

IMPROVING SEISMIC PERFORMANCE: ADD STIFFNESS OR DAMPING?

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ABSTRACT

Structural engineers typically improve the seismic performance of deficient structures by adding strengthening elements to the structural system, which also add stiffness to the structure. However, as performance based design becomes more common practice, the focus is on the total performance of not only the structural system but the building components and contents. A stiffer and stronger building will generally be subjected to lower drifts but higher floor accelerations than a weaker and/or more flexible building. Reduced drift related damage may be accompanied by increased damage to components and contents which are sensitive to accelerations.

This paper examines two common forms of hardware used to strengthen existing buildings, buckling restrained braces (BRB) and viscous damping devices (VDD). Both types of device augment the existing structural system, rather than replace it. A series of nonlinear analyses is used to quantify the performance of two prototype frame buildings strengthened with each type of device. It is shown that equivalent structural performance, in terms of overall deformations, can be achieved with both types of device, and generally for lower cost by BRBs if only moderate levels of drift reduction are required. However, when the total building performance is examined the VDDs provide additional benefits in the form of reduced floor accelerations. The benefits of this may be sufficient to warrant the higher cost solution.

1 INTRODUCTION

The objective of performance based evaluation is to quantify the seismic performance of existing buildings. For buildings which are seismically deficient, the designer then has the options of either providing a new structural system or augmenting the performance of the existing structural system. For buildings which have only moderate deficiencies the latter option is often more cost effective.

Typically, the seismic performance of structures has been improved by adding structural elements, which increase both the strength and the stiffness. These elements will reduce deformations but often at the cost of increased seismic forces due to a reduction in period. The reduced period will also increase floor accelerations, which may increase damage to components and contents.

An alternative to adding structural elements is to modify the dynamic characteristics by adding devices such as viscous damping devices. These devices do not add stiffness but rather increase the damping in the structure, decreasing both forces and accelerations. These devices tend to be more expensive than strengthening elements and so the advantages must outweigh the cost penalty for them to be a cost effective solution for seismic retrofit. This paper examines these advantages by comparing the response of example frames with traditional strengthening elements and with viscous dampers.

2 DEVICE CHARACTERISTICS

Energy absorbing devices for structural systems fall into one of two categories, hysteretic (damping force proportional to displacement) and viscous (damping force proportional to velocity), with visco-elastic devices having characteristics of both. This paper examines a device typical of each, a viscous damping device (VDD) and a buckling restrained brace (BRB), which is a form of hysteretic damper. The hysteretic characteristics of each type, incorporated into a structure which has a capacity of 150 kN at maximum seismic displacement, are shown in Figure 1.

2.1 Hysteretic Damper

A hysteretic damper has the same characteristics as any ductile structural component (an initial elastic stiffness, yield point, and post-elastic stiffness). It is only distinguished from a structural system in that it is not designed to resist all seismic loads but rather is designed to yield at a fraction of the seismic loads and function in parallel with the main structural system. The main function of these components is to absorb energy by plastic deformations but they do add strength and stiffness to the system.

Figure 1(a) shows an example of a damper with a 30 kN peak force. As the force is proportional to displacement, it adds directly to the structural force so the total system force is 180 kN. For this study, it was assumed that the hysteretic damper was a BRB but there are a variety of devices available which share common characteristics (e.g. lead shear devices, friction dampers) and have a similar effect on response (Kelly, 2001).

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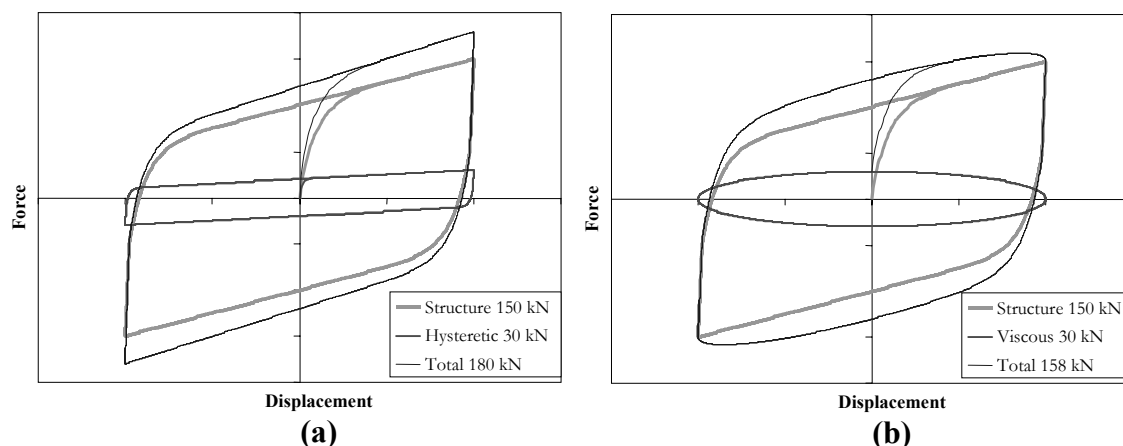


Figure 1. Effect of Device Type on Total Structure Hysteresis (a) Hysteretic Damper and (b) Viscous Damper.

2.2 Viscous Damper

A viscous damper provides a damping force $F_D = C u^\alpha$ where C is the damping coefficient, u is the velocity and α is the damper exponent, generally in the range of 0.4 to 1.0. The velocity is out of phase with displacement and so the damper force is a maximum at zero displacement and reduces to zero at maximum displacement, as shown in Figure 1(b).

For an elastic structural system a VDD will not increase the total force in the system. However, if the structural system yields, as in most seismic frames, the damper and frame forces will be coupled. Figure 1(b) shows that for this example the maximum damper force is 30 kN, the same as for the hysteretic damper, but the total system force is only increased by 8 kN. Design guidelines for this type of device are not provided in NZ codes but can be extracted from U.S. sources (ASCE, 2000).

3 EVALUATION PROCEDURE

The procedure to evaluate the effects of the different damper

types was to analyse two prototype buildings, three story and nine story concrete frames, with various damping configurations. Each building was assumed to be in a higher seismic zone ($z = 0.4$, within 2 km of a fault) on Soil Type D.

The time history method of analysis, based on maximum results from three time records, was used to quantify seismic response using the computer program ANSR-II (Mondkar, 1979). For each configuration scaling factors were calculated according to the procedures specified in NZS 1170 (Standards NZ, 2005) such that the envelope of the three records exceeded the design spectrum within the specified period range. Figure 2 shows an example envelope for a building with a fundamental period of 1.27 seconds.

Although the prototype buildings were modelled with full three dimensional models, all evaluations were performed using a single component of earthquake along one axis of the building. This simplified the evaluation and was considered sufficient to evaluate the effects of the different damper types on response.

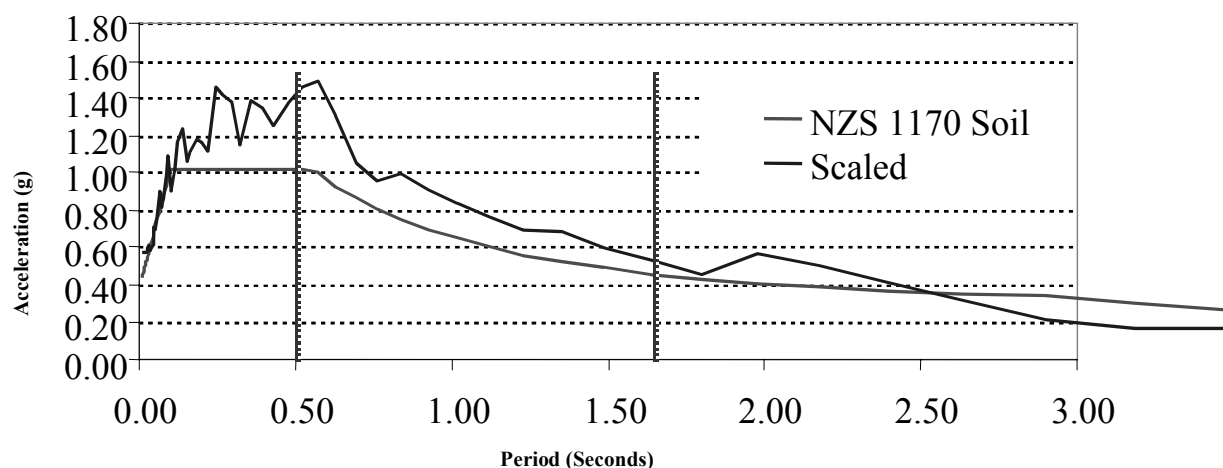


Figure 2. Comparison of Envelope of 3 Scaled Time Histories to Design Response Spectrum from NZS 1170 for Building Period $T = 1.27$ Seconds.

4 EFFECT OF DEVICES ON SEISMIC RESPONSE

4.1 Three Story Frame

The prototype three story concrete frame, shown in Figure 3, had a fundamental period of 0.88 seconds. The VDDs did not alter the period but the BRB options reduced the period to the range of 0.70 seconds (108 kN damping force) to 0.44 seconds (721 kN damping force). A time history analysis produced maximum drifts ranging from 1.94% at the bottom story to

2.34% at the top story. For the purpose of damper evaluation, it was assumed that the deformation capacity of the existing frame elements was such that the maximum interstory drifts were not to exceed 1.0%.

Damper elements were installed along each elevation at all three stories as shown in Figure 3. For the VDDs the damping coefficient, C , was increased until the target drift was achieved. For the BRBs, the area of the brace was similarly increased.

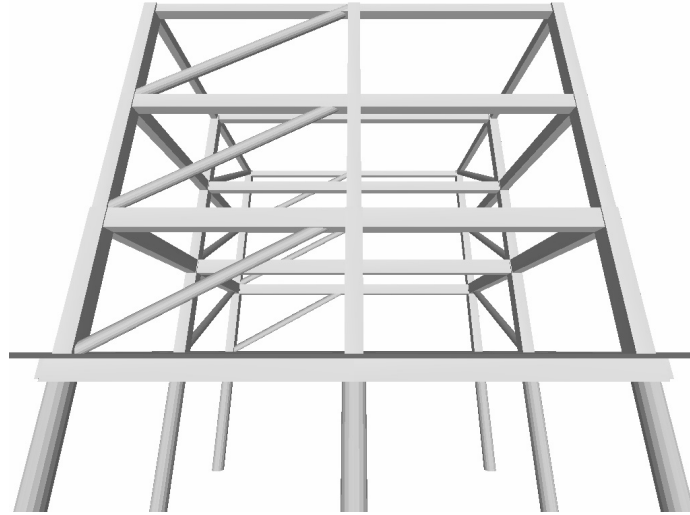


Figure 3. Prototype 3 Story Structure, showing Piles and Viscous Dampers (Diagonals, Buckling Restrained Braces at Same Locations).

Table 1 lists the peak response quantities for the as-is structure and the damping configurations of each type which reduce peak drifts below the 1.0% target value. There are similarities, and differences, between the two damper types:

- Both devices reduce drifts below 1%, to 0.94% for the VDD and 0.98% for the BRB.
- The force in the BRB at 721 kN was twice the VDD damping force of 346 kN to achieve this.
- The VDD reduced the roof acceleration from 0.89g

in the building with no devices to 0.48g. The BRB increased the acceleration, to 1.13g.

- Both types of device increased the base shear coefficient, the VDD by 40% and the BRB by 85%.
- The peak pile force, a measure of the seismic overturning moment, increased by a much larger margin than the base shear, by 75% for the VDD and by 310% for the BRB.

Table 1. Three Story Frame : Peak Response for Each Damping Option.

	No Devices	VDD $C=1750$	BRB $FY=693$
Interstory Drifts			
Base - 1st	1.94%	0.83%	0.98%
1st - 2nd	2.20%	0.94%	0.57%
2nd - 3rd	2.34%	0.80%	0.43%
Damping Force (kN)	0	346	721
Maximum Acceleration (g)	0.89	0.48	1.13
Base Shear Coefficient, V/W	0.34	0.47	0.63
Maximum Pile Seismic Force (kN)	247	432	1012

Figure 4 plots the drift versus damping force for each damper type and the drift distribution with height for the damping values which reduced drifts below 1%. Figure 4(a) shows that initially the BRB is more effective than the VDD, and can reduce drifts from 2.34% to 1.25% with a damping force of

197 kN, compared to 262 kN for the VDD. However, beyond 197 kN increases in BRB damping force have a much smaller effect on drifts and may even increase them. Figure 4(b) shows that the BRB is more effective in reducing upper level drifts than the VDD.

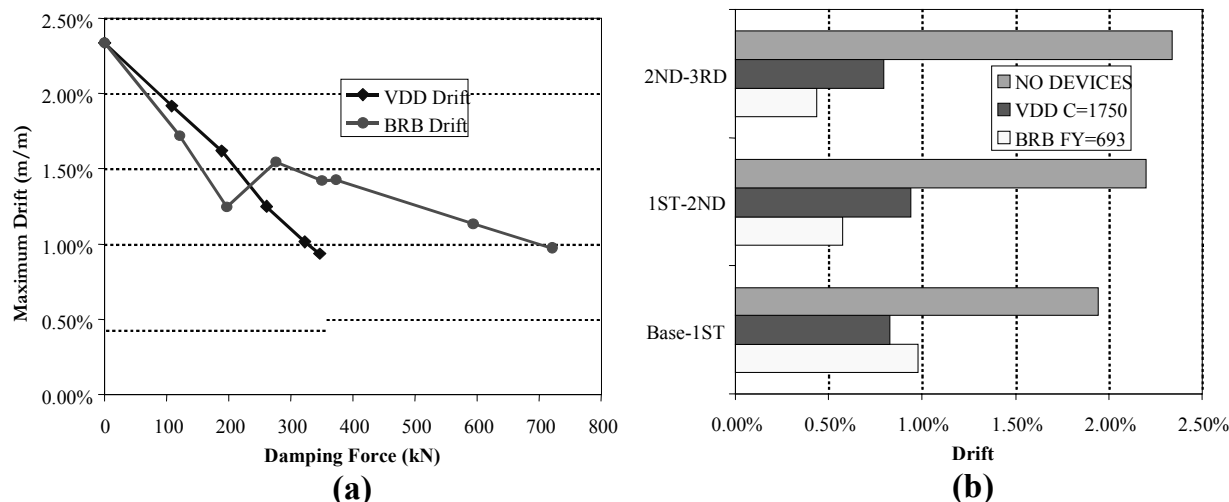


Figure 4. Three Story Frame (a) Effect of Damping Force on Drift (b) Drift Distribution at Optimum Damping Force.

Figure 5 plots the drifts, acceleration and pile force for the VDD and the BRB for the different damping levels. The VDD decreases accelerations continuously as the drifts

decrease. The BRB reduces accelerations for reductions in drift initially, up to damping levels of about 380 kN, but after this the accelerations increase.

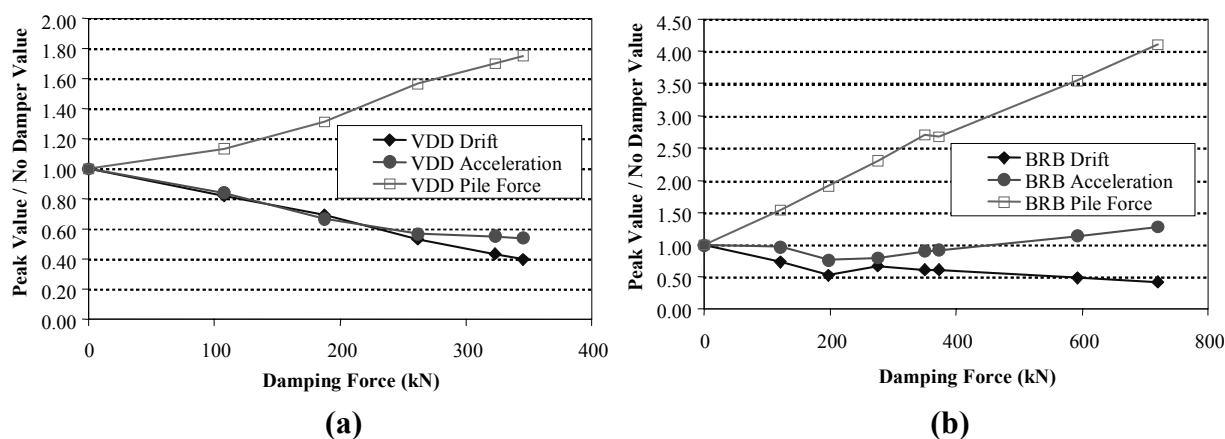


Figure 5. Three Story Frame : Effect of Damper Force on Drift, Acceleration and Pile Force for (a) Viscous Dampers and (b) Buckling Restrained Braces.

4.2 Nine Story Frame

The prototype nine story concrete frame, shown in Figure 6, has a fundamental period of 1.81 seconds. As for the 3-story frame, the VDDs did not alter the period but the BRB options reduced the period to 1.57 seconds for dampers at the 3 bottom stories (386 kN damping force) and to 1.07 seconds with dampers at all stories (2,150 kN damping force). The time history analysis of the as-is building produced maximum drifts of 4.37%, with the highest values in the lowest three

stories.

Damper elements were installed along each elevation at the bottom three stories, as shown in Figure 6. With this configuration, the VDDs with a damping coefficient of $C = 4000$ were able to reduce the drifts to 1.75%. A BRB configuration at the same three stories was able to reduce drifts to only 2.17% regardless of damping force and so the BRBs were installed at all 9 levels of the model and the strength of these increased until a drift of 1.75% was achieved.

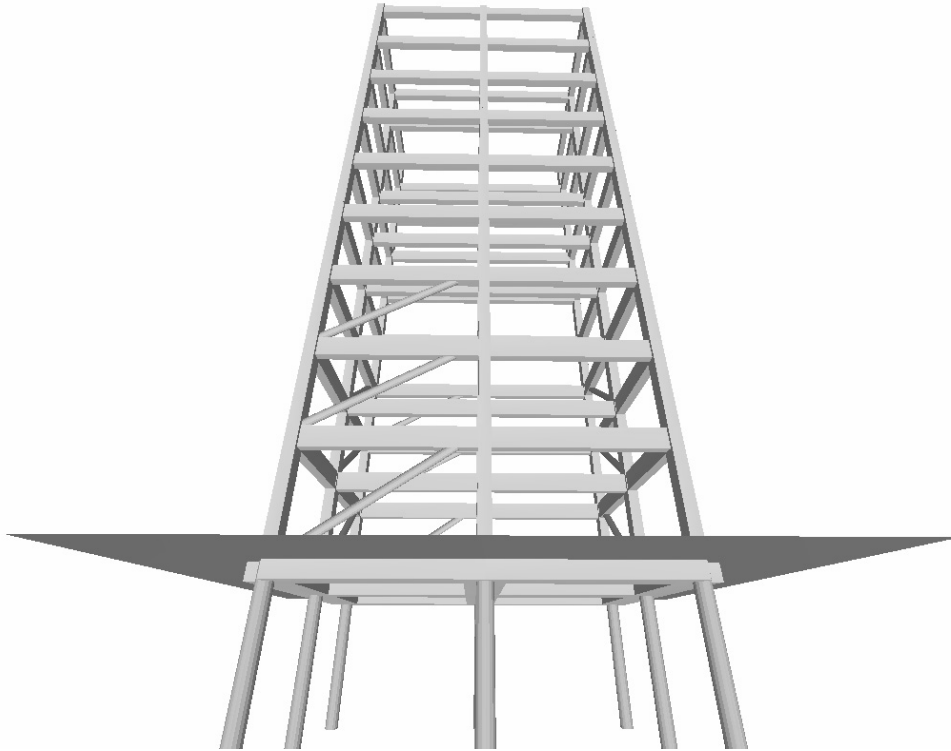


Figure 6. Prototype Nine Story Structure, showing piles and Viscous Dampers at Bottom Three Stories (Diagonals, Buckling Restrained Braces at Same Locations).

Table 2 lists the peak response quantities for the as-is structure and the damping configurations which reduce peak drifts to 1.75%. Also listed are the results for the 3 story BRB configuration which produced the minimum drift of 2.17%. Comparing results from the two configurations which gave a similar drift:

- The force in the BRB, 2,150 kN, was 2.8 times the VDD damping force of 777 kN to achieve this.
- The VDD reduced the roof acceleration, from 0.56g in the building with no devices to 0.38g. The BRB

increased the acceleration to 0.73g.

- Both types of device increased the base shear coefficient, the VDD by 70% and the BRB by 100%.
- The peak pile force, a measure of the seismic overturning moment, increased by a smaller margin than the base shear, by 40%, for the VDD, but by a larger margin of 415% for the BRB.

Table 2. Nine Story Frame : Peak Response for Each Damping Option.

	No Devices	VDD C = 4000	BRB FY = 345 3 Stories	BRB FY = 1980 All Stories
Drift Base-1ST	3.81%	1.68%	1.66%	1.77%
1ST -2ND	4.37%	1.75%	1.71%	1.61%
2ND -3RD	2.38%	1.41%	1.67%	1.40%
3RD -4TH	1.63%	1.60%	2.15%	1.29%
4TH -5TH	1.40%	1.69%	2.17%	1.28%
5TH -6TH	1.30%	1.28%	1.65%	1.27%
6TH -7TH	0.90%	0.73%	1.02%	1.23%
7TH -8TH	0.57%	0.46%	0.63%	1.19%
8TH -9TH	0.34%	0.28%	0.39%	1.08%
Maximum Drift	4.37%	1.75%	2.17%	1.77%
Damping Force (kN)	0	777	386	2150
Maximum Acceleration (g)	0.56	0.38	0.59	0.73
Base Shear Coefficient, V/W	0.18	0.31	0.22	0.36
Maximum Pile Seismic Force (kN)	1392	1944	1916	5773

Figure 7 plots the drift versus damping force function for each damper type and the drift distribution with height for the damping values listed in Table 2. Figure 7(a) shows that initially either configuration of BRB is more effective than the VDD, and can reduce drifts from 4.37% to 2.5%. However, reducing drifts below 2.5% requires much higher forces in the BRB devices than in the VDD. From Figure 7(b), the use of

BRB devices in just the lowest three stories reduces drifts in these stories but increases drifts in the upper levels, an effect which is only slight when VDDs are used in the lowest three stories. If the damping force for the 3 story BRB configuration is increased beyond 345 kN then drifts reduce in the lowest 3 stories but increase in the upper stories.

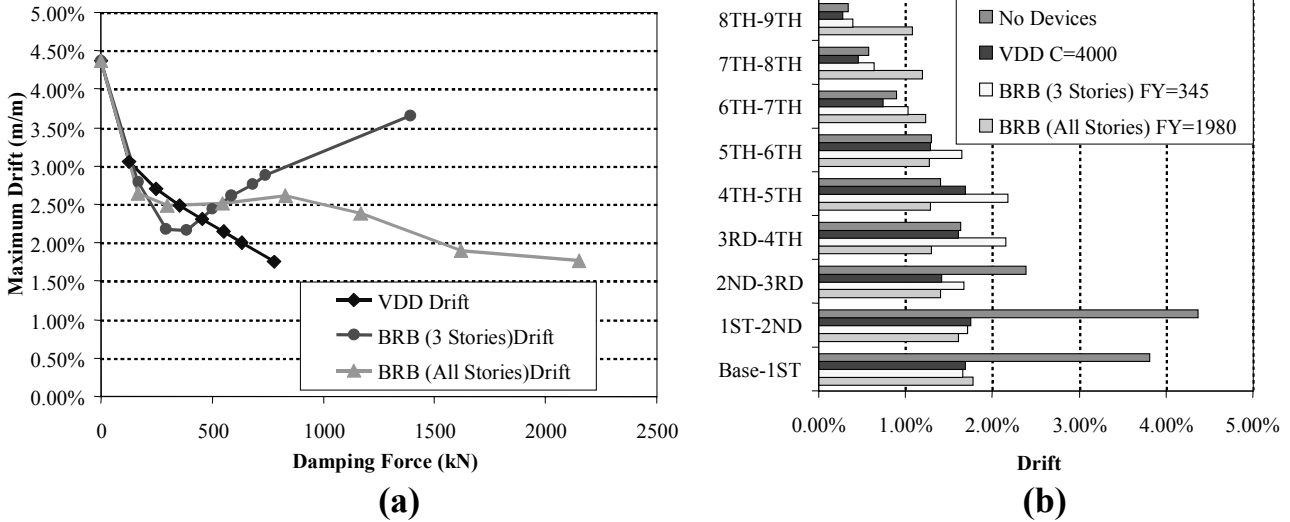


Figure 7. Nine Story Frame (a) Effect of Damping Force on Drift (b) Drift Distribution at Optimum Damping Force.

5 DEVICE PERFORMANCE

The studies on these two prototype buildings, although limited in scope, do provide some indications as to the relative performance of the two types of damping device, the VDD and BRB. In particular,

- The BRB is more effective in reducing drift than VDD, in terms of the amount of reduction for a given damping force, for modest reductions in drift.
- To obtain large reductions in drift, the reverse applies, with the VDD producing larger reductions for a given damping force.
- For equal drift, the building with BRBs will have higher floor accelerations, base shears and

overturning moments than retrofit using VDDs.

- The VDDs become less effective as drift is reduced, that is, a proportionally higher damping coefficient is required to obtain incremental reductions in drift.

This last item, the loss of VDD effectiveness, is because the period remains constant but the displacement reduces, which leads to a reduction in device stroke and velocity as shown in Figure 8. For the 9 story frame, a damping coefficient $C = 500$ reduces drifts by 1.3% (from 4.37% to 3.06%) but an increase in the damping coefficient to $C = 4000$ is required to reduce drifts by a further 1.3% (to 1.75%). This implies that the devices would be less effective for stiff buildings than the flexible buildings in this study.

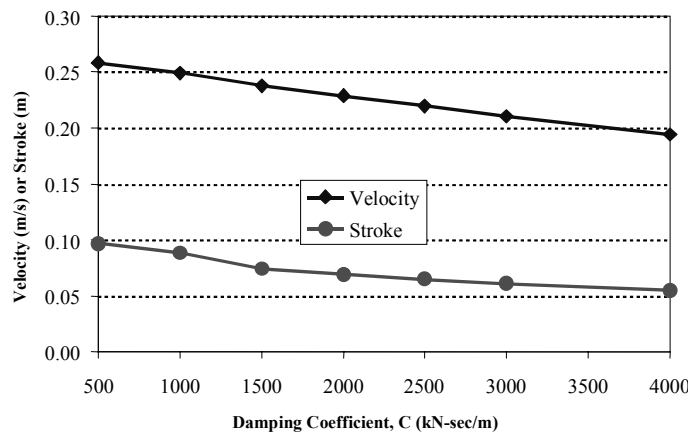


Figure 8. Nine Story Frame : Loss of Damping Effectiveness with Increasing Damping Constant, C.

5.1 Effect on Building Components and Contents

With performance based design, the focus is on the total performance of not only the structural system but the building components and contents. Although reduced drifts will reduce structural damage, this may be accompanied by increased damage to components and contents which are sensitive to accelerations. In general, the BRB solution will increase accelerations and the VDD decrease accelerations compared to the non-strengthened structure. From Tables 1 and 2, the VDD reduces accelerations by 47% and 32% for the 3 and 9 story structures respectively. To achieve the same drifts, the

BRB solution increases accelerations by 27% and 30% respectively.

The peak accelerations indicate the level of seismic forces that will be applied to rigid parts and components. The floor response spectra, as shown in Figure 9 at roof level, indicate the level of load on flexible parts and components. These show that the VDDs tend to reduce accelerations uniformly across a full period range compared to the non-strengthened building. The BRBs tend to give much higher spectral accelerations at the period of the building but have a variable effect at other periods.

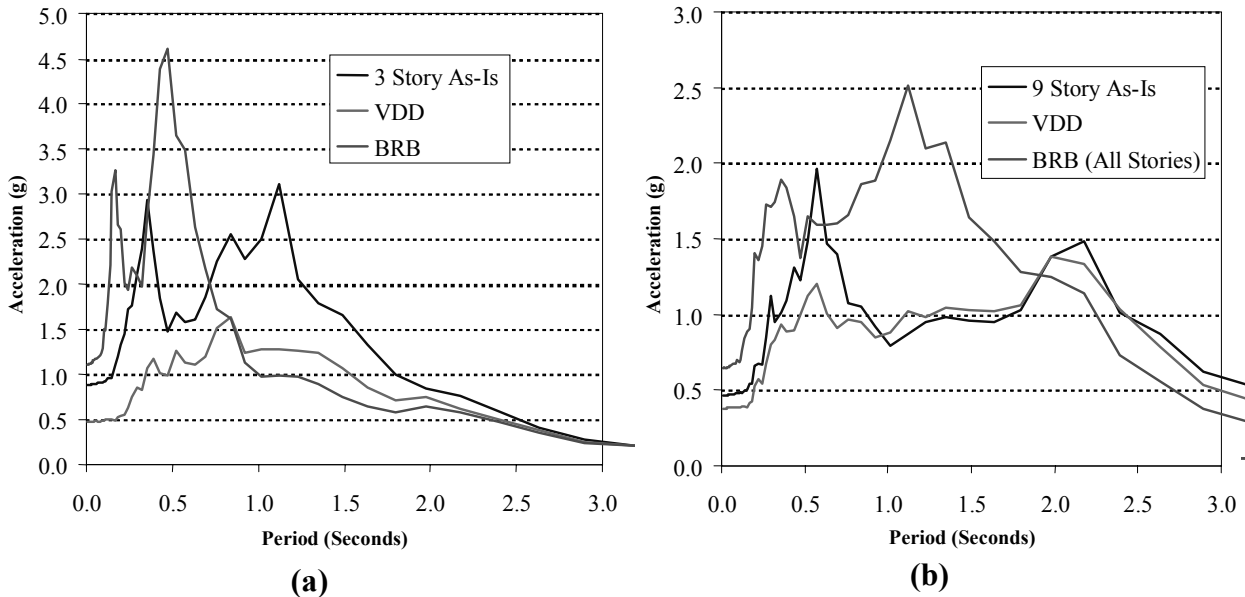


Figure 9. Envelope Roof Response Spectra (5% damping) Generated from 3 Time Histories for (a) Three story Frame and (b) Nine story Frame.

6 CONCLUSIONS

This study has assessed the effectiveness of two devices, viscous dampers and buckling restrained braces, in reducing deformations in flexible frame structures. For relatively small reductions in deformations the BRBs tended to be more effective in terms of reduction in drift for a specified damping force. However, for larger reductions in drift the VDDs were more effective.

The VDDs had a further advantage in that they reduced floor accelerations whereas the BRB increased accelerations. The VDDs also produced smaller increases in base shear forces and overturning moments than the BRB.

Neither type of device has been widely enough used in New Zealand for definitive costs to be developed. However, U.S. anecdotal evidence is that the VDD is about 60% more expensive than the BRB for a given force level. This suggests that the VDD would be more likely favoured over the BRB in two situations:

1. Where it was required to reduce deformations in a flexible building by a large factor (one-half or less the drift of the non-strengthened building).

2. For buildings with high value contents, equipment or other acceleration-sensitive components where there would be advantages from reduced floor accelerations.

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