ground ($T_g \le 0.2$)		Medium Ground ($0.2 < T_g \le 0.75$)		Soft Ground $(0.75 < T_g)$		
T<0.57	76	Gs=1.5	T<0.64	Gs=1.5	T<0.64	Gs=1.5
0.576	$\leq T < 0.64$	Gs=0.864/T	$0.64 \le T < 0.864$	Gs=1.5T/0.64	$0.64 \le T < 1.152$	Gs=1.5T/0.64
0.64<7		Gs=1.35	0.864 <t< td=""><td>Gs=2.025</td><td>1.152<t< td=""><td>Gs=2.7</td></t<></td></t<>	Gs=2.025	1.152 <t< td=""><td>Gs=2.7</td></t<>	Gs=2.7
	р	T ≤ 0.16	0.16 < T	q		
	N=1	p=1.00-(0.20/0.1	6)T p=0.80	Mu _d / N	q = 0.75 $q = 0.75$	/Iu _d / N
	N=2	p=1.00-(0.15/0.1	6)T p=0.85	$0.75 \le M$	$u_{\rm d} / N = 1.0$	
	N=3	p=1.00-(0.10/0.1	6)T p=0.90	-		
	N=4	p=1.00-(0.05/0.1	6)T p=0.95			
	$5 \le N$	p=1.00	p=1.00			

PREDICTION OF FURNITURE DAMAGES

This section describes a simplified prediction method of furniture damages during earthquakes. Figure 10 shows the concept of the prediction. A series of procedure, including rather complicated calculation to estimate the response of the building in consideration, has been coded to a visual aided computer program, thus the program users are not required to have technical knowledge of structural engineering. Motion pictures previously videotaped in the shaking table tests, which are automatically selected corresponding to the prediction results and played, will help architects, owners and inhabitants as well as structural engineers to grasp the seismic safety of their buildings even at the design stage. Figure 11 shows the outline of the program, although it is only available with permission at the moment.



Figure 10 Concept of the furniture damages prediction



Figure 11 Outline of the prediction program

CONCLUSIONS

The authors conducted the shaking table tests for full-sized furniture generally used in offices, hospitals and apartments, aiming to know the behaviors and the damages of the furniture during strong ground motions. Particularly, attentions were paid for the results in case of the random excitations corresponding to the floor response of seismically isolated buildings. Findings from the tests are as follows:

- (1) Furniture could be classified into five groups by the shapes and the supports, like "Unstably placed", "With Casters". The furniture that belong to the same group showed almost similar behaviors and resulted in the same damage level. Where, the damage levels were classified into four groups from "No Damage" to "Extreme Damage".
- (2) Frictions between the furniture and the floor significantly affected the damages. Furniture on slippery floors hardly overturned when subjected to severe excitations, except "Unstably placed" ones.
- (3) The test results almost followed the results in previous reports of rigid bodies.
- (4) Seismically isolated buildings exhibited outstanding performance to protect indoor furniture from serious damages, since the responses of appropriately designed and constructed buildings with the seismic isolation hardly exceed the critical overturning values even in extremely severe earthquakes.

Accepting the test results, the authors considered the followings:

- (5) The evaluation guidelines for furniture damages during earthquakes were proposed when the maximum response values for the floor of the building in consideration is provided.
- (6) A response estimation method for ordinary buildings subjected to the ground motions stipulated in Notification 1461 of year 2000 were introduced utilizing and modifying the response calculation method stipulated in Enforcement Order of Building Standard Law.

Finally, above findings and proposals were coded to a simple computer program to predict the furniture damages during earthquakes.

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