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Paper No. 1911. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ANALYTICAL INVESTIGATION OF THE RESPONSE OF A BUILDING WITH ADDED VISCOUS DAMPERS

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ABSTRACT

An analytical investigation of the seismic response of a multi-story building retrofitted with supplemental viscous damping devices which are implemented at the first floor is presented. A three-dimensional SAP90 computer model of the existing building (without dampers) was used to obtain the reduced, fully populated, two-dimensional stiffness matrix in the longitudinal direction of the building, corresponding to one translational degree of freedom per floor. Using the reduced eight DOF stiffness matrix, a two-dimensional simplified model was constructed, where the floor masses were lumped at the floor nodes. Using a suite of six earthquake ground motions, three design basis site-specific earthquake ground motions and three near-field synthetic earthquakes, a series of non-linear time history dynamic analyses of the two-dimensional simplified model were performed using the computer program SAP90, which considered only the damper element at the first floor to be non-linear. The series of analysis provided an understanding of the sensitivity of the building's structural response to different design, construction, and ground motion parameters. These included the effect of the stiffness of damper assemblies and connections, the effect of the damper non-linearity on the maximum damper and structural base shear forces and response reduction, and the effect of ground motion intensity and frequency characteristics on the response reduction.

KEYWORDS

Seismic Retrofit; Building Response; Earthquake Response; Time-History Analysis; Dynamic Analysis; Viscous Damper; Passive Energy Device

INTRODUCTION

Viscous passive damping devices have lately emerged as one of the alternative technology devices that are available for use in the seismic design of building structures. Recent advances in personal computers and structural analysis programs have made it possible for structural engineering offices to implement this technology in new and seismic retrofit projects. However, the use of such devices in the design offices is still limited due to the added difficulty in performing the required structural analysis involved when compared to conventional methods of design and retrofit. In addition, the engineering experience that structural engineers typically posses in conventional seismic design is lacking when viscous dampers are used. This paper attempts to expand the engineering experience by studying the sensitivity aspects of the seismic response of buildings where viscous dampers are implemented. It also shows the appreciative reduction in building response when viscous dampers are utilized.

An eight story concrete building in Los Angeles was modeled as a two-dimensional eight degrees of freedom structure, corresponding to one translational degree of freedom per floor. The building without added dampers was assumed to be five percent of critical in all modes. The analysis performed on the existing building, using site specific Design Basis Earthquake ground motions (DBE), indicated that the first floor was a weak-soft story, and would pose life-safety hazard during major earthquakes. Therefore, viscous dampers were added at the first floor in order to decrease the ductility demand on the first floor.

This paper discusses in general the reduction in structural response realized when viscous dampers are utilized. A series of studies were performed on the retrofitted building using non-linear time history dynamic analysis to quantify the sensitivity of the reduction in the building's structural response to different design and ground motion aspects.

BUILDING DESCRIPTION

The building considered is an eight-story cast-in-place reinforced concrete frame and shear wall structure that is located near downtown Los Angeles. It was designed under the 1964 UBC and constructed in 1968. The building has a rectangular floor plan that is 63 by 154 feet, and the building height is approximately 114 feet. Story heights are 13 feet for typical floors and 21 feet for the first floor. The foundation support for the structure consists of drilled concrete caissons.

The floor framing system consists of cast-in-place lightweight concrete slabs, beams and girders. Deep transfer girders at the second floor transfer the loads from the columns and walls above the second floor to the first story columns. The lateral load resisting system of the building from the second story through the roof consists of cast-in-place reinforced concrete shear walls. Deep concrete and concrete encased steel transfer girders at the second floor support the shear walls and transfer the lateral overturning forces to the first story columns. The first floor lateral force resisting system consists of only concrete columns, with no concrete walls present.

DESIGN OF THE SEISMIC RETROFIT

The objective of the seismic design criteria for the building was to strengthen the building to provide life safety protection for the Design Level Earthquake, DBE, which has a ten percent probability of exceedence in fifty years. A three-dimensional detailed computer model of the building was developed using a new version of the program SAP90 (Computer & Structures, 1995) that permits the modeling of the non-linear properties and spatial distribution of viscous dampers in the building. The model contained all the concrete beams, columns, and shear walls. The concrete floor and roof were modeled as rigid diaphragms, and the floor mass location and torsional properties were incorporated. The existing concrete beams, columns, and shear walls effective stiffness, i.e., effective moment of inertia, were calculated and used in the model.

A linear dynamic response spectra analysis was performed on the existing building (without dampers) using site-specific Design Level Earthquake spectra. The analysis showed that the first floor columns experienced excessive non-linear deformations, and thus posed a life safety hazard for the building occupants.

The retrofit of the building consisted of introducing viscous passive energy dissipation elements (viscous dampers) in the first floor level. This reduced the building response to earthquake ground motions by dissipating the earthquake ground motion energy through viscous damping. A series of non-linear time history dynamic analysis was performed using four horizontal pairs of DBE spectra-compatible earthquake ground motion records, and the optimum level of added damping and the dampers' non-linear characteristics were obtained. The non-linear time history analysis performed assumed the building elements to remain elastic and the non-linear behavior to be limited only to the viscous dampers.

Viscous dampers dissipate energy based on the principle of fluid flowing through orifices. The behavior of these devices in seismic energy dissipation has been experimentally and analytically verified, and their properties have been confirmed in shaking table testing (Constantinou et al, 1993, and Hanson et al, 1993). The force-velocity relationship of a viscous damper can be modeled by:

$$F = C_0 |\dot{u}|^{\alpha} \operatorname{sgn}(\dot{u}) \tag{1}$$

Where F is the force output, C_o is a damping constant, $\dot{u}$ is the damper's piston rod velocity, and α is a velocity coefficient in the range of 0.4 to 2.0.

Six and eight dampers of 300 kips maximum force per damper were required for the transverse and longitudinal building direction, respectively, with a damping coefficient of $C_o = 100$ kip.sec./in (17.5×10^3 kN.sec/m), and an α coefficient of 0.7. Figure 1 shows a typical location of a damper at the first floor level.

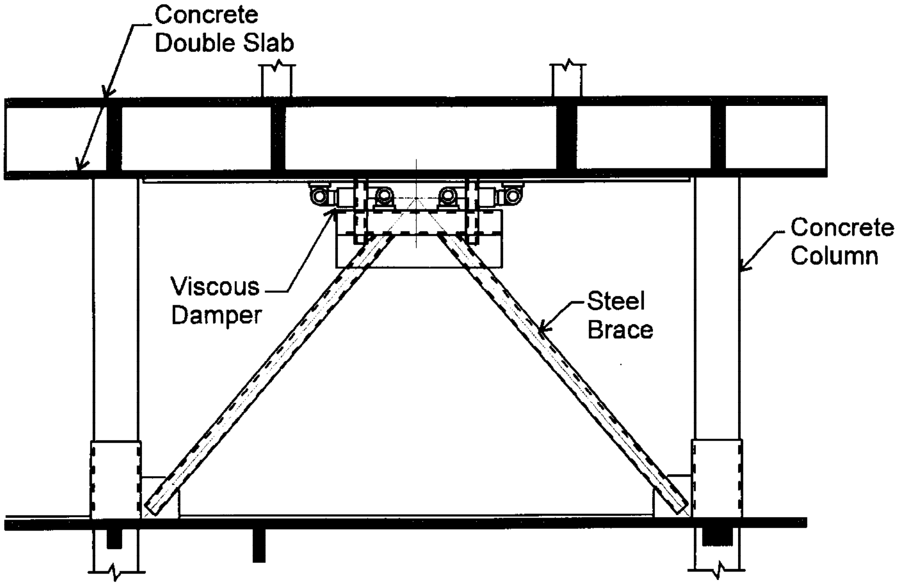

Fig. 1. Typical Configuration of Damper Assembly

ANALYTICAL INVESTIGATION OF THE RESPONSE SENSITIVITY

As part of this research, the three-dimensional SAP90 computer model of the existing building (without dampers) was used to obtain the reduced, fully populated, two-dimensional, eight degrees of freedom (DOF) stiffness matrix in the longitudinal direction of the building, corresponding to one translational degree of freedom per floor. Using the reduced two-dimensional eight DOF stiffness matrix, a two-dimensional SAP90 simplified model was constructed, corresponding to one node per floor. The floor masses were lumped at the simplified model floor nodes. The damping provided by the building alone, i.e., without added external dampers was assumed to be five percent of critical in all modes. Since it was derived from a fully populated stiffness matrix this simplified SAP90 model accounted to all the stiffness coupling between all floors, and when compared to the original three dimensional SAP90 model, the periods and dynamic characteristics were identical in the longitudinal direction.

The ground motions used in this study were three DBE site-specific earthquake ground motions, and three synthetic earthquakes generated to simulate the estimated ground motions of the Northridge Earthquake for a site within five miles of the epicenter, i.e., near-field site. The three synthetic earthquakes were scaled so that their Peak Ground Acceleration, PGA, match those of the DBE site-specific ground motions. Figure 2 shows the acceleration and velocity response spectra of the six ground motions used.

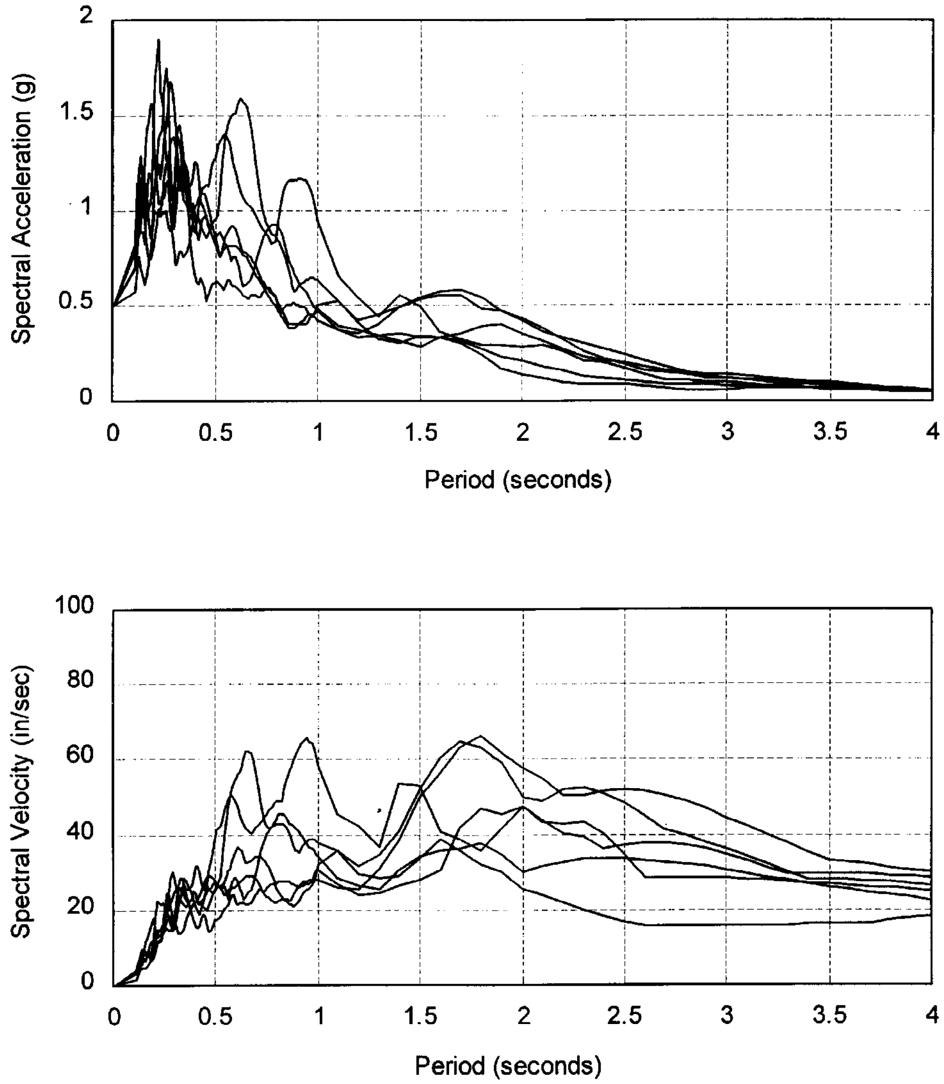

Fig. 2. Acceleration and Velocity Response Spectra for Ground Motion Time Histories

A series of non-linear time history dynamic analyses of the two-dimensional simplified model was performed using the computer program SAP90. The analysis assumed that the building remained essentially linear and only the damper element at the first floor was non-linear. The series of the analysis aimed at understanding the sensitivity of the building's structural response to different design, construction, and ground motion parameters as follows:

a) Effect of the stiffness of damper's bracing and connections on the effectiveness of the damper.
b) Effect of the damper non-linearity (exponent) on:
    - Damper maximum forces and structural base shear.
    - Building base shear and response reduction.
    - Force phase relation between the damper forces and building forces.

c) Effect of ground motion characteristics on the response reduction:
   - Effect of intensity of ground motion.
   - Effect of frequency content and near field ground motion.

Effect of Stiffness of Damper's Braces and Connections

As is typically the case, each damper is installed at the top of a free standing cantilever Chevron brace, and connected to the second floor beam through a rigid connection, as shown in Fig. 1. Chevron brace frames are usually thought of as rigid systems and their properties are determined based on strength. However, as shown in this study, in case of viscous dampers, Chevron braces sized for strength are usually not stiff enough, and the effectiveness of dampers may be greatly compromised.

Figure 3 shows the effect of changing the brace stiffness (size) on the first floor drift, based on one DBE ground motion. It is clearly apparent that the Structural Engineer should design the braces so their stiffness falls near or within the flat area of the curve, so a small variation of the system stiffness would not compromise the effectiveness of the dampers in reducing the response. Also, an allowance should be provided to account for slippage and the flexibility of the connections, which are typically not modeled in the design.

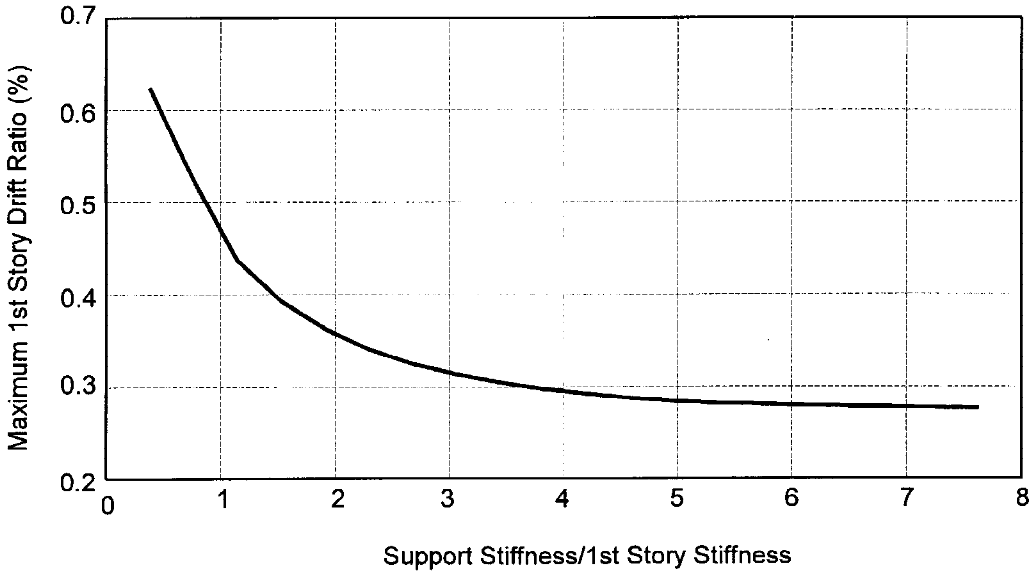

Fig. 3. Effect of Damper Support Stiffness on Damper Effectiveness

Effect of Damper Non-Linearity

The damper non-linear response is directly related to its velocity exponent. Viscous dampers are usually rated in terms of their maximum force outputs and defined by their force velocity relationships. However, the cost of viscous dampers and their assemblies and connections to the structure is directly related to their maximum force output. Therefore, an optimum design for seismic design is achieved when both the building's seismic response reduction is maximized and the damper force output is minimized. Figure 4 shows the effect of changing the velocity exponent on the maximum damper force and response reduction achieved in the first floor drift, based on one DBE ground motion. The optimum point for the design solution is project-dependent and is based on the target response reduction sought, and on the damper force that can be tolerated by the structure.

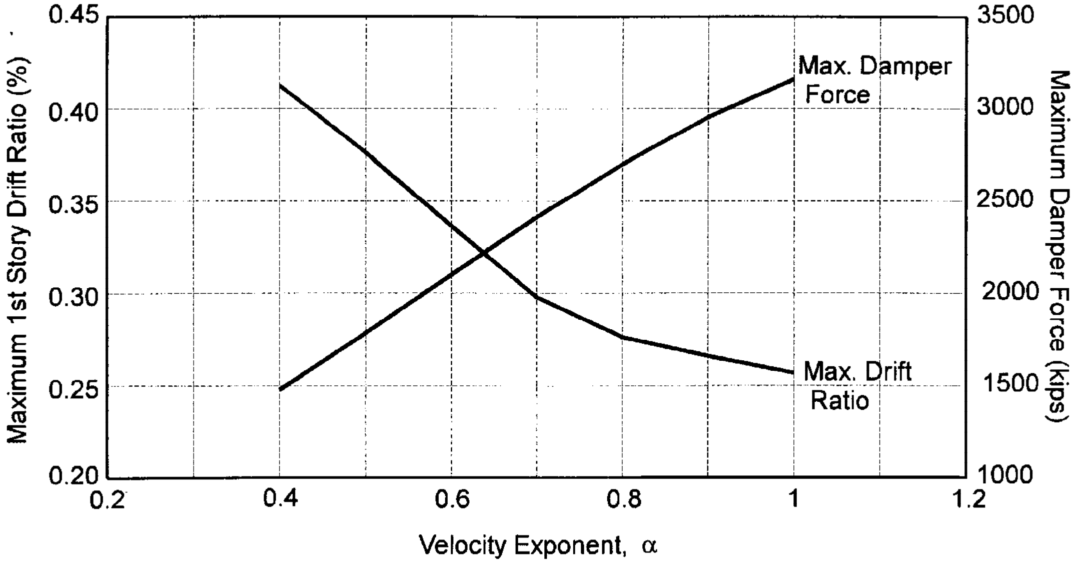

Fig. 4. Effect of Velocity Exponent on Response

Typically, a story shear force is defined as the sum of the shear force in all the elements across that floor. However, in the case of added damping elements, the total story shear force is composed of two parts: First, shear force in the elements of the structure not connected to dampers, and second, shear force in the Chevron braces connected to the dampers, which are the same as the force in the dampers. Where first floor is concerned, the total story shear force is referred to as the total base shear force, and is composed of structure's shear and dampers' force. Figure 5 shows the relation between varying the velocity exponent and maximum base shear force and its two parts. Because of the velocity dependence of the dampers, in the case of linear dampers the maximum of the two parts, i.e., structure's and dampers' force, are 90 degrees out-of-phase. However, as the velocity exponent starts to decrease, more coupling is noticeable.

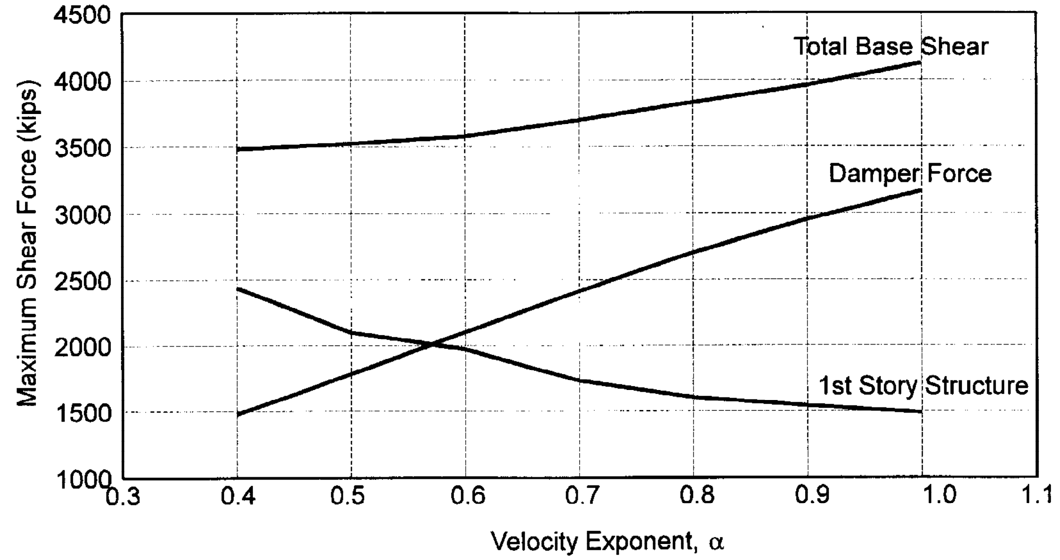

Fig. 5. Relationship Between Velocity Exponent and Maximum Shear Force

Effect of Earthquake Ground Motion Characteristics

Earthquake ground motions can be simply characterized by their intensities and their frequency contents. The intensity of a ground motion can be measured by its Peak Ground Acceleration, PGA, and its frequency content can be shown in its time or frequency spectrum. Another aspect of ground motion is also known as near-field effect, which occurs near the epicenter of major earthquake and evident in a large velocity pulse in its record.

The effect of changing the intensity of ground motion on the seismic response reduction is shown in Fig. 6. It is noted that for linear dampers the reduction is almost uniform and not dependent on the intensity. The response reduction decreases as the intensity increases for non-linear dampers since lower "effective" damping is achieved as the velocity increases.

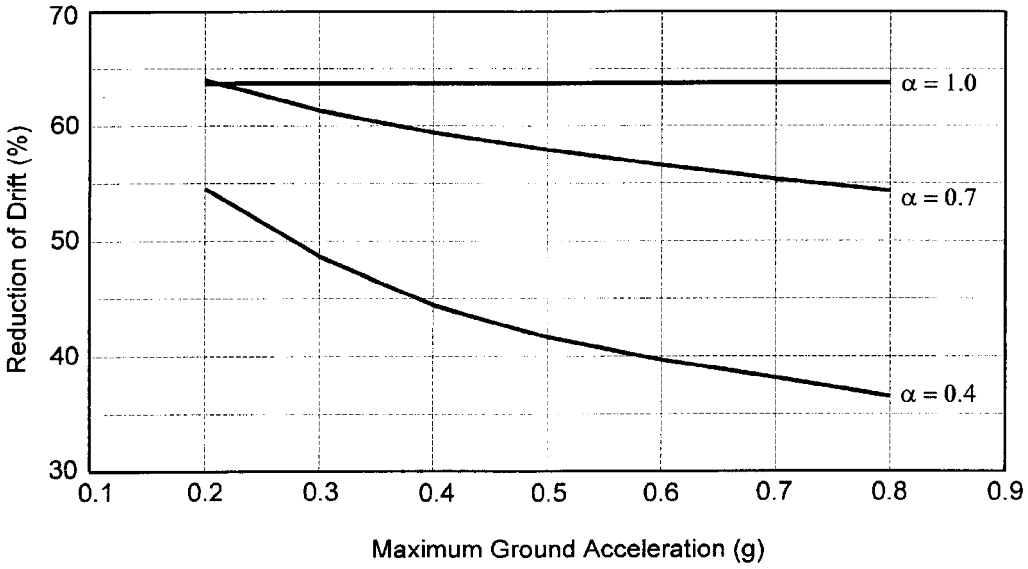

Fig. 6. Variation of Damper Effectiveness with Ground Motion Intensity

The effect of different characteristics and frequency contents of ground motions that are scaled to the same PGA is shown in Table 1 . It is shown that using six totally different earthquake ground motions that the second floor displacement (or first floor drift) response reduction is very similar, which is in average about 54%.

Table 1. Reduction of 1st Story Drift Ratio for Various Earthquakes

Earthquake	1st Story Drift Ratio without Dampers (%)	1st Story Drift Ratio with Dampers (%)	Reduction (%)
Site Specific (1)	0.71	0.30	57.9
Site Specific (2)	0.90	0.42	52.9
Site Specific (3)	0.55	0.26	53.3
Northridge (1)	0.72	0.32	55.6
Northridge (2)	0.86	0.45	48.4
Northridge (3)	1.07	0.49	54.3

CONCLUSIONS

This paper shows the significant benefits and response reduction that can be achieved by the use of viscous dampers. The response sensitivity analysis that was performed to obtain the optimum design and understand the behavior of the building with dampers can be generally applied to existing and new buildings of different configurations.

The research showed that the effectiveness of dampers can be greatly compromised by the stiffness of their assemblies and connections to the ground and the structure. It also showed the great importance that the velocity exponent can have on the optimum seismic design, the base shear, the structure's shear, and on the maximum damper force.

In the case of ground motion it was shown that for linear dampers the response reduction ratio is independent from the shaking intensity, and it decreases as the intensity increases for non-linear dampers. It was also shown that there was no significant effect of variation in ground motion frequency characteristics on the response reduction ratio.

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