Hysteretic Influence on Earthquake Induced Sliding Damage of Contents

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ABSTRACT: This paper investigates the influence of hysteretic characteristics of structures on contents damage. The damage to contents considered was limited to sliding induced damage, excluding rocking induced damage. A single storey structure and contents were modelled numerically using non-linear time-history analyses of a multi-spring idealised model. An understanding of the sliding behaviour of contents under impulse loading of a linear elastic structure was developed, against which the performance of non-linear structures was compared. Analyses of the structures were completed using impulse loading and selected earthquake records over a range of natural periods and strength reduction factors. It was found that increasing strength reduction factors directly reduced contents sliding. Increasing hysteretic damping was shown to reduce contents sliding. From impulse analyses a direct relationship between increasing natural period and a reduction in contents sliding was found. This effect was complicated by varying frequency content of earthquakes. It was found that the magnitude of stiffness changes in structures required to produce shock loads on contents was above that feasibly possibly in real structures.

1 INTRODUCTION

New Zealand is moving toward having seismically sustainable structures (MacRae G.A. *et al*, 2010). That is, the structural system (including the slabs), non-structural components and the building contents should all be protected against damage during very severe earthquake shaking (Chanchí J.C. *et al* 2012). Work is currently ongoing in New Zealand into the behaviour of the structural systems and non-structural components. Little emphasis is currently being given to understand the likely behaviour of contents in a large earthquake. The contents include the plant and equipment, computers, desks, tables and chairs, photocopiers, etc.

Recent discussions indicate that the response of contents may be affected by the hysteresis loop of structures in addition to natural period and other factors. Many of the seismically sustainable structures newly developed have unconventional hysteresis characteristics. For example, rocking frame structures and the use of steel shear walls show sharp changes in stiffness when high velocities may be expected. There is some concern that these stiffness changes may cause an impact type effect on contents and therefore affect the level of contents damage (Chanchí, J.C. *et al*, 2010).

This paper therefore aims to address these concerns and identify the most advantageous hysteretic behaviour with respect to contents damage.

In order to compare the level of damage to contents between structures, a quantitative damage parameter was required. The damage parameter used was that of sliding induced damage. While some research on rocking objects has been performed (Yu P. *et al*, 2011), sliding damage was considered to be a more general measure and less object dependent. However, this requires the development of a sliding damage model which, to the author's knowledge, has not been modelled previously. This choice of damage model does bias the results towards contents with low centres of gravity.

To make the results of this study more applicable to a wide range of structures the effect of hysteretic behaviour was examined over a range of structure periods and a range of strength reduction factors (used as a proxy for ductility).

This paper specifically aims to achieve the following:

a) Develop a robust numerical model that accurately describes the sliding behaviour of contents in structures. And using this model explain the fundamental mechanics of contents sliding.

b) Determine what parameters affect sliding induced contents damage and the influence of hysteretic behaviour (including the effects of sharp stiffness changes in hysteretic behaviour).

2 METHODOLGY

2.1 Model Design

The numerical model, shown in Figure 1, was developed to consider the contents damage in a single story structure. The model could be modified to accommodate multistorey structures but this was outside the scope of this project. To gain a quantitative measure of contents damage such that comparisons could be made, the level of contents damage was defined (in this paper) as the absolute maximum displacement between the floor of the structure and the contents mass, at any time during the analyses.

Figure 2 shows the idealisation of the conceptual model as a spring-mass model such that the structure could be modelled using RUAUMOKO (Carr, 2008) using non-linear time history analysis (NLTHA).

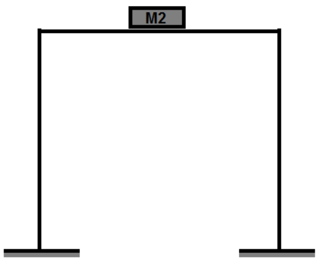

Figure 1. Conceptual Frame Model

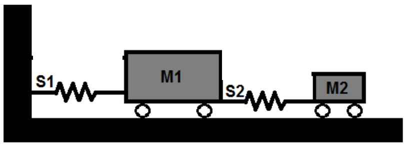

Figure 2. Idealised Spring Model

In Figures 1 and 2, M1 is the mass of the structure, M2 is the mass of the contents, S1 is the spring member describing the hysteretic behaviour of the structure and S2 is the spring member describing the frictional behaviour of the contents-floor interaction. The mass of the contents, M2, is assumed to be much less than that of the structure, M1.

The frictional behaviour of the contents-floor interaction was modelled using a bilinear hysteresis rule to approximate a rigid-plastic relationship. The yield of the bond was set to µmg, where µ is the coefficient of friction (COF). For this paper µ was taken as 0.25 but this can be simply modified.

Specific Limitations of the Model:

- The model assumed a single COF, it did not account for the difference between static COF and kinetic COF.
- The model does not consider damage caused due to a rocking failure mechanism of contents.
- Strength decay was not considered in the hysteretic behaviour of the structures, with the exception of the slacked tendon hysteresis where this was unavoidable.
- The effect of vertical accelerations on frictional bond strength was not considered due to limitations of RUAUMOKO. It was expected that the net effect on results would be small.
- Only hysteretic damping was considered due to complexities in modelling viscous damping.

For both impulse analyses and earthquake analyses MATLAB® was used to control analyses sequencing and automation of RUAUMOKO. (Masuno T. *et al*, 2010)

2.2 Hysteresis rules analysed

A range of hysteresis loops were used in order to gain an understanding of how various structural types affect contents damage. The hysteresis loops studied were:

- **Linear Elastic:** Conventional elastic structure.

- **Bilinear**: Conventional hysteresis loop used in many analyses, mostly for steel structures.
- **Bilinear with Slackness**: This hysteresis loop allows for effects of plastic elongation of tension braces to be considered. Also this hysteresis loop approximately describes the behaviour of a steel plate shear wall.
- **Bilinear Elastic:** Rocking frame without dissipaters.
- **Flag-shaped Bilinear**: This is loop is gaining popularity as it results in very low residual displacements. This loop is associated with rocking frame type structures with the inclusion of energy dissipating mechanism.
- **Takeda:** Conventional hysteresis loop used in many analyses, mostly for concrete structures.
- **Ramberg-Osgood**: A computationally expensive hysteresis loop that models strain hardening in steel, with a characteristic lack of distinct yield point.

2.3 **Impulse Analysis**

Performing impulse analyses (very short duration of constant high acceleration ground motion applied to structure) was essential to:

- Verify that the model was correctly modelling the contents sliding and to an acceptable accuracy.
- Gain an understanding of the fundamental mechanics of contents sliding.
- Compare the behaviour of different hysteresis loops under simple loading.

Verification and Limitations of Numerical Model: It was essential that the testing and verification be performed on impulse analyses as the chaotic nature of earthquake records effectively turned the model into a "black box" scenario, making any errors difficult to identify.

The essential checks used to verify the accuracy of the model were conservation of energy and Newton's second law of motion. Conservation of energy was checked by equating the work performed on the contents over the sliding duration with the increase in kinetic energy of the contents (using total displacements and velocities).

It was proved, using a simple mathematical proof shown below, that the contents behaviour was independent of the mass of the contents, when small masses (relative to the structure) were considered (less than 1% is acceptable, verified using impulse analyses). This is because both the force demands, and the resistance, are linear functions of mass. Therefore, the effect of mass cancels out and the response is dependent on the coefficient of friction only.

$$\begin{aligned} &F_{driving} > F_{Resisting} \\ &m_c a_{structure} > \mu m_c g \qquad (1) \\ &\therefore\ a_{structure} > \mu g \end{aligned}$$

For large contents masses, significant energy is removed from the system due to hysteretic damping (in spring 2), and the independence of mass no longer exists. A ratio between the structure mass and the contents mass of 1000:1 was used for all analyses.

Understanding Sliding Mechanics: One of the fundamental reasons for performing impulse analyses was to gain an understanding of how sliding of contents in a structure physically occurs and what parameters govern the extent of sliding. This was achieved by simply stepping through the time-history response of the system and relating each behavioural transition back to the expected physical behaviour. An impulse analysis was more suitable for this purpose than an earthquake record as it eliminated the complexity of a chaotic loading pattern. For the development and conceptual understanding of contents sliding mechanics, a simple linear elastic structure was used. Linear elastic sliding behaviour was then used as a base case against which the sliding behaviour of structures with different hysteretic characteristics were compared.

Comparison of structural responses under pulse loading: Having established the sliding behaviour of the contents for a linear elastic structure, the structure was then modified to examine the effect of different hysteresis loops on contents damage. To maintain comparability between the responses, the same "backbone" (equal elastic stiffness, yield strength and post elastic stiffness) was used for all the hysteresis loops where possible. To ensure that the parameters chosen to describe the hysteresis loops did not bias the results, parametric studies were conducted to select representative values and ensure that the results were not sensitive to the values chosen. From this it was shown that the model was not sensitive to the bilinear factor *r* and hence a nominal value of 5% was used. A similar process was used to select a Ramberg-Osgood *r* factor of 20 and a Flag-shaped Bilinear Beta factor of 0.5. For the Takeda loop the values used were $\alpha = 0.3$ $\beta = 0.2$, representative of a typical well designed column.

Consideration of sharp stiffness changes under pulse loading: In order to determine if sharp changes in stiffness in a structures response were significant to the level of contents damage, impulse analyses were performed. The time-history response of the contents was then examined, focusing on changes in behaviour at the time of the stiffness change, such as initiation of sliding.

2.4 Earthquake Analysis

Analyses were conducted using a range of earthquake records, the records used were the 20 records from the S.A.C record suite. These analyses were used to examine whether the behaviour observed in the impulse analyses was representative of real earthquake loading and therefore whether the results obtained from the pulse analyses are relevant. To gain a broad understanding of sliding induced damage, seven structures with the seven hysteresis loops were analysed over a range of natural periods and a range of strength reduction factors.

3 RESULTS AND DISCUSSION

3.1 Impulse Analysis Results

Explanation of Simple Sliding Mechanics: The sliding mechanics of the structure and the contents is explained using Figures 3 and 4. Figure 3 shows the total acceleration of the structures floor and the contents with time, while Figure 4 shows the velocity relative to the ground of the floor (M1) and the contents (M2) with time.

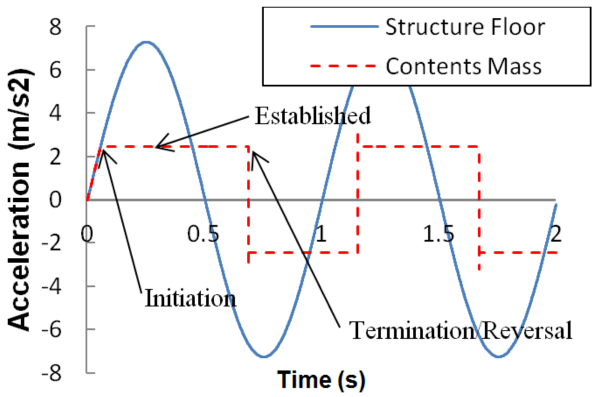

Figure 3. Acceleration time history for M1 & M2 under impulse loading of a linear elastic structure.

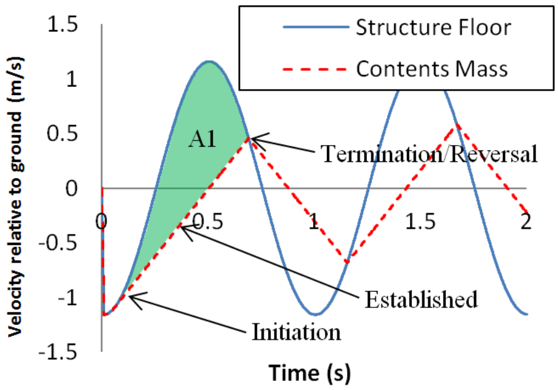

Figure 4. Velocity time history for M1 & M2 under impulse loading of a linear elastic structure

From the diagram it is clear that sliding occurs in three specific stages: initiation, established sliding and termination/reversal.

Sliding Initiation: Shown in Figure 3, initiation occurs when the acceleration of the floor increases such that the maximum frictional bond strength is exceeded ($F_{max} = \mu mg$). The floor subsequently accelerates away from the contents.

Established Sliding: Following separation from the floor, the contents accelerates in the direction of floor movement relative to the contents at a constant acceleration of μg. This acceleration is provided by the frictional drag force of the floor on the contents.

Termination or Reversal of Sliding: Termination or reversal occurs when the velocity of the contents relative to the floor becomes zero, not when the absolute floor acceleration drops below μg as may be intuitive. This is most easily understood by observing that in Figure 4 the gradient of the contents velocity would have to be higher than μg to terminate sliding at any point prior to where the velocities are equal. The acceleration of the floor at the point of intersection of the velocity profiles then determines whether the sliding is terminated or reversed. If the acceleration of the floor is greater than μg in the opposite sense, then the contents immediately returns to established sliding in the opposite sense (relative to the floor not the ground). This is shown in Figures 3 and 4, and will be referred to as "fully developed sliding". If instead the acceleration of the floor is in the opposite sense, but less than μg, the contents will re-establish a frictional bond with the floor until sliding is reinitiated. This will be referred to as "semi-developed sliding" and from analyses is not typical in earthquake responses.

The total displacement of the contents relative to the floor is given by the area marked A1 in Figure 4 and mathematically by Equation 2. This means that the contents sliding is intrinsically linked to the velocity profile of the floor (as the velocity profile of the contents is essentially fixed). From this understanding of sliding mechanics, it is clear that any hysteretic change which reduces A1 will reduce contents damage. This means that either increasing the period of the structure (hence decreasing the gradient of the structure velocity profile) or reducing the peak velocity of the structure will decrease the sliding of the contents.

$$A1 = \int_{initiation}^{termination} (V_{contents} - V_{floor})dt \quad (2)$$

Comparison of Hysteresis Loop Performance under Pulse Loading: Comparison of contents damage between different structures is most clearly explained using the area A1 from Figure 4, but now considering yielding structures. Figure 5 shown below, shows the relative velocity of the structure and the contents for a linear elastic structure, a rocking structure with dissipaters (flag shaped loop) and a bilinear structure.

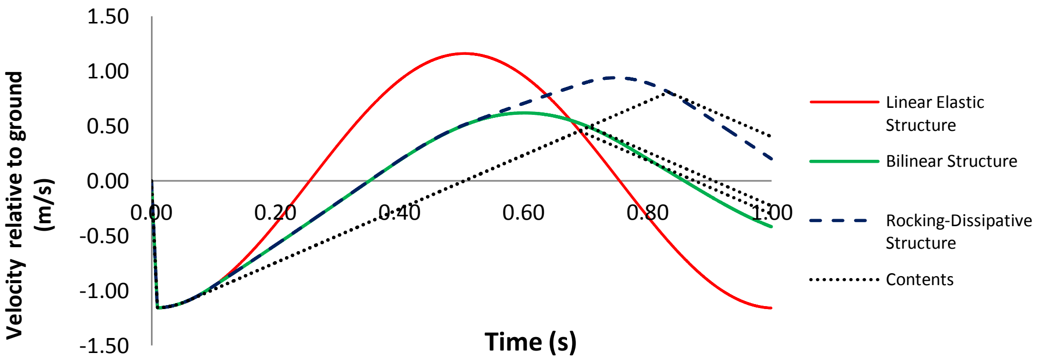

Figure 5. Comparison of Velocity Profiles between Linear elastic structure and yielding structures. R=2, T=1s.

From Figure 5 it is clear how the yielding affects the level of contents damage. The maximum acceleration of the bilinear and flag-shaped loop structure is limited to half that of the linear elastic structure (as R=2) and hence the area between the velocity profiles is more slender, resulting in less damage than the elastic case. The crest height of the velocity profile is governed by elastic energy recovery, or inversely related to hysteretic damping. Therefore the crest heights decrease in order of increasing hysteretic damping. This clearly identifies why the flag shape loop experiences more contents sliding the bilinear loop, the flag shape loop recovers the same elastic energy as the bilinear loop, but additionally 50% of the energy that was plastically lost by the bilinear loop (as β=0.5). Hence, hysteretic damping is inversely related to contents damage. This understanding can be easily extended to explain the behaviour of the remaining yielding hysteresis loops.

The relationship between period of the structure and contents damage is shown below in Figure 6 for multiple structure types. Figure 6 clearly shows that in general there is a definite relationship between increasing natural period and decreasing contents damage for all hysteresis loop types. However, the yielding structures showed a less linear relationship than the linear elastic structure.

As previously explained, increasing the strength reduction factor should decrease the level of contents damage. This relationship for multiple structures is shown below in Figure 7. A very clear relationship is observed for all structures, being approximately linear.

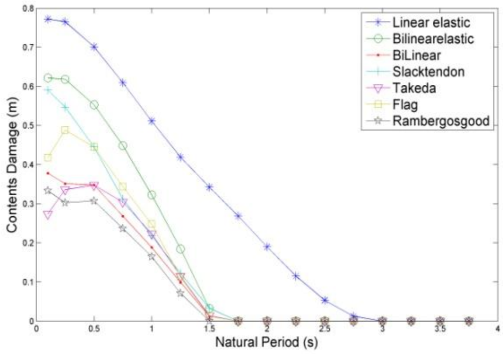

Figure 6. Contents damage in relation to natural period of the structure. R = 2.

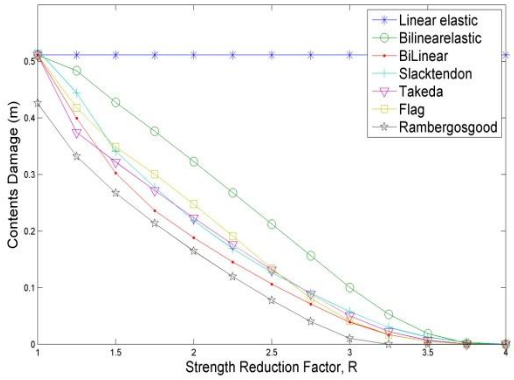

Figure 7. Contents Damage in relation to strength reduction factor R under pulse loading. T = 1s.

Comparing the contents sliding of the seven structures over a range of periods and strength reduction factors as shown in Figures 6 and 7 showed the following:

- The linear elastic structure followed by the bilinear elastic structure consistently produced the highest levels of contents sliding over all impulse analyses.
- The Ramberg-Osgood structure followed by the bilinear structure consistently produced the lowest levels of contents sliding over all pulse analyses.

Effect of sharp stiffness changes on contents damage: Extensive investigation into the effects of sharp stiffness changes was carried out but results showed the effects to be minimal, and required unrealistic COF's, this section has therefore been omitted in the interest of brevity.

3.2 **Earthquake Analysis Results**

Relationship between period and contents damage: As earthquake records contain a range of frequency content, structures of different natural periods do not receive the same excitation. Therefore the linear relationship between increasing natural period and decreasing contents damage was not expected for earthquake loading. However, for a particular period, the level of contents sliding for each hysteresis would be expected to be in similar proportions (relative to the elastic response) to that of the impulse loading response.

Figure 8 below shows the contents damage spectra for the seven hysteretic structures responding to the SAC La2 record (used as an example record). This shows that over a considerable range of periods the pulse analyses correctly predicted the hierarchy of performance of the structures. However, over a range of periods around 1s the predictions from the pulse analyses were incorrect and some structures showed significantly greater damage than expected.

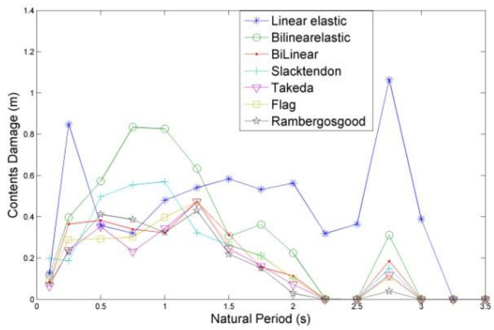

Figure 8. Damage Spectra for the record La2.

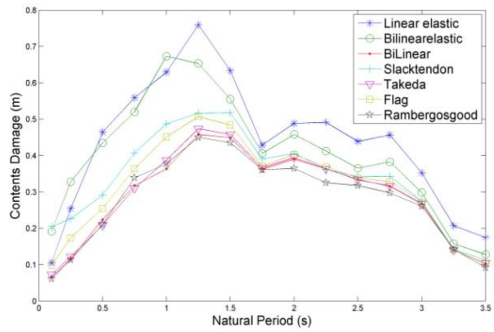

Figure 9. S.A.C Records Average Damage Spectra

It was suspected that the apparent lack of correlation between the impulse analysis predictions and the earthquake results may have been due to the chaotic nature of loading. Therefore the analysis was repeated for the entire SAC record suite and the results averaged in an attempt to produce results containing less scatter. These averaged results are shown above in Figure 9.

Figure 9 above shows that as more earthquake records are considered the average response is much closer to that predicted by the impulse analyses (Figure 6). In fact, the impulse correctly identified the hierarchy of performance of each hysteresis model, with the exception of the slacked tendon structure, which performed worse than expected based on the pulse analyses. This is not surprising as during the earthquake the gap is increased throughout the record due to yielding. Impulse analysis would not have captured this. This suggests that a statistical analysis over many records may provide a probable level of sliding for each hysteresis loop based on natural period, but not an expected level of sliding.

Relationship between strength reduction factor and contents damage: The analysis from the impulse analysis section above comparing the relationship between strength reduction factor and contents damage was repeated but using the earthquake record La2 to determine if the relationship identified in the impulse analyses was observed under earthquake loading. Clearly, for this analysis the level of sliding will be different to the impulse analysis, but it was expected that the same order of hysteresis performance would be observed. Also, it was expected that for each strength reduction factor the proportion of sliding compared to the linear elastic case would be similar for each hysteresis loop. The results of the La2 earthquake are shown below in Figure 10.

Figure 10 shows that in general the relationship between increasing strength reduction factor and reducing contents sliding seen in the impulse analyses was valid, with the exception of the bilinear elastic structure and slacked tendon structure. The order of performance of each structure was in general correctly predicted by the impulse analyses, again with the exception of the slacked tendon due to cumulative slackening. Additionally, the response shows damage greater than the linear elastic response occurred. The proportions of damage when compared to the linear elastic response were clearly not comparable.

Again it was suspected that the lack of correlation between the earthquake response and the impulse response was due to the chaotic nature of the loading. Therefore, as for the period analysis, the analyses were repeated for the entire SAC record suite and the results averaged in an attempt to produce results containing less scatter. These results are shown below in Figure 11.

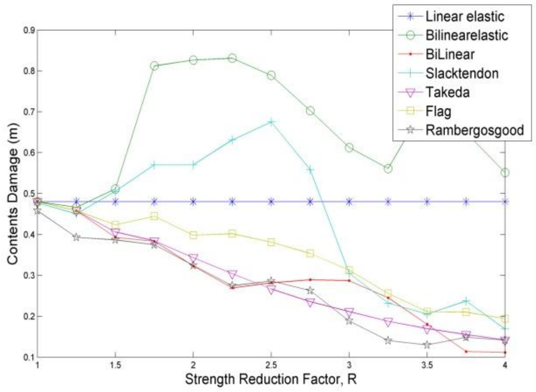

Figure 10. Contents Damage for increasing strength reduction factors for the record La2. T=1s.

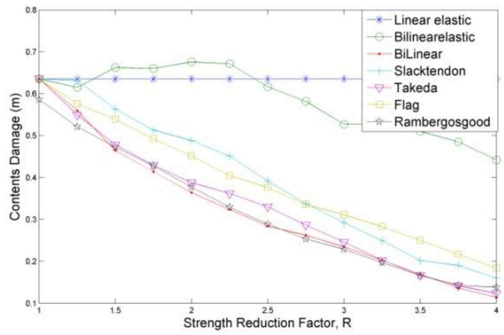

Figure 11. Average contents damage with strength reduction factor over the 20 S.A.C records.

Figure 11 above shows that the average response over 20 records much more closely agrees with the predicted results from the impulse analyses. The averaged results showed clear agreement with the impulse analyses with respect to the order of performance of each hysteresis loop, with the exception of the slacked tendon structure, which showed greater contents damage due to compounding yielding. When compared to the impulse analyses, the same trend of decaying damage with increasing strength reduction factor was observed. It is expected that a statistical analysis over many records could give a probable level of contents damage with increasing strength reduction factor for each structure.

4 CONCLUSIONS

The following conclusions relate to the objectives stated earlier.

a) A numerical model for sliding of contents inside a structure was successfully developed. The model created was simple and reliable and while used exclusively for a single storey structures it can easily be adapted for multistorey structures in future research. The model was successfully used to develop a clear understanding of sliding mechanics of contents in structures.

b) Three key parameters were identified as directly affecting the relationship between hysteretic behaviour and the level of contents damage observed, these parameters are:

   1. The natural period of the structure, when considered in conjunction with spectral acceleration.
   2. Strength reduction factor.
   3. Hysteretic Damping

   For increased structure periods, the differential acceleration between the structures floor and the contents is reduced and hence also the level of contents damage.

   Clearly, as a force of µmg is required to initiate sliding, sliding induced contents damage can only occur over a range of natural periods where the spectral acceleration is greater than µg.

   The effect of increased strength reduction factor is to limit the acceleration of the structure's floor to 1/R times that of the linear elastic structure. This will decrease the relative acceleration between the floor and the contents and hence reduces contents damage.

   Hysteretic damping of the structure reduces the peak velocity of the structures floor and hence decreases the time over which the differential velocity occurs. This therefore decreases the relative displacement between the floor and the contents, thus reducing contents damage.

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