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OPTIMIZATION OF VISCOUS DAMPER PROPERTIES FOR REDUCTION OF SEISMIC RISK IN CONCRETE BUILDINGS

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SUMMARY

Concrete buildings designed in California before 1976 present a major earthquake risk because they do not possess the ductility required to survive the displacements induced by large earthquakes. Consequently, the seismic retrofit of these buildings typically involves the addition of new, stiff structural elements to reduce earthquake-induced displacements. This approach often requires significant strengthening of the structure and typically involves extensive and expensive foundation work that intrudes on building operations. This paper explores the use of viscous dampers as an alternative method for the seismic rehabilitation of non-ductile concrete buildings. The dampers dissipate energy in proportion to velocity and not displacement and therefore do not cause large increases in earthquake forces.

The methodology presented here is based on nonlinear static analyses that are particularly suited to buildings retrofitted with viscous dampers. In such analyses, the effect of external dampers is included by an iterative procedure that modifies the overall building damping to match that from the expected response in the dampers. Once the equivalent damping has been obtained, the design response spectrum is modified to account for the increase in damping. This means that the pushover curve needs to be calculated only once for the unretrofitted building since changes to the damper properties only affect the loading used in the analysis. This approach simplifies and speeds up the optimization by reducing the number of calculations that need to be performed.

The paper presents an optimization technique for selecting damper properties that incorporates the nonlinear behavior of a building. The optimization ensures that the dampers are highly effective, even at relatively small displacements, by selecting properties for dampers at different stories that result in overall minimum cost. An existing building is used as an illustration, and the impact of dampers is evaluated for several building performance levels and ground motion levels.

INTRODUCTION

The 1971 San Fernando Earthquake confirmed that buildings need to possess sufficient ductility, or the ability to sustain inelastic deformations without failure, in order to survive large earthquakes. The

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knowledge gained from the San Fernando Earthquake was incorporated in subsequent building codes to ensure better seismic performance. In concrete buildings, emphasis was placed on the elimination of brittle shear failure modes and the provision of lateral confinement to enable the concrete to achieve the strains imposed by large inelastic displacements. Unfortunately, most concrete buildings constructed before the development of the 1976 Uniform Building Code [1] were designed without the benefit of these more restrictive requirements. Therefore, while these buildings may possess the strength to survive minor to moderate ground shaking without significant damage, they typically do not have enough ductility to survive the displacements induced by larger earthquakes. Older buildings that utilize concrete moment frames as the lateral load resisting system are particularly susceptible. This is because moment frames tend to be more flexible (when compared with concrete shear walls, for example) and therefore deform more during earthquakes. Without sufficient confinement in the form of closely spaced hoops in the plastic hinge zones, a concrete frame cannot remain stable during the large earthquake-induced deformations. In addition, if there is not sufficient shear reinforcement in the beams and columns, brittle shear failures may occur.

There are essentially two ways to improve the seismic performance of concrete moment frames. One method is to improve the deformation capacity of the beams and columns. This can be achieved by applying external confining and shear reinforcement, or jackets made out of steel or composite materials. This is not always possible however, particularly since it is impractical to apply external confinement to beams that are cast monolithically with a concrete floor slab. Another common seismic retrofit approach is to add new structural elements to the building. These new elements, usually concrete shear walls, are designed to possess enough strength and stiffness to reduce the earthquake-induced displacements to a level acceptable to the concrete frame. This approach often requires significant strengthening of the structure by adding new shear walls that may intrude on building operations. In addition, the new shear walls require the construction of new foundations, which are also disruptive and often quite expensive. It is usually not possible to retrofit a building in this manner without significant relocation of the building occupants.

In recent years, supplemental viscous dampers have emerged as a viable option for the seismic rehabilitation of buildings. The additional damping provided by the devices increases the energy absorbed by the structure during earthquakes. This results in a reduction of the displacements and forces induced in structural components. In addition, since dampers dissipate energy in proportion to velocity and not displacement, the damper forces are not in phase with the forces in other structural components. Thus, the foundation work required with conventional retrofit schemes may be eliminated or reduced significantly.

It would therefore seem apparent that dampers should be used to retrofit older, non-ductile concrete buildings. However, it is a widespread opinion that dampers are not effective in concrete buildings because they are not efficient at the lower displacements required to ensure satisfactory performance. This paper illustrates methods of successfully utilizing viscous dampers to improve the seismic performance of concrete moment frame buildings. An existing concrete moment frame building is used to illustrate the concepts. The damper properties are selected by performing an optimization to minimize cost based on nonlinear static analyses. By optimizing the properties of the dampers, they can be made effective even at relatively small displacements. Nonlinear time history analyses are then performed to confirm the results of the analyses.

EXAMPLE BUILDING

An existing four-story reinforced concrete building, which was constructed in the mid 1960s, was selected to illustrate the approach presented in this paper. Figure 1 shows a typical floor plan of the building. The floors consist of waffle slab construction and the building utilizes a concrete moment frame as the lateral load resisting system. As with most buildings of its era, the building's moment frame was not detailed in a manner that would provide the ductility required to survive a major earthquake. While the beams and columns have closely spaced shear reinforcement in the plastic hinge zones, the lateral reinforcement is not anchored within the confined core, as shown in Figure 2. The details shown in Figure 2 will be ineffective during high ductility demands because the lateral reinforcement will lose its confining ability once the cover concrete spalls. Another deficiency in the design is the fact that the typical column shear capacity is less than the shear corresponding to the development of maximum moments in the column. This means that there is a significant possibility of brittle shear failure in the columns during a major earthquake.

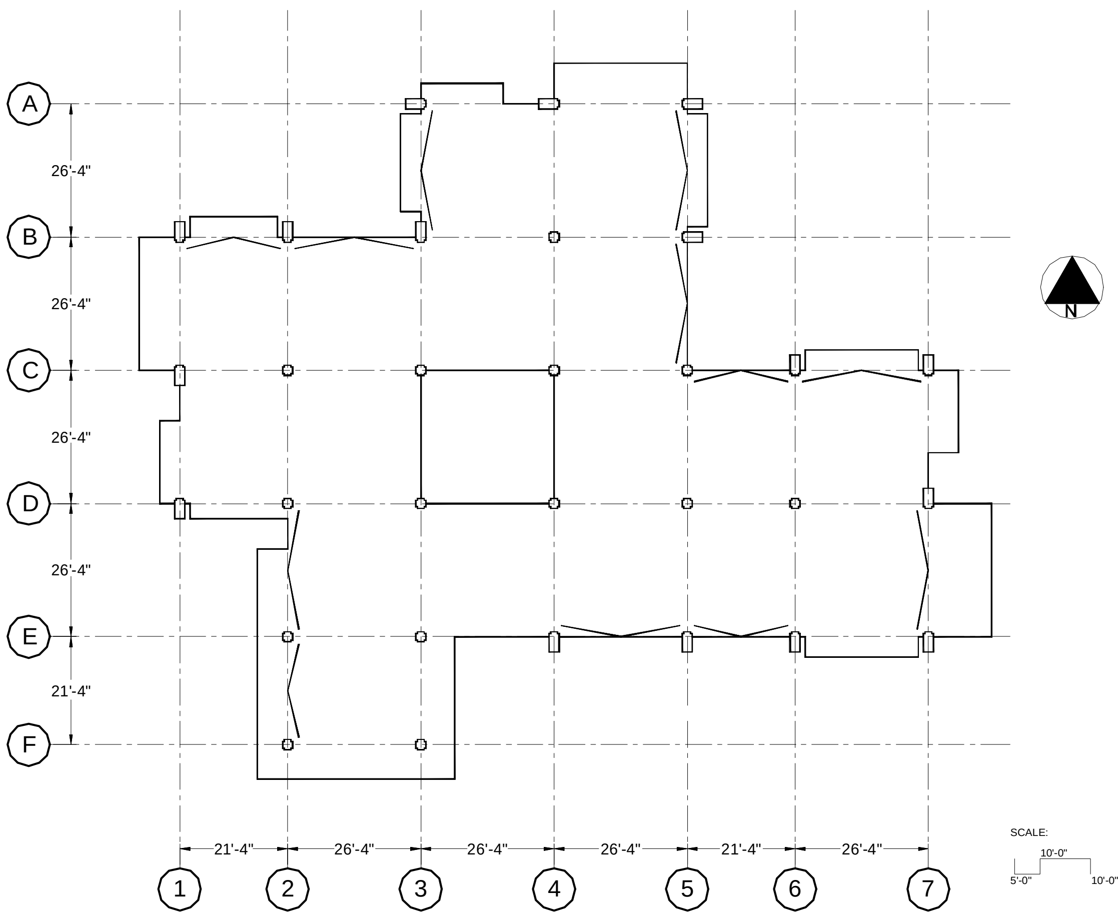

Figure 1 Typical Building Floor Plan

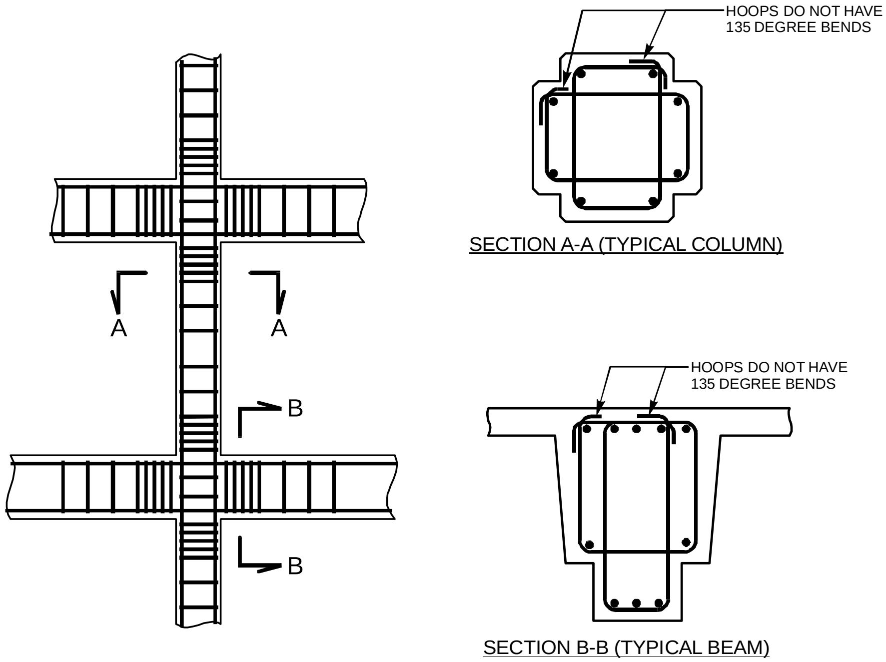

Figure 2 Typical Detailing of Beams and Columns in Plastic Hinge Zones

A nonlinear static (pushover) analysis of the existing structure was performed using the procedures prescribed in FEMA 356 Prestandard for the Seismic Rehabilitation of Buildings [2]. SAP2000 [3] structural analysis program was chosen for modeling and analysis of the structure. Figure 3 illustrates the computer model of the existing building. The beams and columns were classified as nonconforming elements and evaluated for life safety performance during an earthquake with a ten percent chance of being exceeded in fifty years. After developing the pushover curve for the building, the iterative procedure to calculate the displacement demand was performed using an in-house computer program. Figure 4 shows that as expected, the building does not satisfy the life safety criteria.

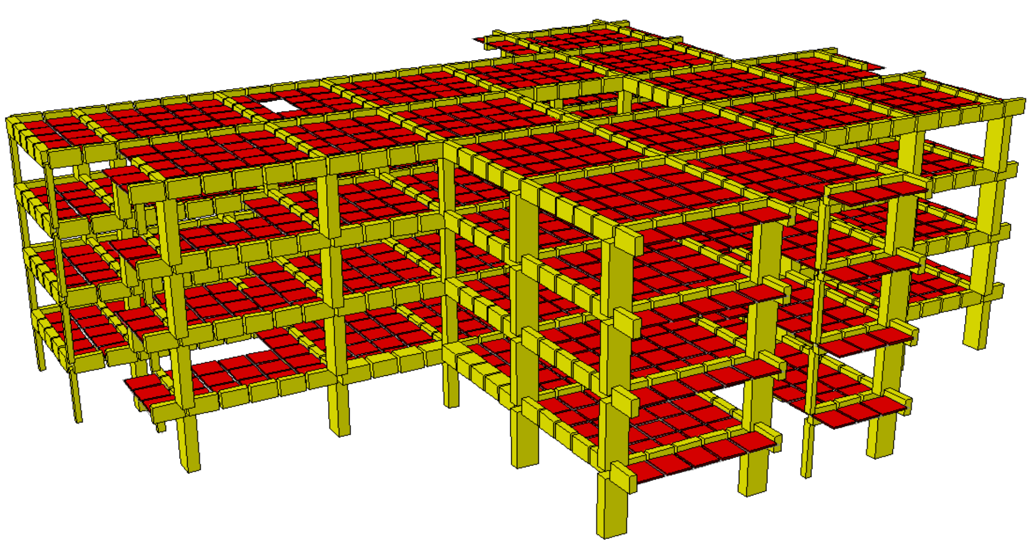

Figure 3 Computer Model of Existing Building

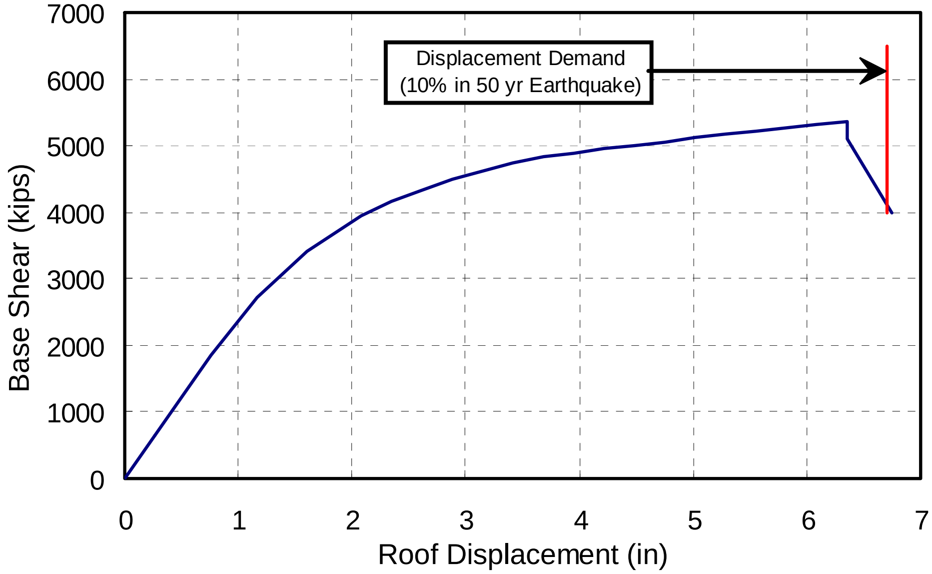

Figure 4 Computer Model Pushover Curve for Existing Building

To alleviate the deleterious effects of an earthquake on the existing building, a retrofit scheme was developed using viscous dampers. The locations of the dampers used in the retrofit scheme are shown by the braces in Figure 1. Dampers where placed at the same location in all four floors of the building. Figure 5 shows a computer model of the retrofitted building. The properties of the dampers were optimized to minimize cost by performing nonlinear static analysis to determine the cheapest dampers that kept the building response within acceptable limits.

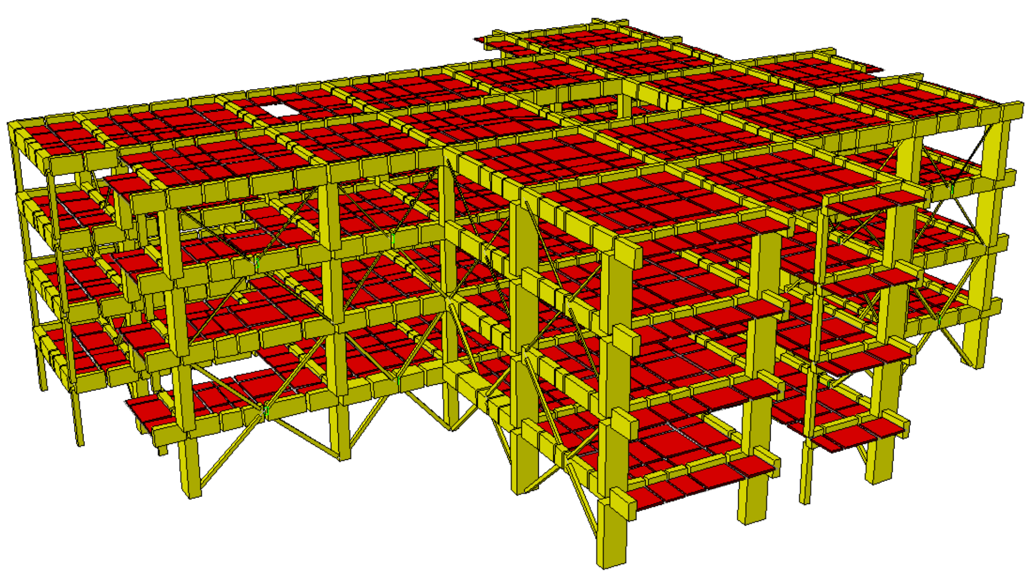

Figure 5 Computer model of the retrofitted building

NONLINEAR STATIC ANALYSIS WITH VISCOUS DAMPERS

FEMA 356 prestandard (FEMA [2]) outlines procedures for performing nonlinear static analyses for buildings that utilize dampers to reduce earthquake response. For the velocity-dependent devices used in this study, the procedures involve reducing the response spectrum, or demand on the building, by the amount corresponding to the additional effective damping provided by the dampers. For a damper with a linear relationship between damper force, F and velocity v, the damping equation is given by (Hart & Wong [4]):

$$F = Cv \tag{1}$$

where C is the damping coefficient for the device. Since the relationship between velocity and displacement, δ is given by:

$$v = \omega\delta \tag{2}$$

in which ω is the natural frequency, Equation (2) can be substituted in Equation (1) to give:

$$F = C\omega\delta = C\frac{2\pi}{T}\delta \tag{3}$$

where T is the period of vibration. Considering the elliptical force versus deformation hysteresis loop for dampers as illustrated in Figure 6, the work, W done by a damper is given by:

$$W = \pi F\delta \tag{4}$$

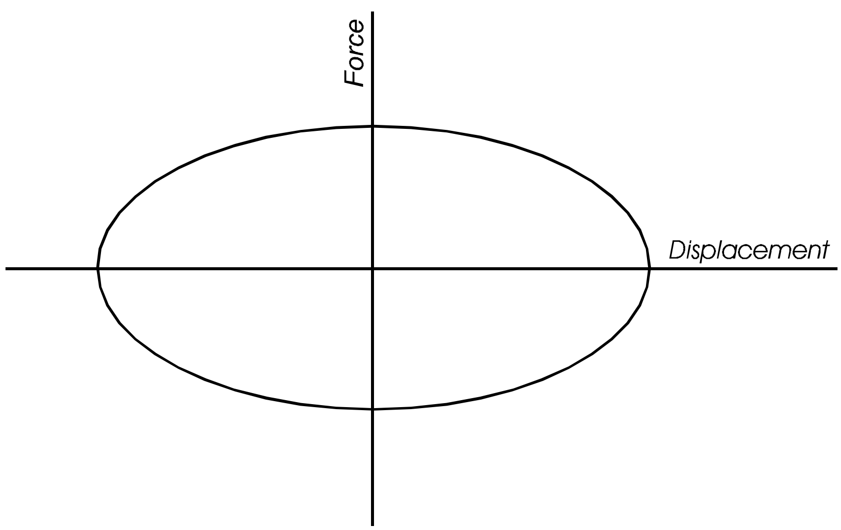

Figure 6 Typical Force versus Displacement Relationship for a Velocity–Dependent Viscous Damper

Substituting Equation (3) into Equation (4) we obtain:

$$W = \frac{2\pi^2}{T}C\delta^2 \tag{5}$$

The FEMA prestandard provides the following equation for the effective damping β_{eff} for a building with velocity-dependent viscous damping devices:

$$\beta_{eff} = \beta + \frac{\sum_j W_j}{4\pi W_k} \tag{6}$$

where W_j is the work done by device *j* in one complete cycle of loading as obtained from Equation (5):

$$W_j = \frac{2\pi^2}{T_{ss}} C_j \delta_{rj}^2 \tag{7}$$

where C_j is the damping constant for device *j*, and δ_{rj} is the relative displacement between the ends of device *j* along the axis of device *j* at a roof displacement corresponding to the target displacement, and the summation of W_j extends over all devices *j*. The maximum strain energy in the frame, W_k, is calculated as

$$W_k = \frac{1}{2} \sum_i F_i \delta_i \tag{8}$$

where F_i is the inertia force at floor level *i*, δ_i represents the floor displacement, and the summation extends over all floor levels. The damping in the framing system, β is usually equal to 5%.

The above derivation must be modified when there is nonlinearity in the response of the dampers, which is in the form of the following relationship (Hart & Wong):

$$F = Cv^{\alpha} \tag{9}$$

where α is the velocity exponent. The force in damper is then given by:

$$F = C(\omega\delta)^{\alpha} = (\frac{2\pi}{T}\delta)^{\alpha} C \tag{10}$$

Consequently, the work done in one elliptical hysteresis cycle of nonlinear dampers will be:

$$W = \pi F \delta = \pi(\frac{2\pi}{T}\delta)^{\alpha} C\delta \tag{11}$$

Using the above relation to calculate the equivalent of Equation (7) for non-linear dampers, we obtain:

$$W_j = \frac{2^{\alpha}\pi^{\alpha+1}}{T_{ss}^{\alpha}} C_j \delta_{rj}^{\alpha+1} \tag{12}$$

Equation (12) is used in to calculate the work done in each damper, W_j, for use in obtaining the equivalent damping the ratio, β_{eff}, with Equation (6).

OPTIMIZATION OF DAMPER PROPERTIES

It is often a challenge to present the damper costs in a manner that is readily accepted and understood by the engineering and construction community. Traditional construction costing tools utilize square footage as the basis for determining and evaluating appropriate costs. However, this method has no relationship to the factors that determine the cost for dampers themselves or the cost to the overall project. Instead, the factors that determine the cost of a damper are the maximum earthquake force and the maximum stroke (displacement). Special requirements such as buckling, impact of installation schemes, environmental exposure to heat, cold, and hazardous materials (which require non-standard metals such as stainless steel), the quantity of dampers for the project and the amount of prototype and production testing also have a significant impact on costs.

Damper costs increase with an increase in maximum force and/or stroke because a larger diameter and/or longer cylinder and piston rod, and thus more material, is needed to resist large loads. Damper costs are determined as a function of the combination of force (F), stroke (S), special requirements (SR) and quantity (Q) or *f* (F, S, SR, Q). Table 1 provides a representation of the relationship between these factors and cost for a variety of viscous dampers. The table does not represent actual costs for a specific type of damper but illustrates general trends for incremental costs for use in the optimization process.

The optimization process offers the community opportunities to minimize the dampers costs for a particular project, while maximizing the benefit to the structure.

Table 1 Variation of Cost for Dampers with Maximum Force and Stroke

	Stroke (S)	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Force (F)									**Quantity (Q)**
50									**275**
100									**250**
150									**200**
200									**175**
250									**150**
300									**125**
350									**100**
400									**75**
450									**50**
500									**25**
Special Requirements (SR):		**Standard**		**Special**		**Very Special**			

Incremental Cost Increase
***f* (F, S, SR, Q)**

Engineers, however, do not know the maximum force or stroke that is required until the design has been completed. Instead, they select the damper properties (damping coefficients, C and the velocity exponents, α, that modify the building response to satisfy the deformation criteria. The maximum forces on the dampers, which are obtained from Equation (9) or (10), and maximum strokes, which are obtained from computer analyses, are then provided to the damper manufacturer. This means that the relationship between damper properties and cost is extremely complex and nonlinear, not only because the effect of damping on building response is a nonlinear phenomenon, but also because there is no direct relationship between the selected damper properties and cost.

This paper presents an optimization procedure that ensures the selection of the most economical damper properties that satisfy the design criteria. Figure 7 shows the basic methodology of the procedure. As shown in the figure, the damper characteristics are selected from a pool of available properties. The developed computer program calculated the displacement demand for the effective damping due to dampers. After each analysis, the costs are determined based on a table such as that shown in Table 1. A key aspect of the methodology is the fact that the optimization is based on a nonlinear static analysis. This approach simplifies and speeds up the optimization by reducing the number of calculations that need to be performed. In a nonlinear static analysis, as explained earlier, the effect of external dampers is included by an iterative procedure that modifies the overall building damping to match that from the expected response in the dampers. Once the equivalent damping has been obtained, the design response spectrum is modified to account for the increase in damping. This means that the pushover curve needs to be calculated only once for the unretrofited building since changes to the damper properties only affect the loading used in the analysis. After the damper properties have been optimized, the results may be confirmed by a more sophisticated nonlinear time history analysis. Table 2 shows the results of the optimization for the example building.

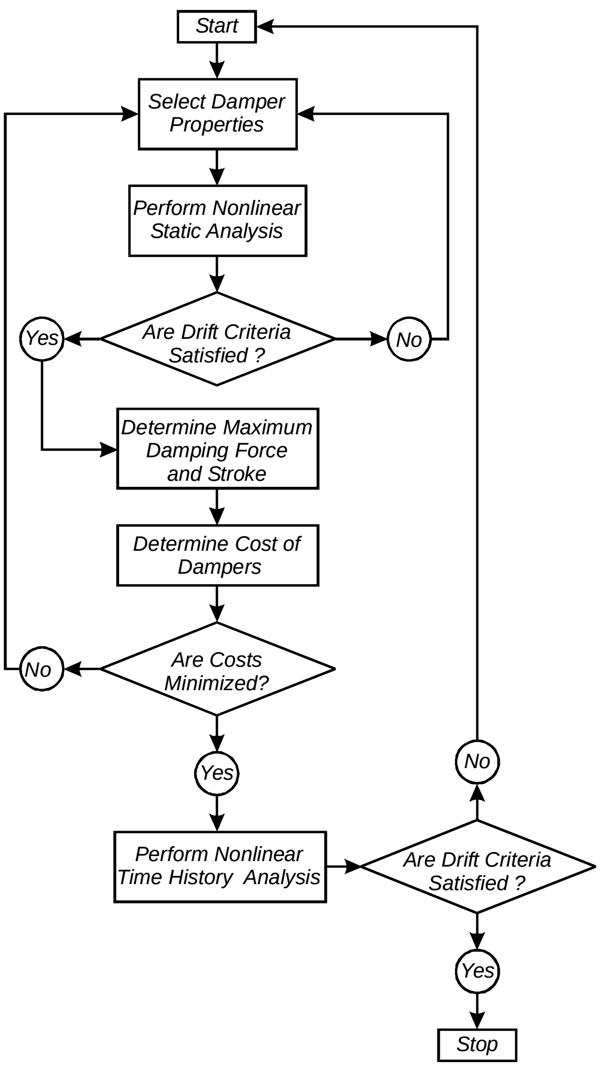

Figure 7 Optimization Procedure for Selecting Dampers

Table 2 Results of the Optimization for the Example Building

Story	Damping Coefficient, *C* (kip-sec/in)	Velocity Exponent, α
1	150	0.4
2	150	0.5
3	100	0.4
4	100	0.4

COMPARISON OF NONLINEAR STATIC ANALYSIS WITH NONLINEAR TIME HISTORY ANALYSES

Figure 8 shows the displacement demand from the design earthquake on the pushover curve for the retrofitted building. The viscous dampers reduced the buildings roof displacement by about 60% and resulted in plastic rotations in beams and columns that are within the acceptable limits for life safety performance.

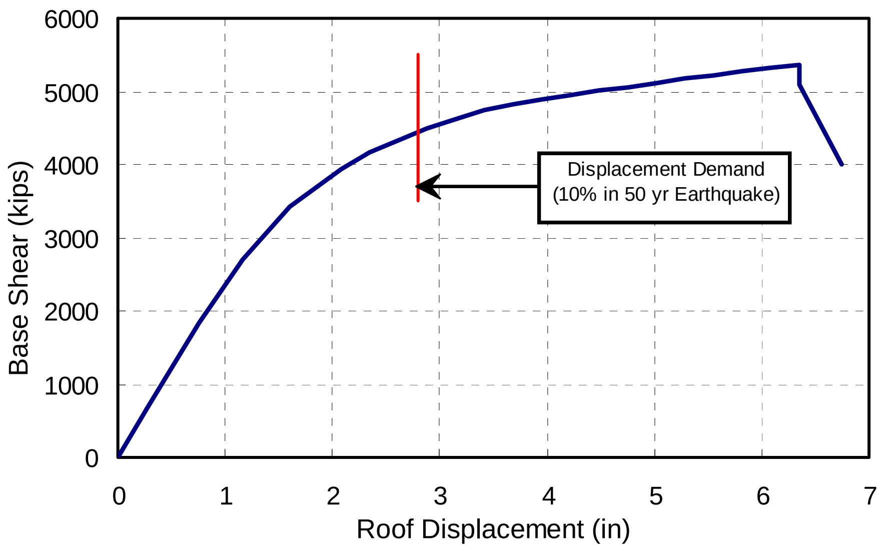

Figure 8 Displacement Demand on Retrofitted Building Using Nonlinear Static Analysis

Nonlinear time history analyses were performed to determine the accuracy of the results obtained from the optimization using nonlinear static analysis. Three acceleration time histories were selected - the S00E component of the El Centro record from the 1940 Imperial Valley Earthquake, the S16W component of the Topanga Canyon record of the 1994 Northridge Earthquake, and the S48W component of the Rinaldi record of the 1994 Northridge Earthquake. The Rinaldi record represents a near source ground motion. The three earthquake ground motions were scaled so that the Effective Peak Acceleration was equal to the design level acceleration as determined by the 1997 Uniform Building Code. Figure 9 shows the response spectra of the time histories in comparison to the Design Earthquake Spectra from the building from the 1997 Uniform Building Code. The near-source nature of the Rinaldi record is apparent in the figure.

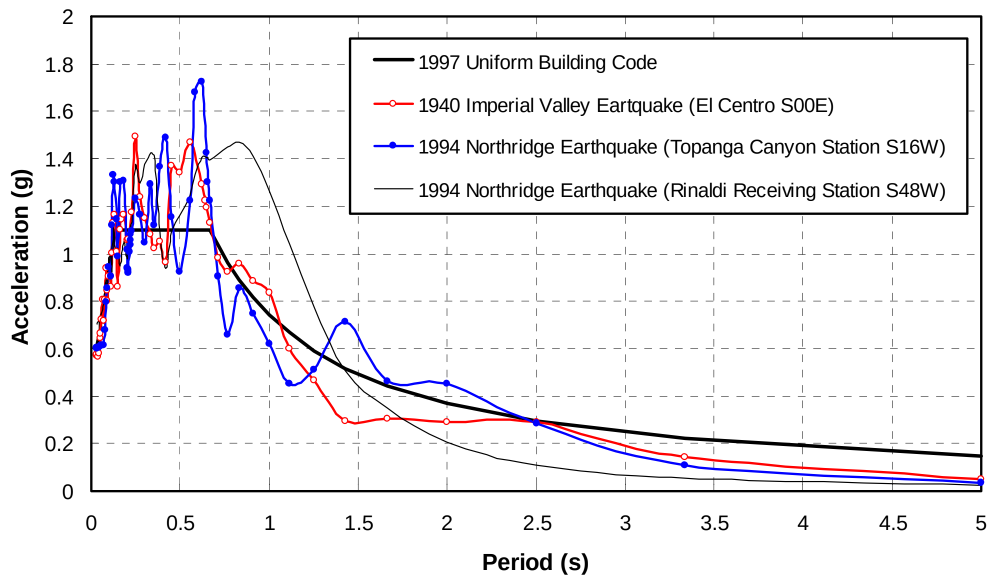

Figure 9 Comparison of scaled 5% Damped Acceleration Response Spectra for Selected Time Histories with Design Spectra from the 1997 Uniform Building Code

Some comparisons of the results from the time history analyses and the nonlinear static analysis are shown in Figures 10 to 12. The analyses compare favorably, with the maximum differences in story drifts and damper forces of 15% for the El Centro and Topanga Canyon Records. For the Rinaldi record, the differences are larger because of the near source velocity pulse. The nonlinear static analysis consistently gives smaller response quantities than the nonlinear time history analyses. This is particularly true for the near-source Rinaldi record. Figures 13 and 14 compare the time history of the roof displacement and base shear of the existing structure with that of the retrofitted structure. The dampers reduce the maximum roof displacement by about 50% and base shear by about 35%.

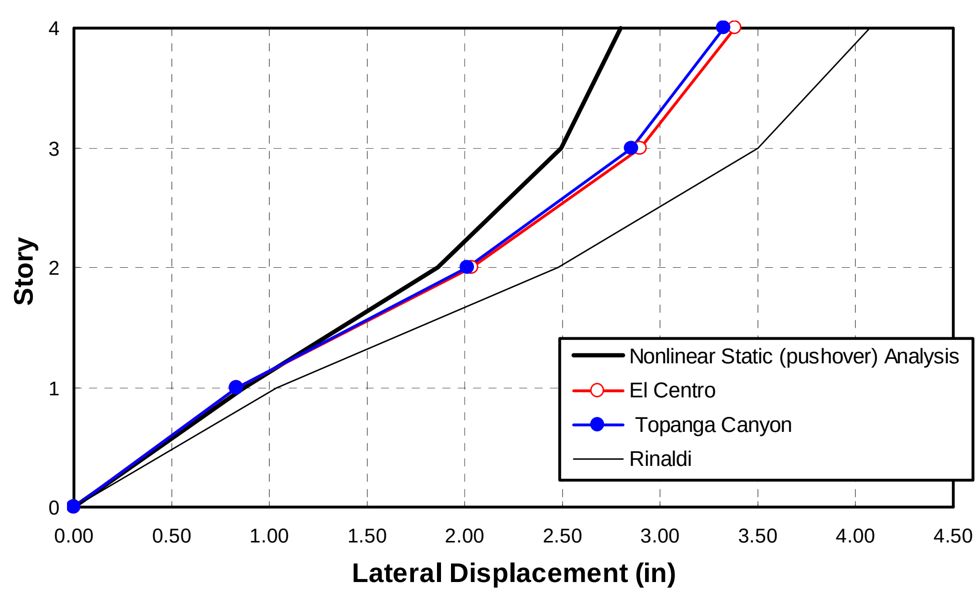

Figure 10 Comparison of Maximum Story Displacements from Various Analyses

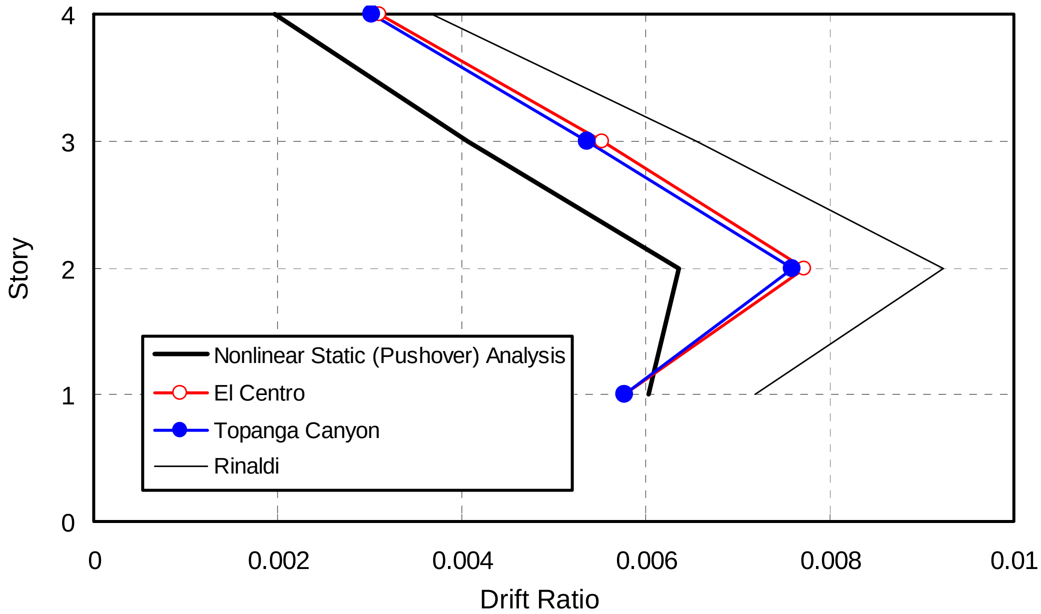

Figure 11 Comparison of Maximum Story Drifts from Various Analyses

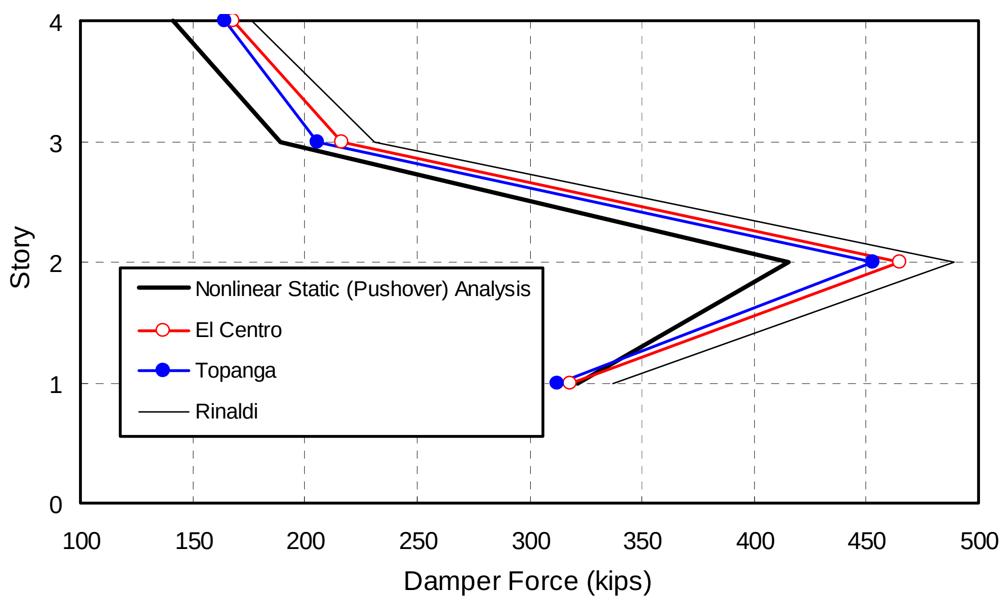

Figure 12 Comparison of Maximum Damper Forces from Various Analyses

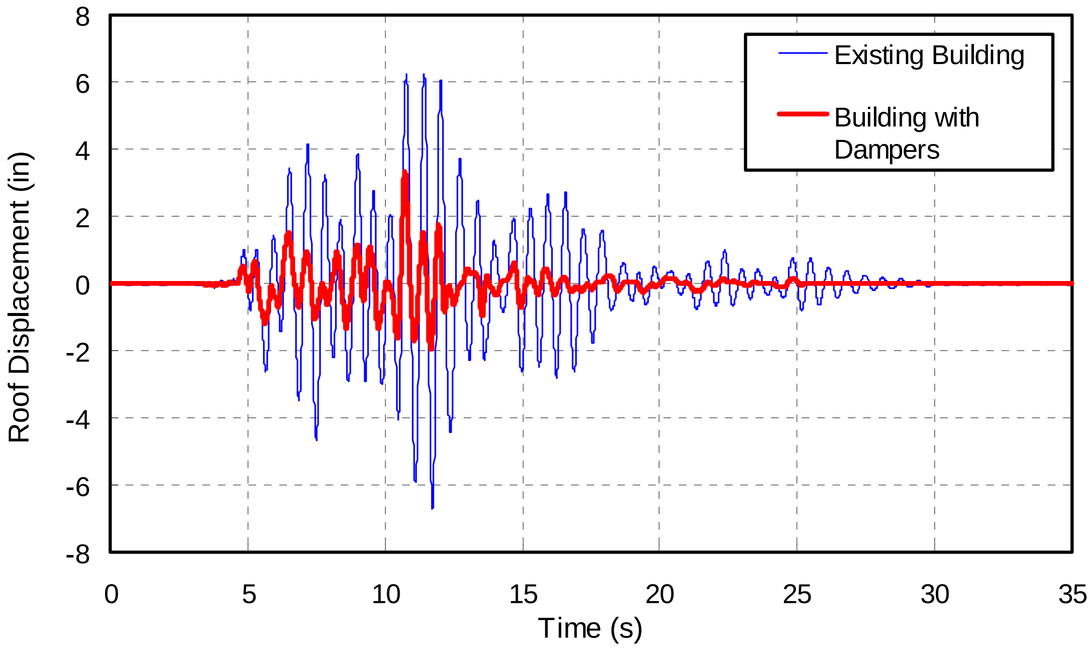

Figure 13 Comparison of Roof Displacement for Existing and Retrofitted Building

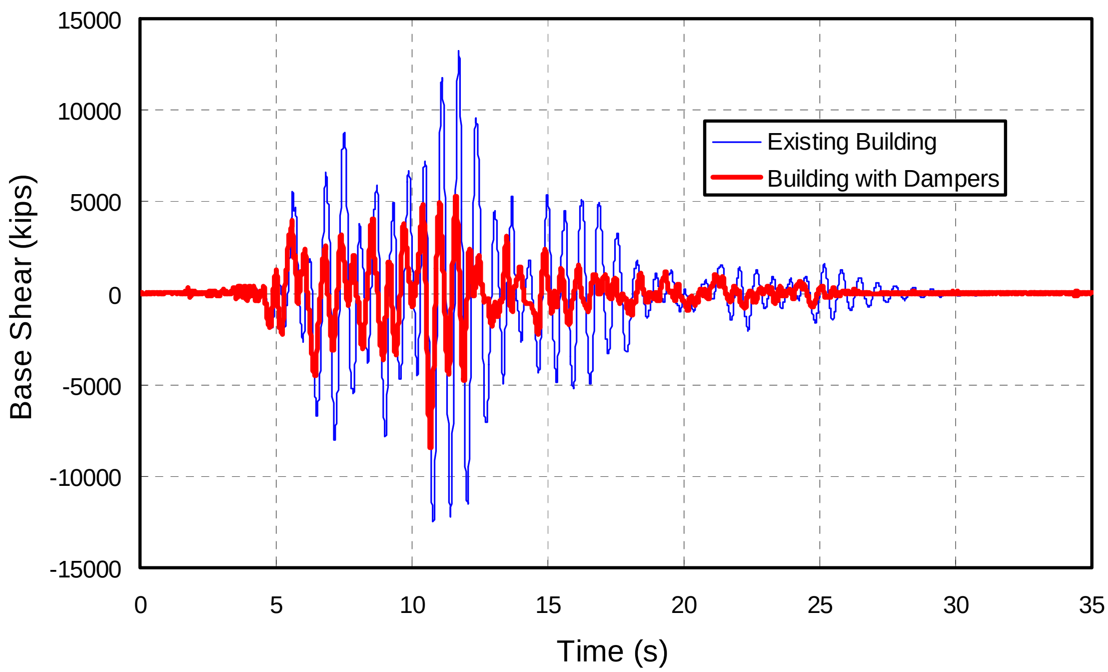

Figure 14 Comparison of Base Shear for Existing and Retrofitted Building

CONCLUSIONS

Viscous dampers can be extremely effective in improving the seismic performance of concrete buildings when the damper properties are optimized to ensure efficient performance. For the building studied, reductions in displacements in the order of 50% were obtained. The plastic rotations in the beams and columns were reduced to levels acceptable for life safety performance. The optimization process also provides the engineer with the ability to minimize the dampers costs for a particular project, while maximizing the benefit to the structure.

Nonlinear static analyses tend to underestimate the response due earthquakes when compared with a nonlinear time history analysis. However, the differences in the two analyses methods are small enough to be acceptable for use in performing the optimization or for developing preliminary designs. Improvement in the displacement coefficient method, which has been recommended by researchers (Miranda [5]) should further improve the accuracy of the results.

The damper characteristics for different stories were selected from a pool of available properties. For each configuration, the cost of dampers was calculated and the configuration that resulted in minimum cost was selected as the optimum solution. This method (Total Enumeration) proved efficient for a building of the size of the example building and with the chosen range of variation for damper properties. However, for buildings with more stories, the total possible permutation of damper properties for different stories will make it impossible to perform total enumeration. In such cases an efficient heuristic search method, such as Genetic Algorithm could be used to perform optimization and will be subject of future studies.

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