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SAFETY OF BASE-ISOLATED BUILDING IN CASE OF IMPACT AGAINST RETAINING WALL

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ABSTRACT
The objective of this research is to analyse the safety of a base isolated building when is subjected to a resonance response in case of long-period ground motion and when this response induce the impact of the building against surrounding retaining walls. As a fundamental study, response of a target base isolated structure subjected to various earthquake input motions is performed. The analytical model considers a gap link element to study the collision against the retaining wall. Maximum acceleration in upper structure increases in case of collision. This acceleration could originate the overturning of building content like furniture.
Keywords: base isolation, collision, earthquake response analysis, link element.

1 INTRODUCTION

In Japan, the use of seismic isolation structures rapidly expanded since the Hyogo-ken Nanbu earthquake (well known as Kobe earthquake) in 1995 due that it absorbed the input energy of the earthquake by the seismic isolation devices and release the columns and beams from the role of energy absorption. Since the Niigata Prefecture Chuetsu Earthquake in 2004, the importance of keep the functionality of strategic buildings, like hospitals, even after a strong earthquake was recognized. Seismic isolation system is effective for serviceability conservation and represents a base for earthquake disaster prevention and mitigation [1].

Currently, buildings using seismic isolation technology reach about 2,800 housing and offices (including hospitals) buildings, and about 4,200 houses. Several of the base-isolated buildings were hit by the Tohoku Region Pacific Offshore Earthquake that occurred in 2011, and the seismic isolation devices worked effectively, greatly contributing to the reduction of earthquake damage [2]. This type of events that are long-duration long-period earthquake ground motion, may induce large deformation of the intrinsically long period base isolated buildings. Therefore, it is necessary to investigate the possibility of the collision with the retaining wall. The base isolation building concentrates large deformations at isolated level. That is, the isolation devices are capable to support large displacements, which permit to isolate the upper structure from large acceleration propagation. In the case of strong earthquakes, this large displacement could exceed the clearance between the isolated structure and the surrounding retaining wall and collision of the isolated structure against retaining walls could occur [3], [4].

In case that the base isolated structure collides with the retaining wall, maximum response acceleration of the upper structure will be produced at time of impact. Therefore, it is necessary to evaluate the influence of the collision in the response of the isolated building. In this research, analytical model for collision investigation is constructed using gap link elements. The target structure is modelled as a multi-degree of freedom system. Models with 40 cm of clearance (collision) and 60 cm (no collision) are employed in this analysis. In addition, a model with collision and higher retaining wall stiffness is employed to investigate the effect of retaining wall stiffness on upper structure response in case of collision.

The analytical models are used to investigate the security of building content in case of collision. Representative furniture like bookshelf in used for this security analysis.

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2 BASE ISOLATED STRUCTURE

The target building for the present study is a seismic isolation office building that belongs to Obayashi Institute of Technology, Kiyose City, Tokyo, Japan [5], [6]. This building was used to carry out a retaining wall collision experiment. The direction of the experimental test is shown in Fig. 1. This figure shows also an elevation view of the building. The structure is a reinforced concrete building of 5 stories with a total mass of about 2600 t. The plan dimension is 14.4 m × 21.6 m, the total floor area is 1600 m^2, and the height is 21.85 m. The seismic isolation system consists of 14 natural rubber laminated isolators and 96 special steel bar dampers. Table 1 shows the main specifications of the laminated rubber isolators. For the present analysis only rubber isolators are considered.

The impact test reported by Miwada *et al.* [1] consisted in a free vibration test with an initial displacement larger that the clearance of 37.5 cm. This initial displacement was applied by high speed release hydraulic jacks and then after release the structure strikes the retaining wall. However, even for large initial displacement of the order of 100 cm, the maximum acceleration at impact was of the order of 200 cm/s^2. It is important to note that the maximum acceleration in this test is a low acceleration that differs from larger acceleration that could be observed in case of earthquakes. Then, for analysis of impact or collision in case of earthquakes, it is necessary to create a model for this purpose.

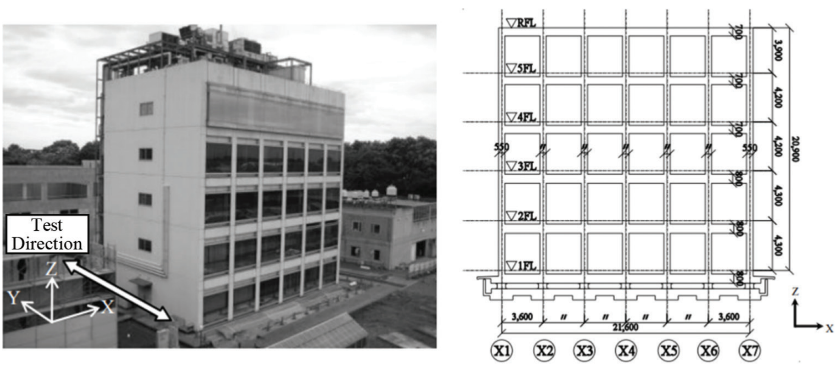


Figure 1: Target structure.

Table 1: Characteristics of laminated rubber isolator.

Rubber thickness and number of layers	4.4 mm × 64 layers = 268.4 mm
Rubber diameters (external and internal)	756 mm, 150 mm
Metal plate thickness and number of layers	2.3 mm × 60 layers = 138.0 mm
Metal plate diameters (external and internal)	740 mm, 150 mm
Primary shape factor	33.5
Secondary shape factor	2.8
Rubber static shear coefficient	0.549 N/mm^2
Rubber Young modulus	1.128 N/mm^2
Rubber coating thickness	8 mm

3 ANALYTICAL MODEL

The analytical model was simplified to investigate only the maximum responses at each floor of the building. Then, the building was modelled as a shear type model of a six masses system combining the base isolation layer and the upper structure (five layers) using finite element analysis software SAP 2000. Figure 2 shows the lumped mass model, and Table 2 shows the properties of the base isolation layer and superstructure. The total mass of the superstructure is 2653.62 t.

The mass of this analysis model includes fixed loads such as ceiling and slabs and does not include live loads. The stiffness of the upper structure was calculated by the D value method, and the stiffness of the base isolation layer was obtained from the eqn. (1), which is used to fix the target period of vibration of the isolated structure.

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{1}$$

where: m = total mass of the structure
k = lateral stiffness of the isolation devices
T = target period of vibration of the isolated structure

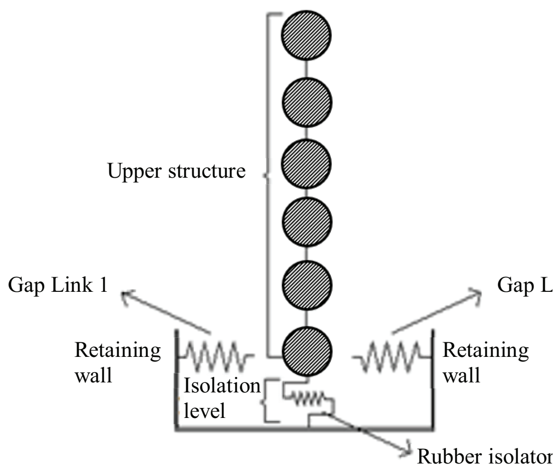


Figure 2: Lumped mass system.

Table 2: Properties of the lumped mass model.

Story	Mass (t)	Story height (cm)	Stiffness (kN/mm)
5th	351.50	390	1647.24
4th	430.34	420	1420.36
3rd	435.21	420	1420.36
2nd	467.40	430	4936.08
1st	548.65	430	6419.49
Base isolated	420.51	80	12.90

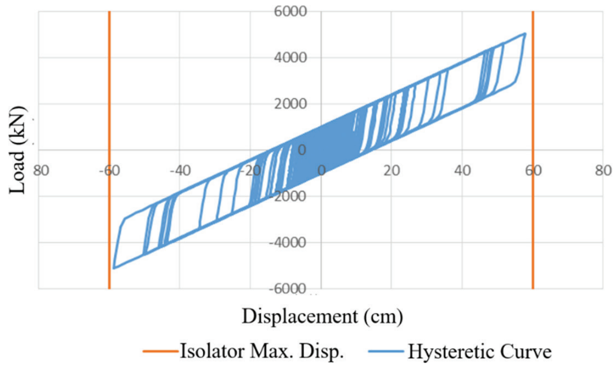


Figure 3: Inelastic response of isolation layer for time history analysis.

The stiffness of the isolation layer corresponds to the equivalent stiffness for 100% of isolation deformation. For time history analysis the isolator is considered as nonlinear element. As illustrative example the behaviour of the inelastic behaviour of the isolation layer is shown in Fig. 3.

3.1 Clearance and collision modelling

The collision against retaining wall is modelled with a gap link element. This element reacts when displacement exceeds a specify clearance and the element works in compression with a specified stiffness. The load displacement relationship for this element is shown in Fig. 4. Link elements were considered at both sides of the model shown in Fig. 1.

For comparison three analytical models were considered: model A with 40 cm of clearance and specify retaining wall stiffness, model B with 60 cm of clearance to ensure no collision against retaining wall, and model C with 40 cm of clearance and increased retaining wall stiffness. In this case stiffness of model C is twice stiffness of model A. Characteristics of these models are summarized in Table 3.

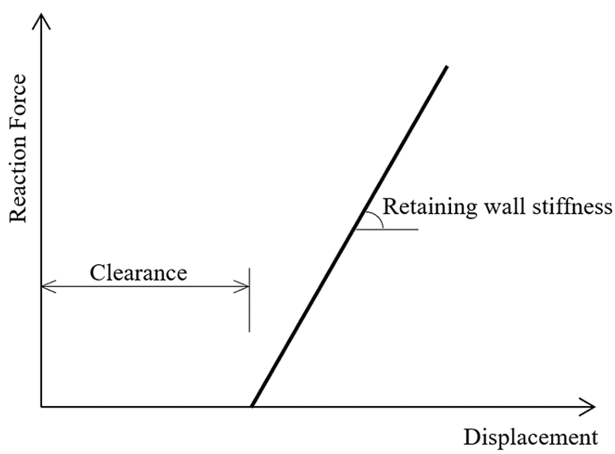


Figure 4: Gap element for collision modelling.

Table 3: Properties of analysis models.

Model	Clearance (cm)	Retaining wall stiffness (kN/cm)	Collision condition
Model A	40	1000	Collision
Model B	60	1000	No collision
Model C	40	2000	Collision

4 TIME HISTORY RESPONSE ANALYSIS

First, predominant period of the model was obtained by means of an elastic modal analysis considering the equivalent stiffness of the isolation layer. From this analysis was obtained a predominant period of 2.86 s, which is compatible with that of 2.79 reported by Miwada *et al.* [1]. Then, the model was subjected to earthquake input motion to study its dynamic response characteristics. In this case, inelastic time history analysis was performed since behaviour of rubber isolator is modelled as inelastic. Upper structure is modelled with elastic and linear springs.

In total four waves were used, two of which have short-period seismic waves and the other two waves have long-period seismic waves. The records were standardized to have a maximum velocity of 50 cm/s. The characteristics of this input motions are shown in Table 4. ELC-NS and KOBJ-NS are signals with short period content and TOKYO-NS and HACH-NS are waves with long period characteristics. It is also remarkable that long period input motions are also long duration earthquakes. In addition, response spectra for these four input motions are shown in Fig. 5.

The maximum input acceleration to the building foundation is compared with the maximum response acceleration of the upper part of the structure. These results are presented in Table 5. Reduction ratio of the acceleration is also shown in this table.

4.1 Effect of type of input motion and clearance

From Table 5, it can be observed that maximum response acceleration is obtained for long-duration long-period earthquakes. This is observed for all models, including model B that corresponds to the case of no collision. Short period earthquakes present same maximum acceleration responses for the three models since no collision was observed in these cases.

Table 4: Selected input motions for time history analysis.

Input name	Earthquake (station), year	Max. acc. (m/s^2)	Max. vel. (cm/s)	Duration (s)
ELC-NS	Imperial Valley (El Centro), 1940	510.8	50.0	53
KOBJ-NS	Hyogo-ken Nambu (Kobe, JMA), 1995	423.8	50.0	20
TOKYO-NS	East Japan off Pacific Ocean (Tokyo, Edogawa), 2011	460.7	50.0	720
HACH-NS	Tokachi-oki (Hachinoje), 1968	348.6	50.0	234

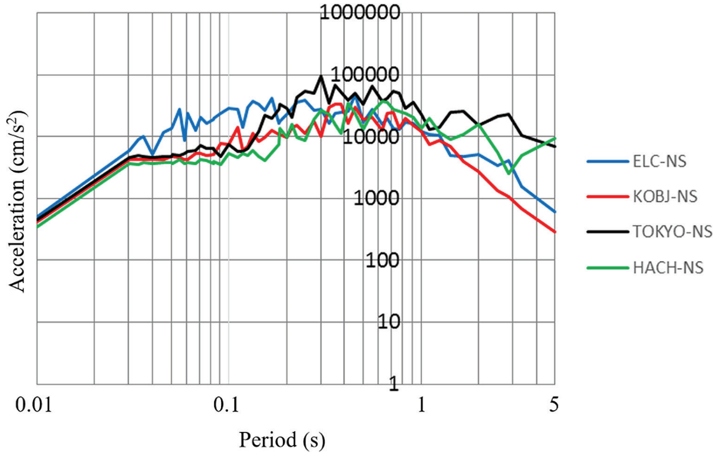


Figure 5: Acceleration response spectra for selected input motion.

Table 5: Maximum response accelerations and reduction ratio.

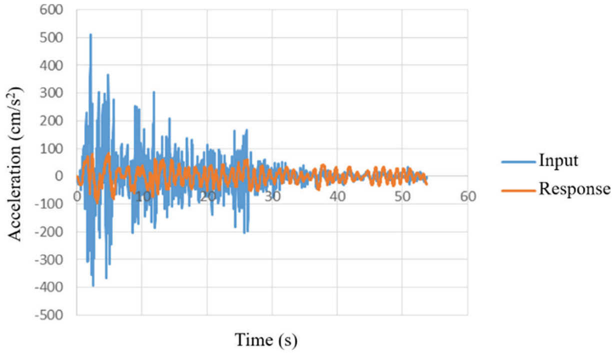
Input	Max. Acc. (cm/s^2)	Response Acceleration (cm/s^2) Model A	Model B	Model C	Reduction Ratio A	B	C
ELC-NS	510.8	96.31	96.31	96.31	0.19	0.19	0.19
KOBJ-NS	423.8	84.75	84.75	84.75	0.20	0.20	0.20
TOKYO-NS	460.7	965.06	200.51	1242.88	2.09	0.44	2.70
HACH-NS	348.6	350.54	169.43	400.60	1.01	0.49	1.15

The effect of clearance in the response of the structure is observed for long-period earthquakes by comparing responses of models A and B. It is obvious that when enough clearance is set up (model B) the maximum acceleration response is reduced since no collision is observed.

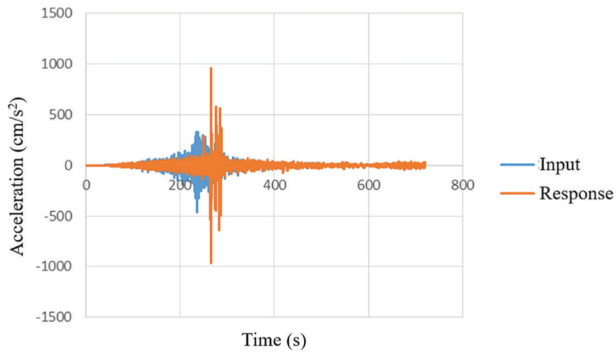
Figure 6 shows the representative analysis results. Figure 6(a) shows the input acceleration and the response acceleration for model A (40 cm of clearance) in case of El Centro input motion (short-period signal). Figure 6(b) shows the results for the same model A in case of Tokyo-NS input motion (long-period earthquake). In this case, acceleration response shows sharp peaks that correspond to impact instants. Figure 6(c) presents the response for model B (60 cm of clearance) in case of Tokyo-NS input. In this case sharp peaks are not observed in the acceleration response.

4.2 Effect of the Retaining Wall Stiffness

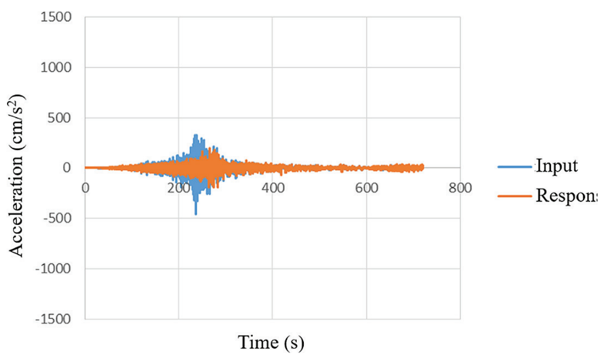
The stiffness of the retaining wall affects the maximum acceleration response and the maximum reaction force of the wall. In Table 5 results for model A and model C in case of long-period earthquake can be used for comparison of acceleration response. Results show that acceleration response increase by a factor of 1.29 for Tokyo-NS input and 1.14 for Hachinoje (HACH-NS) input. The variation of the reaction force of the retaining wall is shown in Fig. 7. This force is the reaction force of link elements which are used for collision



(a) Acceleration response for model A, El Centro input motion.



(b) Acceleration response for model A, Tokyo-NS input motion.

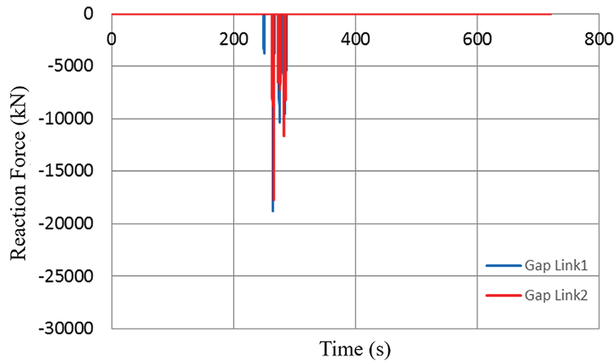


(c) Acceleration response for model B, Tokyo-NS input motion.

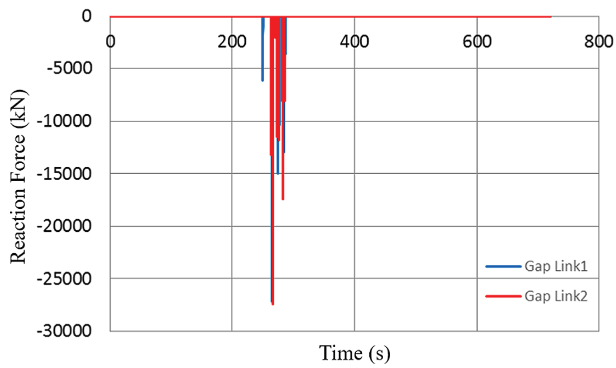
Figure 6: Typical time history acceleration response.

modelling. Figure 7(a) shows the results for model A and Tokyo-NS input and Fig. 7(b) shows the results for model C and same input. Results for model C that has higher stiffness present bigger reaction force.

Distribution of acceleration responses along structure height is shown in Fig. 8. For comparison, results for model B (no collision) and model C (collision and high retaining wall stiffness) are presented. Figure 8(a) shows the case of no collision and it can be observed reduction of the acceleration response for all input motions. In case of model C (Fig. 8(b)),

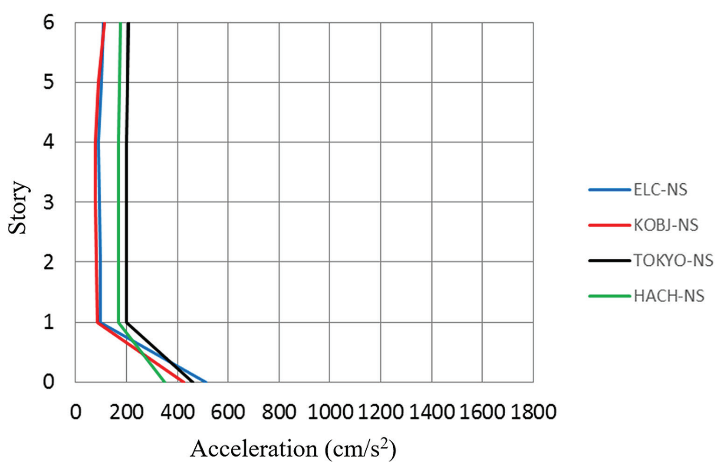


(a) Reaction force of retaining wall model A, Tokyo-NS input.

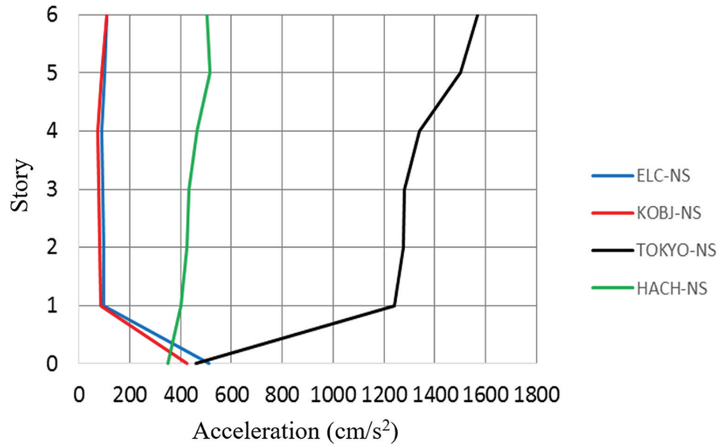


(b) Reaction force of retaining wall model C, Tokyo-NS input.

Figure 7: Reaction force of retaining wall in case of collision.



(a) Maximum acceleration along story height for model B (no collision).



(b) Maximum acceleration along story height for model C (collision).

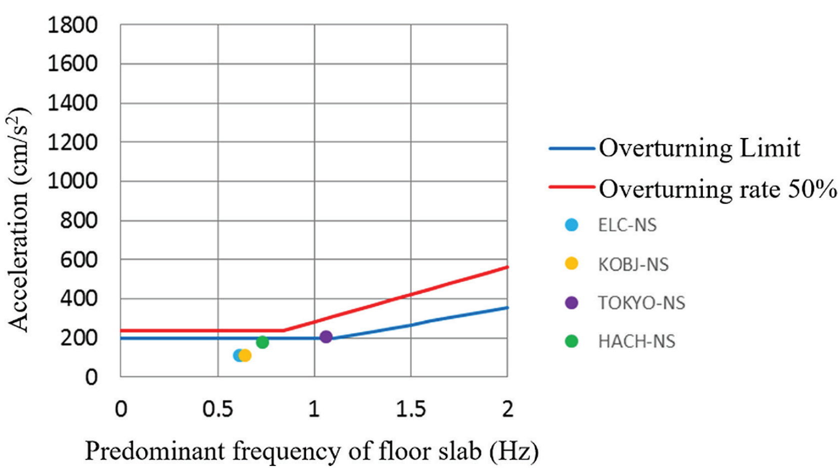
Figure 8: Maximum acceleration responses.

an amplification of acceleration response is observed for long-period earthquakes. This is due to the collision against retaining wall. These acceleration responses are used to investigate the safety of indoor contents.

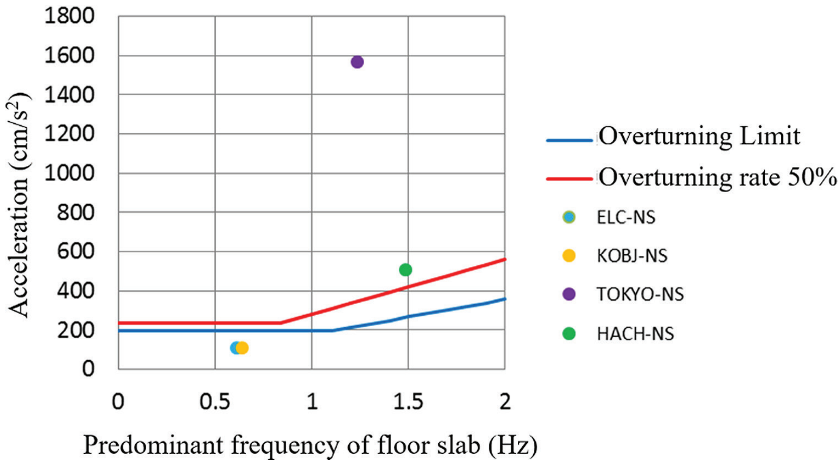
5 SECURITY EVALUATION FOR IMPACT CASE

Evaluation of building content safety is evaluated based on flow of failure and sliding of furniture proposed by Kaneko *et al.* [7]. This evaluation is performed defining an overturning limit acceleration and a slipping start acceleration. These parameters depend on furniture type, dimensions, and friction coefficient between furniture and floor slab. In this analysis a representative furniture (book shelf) is selected. Dimensions of this furniture are 200 cm height, 40 cm width (b/h = 0.20) and a friction coefficient of 0.3.

Maximum responses for each input motion compared with limit accelerations are shown in Fig. 9. In case of no collision (model B) maximum response, accelerations do not exceed the overturning limit as is shown in Fig. 9(a).



(a) Bookshelf fall acceleration and floor response for model B (no collision).



(b) Bookshelf fall acceleration and floor response for model C (collision).

Figure 9: Maximum acceleration responses.

Results for model C are shown in Fig. 9(b). In this case, collision occurs for long-duration, long period earthquakes and observed maximum accelerations exceed the overturning limits. Then is it clear that overturning of bookshelf can be originated due to high acceleration of upper floors.

6 CONCLUSIONS

Using seismic waves with different frequency content characteristics, nonlinear time-history response analysis of a base-isolated reinforced concrete building was performed considering collision against retaining wall.

Evaluation of furniture safety by simple prediction method was carried out. Collision occurs for long period input motions and small clearance (model A and model C). In these cases, high acceleration responses were observed.

Analysis of building content safety suggested that high acceleration originated by impact could produce overturning of the furniture with high aspect ratio (bookshelf).

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