Improvement of traditional masonry wall construction for use in low-rise / low-wall-density buildings in seismically prone regions

NZSEE 2001 Conference

Luis A. Toranzo[1] , Athol J. Carr[2] and Jose I. Restrepo[3]
[1] *PhD Candidate, Dept. of Civil Engineering, University of Canterbury, Christchurch*
[2] *Reader, Dept. of Civil Engineering, University of Canterbury, Christchurch*
[3] *Senior Lecturer, Dept. of Civil Engineering, University of Canterbury, Christchurch*

ABSTRACT: The current trend of designing structures to meet performance-based demands could severely limit the use of some traditional construction materials and systems. Masonry construction, used in conjunction with reinforced concrete frames, as used extensively in Latin America, is among those affected. This limitation is due to the poor performance of conventional masonry systems in past earthquakes. This paper discusses the option of using reinforced concrete frames infilled with masonry, acting together as a series of rocking walls providing a desired performance level. Such system may be used in buildings with a low density of elements where the demand expected in conventionally built masonry walls might result in structural damage in moderate earthquakes. Rocking walls can be designed to rock while ensuring no damage will occur anywhere else in the structure. During the rocking process the system has a much lower equivalent stiffness than before rocking is triggered. Most often this means that the inertial forces are reduced as the response is shifted into a less demanding region of the acceleration spectra. The softening of the system also lets other flexible elements participate in the response. Triggering of the rocking may be set for levels of excitation greater than frequent earthquakes for which the element can be designed to behave as a fixed-base wall. Rocking also allows the use of hysteretic energy dissipators at the base of the wall. It was found that these energy dissipators could add up to 20% of equivalent viscous damping to the system.

1 INTRODUCTION

Due to the relative poor seismic performance of some traditional systems, the necessity of a performance-based seismic-design approach for new structures was identified some years ago (SEAOC, 1995). Many times though, the poor behavior of a structure has been misinterpreted. That is the case of many masonry structures in which the faulty behavior has been blamed on the material alone. As a consequence of this, masonry is widely though to be unsuitable to comply with performance-based requirements in seismically prone regions.

This paper shows that it is possible to reach an acceptable performance in a structure choosing an appropriate structural system. The paper addresses an alternative system suitable for a very common type of building in Peru, mainly intended for classrooms in schools, which has caused many upsets in past years due to its poor seismic performance. The alternative system is expected to yield a sounder behavior of the whole structure. The main feature of the system is the provision of rocking masonry walls. These basic structural subsystems are evaluated here and a design procedure based on the Direct Displacement Method (Priestley & Kowalsky, 2000) is proposed at the end of the paper. Although the procedure presented here can not be applied to an entire building, it shows that a rocking wall can be adapted to be a reliable system itself. A procedure, similar to the one presented here, is being developed by the authors to address the design of a complete building with rocking walls.

2 MOTIVATION OF THE STUDY

In 1996, a 6.4 Richter-magnitude earthquake struck the coastal region of Peru. Quiun et al (1997) report that, among others, 91 school buildings were damaged or destroyed. Many of them were new buildings that had been built in the zone in the previous five years. The typical architecture of the buildings is shown in figure 1, with dimensions varying in different cases. It can be observed that the necessity of large open space for classrooms limits the amount of lateral-force-resisting elements. Typically, in the new buildings, confined masonry is used in the shorter direction, whereas RC frames, with masonry panels isolated from the RC frame by gaps in the sides and top of the panel, are used in the longer direction. In Latin-America, confined masonry refers to unreinforced masonry walls surrounded by reinforced concrete beams and columns that are cast after the walls are erected.

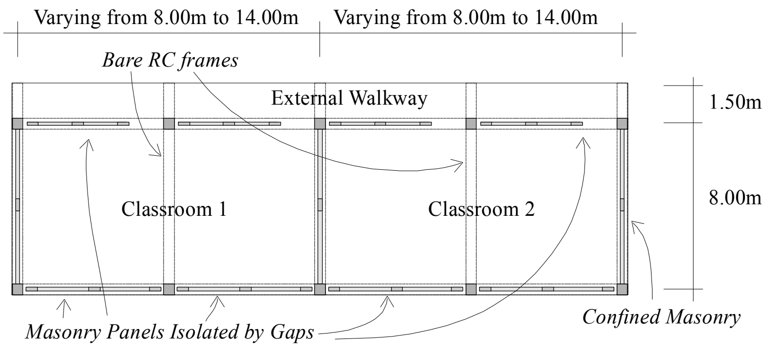

Figure 1. Typical Plan of a School Building in Peru

The poor seismic performance of the buildings had different sources. In the direction were confined masonry was used, RC components were not damaged but some masonry infills were damaged. Given the greater stiffness of the masonry walls, they attracted most of the lateral inertia forces; the contribution of bare-RC-frames in the same direction, to the lateral resisting capacity of the system, was minimum.

In the other direction, where the masonry panels were isolated from the RC frames using gaps, the gaps failed to prevent any interaction between both systems. The worst case was observed when the masonry panels had a height shorter than the total storey height. Short column failures were commonly observed there.

Although part of the poor performance could be blamed on the bad quality of the construction, it was clear that the structure needed to be reviewed if such experience wanted to be avoided in the future. The problems derived due to the lack of adequate detailing (like smaller gaps and insufficient stirrups) were addressed demanding stricter construction supervision. Strengthening the faulty components of the system was proposed to solve problems related to the very system. In many cases it leads to replacing the masonry walls for RC walls. In the Peruvian context, it means a significant increment of the costs.

The challenge is, therefore, finding a structural system in which the traditional materials could be used but being able to meet the demands of a performance-based seismic-design.

3 ROCKING MASONRY WALLS AS A RELIABLE ALTERNATIVE SYSTEM

Almost 50 years ago it was observed that rocking structural systems were able to avoid damage during earthquakes provided the structures could maintain their stability (Housner, 1956). Their formal use as such was very limited though. In the nineties, a renewed interest was placed on them, as researchers were looking for new alternative systems able to survive earthquakes without significant damage. Masonry structures were also addressed in the process (Madan et al., 1996).

Rocking walls, made either from masonry or RC, appear to be a good alternative for medium height buildings, with low density of walls, such as the ones described above. Rocking of the walls allows larger lateral displacements of the building without significant damage in the walls and provides an efficient re-centering mechanism to the building. The larger flexibility, in most cases, would move the response of the building into a less demanding region of the acceleration spectra. The "softening" of the walls through rocking will also let the demand be evenly distributed among all the lateral resisting elements, including the bare frames. The nature of the rocking motion also forces a more even distribution of the deformation along the height of the building with an almost linear shape, preventing concentration of the deformation in only some floors. A comprehensive discussion of requirements of a building featuring rocking walls can be found elsewhere (Toranzo, 2001).

Next, the mechanics of a single rocking wall are studied and, later, a procedure for the design of single rocking walls to meet admissible deformations is presented.

4 MECHANICHS OF A ROCKING WALL

Although a number of papers have addressed the kinematics of the rocking of a rigid block (Housner, 1963; Makris and Roussos, 1998; Yeong-Bin et al., 2000), little has been done to provide the elements required for a comprehensive seismic design of such systems. The paper, therefore, will address that task.

A rocking wall is a non-linear oscillating system, however, for small lateral displacements, it can be reasonably linearly modeled between successive impacts with equation 1 (Housner, 1963):

$$\theta = \alpha - (\alpha - \theta_o) \cosh\left(\sqrt{\frac{WR}{I_o}}\ t \right) \tag{1}$$

Where I_o is the rotational inertia about O (see figure 2), θ_o is the initial rotation angle, W is the weight of the wall and α and R define the shape and size of the wall as shown in Figure 2.

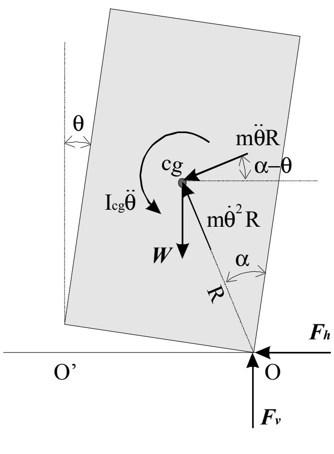

Figure 2. Rocking Rigid Block

It also can be demonstrated that the amount of energy dissipated at impact, assuming no bouncing of the impacting end is defined as follows (Housner, 1963):

$$r = \left(\frac{\dot{\theta}_2}{\dot{\theta}_1} \right)^2 = \left[1 - \frac{W}{g} \frac{R^2}{I_o} (1 - \cos 2\alpha) \right]^2 \tag{2}$$

The dissipation of energy at impact leads to a smaller amplitude of the oscillation after each impact. Priestley et al. (1978) found that the decaying amplitude of the rocking motion could be reasonably represented by equivalent viscous damping. The equivalent viscous damping for a rocking wall with perfect-plastic impacts can be defined for a given kinetic-energy reduction factor, r, with the following equation:

$$\lambda = \frac{1}{n\pi} \ln\left[\frac{\theta_o/\alpha}{1-\sqrt{1-r^n\left[1-(1-\theta_o/\alpha)^2\right]}}\right] \quad (3)$$

Within practical limits, this equation is rather insensitive to changes in the number of impacts, n. and the ratio θ_o/α. Taking $4 > n > 20$ and $0.05 < \theta_o/\alpha < 0.5$ will yield similar results for λ.

4.1 *Forces in the Rocking System*

The forces expected during rocking and at impact have to be defined, being the latter the most demanding for the rocking wall.

4.1.1 *Forces in the System between Impacts*

A general expression for the forces between impacts can be drawn from figure 2.

$$F_h = -m\ddot{\theta}R\cos(\alpha-\theta) - m\dot{\theta}^2 R\sin(\alpha-\theta) \quad (4)$$

$$F_v = W + m\ddot{\theta}R\sin(\alpha-\theta) - m\dot{\theta}^2 R\cos(\alpha-\theta) \quad (5)$$

If one ignores the dynamic forces and assumes that the angle θ is small compared to α, the following approximate static solution may represent the forces F_h and F_v between impacts:

$$F_h = W\tan\alpha \quad (6)$$

$$F_v = W \quad (7)$$

Evaluation of equations 4 and 5 shows that, within practical limits, the static solutions are an upper limit of the dynamic solutions and yield similar results. It is proposed, therefore, to use the simpler approximate static solution for design purposes. A more accurate approximation of the average force "felt" by the walls during the rocking process can be obtained using the effective height, h_{eff}, derived from the linear deformation pattern of the wall. This value however, is unconservative in some cases.

4.1.2 *Forces in the System at Impact*

The forces developed at impact are expected to be the largest forces during the process, and therefore, control the design of the wall strength. Hence, for design purposes, it is important to define a close equation for the expected impact force at the base of the wall. In the calculation that follows, it was necessary to relate F_h to F_v. For the type of structures that one is interested in, neglecting the rotational inertia and assuming that $\theta >> \alpha$, yields a simple and still reliable relationship:

$$F_h = F_v\tan\alpha \quad (8)$$

The impact force will be defined using an impact amplification factor f_{imp}, applied to the static approximate solution defined in equations 6 and 7. The impact problem in deformable bodies is rather complex as it involves the analysis of travelling shock waves through the deformable body. For the purposes of this analysis though, simplified energy considerations will be used. All the flexibility of the system will be constrained to the contact elements, which combines the stiffness of the foundation and the stiffness of the wall. The horizontal and vertical springs have stiffness k_x and k_y respectively. The initial conditions of the system are defined by the uplifting of one end of the wall up to a height h_i. Then, the wall is released.

Three stages were defined, from which the energy is compared. The initial conditions of the system, where the wall presents it maximum uplift, define stage 1. Stage 2 is defined immediately before impact, where one finds the maximum velocity. And stage 3 is defined at the maximum deformation of the contact elements.

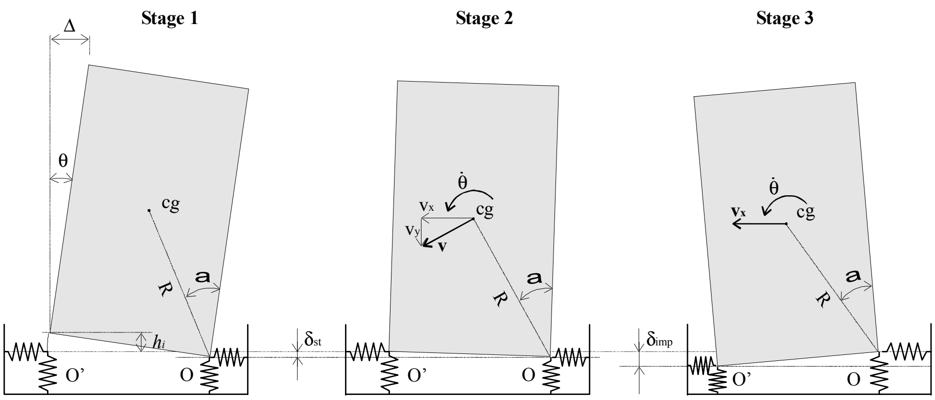

Figure 3. Simplified Impact Process of a Rocking Wall

Toranzo (2001) presented the results of this analysis for the general case. In most practical cases, however, the general equation presented in that reference can be simplified to:

$$f_{imp} = \frac{\left[1+\sqrt{1+4\left(\frac{mv^2 \sin^2 \alpha}{W^2/k_y}\right)}\right]}{2} \tag{9}$$

Where v is the velocity immediately before impact and is defined as:

$$v^2 = gh_i \frac{1}{\left(1+\frac{I_{cg}}{mR^2}\right)} \tag{10}$$

It is important to note that, in the previous and following analysis, the excitation at the base was not accounted for. This means that, in the event of an earthquake, the work done by the base shear at the foundation is not taken into account. This affects the balance of energy as developed above. Numerical analysis shows that, although this fact results in scatter of the results, the equations developed above produce results good enough for design purposes. The numerical analysis also allowed for inelastic behavior of the components of the structure, and still the predictions were very close to the observed behavior.

5 ADAPTING ROCKING WALLS TO MEET A TARGET PERFORMANCE

There are many papers reporting large variability in the response of rocking blocks to seismic-type oscillations at the base (Chik-Sing et al, 1980, Makris and Roussos, 1998). This is mainly due to the lack of a controlled way to dissipate the energy inputted into the system. Research conducted on RC rocking walls has shown that the presence of hysteretic-energy-dissipators might improve the response of a rocking system. The dissipators can be pieces of mild steel that yield as the wall uplifts while rocking (Restrepo et al., 2001). Later, it will be demonstrated that the incorporation of hysteretic-energy-dissipators is enough to obtain a reliable structural system out of the rocking wall.

5.1 *Forces Present in a Rocking System with Hysteretic Energy Dissipators at the Base*

Similar considerations to the ones drawn from the wall without dissipators are applied here. The dissipators affect the response insofar as lessening the effective weight of the wall and performing negative work due to yielding. Here on, the dissipators are represented by two pieces of mild steel, placed symmetrically as shown in figure 4.

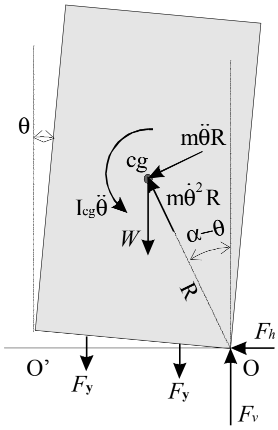

Figure 4. Rocking Wall with Hysteretic-Energy-Dissipators

5.1.1 *Forces in the System before Impact*

Again, the static solution provides an upper limit in the definition of the forces F_h and F_v. For this case, neglecting the rotation angle θ, they will be defined as:

$$F_h = (W - 2F_y)\tan\alpha \tag{11}$$

$$F_v = W - 2F_y \tag{12}$$

Where F_y is the yielding force of the dissipators.

5.1.2 *Forces in the System at Impact*

The wall with energy dissipators can be analyzed similarly as the one without dissipators. Apart from the energy at the three defined stages, however, one must account for the work done by the hysteretic-energy-dissipators as they yield all the way until the impact process finishes. It was assumed that, in all three stages, the dissipators are "yielding". Thus, the elastic energy that they store will be the same in any stage and, therefore, will be cancelled out when comparing any of them.

Comparing stages 1 and 2, and accounting for the work done by the dissipators from stage 1 to stage 2, one can define the velocity immediately before impact. In equation 13, k_{hd} is the longitudinal stiffness of one dissipator (Toranzo, 2001):

$$v^2 = \frac{W}{m} h_i \frac{\left(1 - \frac{2F_y}{W} + \frac{8F_y^2/k_{hd}}{Wh_i}\right)}{\left(1 + \frac{I_{cg}}{mR^2}\right)} \tag{13}$$

Comparing stages 2 and 3, and accounting for the negative work done by dissipators, leads to a quadratic equation whose solution for the base spring deformation δ_{imp} is (Toranzo, 2001):

$$\delta_{imp} = \frac{(W - 2F_y) + \sqrt{(W - 2F_y)^2 + 4k_y\left(\frac{k_y}{k_x}\tan^2\alpha + 1\right)mv^2\sin^2\alpha}}{2k_y\left(\frac{k_y}{k_x}\tan^2\alpha + 1\right)} \tag{14}$$

This is not the maximum deformation that the springs at the base sustain though. It was observed in the preliminary numerical analysis that towards the end of this process, the force in the dissipators change direction due to the uplifting of the other end of the rocking system. Equilibrium conditions, therefore, demand an increase in the reaction at the base of the wall of a magnitude equal to $4F_y$. The maximum deformation, therefore, is defined by:

$$\delta_{imp}^{*} = \delta_{imp} + 4\frac{F_y}{k_y} \quad (15)$$

The extra energy stored in the system is reflected in a decrease of the horizontal velocity after the process, which was not observed in the walls without energy dissipators. The impact amplification factor is then defined by:

$$f_{imp} = \frac{\delta_{imp} k_y}{W + 2F_y} \quad (16)$$

5.2 *Total Accelerations in the System*

Total accelerations are an important parameter within a performance-base scheme. As the rocking system uncouples, at some extent, the oscillation of the wall from the shaking at the base, one can attempt to predict the total accelerations that might appear in the system during an earthquake from the no-base-shaking model. The acceleration can be drawn from equation 3 or derived from the expected inertial forces in the system. The second option is more appealing as simple close force-equations have been derived to define the expected forces in the center of gravity of the system (they are the same as the reactions at the base). Following this approach, the expected total horizontal acceleration, a_{hi}, at any height of the wall, h_i, can be derived from equation 17. Noise must be expected though from the higher modes, as they are not uncoupled.

$$a_{hi} = \frac{h_i}{h_{cg}} \frac{F_h}{m} \quad (17)$$

The impact amplification factor, f_{imp}, has to be used to define the peak accelerations when impact occurs. The same approach might be used to define vertical accelerations, although in this case there is not uncoupling at all from the base vertical shaking.

6 ADAPTATION OF THE DIRECT DISPLACEMENT METHOD FOR THE DESIGN OF ROCKING WALLS

The Direct Displacement Method (Priestley & Kowalsky, 2000) can be used to make the rocking walls meet performance-based demands. The procedure, adapted for rocking walls, is described next. There, an equivalent system with effective height, h_{eff}, and effective mass, m_{eff}, is used to represent the rocking system. It will allow analyze and design a wall with a number of masses attached to it. In the definition of h_{eff} and m_{eff}, a linear lateral displacement pattern can be assumed reliably.

6.1 *Definition of the Maximum Displacement*

The maximum displacement is defined by the permissible drift at every earthquake level. As the wall is expected to behave like a rigid body, the maximum displacement is taken as:

$$\Delta = h_{eff}\, drift_{permissible} \quad (18)$$

6.2 *Definition of the Effective Period (T_{eff})*

The effective period is taken from displacement spectra. The displacement spectra for damping levels different than 5% can be derived using the equation proposed in the EC8 and suggested by Priestley & Kowalsky (2000) for this purpose.

$$\Delta_{(T,\xi)} = \Delta_{(T,5)} \left(\frac{7}{2 + 100\lambda} \right)^{1/2} \tag{19}$$

If the length of the base of the rocking wall is already defined, one has to assume a level of damping that is to be verified later in the process. If that length has not been defined yet, one can select any level of damping, and by the end of the design process, the required base length will be determined.

6.3 *Definition of the Effective Stiffness (K_{eff})*

This is derived treating the system as a 1 degree of freedom one. The effective stiffness is therefore calculated with the equation:

$$K_{eff} = \frac{4\pi^2}{T_{eff}^2} m_{eff} \tag{20}$$

6.4 *Definition of the Effective Base Shear (V_{eff})*

As the system is treated as elastic, with viscous damping, the base shear is calculated with:

$$V_{eff} = K_{eff} \Delta \tag{21}$$

6.5 *Definition of the Required Capacity of the Energy Dissipators (F_y)*

It can be calculated reorganizing equation 15:

$$F_y = \frac{1}{2} \left(\frac{V_{eff}}{\tan \alpha} - W \right) \tag{22}$$

6.6 *Checking of the Actual Equivalent Viscous Damping of the System (λ)*

Preliminary numerical analysis of rocking walls with energy dissipators, showed that this system presents a well-defined hysteretic loop. Some results are shown and compared in the following figure with the force-displacement diagram of a rocking wall without dissipators.

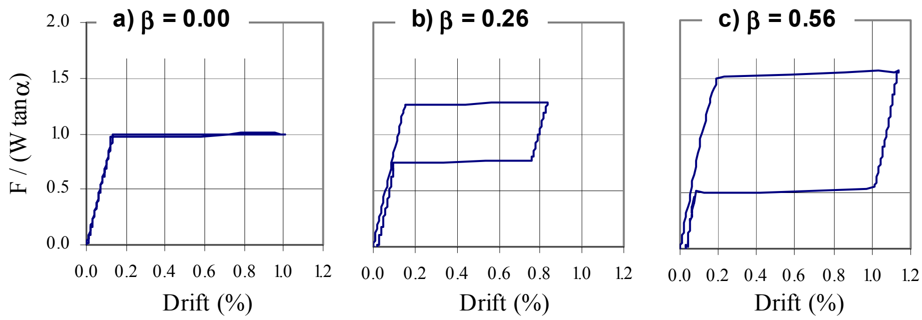

Figure 6. Hysteresis Loops in Rocking Walls without ($\beta = 0$) and with ($\beta > 0$) Dissipators

The energy dissipated by the dissipators is clearly shown in figure 6 (β is defined in equation 24). The equivalent viscous damping of the system can be derived as (Toranzo, 2001):

$$\lambda = \frac{2}{\pi} \frac{\beta}{(1+\beta)} \left[1 - \frac{W(1-\beta)\tan\alpha / k_{fb}}{\Delta} \right] \tag{23}$$

Where $$\beta = \frac{2F_y}{W} \tag{24}$$

And k_{fb} is the stiffness of the wall before rocking occurs. When designing for the more demanding earthquake levels, the deformation of the rocking wall before rocking is much smaller than the total deformation of the system, Δ. If that is expected, equation 23 may be reduced to:

$$\lambda = \frac{2}{\pi}\frac{\beta}{(1+\beta)} \tag{25}$$

At this point one has to add the equivalent viscous damping due to impact as described in section 4. However, the nature of the process is different when the wall has energy dissipators. The reduction factor, r, can be reasonably calculated reducing the total weight, W, to $W\text{-}2Fy$. Then, equation 2 becomes:

$$r = \left[1 - \frac{(W-2F_y)}{g}\frac{R^2}{I_o}(1-\cos 2\alpha)\right]^2 \tag{26}$$

With this value of r, one can take the equivalent viscous damping due to impact from equation 3. The total equivalent viscous damping, now has to be compared with the initially assumed one. If it is different, the cycle has to be repeated. Note that there might be more than one combination to reach the required equivalent viscous damping. Larger values of F_y (larger energy dissipation through dissipators) lead to less energy dissipated through impact and vice-versa. Dissipation through the dissipators should be preferred as large amounts of energy dissipated at impact imply more violent impact processes that may lead to large peaks in forces and accelerations. For practical purposes, r adds to the system equivalent viscous damping between 2% and 5%. Hence, if dissipators are being used, it could be neglected or add conservatively an extra 2% to the system.

When the length of the base of the wall has not been defined, the value of β can be calculated from equation 23 or 25. Then, F_y can be calculated from equation 24. It leaves only $\tan\alpha$ to be defined. Then, $\tan\alpha_{eff}$ can be calculated with:

$$\tan\alpha_{eff} = \left(\frac{V}{W+2F_y}\right) \tag{28}$$

And finally $$B = \frac{h_{eff}}{2}\tan\alpha_{eff} \tag{29}$$

6.7 *Expected Deformation in Other Earthquake Levels*

Assuming that for any case the deformation before rocking begins is smaller than the total maximum deformation, the equivalent viscous damping of the system will be the same. It can be observed that a typical displacement spectra follows a fairly straight line. When that is the case, it can be demonstrated that the maximum displacement for a earthquake level different than the design one is as stated in equation 30. Where RF is the risk factor as the type proposed by the NZS 4203 (1992).

$$\Delta_{RP\neq 500\,years} = (RF)^2\,\Delta_{RP=500\,years} \tag{30}$$

6.8 *Maximum Expected Absolute Acceleration*

Due to the rigid-body type motion of the structure, the maximum total acceleration is expected to occur at the top of the building. Equation 17 along with the impact factor, f_{imp}, can be used to that end.

6.9 *Detailing the Wall*

After the required performance has been met, detailing of the wall proceeds. All the elements have been defined above and one only needs to calculate the design base shear, for which, the impact amplification factor is calculated according to section 5.

7 CONCLUSIONS

An alternative structural system with the potential to improve the seismic performance of medium-height, low-density buildings has been presented. The system would allow traditional materials be reliably used in this type of building.

The procedure developed in the last part of the paper demonstrates that, providing hysteretic-energy-dissipators to the rocking wall, one ends up with a system able to a meet a set of performance requirements.

8 ACKMOWLEDGEMENTS

Special thanks are due to the Ministry of Foreign Affairs of New Zealand, who is sponsoring the studies of Mr. Luis Toranzo through a NZODA Scholarship.

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9 RETURN TO INDEX