Building content sliding demand – Analytical studies of contents in elastic, MDOF structures

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ABSTRACT: This paper aims to characterise the sliding behaviour of building contents in elastic, single and multi-degree of freedom structures subject to ground acceleration. The behaviour described in previous literature was validated with impulse and ground motion records in OpenSEES. The model was extended to consider sliding that was obstructed due to a barrier such as a wall. It was found that obstructed contents' sliding displacements were up to five times larger than unobstructed sliding displacements. Further analyses were conducted, in order to understand how obstructed and unobstructed sliding behaviour changes with the natural period of the structure. There was a significant reduction in sliding for structures with natural periods exceeding 1.3s, with all sliding ceasing for natural periods greater than 3.25s. For multi-degree of freedom structures, the relative sliding of the contents in the higher floors of the structure was 200 times greater, on average, than the ground floor. This behaviour was attributed to the dependency of the contents' sliding displacement on the peak total floor acceleration and peak total floor velocity, both of which increased up the height of the building. While floor acceleration initiates sliding, a new parameter called the Modified Total Peak Floor Velocity, which considers both velocity and acceleration effects, correlated well with contents sliding.

1 INTRODUCTION

Building contents' movement can cause economic loss, loss of life and significant inconvenience. Contents' movement and damage may result from high accelerations, impact, overturning, sliding or items falling off supports. Anecdotal evidence shows that items such as televisions have overturned causing loss of life, bookshelves that have toppled over blocked building egress and photocopiers have slid across office spaces resulting in damage to the building and other nearby contents.

In order to better understand building losses and to be able to predict the level of shaking based on observations of contents' movement, there is a need to better understand the dynamic behaviour of contents' movement during earthquakes. In order to meet this objective, this paper seeks to answer the following questions:

1. Does the behaviour of contents located beside a barrier (obstructed sliding), such as a wall, differ from that with no restraint in either direction?
2. How is the sliding behaviour affected by the floor shaking characteristics, such as the effect of shaking at different levels of a building?

2 Literature review

Studies conducted by Aslam (1975) compared test and theoretical sliding responses of a rigid block under sinusoidal horizontal acceleration. It was shown that the sliding response of a rigid block can be successfully predicted under earthquake ground motion. The general sliding behaviour to impulse excitation was:

1. Initially the contents and the floor of the structure respond together.
2. Once the acceleration of the structure exceeds μg, contents sliding initiates. The contents slide at a constant acceleration of μg.

3. The contents continue to slide until the velocity of the contents, relative to the floor, becomes zero. Reversal occurs if structure's acceleration exceeds μg in the opposite direction.

Studies conducted by English (2012) and Lin (2013) quantified sliding of building contents subjected both impulse and ground motion excitations and verified the findings of Aslam (1975). Lin focused on understanding the mechanisms and likely magnitudes of content sliding in elastically responding structures whilst English focused on the influence of hysteretic characteristics of structures on contents damage.

Both English and Lin modelled sliding behaviour with a simple, two degree of freedom structure-contents sliding system using the software RUAUMOKO-2D. Their model represents unobstructed movement in which building contents move freely in a horizontal plane, or floor, subjected to impulse and ground motion excitations.

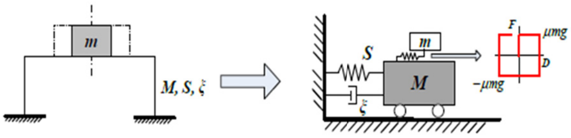


Figure 1. Structure-contents sliding model as proposed by Lin (2012).

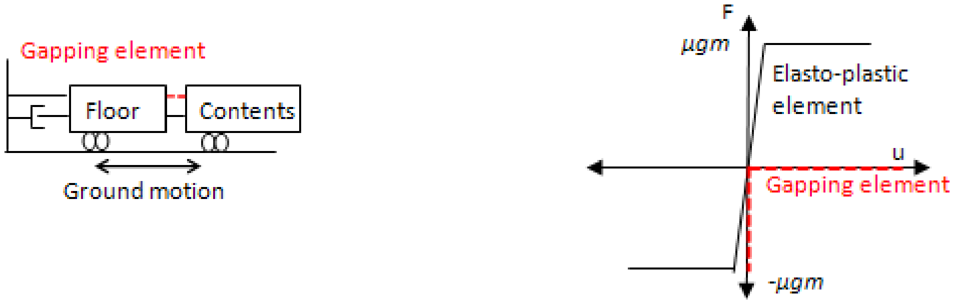
Lin found that the magnitude of sliding may be more than five times the spectral displacement of the building. Lin noted that Gazetas (2009) found that the effect of vertical components of ground motions was not generally significant for building contents sliding. English found that the magnitude of stiffness changes in structures required to produce shock loads on contents was above that feasibly possibly in real structures.

To the author's knowledge, the consequences of a barrier, such as a wall, and floor record differences over the building height have not been considered in any previous studies.

3 METHODOLOGY

3.1 Contents sliding model for SDOF structure

A simple, two degree of freedom structure-contents system was developed in OpenSEES (McKenna, 2000) using the model by English (2012) and Lin (2013) for unobstructed sliding cases. An additional stiff gapping element was added between the structure and contents nodes for modelling obstructed sliding cases. An illustration of the model is shown in Figure 2a.



(a) Structure-contents sliding system in OpenSEES.

(b) Force-displacement relationship.

Figure 2. Structure-contents model in OpenSEES.

Sliding initiates once the sliding resisting force, $F_{resisting,}$ is exceeded. This satisfies Coulomb's law of friction according to Equation 1.

$$F_{Resisting} = \mu mg \tag{1}$$

where μ is the coefficient of friction, m is the contents mass, and g is the acceleration due to gravity.

The sliding resisting force-displacement relationship of the contents was modelled using an elasto-plastic hysteresis loop with high initial stiffness as shown in Figure 2b. The yield bond force was set to μmg. The gapping element has zero stiffness in tension and infinite stiffness in compression, to prevent sliding in the negative direction. The addition of the two corresponding hysteresis loops restricts movement of the contents into the obstruction but allows the contents to move freely away from the obstruction. The model assumed a single coefficient of friction, which was consistent with that used in experiments by Aslam (1975), Yeow (2013) and Nagao (2012). For this study, the model did not account for the difference between static and kinetic coefficients of friction.

Rayleigh damping ratio of 5% was assumed as this is a typical value assumed for buildings. Due to the constraints of OpenSEES both the structure and contents were modelled with 5% damping. To mitigate mass hysteretic damping effects of the content, a mass ratio of 1:1000 for contents: structure was assumed, as suggested by English (2012).

The suite of ground motion records used in this study is the SAC Suite of records selected to represent a 10% in 50 years probability of exceedence for Los Angeles (Somerville, 1997). There are 10 sets of records, each with two orthogonal horizontal components. Each component was run in 2 directions to avoid directionality effects. These ground motions were chosen as they are consistent with those used by Lin (2012).

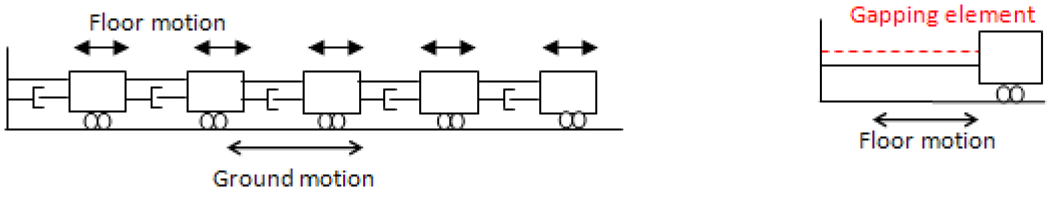
It was found that for all records, it was sufficient to use one tenth of the time-step of the ground motion file for the time history integration time step. This produced accurate results, without a large cost on the computational efficiency of the model.

Studies were also conducted to assess the sensitivity of the model to (i) the initial and post elastic stiffness of the contents element, (ii) applied damping ratio, and (iii) the coefficient of friction on a single storey structure with a natural period of 1.3s and subject to the La9 ground motion record from the SAC Suite (Somerville, 1997). This record caused larger displacements than the other La ground motion records at a period of 1.3s.

A spectra for the lognormal median and 84^{th} percentile peak relative contents' sliding displacement was created by running both obstructed and unobstructed sliding analyses for all files in the SAC suite for structure periods ranging from 0.0 to 5.0s.

3.2 Contents sliding model for MDOF structures

A two-step analysis was used to model contents' sliding for a multi degree of freedom (MDOF) system. The first step was to model a five storey structure subjected to a range of ground motions, as shown in Figure 3a. The total acceleration and velocity histories were recorded for each floor for use in the second step of the analyses. The structure model had the same structural properties as the elements and nodes in the SDOF system except for the element stiffnesses, which were adjusted to give the system a specific period.



(a) Model of five story structure used to obtain floor ground motion accelerations.

(b) Model of contents on floor.

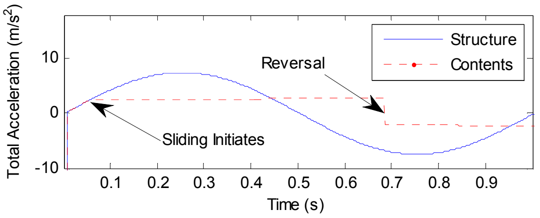
Figure 3. Two step multi-storey structure-contents model.

The second step represented the contents' response. The floor acceleration history obtained at each floor in the first step were input into the contents only model and the content acceleration, velocity and displacement responses were recorded. The contents model, shown in Figure 3b, had the same properties as the contents element and node in the single degree of freedom system.

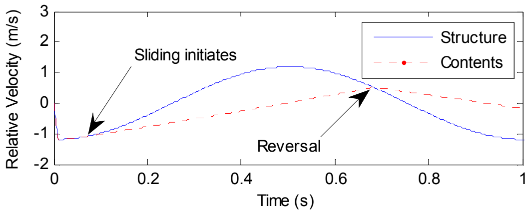
4 SDOF UNOBSTRUCTED AND OBSTRUCTED SLIDING RESPONSE TO IMPULSE AND GROUND MOTION LOADING

4.1 General behaviour

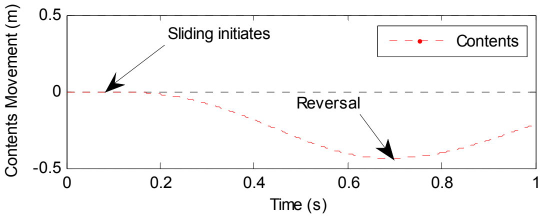
Figures 4 a-c show the system's acceleration, velocity and displacement response to a 0.01s impulse loading for 5% damping with a force large enough to initiate sliding of 13.5kN. At approximately 0.7s the contents' sliding reverses. This is where the velocities of the contents and structure are the same (zero relative velocity) and where the structure's acceleration exceeds $-\mu g$. Figure 4d shows the contents' relative sliding displacement response to the La9 ground motion record. Sliding initiates after approximately 18s. The sliding displacements are cumulative throughout the cycles of the ground motion, resulting in a maximum relative sliding displacement of 1.15m. Sliding ceases at 26s with a residual displacement of -0.2m.This behaviour matches that of Lin (2013) and English (2012).



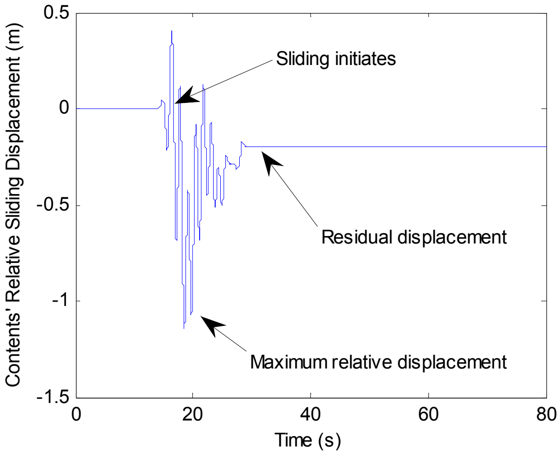
(a) Acceleration vs. time for impulse excitation.



(b) Velocity vs. time for impulse excitation.



(c) Displacement vs. time for impulse excitation.



(d) Displacement vs. time for ground motion excitation (La9, 5% damping and Tn=1.3s).

Figure 4. Response of structure-contents sliding system to impulse and ground motion excitations.

4.2 Stiffness sensitivity analysis

The elastic and the post-elastic stiffness of the contents' element had a significant effect on both the accuracy of the results and the computational time required to run the analyses. This model utilised axial deformation; thus the axial stiffness, *AE/L*, was used. The stiffness was varied by changing *E*, the Elastic Modulus of the elements, while *A*, the cross-sectional area, remained constant.

Throughout the analysis, the Modified Newton Method, an iterative scheme to solve the equation of motion by using the initial tangent stiffness guess rather than the current tangent, was used as it reduces the errors associated with using the tangent stiffness, rather than the secant stiffness. It can be seen in Table 1 that the results became increasingly varied at high contents' stiffness values; the larger the elastic stiffness becomes the more accurate the model is. However for the post elastic stiffness this is the opposite. The ratio of post elastic to elastic stiffness remained constant whilst the elastic and post elastic stiffnesses could have been closer to infinity and zero respectively, significantly extra computational effort would have been required; thus it was decided that an AE_1/L of 5000 N/m would be adequate.

In order to accurately model impact between the two nodes, the content and the obstruction, the stiffness of the contents' node after impact was required to be very small. It can be seen in Table 1 that results stabilised at an AE_2/L of 5×10^{-8} N/m. All stiffness values required a similar computational effort and time, thus this stiffness was deemed sufficient for the model.

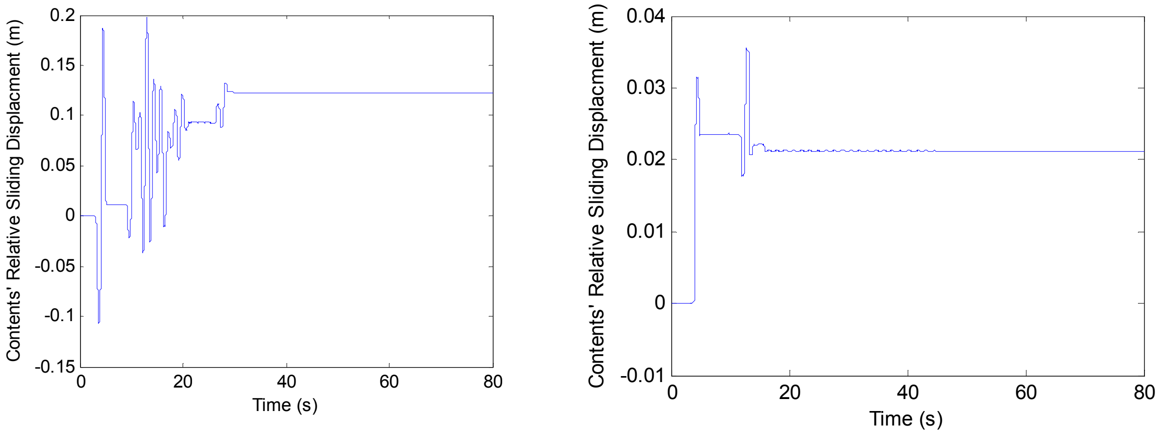
Table 1. Sensitivity of contents; relative sliding displacement to content's elastic and post elastic stiffness using ground motion file La9, with 5% damping and T_n=1.3s.

Elastic Stiffness				Post Elastic Stiffness			
AE_1/L (N/m)	**Unobstructed (m)**	**Obstructed $^+$ (m)**	**Obstructed $^-$ (m)**	**AE_2/L (N/m)**	**Unobstructed (m)**	**Obstructed $^+$ (m)**	**Obstructed $^-$ (m)**
2500	1.784	10.119	7.765	5.00E-06	1.771	10.278	7.693
5000	1.771	10.324	7.698	5.00E-08	1.771	10.324	7.698
25000	1.774	10.358	7.454	5.00E-10	1.771	10.324	7.698

4.3 Effect of friction coefficient on sliding response

The analytical study conducted by Lin (2013) considered a coefficient of friction of 0.25 in the analyses, which is representative of plywood Aslam (1975), while experimental results from Yeow (2013) showed that 0.40 is a reasonable value to use for carpet flooring surfaces. As such, a short investigation was done into the effect of the coefficient of friction on the sliding response.

It was found that higher friction coefficients lead to lower sliding displacement for unobstructed movement in all cases, as the ground motion required to induce sliding has to exceed a larger $F_{resisting}$, as per Equation 1. This is shown in Figure 5.



(a) μ = 0.25 damping (La1 , 5% damping, T_n = 1.4s).

(b) μ = 0.40 damping (La1 , 5% damping, T_n = 1.4s) .

Figure 5. Response of unobstructed system to ground motion excitation.

However in a small number of obstructed sliding cases, for example La9, 5% damping, T_n = 1.4s, the contents displaced further with a higher friction coefficient. This is because the acceleration required from the ground motion to cause the cessation or reversal of sliding is greater and thus the contents travel further during that excursion.

4.4 General obstructed sliding behaviour

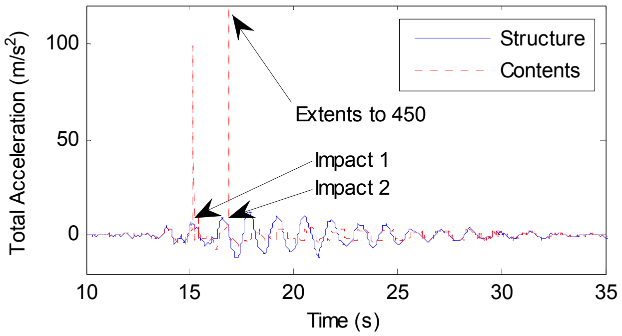
The behaviour of the system is identical to the unobstructed sliding case except that:

- If the structure (barrier) and contents' nodes are moving toward each other and the structures acceleration does not exceed μg i.e. sliding is not reversed, the structure will impact the contents. Collision of the content with the structure will cause an impulse load on the content and instantaneously reverse the content to slide in the opposite direction at an acceleration equal to or greater than μg, depending on the acceleration of the structure at the time of impact.

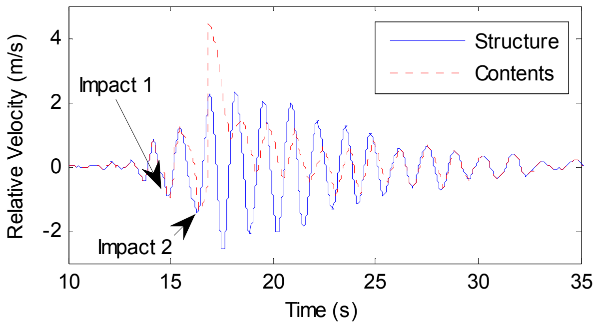
- If the contents are sliding in the same direction as the barrier, the contents may impact the structure if the contents are travelling at a greater velocity.

At impact, momentum is conserved and the contents displace away from the structure at a velocity up to 1,000 greater than the structure. Sliding in that direction ceases when the relative velocity of the contents to the floor becomes zero. The increased velocity due to impact results in significantly greater sliding displacements for obstructed movement than unobstructed movement.

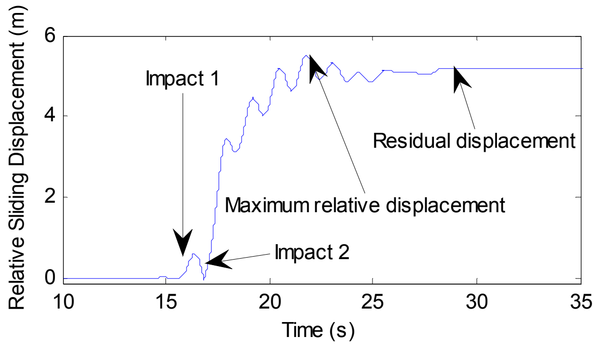
An example of obstructed sliding can be seen in Figure 6. Here, sharp acceleration peaks (similar to that of impulse loads) can be observed from Figure 6a whenever the content impacts against the structure. In addition, a sudden increase in sliding displacement can be observed after the second impact, and the maximum relative sliding displacement in this case was 5.50m as shown in Figure 6c.



(a) Acceleration vs. time.



(b) Velocity vs. time.



(c) Displacement vs. time.

Figure 6. Obstructed sliding response (La9, 5% damping, $T_n = 1.3$s).

For these analyses impact typically occurred between zero and two times. It is important to note that a greater number of impacts does not induce larger sliding displacements as the content must return back to zero relative displacement (barrier location) in order to impact again, as shown in Figure 6.

5 CHARACTERISATION OF UNOBSTRUCTED AND OBSTRUCTED SLIDING FOR SDOF STRUCTURES USING SAC SUITE

In order to assess the effects of the structure's natural period on contents' peak relative sliding displacement, the peak sliding displacements for each of the 20 SAC Suite ground motions were obtained for periods ranging between 0.1 and 5.0s. Figure 7 shows a plot of the lognormal median (LN) and 84th percentile (84th) values for each period. The positive and negative signify the different directions of sliding. It is important to note that, as only elastic structures were considered, the actual sliding displacements are likely to be much lower, due to the decreased floor acceleration that the structure would feel as it moves plastically.

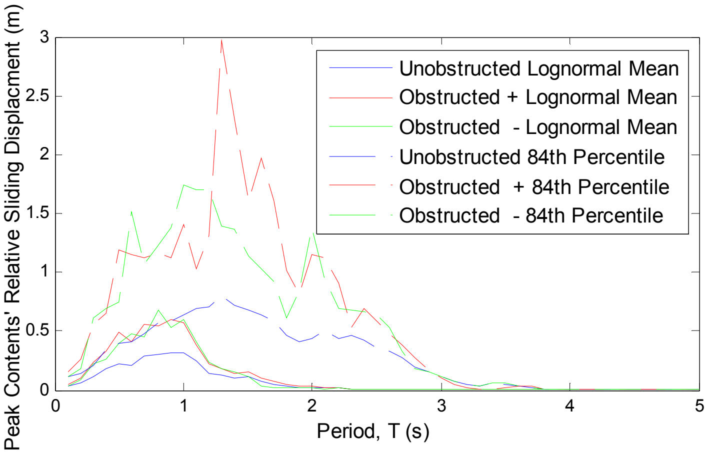


Figure 7. Spectra plot of lognormal median sliding displacements obtained for obstructed and unobstructed movement.

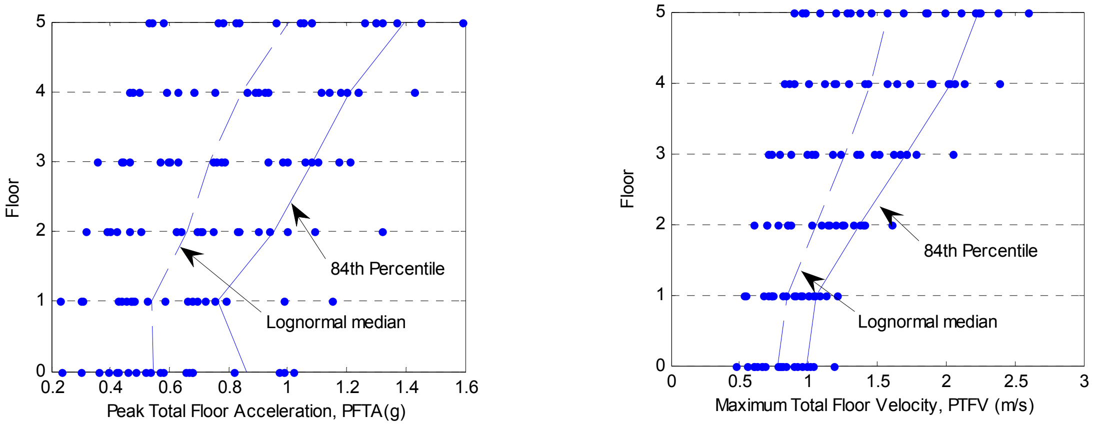
It can be seen in Figure 7 that there is a significant reduction in sliding displacements for structures with natural periods exceeding 1.3s, with all sliding ceasing at approximately 3.25s. This varies with different sets of ground motion records, for example, if the set of ground motion records were of a higher intensity, then the accelerations felt by a structure with a natural period of 1.3s would be significantly higher, thus resulting in greater sliding displacements. The cessation of sliding is because structures with larger natural periods experienced smaller floor accelerations that did not exceed μg, thus sliding did not initiate. These results are consistent with English (2012).

It can be seen that the obstructed contents' sliding displacements exceeded the unobstructed contents' sliding displacements by up to five times. This can be directly attributed to the impact between the contents and the structure. The unobstructed contents slid only with an acceleration of μg, whereas the obstructed contents slid with much larger accelerations induced through impact.

6 CHARACTERISATION OF UNOBSTRUCTED AND OBSTRUCTED SLIDING FOR MDOF STRUCTURES USING SAC SUITE

6.1 General structural behaviour

Figures 8a and 8b show the amplification of the floor acceleration and velocity with height. Although this structure is dominated by the lower modes of vibration, the higher modes significantly affect the floor accelerations and velocities.



(a) Peak total floor acceleration

(b) Peak total floor velocity

Figure 8. Response of each floor to ground motion excitation

6.2 Floor effects on peak contents' sliding displacements

For multi degree of freedom structures, increased sliding was exhibited in the higher floors of the structure, as shown in Figure 9. This behaviour was attributed to the correlation of the contents' relative sliding displacement on the peak total floor acceleration (PTFA) and peak total floor velocity (PTFV), both of which increased up the height of the building, as shown earlier in Figures 8a and 8b. Higher floor accelerations mean that sliding is more likely to occur earlier. English et al (2012) showed that the magnitude of sliding is also dependent of the relative velocity of the content to the floor, that is, if the floor velocity is higher, then the relative velocity between the floor and contents is also likely to be higher.

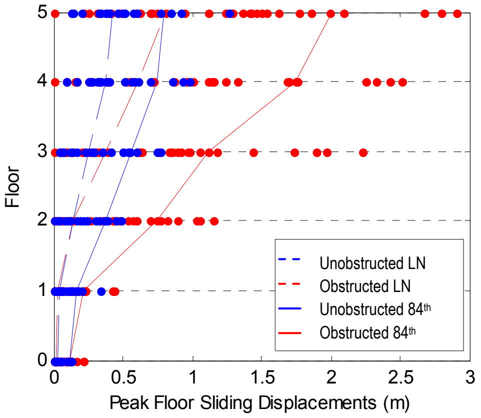


Figure 9. Peak contents' sliding displacement for each floor.

6.3 Correlation of sliding displacements to various demand parameters

It was found that the peak unobstructed sliding displacement correlated strongly both the PTFA and PTFV for unobstructed sliding, whereas for obstructed sliding it depends more heavily upon PTFV. This can be attributed to the structure-contents behaviour at impact; that the velocity of the structure significantly affects the velocity of the content, resulting in larger displacements for a similar sliding time. This can be seen in Table 2.

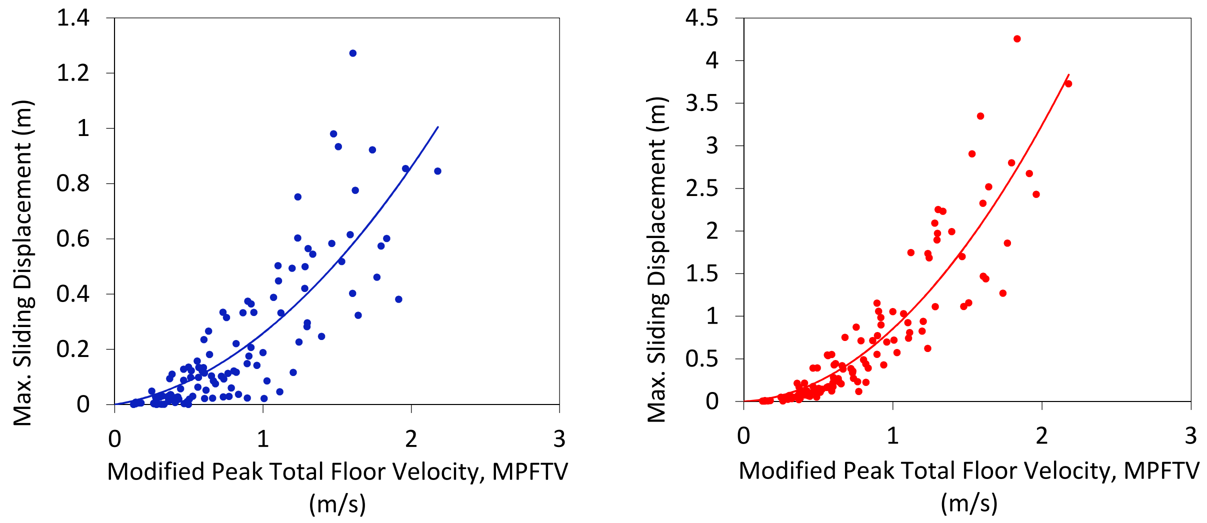
Table 2. Correlation of peak relative contents sliding displacement to PTFA, PTFV and MPTFV.

Correlation to	Unobstructed Sliding	Obstructed Sliding
PTFA	0.6675	0.6975
PTFV	0.6635	0.8201
MPTFV	0.6907	08279

While PTFA initiates contents sliding, PTFV has a significant effect on the magnitude of sliding. As such, Yeow (2013) proposed using a modified peak total floor velocity, *MPTFV*, as a rough approximation of the relative velocity of the content to the floor. This can be calculated using Equation 2. The correlation of *PTFA, PTFV* and *MPTFV* with sliding displacement is shown in Table 2 above. A second order polynomial for the trend line was the best fit.

$$MPTFV = PTFV \langle 1 - \frac{\mu}{PTFA} \rangle \qquad (2)$$

Figure 10 shows the correlation of the maximum sliding displacements to *MPTFV*. A 2nd order, polynomial trend line was added to relate the parameters. By visual inspection it can be seen that the correlation for obstructed sliding is greater than for unobstructed sliding. This is because the floor velocity affects the contents sliding displacement more for obstructed sliding as discussed earlier and shown in Table 2.



(a) Unobstructed sliding.

(b) Obstructed sliding.

Figure 10. Maximum sliding displacements vs. MPTFV for files LA1-20 and T_n=0.1-5.0s.

7 CONCLUSIONS

From the analyses of the single-storey and multi-storey structures with contents unobstructed or obstructed by a barrier, such as a wall, it was shown that, due to the behaviour at impact, contents with obstructed sliding moved up to five times further than contents free to move unobstructed on average. Impact occurred between zero and to times for all ground motion records.

For multi degree of freedom structures, the relative sliding of the contents in the higher floors of the structure was 200 times greater, on average, than the ground floor. A ‘Modified Peak Total Floor Velocity’ was proposed which had a stronger correlation to contents’ relative sliding displacement compared to Peak Total Floor Velocity or Peak Total Floor Acceleration.

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