Comparison of optimal versus a convenient method for viscous damper design

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ABSTRACT

A simple and convenient method often adopted by practising engineers designing supplemental viscous dampers to a building is to calculate damping coefficients of viscous dampers corresponding to a desired added damping ratio. Various methods for distributing damping coefficients along the height of the building exist such as direct displacement-based design (DDBD) methodology or shear strain energy (SSE) method (ASCE 7-16).

In the article, a mathematically optimization algorithm method is proposed and compared with shear strain energy method. Nonlinear time history analysis of two 10-storey structures with steel moment frame with viscous dampers under a number of ground motions has been carried out. The objective of optimization is to obtain the target interstorey drifts by determining the optimal damper placement and damper coefficient distribution up the building height.

Result of analysis have indicated that all distribution methods may result in similar seismic responses if the overall added damping ratios are the same. If the viscous dampers are selected to have the same damping coefficient, the optimal design method (ODM) will require the least number of dampers but with the largest damper force capacity. On the other hand, if the adoption of a greater number of dampers with a reduced force capacity were to occur through the utilization of SSE methods, the requirement for multiple parallel frames may arise. However, this solution may not be practical due to limitations in architectural space arrangement and costs of a larger quantity of dampers.

From the above comparison, it is realised that the cost and architectural planning effectiveness of the total number of dampers versus the maximum force capacity of each damper should be considered when justifying the design for supplemental viscous dampers.

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 structural damage it suffers. However, some high importance structures such as hospitals 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.

Recently various types of supplemental damping devices have been developed around the world to minimize the possibility of structural and non-structural damage. Supplemental damping devices can absorb energy and add damping to buildings to reduce their seismic response. Among others, supplemental viscous dampers have gained increasing popularity in recent years attributing to their negligible influence on the fundamental natural period of the structure and their ability to provide this damping with negligible damage to the units themselves.

The cost of viscous dampers for a construction project mainly depends on two factors: the total number and required load capacity. These factors are strongly related to the damping coefficient added and the distribution of damping resistance in a building. To date, the design methods of added viscous dampers to buildings may be identified by two primary categories. The first category is the most commonly used method by practicing engineers, which has focused on the development of simple design formulas for calculating the added damping ratio to the building (ASCE7-16, ASCE 41-17, direct displacement-based design (Sullivan and Lago (2012)).

In the second category, there have been many studies concerning the optimal design of dampers regarding the damper placement and damper coefficient distribution to the building (Zhang and Soong 1992, Tsuji & Nakamura 1996, Takewaki 1997a,b, Garcia 2001, Garcia and Soong 2002, Singh and Moreschi 2002, Wongprasert and Symans 2004, Lavan and Levy 2005, Lavan 2015).

Even though the optimal design methods suggest systematic and efficient design procedures for viscous dampers, these methods are neither simple nor practical for engineers who often prefer to use simple and convenient formulas for damper design. Moreover, optimal design methods will require the least number of dampers but with the largest damper force capacity. The dampers with larger force capacity may be required such that the size of structural members adjacent to the dampers may be a concern. Alternately, using DDBD/SSE methods, if more dampers with smaller force capacity are adopted, the dampers may have to be installed to number of parallel frames, architectural constraints regarding space arrangement and costs of a larger quantity of dampers may make this option unfeasible.

This study compared the relative performance of a 10-storey building with viscous dampers which is designed using optimal and a shear strain energy design method in terms of drifts, and forces on the dampers and adjacent members of dampers using response time history analysis.

2 DESIGN METHODS

Here, shear strain energy and optimal design methods are explained.

2.1 Shear Strain Energy Method

Based on this method, the damping coefficient along the height of the structure is distributed with respect to the storey shear strain energy corresponding to the first vibration mode of the structure in the direction of consideration. This concept has been adopted in some seismic design codes such as ASCE 41-17 and ASCE 7-16. The storey strain energy in the frame (U_i) is determined using Eq.1 where F_i and δ_i shall be taken as the inertia force and floor displacement at floor level i.

$$U_i = \frac{1}{2}F_i \times \delta_i \tag{1}$$

This method is considered rational because putting more damping coefficient at the location where the storey shear strain energy is larger will result in a greater contribution from the viscous dampers to the system damping ratio such that the dampers can be used more efficiently.

2.2 Optimal Design Method

Based on this method, the optimal damper placement and coefficient is calculated to obtain the target interstorey drifts and floor absolute accelerations. To more efficiently make use of the existing design methods and reduce the computational time, first the total damping coefficient is distributed only to those storeys with shear strain energy larger than the average storey shear strain energy as follow:

$$U_j \geq \frac{\sum U_i}{N} \tag{2}$$

where N is the total storey number of the building, then the coefficients are updated to obtain the target drift and floor accelerations.

$$\min C_j \propto \ subject\ to\ \frac{\max Drift}{Allowable\ Drift} \leq 1\ \&\ \frac{\max Acceleration}{Allowable\ Acceleration} \leq 1 \tag{3}$$

Finally, the number of dampers at each storey is minimized based on the capacity of the structural member adjacent to the damper at each storey.

3 CASE STUDY

3.1 Properties of the structure

The case study is a ten-story 2D steel framed office building with an Importance Level of 3 located in Wellington, NZ with a soil type D. The model configuration is shown in Figure 1. A constant mass of 100 Tons was lumped at each floor. The structure is also assumed to have constant story height, h, of 4m and bay length of 8m. The main period of the structure obtained from the dynamic analysis was 1.28s which has been used in scaling the ground motions to the target spectrum. The main frame without viscous damper is designed to 75% of the total base shear based on ASCE 7-16 to have complete load path and resilient structure with ductility of 1.25 and Sp of 0.9.

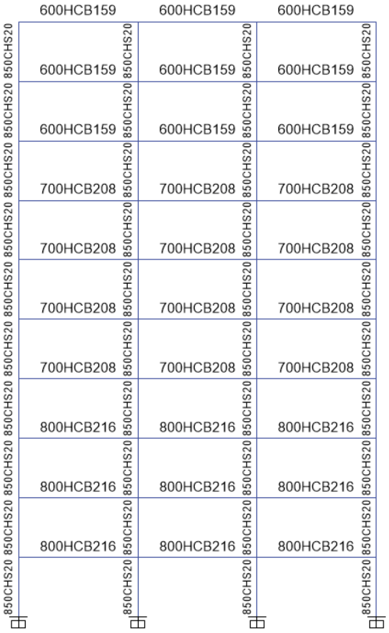


Figure 1: Case Study Model

4 GROUND MOTIONS SELECTION AND SCALING

Seven ground motions have been used for analysis of the structure as shown in Table 1. Response time history analyses were performed on the prototype building using the selected earthquake ground motions. Critical initial stiffness proportional damping of 5% is assumed for all modes. All earthquake records are scaled to the elastic design spectral acceleration at the fundamental period of the structures considered. The reason for scaling the ground motions to the single-period spectral acceleration is to keep all the selected ground motions at the same amplitude of acceleration around the natural period of the building as much as possible to catch the influence of velocity pulse period amplitude more precisely.

Table 1. Input earthquakes

RSN	Earthquake	R_{JB} (km)	Mw	Scale factor
179	Imperial Valley-06	4.9	6.53	1.5
1085	Northridge-01	0.0	6.69	0.88
1503	Chi-Chi, Taiwan	0.6	7.62	0.78
6897	Darfield, NZ	5.3	7.0	3.0
4022909	Tokachi-Oki, Japan	65.2	8.29	2.64
4040371	Tohoku, Japan	22.8	9.12	0.75

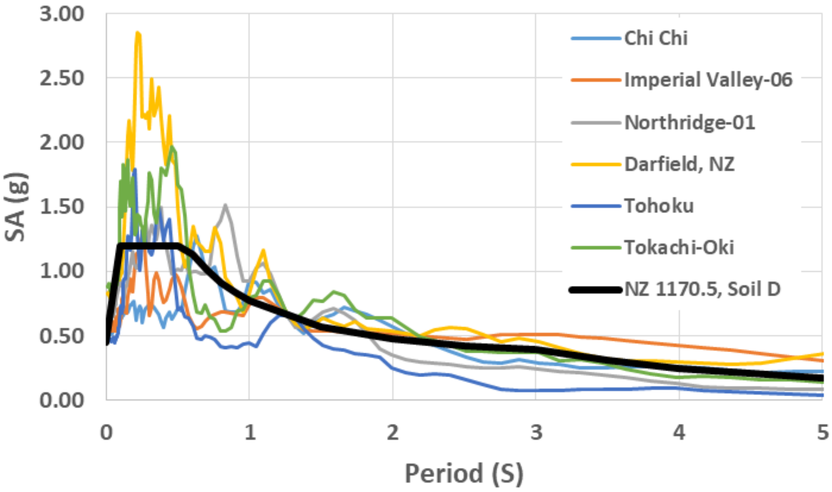
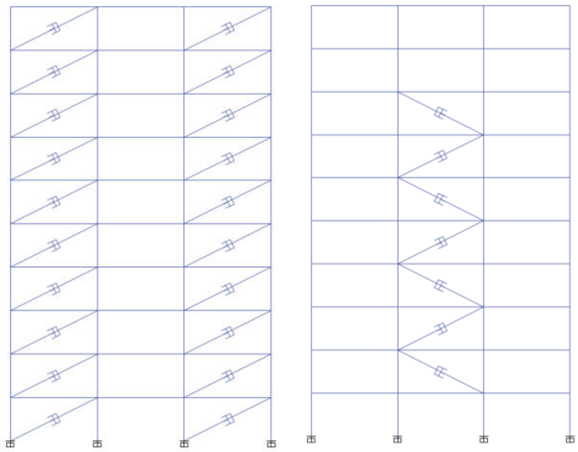


Figure 2: Spectral Acceleration of Ground Motions vs NZ1170.5 (Soil D)

5 COMPARISON OF DISTRIBUTION METHODS

Figure 3 and Table 2 compares the damper configuration and coefficients designed using the two methods. Type b and c are both designed using ODM but with different configurations. It is seen that the damping coefficients determined from the two methods are different up the height of the structure.

The largest damping coefficient from SSE is located at the first storey. At some storeys especially higher storeys where the storey shear strain energy is small, the damping coefficients are small. The damping coefficients distributed by ODM are only necessary to the second to seven storeys. The damping coefficients at these storeys are then greater than those determined from SSE method. However, it is seen that the total damping coefficient is the smallest when designed using ODM. Table 2 also shows the maximum damper forces under Imperial Valley-06 ground motions along the height of the building. The damping forces using ODM are greater than those determined from SSE method which is consistent with the distribution of damping coefficients. However, it is seen that the total damping force is the smallest when designed using ODM.



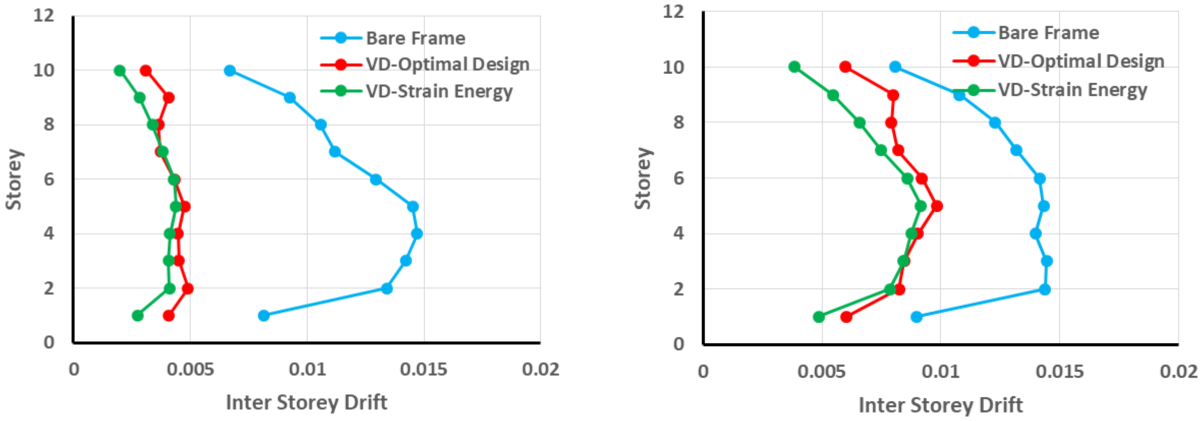
a) SSE b) ODM

Figure 3: Different Distributions of viscous dampers

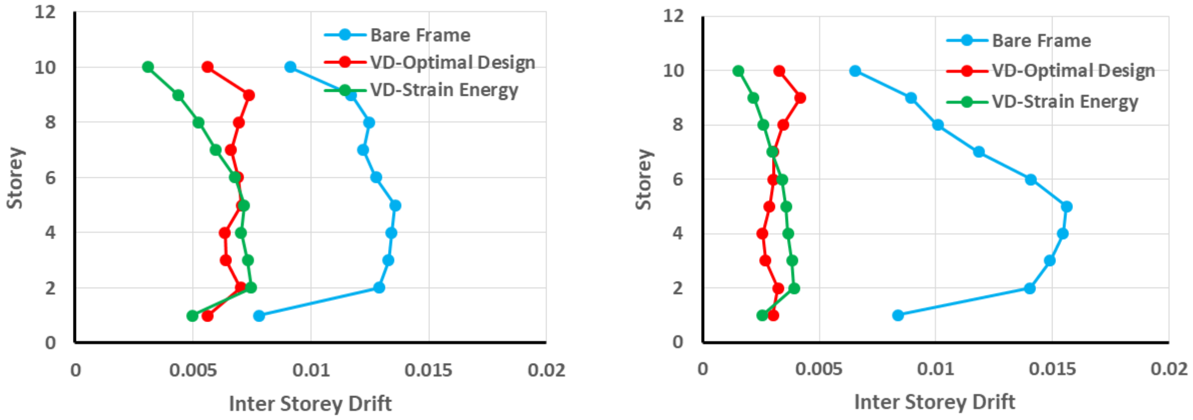
Table 2: Damper coefficients and forces (Northridge-01)

Storey	**SSE**		**ODM**	
	C (kN-s/m)	F (kN)	C (kN-s/m)	F (kN)
10	735	250		
9	1060	440		
8	1358	625	3100	1400
7	1627	800	4012	2200
6	1812	960	4120	1800
5	1961	1100	4220	2300
4	2135	1120	5980	2700
3	2302	1150	6305	3360
2	2461	1230	6150	2830
1	3101	1270		
Total	37103(=2x18551)	17430(=2x8715)	33887	16590

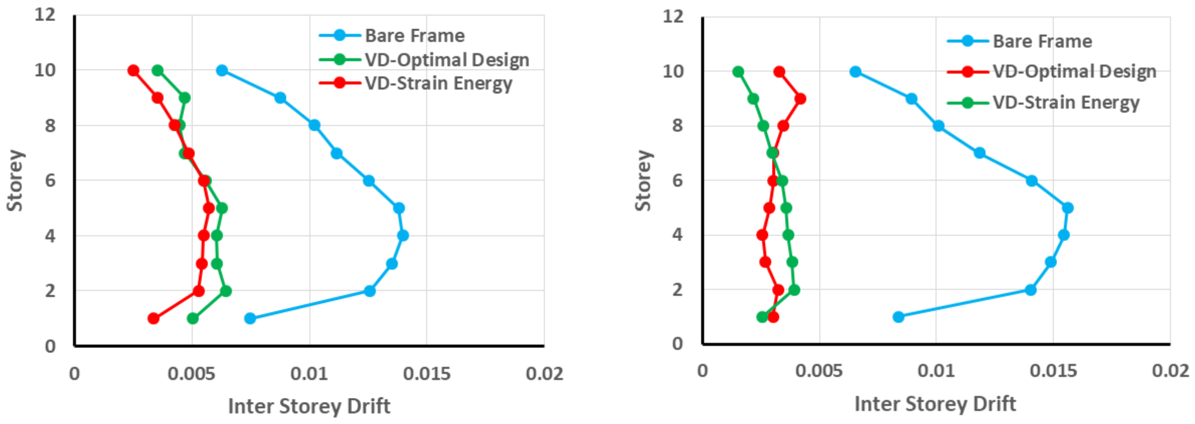
The maximum seismic drift responses of the structure subjected to the six earthquakes are summarised in Figure 4 from which it is observed that the maximum lateral displacements of the structure are almost the same no matter how the damping coefficient is distributed. This result is reasonable because the added damping ratio by the two methods is almost identical. This result is also considered reasonable since the structure has the same added damping ratio and natural period.



a) Imperial Valley-06 b) Northridge-01



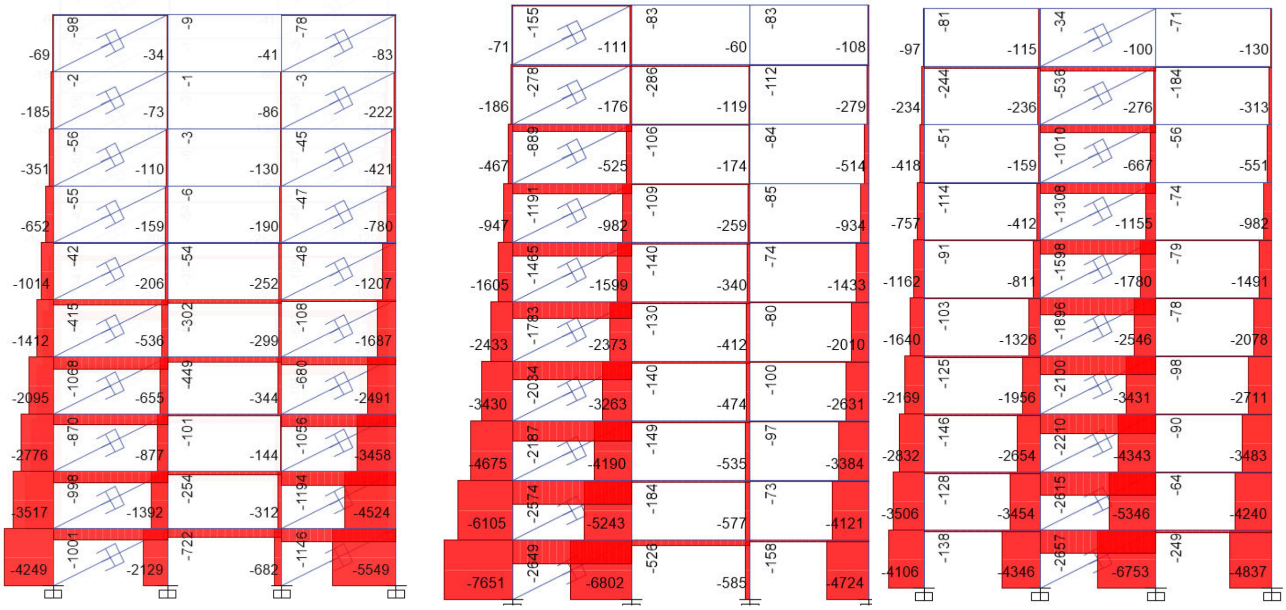
c) Darfield, NZ d) Tokachi-Oki, Japan



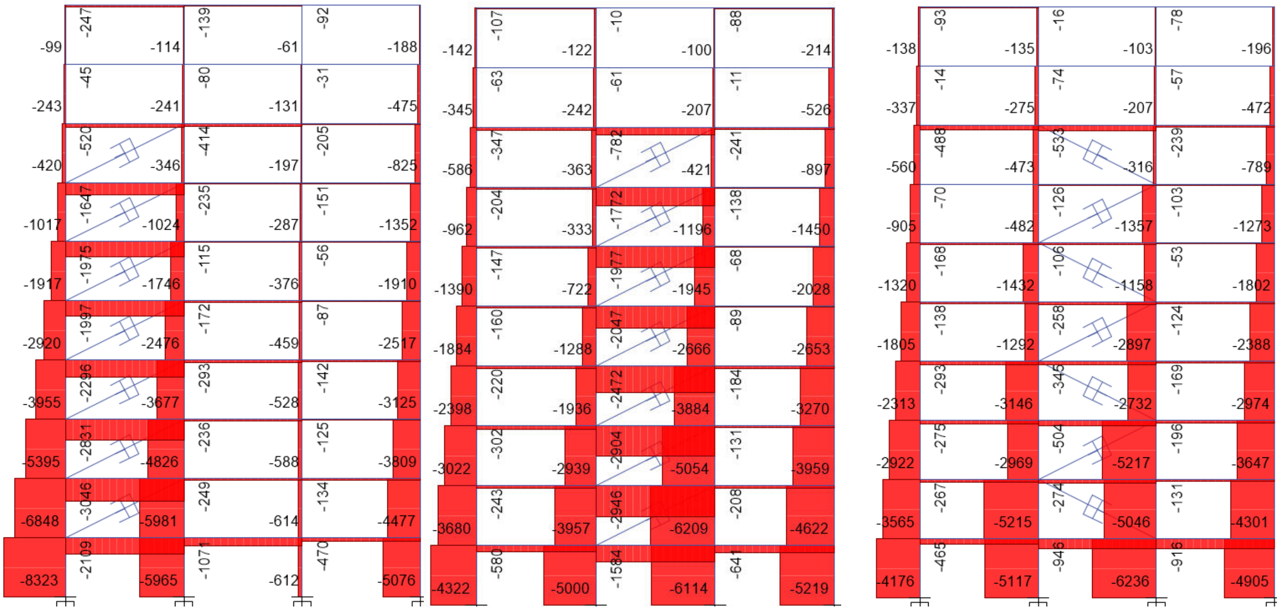
e) Chi Chi f) Tohoku, Japan

Figure 4: maximum seismic drift responses of the structure

Figure 5 also compares the axial forces on the structural members adjacent to the dampers in six different configurations. It shows that in general using either design methods, by decreasing the number of dampers, the axial loads on columns and beams are increasing. Based on that the structural members adjacent to the larger damper forces shall have sufficient capacity to transfer the larger forces. It also shows that the placement of the damper relative to the moment frame actions is critical and can amplify the axial loads on the columns (Figure 5d versus Figure 5e). Figure 5f also shows that by changing the direction of the damper over the height of the building, the applied axial loads from the dampers to the beams will be decreased.



a) SSE(i) b) SSE (ii) c) SSE (iii)



d) ODM(i) e) ODM (ii) f) ODM (iii)

Figure 5: Comparison of axial forces on structural members adjacent to viscous dampers (Northridge-01).

6 CONCLUSION

Based on the response history analyses conducted on the prototype building using the real ground motions, the following conclusions can be made:

1. If the viscous dampers are selected to have the same damping coefficient, the optimal design method will require the least number of dampers but with the largest damper force capacity.
2. The structural members adjacent to the larger damper forces shall have sufficient capacity to transfer the larger forces.
3. The placement of the damper relative to the moment frame actions is critical and can amplify the axial loads on the columns.
4. By alternating the directions of the dampers above the height of the building, the increasing axial loads on the beams (drag forces) can be minimized.

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