Retrofit of the William Clayton building using additional damping

NZSEE
2001
Conference

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ABSTRACT: The William Clayton building was one of the first buildings in the world to be designed with seismic isolation using lead rubber bearings (Megget 1979a). Associated with this unique design was the expectation that the building would be relatively undamaged during an extreme seismic event. Recent experiences, particularly from the 1994 Northridge and 1995 Kobe earthquakes, have shown that a large magnitude, long period pulse is often prevalent in earthquake records at sites within a few kilometres of the active fault during an earthquake. As the William Clayton building is located within a "near field" region in Wellington, it has been suggested that it may be vulnerable to a large magnitude near field earthquake for which it was not designed. Using numerical modelling, possible forms of retrofit for the William Clayton building are investigated by adding various forms of damping to the base of the structure. In optimising the performance of the building for both near field and far field "design level" earthquakes, it is concluded that linear viscous dampers added to the base of the structure can effectively control the response during large magnitude near field earthquakes with minimal impact on the design response. This conclusion is consistent with previous studies on models of other generic seismically isolated buildings.

1 INTRODUCTION

Seismic isolation was used in the design of William Clayton building, shown in Figure 1a, to give it a long natural period and subsequently minimise the acceleration demand on the building. Inherent in the isolation system is a relatively high level of damping to help control isolator displacements in the building.

Recently it has been observed that structures, particularly flexible structures with long fundamental periods, have suffered considerable damage during large magnitude earthquakes where the site was located within a few kilometres of the fault (Hall et al. 1995, Hall 1998, McVerry 1997). In these regions the earthquakes are referred to as near field earthquakes.

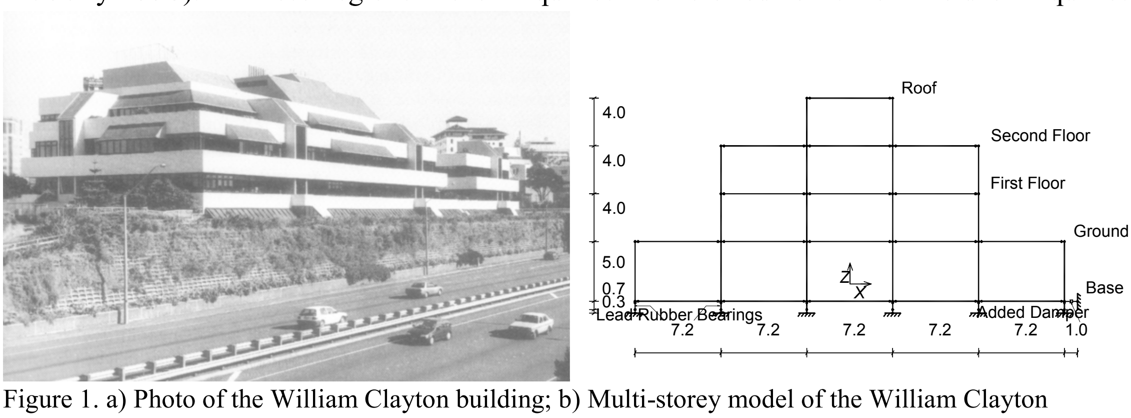


Figure 1. a) Photo of the William Clayton building; b) Multi-storey model of the William Clayton building

Studies of the earthquake records in near field regions have shown that many of these records exhibit a large magnitude, long period pulse. This is attributed to forward rupture directivity effects (Somerville 2000) caused by the propagation of the rupture along a fault during an earthquake. Seismically isolated buildings also have long fundamental period and if not specifically designed to allow for the large displacement demand, are likely to be vulnerable to these forward directivity effects. The William Clayton building was designed in the late 1970's before the variation in ground motions was well understood. As a result the displacement capacity of the isolation system for the William Clayton building is expected to be inadequate during a near field earthquake.

Various systems have been suggested for the retrofit of seismically isolated buildings to counter the effects of probable large isolator displacements during a near field earthquake (Skinner & McVerry 1995). However, these systems often require a large seismic gap which external constraints disallow, or induce forces in the structure significantly larger than those for which the building was designed. The maximum displacements at the base of the William Clayton building are constrained to 150mm by the proximity of a nearby retaining wall. Therefore additional damping, known to decrease the maximum displacements of a structural system, is proposed as a possible form of retrofit. As large levels of damping would be required, it was considered likely that the type of damping will be important in optimising the response of the building.

As a first approximation near field earthquakes may be considered to behave like a pulse applied at ground level. Standard vibration theory, e.g. as outlined in Chopra (1995) shows that for a linear single degree of freedom system the maximum displacement in response to a half sinusoidal pulse can be reduced by up to 40% using 40% additional viscous damping. It was considered likely that additional damping would be even more effective than for the above case, due to differences between the response to a pulse and the response to a near field earthquakes, and also due to the added influence of the non-linear nature of the as-built isolation system. Therefore additional damping should result in a feasible retrofit if there are minimal adverse effects to the non-near field performance of the building.

Two past studies have suggested a possible retrofit for the William Clayton building using different forms of additional damping (Davidson et al. 1998, Zhao et al. 2000). This study aims to propose a more optimum form of retrofit.

2 MODEL OF THE WILLIAM CLAYTON BUILDING

The William Clayton building is a four storey reinforced concrete frame structure as described by Megget (1979a). To determine the lateral performance of the isolation system, a typical frame of the building in the transverse plane was modelled using SAP2000 (Computers and Structures 1998).

To investigate the lateral performance of the frame to near field and design level earthquakes, suitable scale factors for earthquake ground motions were required. These were arrived at by following the guidance provided by the 1997 Uniform Building Code (UBC) where in any seismic zone, the spectral ordinates for a near field site are twice those for a standard design. To obtain these scale factors a single degree of freedom model of the frame was developed using a non-linear shear element to represent the isolation system and a rigid mass to represent the superstructure. Using this model the maximum displacement of the isolation system was calculated from a time history analysis using the El Centro NS acceleration record scaled by 1.5, the same earthquake record as that used in the original design of the building. Had the structure been designed using the UBC for a zone outside a near field region, a seismic coefficient equal to 0.42 would result in the same displacement. Consequently, using the UBC philosophy a seismic coefficient of 0.84 was chosen as suitable for the structure being located within two kilometres of a fault. Using this new seismic coefficient an analysis using the UBC approach was made to calculate the expected near field response of the isolation system assuming the same bilinear properties as for the design response. This analysis suggested that the maximum near field displacement of the system would be 273mm, almost double the maximum allowable dictated by the proximity of retaining walls adjacent to the William Clayton building.

A number of earthquake acceleration records from past earthquakes, previously identified as containing forward directivity near field ground motion (Somerville 1998, McVerry 1997), were

Table 1. Selected design level and near field earthquakes

Year	Reference	Earthquake	Station	Comp.	Mag.	Epicentral Distance (km)	Focal Depth (km)	Soil Type	Peak Accn (g)	Peak Vel (m/s)	v/a (s)	Scale Factors
Design Level Earthquakes												
1940	**El Centro**	Imperial Valley	El Centro Array #9	NS	6.9	8	9	Soil	0.35	0.32	0.09	1.50
1966	**Parkfield**	Parkfield	California Array #2	N65E	6.1	36	7	Soil	0.50	0.78	0.16	0.55
1977	**Bucharest**	Bucharest	Building Res. Inst.	NS	7.2	n/a	94	Soft Soil	0.20	0.72	0.37	0.55
1992	**Joshua Tree**	Landers	Joshua Tree	EW	7.3	14	5	Soil	0.28	0.43	0.15	0.95
Average					6.9	19	29		0.33	0.56	0.19	0.89
Near Field Earthquakes												
1994	**Northridge (Sim.)**	Northridge	Artificial E04		6.7	25	19	Soil	0.77	1.76	0.23	0.50
1994	**Rinaldi**	Northridge	Rinaldi	S49W	6.7	10	19	Soil	0.84	1.70	0.21	0.60
1994	**Sylmar**	Northridge	Sylmar Hospital	360	6.7	16	19	Soil	0.84	1.29	0.16	0.65
Pred.	**Elysian Park**	Elysian Park	Artificial E05		7.0	9	9	Rock	0.93	1.76	0.19	0.90
1992	**Lucerne**	Landers	Lucerne	N90E	7.3	42	5	n/a	0.73	1.46	0.20	1.20
1979	**Imperial Valley**	Imperial Valley	Array #7	230	6.4	29	12	Soil	0.46	1.13	0.25	1.25
Average					6.8	22	14		0.76	1.52	0.21	0.85

selected. For their use in this study, the scale factors that ensured that they caused the maximum displacement of the single degree of freedom isolator model to be equal to the near field response as calculated using the UBC were recorded. Similarly design level earthquakes, in addition to El Centro, were selected and scaled so that the displacement response to these earthquakes was the same as that for design. The design level earthquakes were used for later comparison of the impact of possible retrofits on the performance of smaller non near field earthquakes. A list of the earthquake records, including some properties and scale factors, is given in Table 1.

The structure was then modelled in SAP2000 as a full two dimensional frame incorporating the properties of the isolation system and beams and columns of the superstructure (Fig. 1b). The dimensions and properties of the model were chosen to represent properties of the real structure as in the initial time history analysis performed during the design of the building in Drain2D by Megget (1979b). Each beam and column was modelled with rigid end zones of 0.25m at either end of the element to allow for the joint regions. Plastic hinges were modelled at the end of the rigid end zones using zero length non linear links. These were given a high initial stiffness, so that the effect of each hinge was negligible while the element remained elastic, and appropriate post-yield stiffness to be consistent with the original Megget model when the elements yielded. The isolation system was modelled with 6 non-linear shear elements. The mass of the building was distributed at each floor as per the original analysis with a rigid diaphragm assumed by slaving the nodes at each floor. Damping is modelled in Drain2D as Rayleigh damping using mass and stiffness proportional damping coefficients. For modelling in SAP2000 these were converted to a fraction of critical damping for each mode. To verify that the model of the building in SAP2000 was comparable to the original Drain2D model, the El Centro response of the building was compared using time history analyses in Drain2DX, a current equivalent version of Drain2D, and SAP2000. The base and top floor displacements of the building are compared in Figure 2.

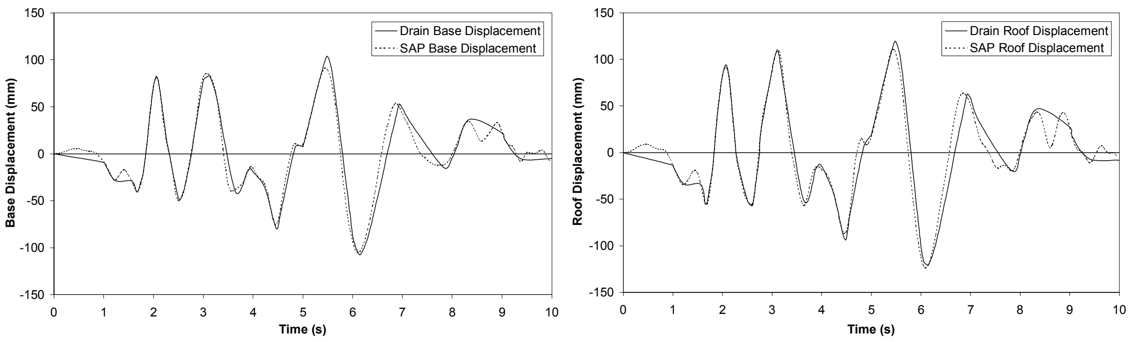


Figure 2. Comparison of 1.5 El Centro time histories using SAP2000 and Drain 2DX at a) base and b) roof

3 RESPONSE OF THE AS-BUILT BUILDING

To help assess the response of the as-built William Clayton building the inter-storey yield displacements were determined from a pushover analysis. The pushover analysis was performed on the superstructure of the building using equivalent static lateral forces with the isolation system locked. From the displacement-base shear plot, the yield displacement at the top floor was calculated at 42 mm, from which inter-storey displacements at each floor were subsequently calculated.

Using the yield displacements the ductility of each floor was calculated in response to each earthquake from the time history analyses of the frame. The average inter-storey displacement ductility for the design level earthquakes was between 0.4 for the first floor, to 0.2 for the top floor. The near field response of the upper floors had ductility's of approximately two times these values therefore they remained essentially elastic. At the isolation layer the design displacement was 108 mm averaged over the design level earthquakes, which is equal to the design displacement from the original El Centro time history analysis in Drain2D. The average near field displacement was equal to 273 mm which is almost two times the maximum allowable displacement of 150 mm. Therefore, it became apparent that there was a need to reduce the maximum near field displacement of the isolation system, while the performance of the upper levels appeared to be adequate in response to near field earthquakes.

4 OPTIONS FOR RETROFIT USING ADDITIONAL DAMPING

From earlier studies on generic seismically isolated structures (Carden 2000) various levels of six different forms of additional damping were attempted as a means to retrofit the isolation system of the buildings. These forms of damping included four forms of additional viscous damping, additional hysteretic damping, and a dual level hysteretic buffer as suggested by Skinner and McVerry (1995). From the study of the generic structures it was found that a dual level hysteretic buffer was unable to adequately reduce the maximum displacement of the isolation system in response to near field earthquakes. Consequently it was not considered for retrofit of the William Clayton building.

The force in a viscous damper can be described by Equation 1. Four various forms of viscous damping were differentiated by the velocity exponent which typically ranges between one, for linear viscous damping, and zero, for properties equivalent to elasto-plastic hysteretic damping.

$$F_{Damp} = c\dot{u}^{\gamma} \qquad (1)$$

where c = damping constant; $\dot{u}$ = damper velocity; γ= velocity exponent.

In the earlier studies additional dampers with three velocity exponents equal 1.0, 0.5 and 0.3 which are inside the typical range for commercially available dampers, were attempted for retrofitting seismically isolated buildings. A fourth form of damping, with a velocity exponent of 1.5, was also modelled although a damper with such properties may not be currently available. From these previous studies two velocity exponents, equal to 1.0 and 0.5 were considered most effective. These were consequently used in attempts to retrofit the William Clayton building. Different levels of damping were defined by varying the damping constant. Damping constants were calculated based on 5, 10, 20, 30 and 40% of additional damping using Equation 2. In this equation k is based on the secant stiffness of the isolation system at the design displacement.

$$c = 2\xi\sqrt{\frac{Wk}{g}} \qquad (2)$$

where ξ = fraction of critical damping; W = total weight of the building; k = secant stiffness of the isolation system at the design displacement; and g = acceleration due to gravity.

Additional elasto-plastic hysteretic damping was also used in an attempt to control the maximum near field displacements of the isolation system. A high initial stiffness was assumed therefore the properties of the additional hysteretic damping was governed by the yield force. Various levels of hysteretic damping were defined by yield forces equal to 0.02W, 0.05W, 0.10W, and 0.15W, where W is the total weight of the frame of the William Clayton building.

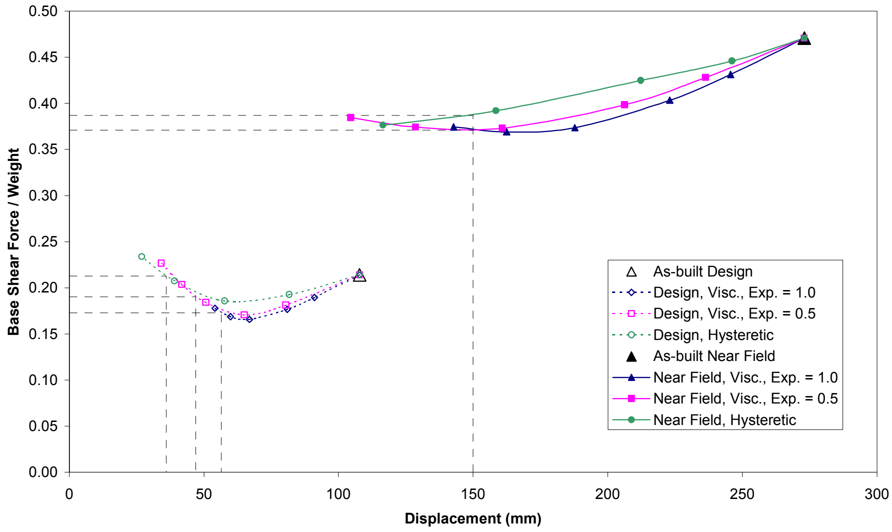


Figure 3. Average design and near field response of isolation system retrofitted with three forms of damping

5 AVERAGE RESPONSE WHEN RETROFITTED USING ADDITIONAL DAMPING

The maximum displacement and base shear at the base of the William Clayton building with different levels of each form of addition damping, averaged over the individual design and near field earthquakes respectively, is shown in Figure 3. The design response is represented by the set of curves on the left hand side while the near field response is represented by the set of curves on the right. Each curve represents a different form of damping and the points indicate increasing levels of damping from the as-built response on the right hand side of each set of curves.

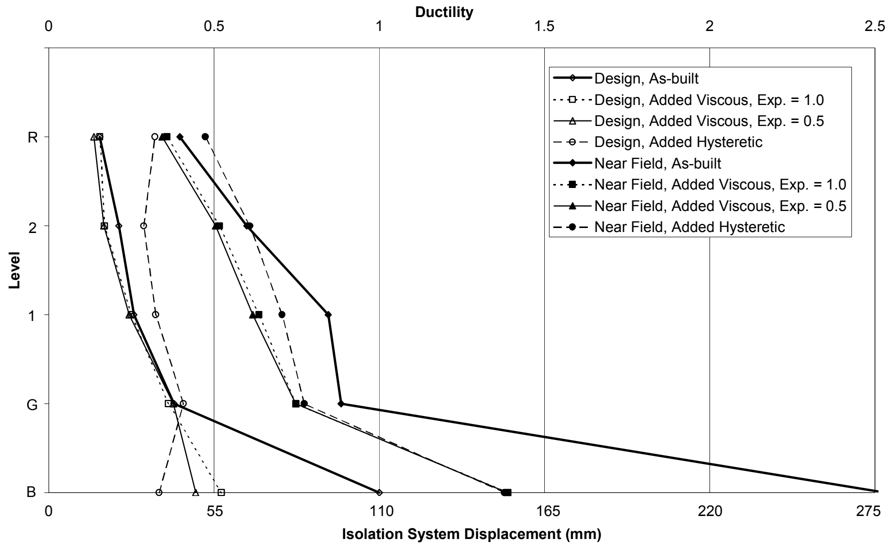
Figure 3 shows that additional damping is able to reduce the maximum near field displacement to less than the maximum allowable displacement of the isolation system. The optimum level of damping for each form of additional damping was defined as the level of damping which reduced the average near field displacement response to the maximum allowable displacement of 150mm and was interpolated from Figure 3.

Base shear was used as an indicator of the performance of each form of damping as it is proportional to the forces in the superstructure of the building. The base shear response using both forms of additional viscous damping was equal at their corresponding optimum levels, while the base shear using additional hysteretic damping was 5% higher.

Considering the design level response, the base shear using linear viscous damping was the lowest the previously determined optimum damping level. The reduction in the average design level displacement was also the smallest indicating that this form of additional damping was most effective as it had the smallest impact on the performance of the building during a design level earthquake. Conversely the base shear was largest using the optimum damping level of additional hysteretic damping and the reduction in the maximum displacement of the isolation system was also largest indicating that additional hysteretic damping had the greatest impact on the design response.

Figure 4 shows the displacement response of the superstructure of the building using the corresponding optimum levels of additional damping, again averaged over the individual design level and near field earthquakes respectively. The top horizontal axis gives the inter-storey ductility of each level excluding the base, while the displacement of the base is given on the bottom horizontal axis. It shows that the deformations in the superstructure with the two forms of additional viscous damping are similar but that additional hysteretic damping induced larger displacements indicating a larger level of damage in the superstructure.

It can be concluded that additional linear viscous damping is the most effective form of retrofit. The level of damping required corresponds to a damping constant equal to 0.320 W



(s/m), where W is the total weight of the frame. This is equivalent to 36% of critical viscous

Figure 4. Average inter-storey drift at each floor

damping based on the effective period (1.44sec) of the isolation system at the design displacement. This type and level of damping can be achieved using commercially available dampers such as "Taylor Devices" (Taylor Devices Inc. 1999).

6 RESPONSE OF INDIVIDUAL EARTHQUAKES

A study of the coefficients of variation for the displacements at each floor, with the building retrofitted using different forms of damping, showed that the variation between the individual earthquakes was smallest when the building was retrofitted using additional linear damping. This indicated that the response of the building with linear viscous damping was least sensitive to the type of earthquake.

Figure 5 shows the maximum displacement and base shear response to the individual earthquakes when increasing levels of linear viscous damping are added to the base of the building. Even though the smallest variation in individual earthquake response was obtained using linear viscous damping, it can be seen that the variation is quite large. In response to the Bucharest record, which was included to investigate the effects of additional damping on a soft soil earthquake record, the building showed the most favourable performance out of the design level earthquakes. Joshua Tree which exhibits backward directivity ground motion, less damaging but equally as likely as forward directivity ground motion, showed a close to average response. The least favourable design level response was obtained from the El Centro ground motion when linear viscous damping was added. However even for this record, at large levels of damping the base shear was less than the base shear in the as-built building.

The near field earthquakes also showed some variation in response. The maximum displacement and base shear were very effectively reduced in response to the Sylmar Hospital record. In contrast the most severe response of the building, when additional damping was added, was found when the building was subjected to the artificial Elysian Park record. With the optimum level of additional damping as previously calculated the maximum displacement in response to this earthquake would have been 190 mm, 25% greater than the maximum allowable displacement. However, even for this worst case, the as-built displacement was reduced by 67% of that necessary to prevent the isolation system exceeding the maximum allowable displacement, therefore a large portion of the damage due to the maximum displacement being exceeded would be prevented.

A better understanding of the characteristics of near field earthquakes which cause the differences in response, coupled with a prediction of the properties of a potential near field earthquake, would help to optimize the retrofit of this building and predict the response of other similar structures.

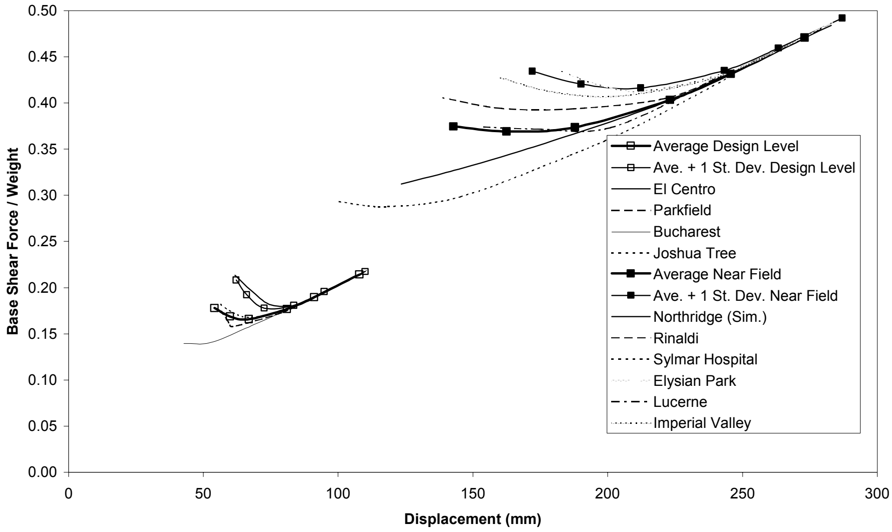


Figure 5. Individual earthquake response at the base for various levels of linear viscous damping

7 ACCELERATIONS AT EACH FLOOR

The accelerations at each floor were calculated to further investigate the impacts of possible retrofits using various forms of additional damping on the design level response of the building. Figure 6 shows the acceleration spectra at the base and top floors in response to El Centro, the design level earthquake inducing the least favourable response. It can be seen that, for periods between 0.3 and 1.1 seconds, the accelerations in the structure are increased. However, the increase in acceleration is smallest using additional linear viscous damping. This increase was two to three times larger using additional hysteretic damping, particularly at the upper floors. Thus, the acceleration spectra again confirm that additional linear viscous damping is a good form of retrofit.

The magnitude of acceleration tends to indicate the amount of damage to non-structural components in a building. The spectra show that the accelerations will not be increased or will be even reduced for items in the building with a natural period of less than 0.3 seconds or larger than 1.1 seconds. Therefore, if there are particularly important items in the building and there is a concern that as a consequence of the retrofit they will sustain more damage during a moderate earthquake, these items could be individually isolated or restrained to reduce potential damage.

8 CONCLUSIONS AND FUTURE WORK

The maximum near field displacement response of the isolation system in the William Clayton building, using criteria taken from the 1997 Uniform Building Code, is predicted to be almost twice the maximum allowable response for the existing isolators. This would cause damage to structures surrounding the building and induce large forces in the superstructure as a result of a subsequent impact. It was found that additional damping in the isolation system was able to limit the displacements to the maximum allowable level.

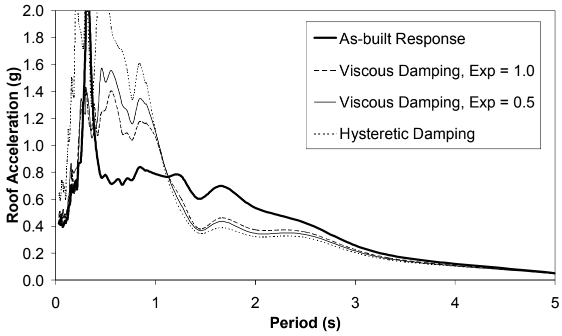


Figure 6. El Centro acceleration floor spectra at the base and top floor

The most effective form of damping was additional linear viscous damping with a damping constant of 0.320W (s/m). Using this form of additional damping the near field response was reduced with minimal impact to the performance of the building during a design level earthquake.

It is anticipated that this study could be applied to the detailed design of a retrofit for the William Clayton building using commercially available viscous dampers. However the concepts presented could help to optimize the design and retrofit of other structures using passive energy dissipation.

The study was based on the average response of six near field earthquakes taken from previous earthquake recordings in California. The variation in response from the different earthquakes was smallest using additional linear viscous damping, however this variation was substantial. A study of the properties of the earthquake records which account for the variation in response, coupled with the development of a model that could more precisely predict the properties of expected ground motion at the site would help to optimize the retrofit of the William Clayton building.

ACKNOWLEDGEMENTS

We would like to acknowledge the others, particularly Dr T.J. Larkin, who offered assistance in this project. Furthermore we would like to thank the EQC for their financial support for this project.

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