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PLACEMENT OF FLUID VISCOUS DAMPERS TO IMPROVE TOTAL-BUILDING SEISMIC PERFORMANCE

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Abstract: Retrofitting conventional buildings with fluid viscous dampers (FVDs) can improve interstorey drifts and floor accelerations: parameters that characterize seismic demands. Many damper placement methods have been proposed, however an optimal method has not been identified. This paper compares several frequently cited damper placement methods. Structural and nonstructural performance is assessed using expected post-earthquake repair costs. The total viscous damping coefficient is constrained for all placement methods. The scope is limited to linear FVDS, concentric braced frames, and regular structures. The examined iterative methods that attempt to optimize seismic performance did not achieve that objective. The storey shear strain energy method and uniform damping generally produced repair costs that are more favorable than, or equal to, the other placement methods. It appears unlikely that large repair cost improvements can be achieved using an “optimal” damper placement method for low- and mid-rise structures.

1 INTRODUCTION

Fluid viscous dampers (FVDs) are one of the most promising dampers for nonstructural performance as they can improve both interstorey drifts and floor accelerations (R. Vargas and Bruneau 2007; R. E. Vargas and Bruneau 2006; Pavlou and Constantinou 2006; Wanitkorkul and Filiatrault 2008; Dicleli and Mehta 2007; Christopoulos and Filiatrault 2006; Astrella and Whittaker 2005). The distribution of dampers within a building is a critical decision that affects both structural response and damper investment. Many placement methods have been proposed, however only limited comparisons of the resulting seismic performance have been conducted (Whittle et al. 2012; Takewaki 1997; Hwang, Lin, and Wu 2013; Lopez-Garcia 2001; Lopez Garcia and Soong 2002; Landi, Conti, and Diotallevi 2015; Levy and Lavan 2006; Cimellaro and Retamales 2007). Variations between storeys and between structural parameters generally prevent an optimal placement method from being conclusively determined. Common limitations of previous research include the use of simplified shear building models, limited ground motion sets, and a small number of placement methods.

This paper evaluates the effectiveness of six damper placement methods considering total-building seismic performance. The placement methods are selected based on prevalence in literature and level of practicality. The total damper coefficient is constrained to be the same in each case. Structural modelling and time history analyses are conducted using OpenSees (McKenna 2017). Expected post-earthquake repair costs are calculated using the FEMA P-58 seismic performance assessment procedure (FEMA 2012). The scope of this paper is limited to regular, concentric braced frame (CBF) structures and linear FVDs. The following discussion should only be extended to other types of structures cautiously.

2 METHODS

2.1 Structural Design

Four-, eight- and 16-storey Eurocode-compliant building designs from the Del Gobbo et al. study (Del Gobbo, Williams, and Blakeborough 2018) were used in this paper, referred to as 4S, 8S and 16S respectively. The steel CBF buildings are representative of structures designed to modern codes for regions with significant seismic hazard. The structures were designed to resist dead, imposed, snow, wind and seismic loads (PGA=0.306g) using the Eurocodes (CEN 2010a, 2010b, 2013, 2010c). Elevations of the structures are shown in Figure 1, with possible FVD locations indicated in red. Figure 2 provides plan views of the structures. The first period (T_1) of the four-, eight- and 16-storey structures were 0.52s, 0.97s and 2.34s, respectively.

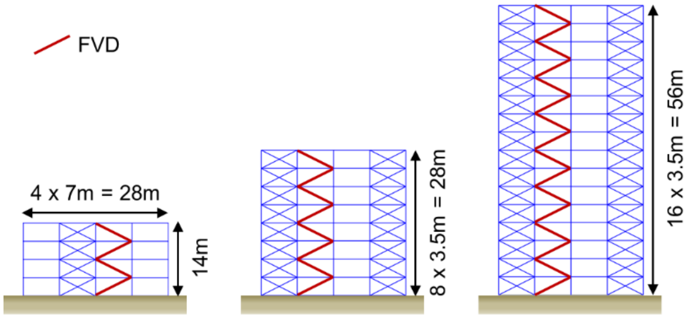
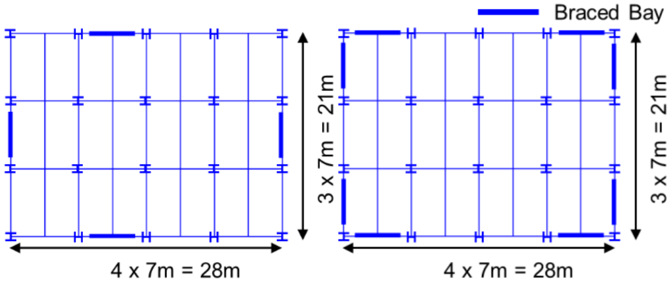


Figure 1: Elevation of office buildings with locations of fluid viscous dampers (FVDs)



(a) (b)

Figure 2: Plan of office buildings (a) 4S (b) All other buildings

2.2 OpenSees Modeling

The structures were modelled in OpenSees (McKenna 2017). Braces were modelled using the Uriz et al. method (Uriz, Filippou, and Mahin 2008) and FVDs were modelled as linear viscous dashpots. Inherent damping of 5% was considered, chosen to match the default for the Eurocode 8 horizontal response spectrum, using mass and tangent stiffness proportional Rayleigh damping (Charney 2008; D’Aniello et al. 2013).

2.3 Ground Motion Suites

Two suites of 25 ground motions, one representing the ultimate limit state (ULS) and one representing the serviceability limit state (SLS), were compiled for each building. Structures are designed to withstand the ULS earthquake (10% probability of exceedance in 50 years) while retaining structural integrity. Damage at the SLS (10% probability of exceedance in 10 years) should be limited to a point that does not compromise building serviceability (CEN 2013). The Eurocode 8 (CEN 2013) response spectrum was used as the target spectrum. Ground motion records were scaled and selected based on the mean squared error between the ground motion and target spectra over the period range of $0.2T_1$ and $2T_1$. The ground motion records were obtained from the PEER ground motion database (PEER 2013). All information regarding the ground motion suites is available in the Del Gobbo et al. study (Del Gobbo, Williams, and Blakeborough 2018).

2.4 FEMA P-58 Building Model

The FEMA P-58 intensity-based nonlinear procedure was used to evaluate seismic performance in terms of repair costs. Damageable building components, both structural and nonstructural, were represented using fragility and repair cost functions. Structural results from nonlinear time history analyses were used with fragility functions to determine probable damage states for the components. Repair cost functions estimated the corresponding losses in dollars. Structural fragility groups and quantities were determined by the structural design. Nonstructural fragility groups and quantities were selected according to the median commercial office building quantities from the Normative Quantity Estimation Tool (FEMA 2012). Direct repair costs in 2011 US dollars resulting from damage to building assets were calculated, while indirect costs due to building downtime were out of scope.

2.5 Damper Placement Methods

Six damper placement methods were selected for comparison. They include both simple (#1-4) and iterative (#5-6) methods. Each method was selected based on prevalence in literature and level of practicality. The following damper placement methods were implemented:

1. Uniform damping
2. Stiffness proportional damping
3. Storey shear strain energy method (SEM) (Hwang, Lin, and Wu 2013)
4. Efficient storey shear strain method (ESEM) (Hwang, Lin, and Wu 2013)
5. Simplified sequential search algorithm (SSSA) (Lopez-Garcia 2001)
6. Fully stressed design algorithm (FSDA) (Levy and Lavan 2006)

2.5.1 Simple Placement Methods

Uniform damping evenly distributes the total viscous damping coefficient throughout the building height. The damping coefficient at storey j (c_j) is

[1] $c_j = \frac{C_{total}}{n}$,

where C_{total} is the total viscous damper coefficient added to the structure and n is the number of storeys.

Stiffness proportional damping distributes C_{total} based on relative storey stiffness. Each storey is given a damping coefficient of

[2] $c_j = \frac{K_j}{\sum_i K_i} C_{total}$,

where K_j is the stiffness of storey j and i is each storey.

The SEM (Hwang, Lin, and Wu 2013) distributes the total damping coefficient in proportion to the shear strain energy of the structure’s first mode. The damping coefficient for each storey is

[3] $c_j = \frac{S_j \phi_{rj}}{\sum_i S_i \phi_{ri}} C_{total}$,

where ϕ_{rj} is the relative modal displacement of storey j and S_j is a storey parameter proportional to the shear force. The parameter S_j is

[4] $\mathrm{S_j} = \sum_{i=j}^{roof} m_i \phi_i,$

where m_i is the mass of the ith-storey and ϕ_i is the modal displacement.

The ESEM (Hwang, Lin, and Wu 2013) is a modification of the SEM. The damping coefficient is allocated only to the storeys with a shear strain energy greater than the average storey shear strain energy. The damping coefficient is distributed to the “efficient” storeys using

[5] $c_j = \frac{S_j \phi_{rj}}{\sum_{z=1}^{k} S_z \phi_{rz}} C_{total}$

where k is the number of storeys whose shear strain energy is greater than the average storey shear strain energy and z refers to all storeys meeting that condition.

2.5.2 Iterative Placement Methods

The SSSA distributes damping in an incremental manner. A time history analysis is conducted of the bare frame and location indices are determined for each storey. An incremental damping coefficient is allocated to the storey with the greatest location index. The damper properties are incorporated into the model and the process is repeated until all dampers have been placed. The location index is maximum interstorey velocity when using linear FVDs.

The SSSA results are dependent on the ground motion used to perform the time history analyses. This study used seven ground motions for each building to conduct the SSSA. The ground motions were chosen based on the smallest mean squared error with respect to the Eurocode 8 spectrum. The median damper coefficient values were selected as the final damper distribution.

The modified FSDA (Lavan and Levy 2009) was the second iterative method implemented in this study. The FSDA minimizes the mean squared interstorey drift for a constrained amount of damping coefficient. The recurrence relationship of

[6] $c_j^{k+1} = c_j^k \left(pi_j^k\right)^{\frac{1}{q}} \frac{C_{total}}{\sum_i c_i^k \left(pi_i^k\right)^{\frac{1}{q}}}$

is used to allocate damping coefficients based on a performance index pi_j^k, where c_j^k is the damping coefficient of the jth-storey at iteration k, and q is a convergence parameter equal to 0.5 for linear problems. The maximum interstorey drift normalized by the allowable interstorey drift is the performance index for 2D linear models. The algorithm terminates once $c_j^{k+1} \approx c_j^k$ for two subsequent iterations. A uniform distribution was used as initial c_j values. The same suite of ground motions from the SSSA were used to conduct the FSDA.

2.6 Comparison Constraint

The total damping coefficient was fixed for each building height, corresponding to 15% total damping in the first mode. The target damping ratio was chosen based on a previous study that evaluated structural parameters (Occhiuzzi 2009). The 15% damping ratio is an approximation, as the final vertical distribution of dampers along the building height can affect the achieved damping ratio.

The C_{total} value was calculated using the energy method from Whittaker et al. (Whittaker et al. 2003) modified to improve its accuracy:

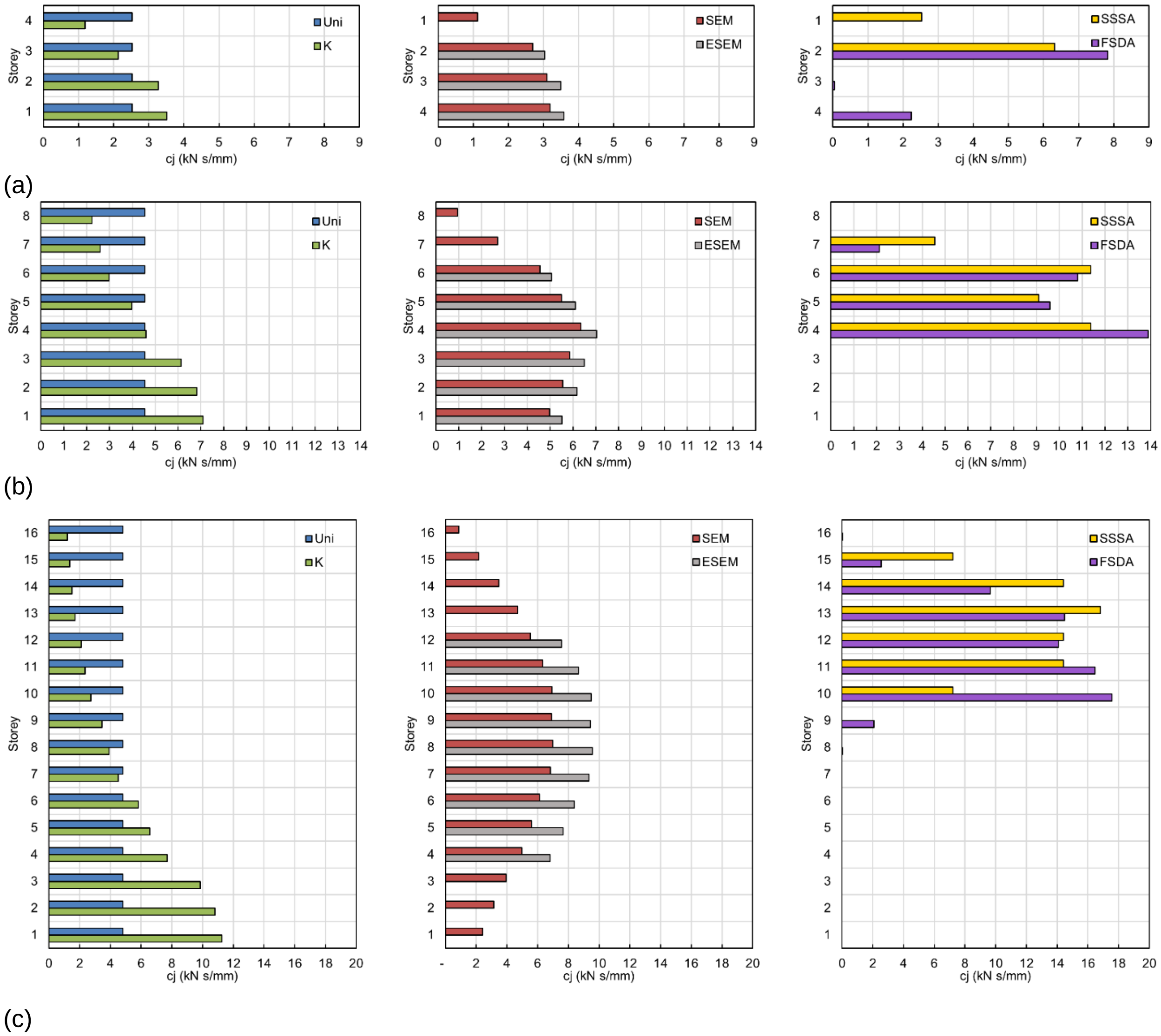
[7] $\zeta_d = \frac{T_1 \sum_j C_j \cos^2 \theta_j \phi_{rj}^2}{4\pi M_1^p \sum_i m_i \phi_i^2},$

where ζ_d is the supplemental damping ratio, θ_j is the angle of damper inclination at storey j, and M_1^p is the modal mass participation factor of the first mode. A uniform damping distribution was assumed. The total damping coefficient was calculated to be 10107 Ns/mm, 36412 Ns/mm, and 76865 Ns/mm for the four-, eight- and 16-storey structures, respectively.

3 RESULTS

3.1 Damper Distributions

The damper distributions resulting from each placement method are compared in Figure 3, where Uni refers to uniform damping and K refers to stiffness proportional damping. Uniform and stiffness proportional damping produced the expected results. The SEM and the ESEM generally placed dampers in the middle storeys, with reduced values of damping in the lower and upper storeys. The SSSA and the FSDA concentrated dampers in the middle to upper storeys.



(a)

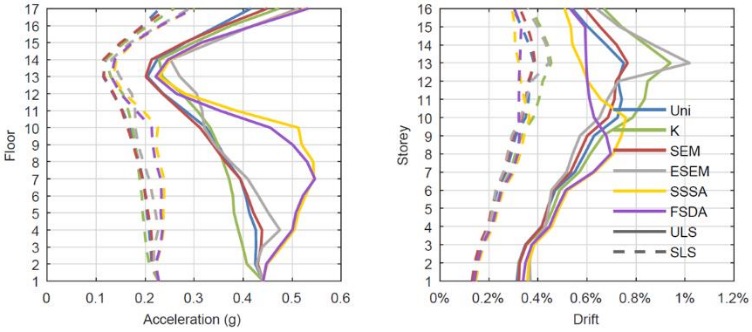
(b)

(c)

Figure 3: Damping coefficient distributions resulting from several damper placement methods (a) four-storey building (b) eight-storey building (c) 16-storey building

3.2 Engineering Demand Parameters

Damper placement methods are conventionally evaluated by comparing engineering demand parameter (EDP) results. The mean of the peak absolute floor accelerations and interstorey drifts per building level are shown in Figure 4 for the 16-storey building. This sample was representative of the typical results for all buildings. No single damper placement method produces optimal results for both interstorey drifts and accelerations. Variations among the SLS results are minimal.



(a) (b)

Figure 4: Comparison of the mean peak EDPs from the different damper placement methods for the 16-storey building (a) absolute acceleration (b) interstorey drift

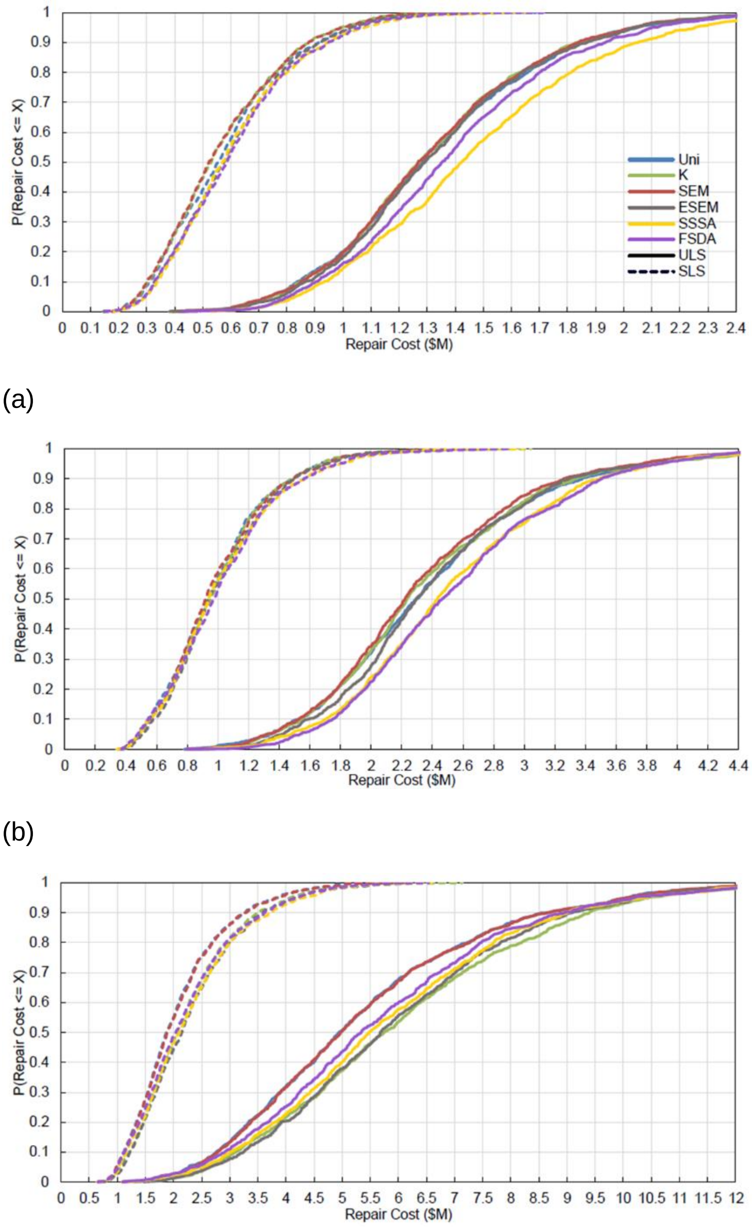
The iterative methods resulted in larger ULS accelerations below the concentration of FVDs with respect to the non-iterative methods. The iterative methods generally resulted in poor ULS interstorey drift control at the storeys without significant damping coefficients and improved interstorey drift control at the upper storeys where FVDs are concentrated (with respect to the non-iterative methods).

Stiffness proportional damping and the ESEM exhibited large ULS interstorey drifts at storey 13 of the 16-storey building. This reveals a limitation of these damper placement methods, as stiffness discontinuities, weak storeys or other structural shortcomings may not be addressed.

An optimal placement method cannot be identified due to variations between storeys and between structural parameters. The use of repair costs is a more appropriate measure of total-building seismic performance that can avoid the limitations of evaluations solely based on EDPs.

3.3 Repair Costs

Cumulative distribution functions of the ULS and SLS total repair costs are shown in Figure 5. The SLS total cost distributions did not significantly vary between the different damper placement methods. In comparison, the ULS costs differed among the various placement methods. The SEM and uniform damper placement generally produced smaller repair costs than the other methods, while the iterative approaches (the SSSA and the FSDA) resulted in larger repair costs. Performance variations between the damper placement methods should not be overstated. All damped models significantly outperformed the bare frame.



(a)

(b)

(c)

Figure 5: Cumulative distribution functions of total repair costs (a) Four-storey (b) Eight-storey (c) 16-storey

The iterative methods purport to optimize a representative measure of seismic performance. However, they often produced the least favorable repair cost distributions. This is partially a consequence of the iterative methods optimizing parameters other than repair costs. Optimizing for a single parameter, such as interstorey drift, may worsen another parameter, such as floor acceleration, that also has a significant impact on earthquake damage. The iterative methods also optimize a local parameter (interstorey drift or velocity of each storey), which indirectly assumes that the performance of each local parameter is independent. In contrast, the placement of a FVD in one storey will change the performance of additional storeys. Further complexities are introduced since the total repair cost is dependent on each individual building level. The concentration of dampers in a small number of storeys encouraged by the SSSA, the FSDA, and the ESEM has an overall negative effect on total-building seismic performance.

4 CONCLUSION

This paper evaluated and compared the effectiveness of several major damper placement methods considering structural and nonstructural performance measured in repair costs. The study was limited to linear FVDs in regular, CBF structures. The total damping coefficient was constrained. Within this scope the following conclusions can be drawn, which should be extended to other types of structure cautiously.

The SEM and uniform damping generally produced repair costs that are more favorable than other damper placement methods. The iterative methods did not optimize total-building seismic performance. Optimizing for a single parameter may worsen another parameter that also impacts post-earthquake repair costs. The concentration of dampers in a small number of storeys encouraged by the SSSA, FSDA, and ESEM has an overall negative effect on seismic performance.

It appears that pursuing optimized linear FVD placement is unlikely to produce significant improvement in post-earthquake repair costs for low- and mid-rise structures. To improve the total-building seismic performance of low- and mid-rise structures using linear FVDs, the SEM or uniform damping should be used with a large target total damping ratio. Damper placement optimization may be more successful for high-rise structures. Practical considerations, such as structural deficiencies of the un-retrofitted structure, may further constrain the placement of dampers.

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