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Seismic performance of chevron braced steel frames with and without viscous fluid dampers as a function of ground motion and damper characteristics

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Abstract

This study is aimed at comparing the seismic performance of steel chevron braced frames (CBFs) with and without viscous fluid dampers (VFDs) as a function of the intensity and frequency characteristics of the ground motion and VFD parameters. For this purpose, comparative nonlinear time history (NLTH) analyses of single and multiple story CBFs with and without VFDs are conducted using ground motions with various frequency characteristics scaled to represent small, moderate and large intensity earthquakes. Additionally, NLTH analyses of single and multiple story CBFs with VFDs are conducted to study the effect of the damping ratio and velocity exponent of the VFD on the seismic performance of the frames. The analysis results revealed that the seismic performance of the CBFs without VFDs is very poor and sensitive to the frequency characteristics and intensity of the ground motion due to brace buckling effects. Installing VFDs into the CBFs significantly improved their seismic performance by maintaining their elastic behavior. Furthermore, VFDs with smaller velocity exponents and larger damping ratio are observed to be more effective in improving the seismic performance of the CBFs. However, VFDs with damping ratios larger than 50% do not produce significant additional improvement in the seismic performance of the CBFs.

Keywords: Steel; Frames; Bracing; Viscous fluid damper; Seismic

1. Introduction

In steel buildings, one of the most commonly used steel braced frame type is a chevron braced frame (CBF) since its brace configuration provides an open space for architectural arrangements. Seismic energy dissipation in a CBF solely depends on the nonlinear cyclic response of the braces. Cyclic axial force–deformation behavior of a brace is unsymmetric in tension and compression and typically exhibits substantial strength and stiffness deterioration due to buckling effects [1]. Thus, when subjected to a strong ground motion, inelastic buckling of the braces in a CBF results in loss of lateral stiffness and strength of the frame [2]. Furthermore, it is difficult to achieve well-distributed ductility demands along the height of the CBF due to the premature buckling of the braces at certain floor levels [3] resulting in soft-story formations, dynamic instability [4] and hence substantial damage to the frame members.

Because of the above-mentioned poor performance characteristics, a large number of CBFs suffered considerable damage in past earthquakes [5–10]. Consequently, numerous research studies have been initiated in recent years to improve the performance of CBFs through the introduction of new structural configurations [2,11], the use of high performance materials [12], buckling restrained braces [1] as well as passive energy dissipation devices such as hysteretic [13], friction [14] and viscous fluid dampers (VFDs) [15–17]. Among all these seismic performance improvement techniques, using VFDs in a structure has the unique advantage of reducing the structure base shear force and deflections at the same time since the velocity-dependent maximum VFD force is out of phase with the maximum deflection of the structure [17]. Furthermore, the addition of VFDs into a structure does not alter the force–displacement relation-

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ship and hence the dynamic modal characteristics of the structure [18]. Consequently, VFDs seem to be viable tools for improving the seismic performance of CBFs.

Many research studies concerning the effect of VFDs on the seismic performance of building structures have been conducted in the past [16–20]. However, a comparative research study on the seismic performance of CBFs with and without VFDs as a function of ground motion and damper parameters is scarce. Thus, this study focuses on comparing the seismic performance of CBFs with and without VFDs as a function of the intensity and frequency characteristics of the ground motion as well as the damping ratio and velocity exponent of the VFD. The results from such a research study may then be used to measure the efficiency of VFDs for improving the seismic performance of CBFs as a function of the ground motion characteristics and VFD parameters and arrive at important decisions related to the seismic retrofitting and design of CBFs using VFDs.

2. Background

Seismic performance of CBFs has been studied by many researchers [1–4]. From these research studies it was found that energy dissipation in CBFs depends on the unstable nonlinear response of the braces [1] that may result in loss of lateral stiffness and strength of the frame [2]. Furthermore, it was concluded that it is difficult to achieve well distributed ductility demands along the height of the CBF [4] due to premature buckling of the braces at certain floor levels [3].

To alleviate the effect of these poor performance characteristics, many research studies have been conducted. Khatib et al. [2] introduced a new structural configuration called a "zipper frame". It was found that the "zipper frame" configuration resulted in simultaneous buckling of the braces at all story levels and hence a well distributed energy dissipation along the height of the frame. Dicleli and Mehta [11] introduced a vertical shear link between the chevron braces and the frame beam to improve the performance of the CBFs. It was found that the yielding of the shear link prior to buckling of the braces resulted in a more stable cyclic lateral force–deformation behavior and a better energy dissipation mechanism. Wilson and Wesolowsky [12] conducted an extensive state-of-the-art review of the application of shape memory alloys for seismic response modification of structures. It was found that such high-tech materials could be used successfully in steel braced frames to improve their seismic performance. Analytical studies have revealed that shape memory alloys may reduce the inter-story drift of braced frames by as much as 50%. However, the one noted drawback was the increase in acceleration, as high as 200% at some story levels. Sabelli et al. [1] studied the effect of installing buckling-restrained braces in CBFs on the seismic response of such frames. It was found that buckling-restrained braces provide an effective means for overcoming many of the potential problems associated with special CBFs. Passive energy dissipation devices such as hysteretic [13], friction [14] and viscous fluid dampers (VFDs) [15–17] have also been used to improve the seismic performance of steel frames. However, using VFDs in a structure was found to have the unique advantage of reducing the structure base shear force and deflections at the same time [17].

Many research studies concerning the effect of VFDs on the seismic performance of building structures have been conducted in the past [16–20]. Constantinou and Symans [15, 16] and Tsai et al. [19] conducted experimental and analytical studies on the seismic response of steel buildings with VFDs. It was concluded that the inclusion of VFDs in the tested structures resulted in reductions in story drifts of 30%–70% and story shear forces of 40%–70%. It was also concluded that VFDs reduced column bending moments, while introducing additional column axial forces out-of-phase with the bending moments. Thus, it was suggested that this behavior prevents the compression failure of weak columns in retrofitting applications. Martinez-Rodrigo and Romero [18] conducted analytical research studies to build a simple methodology leading to an optimum retrofitting option for moment resisting frames with linear and nonlinear VFDs. It was observed that for close to unity values of the nonlinear velocity exponent, the envelope of the response remains almost constant while the forces in the dampers are effectively reduced from the linear case. The maximum force experienced by the dampers in the nonlinear case may be reduced by more than 35% in comparison with the linear retrofitting case with a similar structural seismic performance. Uriz and Whittaker [20] investigated the use of linear fluid viscous damping devices for the seismic retrofit of a three-story, pre-Northridge steel-framed building. It was found that using VFDs with an equivalent viscous damping of 40% of critical resulted in reductions in the displacement of the frame by a factor exceeding two. However, although plastic rotations in the beams were substantially reduced, they were not totally eliminated.

3. Research objective and outline

The main objective of the present research study is to investigate the effect of VFDs on the seismic performance of CBFs as a function of the intensity and frequency characteristics of the ground motion and VFD parameters. For this purpose, first, an analytical brace-buckling model is developed to simulate the inelastic cyclic behavior of the braces in CBFs using the finite element based program ADINA [21]. Next, 84 comparative nonlinear time history (NLTH) analyses of single two, four and eight story CBFs with and without VFDs are conducted using seven seismic ground motions with various frequency characteristics scaled to represent small, moderate and large intensity earthquakes. These comparative analyses are performed mainly to study the effect of the ground motion properties and the number of stories on the seismic performance of CBFs with and without VFDs. Subsequently, 224 additional NLTH analyses of single and four story CBFs with VFDs are conducted to study the effect of the damping ratio and velocity exponent of the VFD on the seismic performance of the frames. In the last phase of the research, practical implications of using VFDs in CBFs are outlined and important conclusions and recommendations collected from the NLTH analyses results are summarized.

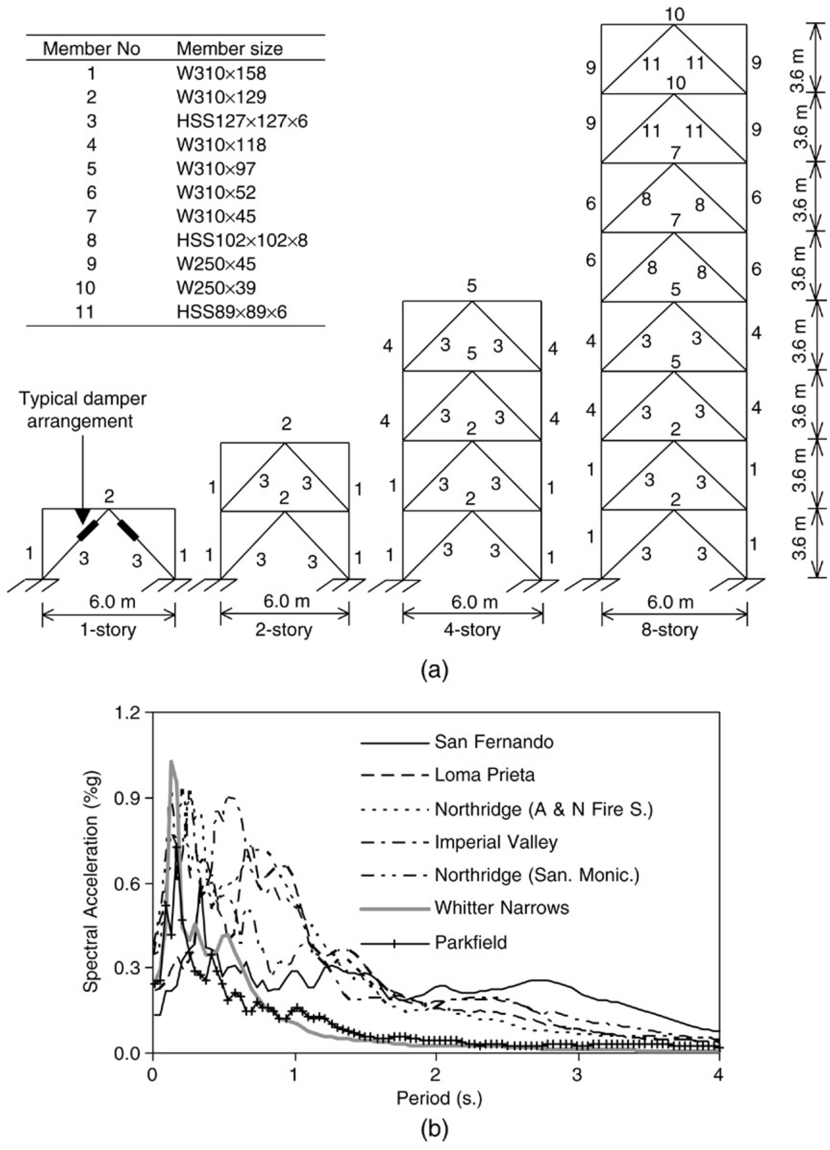


Fig. 1. (a) Frame models. (b) Acceleration response spectra of the earthquakes used in the analyses.

4. Details of the frames considered for analyses

The details of the one, two, four and eight-story frames considered for NLTH analyses are demonstrated in Fig. 1(a). The frame members are numbered from 1 to 11 and their sizes are tabulated across each number in the same figure. First, the eight-story frame is configured such that each two-story levels have the same member sizes, the lateral strength of the frame gradually decreases at the higher story levels and the frame exhibits nonlinear behavior under moderate to high intensity ground motions. The design of the frame is performed using the AISC Load and Resistance Factor Design Specifications for Structural Steel Buildings [22] using weak beam–strong column approach for seismic resistance and ignoring the vertical support provided by the chevron braces to the beams for gravitational load design per current state of practice. The beams are assumed to be rigidly connected to the columns. The frame members are assumed to be made of ASTM A36 steel with yield strength of 248 MPa and modulus of elasticity of 200 000 MPa, while the tubular braces are assumed to be made of ASTM A500 Grade B steel with yield strength of 318 MPa. The one, two and four-story frames are then assumed to form the bottom one, two and four stories of the eight-story frame respectively. This was done to solely study the performance of the CBFs with and without VFDs as a function of the number of stories. The elastic and modal properties of the frames which are the elastic stiffness and elastic limit (top displacement) based on a triangular lateral load distribution as well as the modal periods, T_1, T_2, T_3 corresponding to the first three lateral vibration modes are provided in Table 2. For the CBFs with VFDs, the dampers are assumed to be mounted along the existing chevron braces. A typical VFD arrangement is illustrated on the single story frame in Fig. 1(a). Similar damper arrangements (damper installed along the brace) have also been used in the studies of Constantinou and Symans [15] and Martinez-Rodrigo and Romero [18]. It is worth mentioning that a damper arrangement where the dampers are mounted parallel to the beam at the top of the chevron braces may offer additional benefits. In such a damper arrangement, the dampers are generally subjected to higher relative velocities and hence produce better energy dissipation and resistance to seismic forces. However, the damper arrangement used in this study is chosen as it is generally more suitable for seismic retrofitting applications of CBF.

5. Ground motions considered for analyses

Seismic ground motions are generally characterized by their peak ground acceleration, A_p, to peak ground velocity, V_p, ratios [23] which represent their dominant frequency and energy content. Ground motions with intense long-duration acceleration pulses have low A_p/V_p ratios, whereas those with high frequency, short-duration acceleration pulses have high A_p/V_p ratios. Consequently, ground motions with various A_p/V_p ratios are considered to assess the performance of the CBFs with and without VFDs for a wide range of ground motion characteristics. For this purpose, a set of seven ground motions with A_p/V_p ratios ranging between 5.5 and 21.5 s^{-1} are considered (Table 1). The acceleration response spectra of the ground motions are presented in Fig. 1(b). The ground motions are scaled to have $A_p = 0.20g$, $0.35g$ and $0.50g$ representing respectively, small, moderate and large intensity earthquakes.

6. Brief review of viscous fluid dampers

VFDs operate on the principle of fluid flow through orifices. Details of a typical VFD are illustrated in Fig. 2(a). A VFD consists of a piston within a damper-housing filled with a compound of compressible silicone fluid. The piston head contains a number of small orifices through which the fluid passes from one side of the piston to the other. Thus, the VFD dissipates the earthquake input energy through the movement of a piston in a highly viscous fluid based on the concept of fluid orificing [24]. The force, F, in a VFD is calculated as;

$$F = CV^{\alpha} \tag{1}$$

where C is the damping constant, V is the velocity at which the damper is oscillating and α is the velocity exponent. An idealized force–displacement loop of a VFD is presented in Fig. 2(b). The simplest form of VFD is a linear VFD, for which the velocity exponent, α, is equal to 1.0. Typical values of α range between 0.5 and 2.0 [25]. VFDs with α larger than 1.0 are generally not used in seismic design applications. Those with α smaller than 1.0 are called nonlinear VFDs.

For a multiple story CBF with VFDs mounted diagonally along the chevron braces, the damping ratio, ζ_k, of the frame at the kth mode of vibration is expressed as [15];

$$\xi_k = \frac{\sum_j C_j \cos^2\theta(\phi_j - \phi_{j-1})^2}{2\omega_k \sum_j m_j \phi_j^2} \tag{2}$$

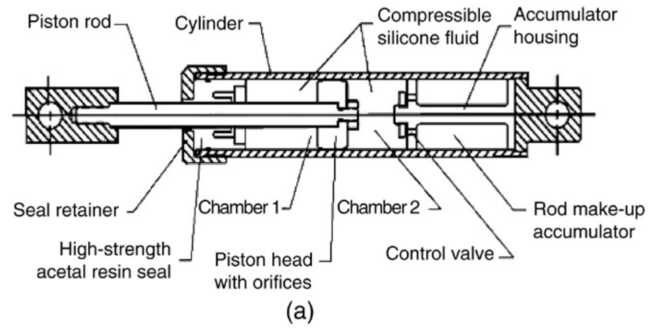


Fig. 2. (a) Typical detail of a viscous fluid damper. (b) Force–displacement loop of a viscous fluid damper.

where C_j is the sum of the damping constants of the VFDs at the jth story level, θ is the angle of inclination of the VFDs at the jth story level, Φ_j is the modal displacement of the jth floor in the kth mode of vibration, ω_k is the modal circular frequency in the kth mode of vibration and m_j is the mass of the jth floor. In seismic design applications, typical damping ratios in the first mode of vibration range between 10% and 50%.

7. Modeling of the CBF for NLTH analyses

A direct integration NLTH analysis procedure is adopted to perform the seismic analyses of the frames using the nonlinear finite element based program ADINA [21]. For the analytical modeling of the CBFs, to investigate the sensitivity of the frame nonlinear responses to the level of structural damping used in the analyses, the single story CBF without VFDs is analyzed for damping ratios ranging between 2% and 5% using a ground motion with $A_p/V_p = 10.6$ s^{-1} and $A_p = 0.5g$ and the results are presented in Fig. 3(a). It is observed that the effect of the level of damping used in the analyses on the seismic response of the frame is negligible since a large portion of the earthquake input energy is dissipated by yielding of the frame components. Thus, a 5% mass proportional Rayleigh structural damping [26] is used in the analyses of the frames. To calculate the structural damping constant, the Rayleigh mass proportionality factors for each frame are obtained based on the natural circular frequencies of their first vibration mode, which are obtained from eigenvalue analyses of the frames. Second order effects are included in the analyses of the frames by using the large displacement/rotation option in ADINA. The nonlinear properties of the frame members are defined in ADINA as (i) a set of moment curvature diagrams for various levels of axial loads and (ii) a stress–strain relationship. The moment–curvature diagrams of the frame members for

Table 1
Properties of seismic ground motions used in the analyses

Earthquake	Station	A_p (g)	V_p (cm/s)	A_p/V_p (1/s)
San Fernando, 1971	8244 Orion Blvd	0.13	23.9	5.5
Loma Prieta, 1989	Oakland Outer Wharf	0.22	35.4	6.1
Northridge, 1994	Arleta & Nordhoff Fire Station	0.34	40.4	8.4
Imperial Valley, 1940	El Centro	0.35	32.3	10.6
Northridge, 1994	Santa Monica City Hall.	0.37	24.9	14.6
Whitter Narrows, 1987	90079 Downey Birchdale	0.24	13.7	17.4
Parkfield, 1966	Cholame, Shandon	0.24	10.8	21.5

Table 2
Elastic and modal properties of the frames

Frame	Elastic stiffness (kN/m)	Elastic limit (mm)	T_1 (s)	T_2 (s)	T_3 (s)
1-story	125 000	6.3	0.293	N/A	N/A
2-story	66 667	11.8	0.349	0.129	N/A
4-story	29 762	27.2	0.479	0.168	0.099
8-story	7979	69.7	0.836	0.285	0.150

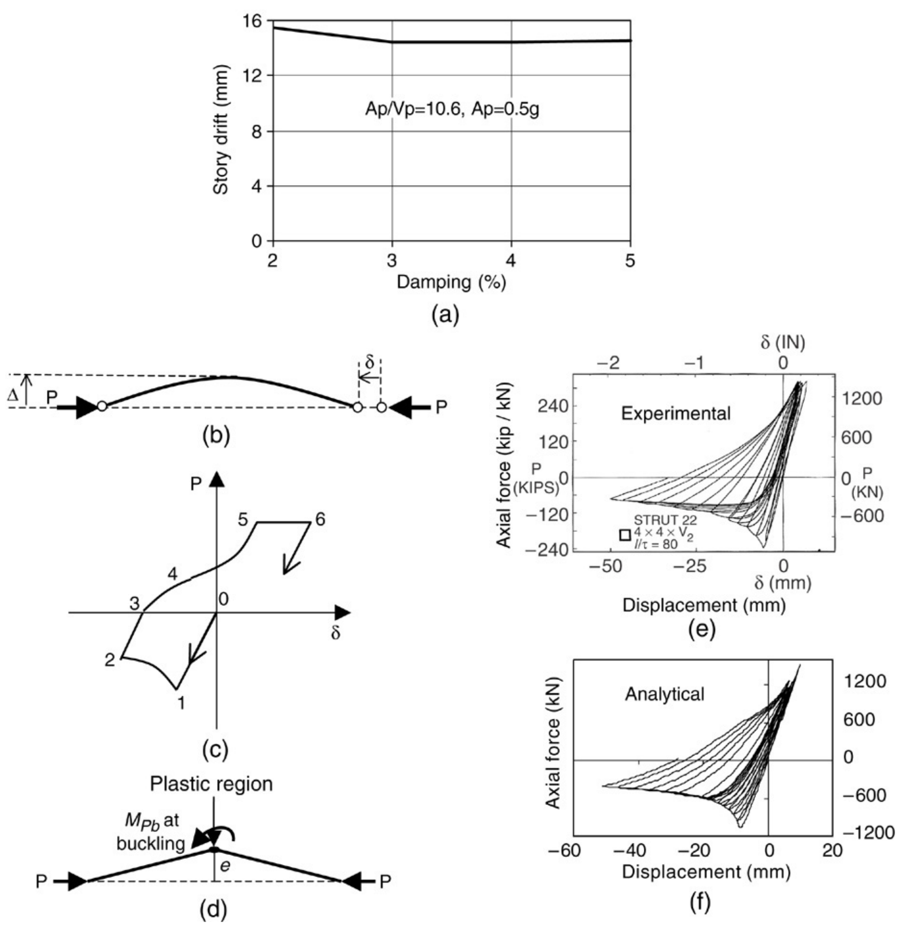


Fig. 3. (a) Story drift of one-story frame versus structural damping ratio. (b) Buckling brace. (c) Typical brace axial force–deformation behavior. (d) Nonlinear brace model. (e) Experimental hysteresis loop. (f) Analytical hysteresis loop from ADINA [21].

axial load levels ranging between $P = 0$ and $P = 0.8Py$ are obtained using a spreadsheet program to define the axial force–moment interaction relationship for the frame members including the beams, columns and brace members undergoing flexural buckling.

7.1. Modeling of brace inelastic cyclic behavior in CBFs without VFDs

In a CBF, principally the inelastic cyclic behavior of the braces results in the dissipation of earthquake energy. Hence, an accurate analytical simulation of this behavior including buckling effects is required in the analyses.

The inelastic behavior of steel braces is generally expressed in terms of an axial load, P, an axial displacement, δ, and a transverse displacement, Δ, at the mid-point of the brace as shown in Fig. 3(b). A typical buckling curve of a brace member under cyclic axial load is illustrated in Fig. 3(c) [27]. In the figure, segment 0–1 shows the linear elastic range prior to buckling. Segment 1–2 shows the buckling phase due to the initial imperfections combined with second order moments where at a critical value of the transverse displacement, Δ, of the brace, the second order moment in the brace will be equal to its plastic moment capacity under the applied axial load. The drop in the axial force resistance of the brace along segment 1–2 is basically due to the moment–axial force interaction effects. Segment 2–3 displays the unloading phase while segments 3–4–5–6 shows the phases where the load is reversed and the brace yields in tension (segment 5–6).

To simulate the inelastic cyclic behavior described above, an analytical brace model shown in Fig. 3(d) is developed in ADINA [21]. An imperfection, e, is introduced at the centre of the brace to produce a kinked element for simulating the global buckling effects using large displacement analysis procedure. The imperfection, e, is given by the following equation [28];

$$e = \frac{M_{pb}}{P_b}\left(1 - \frac{P_b L^2}{12EI}\right) \tag{3}$$

where L, E, I and M_{pb} are respectively the length, elastic modulus, moment of inertia, and plastic moment capacity of the brace at buckling load. The imperfection is calculated such that when the axial load reaches the buckling load, the plastic moment capacity is reached at the vertex of the kinked brace element due to second order effects. Beyond this point, the axial load capacity of the brace constantly decreases due to the combined effects of increasing second order moments and moment–axial force interaction as the member buckles. Accordingly, a plastic hinge region accounting for moment–axial force interaction is defined at the vertex of the kinked brace element using a set of axial-force–moment–curvature relationships for the brace. Furthermore, the inelastic axial stress–strain relationship of the brace is defined to simulate its nonlinear behavior in tension.

Fig. 3(e) and (f) show respectively the experimental [29] and analytical axial force–displacement hysteresis loops for a tubular brace member (TS4 × 4 × 1/2) with a slenderness ratio of 80. The brace is subjected to gradually increasing cyclic axial displacements. From the comparison of the two figures it is clear that the general characteristics of the hysteresis loop of the analytical model are similar to those of the experimental model. Thus, it is used in the analyses of the CBF to model the nonlinear cyclic behavior of the braces.

7.2. Modeling of CBF with nonlinear VFDs

The frames with VFDs are modeled in ADINA [21] by adding damper elements to each of the braces of the existing CBF models defined earlier. Thus, all the frame nonlinearities are considered in the case of the CBFs with VFDs in the comparative studies. However, in the second part of the study, where the effect of damper parameters on the seismic response of the frames is studied, nonlinear frame behavior was ignored. This was done to have a fair assessment of the effect of changing the damper parameters (damping constant and velocity exponent) on the seismic response of the frames. The damper element in ADINA [21] requires the input of the damping constant C and the velocity exponent, α. For a specified value of damping ratio, ζ, at the first vibration mode of the frame, the value of the damping constant, C_j at each story level j, is calculated from Eq. (2) assuming that all the dampers within the frame have identical properties. The modal parameters in Eq. (2) are obtained from the eigenvalue analyses of the frames. The calculated damping constant at each story level is then divided by two and assigned to each damper element mounted along the two braces. The calculated damping ratios, ζ, are solely used as reference values in the figures throughout the paper to demonstrate the effect of increasing level of damping on the seismic response of the CBFs with VFDs regardless of the α values considered in the analyses.

8. Comparative seismic analyses of CBFs with and without VFDs

To study the effect of VFDs on the seismic performance of CBFs, a damping ratio of 50% of critical damping in the first mode of vibration is considered for the calculation of the damping constants of the VFDs in the structural model. Although a 50% damping ratio may be considered large in some practical applications, it was chosen to clearly observe the difference between the seismic behavior of CBFs with and without VFDs. Damping values smaller than 50% of critical (10% and 30%) are considered in the parametric studies presented in the subsequent sections. The dampers are assumed to be nonlinear with the velocity exponent, α, having a value of 0.5. A total of 84 NLTH analyses are conducted. The analyses results are discussed in the following subsections and demonstrated in Figs. 4(a)–(d), 5 and 6.

8.1. Performance of the CBF with and without VFDs in relation to ground motion intensity

In this section, performances of the CBFs with and without VFDs are compared and studied in relation to the intensity of the ground motions. Fig. 4(a) compares the average of the maximum inter-story drifts from the seven earthquakes for one, two, four and eight-story CBFs with and without VFDs as a function of the intensity of the ground motions. For all the ground motion intensities and CBFs considered, the presence of VFDs produces significant improvements in the seismic response of the frames as shown in the figure. The kinetic + strain, hysteretic and structural damping energy time history of the one-story CBF without VFDs subjected to the ground motion with $A_p!V_p = 10.6\ \mathrm{s}^{-1}$ and $A_p = 0.5g$ and kinetic + strain, and viscous fluid damping energy time history of the same frame with VFDs subjected to the same

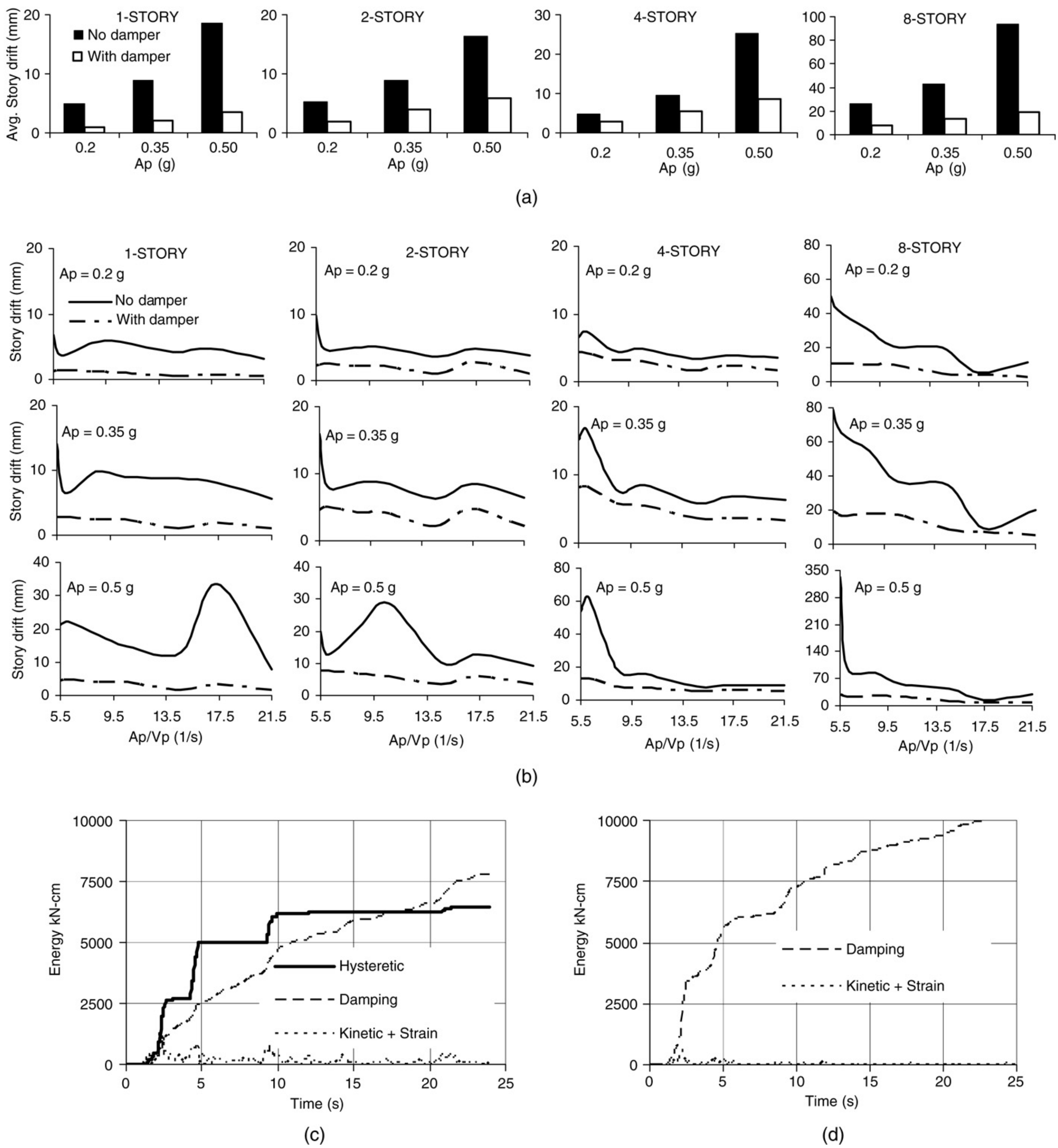


Fig. 4. (a) Average of the maximum inter-story drifts of CBFs with and without VFDs from the seven earthquakes as a function of A_p for one, two, four and eight-story frames. (b) Maximum inter-story drifts of one, two, four and eight-story CBFs with and without VFDs as a function of the A_p/V_p ratio of the ground motion for $A_p = 0.20$, 0.35 and 0.50g. (c) Energy versus time plot for the one-story CBF without VFDs subjected to the ground motion with $A_p/V_p = 10.6\ \mathrm{s}^{-1}$ and $A_p = 0.50$. (d) Energy versus time plot for the one-story CBF with VFDs subjected to the ground motion with $A_p/V_p = 10.6\ \mathrm{s}^{-1}$ and $A_p = 0.50$.

ground motion are presented in Fig. 4(c) and (d) respectively. As observed from the figures, in the frame with VFDs, most of the energy is dissipated by VFDs (hysteretic energy is equal to zero due to elastic behavior). The energy dissipated by the VFDs prevents the buckling of the braces (damper forces are found to be smaller than the buckling capacity of the braces) and causes the frame members to remain within their elastic limits. This results in considerably smaller inter-story drifts of the CBFs with VFDs than those without VFDs. Furthermore, it is observed that the ratios of the average maximum inter-story drifts of the CBFs without VFDs to those with VFDs range between 1.65 and 5.32. In most structures equipped with VFDs,

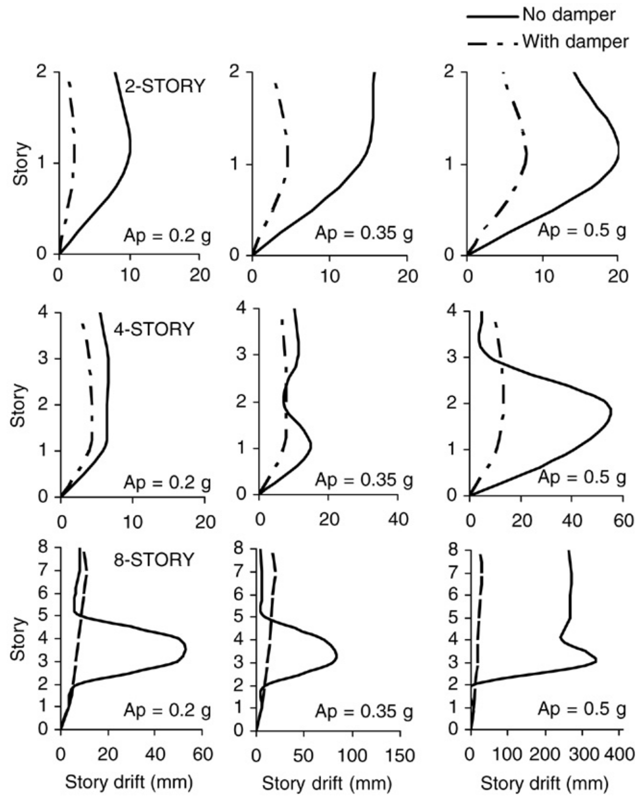


Fig. 5. Displacement profile of the two, four and eight-story CBFs with and without VFDs for various A_p ($A_p/V_p = 5.5\ \mathrm{s}^{-1}$).

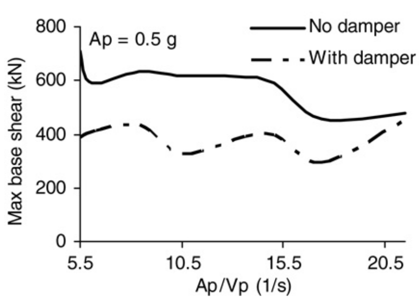


Fig. 6. Comparison of the maximum base shear forces vs. A_p/V_p ratio of the ground motion for a one-story frame.

the reduction in the seismic drift response is of the order of 1.5–2.5 times. The larger reduction in the seismic drift response of CBFs (1.65–5.32) is partly due to the buckling of the braces in CBFs without VFDs yielding unusually large inter-story drift values compared to other types of structures. Thus, VFDs are observed to be very efficient devices for mitigating the effect of seismic forces particularly for CBFs. Moreover, it is observed that the ratio of the average maximum drift of the CBF without VFD to that with VFD is a function of the intensity of the ground motion and the number of stories. The dependency of this drift ratio on the intensity of the ground motion and the number of stories is found to result from the buckling of the braces. Buckling of the braces in CBFs without VFDs is generally more predominant for frames with larger number of stories subjected to ground motions with larger intensities. In such frames, the buckling of the braces at certain floor levels results in soft story formations. This, in turn, produces considerable plastic penetrations into the essential structural components of the CBFs that lead to large inter-story drifts and hence large drift ratios.

In summary, it is found that using VFDs forms an effective design and retrofit strategy for CBFs and it is generally more helpful for frames with larger number of stories located in regions of high risk of seismic activity. In retrofitting applications, the presence of the braces in CBFs is anticipated to facilitate the installation of the VFDs at relatively smaller cost compared to other types of structures such as moment resisting frames. However, in design or retrofitting applications, the engineer should estimate the level of axial force that may be exerted by the dampers to prevent the buckling of the braces.

8.2. Performance of the CBF with and without VFDs in relation to the frequency characteristics of the ground motion

In this section, performances of the CBFs with and without VFDs are compared and studied in relation to the frequency characteristics or A_p/V_p ratio of the ground motion. Fig. 4(b) compares the maximum inter-story drifts of one, two, four and eight-story CBFs with and without VFDs as a function of the A_p/V_p ratio of the ground motions. It is observed that CBFs without VFDs generally display a good response over the range of A_p/V_p ratios considered for low to moderate intensity ground motions and for lower number of stories. Nonetheless, for high intensity ground motions and for larger number of stories, a sudden deterioration in the lateral strength and stiffness and an ensuing increase in the maximum drift response of the frames are observed due to the effect of brace buckling and the behavior of the CBF becomes highly sensitive to the A_p/V_p ratio of the ground motion. For high intensity ground motions ($A_p = 0.5g$), it is observed from Fig. 4(b) that the largest seismic drift responses of the frames with smaller number of stories are produced by ground motions with higher A_p/V_p ratios while those of the frames with larger number of stories are produced by ground motions with lower A_p/V_p ratios. For instance for one, two, four and eight-story frames, the peak drift responses occur respectively at $A_p/V_p = 17.4$, 10.6, 6.1 and 5.5 s^{-1}. This may be mainly due to the fundamental inelastic vibration period of the CBFs falling within the range of the dominant period of the ground motion which may be approximated as $2\pi V_p/A_p$ [23]. The sensitivity of the response of the CBFs without VFDs to the A_p/V_p ratio of the ground motion at high intensities makes the performance of such frames unreliable especially in regions of high risk of seismic activity.

For CBFs with VFDs, it is observed from Fig. 4(b) that the seismic response of the frames is much more uniform than that of the CBFs without VFDs over the range of A_p/V_p ratios considered. Thus, installing VFDs makes the seismic response of the CBF relatively less sensitive to the number of stories and frequency characteristics of the ground motion and hence the design and performance of such frames with VFDs becomes more reliable.

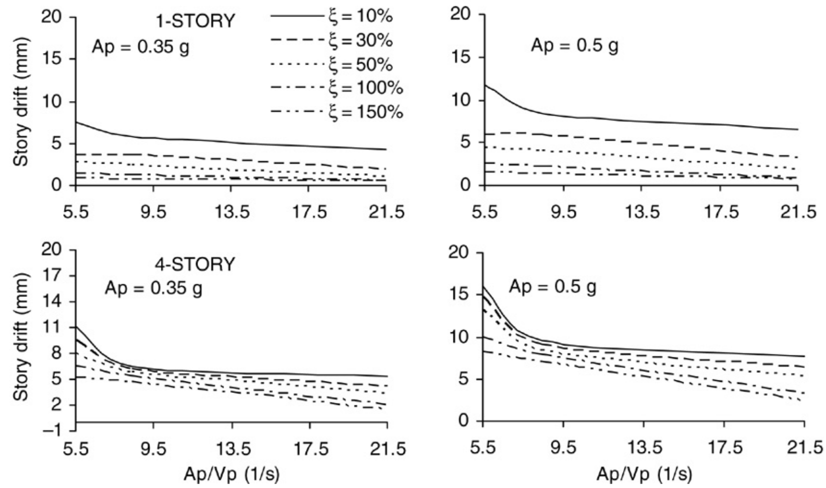


Fig. 7. Maximum inter-story drifts of one and four-story CBFs with VFDs as a function of the A_p/V_p ratio of the ground motion for various damping ratios and $A_p = 0.35$ and $0.50g$.

8.3. Effect of VFD on the displacement profile of the CBF

Fig. 5 compares the deformed shapes of the two, four and eight-story CBFs with and without VFDs for a ground motion with $A_p/V_p = 5.5\ \text{s}^{-1}$ scaled to $A_p = 0.2g$, $0.35g$ and $0.5g$. The deformed shapes of the frames are obtained at the instant when the maximum inter-story drift occurs.

For the CBFs with lower number of stories subjected to lower ground motion intensities ($A_p = 0.2g$), although the VFDs result in much smaller frame lateral displacements, the shape of the displacement profile remains relatively similar to that of the CBFs without VFDs. However for CBFs with higher number of stories subjected to larger ground motion intensities ($A_p = 0.35g$ and $0.50g$), the displacement profile of the frames with and without VFDs are totally different. In such frames, the buckling of the braces dominates the behavior of the CBFs without VFDs where inter-story drifts much larger than those of the CBFs with VFDs are observed. The buckling of the braces in CBFs without VFDs results in soft story formations as observed from Fig. 5 and concentration of the energy dissipation at the intermediate story levels. Nevertheless, the CBFs with VFDs exhibit a more uniform lateral displacement profile and distribution of energy demand as well as smaller inter-story drifts compared to the CBFs without VFDs for all the ground motion intensities considered.

8.4. Effect of VFD on the base shear

The effect of VFDs on the maximum base shear force of the one-story frame is demonstrated in the form of a graph between the maximum base shear force vs. the A_p/V_p ratio of the ground motions in Fig. 6 for $A_p = 0.5g$. It is observed that installing VFDs into CBFs results in a reduction in the base shear force for the range of A_p/V_p ratios considered. This finding is in agreement with the observations from similar previous research studies on other types of structures [15,20]. However, as observed from Fig. 6, the reduction in the base shear force is relatively less at A_p/V_p ratios where brace buckling behavior becomes more dominant. This is mainly due to the reduction in the lateral strength of the frame associated with buckling phenomenon.

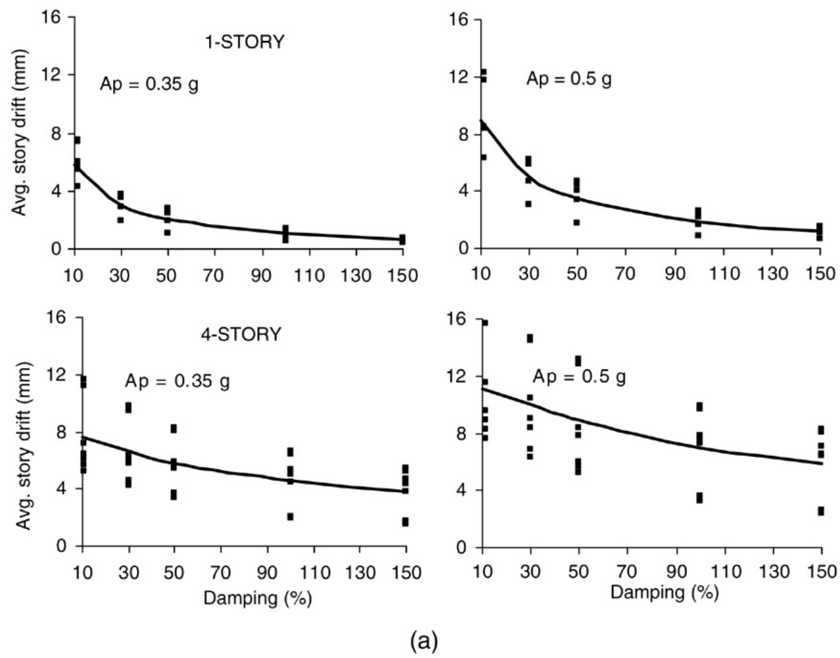
9. Effect of VFD parameters on the seismic performance of CBF

In this section, a parametric study involving a total of 224 NLTH analyses is conducted to investigate the effect of VFD parameters on the seismic performance of the frames using one and four-story CBFs. For this purpose, the damping ratio, ζ, of the frames corresponding to their first vibration mode is varied between 10% and 150% of critical while keeping the value of the velocity exponent, α of the VFDs at 0.5 to solely study the effect of the damping ratio, ζ, on the seismic response of the frames. For each specific ζ value considered, the damping constant C for the VFD is calculated using Eq. (2) and assigned to the damper elements in the frame models. Although, values of ζ larger than 50% are not practical, they are considered in the parametric study to measure the benefits of higher percentage of damping on the performance of the frames. Similarly, keeping the value of the damping ratio, ζ at 50%, the value of the velocity exponent, α, is varied between 0.3 and 1.0 to study the effect of α on the seismic response of the frames. The NLTH analyses results are discussed in the following subsections.

9.1. Effect of viscous damping ratio on the seismic performance

9.1.1. Viscous damping ratio vs. A_p/V_p ratio

Fig. 7 displays the maximum inter-story drifts of the one and four-story CBFs as a function of the A_p/V_p ratio of the ground motions for $\zeta = 10\%$, 30%, 50%, 100% and 150% for $A_p = 0.35$ and $0.50g$. It is observed that generally, the maximum inter-story drift of the CBFs with VFDs decreases as the A_p/V_p ratio of the ground motion increases for the range of ζ values and ground motion intensities considered. This is mainly due to the smaller energy content of ground



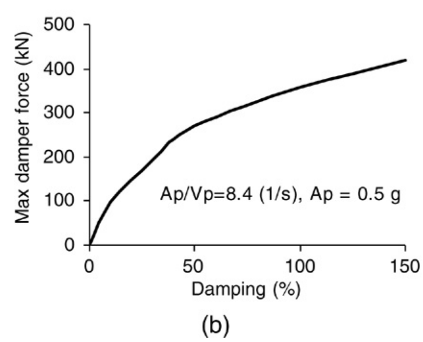


Fig. 8. (a) Average of the maximum inter-story drifts of CBFs with VFDs from the seven earthquakes as a function of the damping ratio for one and four-story frames and $A_p = 0.35$ and $0.50g$. (b) Maximum damper force as a function of the damping ratio for one-story frame.

motions with high A_p/V_p ratios, which are characterized by high frequency, short-duration acceleration pulses that load and unload the structure in short time intervals. Such grounds motions also contain smaller peak velocity pulses and hence produce smaller VFD forces. It is also observed that the relationship between the maximum inter-story drift and the A_p/V_p ratio of the ground motion becomes nearly linear for damping values equal to or greater than critical ($\zeta \geq 100\%$) due to diminishing structure oscillations associated with the behavior of over-damped systems that produce a smoother frame response over the range of A_p/V_p ratios considered. Furthermore, the variation of the maximum inter-story drift of the four-story frame as a function of the A_p/V_p ratio of the ground motion is found to be more precipitous than that of the one-story frame. This is mainly associated with the larger fundamental period of the four-story frame falling within the range of the dominant period of the ground motions with lower A_p/V_p ratios, thus producing larger inter-story drifts due to resonance effects. However, for the four-story frame, the reduction in the maximum inter-story drifts as a function of the damping ratio seems to be less than that of the one-story frame. This will be formally investigated in the section below.

9.1.2. Seismic response of the frames vs. damping ratio

The average of the maximum inter-story drifts of the one and four-story CBFs from the seven earthquakes is plotted in Fig. 8(a) as a function of the damping ratio for $A_p = 0.35$ and $0.50g$. It is observed that the relationship between the maximum inter-story drift and the damping ratio is nonlinear and similar regardless of the value of the peak ground acceleration. As expected, the maximum inter-story drift decreases as the damping ratio increases. However, the reduction in the maximum inter-story drift as a function of the damping ratio is significant only for damping ratios smaller than or equal to 50%. For ζ values larger than 50%, the relatively smaller reduction in the maximum inter-story drift of the frame (Fig. 8(a)) is accompanied by a relatively large increase in the damper force as observed from Fig. 8(b). Thus, using VFDs, which will produce damping ratios larger than 50%, does not seem to be practical. In fact, damping ratios ranging between 10% and 30% seem to produce the largest reduction in the seismic force while having reasonable damper forces as the curves in Fig. 8(a) are steeper within that range. It is also observed that the reduction in the inter-story drift values becomes totally negligible for damping values larger

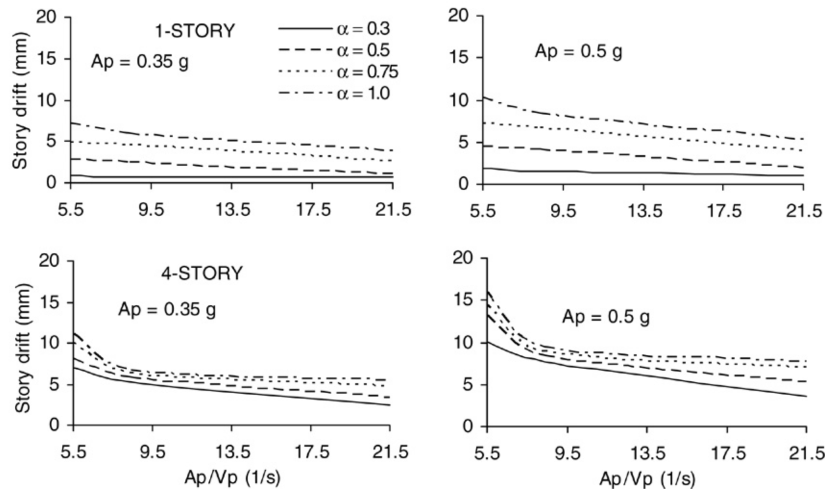


Fig. 9. Maximum inter-story drifts of one and four-story CBFs with VFDs as a function of the A_p/V_p ratio of the ground motion for various α values and $A_p = 0.35$ and $0.50g$.

than critical ($\zeta \geq 100\%$). Furthermore, Fig. 8(a) reveals that for the four-story frame, the rate of reduction of the maximum inter-story drift as a function of the damping ratio is lower than that of the one-story frame. This is mainly due to the smaller relative damper velocities at higher stories of the four-story frame producing less damping effect compared to that of the single story frame. Thus, it may be more efficient to place dampers with relatively larger damping capacity at the lower stories of multiple story CBFs.

It is observed that the data presented in Fig. 8(a) has some scatter. This scatter is mainly associated with different frequency characteristics (A_p/V_p ratios) of the ground motions used in the analyses, which produce different damper velocities.

9.2. Effect of VFD's velocity exponent on the seismic performance

9.2.1. Velocity exponent vs. A_p/V_p ratio

Fig. 9 displays the maximum inter-story drifts of the one and four-story CBFs as a function of the A_p/V_p ratio of the ground motions for $\alpha = 0.30$, 0.50, 0.75 and 1.00 for $A_p = 0.35$ and $0.50g$. It is observed that generally, the maximum inter-story drift of the CBFs with VFDs decreases as the A_p/V_p ratio of the ground motion increases for the range of α values and ground motion intensities considered. This is again mainly due to the smaller energy content of ground motions with high A_p/V_p ratios. It is also observed that the variation of the maximum inter-story drift as a function of the A_p/V_p ratio of the ground motions is steeper for larger α values. From the above discussion it may be concluded that using VFDs with smaller α values reduces the sensitivity of the CBFs to the frequency characteristics of the ground motion. As a result, the actual performance of the structure becomes more reliable regardless of the type of ground motion used in the design or retrofitting calculations.

The variation of the maximum inter-story drift of the four-story frame as a function of the A_p/V_p ratio of the ground motion is also found to be steeper than that of the one-story frame for the range of α values considered. As explained earlier, this is mainly associated with the larger fundamental period of the four-story frame falling within the range of the dominant period of the ground motions with lower A_p/V_p ratios, thus producing larger inter-story drifts due to resonance effects.

9.2.2. Seismic response of the frames vs. velocity exponent

The average of the maximum inter-story drifts of the one and four-story CBFs from the seven earthquakes is plotted in Fig. 10(a) as a function of the velocity exponent, α, for $A_p = 0.35$ and $0.50g$. It is observed that the relationship between the maximum inter-story drift and the velocity exponent is nearly linear and similar regardless of the value of the peak ground acceleration. The maximum inter-story drift increases as the velocity exponent increases. This trend results from the values of damper velocities which are smaller than 1.0 m/s for the range of A_p/V_p ratios and ground motion intensities considered in this study. From Eq. (1) and Fig. 10(b), it is clearly observed that for damper velocities smaller than 1.0 m/s, VFDs with larger α values produce smaller damper resistance, which in turn, leads to larger inter-story drifts. Furthermore, Fig. 10(a) reveals that for the four-story frame, the rate of change of the maximum inter-story drift as a function of the velocity exponent is lower than that of the one-story frame. This is again mainly due to the smaller relative damper velocities at higher stories of the four-story frame producing less damping effect compared to that of the single story frame.

10. Practical implications of using VFDs

In this section, the practical implications of using VFDs for seismic retrofitting and design of CBFs are studied. Fig. 11(a) shows the maximum inter-story drifts of a four-story CBF without VFDs (zero damping) and with VFDs producing 30% and 50% damping ratio in the first vibration mode. The allowable story drift limits for building seismic use groups I, II and III as per the international building code [30] are also demonstrated on the same plot. The figure is obtained for

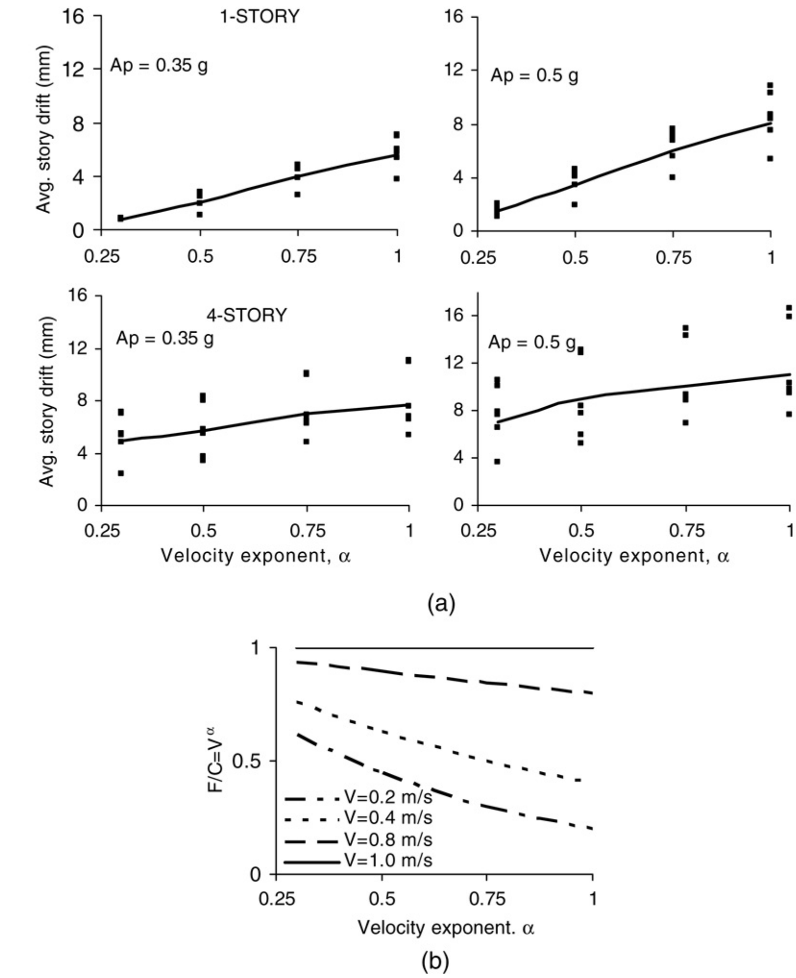


Fig. 10. (a) Average of the maximum inter-story drifts of CBFs with VFDs from the seven earthquakes as a function of the damper velocity exponent for one and four-story frames and $A_p = 0.35$ and $0.50g$. (b) Variation of normalized damper force with respect to C as a function of velocity exponent for various damper velocities.

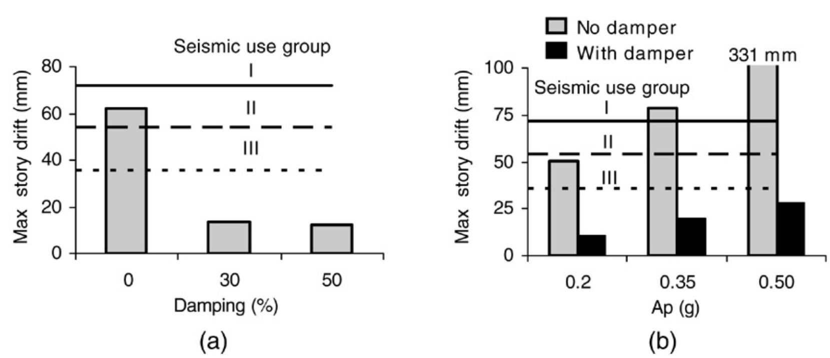


Fig. 11. (a) Comparison of code mandated allowable drifts with those of a four-story CBF without VFDs and with VFDs having various damping levels ($A_p = 0.50g$, $A_p/V_p = 6.1\ \mathrm{s}^{-1}$). (b) Comparison of code mandated allowable drifts with those of an eight-story CBF with and without VFDs for various A_p values ($A_p/V_p = 5.5\ \mathrm{s}^{-1}$).

$\alpha = 0.5$, $A_p/V_p = 6.1\ \mathrm{s}^{-1}$ and $A_p = 0.5g$. As observed from the figure, installing dampers into the frame system dramatically reduces the large drift values resulting from the buckling of the braces to levels below the code mandated drift limits. However, larger damping values (e.g. $\zeta = 50\%$) does not seem to benefit the CBFs considerably since a reasonably small value of additional damping (e.g. $\zeta = 10\%$–30%) is adequate to force the response of the frame into the elastic range (i.e. no brace buckling).

Fig. 11(b) displays the maximum inter-story drifts of an eight-story CBF with and without VFDs for $A_p = 0.20g$, $0.35g$ and $0.50g$. The allowable story drift limits for seismic use groups I, II and III as per the international building code [30] are also demonstrated on the same plot. The figure is obtained for $\zeta = 50\%$, $\alpha = 0.5$, $A_p/V_p = 5.5\ \mathrm{s}^{-1}$. It is observed from the figure that installing VFDs into the frame system reduces the large drift values resulting from the buckling of the braces to levels below the code mandated drift limits for the range of A_p values considered. As observed earlier, installing dampers becomes more beneficial for higher ground motion intensities and frames with larger number of stories where brace buckling dominates the behavior of the CBF (Fig. 11(a) and (b)).

In summary, using VFDs with $\zeta = 10\%$–30% for seismic retrofitting or design of CBFs seems to dramatically improve the response of the frames and produce drift values smaller than those allowed by the building design codes.

11. Conclusions

The effect of VFDs on the seismic performance of CBFs as a function of the intensity and frequency characteristics of the ground motion and VFD parameters is investigated. It is observed that CBFs without VFDs generally display a good response over the range of A_p/V_p ratios considered for low to moderate intensity earthquakes and for lower number of stories. Nonetheless, for high intensity earthquakes and for larger number of stories, a sudden deterioration in the lateral strength and stiffness and an ensuing increase in the maximum drift response of the frames are observed due to the effect of brace buckling and the behavior of the CBF becomes highly sensitive to the A_p/V_p ratio. Nevertheless, for the CBFs with VFDs, the dampers prevent the buckling of the braces and cause the frame members to remain within their elastic limits. Thus, the frames exhibit smaller inter-story drifts than the code mandated allowable limits as well as a more uniform lateral displacement profile and distribution of energy demand compared to the CBFs without VFDs. Additionally, for CBFs with VFDs, the seismic response of the frames is found to be significantly less sensitive to the A_p/V_p ratio of the ground motion and the number of stories for the damper parameters considered. Thus, using VFDs forms an effective design and retrofit strategy for CBFs.

The parametric studies concerning the effect of damping ratio and the velocity exponent on the seismic response of the CBFs with VFDs revealed that the relationship between the maximum inter-story drift and the damping ratio is nonlinear and similar regardless of the value of the A_p. As expected, the maximum inter-story drift decreases as the damping ratio increases. However, the reduction in the maximum inter-story drift is more significant for damping ratios ranging between 10% and 30%. Furthermore it is found that it may be more efficient to place dampers with relatively larger damping capacity at the lower stories of multiple-story CBFs. It is also observed that the maximum inter-story drift linearly increases as the velocity exponent increases. Additionally, using VFDs with smaller α values is found to reduce the sensitivity of the CBFs to the frequency characteristics of the ground motion and hence the performance of the structure becomes more reliable. In summary, it is recommended that using VFDs with small α values and producing damping ratios within the range of 10%–30% is very effective for the seismic design and retrofitting of CBFs with large number of stories subjected to high intensity ground motions.

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