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Seismic performance of steel buildings with fluid viscous dampers relative to base isolation

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ABSTRACT

In order to aid in post-earthquake response and recovery efforts, hospitals and other critical structures must remain operational after a Collapse Avoidance Limit State (CALS) earthquake event. Protective systems (base-isolation and supplemental damping) provide a means to reliably and economically achieve improved structural and non-structural performance. Base isolation is an effective way to protect critical structures from earthquake damage. However, it can be a costly approach as the entire structure must be supported on lead rubber or sliding bearings and can also involve major building modification. Fluid viscous dampers as a supplemental damping system located throughout a frame structure can achieve similar results at significantly lower cost. To date use of fluid viscous dampers (FVDs) in New Zealand has been extremely limited for framed buildings.

This paper will briefly demonstrate the relative performance between these two systems for a 4 story steel building with Importance Level 3 (IL3) in terms of both drifts and floor accelerations using a non-linear time history analysis. It is shown that equivalent structural performance, in terms of inter-story drifts and floor accelerations, can be achieved with both types of systems, and generally for lower cost by viscous dampers. This shows that viscous dampers offer an attractive alternative to base isolation in terms of cost and ease of installation.

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1 INTRODUCTION

The typical philosophy in the conventional seismic design is that a structure is permitted to undergo damage when subjected to a design level earthquake excitation. As a consequence, plastic hinges in the structure must be developed to dissipate the seismic energy. However, the development of the plastic hinges relies on large inelastic deformations to achieve a high level of structural ductility. The more ductility a structure sustains, the more damage it suffers. However, some high importance structures such as hospitals and fire stations have to retain their functionality after a major earthquake. These structures should be strong and rigid enough to prevent large displacements and accelerations so that they can be reoccupied immediately or shortly after a large (design level) event. This target objective is compared with performance objectives for existing construction in Figure 1. In this figure, Group I buildings represent ordinary occupancy, such as an office building, while Group III buildings are essential facilities, such as a hospital (MacRae and Clifton, 2013).

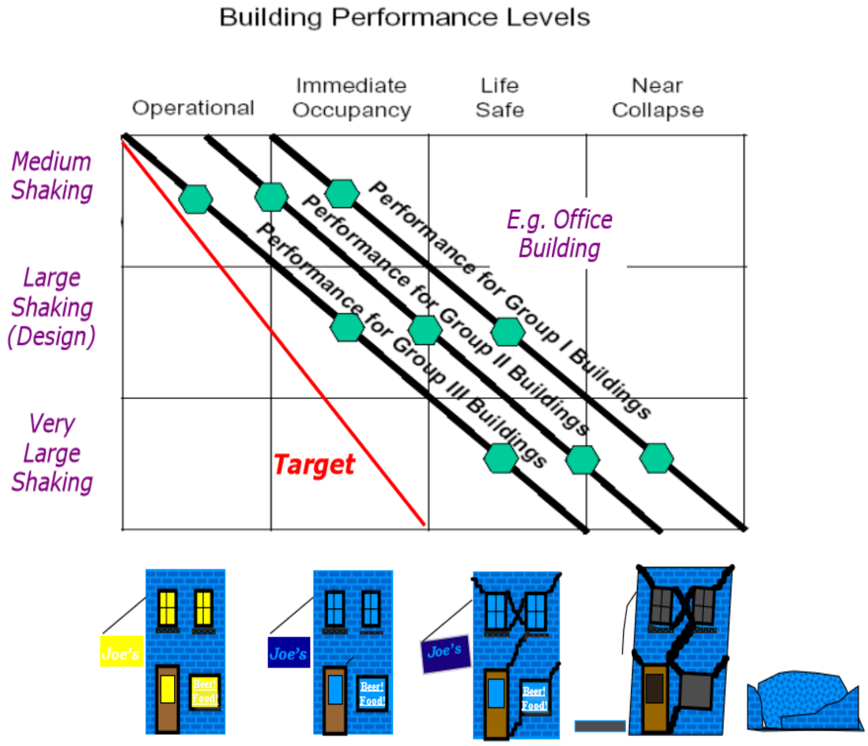


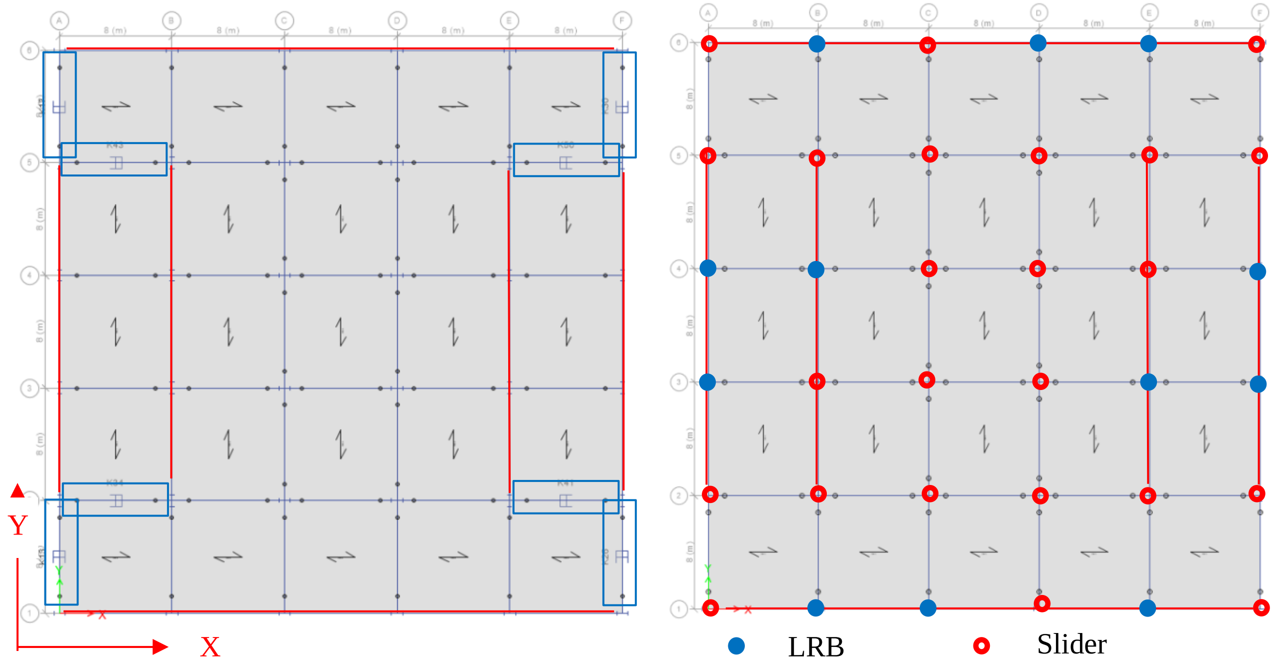
Figure 1: Possible Target Performance Objective for Damage-Resistant Structure (MacRae and Clifton, 2013)

Recently, an increasing number of seismic control systems have been developed around the world to minimize the possibility of structural damage. These control systems primarily include seismic isolation systems and supplemental damping systems. Base isolation requires the building to be separated from the ground by isolation devices which can dissipate energy. Supplemental damping devices can absorb energy and add damping to buildings to reduce their seismic response. Damping devices are divided into two main categories: displacement-dependent devices and velocity-dependent devices. An example of displacement-dependent devices are friction dampers which exhibit hysteretic force-displacement behaviour. An example of velocity-dependent devices are dampers operating by forcing fluid through an orifice (e.g. fluid viscous dampers (FVD)).

This study illustrates the relative performance and cost differences between the use of fluid viscous dampers and base isolation for a 4 story building with an NZS1170 Importance Level 3 (IL3) in terms of both drifts and floor accelerations using a non-linear time history analysis.

2 BUILDING DESCRIPTION

The example building is a four-story steel framed office building located in Wellington, NZ with a seismic coefficient derived from a Hazard Factor (Z) of 0.4 and soil type C. The building has a square plan configuration measuring 40m, in both principle directions (Figure 2). The typical story height is 4m (Figure 3). The floors consist of 70mm concrete topping over composite metal deck.



(a) With Viscous Dampers (b) With Base Isolation

Figure 2: Typical Floor Framing Plan with SMRF Locations

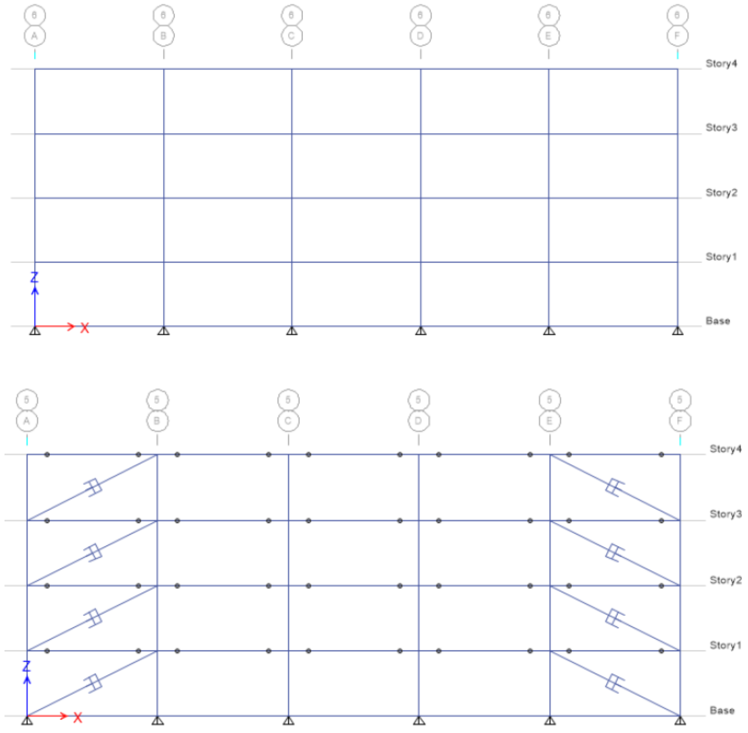


Figure 3: Typical Building Elevation with and without Dampers

The seismic force resisting system consists of steel moment resisting frames located along Gridlines A, B, E, F in Y-Direction, and 1 and 6 in X-direction. These frames are shown with red lines in Figure 2. The location of supplemental damping devices and base isolations is shown in Figure 2a, b. The number and layout of these devices are determined in the preliminary design.

The foundations elements are designed and detailed with adequate strength and stiffness to provide fixity such that the column bases of the SMRF can be modelled assuming fixed bases.

3 GROUND MOTION SELECTION AND SCALING

The ground motion selection and scaling follow the requirements of NZS1170.5 Section 5.5. Six ground motions have been used for design as shown in Table 1. The period range of interest for scaling is taken as 0.4 to 1.2 times the effective period using nominal isolation system properties. The period range is widened to allow for potential changes to the isolation system (that may result during developed and detailed design). Thus, the period range for the Collapse Avoidance Limit State (CALS = 1.5 × ULS) and Ultimate Limit State (ULS) is between 0.6s to 3.5s and 0.5s to 3.1s respectively.

Table 1: Input earthquakes

Record name	Location	Year	Mw	Scale factor (CALC)	Scale factor (ULS)
HKD109	Tokachi-Oki, Japan	2003	8.3	2.43	1.7
HKD113	Tokachi-Oki, Japan	2003	8.3	6.39	4.25
IBR018	Tohoku, Japan	2011	9	3.52	2.42
Tabas	Tabas, Iran	1978	7.4	1.14	0.78
WDFS	Kaikoura, NZ	2016	7.8	1.49	0.99
Duzce	Duzce, turkey	1999	7.2	1.33	0.93

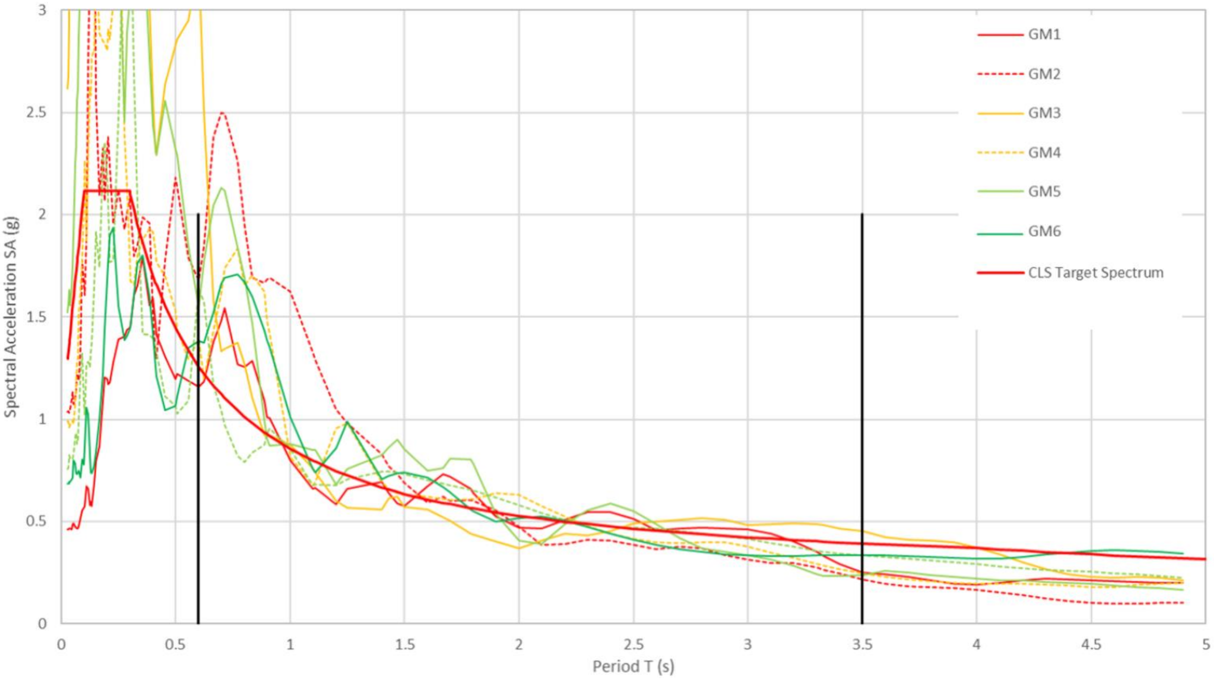


Figure 4: Response Spectra of Scaled CALS Ground Motions

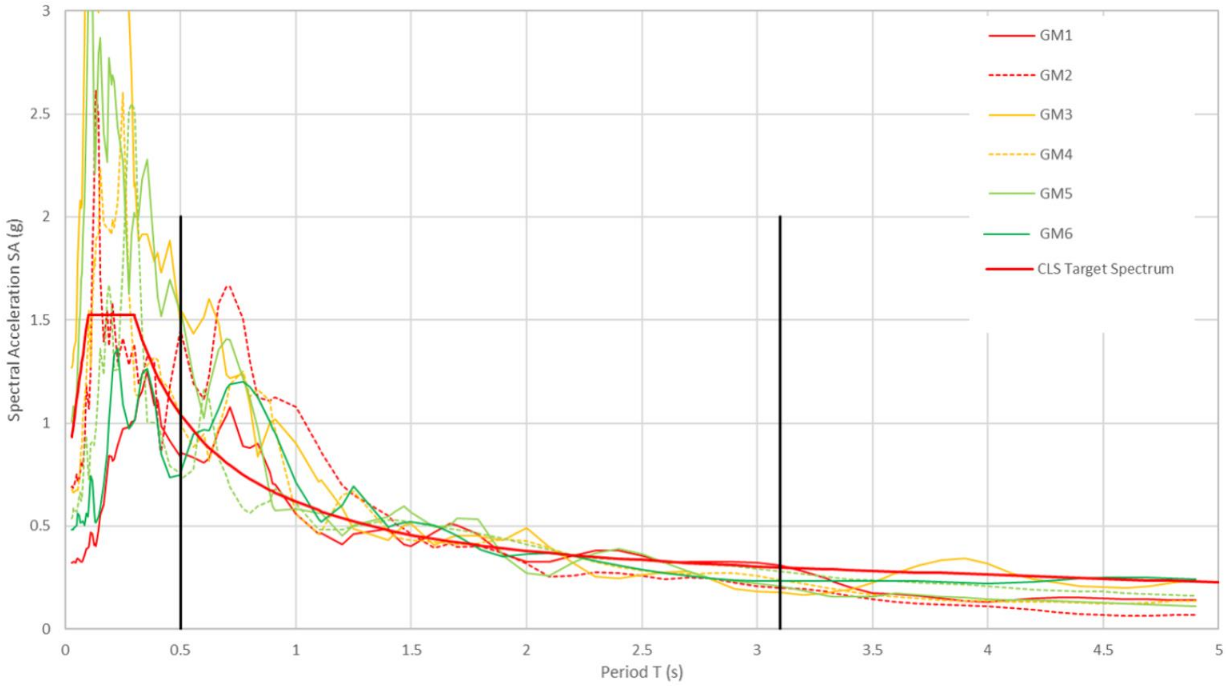


Figure 5: Response Spectra of Scaled ULS Ground Motions

4 PRELIMINARY DESIGN CONSIDERATIONS

In this study, the viscous damper and isolation design approach is based on the ASCE 7-2016 Standard.

4.1 Viscous Damper Design Procedure

The Standard requires that the damping system has a Seismic-Force-Resisting System (SFRS) that provides a complete load path. Therefore, the lateral load resisting system incorporates fluid viscous dampers in combination with a steel moment frame. A design procedure for SFRS and damping systems based on equivalent lateral force is given in the following steps:

1) Calculate minimum base shear:

$$V_{min} = \frac{V_{code}}{B_{v+I}} \geq 0.75V_{code} \tag{1}$$

2) SFRS must be designed for V_{min}.

3) The fundamental mode shape, ϕ_{i1}, and participation factor, Γ_1, shall be determined by either dynamic analysis using the elastic structural properties and deformational characteristics of the resisting elements or using Eqs. 2 and 3:

$$\emptyset_{i1} = \frac{h_i}{h_n} \tag{2}$$

$$\Gamma_1 = \frac{\overline{W_1}}{\sum_{i=1}^{n} w_i \emptyset_{i1}} \tag{3}$$

4) Residual mode shape, $\emptyset_{iR}$, participation factor, Γ_R, effective residual mode seismic weight of the structure, $\overline{W_R}$, and effective period, T_R, shall be determined using Eqs. 4 Through 7:

$$\emptyset_{iR} = \frac{1-\Gamma_1 \emptyset_{i1}}{1-\Gamma_1} \tag{4}$$

$$\Gamma_R = 1 - \Gamma_1 \tag{5}$$

$$\overline{W_R} = W - \overline{W_1} \quad (6)$$

$$T_R = 0.4T_1 \quad (7)$$

5) Select a supplementary viscous damping (β_{v1}) in the first and second modes.

6) Calculate damping coefficient:

$$B_1 = \frac{4}{5.6-\ln(100\beta_{v1})} \quad (8)$$

7) The damping constants (C_L) for linear viscous dampers shall be determined using Eq.9:

$$\beta_{v1} = \frac{E_{vd}}{4\pi E_{es}} = \frac{\pi \sum_1^{N_d} C_{Li}\varphi_{i1}^2 cos^2\gamma_i}{T_1 \sum_1^{N_f} k_i\varphi_{i1}^2} \quad (9)$$

8) The damping constant for a nonlinear viscous damper is determined using Eq.10 (Christopoulos and Filiatrault, 2006) where α is the damping exponent (between 0.1 to 1.0), ω is circular frequency of the structure and X_0 is the design displacement of the dampers:

$$C_{NL}= C_L \frac{\sqrt{\pi}}{2} (\omega X_0)^{1-\alpha} \quad (10)$$

9) Residual viscous damping (β_R) can be obtained using Eq. 11:

$$\beta_R = \frac{E_{vd}}{4\pi E_{es}} = \frac{\pi \sum_1^{N_d} C_{Li}\varphi_{iR}^2 cos^2\gamma_i}{T_R \sum_1^{N_f} k_i\varphi_{iR}^2} \quad (11)$$

10) Calculate Residual damping coefficient:

$$B_R = \frac{4}{5.6-\ln(100\beta_{vR})} \quad (12)$$

11) Calculate fundamental mode base shear:

$$V_1 = C_1\overline{W_1} \quad (13)$$

12) Calculate Residual mode base shear:

$$V_R = C_R\overline{W_R} \quad (13)$$

13) Determine the design base shear, V:

$$V=\sqrt{V_1^2 + V_R^2} \geq V_{min} \quad (14)$$

14) The properties of materials used in devices may vary considerably due to temperature, aging, contamination, history of loading, among other factors. To consider this, the property modification or λ factors are used to modify the nominal properties to an appropriate upper or lower bound. In this study, the upper and lower bound factors are 1.15 and 0.85.

15) Design the elements of the SFRS for the design forces and displacements.

16) Design the elements of the damping system for the maximum forces generated by the damping devices and by the SFRS under the design earthquake.

17) Design the damping devices for the forces, inter-story drifts and inter-story velocities corresponding to the Collapse Avoidance Limit State (CALS) earthquake.

For the example building the first and second modes of vibration are translation in the North-South and East-West directions, respectively. An added damping of 15% of critical is targeted in each of these modes, giving a damping ratio in the first and second modes, ξ_1 and ξ_2, of 0.15. Based on this, the seismic system is designed such that 70% of the design base shear is resisted by the moment frame and 30% of the design base shear is resisted by the FVD's.

4.2 Base Isolation Design Procedure

A design procedure for isolators based on ASCE 7-2016 is given in the following steps:

1. Select number of lead rubber bearings (LRB) and sliders;

2. Size bearings by choosing approximate values for the diameter of bearing (D_B), lead (D_L) and it's total thickness (T_r) based on Constantinou et al. (2011):

    - D_B should be in the range of $3D_L$ to $6D_L$
    - T_r should be about equal to or larger than D_L

3. Calculate the characteristic strength Q_d for LRBs using Eq.15 where D_L is the lead core and σ_{YL} is the effective yield stress of lead:

$$Q_{d,LRB} = \frac{\pi D_L^2 \sigma_{YL}}{4} \tag{15}$$

4. Calculate the post-elastic stiffness k_d using Eq.16 where f_L accounts for the effect of the lead core, being 1 to 1.2:

$$k_d = \frac{G f_L \pi (D_B^2 - D_L^2)}{4T_r} \tag{16}$$

5. Calculate the characteristic strength Q_d for the sliders using Eq.17:

$$Q_{d,Sl} = \mu W_i \tag{17}$$

6. The properties of materials used in bearings may vary considerably due to temperature, aging, contamination, history of loading, among other factors. To consider this, the property modification or λ factors are used to modify the nominal properties to an appropriate upper or lower bound. In this study, the upper and lower bound factors for yield stress of lead, shear modulus of rubber and friction are considered 1.4, 1.35, 1.5 and 0.85,0.85 and 0.8 respectively.

7. Calculate total $Q_{d,total}$ and $k_{d,total}$ by considering all bearings and sliders

$$Q_{d,total} = \lambda_{LRB} \times n_{LRB} \times Q_{d,LRB} + \lambda_{Sl} \times n_{Sl} \times Q_{d,Sl}$$

$$k_{d,total} = \lambda_{LRB} \times n_{LRB} \times k_{d,LRB}$$

8. Estimate the maximum displacement D_M

9. Calculate effective stiffness

$$k_M = k_{d,total} + \frac{Q_{d,total}}{D_M}$$

10. Calculate effective period

$$T_M = 2\pi \sqrt{\frac{W}{k_M g}}$$

11. Calculate effective damping

$$\beta_M = \frac{4Q_{d,total}\,(D_M - D_y)}{2\pi k_M D_M^2}$$

12. Calculate damping coefficient

$$B_M = \frac{4}{5.6 - \ln(100\beta_M)}$$

13. Calculate the maximum displacement D_M based on acceleration at effective period, T_M:

$$D_M = \frac{Acc}{\omega^2} = \left(\frac{T_M}{2\pi}\right)^2 Acc.$$

14. Compare calculated D with estimated D assumed in Step 8. If different, go back to step 8, use a different D, and follow steps 8-13.

15. Calculate the required individual rubber layer thickness to maintain stability of the bearing *where* P_u is the factored ultimate compression load (kip), the δ is 2 $\cos^{-1}(D_{TM}/D_{B})$:

$$t \le 0.218\,\frac{G D_B^4\,(1-{D_L}/{D_B})(1-{D_L^2}/{D_B^2})}{(1-{D_L^2}/{D_B^2})}\,\frac{(\delta - \sin\delta)}{\varphi \pi P_u}$$

16. An acceptable design is typically one where the rubber layer thickness is in the range of 0.25 to 0.75 inches and where the shear strain (total displacement D_M divided by T_r) is in the 200-250% range. If this is not achieved then perform another iteration by altering the values in Step 1.

4.3 Design Output

Based on the preliminary design procedure, the properties of the example building, viscous dampers, bearing and isolation system force displacement behaviour considering upper and lower bound factors are shown in Table 2 to 4 and Figure 6.

Table 2: Properties of example buildings

Items	Properties
Inter-storey height [m]	4
Bay length [m]	8
Building width [m]	8
Dead +SDL Load [kPa]	3.55
Live Load [kPa]	3
Column dimensions [mm]	800 WB 180, 800 WB 168
Beam dimension [mm]	800 WB 168
Seismic Weight [kN]	29343

Table 3: Viscous damper properties

Items	Symbol	Value	Units
Damping Coefficient	C_{NL}	50	kN-s/mm
Damping exponent	α	0.5	
Maximum Force, (upper bound)	F_{max}	1000	kN
Maximum Stroke, (lower bound)	U_{max}	±100	mm

Table 4: Base isolator properties

Items	Symbol	Value	Units
Nominal effective yield stress of lead	σ_{YL}	10	MPa
Nominal shear modulus of rubber	G	0.45	MPa
Nominal friction coefficient (fast)	μ	0.1	
Lead core diameter	D_L	135	mm
Bonded rubber diameter	D_B	800	mm
Total thickness of rubber	T_r	240	mm
Yield displacement	Y	15	mm
LRB Characteristic Strength (nominal)	Q_d	143	kN
LRB Post-elastic Stiffness (nominal)	k_d	0.92	kN/mm

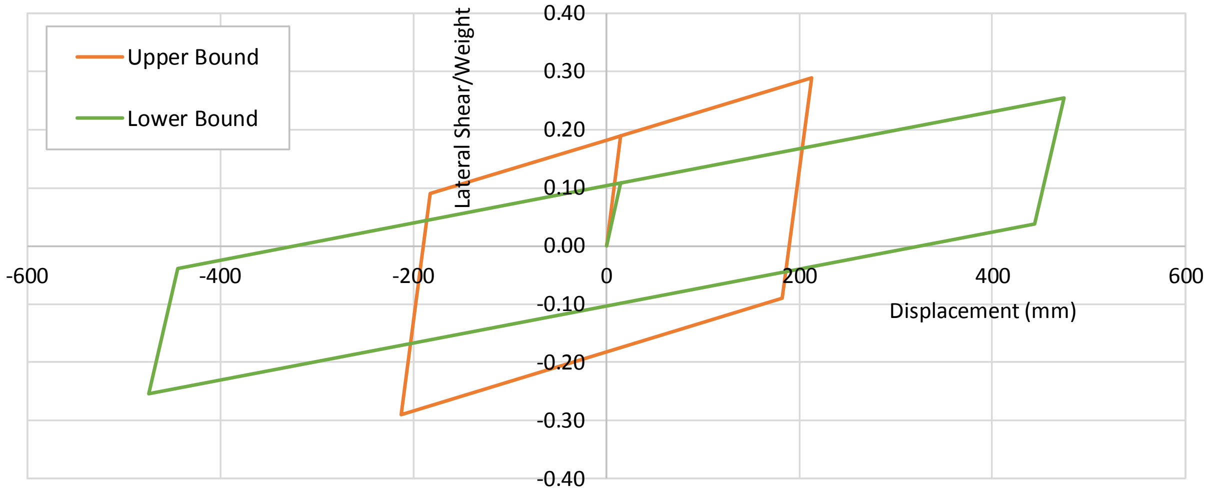


Figure 6: Isolation System Force-Displacement Behaviour, CALS

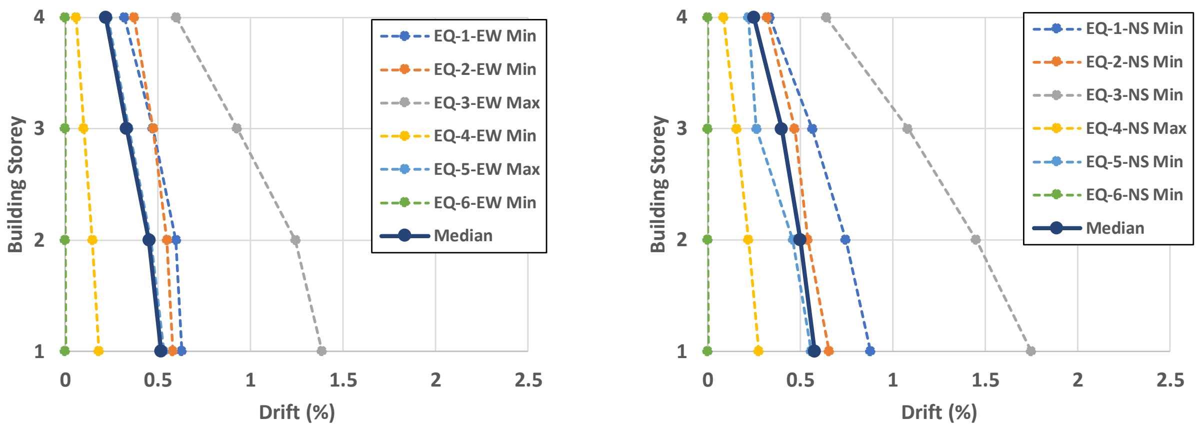
5 ANALYSIS AND RESULTS

For the purposes of the comparative study the building was modelled in 3D using ETABS 2016. Nonlinear time history analyses were performed on each building with non-linear elements used for the viscous dampers, base isolation devices and moment frames.

Each of the models were analysed using a total of 6 ground motion pairs selected based on the seismic sources that contribute to the hazard for Wellington as shown in Table 1.

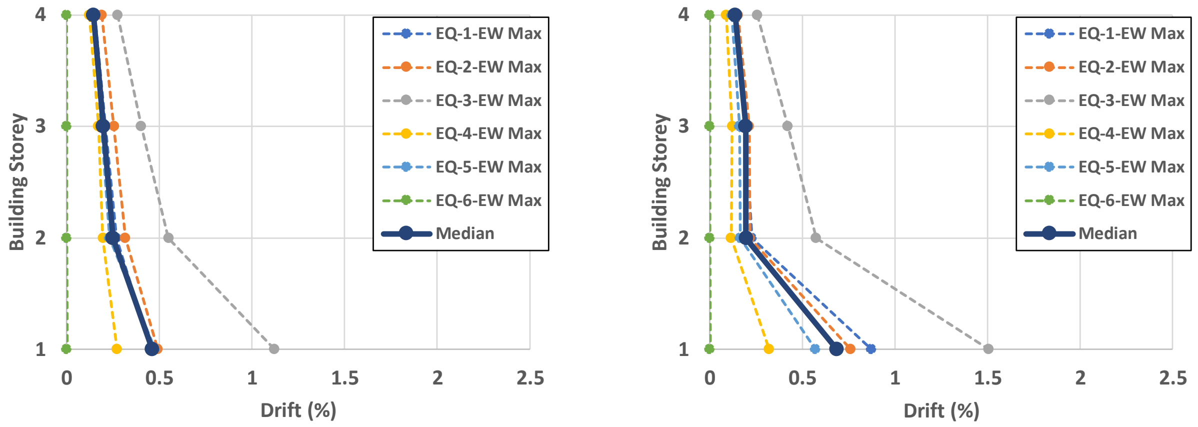
Figure 7 and Figure 8 compare the peak drift and acceleration response of the structures using time history analysis. Here, the peak response can be occurred in both positive and negative directions of the structure. The Max and Min labels in the legend of the figures, are represented of the response in positive and negative directions. It can be seen that the maximum drift for each record and median of them at CALS for both FVD and Isolation systems is similar.

The most significant difference between the two systems is the peak acceleration response at each level. The acceleration response for the structure using viscous dampers is almost uniform over the full height, apart from the 3rd ground motion which was found to increase with height. The acceleration response for the structure using base isolators was also found to be relatively uniform with height, however a maximum peak acceleration was noted to occur at the isolator level. It is noted for both systems the maximum peak median acceleration is similar.



Viscous Damper, X Direction

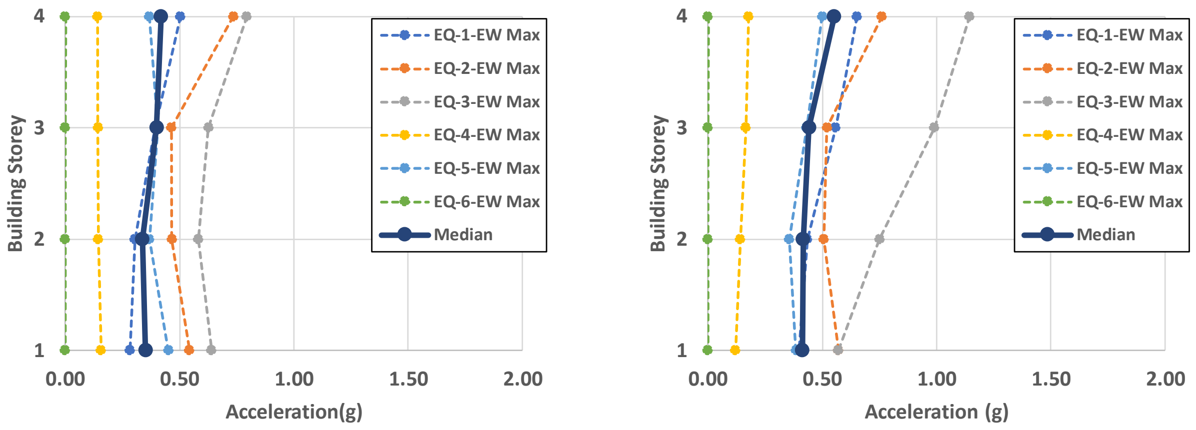
Viscous Damper, Y Direction



Base Isolation, X Direction

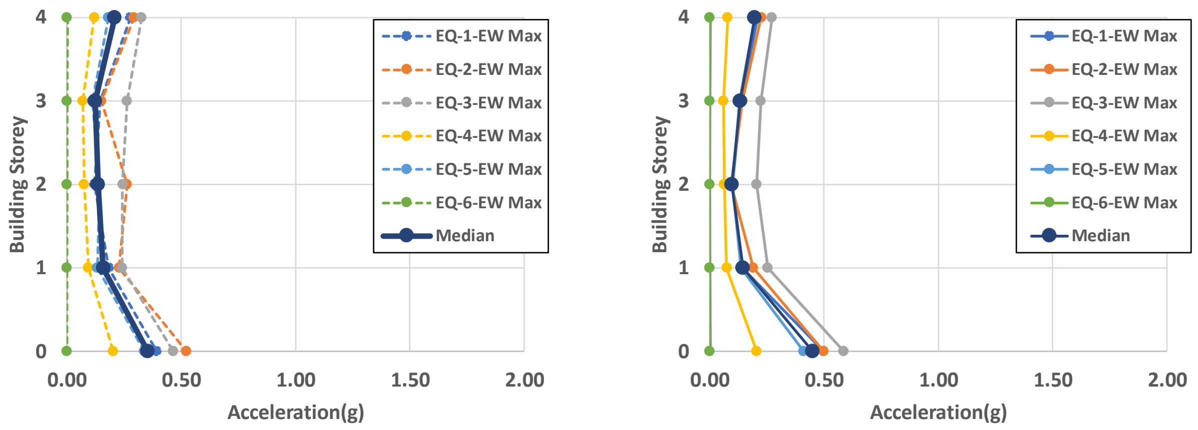
Base Isolation, Y Direction

Figure 7: Drift Response of the Structure Using Viscous Dampers & Base Isolators, CALS Records



Viscous Damper, X Direction

Viscous Damper, Y Direction



Base Isolation, X Direction

Base Isolation, Y Direction

Figure 8: Acceleration Response of the Structure Using Viscous Dampers & Base Isolators, CALS Records

6 RELATIVE PERFORMANCE

Inter-storey drift, and floor acceleration are important variables that can be used to evaluate the relative performance of the structural framing system.

Given that the median inter-storey drift and acceleration response are similar between the two systems, it can be expected that the damage to the structural frame facade, partitions etc will be similar between the two systems. At the upper floors the peak floor accelerations are slightly greater for the FVD system, so it could be expected that building content and secondary structures could sustain slightly greater damage than for the isolator system at upper levels.

7 CONCLUSION

This paper demonstrates the relative performance between the base-isolation and supplemental damping systems for a 4-story building with Importance Level 3 (IL3) in terms of both drifts and floor accelerations using a non-linear time history analysis. It is shown that equivalent structural performance, in terms of inter-story drifts and floor accelerations, can be achieved with both types of systems. This shows that viscous dampers offer an attractive alternative to base isolation and are worth considering when evaluating potential costs and ease of installation.

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