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Evaluation of Accuracy of Simplified Methods of Analysis and Design of Buildings with Damping Systems for Near-Fault and for Soft-Soil Seismic Motions

by

Eleni A. Pavlou and Michael C. Constantinou
University at Buffalo, State University of New York
Department of Civil, Structural and Environmental Engineering
Ketter Hall
Buffalo, New York 14260

Technical Report MCEER-04-0008

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1 Graduate Research Assistant, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York
2 Professor and Chairman, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York

MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
University at Buffalo, State University of New York
Red Jacket Quadrangle, Buffalo, NY 14261

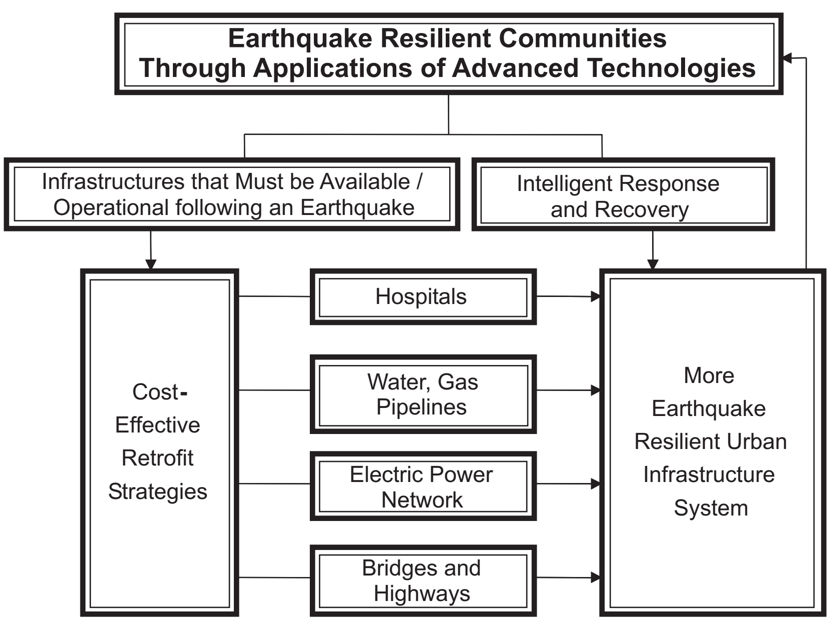
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report assesses the validity of the simplified methods of analysis and design of buildings with damping systems specified in FEMA's National Earthquake Hazard Reduction Program Recommended Provisions for Seismic Regulations for New Buildings and Other Structures issued in 2000 and updated for 2003, and the upcoming ASCE-7 Standard for 2005 when the effects of near-field and soft-soil ground motions are taken into account. The procedures outlined in these documents are largely based on studies that excluded these effects. To determine their impact, both single- and multi-degree-of-freedom structures with linear and nonlinear viscous damping devices were studied using two sets of near-field ground motions and one set of soft-soil ground motions.

The study found that the damping coefficient values are accurate or conservative; the ductility demand for near-field and soft-soil motions are very similar to those previously observed for far-field motions; simplified methods of analysis for single-degree-of-freedom systems produce results on displacement and acceleration that are generally of acceptable accuracy or conservative for near-field or soft-soil motions and are very similar to that previously observed for far-field motions; and their application to steel moment frames with linear and nonlinear viscous damping systems provided conservative estimates of drift and predictions for damper forces and member actions in good overall agreement with the average of results of nonlinear response-history analysis.

ABSTRACT

The effect of near-field and soft-soil ground motions on structures with viscous-damping systems was examined. Damping modification factors for damping ratios up to 100% of critical were obtained for sets of near-field and soft-soil ground motions and compared to the values presented in 2000 NEHRP Recommended Provisions. A study was carried out for the ductility demand in structures without and with damping systems, where the damped buildings were designed for a smaller base shear than conventional buildings in accordance with the 2000 NEHRP Provisions. Nonlinear response-history and simplified methods of the 2000 NEHRP Provisions were used to analyze single-degree-of-freedom systems and 3-story moment frames with linear viscous and nonlinear viscous damping systems to acquire knowledge on the influence of near-field and soft-soil ground motions on the accuracy of simplified methods of analysis.

ACKNOWLEDGEMENTS

Financial support for this project was provided by the Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, Task on Rehabilitation Strategies for Buildings. The work was performed under the direction of Technical Subcommittee 12, Base Isolation and Energy Dissipation, of the Building Seismic Safety Council, which was tasked with developing analysis and design procedures for inclusion in the 2000 and 2003 editions of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*. The work of Technical Subcommittee 12 was supported by the Federal Emergency Management Agency.

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SECTION 1

INTRODUCTION

FEMA's *National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* of year 2000 (BSSC, 2001), the upcoming Provisions for year 2003, and the upcoming ASCE-7 Standard for year 2005 contain the first simplified methods for analysis and design of buildings with damping systems. These procedures are largely based on studies that excluded the effects of near-field and soft-soil seismic excitations (Ramirez et al., 2001, 2002a, 2002b, 2003, Whittaker et al., 2003). This study concentrates on a systematic assessment of the validity of these methods for these special classes of seismic excitations.

Several studies have lead to the use of passive energy dissipation systems in new and existing construction. However, matters pertaining to how these systems would respond under near-fault and soft-soil seismic excitations have been very limited. The studies of Uriz and Whittaker (2001), Filiatrault et al. (2001), and Miyamoto and Singh (2002) concentrated on the performance of buildings with damping systems in near-field and other motions. Based on response history analyses, these studies concluded that damping systems are effective in reducing deformations and plastic hinge rotations but likely not sufficient to prevent damage in pre-Northridge designed buildings. Several more studies concentrated on the effect of near-fault motions on structures without damping systems, which however, also provide insight into the behavior of structures with damping systems (e.g., Chopra and Chintanapakdee (2001); Iwan et al. (2000); Baez and Miranda (2000); Alavi and Krawinkler (2000); MacRae et al. (2001)).

Recently, Ramirez et al. (2001, 2002a, 2002b, 2003) evaluated the accuracy of simplified methods of analysis of buildings with damping systems. Particularly, the simplified analysis methods of 2000 NEHRP Recommended Procedures (BSSC, 2001) and 1997 NEHRP Guidelines for the Seismic Rehabilitation of Buildings (ATC, 1997) have been evaluated and shown to produce results of acceptable accuracy. However, the studies did not consider near-field and soft-soil earthquake motions so that the conclusions presented in the Ramirez et al. papers do not necessarily apply to such conditions.

To shed some light on these issues, structures with linear and nonlinear viscous damping systems were employed to examine how the response to near-field and soft-soil ground motions differs from that to far-field motions. This study presents:

(1) information on three sets of ground motions used in this study: two sets of near-field motions and one set of soft-soil motions;

(2) a comparison of the values of damping coefficients obtained through analyses with the near-field and soft-soil motions, and the values listed in the *2000 NEHRP Provisions* to modify the 5-percent damped response spectrum for the effects of higher damping;

(3) a comparison of ductility demands in structures without and with damping systems, where the damped buildings are designed for a smaller base shear than conventional buildings;

(4) results of the simplified method of analysis for single-degree-of-freedom structures with damping systems, consisting of linear viscous, nonlinear viscous, and yielding damping devices, along with the results of nonlinear response history analysis; and

(5) a comparison of results of dynamic response history analysis and of simplified analysis of 3-story frames with linear and nonlinear viscous damping systems.

SECTION 2

GROUND MOTIONS USED IN THIS STUDY

2.1 Near-Field Ground Motions

Near-field ground motion recordings (e.g., 1994 Northridge, California; 1995 Kobe, Japan; 1999 Izmit, Turkey; 1999 Chi-Chi, Taiwan) have highlighted characteristics that are uniquely different from the far-field ones. These include distinctive pulse-like time histories, high peak velocities, and large ground displacements. Near-field earthquakes recorded along the fault in the direction of rupture usually exhibit forward-directivity effects such as large pulse of motion in the velocity and displacement histories (Somerville, 1999). These pulses are generally more intense on the fault-normal component. Motions recorded at stations located away from the direction of fault rupture do not exhibit such pronounced pulses.

Two ensembles of actual near-field ground motions with both forward and backward directivity, recorded in historic events were considered in this study to cover the range of characteristics contained in typical near-fault ground motions. The first set of near-field ground motions, herein referred to as NF1, assembled by Somerville (1997), includes ten near-field motions on stiff soil selected from a suite of time histories that had been developed for major crustal earthquakes in UBC Zone 4. These time histories represent near-field ground motions from earthquakes having a variety of faulting mechanisms in the magnitude range of 6.7 to 7.5, and distance range of 0 to 10 km. The ground motions have been either recorded or modified to NEHRP site class D conditions. The NF1 earthquake histories are presented in Table 2-1. Figure 2-1 shows the average 5%-damped response spectrum of the NF1 fault-normal and fault-parallel components.

A second ensemble of near-field ground motions, referred to as NF2, is utilized for comparison purposes. The NF2 set of motions is presented in Table 2-2. It includes only Californian records, which are rotated from their original recorded orientation to fault-parallel and fault-normal components and then multiplied by the scale factors presented in Table 2-2. The scale factors were selected by the procedure described in Tsopelas et al. (1997) so that the fault-normal and fault-parallel components represent, on the average, a

Table 2-1. First Set of Near-Field Earthquake Histories (NF1)

EARTHQUAKE	STATION	MOMENT MAGNITUDE	CLOSEST TO FAULT RUPTURE DISTANCE (km)
Northridge (1994)	Olive View	6.7	6.4
	Rinaldi	6.7	7.5
Loma Prieta (1989)	Los Gatos	7	3.5
	Lex Dam	7	6.3
Kobe (1995)	Kobe	7	3.4
	Takatori	6.9	4.3
Erzincan (1992)	Erzincan	6.9	2.0
Tabas (1978)	Tabas	7.4	1.2
Landers (1992)	Lucerne	7.4	1.1
Cape Medocino (1992)	Petrolia	7.1	8.5

Table 2-2. Second Set of Near-Field Earthquake Histories (NF2)

EARTHQUAKE	STATION	MOMENT MAGNITUDE	CLOSEST TO FAULT RUPTURE DISTANCE (km)	SCALE FACTOR
Imperial Valley (1979)	El Centro Array #6	6.5	1.0	0.657
	El Centro Array #7	6.5	0.6	0.723
Northridge (1994)	Rinaldi	6.7	7.5	0.439
	Sylmar Hospital	6.7	6.4	0.625
	SCS	6.7	6.2	0.556
	SCSE	6.7	6.1	0.608
	Newhall	7.1	7.1	0.691
Loma Prieta (1989)	Corralitos	6.9	5.1	1.356
	Capitola	6.9	14.5	1.519
Cape Medocino (1992)	Petrolia	7.1	8.5	0.823

2000 NEHRP spectrum with $S_{D1} = 0.6$, $S_{DS} = 1.0$, and $T_S = 0.6$ seconds. The selection of the records in ensemble NF2 was made by Lord (1996). Figure 2-2 presents the average 5%-damped response spectra of the NF2 fault-normal and fault-parallel components, and the target NEHRP spectrum.

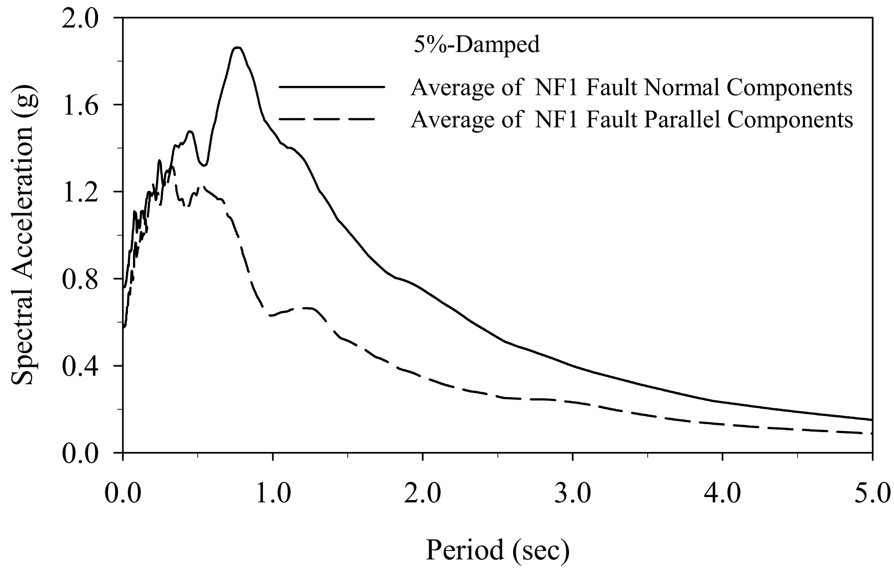


Figure 2-1. Average Spectral Acceleration of NF1 Fault-Normal and Fault-Parallel Components

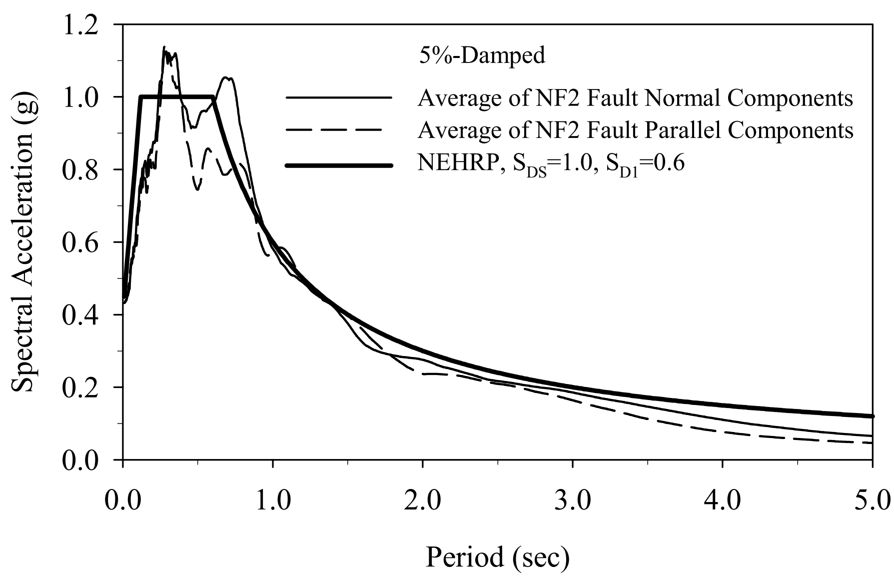


Figure 2-2. Average Spectral Acceleration of NF2 Fault-Normal and Fault-Parallel Components

2.2 Soft-Soil Ground Motions

Fourteen horizontal components of seven soft-soil earthquake histories (referred to as SS) were utilized in the analysis. The magnitude of the earthquakes ranged from 6.7 to 7.5; the epicentral distance varied from 16 to 166 km; and site conditions characterized by Site Class E in accordance with the 2000 NEHRP. The applicable design response spectrum, which represents the target design-response spectrum, involved parameters $S_{D1} = 0.75$, $S_{DS} = 0.8$, and $T_s = 0.94$ seconds. These motions were selected and scaled on the basis of the process presented in Tsopelas et al. (1997). Table 2-3 presents the soft-soil motions selected to represent the 2000 NEHRP class E spectrum and their scale factors. Figure 2-3 presents the average spectral values of the 14 soft-soil scaled components. It should be noted that the scaled components represent, on the average, well the 2000 NEHRP Class E spectrum for periods above 1.0 sec, but they are conservative for shorter periods.

Table 2-3. Soft-Soil Earthquake Histories (SS)

EARTHQUAKE	STATION	COMP.	SCALE FACTOR	MOMENT MAGNITUDE	CLOSEST TO FAULT RUPTURE DISTANCE (km)
Northridge (1994)	Sylmar	90 360	0.99 0.59	6.7	16
Loma Prieta (1989)	Gilroy #3	90 0	1.74 2.20	7.1	32.5
	Hollister & Pine	90 0	2.46 1.21	7.1	49.6
Landers (1992)	Barstow-Vineyard	90 0	3.03 3.46	7.5	93.5
	Amboy	90 0	4.26 3.79	7.5	74.2
	Hotsprings	90 0	4.01 3.65	7.5	29.1
Southern Alaska (1979)	Yakutat	09 279	3.20 2.45	7.3	166

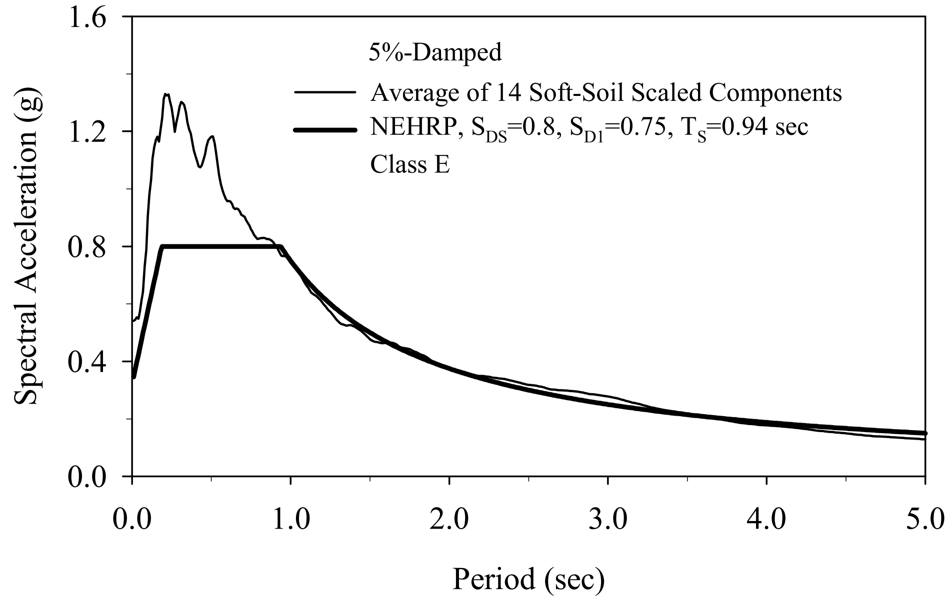


Figure 2-3. Average Spectral Acceleration of Soft-Soil Ground Motions

SECTION 3

MODIFICATION OF RESPONSE SPECTRUM FOR HIGH DAMPING

3.1 Introduction

Since response spectra are typically specified for 5% viscous damping, it is necessary to modify these spectra if different levels of damping are required. Elastic response spectra for levels of viscous damping greater that 5% were utilized in the analysis of structures, with linear viscous and nonlinear viscous damping systems.

In order to reduce the elastic spectral demands for increases in damping, the damping coefficient B is used. The values of the damping coefficient that appeared in *2000 NEHRP Provisions* were based on the work of Ramirez et al. (2001), in which near-field and soft-soil ground motions were excluded. In this study, the influence of these types of ground motions is examined.

3.2 Modification of Response Spectrum for High Damping

Linear response-history analyses were carried out for the three sets of earthquake motions (NF1, NF2, SS), to calculate values for the damping coefficient for damping ratios up to 100% of critical, based on the procedure presented in Ramirez et al. (2001). In particular, the value of the damping coefficient B for a particular period is obtained as the ratio of the average 5%-damped spectral acceleration, $S_a(T,0.05)$, to the average spectral acceleration for a different damping ratio β, $S_a(T,\beta)$

$$B=\frac{S_a(T,0.05)}{S_a\left(T,\beta\right)} \tag{3-1}$$

Figure 3-1 presents a comparison between the damping coefficients for damping ratios of 10% to 100%, obtained through linear response history analyses using the two sets of near-field motions, NF1 and NF2. It is apparent that the values of the damping coefficient for both the fault-normal and fault-parallel components of the two sets of ground motions are close despite the substantial differences in the two ensembles of near-field motions used in the study. Based on these results, only damping coefficients calculated for the NF1 set of motions are compared with the damping coefficients presented in *2000*

NEHRP Recommended Provisions. Figures 3-2 and 3-3 show the calculated damping coefficients and the coefficients presented in *2000 NEHRP Recommended Provisions*, for the NF1 fault-normal and NF1 fault-parallel components, respectively. The 2000 NEHRP values of coefficients B are presented in Figures 3-2 and 3-3 for values of $T_S/5$ equal to 0.24 seconds for fault-parallel and equal to 0.6 seconds for fault-normal components (T_S is the value of period at the intersection of the acceleration-sensitive and velocity-sensitive regions of the response spectrum and $T_S/5$ is the cutoff period below which the value of B linearly reduces to unity). These values of parameter T_S are consistent with the NF1 fault-parallel and fault-normal average spectra of Figure 2-1, respectively. The difference in period T_S value between fault-normal and fault-parallel components is generally recognized (e.g., Chopra and Chintanapakdee (2001)). The results in Figures 3-2 and 3-3 demonstrate that with proper selection of parameter T_S, the 2000 NEHRP values of damping coefficient B are generally accurate or conservative for near-fault motions and for periods up to 3 seconds. It should also be noted that the 2000 NEHRP values of coefficient B are unconservative for damping ratios over 40% and for periods above about 2.5 seconds when used for near-fault excitations. However, values of the damping ratio exceeding 40% are typically associated with the higher modes of vibration, for which the period is low.

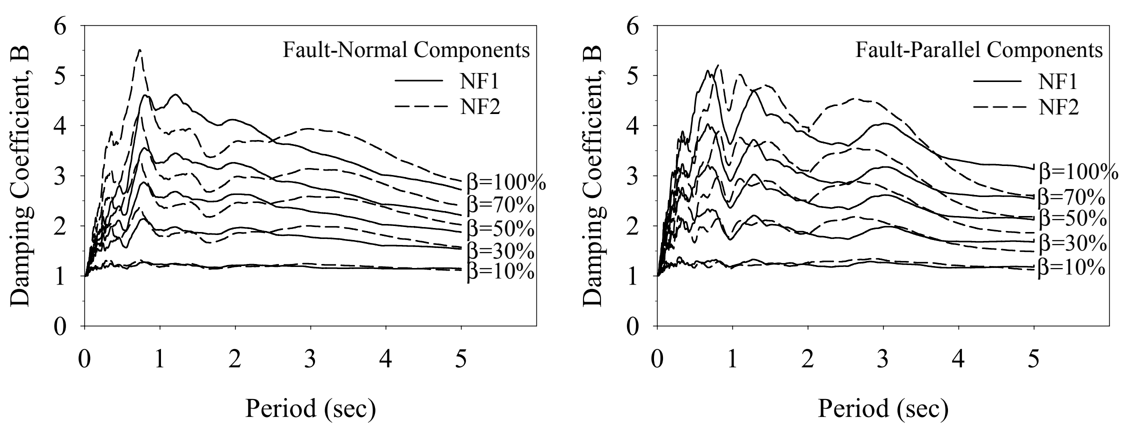


Figure 3-1. Comparison of Calculated Damping Coefficients for NF1 and NF2 Sets of Near-Field Motions

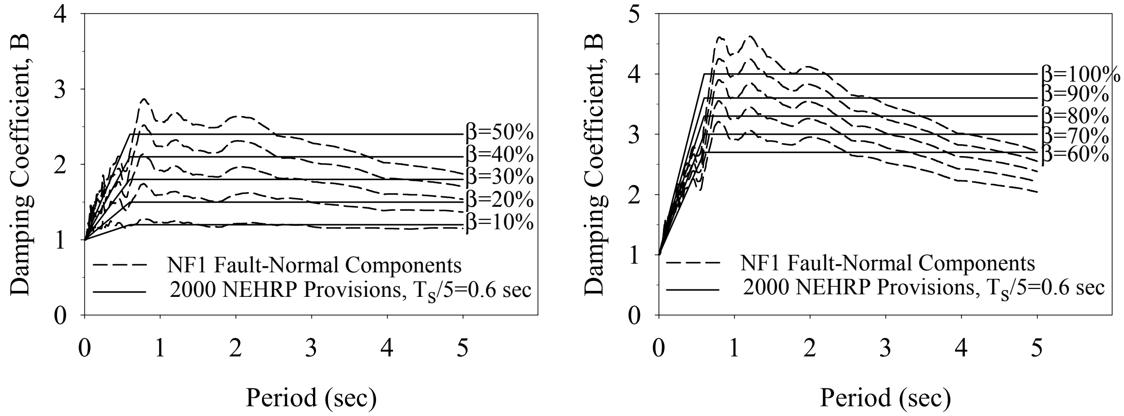


Figure 3-2. Calculated and NEHRP Damping Coefficient for NF1 Fault-Normal Components

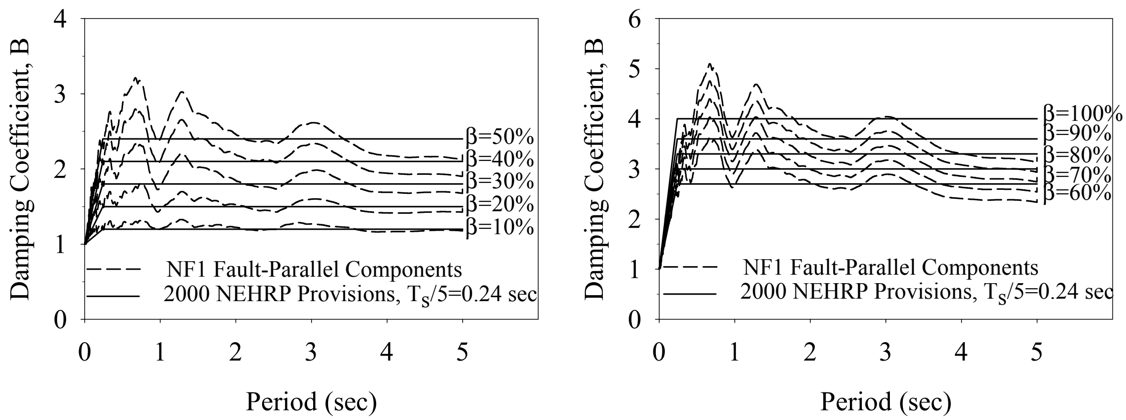
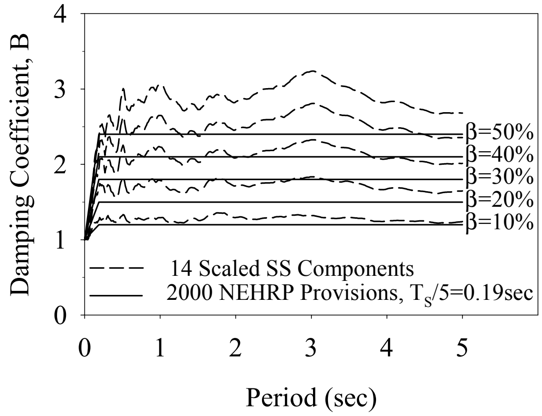


Figure 3-3. Calculated and NEHRP Damping Coefficients for NF1 Fault-Parallel Components

Moreover, damping coefficients for damping ratios up to 100% of critical are calculated using the soft-soil ground motions. Figure 3-4 shows the damping coefficients obtained from the analysis together with the values presented in *2000 NEHRP Recommended Provisions*. The results demonstrate that the 2000 NEHRP values of damping coefficient B are accurate or conservative for soft-soil ground motions and for periods up to 5 seconds.



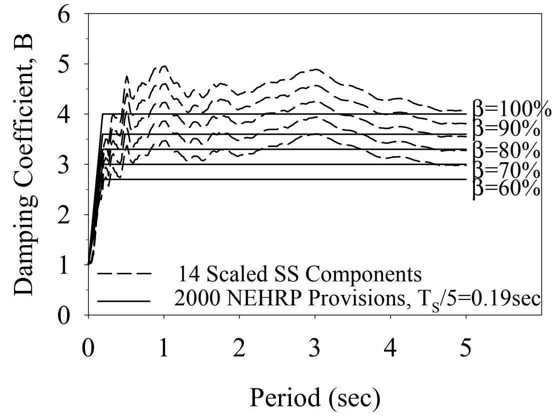


Figure 3-4. Calculated and NEHRP Damping Coefficients for Soft-Soil Ground Motions

SECTION 4

DESCRIPTION OF ANALYZED NONLINEAR SYSTEMS

4.1 Single-Degree-of-Freedom Systems

Single-degree-of-freedom systems with perfect non-degrading bilinear hysteretic behavior and bilinear elastic behavior were considered in this study. Figure 4-1 illustrates the force-displacement relations of the analyzed systems. The behavior of the structural systems exclusive of the damping devices is described by the elastic period, $T_e = 2\pi\sqrt{D_y / A_y}$, the post-yielding to elastic stiffness ratio, α, and the ductility-based portion of the R-factor, $R_\mu = S_{ae} / A_y$, where S_{ae} is the spectral acceleration at period T_e for a damping ratio of 5% and A_y represents the acceleration at yield. Each system analyzed was assumed to have 5% inherent viscous damping, β_i.

Analyses were performed on the bilinear hysteretic system with and without supplemental viscous damping. The added viscous damping is characterized by the viscous damping ratio, β_v. Description of the characterization of linear viscous and nonlinear viscous damping devices is presented in Ramirez et al. (2001). The values of the parameters used in the analyses for the bilinear hysteretic system with linear and nonlinear viscous damping devices are presented in Table 4-1. Note that for nonlinear viscous damping devices, the velocity exponent is 0.5.

Moreover, Table 4-2 presents the values of the parameters used in the analyses on the bilinear elastic system with linear viscous damping devices.

In addition, analyses were carried out for the bilinear hysteretic system with yielding damping devices. The parameters used for these systems are tabulated in Table 4-3. Note that for this system two additional parameters are needed: the ratio of the elastic stiffness of the structure inclusive of the damping devices K_t to the elastic stiffness of the structure exclusive of the damping devices K_e, K_t / K_e, and the ratio of the strength of the damping devices F_d to the strength of the structural frame F_y, F_d / F_y.

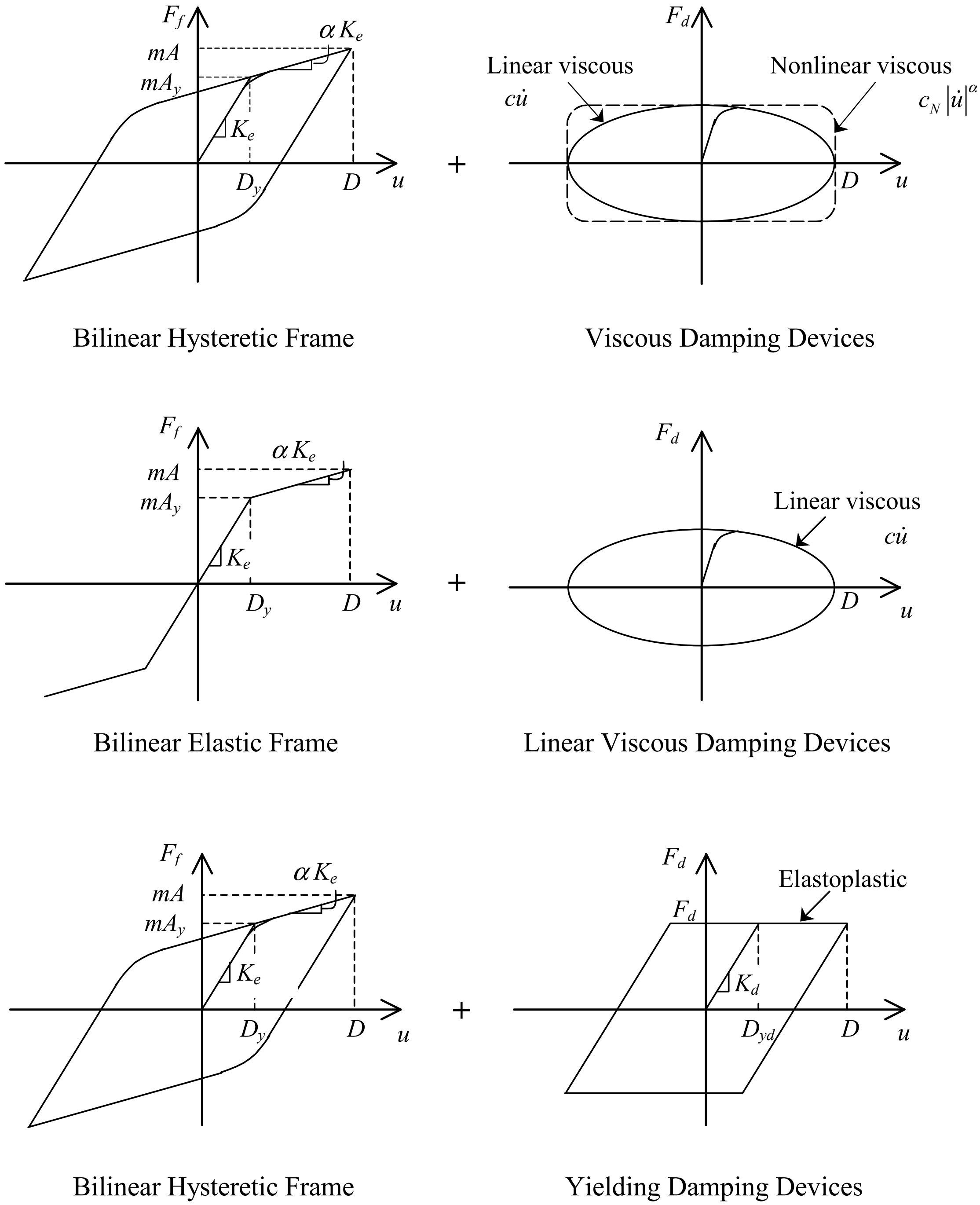


Figure 4-1. Behavior of Analyzed Single-Degree-of-Freedom Systems

Table 4-1. Values of Parameters in Study of Bilinear Hysteretic Frame with Viscous Damping Devices

Elastic Period, T_e (sec)	0.5, 1.0, 1.5, 2.0
Ductility-based Portion of R-Factor, R_μ	2, 3.33, 5
Post Elastic to Elastic Stiffness Ratio, α	0.05, 0.15, 0.25, 0.50, 1.00
Inherent Damping Ratio, β_i	0.05
Added Linear / Nonlinear Viscous Damping Ratio, β_V	0.15, 0.25

Table 4-2. Values of Parameters in Study of Bilinear Elastic Frame with Linear Viscous Damping Devices

Elastic Period, T_e (sec)	0.5, 1.0, 1.5, 2.0
Ductility-based Portion of R-Factor, R_μ	2, 3.33
Post Elastic to Elastic Stiffness Ratio, α	0.05
Inherent Damping Ratio, β_i	0.05
Added Linear / Nonlinear Viscous Damping Ratio, β_V	0.15, 0.25

Table 4-3. Values of Parameters in Study of Bilinear Hysteretic Frame with Yielding Damping Devices

Elastic Period, T_e (sec)	0.5, 1.0, 1.5, 2.0
Ductility-based Portion of R-Factor, R_μ	2, 3.33
Post Elastic to Elastic Stiffness Ratio, α	0.05
Inherent Damping Ratio, β_i	0.05
Stiffness Ratio K_t/K_e	2, 6, 10
Strength Ratio F_d/F_y	0.1, 0.2, 0.3, 0.4, 0.5

4.2 3-Story Building Frames

In addition to single-degree-of-freedom analyses, analyses were conducted for 3-story special steel moment resisting frames with linear and nonlinear viscous damping systems. The damping system was installed in diagonal configurations. Figures 4-2 through 4-5 present elevations of the frames that are defined as 3S-75, 3S-80, and 3S-100 in Ramirez et al. (2001, 2003). The frames in Figures 4-2, 4-3, and 4-4 and 4-5 were designed to have base shear strength of $0.75V$, V, and $0.8V$, respectively, where V is the base shear for the building frame without a damping system for seismic excitation described by the NEHRP spectrum with parameters $S_{DS} = 1.0$, $S_{D1} = 0.6$, and $T_s = 0.6$ seconds. Damping systems were then added to these frames and proportioned in accordance with the *2000 NEHRP Recommended Provisions* to satisfy the drift criteria. Specifically, a total of five examples were analyzed: (a) frame 3S-75 with linear viscous damping system to provide 10% viscous damping ratio when assuming elastic frame behavior (Figure 4-2); (b) frame 3S-100 with linear viscous damping system to provide 20% viscous damping ratio when assuming elastic frame behavior (Figure 4-3); (c) frame 3S-80 with nonlinear viscous damping system to provide 10% viscous damping ratio when assuming elastic frame behavior in NF1 fault-normal components. As a result of the nonlinear behavior of the viscous devices the effective damping depends on the amplitude of displacement, which in turn depends on the characteristics of the excitation. To achieve 10% damping ratio, the damping constant C (see Figure 4-4) had to be set at 23 kN-(s/mm)$^{0.5}$ for the NF1 fault-normal components. The same value was used for the analyses with the NF1 fault-parallel components achieving a damping ratio of 14%; (d) frame 3S-80 with nonlinear viscous damping system to provide 10% viscous damping ratio when assuming elastic frame behavior in soft-soil motions (Figure 4-5); and (e) frame 3S-80 with nonlinear viscous damping system to provide 20% viscous damping ratio when assuming elastic frame behavior (Figure 4-6). Detailed description of the above systems is presented in Ramirez et al. (2001).

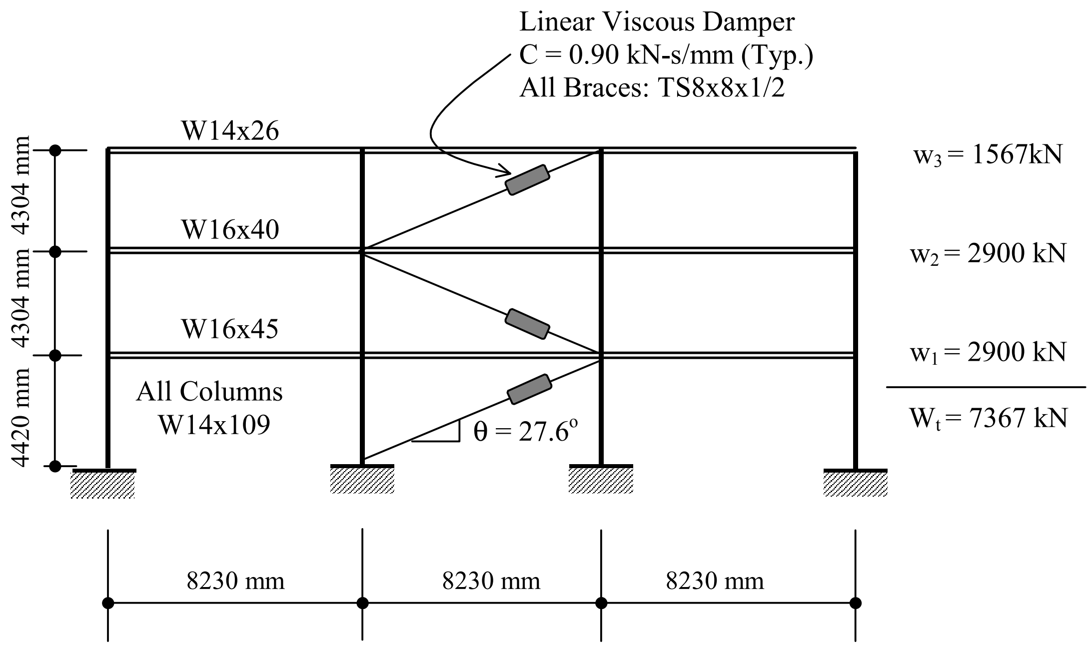


Figure 4-2. Frame 3S-75 with Linear Viscous Damping System to Provide 10% Damping Ratio when Assuming Elastic Frame Behavior

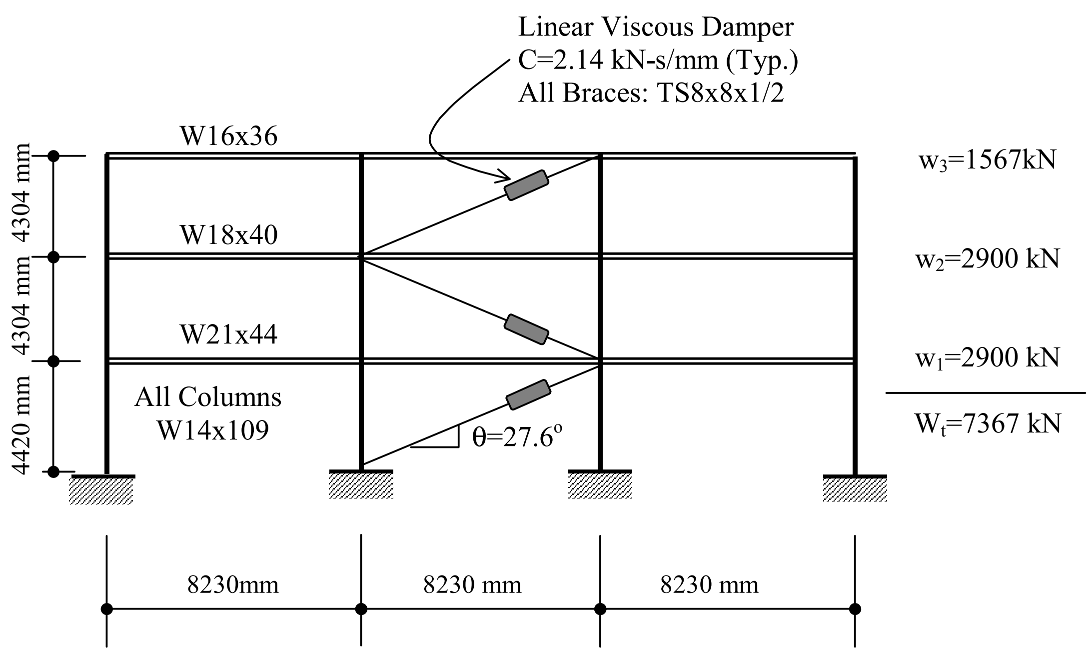


Figure 4-3. Frame 3S-100 with Linear Viscous Damping System to Provide 20% Damping Ratio when Assuming Elastic Frame Behavior

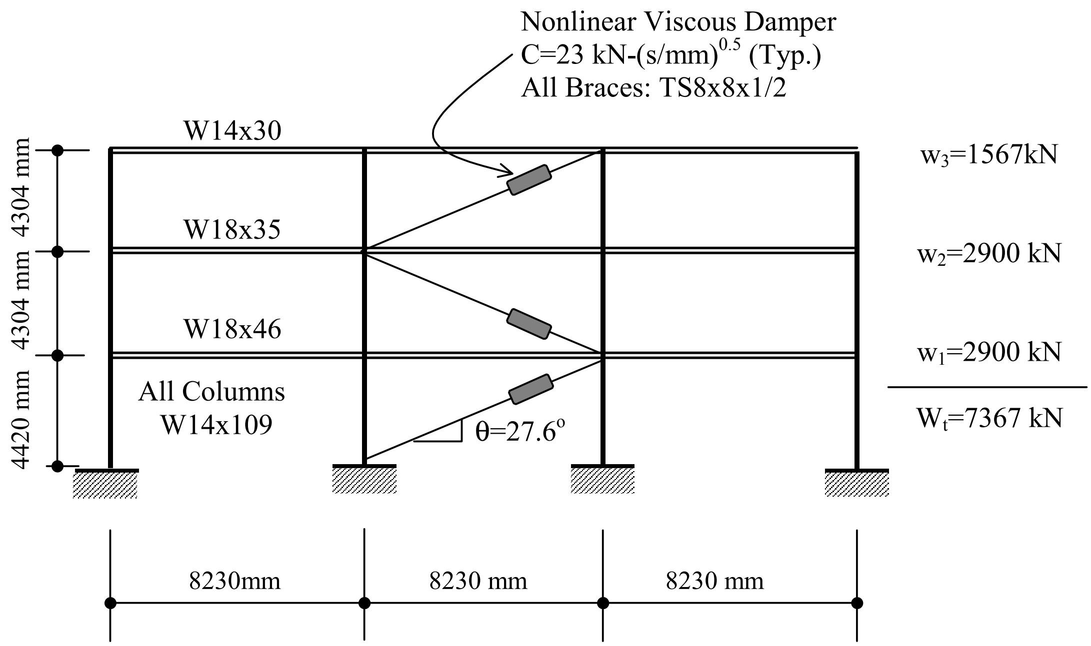


Figure 4-4. Frame 3S-80 with Nonlinear Viscous Damping System to Provide 10% Damping Ratio when Assuming Elastic Frame Behavior in NF1 Fault-Normal Components (for NF1 Fault-Parallel Components, the Damping Ratio is 14%)

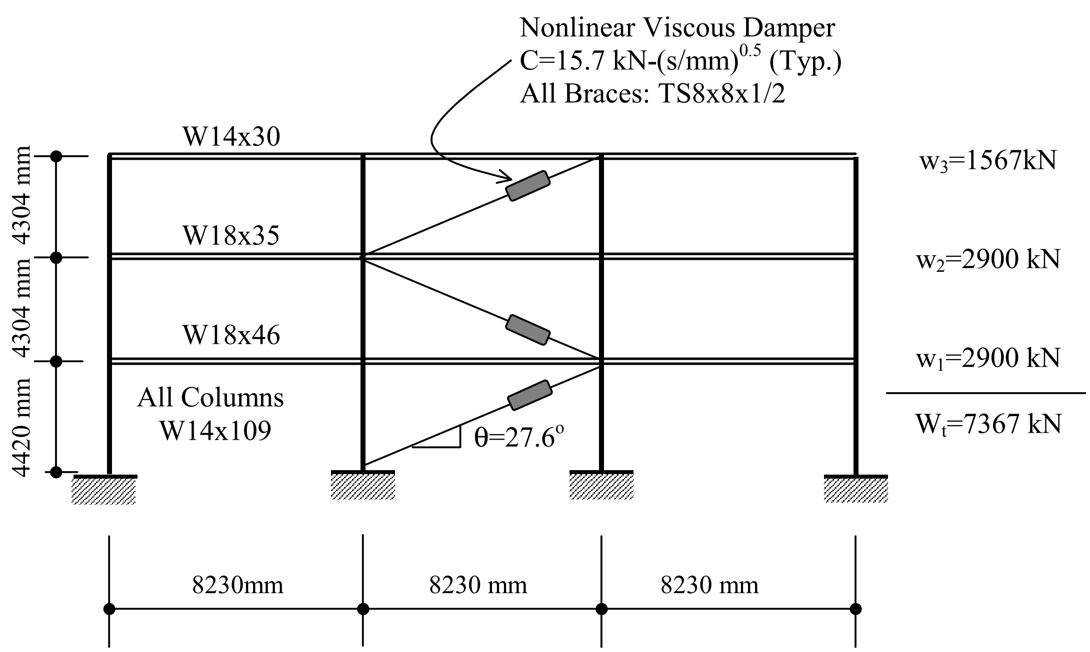


Figure 4-5. Frame 3S-80 with Nonlinear Viscous Damping System to Provide 10% Damping Ratio when Assuming Elastic Frame Behavior in Soft-Soil Motions

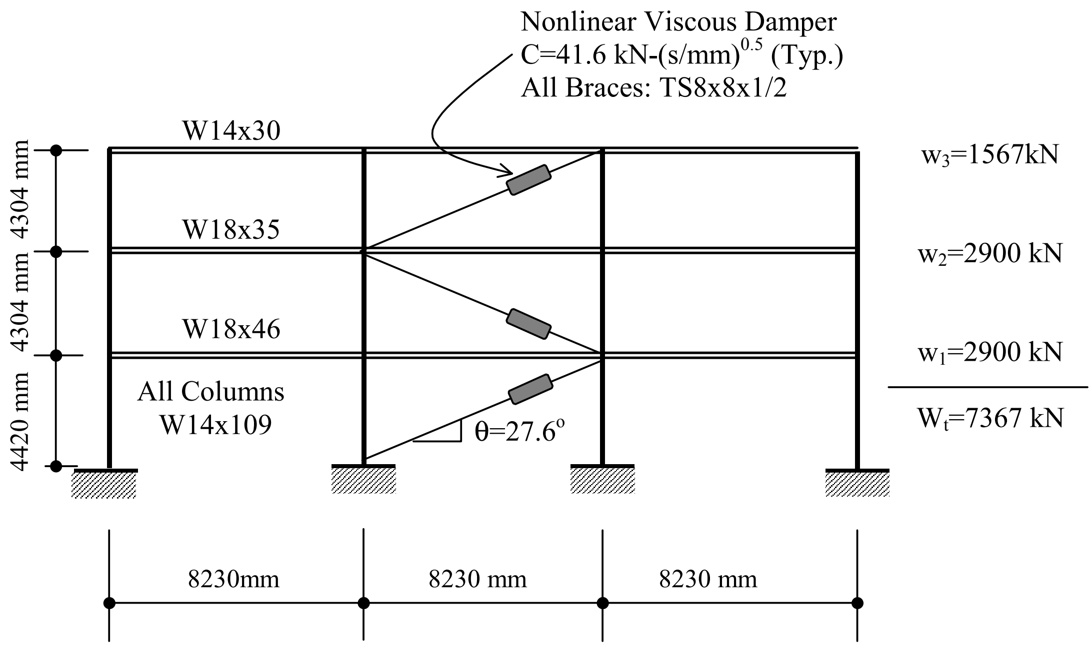


Figure 4-6. Frame 3S-80 with Nonlinear Viscous Damping System to Provide 20% Damping Ratio when Assuming Elastic Frame Behavior in NF1 Fault-Normal Components (for NF1 Fault-Parallel Components, the Damping Ratio is 28.8%)

SECTION 5

DISPLACEMENT DUCTILITY DEMANDS IN STRUCTURES WITH VISCOUS DAMPING SYSTEMS

5.1 Introduction

The *2000 NEHRP Recommended Provisions* permit the design of structures that contain a damping system for a lower base shear than that for the corresponding structure without a damping system. Particularly, the minimum base shear for frames with a damping system is the greater of V/B or $0.75V$, where V is the seismic base shear of the undamped frame and B is the damping coefficient for the combined inherent and viscous damping under elastic conditions. This was primarily based on studies that only included the effects of far-field ground motions. Herein, response-history analyses are performed using near-field and soft-soil ground motions, to investigate whether the ductility demand in the damped systems is comparable to that in the corresponding undamped systems, considering that the latter systems are both stiffer and stronger than the damped frame.

5.2 Evaluation of Displacement Ductility Demands in Structures with Viscous Damping Systems

In order to establish values of the displacement ductility demand for the near-field and soft-soil ground motions, nonlinear time history analyses were performed on the ductile single-degree-of-freedom framing systems with and without supplemental linear viscous damping. The yield strength of the damped systems varied between 0.55 ($B=1.8$ for $\beta_V+\beta_i$=0.30) and 0.67 ($B=1.5$ for $\beta_V+\beta_i$=0.20) times the strength of the corresponding undamped systems. The elastic period T_{ed} of the damped system was related to the period T_e of the corresponding undamped system as follows (Ramirez et al., 2001, 2002b)

$$\frac{T_{ed}}{T_e} = B^{0.5} \quad \text{for} \quad T_e \le T_s$$
$$\frac{T_{ed}}{T_e} = B \quad \text{for} \quad T_e > T_s \tag{5-1}$$

Figures 5-1 and 5-2 compare the calculated average displacement ductility ratio for the undamped and the damped systems for the 10 NF1 fault-normal components. Figure 5-3 presents a comparison of the minimum, average, and maximum displacement ductility ratio of the undamped and the 20%-damped systems for $\alpha = 0.05$. Figures 5-4 through 5-6 present results obtained from analyses of 20%- and 30%-damped systems for the 10 NF1 fault-parallel components. Figures 5-7 through 5-9 present results obtained from analyses of 20%- and 30%-damped systems for the soft-soil earthquake motions.

The results in Figures 5-1 to 5-9 demonstrate that, in general, the ductility demand in damped structures with lower stiffness and strength is comparable to or less than that in undamped structures for near-field and soft-soil earthquake motions. Whereas the trends in ductility demand of undamped and of damped structures seen in Figures 5-1 to 5-9 are similar to those observed in the case of far-field or stiff-soil earthquake motions (Ramirez et al., 2001, 2002b), the average ductility demand and the scatter in the ductility demand for short-period damped and undamped structures in the near-field earthquake motions attributed to overestimation of the response due to inability to select and scale the soft-soil motions to match the target spectrum in the low period range (see Figure 2-3). Also, it may be observed in Figures 5-1 to 5-9 that in all cases studied, the average displacement ductility ratio for long periods is approximately equal to the ductility-based portion of the R-factor, R_μ.

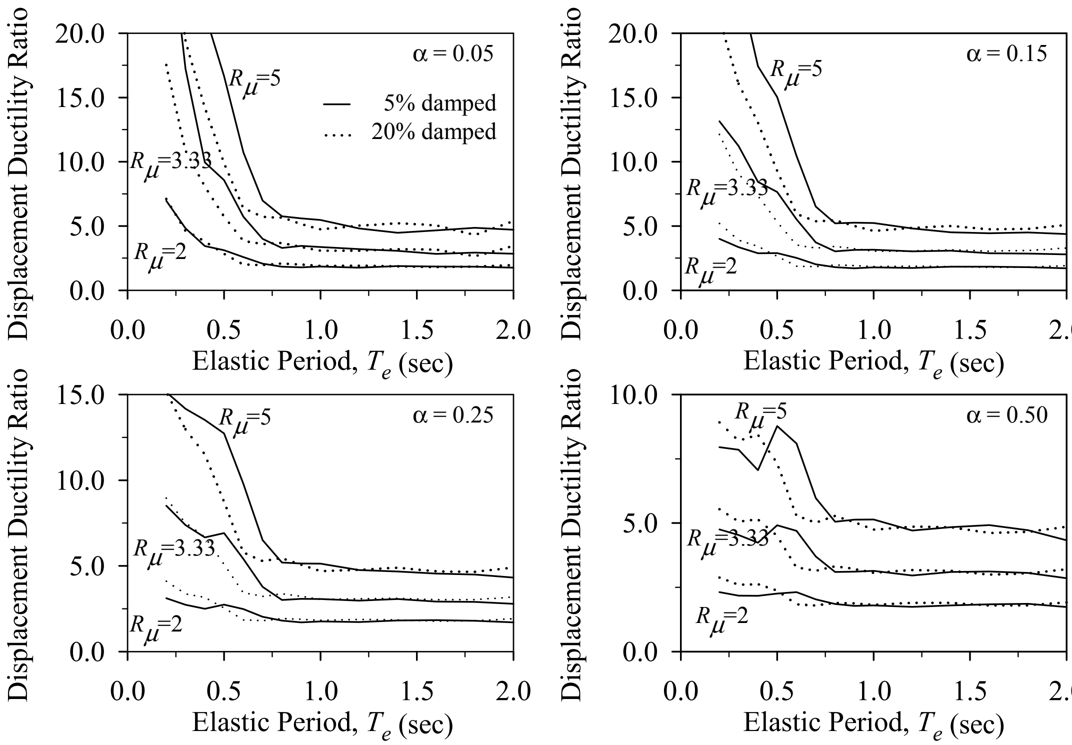


Figure 5-1. Comparison of Average Displacement Ductility Ratio for 5%- and 20%-Damped Systems – NF1 Fault-Normal Components

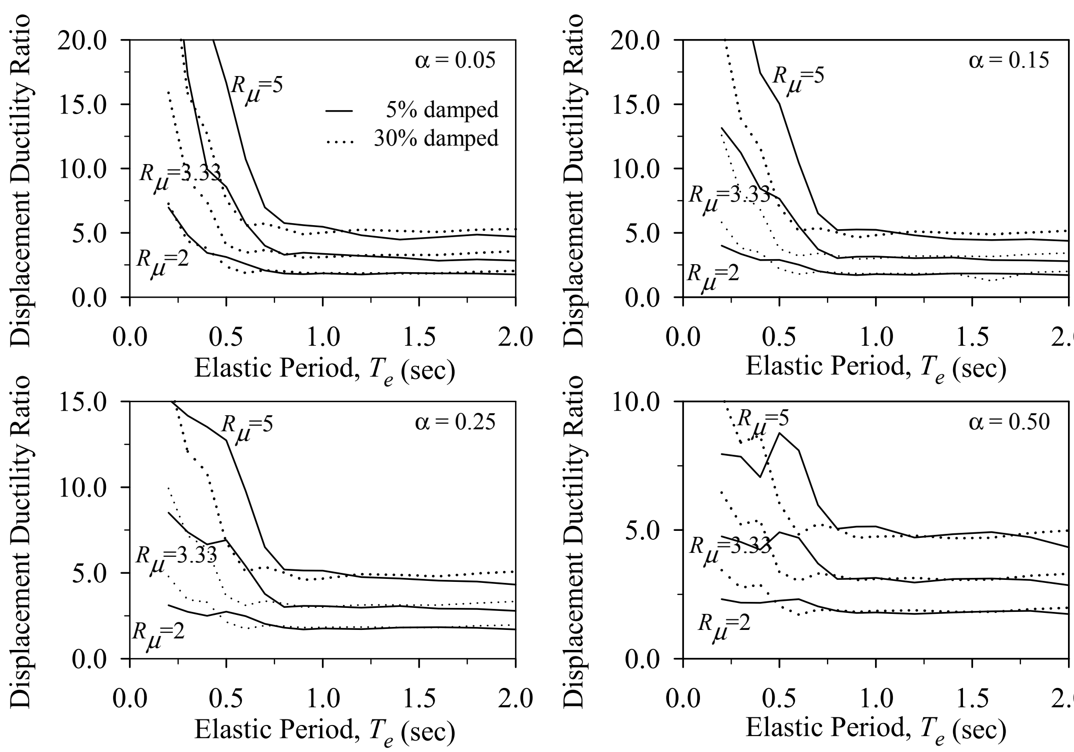


Figure 5-2. Comparison of Average Displacement Ductility Ratio for 5%- and 30%-Damped Systems – NF1 Fault-Normal Components

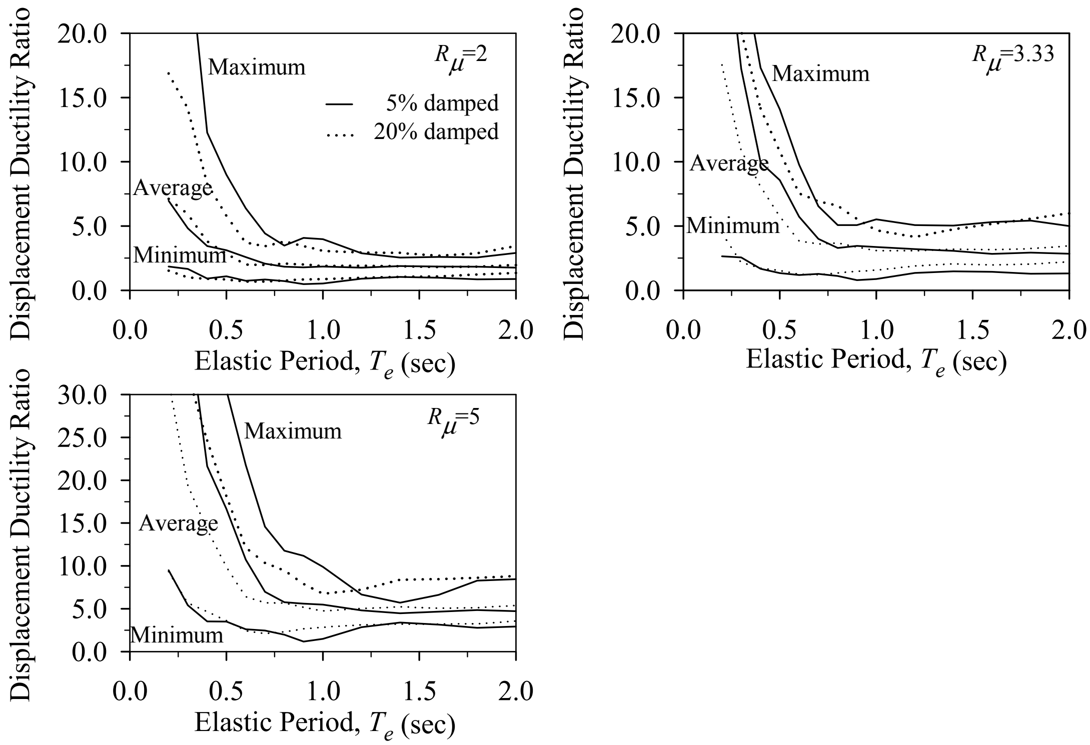


Figure 5-3. Comparison of Maximum, Average, and Minimum Displacement Ductility Ratios of 5%- and 20%-Damped Systems with $\alpha = 0.05$ – NF1 Fault-Normal Components

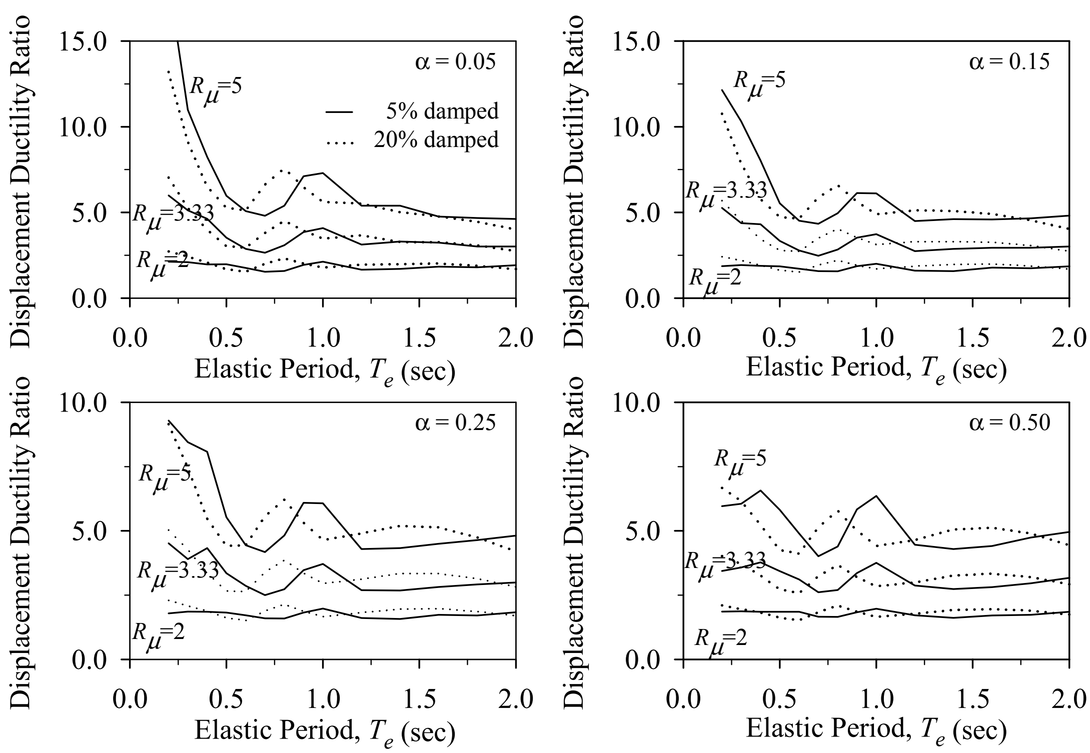


Figure 5-4. Comparison of Average Displacement Ductility Ratio for 5%- and 20%-Damped Systems – NF1 Fault-Parallel Components

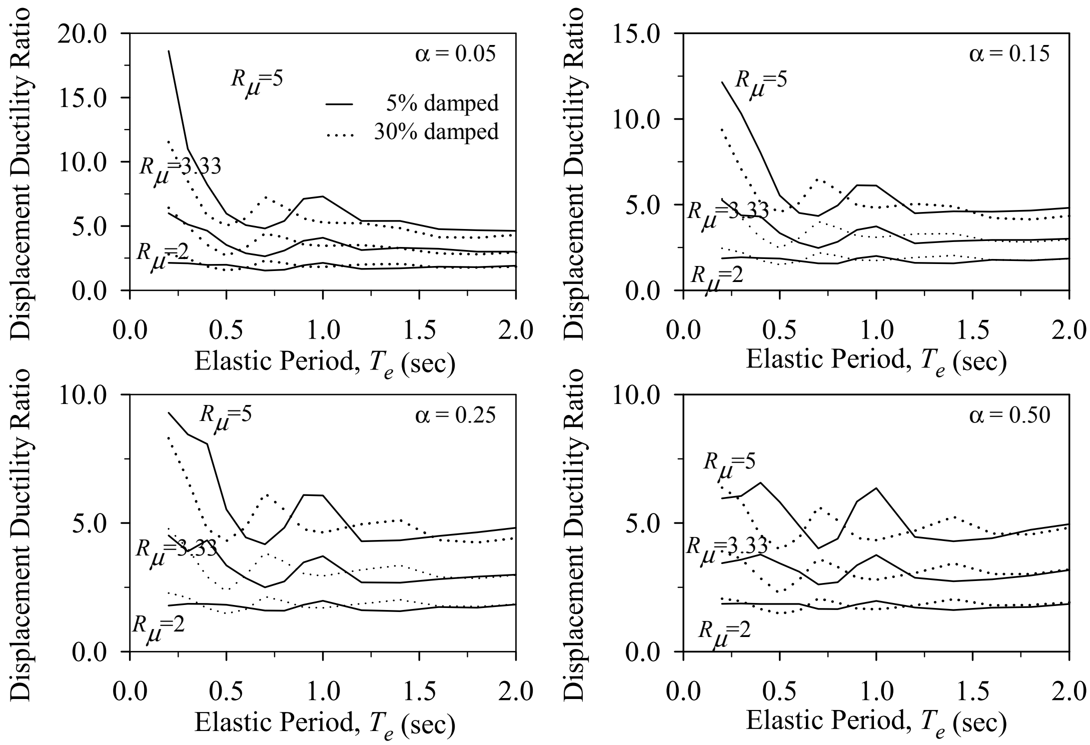


Figure 5-5. Comparison of Average Displacement Ductility Ratio for 5%- and 30%-Damped Systems – NF1 Fault-Parallel Components

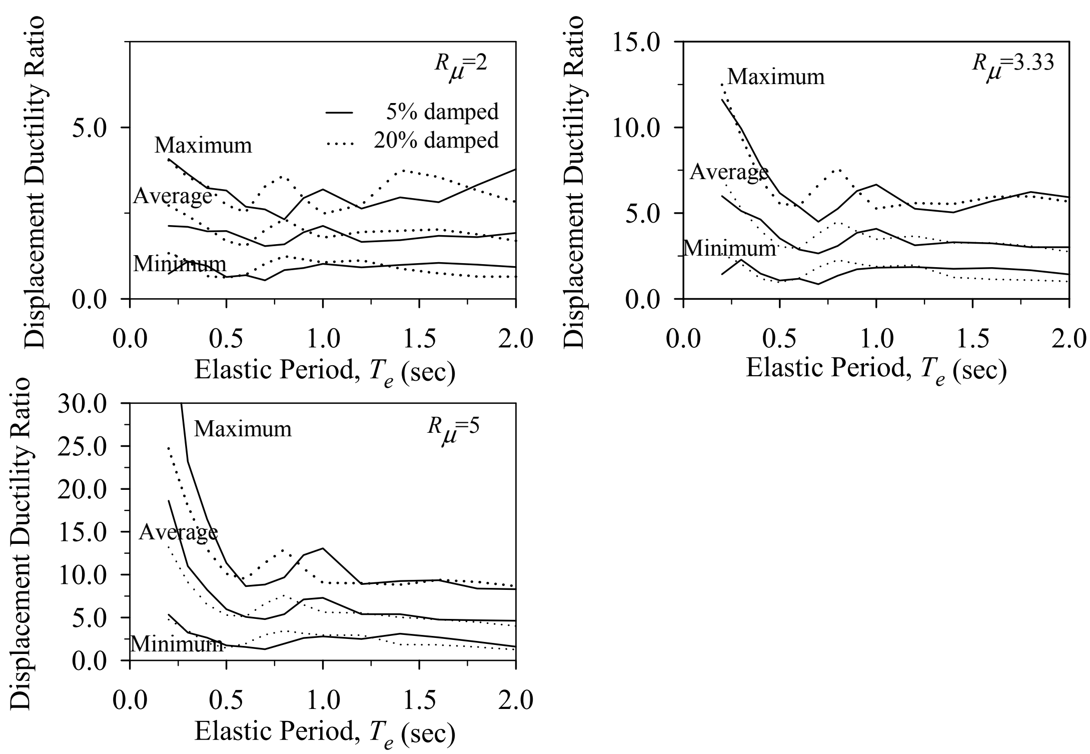


Figure 5-6. Comparison of Maximum, Average, and Minimum Displacement Ductility Ratios of 5%- and 20%-Damped Systems with $\alpha = 0.05$ – NF1 Fault-Parallel Components

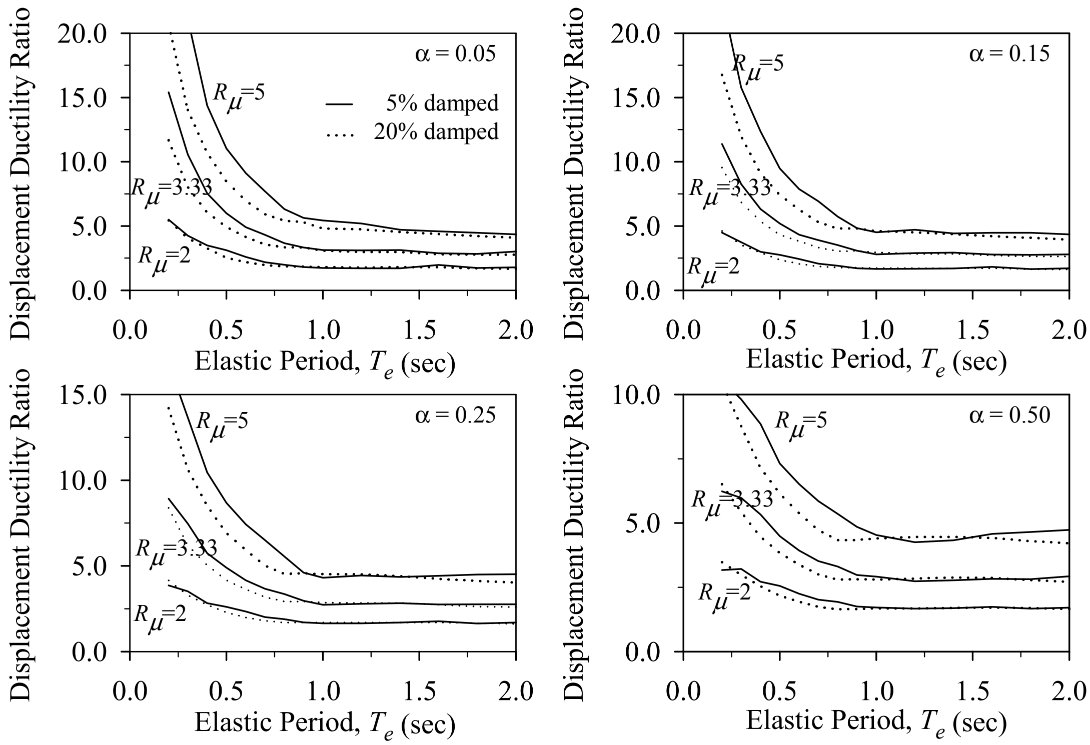


Figure 5-7. Comparison of Average Displacement Ductility Ratio for 5%- and 20%-Damped Systems – Soft-Soil Earthquake Motions

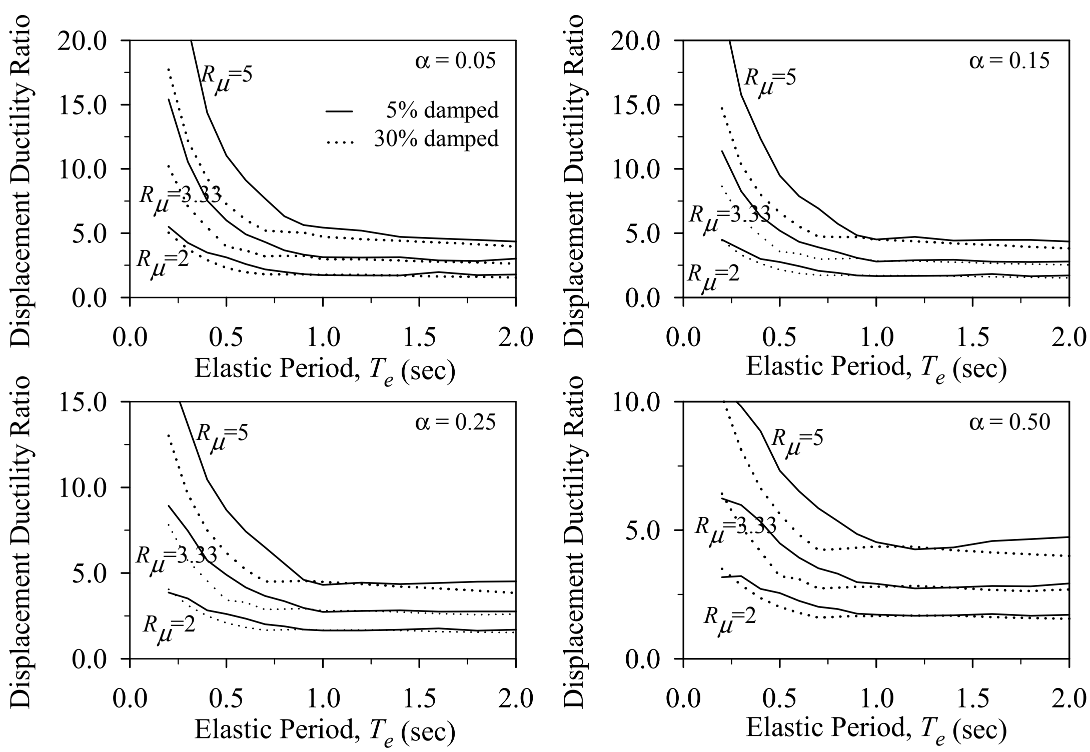


Figure 5-8. Comparison of Average Displacement Ductility Ratio for 5%- and 30%-Damped Systems – Soft-Soil Earthquake Motions

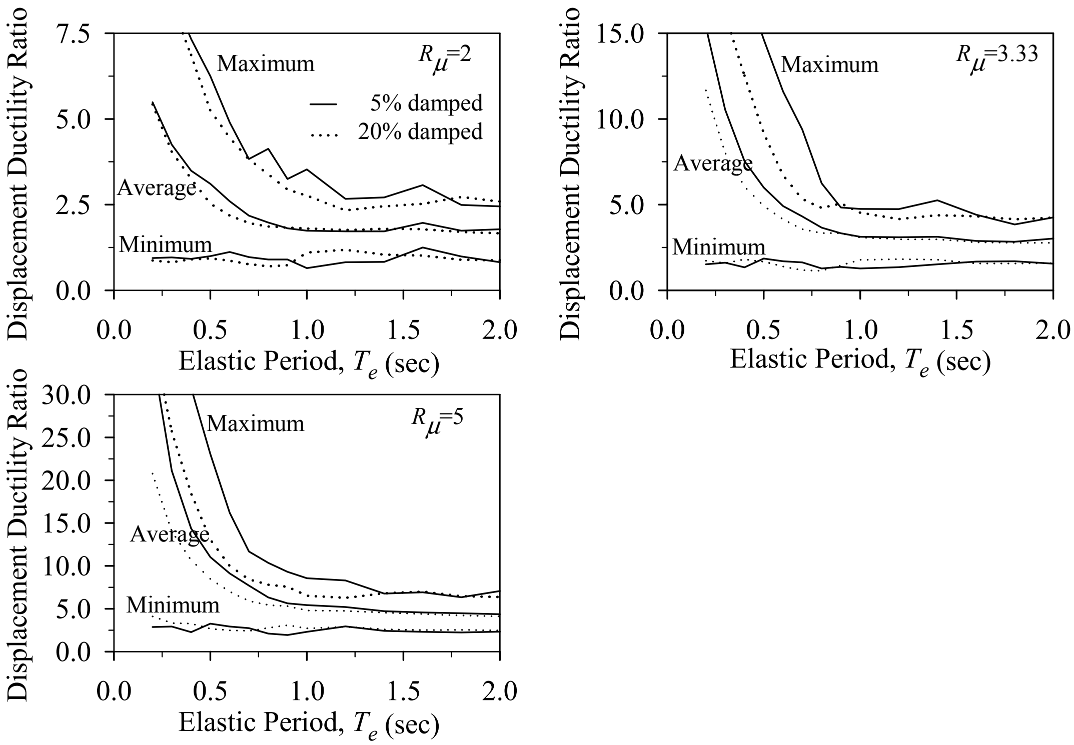


Figure 5-9. Comparison of Maximum, Average, and Minimum Displacement Ductility Ratios of 5%- and 20%-Damped Systems with $\alpha = 0.05$ – Soft-Soil Earthquake Motions

SECTION 6

RESULTS OF ANALYSIS

6.1 Introduction

Simplified methods for analysis and design of buildings with damping systems were addressed, for the first time, in the *2000 NEHRP Provisions* (BSSC, 2001). The study reported herein focuses on the assessment of the validity of these methods for near-fault and for soft-soil earthquake motions.

The Equivalent Lateral Force Procedure for Structures with Damping Systems of *2000 NEHRP Recommended Provisions* is intended to provide a simplified approach for directly determining the nonlinear response behavior of a structure at different levels of lateral displacements. In these procedures, the actual inelastic system is replaced by an equivalent linear single-degree-of-freedom system. Therefore, it is of interest to evaluate the accuracy of the simplified methods to predict the inelastic response of single-degree-of-freedom systems, for several levels of added linear viscous, nonlinear viscous damping, and for yielding damping devices.

The simplified method of analysis of the *2000 NEHRP Provisions* for single-degree-of-freedom systems is iterative, since it is based on an assumed value of displacement D, calculation of the effective period and effective damping, calculation of the displacement using the response spectrum after modification for increased damping, and comparison of the calculated and assumed values of displacement. In this case, the average 5%-damped spectra of Figures 2-1 through 2-3 were used. Details of the calculation of the effective stiffness and effective damping, for single-degree-of-freedom structures with linear viscous, nonlinear viscous, and yielding damping systems, are discussed in Ramirez et al. (2001, 2002a).

6.2 Results of Simplified Method of Analysis and Comparison to Results of Nonlinear Response History Analysis

6.2.1 Single-Degree-of-Freedom Systems

Nonlinear response history analyses for the near-field motions listed in Tables 2-1 and 2-2 and for the soft-soil ground motions listed in Table 2-3, of each of the single-degree-of-freedom system described by the parameters listed in Tables 4-1 through 4-3 were performed to investigate the accuracy of the simplified methods. Figures 6-1 through 6-33 present a comparison of the results of nonlinear history analysis and the results of the simplified method of analysis. Graphs of the peak displacement, peak velocity and peak acceleration are presented by plotting the average results of the nonlinear history analyses on the vertical axis against the results of the simplified method of analysis on the horizontal axis.

The simplified method of analysis results in the maximum displacement D. The maximum velocity, V, was calculated either as the pseudo-velocity or as the pseudo-velocity times a velocity correction factor,

$$V = \left(\frac{2\pi}{T_{eff}} \right) D \cdot CFV \tag{6-1}$$

where T_{eff} is the effective period of the system, calculated as $T_{eff} = 2\pi\sqrt{D/A}$, A is the acceleration at the instance of maximum displacement and CFV is the correction factor tabulated in Table 6 of Ramirez et al. (2002a). The maximum acceleration is determined by the procedure described in Ramirez et al. (2002a) which has been incorporated in the 2000 NEHRP.

These figures demonstrate that the 2000 NEHRP simplified methods of analysis yield good and most often conservative estimates of peak displacement and peak acceleration, and reasonable estimates of peak velocities (when estimated as pseudo-velocity), for all classes of earthquake motions. Specifically, the simplified method of analysis under predicts the peak velocity for structures with a large effective period (say $T_{eff} > 1.5$ seconds), but over predicts the peak velocity for structures with effective period less than 1.0 second. When the correction factor for velocity (per Ramirez et al. (2001, 2002a)) is utilized, the prediction of velocity by the simplified method is very good. It is interesting to note that values of the correction factor for velocity have been determined by Ramirez et al. (2001, 2002a) on the basis of analyses with motions without near-field or soft-soil characteristics.

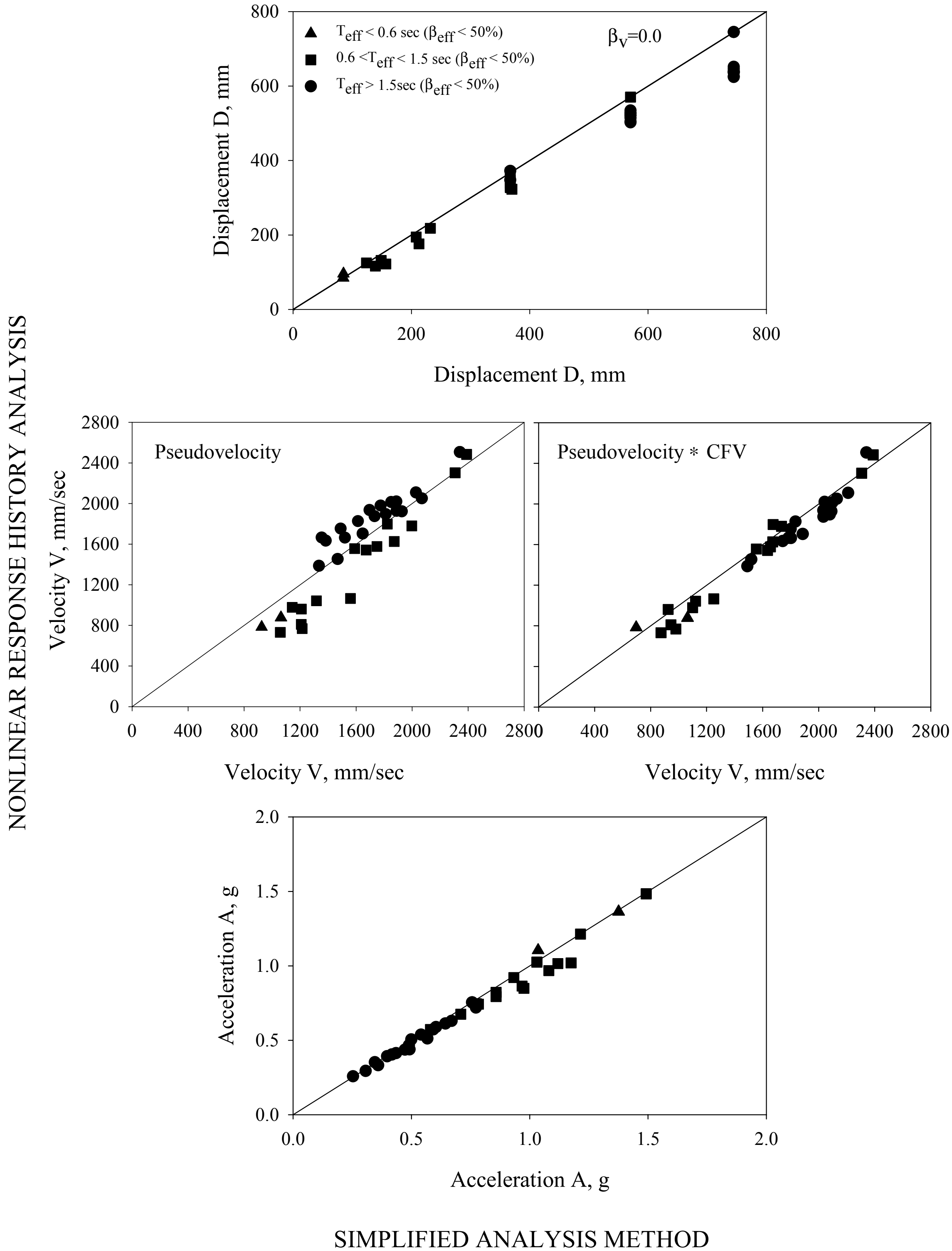


Figure 6-1. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems without Damping Devices - NF1 Fault-Normal Components

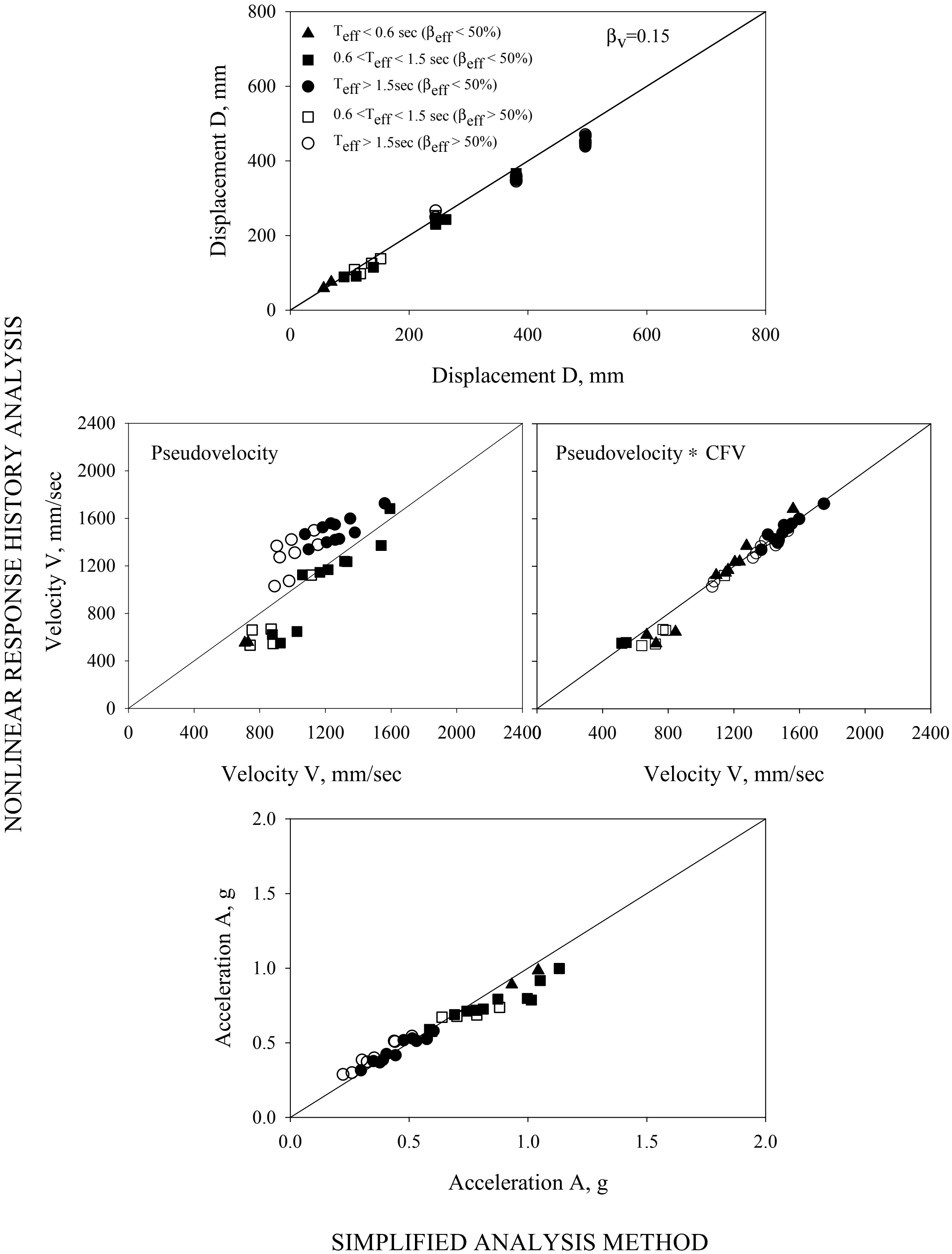


Figure 6-2. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - NF1 Fault-Normal Components

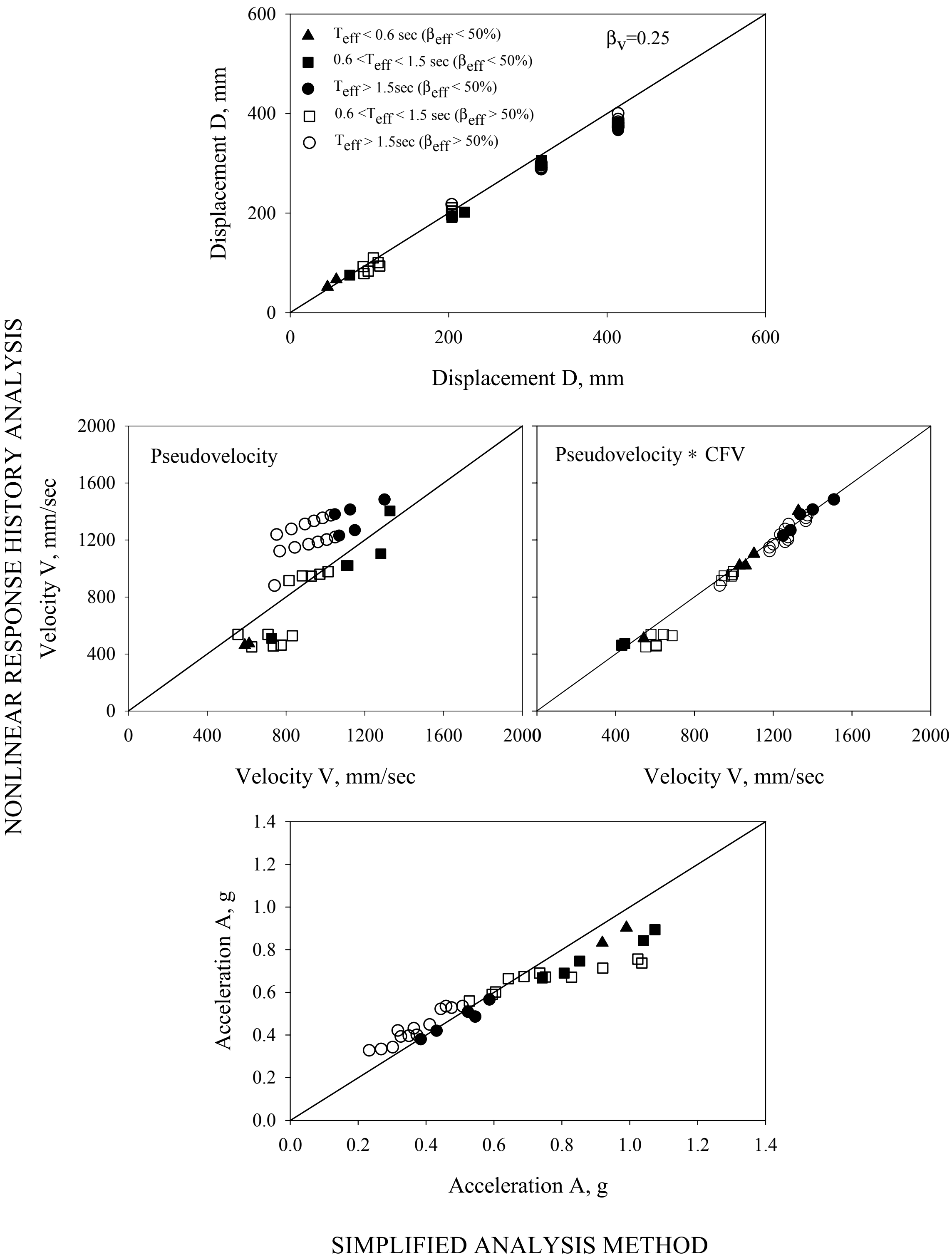


Figure 6-3. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - NF1 Fault-Normal Components

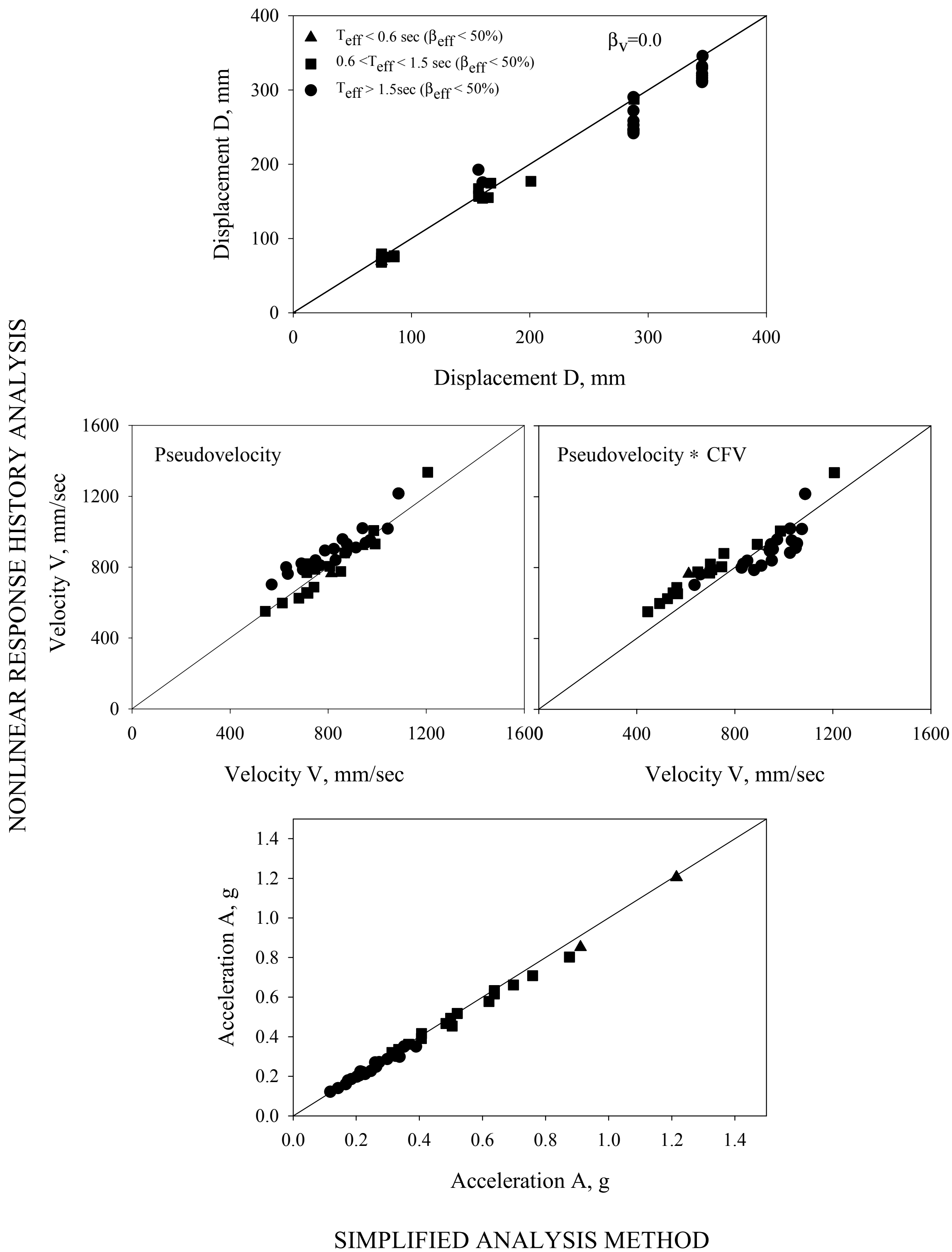


Figure 6-4. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems without Damping Devices - NF1 Fault-Parallel Components

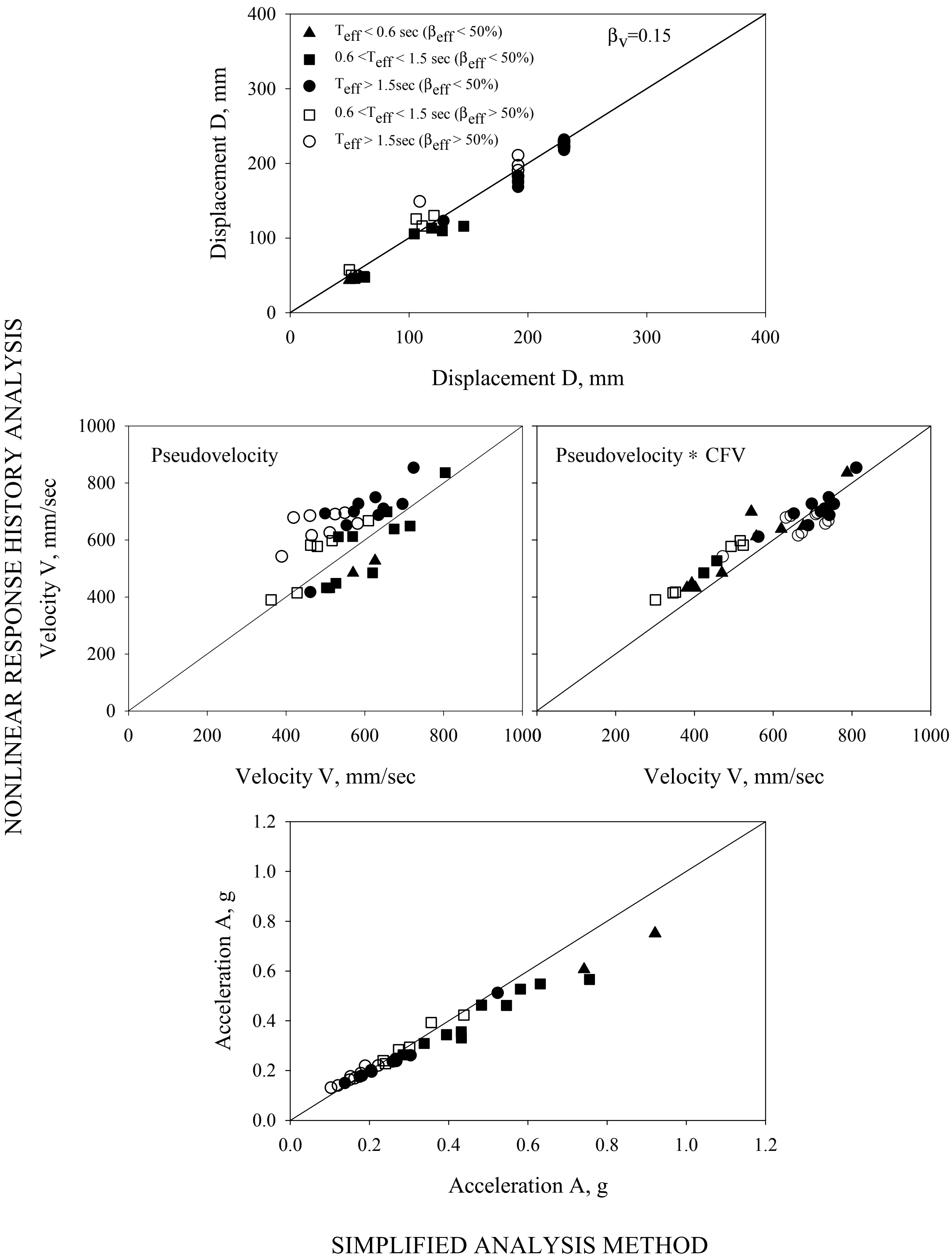


Figure 6-5. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - NF1 Fault-Parallel Components

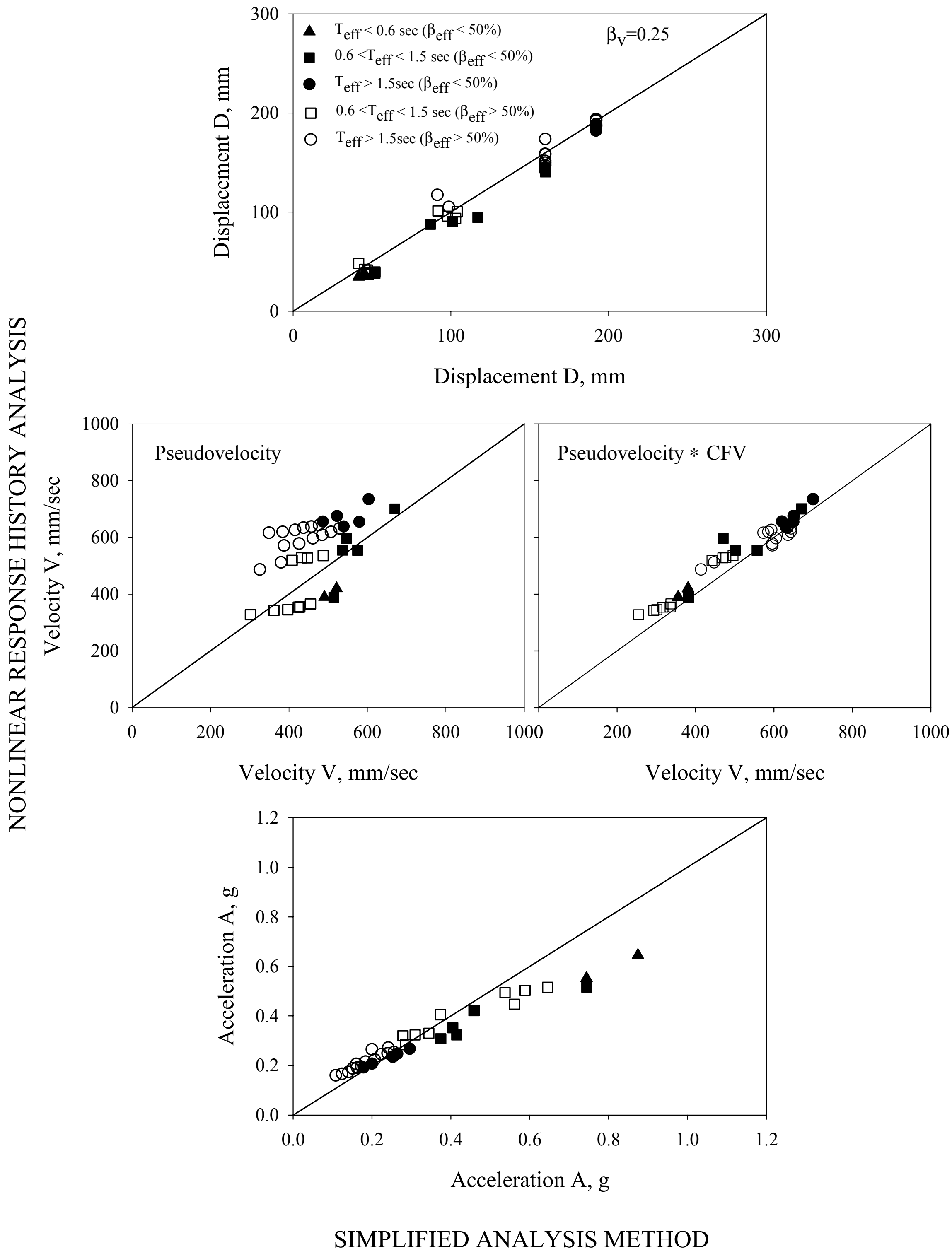


Figure 6-6. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - NF1 Fault-Parallel Components

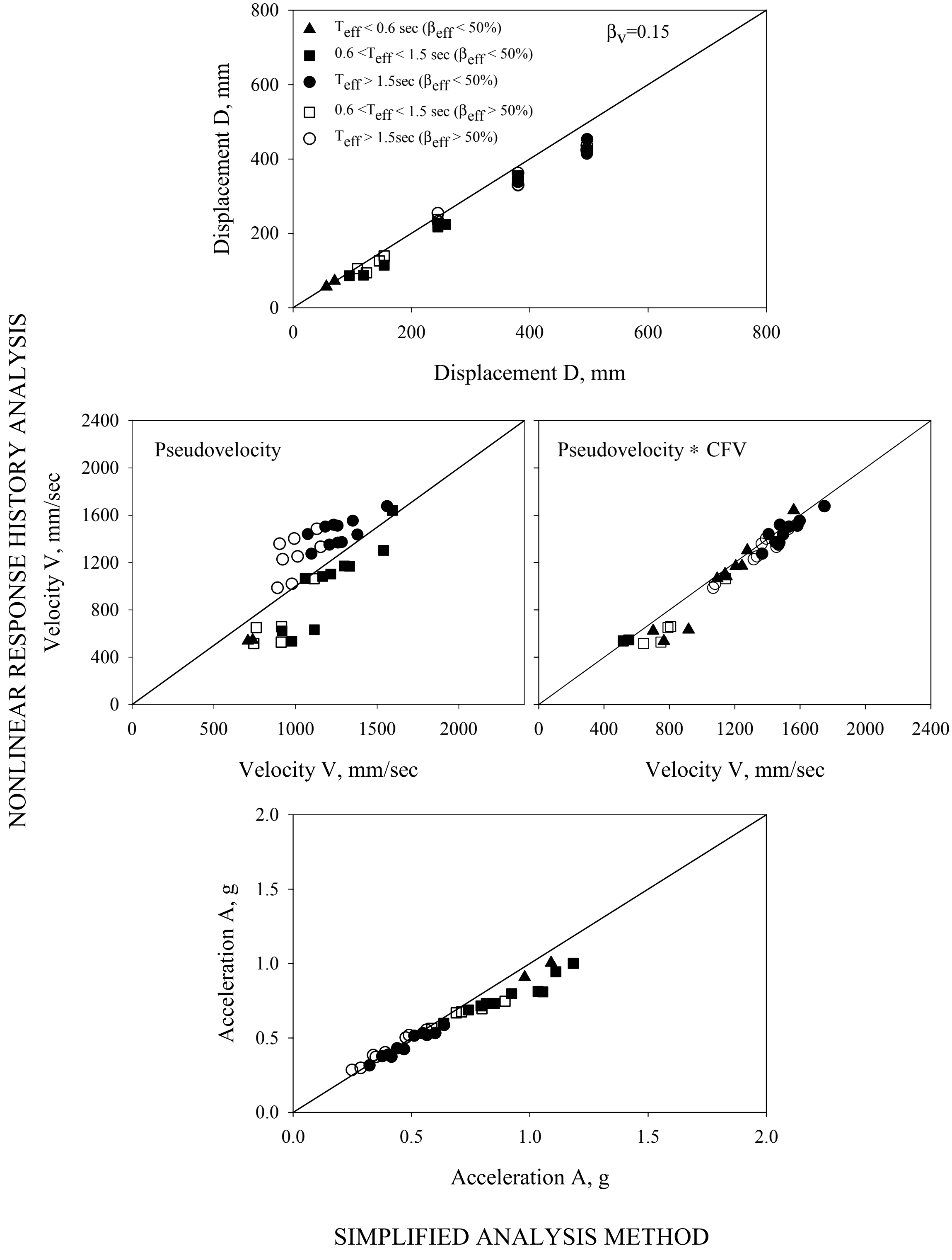


Figure 6-7. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.15$ - NF1 Fault-Normal Components

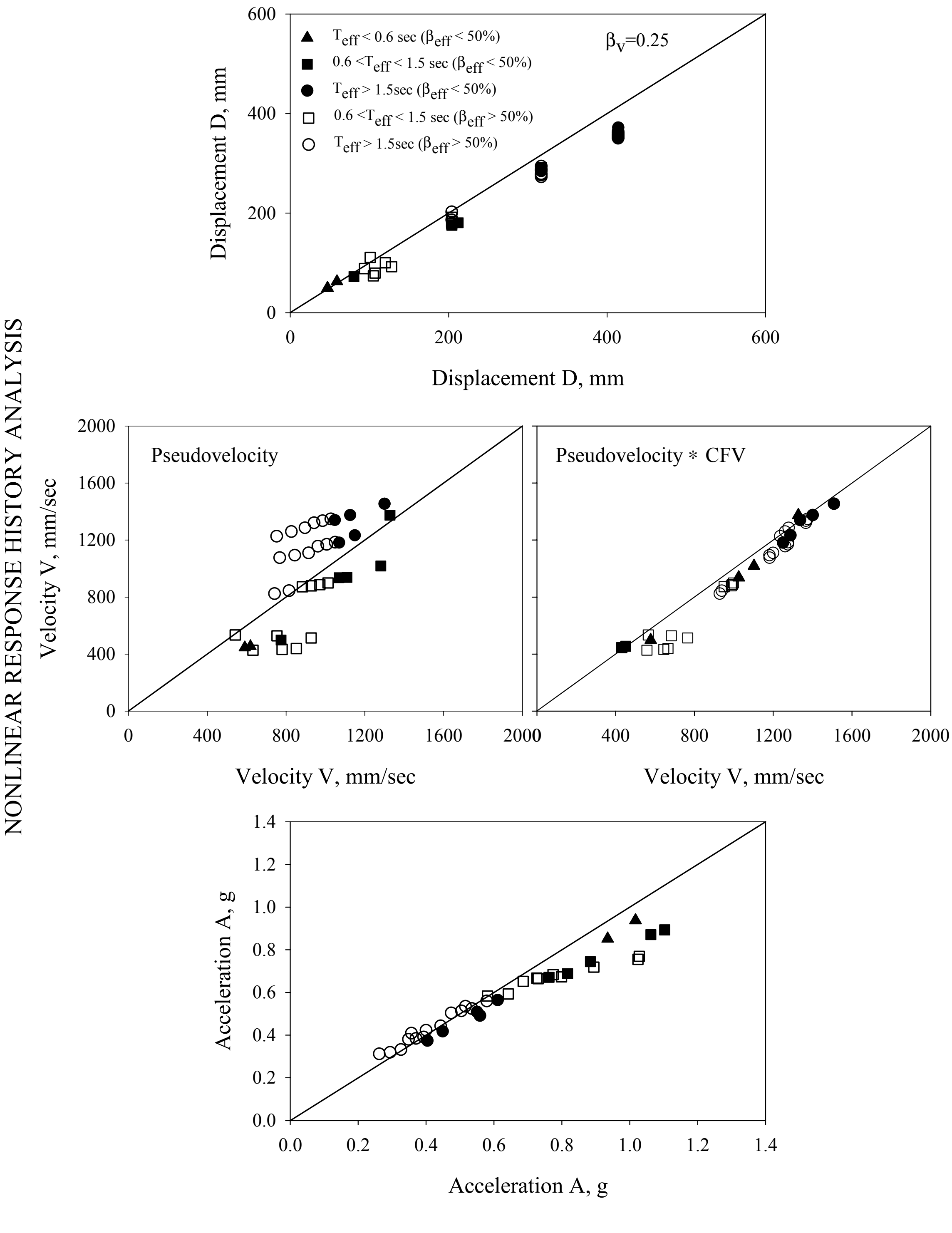


Figure 6-8. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.25$ - NF1 Fault-Normal Components

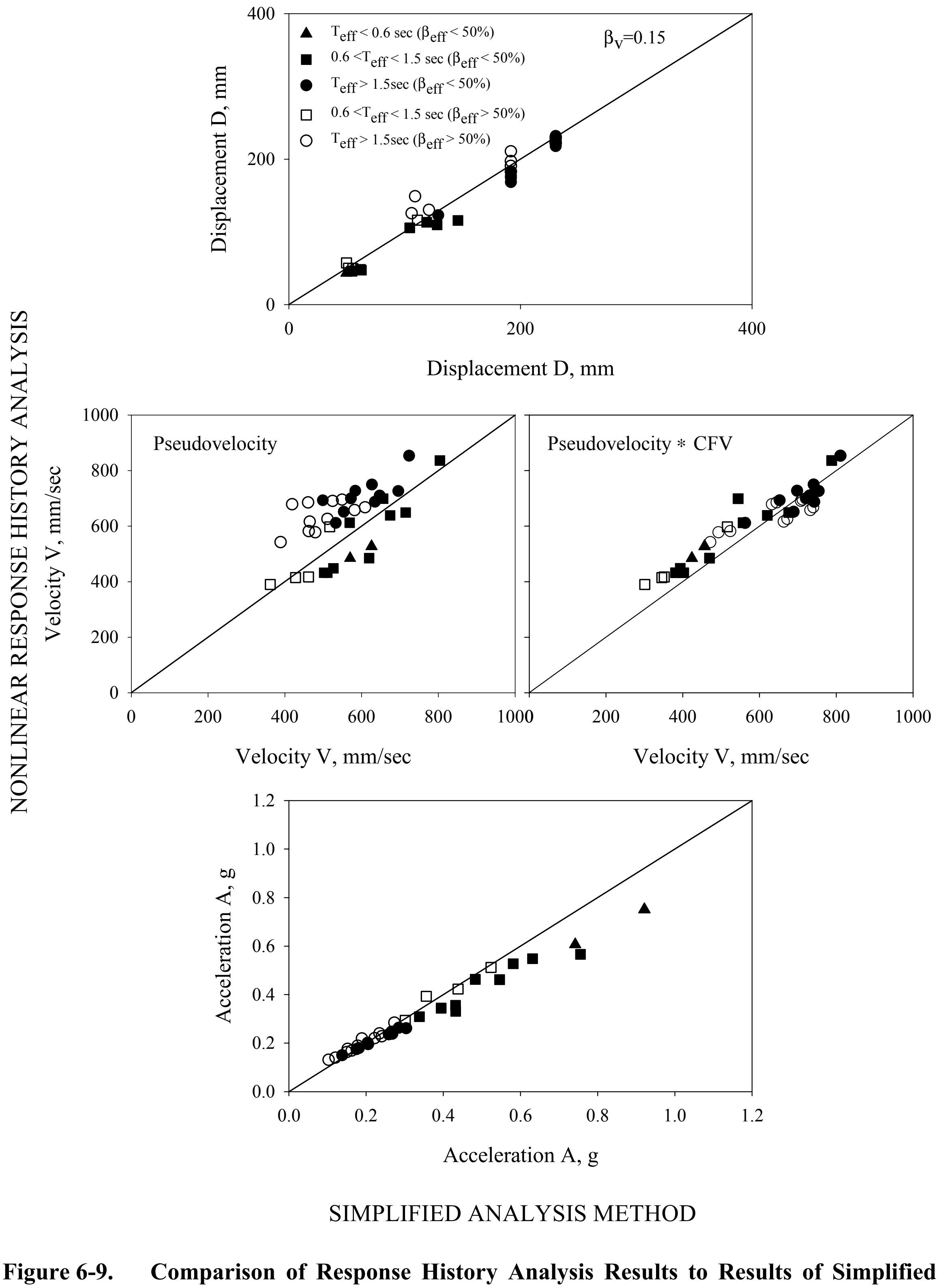


Figure 6-9. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.15$ - NF1 Fault-Parallel Components

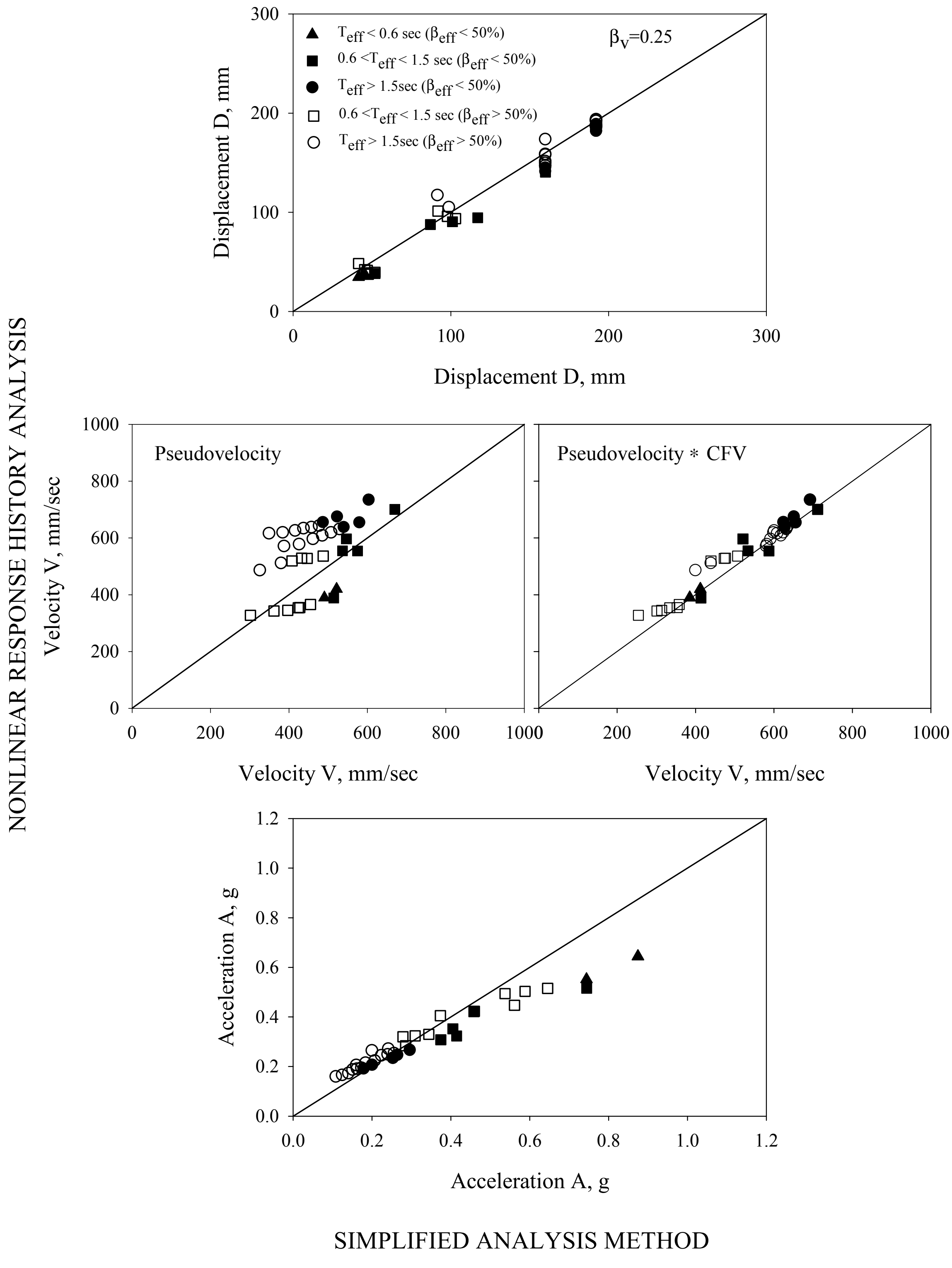


Figure 6-10. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.25$ - NF1 Fault-Parallel Components

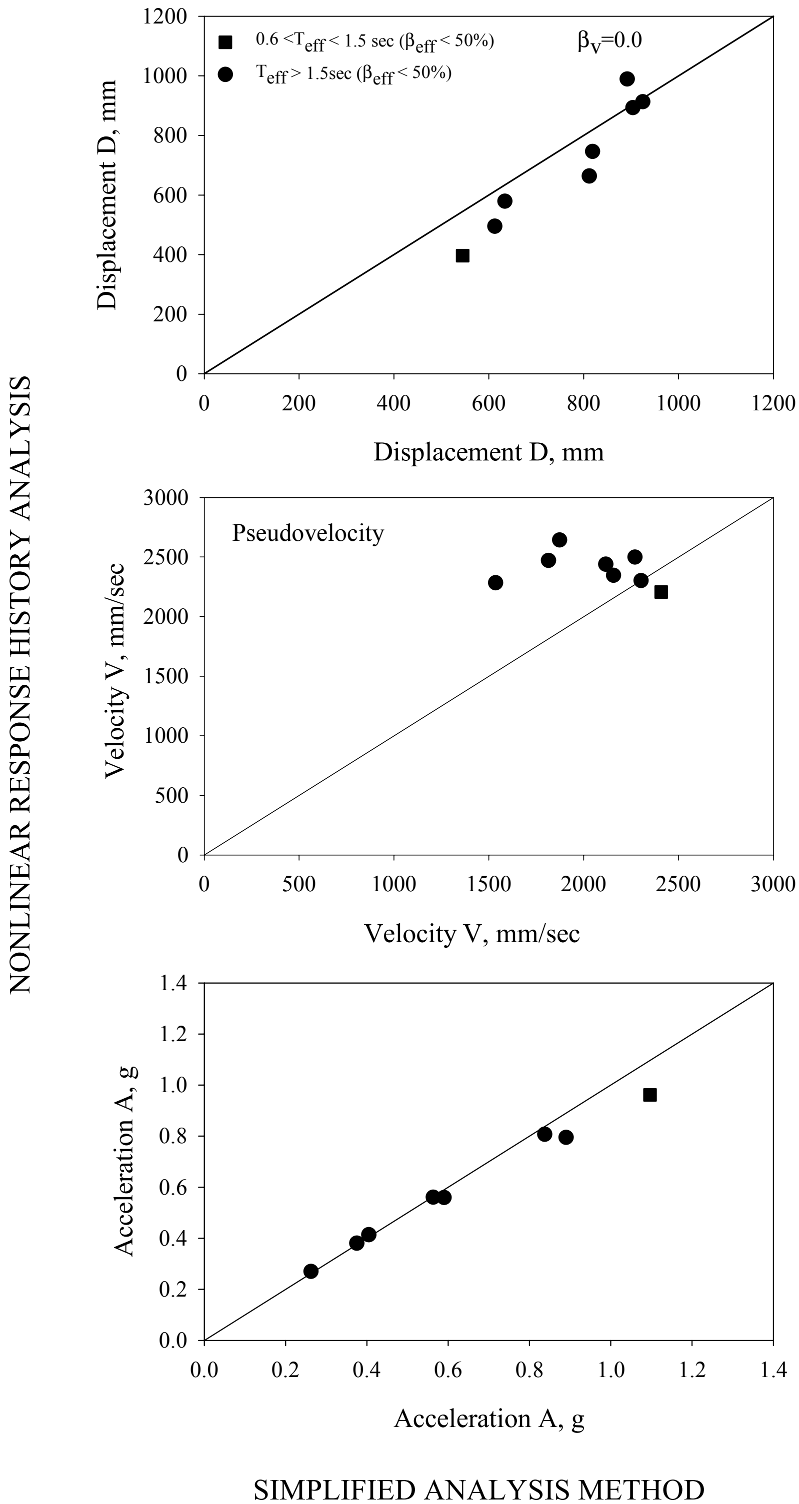


Figure 6-11. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Elastic Systems without Damping Devices - NF1 Fault-Normal Components

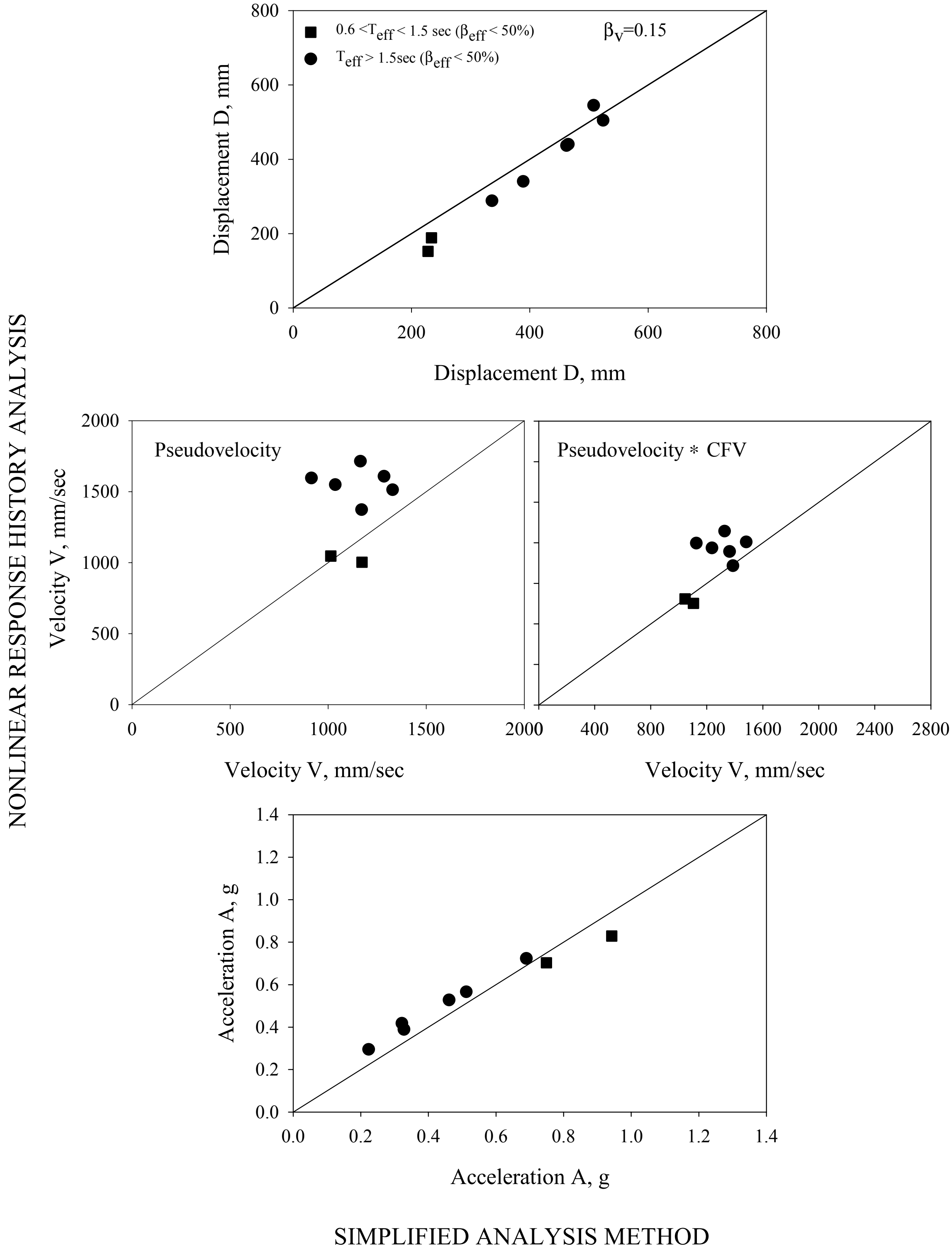


Figure 6-12. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Elastic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - NF1 Fault-Normal Components

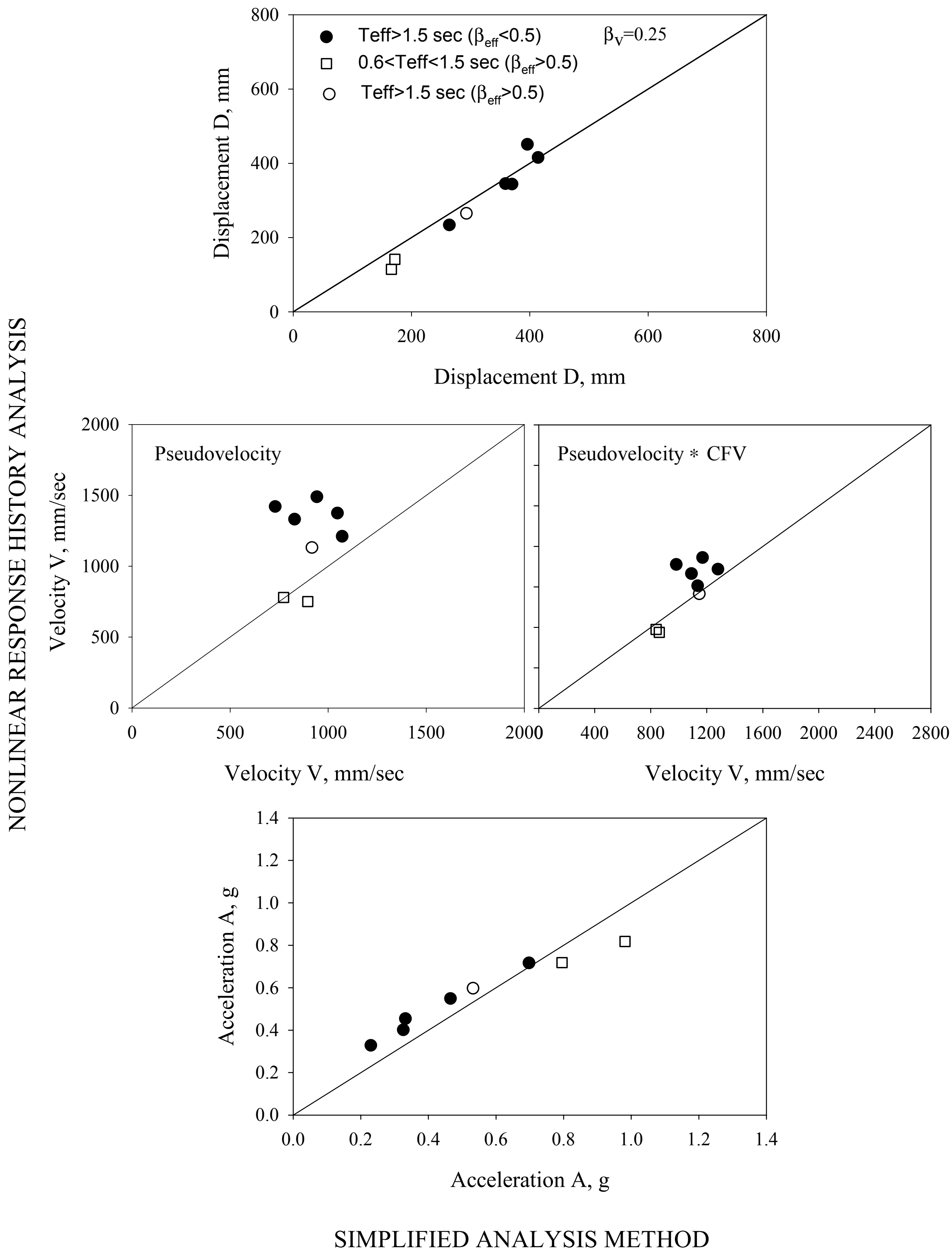


Figure 6-13. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Elastic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - NF1 Fault-Normal Components

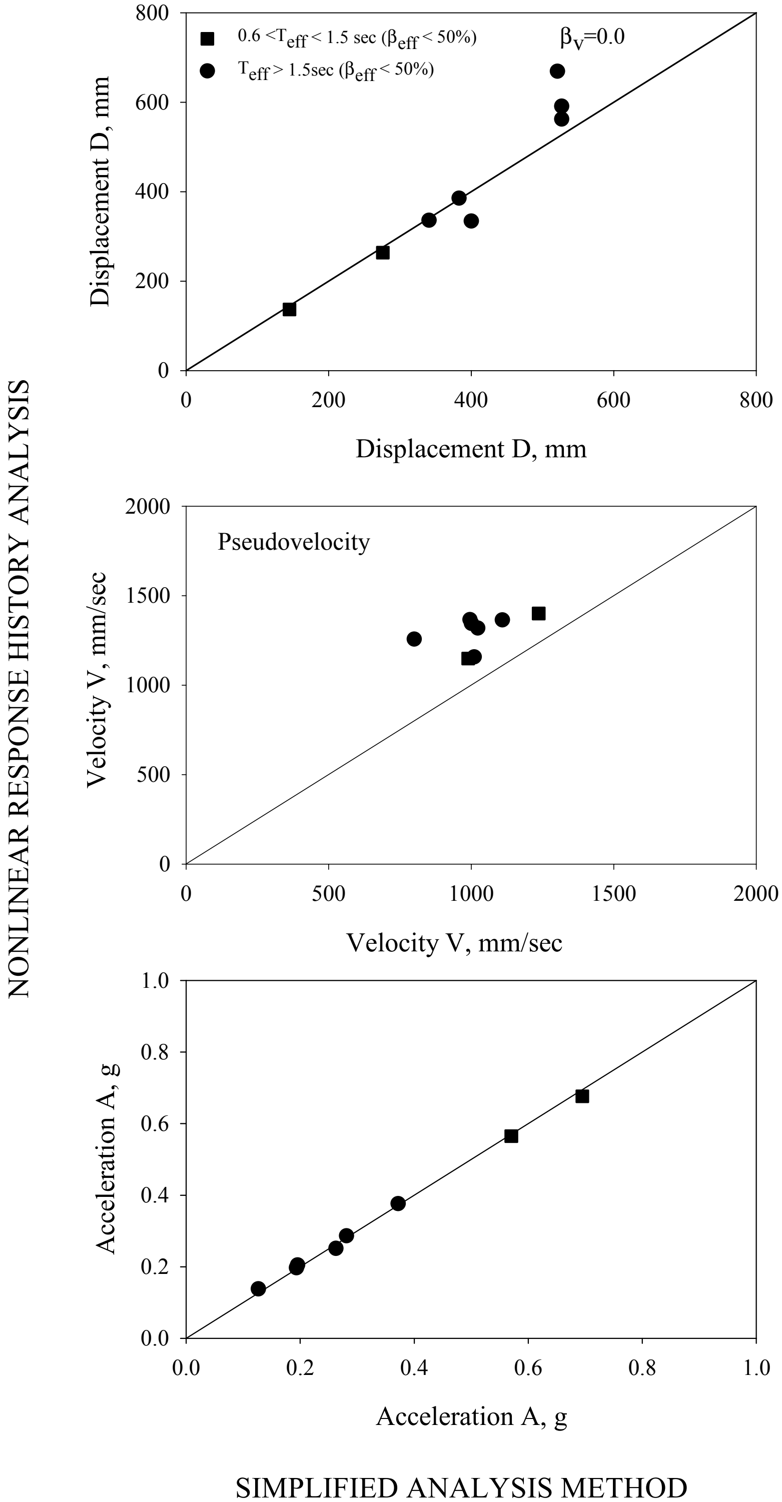


Figure 6-14. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Elastic Systems without Damping Devices - NF1 Fault-Parallel Components

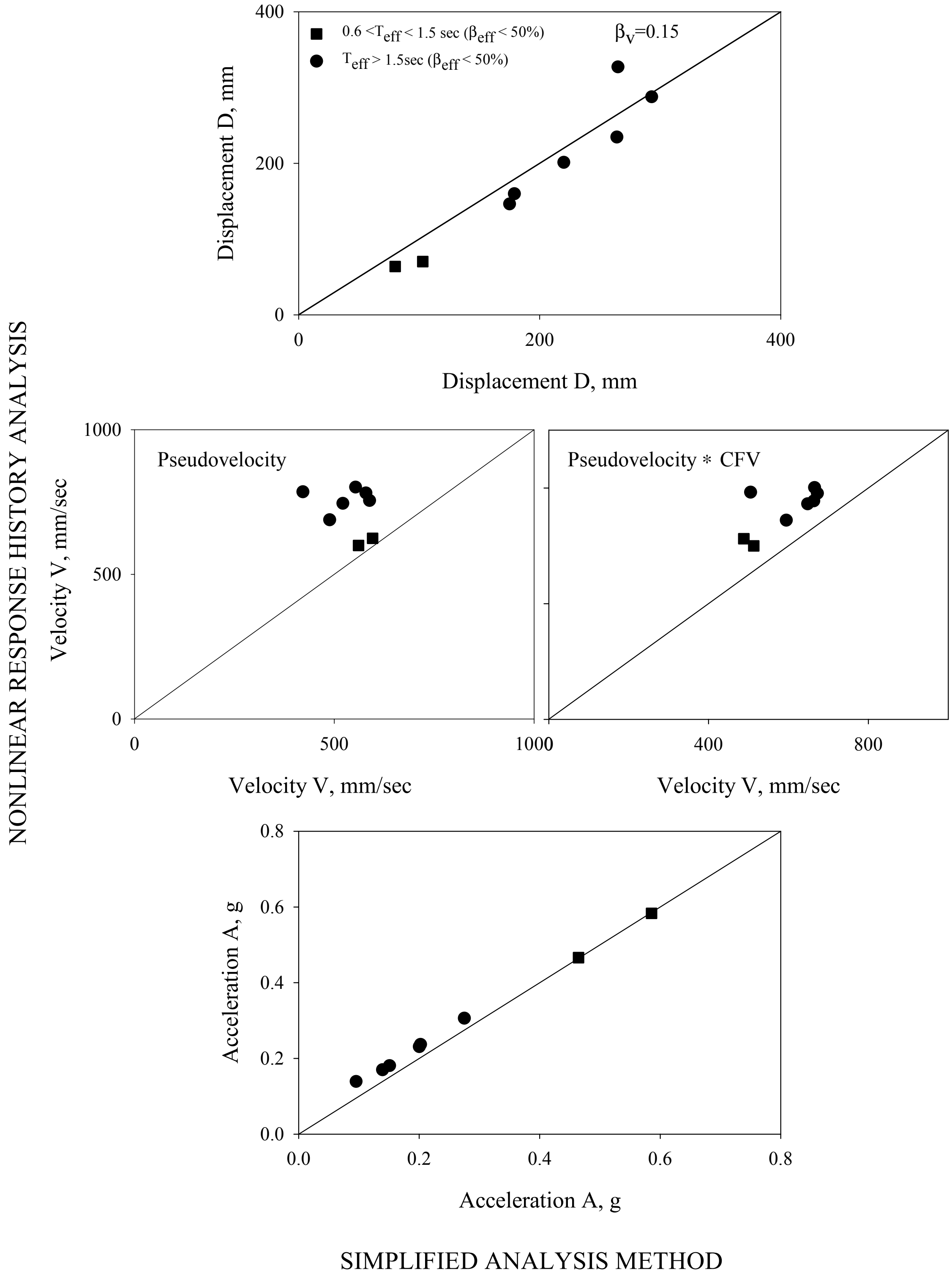


Figure 6-15. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Elastic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - NF1 Fault-Parallel Components

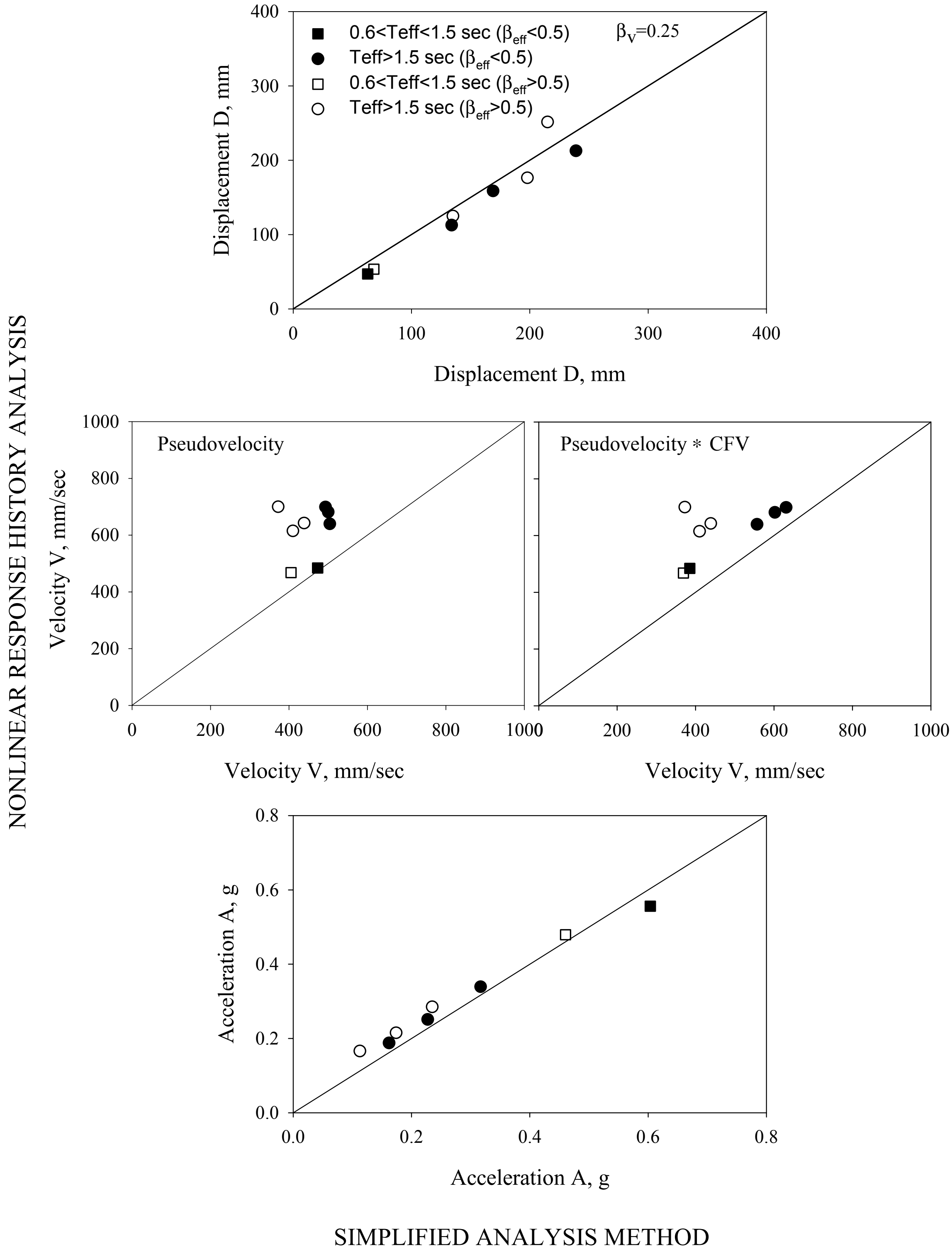


Figure 6-16. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Elastic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - NF1 Fault-Parallel Components

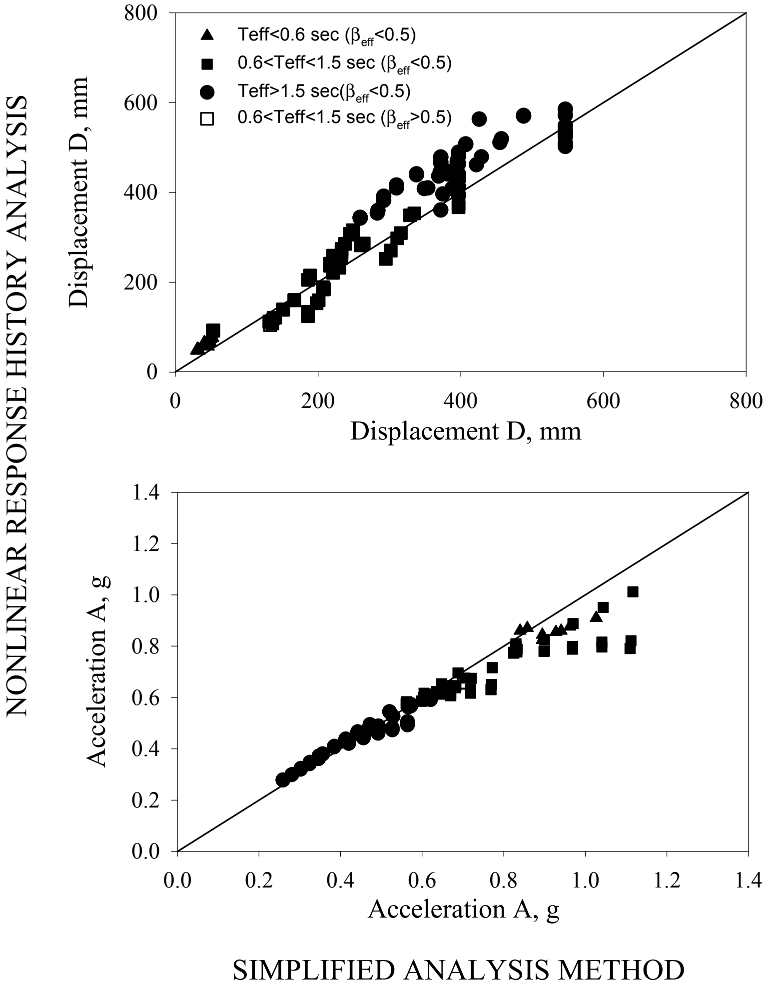


Figure 6-17. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Yielding Damping Devices- NF1 Fault-Normal Components

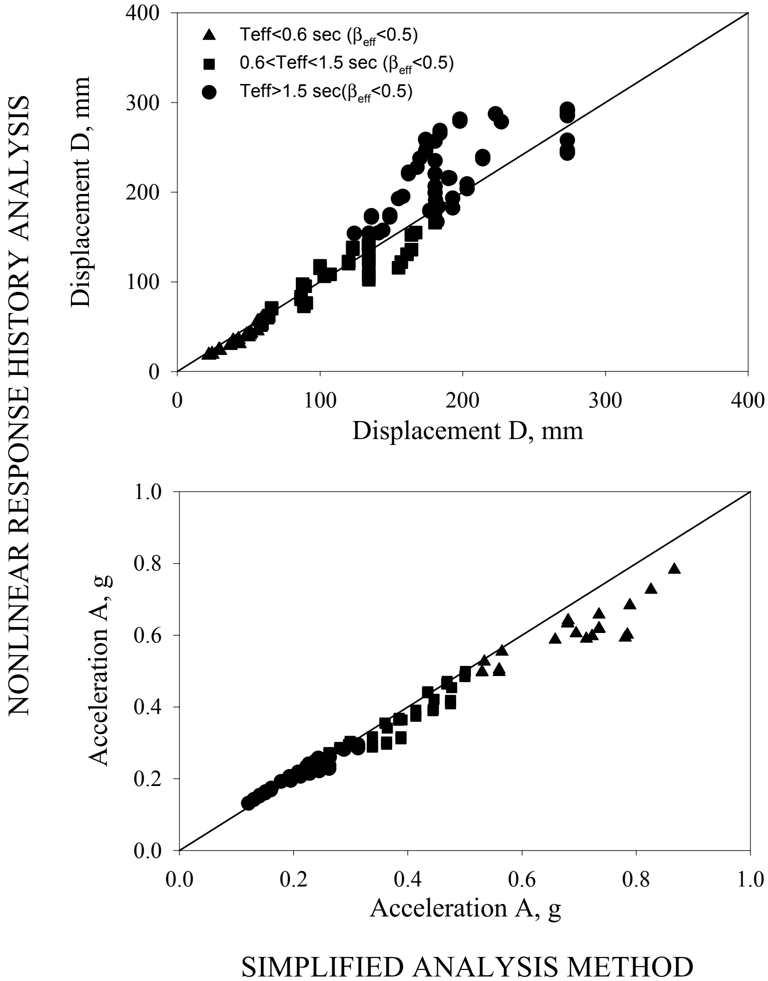


Figure 6-18. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Yielding Damping Devices- NF1 Fault-Parallel Components

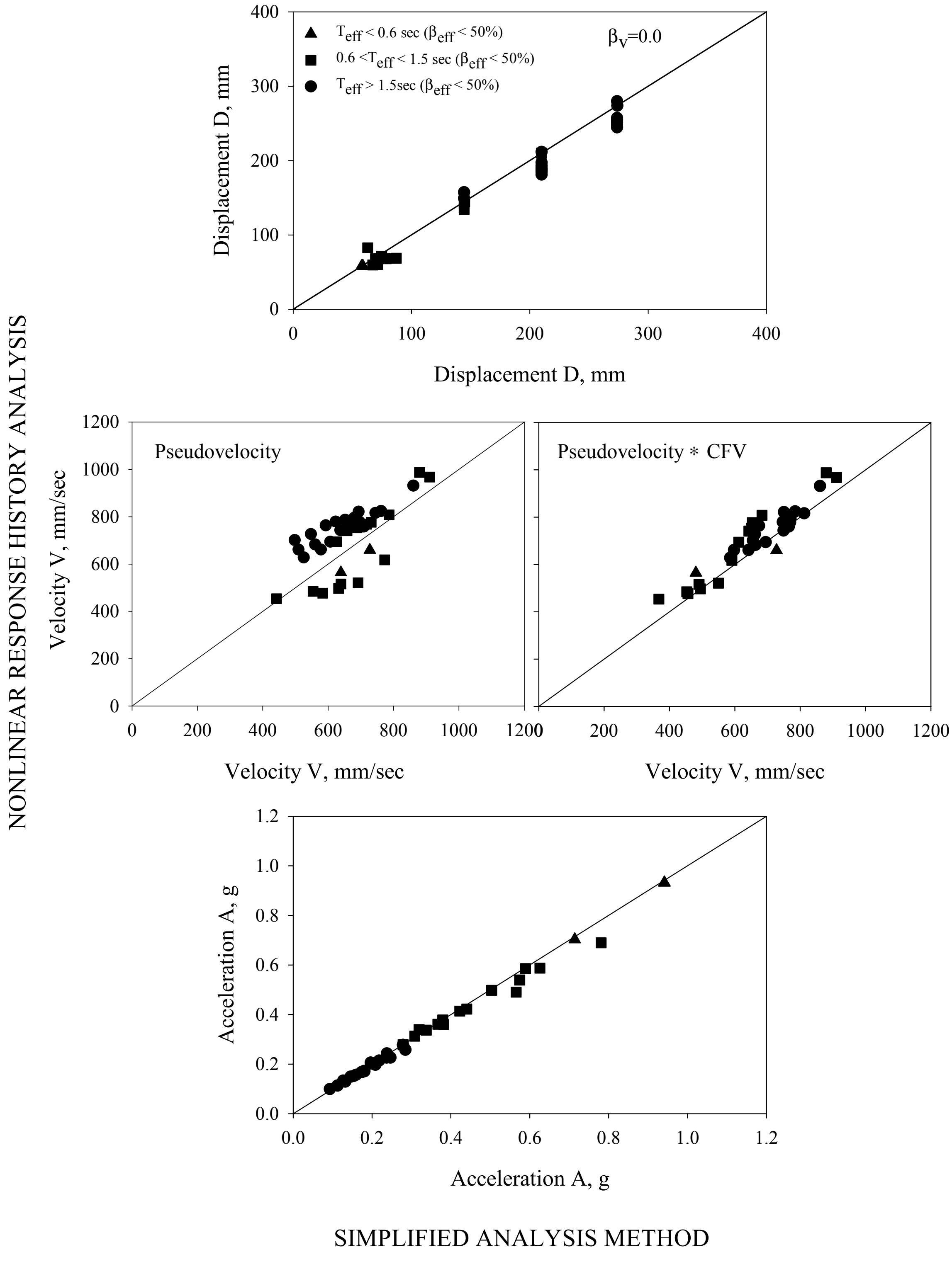


Figure 6-19. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems without Damping Devices – NF2 Fault-Normal Components

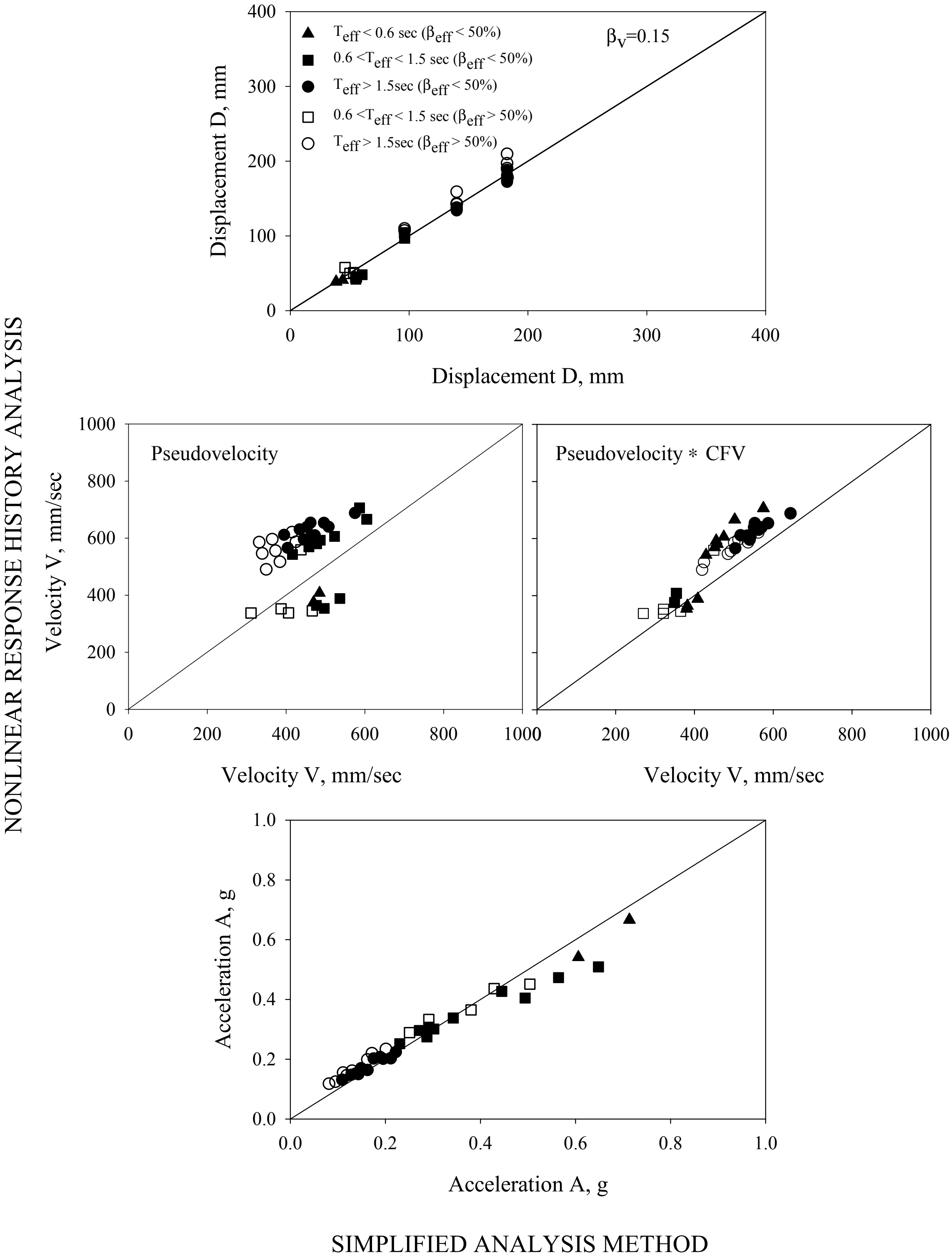


Figure 6-20. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - NF2 Fault-Normal Components

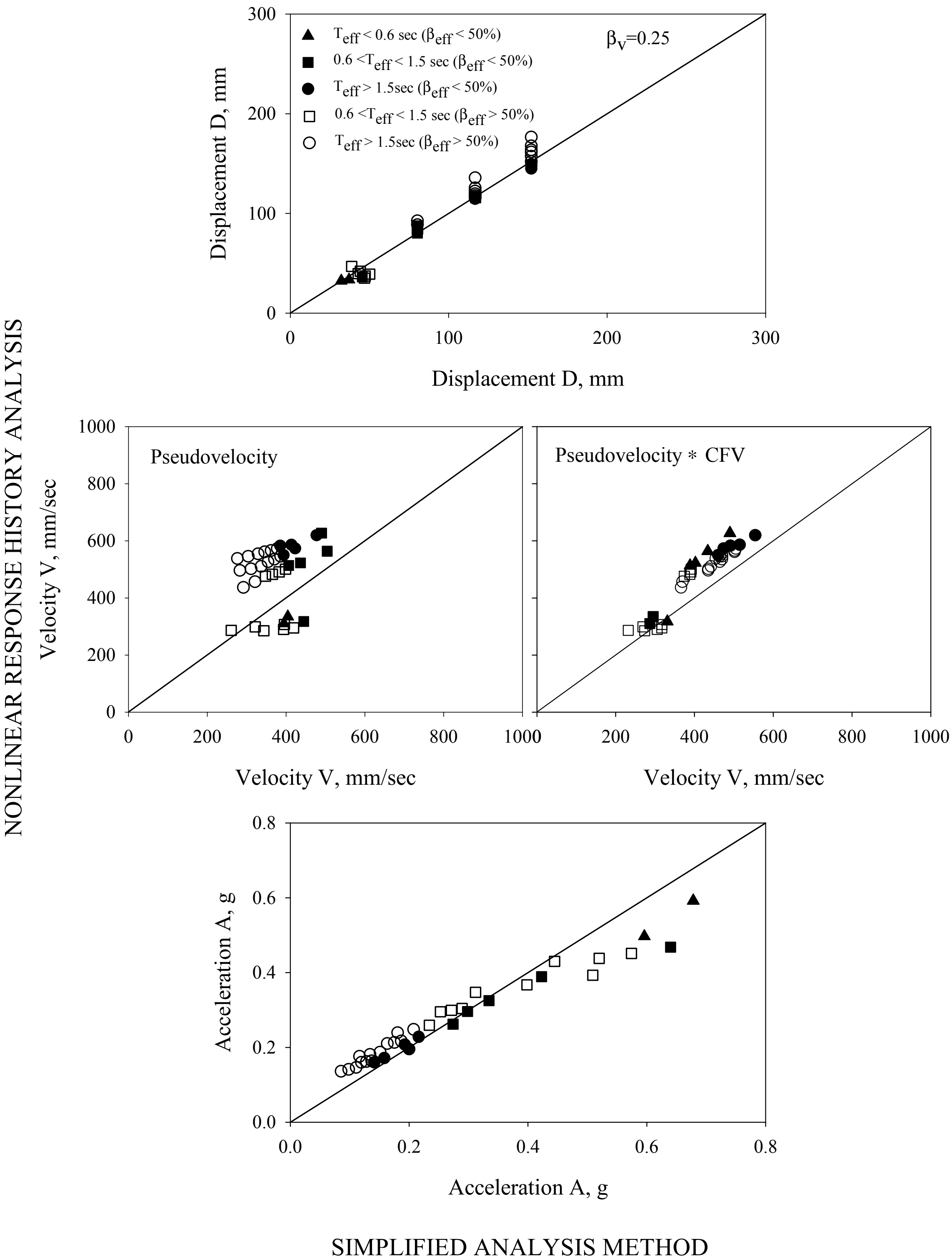


Figure 6-21. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - NF2 Fault-Normal Components

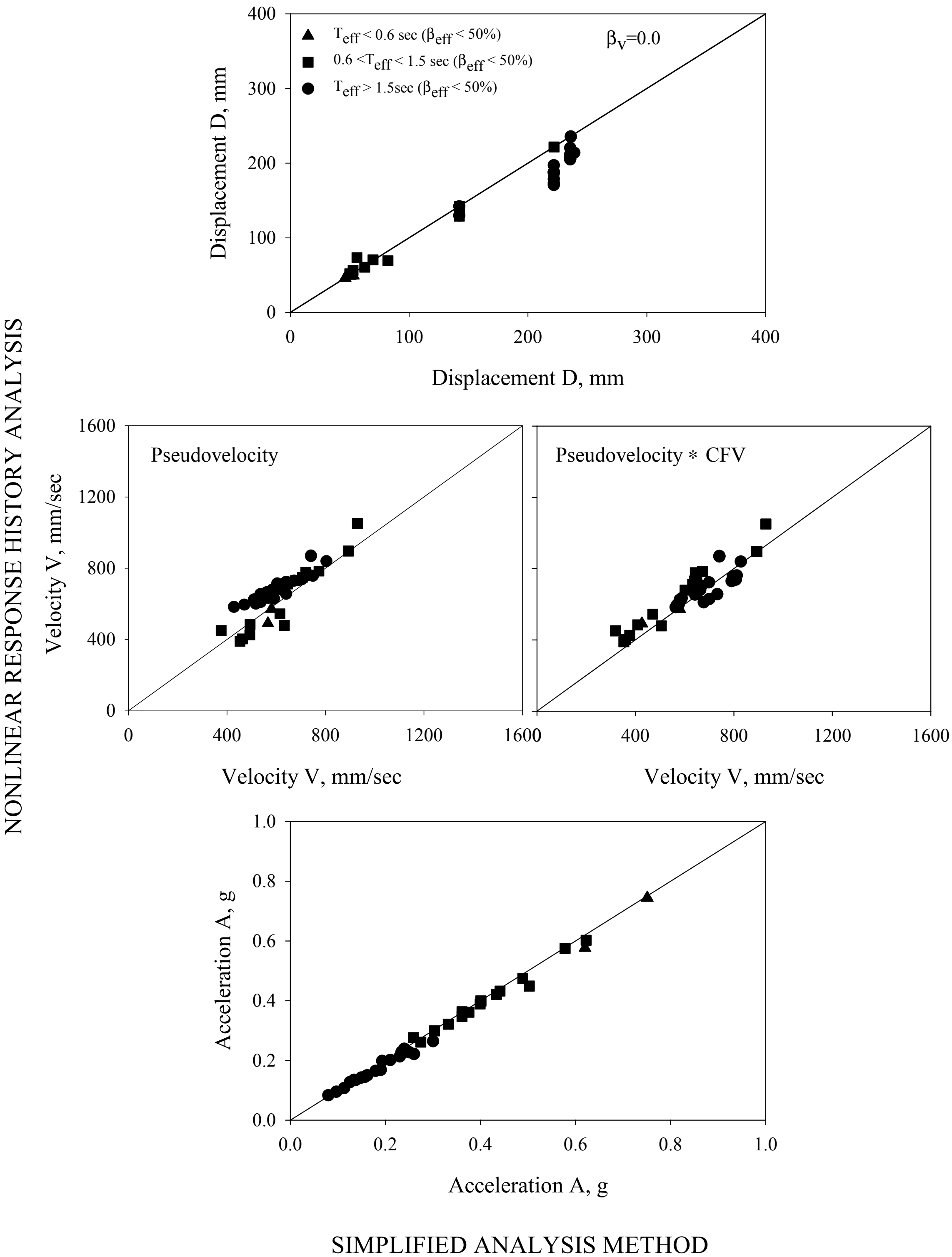


Figure 6-22. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems without Damping Devices – NF2 Fault-Parallel Components

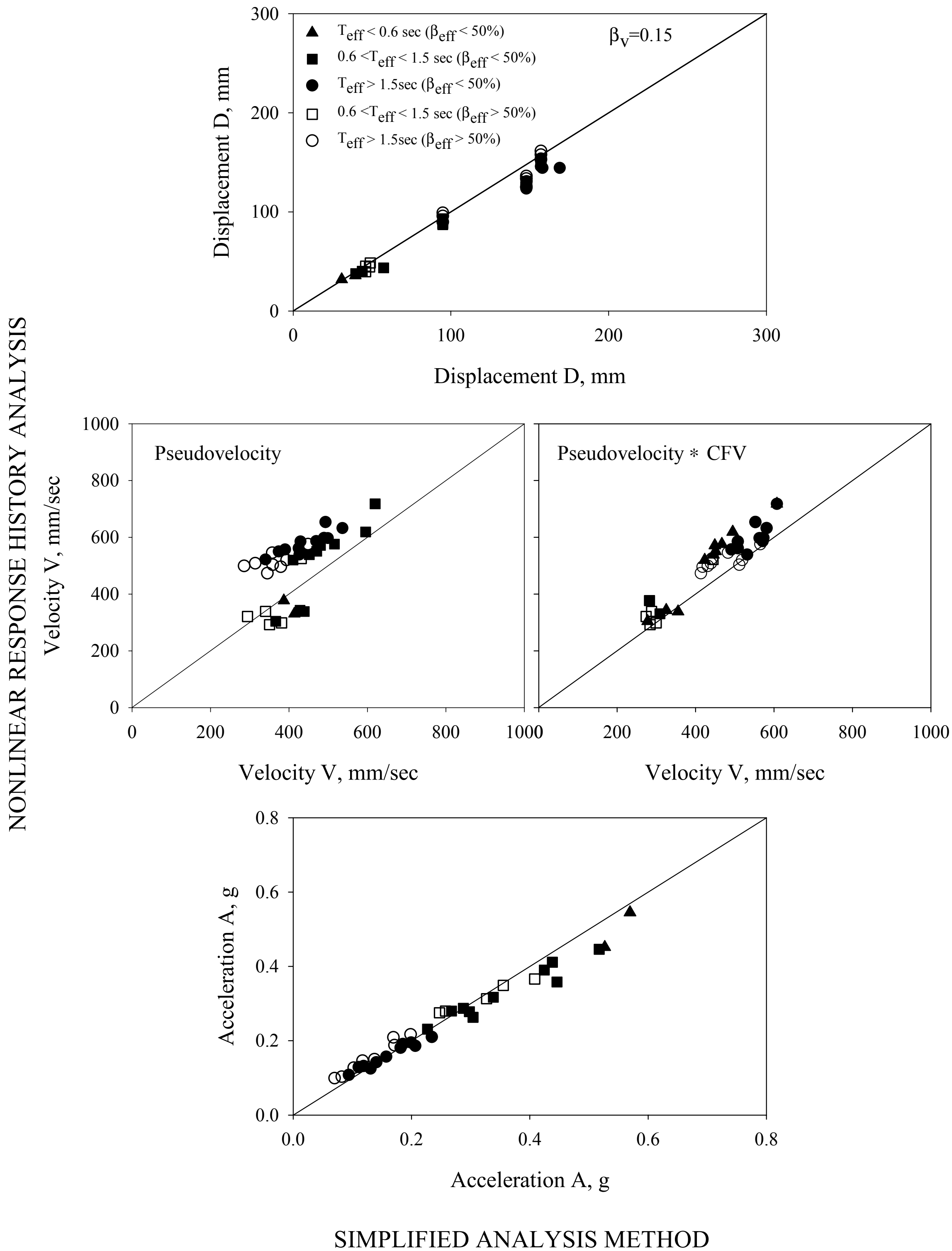


Figure 6-23. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - NF2 Fault-Parallel Components

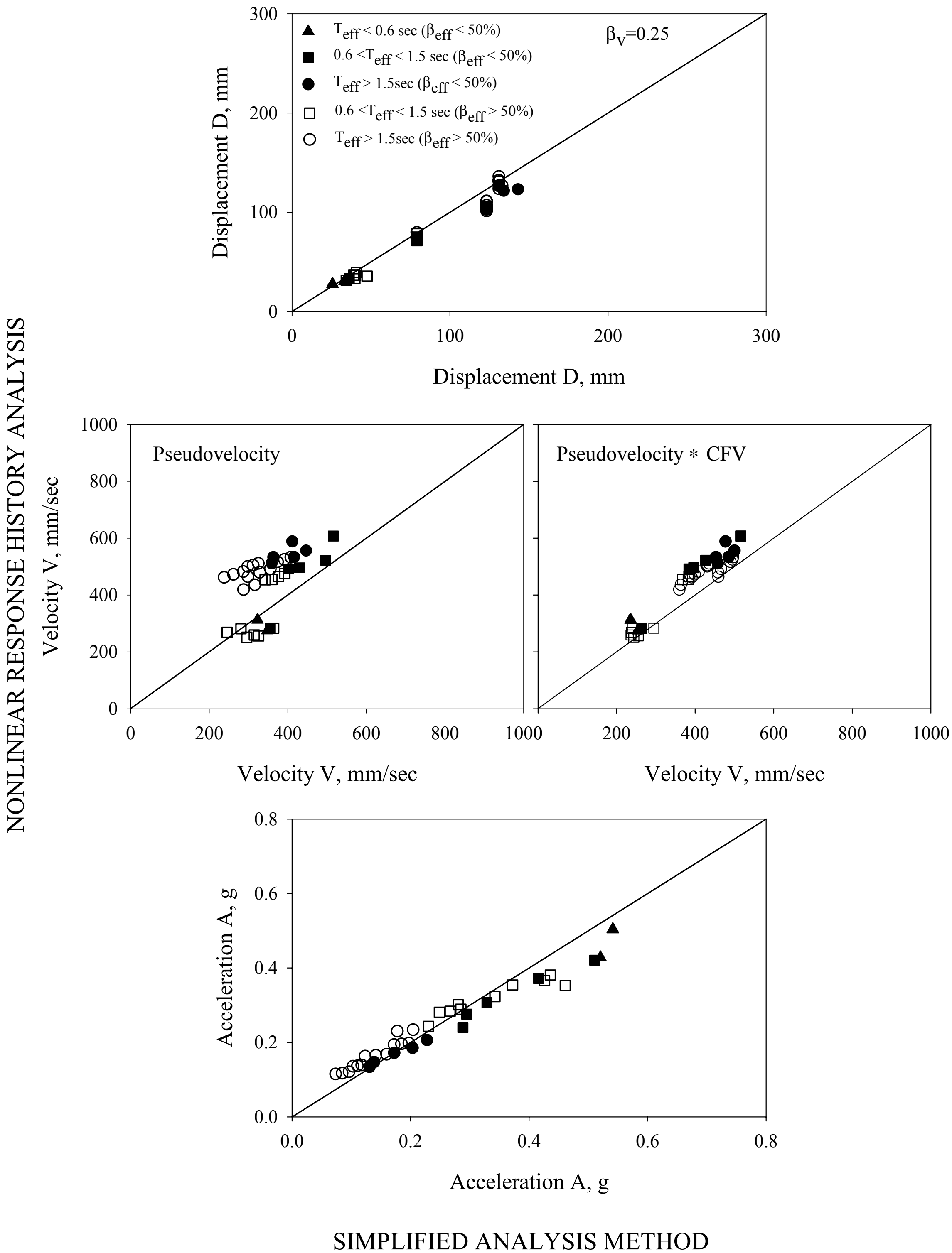


Figure 6-24. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - NF2 Fault-Parallel Components

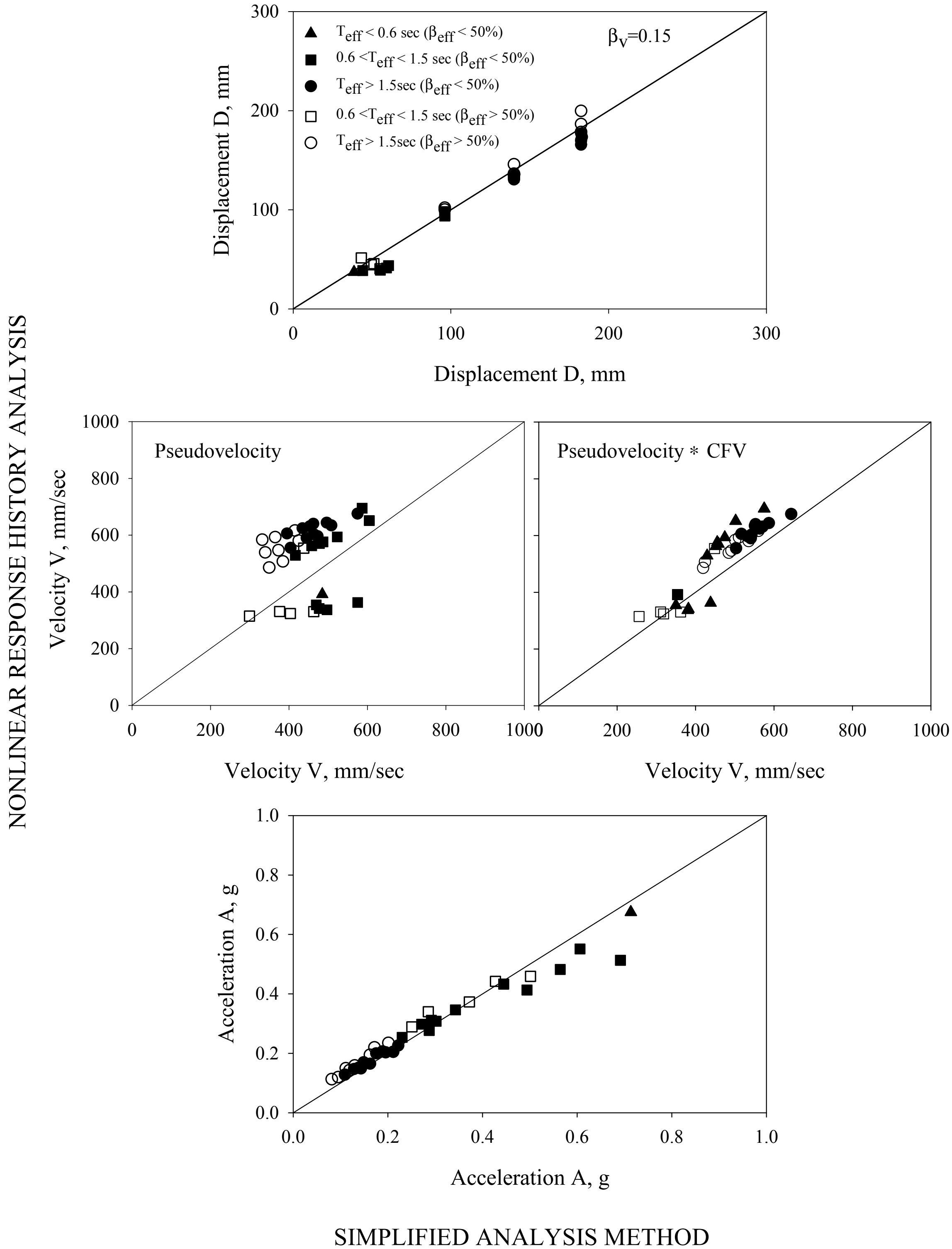


Figure 6-25. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.15$ - NF2 Fault-Normal Components

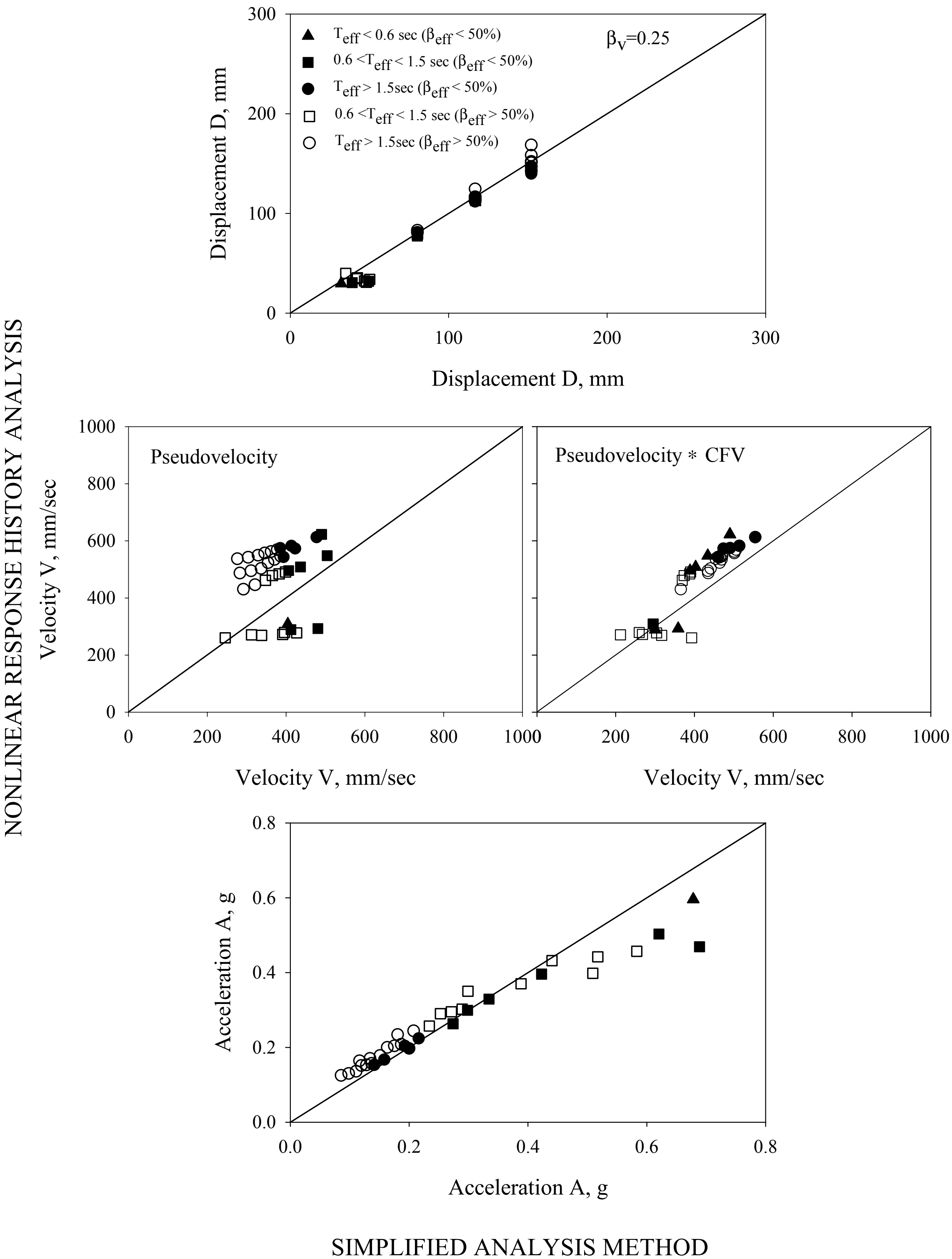


Figure 6-26. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.25$ - NF2 Fault-Normal Components

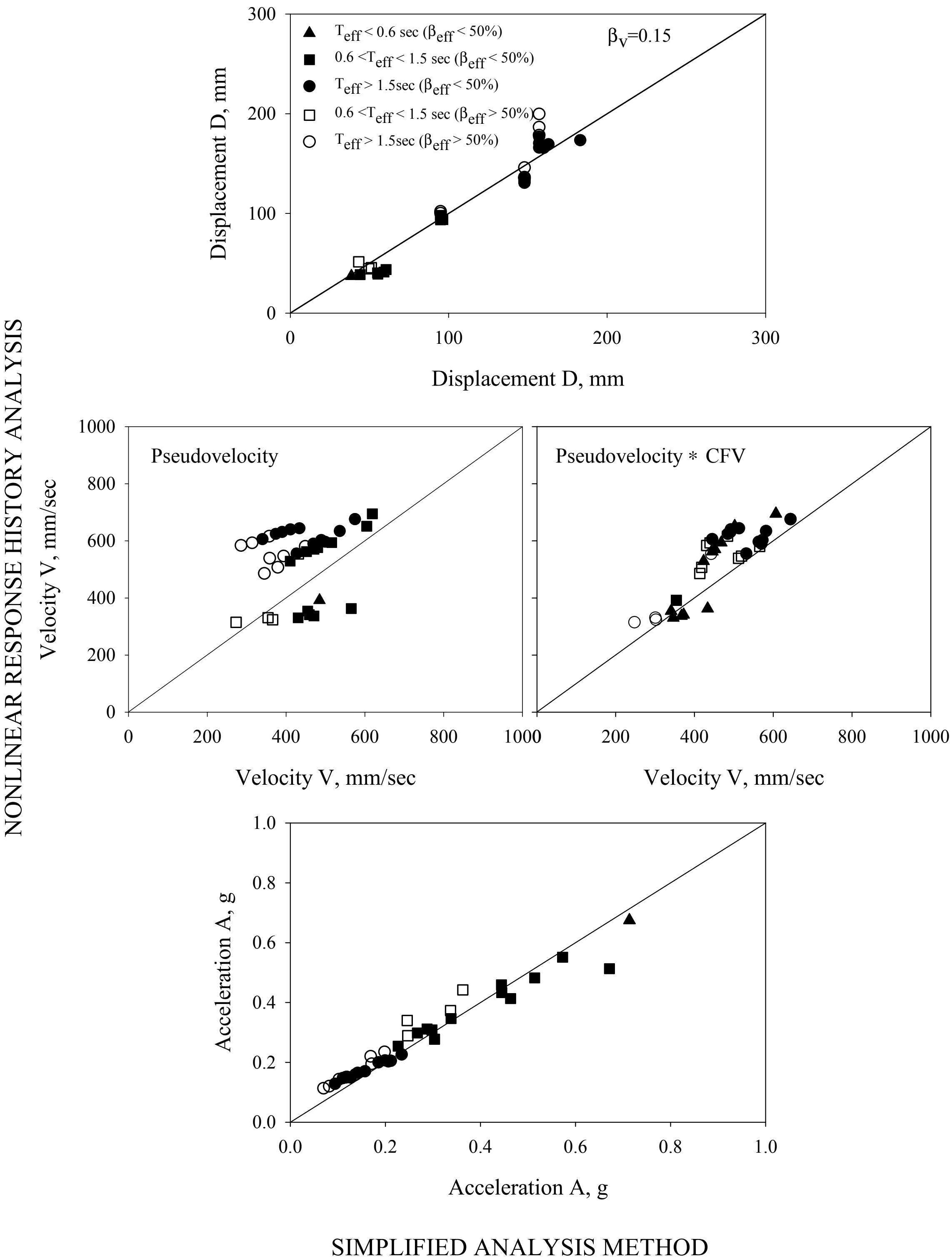


Figure 6-27. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.15$ - NF2 Fault-Parallel Components

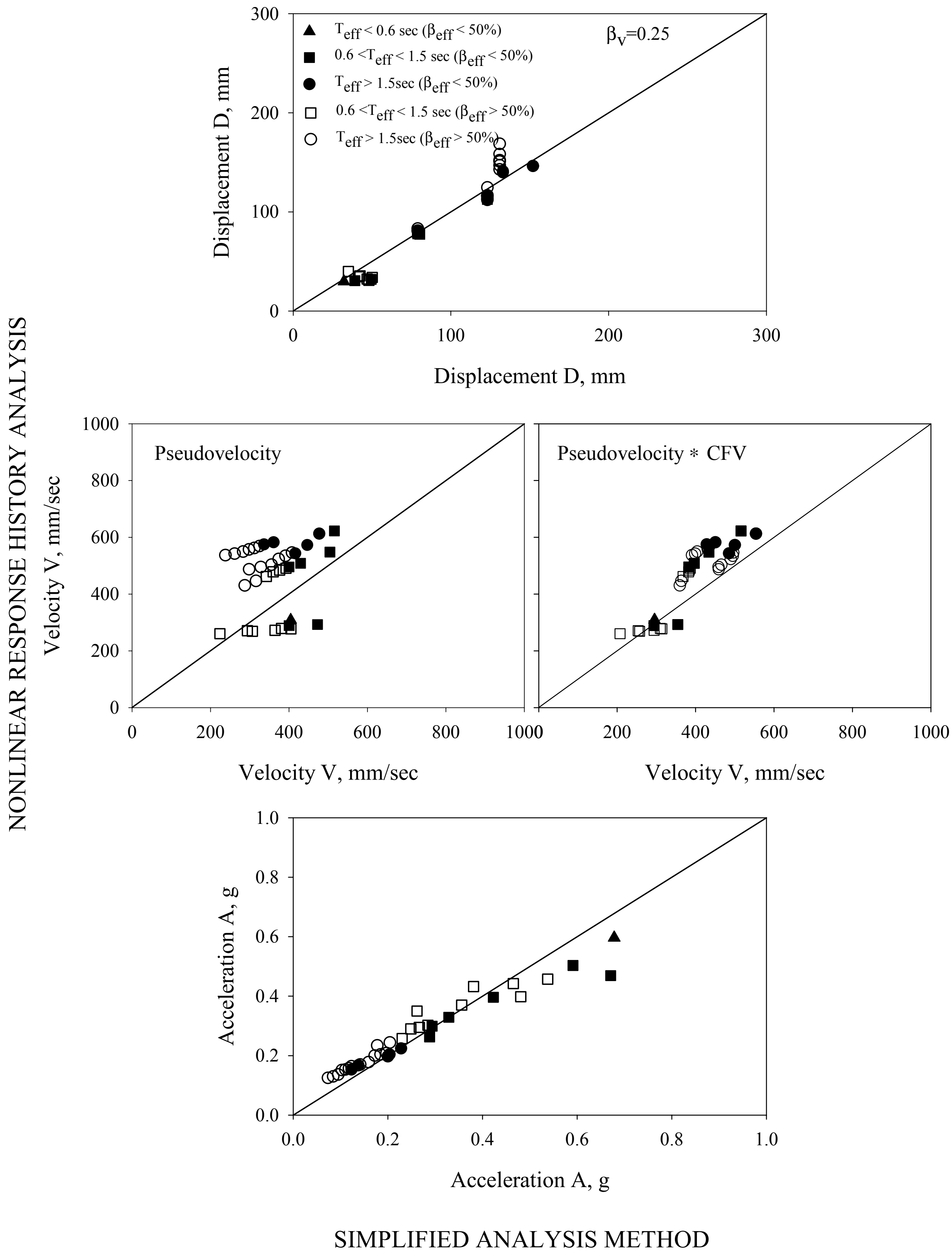


Figure 6-28. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Nonlinear Viscous Damping Devices, $\beta_V = 0.25$ - NF2 Fault-Parallel Components

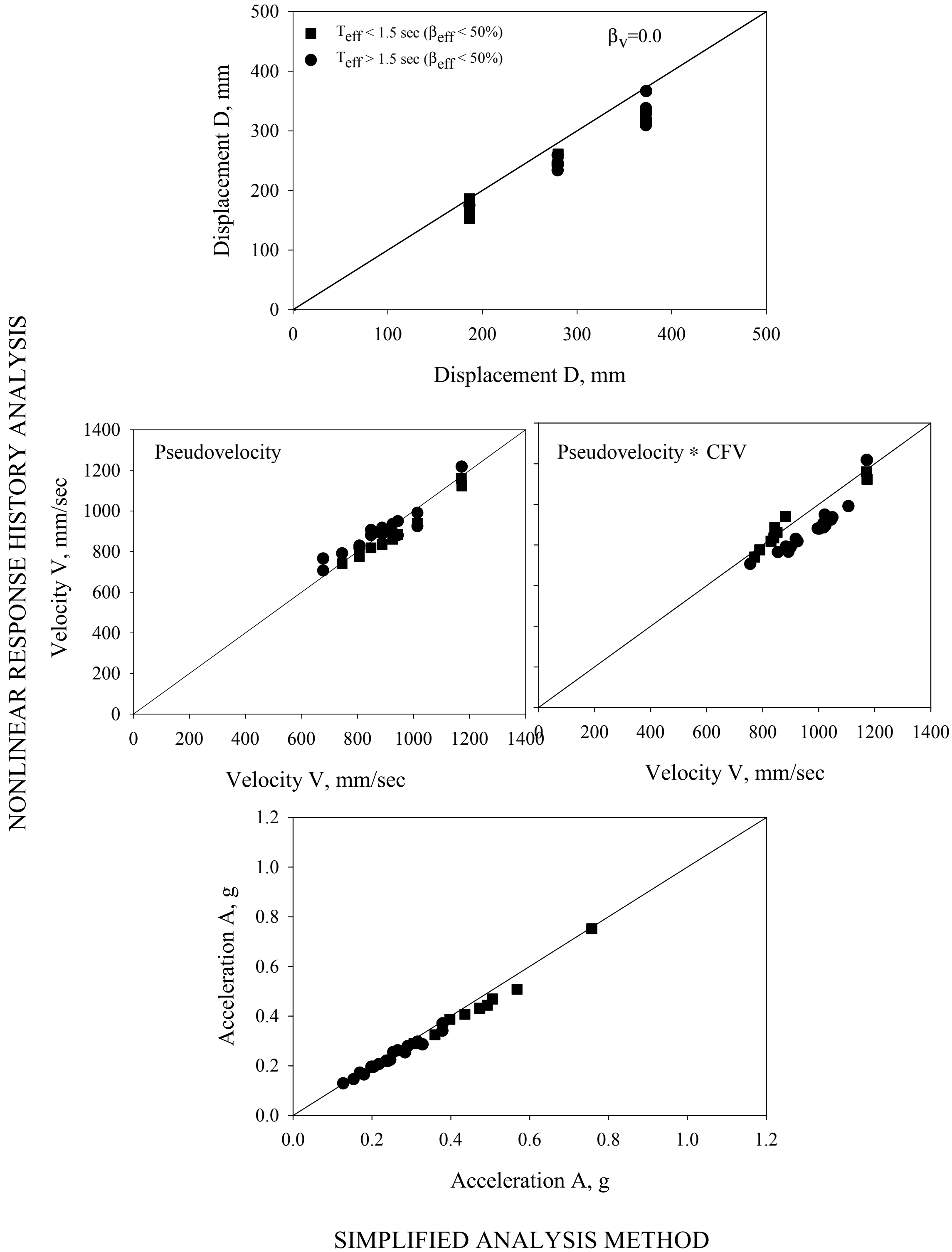


Figure 6-29. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems without Damping Devices – Soft-Soil Motions

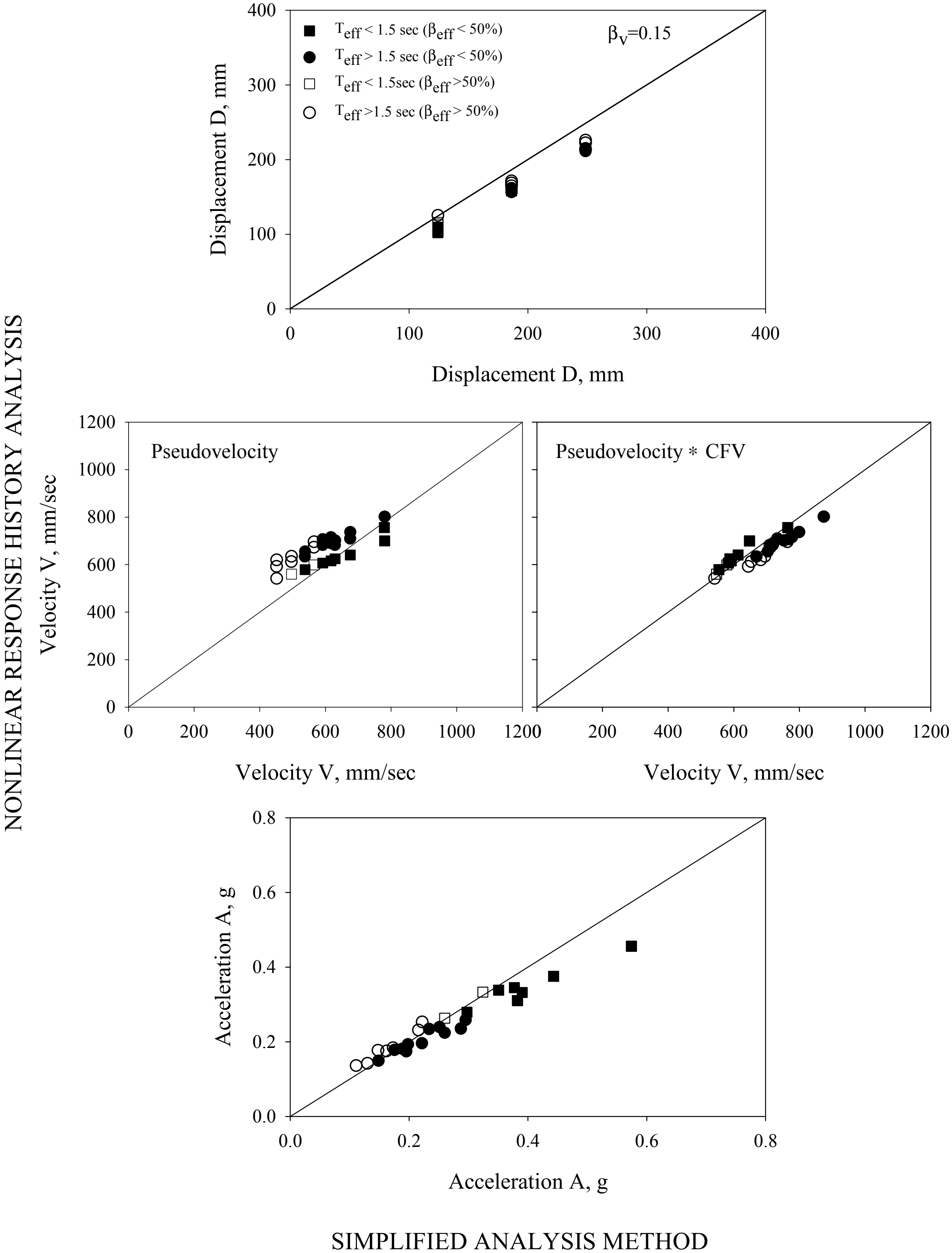


Figure 6-30. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.15$ - Soft-Soil Motions

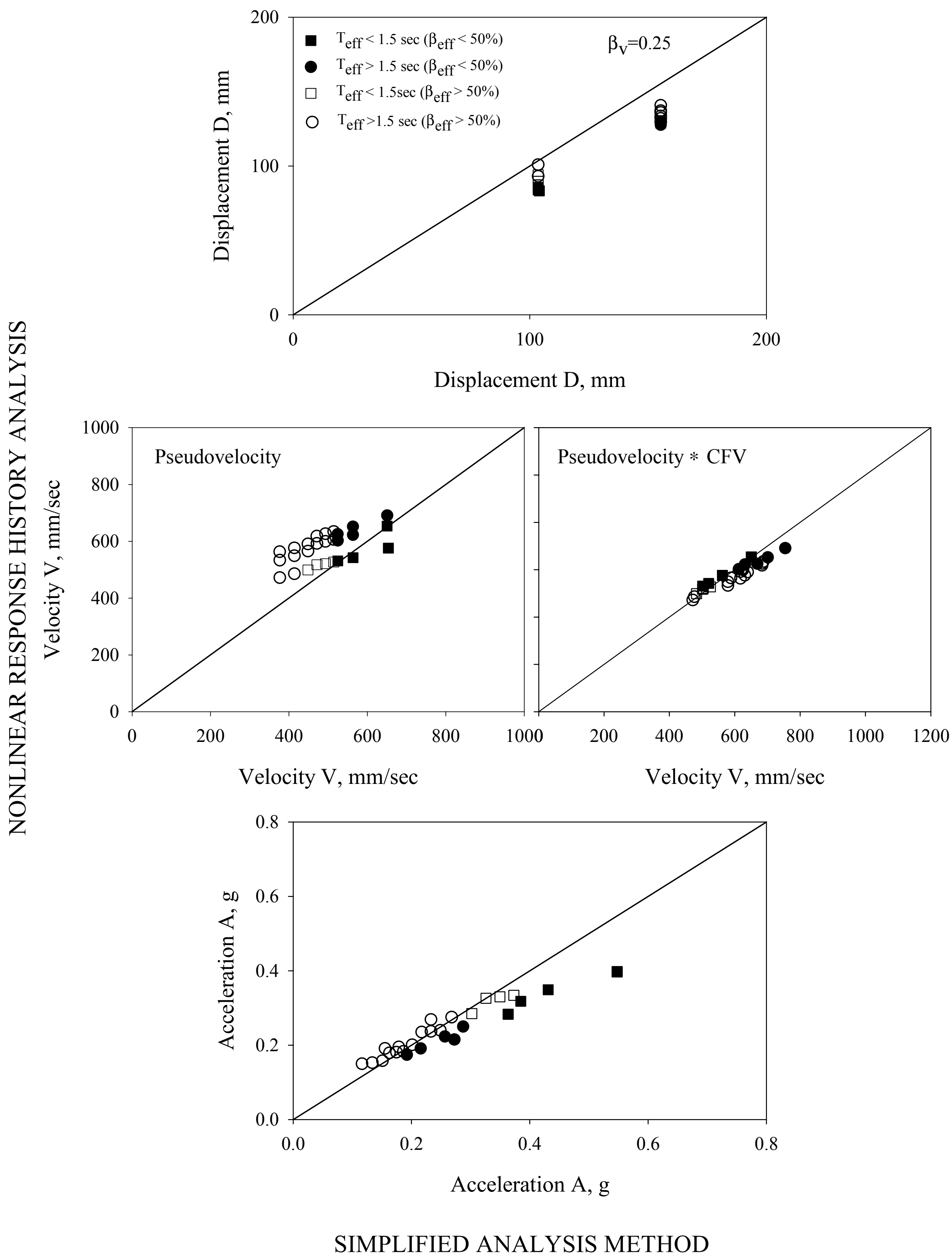


Figure 6-31. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Linear Viscous Damping Devices, $\beta_V = 0.25$ - Soft-Soil Motions

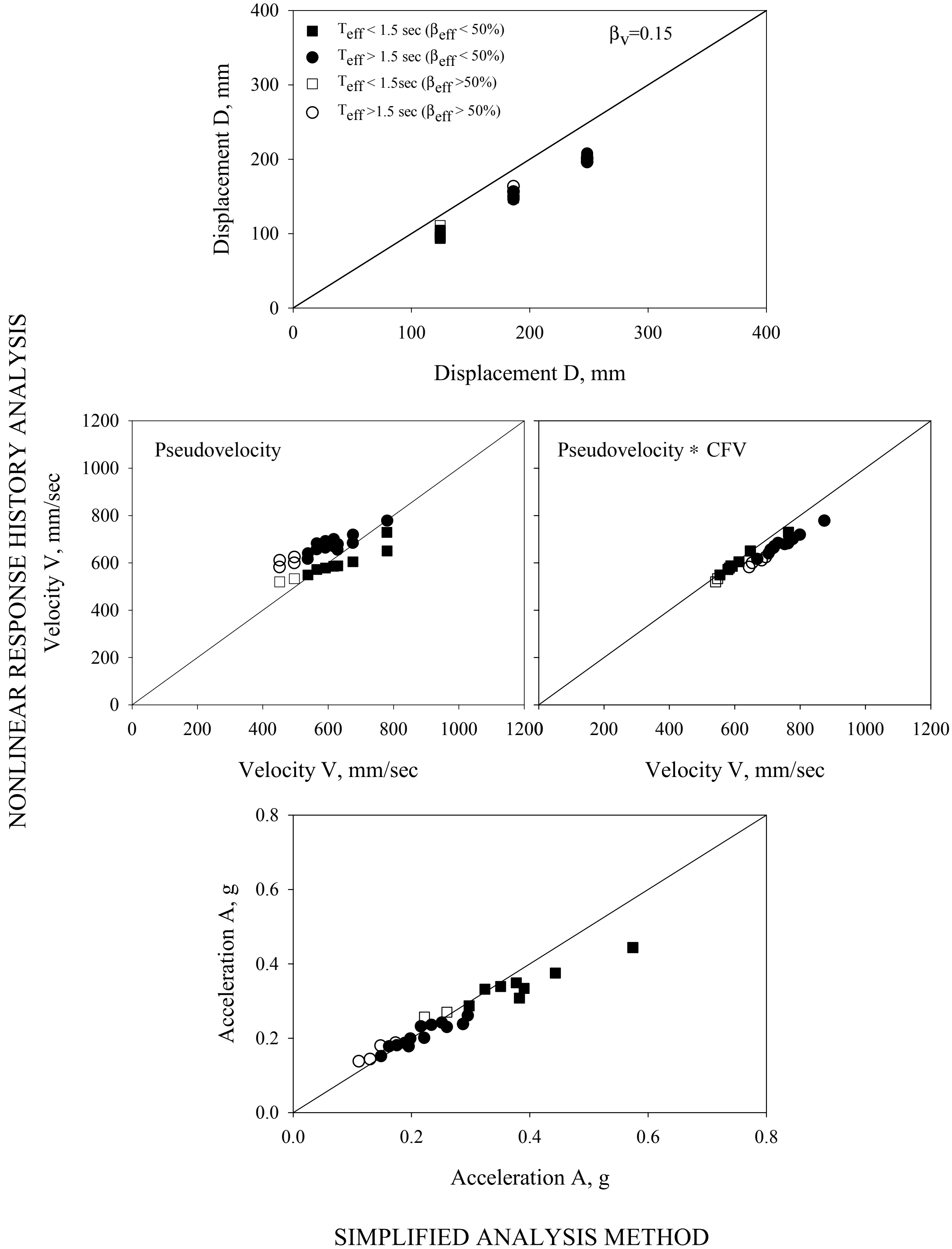


Figure 6-32. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Non-Linear Viscous Damping Devices, $\beta_V = 0.15$ - Soft-Soil Motions

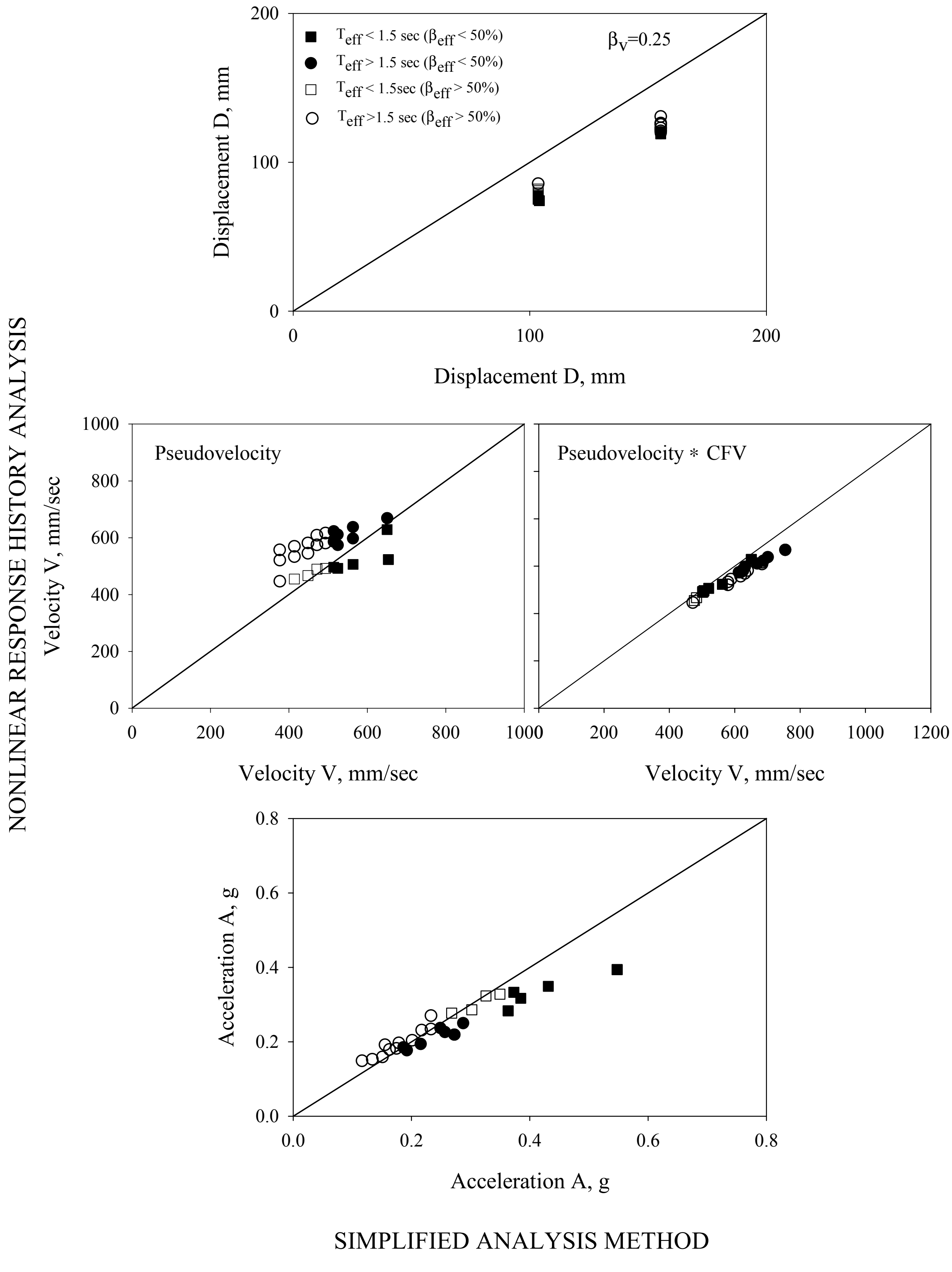


Figure 6-33. Comparison of Response History Analysis Results to Results of Simplified Method of Analysis for Bilinear Hysteretic Systems with Non-Linear Viscous Damping Devices, $\beta_V = 0.25$ - Soft-Soil Motions

6.2.2 3-story Building Frames

To further examine extensively the influence of near-field and soft-soil ground motions on the accuracy of simplified methods of analysis, multi-degree-of-freedom systems were considered. Known sources of error exist in the simplified analysis of multi-degree-of-freedom systems, other than that due to the replacement of the yielding system by an equivalent linear and viscous system. Particularly, the contribution of higher modes of vibration in near-field seismic excitation is known to be significant in tall buildings (e.g., Iwan et al. (2000)). Whereas the simplified analysis method of 2000 NEHRP is restricted to short structures with height that does not exceed 30 m (typically 7-story or less), there is need to evaluate the method for multi-story buildings in near-field and soft-soil excitations.

Accordingly, validation studies of the equivalent lateral force (ELF) and the modal analysis (RSA) procedures of *2000 NEHRP Recommended Procedures* of 3-story steel moment frames with damping systems located close to a fault or at a soft-soil site were performed. The theoretical basis of these procedures has been presented in Whittaker et al. (2003) and Ramirez et al. (2001). The accuracy of the simplified methods of analysis is investigated by comparison to the results of nonlinear response-history analysis. Nonlinear response-history analysis of the 3-story frames was performed using computer program IDARC2D (Valles et al., 1996). Modeling details regarding the program IDARC2D are presented in Ramirez et al. (2001).

Results of the simplified methods of analysis and nonlinear response-history analysis are tabulated in Tables 6-1 through 6-11 for minimum, maximum, average, and average plus one standard deviation (avg+1σ) responses. Included in the tables are (a) peak interstory drifts, (b) peak interstory velocities, (c) peak damper forces, (d) story shear forces at the time of maximum drift, and (e) maximum story shears (including the viscous component). The results reported in Tables 6-1 through 6-11 attest to the accuracy of the equivalent lateral force (ELF) and the modal analysis (RSA) procedures of *2000 NEHRP Recommended Procedures* for buildings with damping systems. Both methods provided conservative estimates of drift and predictions for damper forces and member actions in good overall agreement with the average of results of nonlinear response-history analysis.

Table 6-1. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-75 with Linear Viscous Damping System to Provide 10% Viscous Damping Ratio – NF1 Fault-Normal Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	215		215		94	198	265	328
	2	255		250		125	213	273	328
	1	164		155		97	176	229	262
Interstory Velocity (mm/sec)	3	683	**780**	796	**827**	342	753	978	1051
	2	810	**926**	663	**848**	369	765	997	1047
	1	700	**682**	477	**552**	298	647	850	915
Damper Force (kN)	3	544	**622**	635	**659**	274	602	782	840
	2	646	**738**	529	**677**	295	612	797	837
	1	559	**544**	380	**440**	238	517	680	731
Story Shear at Max. Disp. (kN)	3	725		910		382	694	894	958
	2	1057		1100		1095	1342	1519	1604
	1	1819		1622		1405	1637	1811	1913
Max. Story Shear (kN)	3	887	**901**	1083	**1072**	496	797	972	1119
	2	1280	**1325**	1282	**1333**	1254	1558	1760	1935
	1	1918	**1912**	1694	**1709**	1740	2238	2579	2745

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-2. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-75 with Linear Viscous Damping System to Provide 10% Viscous Damping Ratio – NF1 Fault-Parallel Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	112		113		61	98	131	151
	2	133		127		67	112	150	184
	1	89		80		39	78	112	152
Interstory Velocity (mm/sec)	3	468	**460**	577	**515**	287	526	660	694
	2	555	**546**	435	**472**	340	484	577	625
	1	499	**435**	331	**324**	237	348	426	453
Damper Force (kN)	3	373	**367**	460	**411**	229	420	528	554
	2	443	**436**	347	**377**	271	386	461	500
	1	398	**347**	264	**258**	189	278	341	362
Story Shear at Max. Disp. (kN)	3	618		765		421	537	623	731
	2	1039		1059		899	1096	1227	1367
	1	1578		1477		1123	1382	1528	1528
Max. Story Shear (kN)	3	717	**709**	881	**856**	513	706	841	936
	2	1161	**1165**	1157	**1165**	963	1239	1384	1446
	1	1638	**1623**	1517	**1513**	1172	1665	1905	1980

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-3. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-75 with Linear Viscous Damping System to Provide 10% Viscous Damping Ratio – NF2 Fault-Normal Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	78		78		63	82	100	114
	2	93		87		77	90	105	118
	1	65		55		46	55	63	74
Interstory Velocity (mm/sec)	3	389	**351**	455	**383**	303	503	611	663
	2	462	**417**	351	**342**	314	454	542	594
	1	424	**351**	263	**237**	223	296	344	353
Damper Force (kN)	3	310	**280**	363	**306**	242	402	488	530
	2	368	**332**	280	**273**	251	363	433	475
	1	338	**280**	210	**189**	178	237	275	282
Story Shear at Max. Disp. (kN)	3	583		663		419	577	670	725
	2	1034		1047		861	1094	1229	1298
	1	1499		1387		1100	1328	1478	1533
Max. Story Shear (kN)	3	659	**646**	750	**727**	541	655	750	826
	2	1122	**1117**	1118	**1116**	1006	1201	1325	1381
	1	1545	**1528**	1418	**1412**	1361	1594	1738	1807

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-4. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-75 with Linear Viscous Damping System to Provide 10% Viscous Damping Ratio – Soft-Soil Scaled Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	105		108		50	89	110	119
	2	125		121		66	103	128	150
	1	82		76		45	68	92	121
Interstory Velocity (mm/sec)	3	408	**415**	561	**494**	186	511	665	812
	2	484	**492**	410	**443**	200	484	613	714
	1	419	**377**	318	**307**	117	341	460	618
Damper Force (kN)	3	325	**331**	448	**394**	149	408	531	649
	2	386	**392**	327	**354**	160	386	490	571
	1	334	**300**	253	**245**	93	273	368	494
Story Shear at Max. Disp. (kN)	3	568		767		328	511	598	665
	2	1030		1072		868	1074	1176	1326
	1	1466		1484		1185	1364	1491	1639
Max. Story Shear (kN)	3	655	**653**	877	**852**	341	659	790	918
	2	1134	**1142**	1162	**1169**	873	1213	1349	1397
	1	1521	**1513**	1519	**1515**	1278	1591	1753	1839

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-5. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-100 with Linear Viscous Damping System to Provide 20% Viscous Damping Ratio – NF1 Fault-Normal Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	152		153		62	127	171	220
	2	182		181		82	160	209	261
	1	111		108		55	129	178	231
Interstory Velocity (mm/sec)	3	550	**642**	651	**680**	240	523	679	768
	2	661	**771**	614	**748**	309	673	886	979
	1	479	**497**	408	**462**	252	541	725	778
Damper Force (kN)	3	1038	**1211**	1228	**1283**	454	990	1286	1454
	2	1247	**1455**	1159	**1412**	584	1275	1678	1854
	1	904	**938**	770	**871**	477	1025	1372	1472
Story Shear at Max. Disp. (kN)	3	712		930		544	658	736	792
	2	1368		1402		1439	1669	1826	1942
	1	1858		1896		2056	2228	2402	2641
Max. Story Shear (kN)	3	1230	**1311**	1484	**1487**	631	825	948	1036
	2	2009	**2131**	1998	**2128**	1579	2140	2488	2590
	1	2226	**2257**	2203	**2251**	2391	3280	3825	4013

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-6. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-100 with Linear Viscous Damping System to Provide 20% Viscous Damping Ratio – NF2 Fault-Normal Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	58		58		37	52	64	74
	2	70		68		47	66	82	95
	1	44		41		30	42	51	60
Interstory Velocity (mm/sec)	3	311	**275**	356	**296**	191	350	428	428
	2	374	**330**	330	**304**	229	403	489	494
	1	289	**235**	221	**194**	155	262	314	313
Damper Force (kN)	3	587	**519**	673	**559**	362	662	810	811
	2	706	**623**	623	**574**	433	762	926	936
	1	546	**444**	418	**366**	293	495	595	593
Story Shear at Max. Disp. (kN)	3	645		712		371	557	648	688
	2	1326		1331		925	1281	1472	1513
	1	1699		1677		1285	1691	1919	1941
Max. Story Shear (kN)	3	817	**783**	918	**858**	471	651	756	777
	2	1458	**1429**	1436	**1416**	1043	1447	1698	1856
	1	1706	**1669**	1651	**1630**	1383	1986	2335	2521

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-7. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-80 with Nonlinear Viscous Damping System to Provide 10% Viscous Damping Ratio – NF1 Fault-Normal Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	211		213		73	189	268	349
	2	249		243		100	204	358	358
	1	161		150		76	164	224	292
Interstory Velocity (mm/sec)	3	727	**820**	883	**895**	289	726	976	1024
	2	858	**967**	687	**872**	313	755	1003	1020
	1	755	**728**	515	**578**	287	642	856	913
Damper Force (kN)	3	553	**604**	600	**621**	368	583	677	693
	2	601	**656**	560	**637**	383	595	686	692
	1	555	**550**	467	**509**	367	549	633	655
Story Shear at Max. Disp. (kN)	3	811		1057		456	723	906	1008
	2	1145		1179		1061	1385	1575	1644
	1	2034		1832		1488	1803	1998	2108
Max. Story Shear (kN)	3	1026	**1062**	1248	**1273**	525	871	1074	1244
	2	1454	**1497**	1469	**1512**	1340	1680	1894	2044
	1	2205	**2252**	2001	**2045**	1887	2349	2642	2835

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-8. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-80 with Nonlinear Viscous Damping System to Provide 10% Viscous Damping Ratio – NF1 Fault-Parallel Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	102		103		42	75	103	113
	2	120		113		50	93	144	144
	1	82		71		33	65	94	120
Interstory Velocity (mm/sec)	3	484	**454**	609	**523**	250	477	610	651
	2	571	**536**	430	**447**	265	472	595	609
	1	528	**446**	343	**318**	205	331	405	418
Damper Force (kN)	3	447	**442**	498	**466**	343	473	535	553
	2	486	**480**	441	**455**	352	471	528	535
	1	469	**426**	377	**371**	310	394	436	443
Story Shear at Max. Disp. (kN)	3	679		845		392	533	662	804
	2	1116		1133		860	1130	1324	1471
	1	1732		1612		1136	1490	1689	1788
Max. Story Shear (kN)	3	862	**863**	1017	**1008**	497	742	892	944
	2	1351	**1357**	1354	**1363**	943	1299	1481	1531
	1	1882	**1879**	1753	**1758**	1262	1780	2031	2126

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-9. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-80 with Nonlinear Viscous Damping System to Provide 10% Viscous Damping Ratio – Soft-Soil Scaled Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	101		105		37	86	102	108
	2	119		114		51	98	124	143
	1	81		72		35	63	91	120
Interstory Velocity (mm/sec)	3	446	**432**	636	**542**	180	557	717	949
	2	526	**510**	423	**439**	180	479	1825	741
	1	479	**414**	350	**322**	110	339	444	604
Damper Force (kN)	3	294	**296**	349	**322**	198	349	405	456
	2	319	**321**	296	**307**	198	324	369	403
	1	304	**281**	259	**254**	155	272	316	363
Story Shear at Max. Disp. (kN)	3	646		893		277	574	709	758
	2	1107		1153		767	1114	1270	1477
	1	1655		1662		1147	1440	1646	1773
Max. Story Shear (kN)	3	756	**760**	990	**989**	323	756	896	1061
	2	1249	**1256**	1286	**1293**	791	1275	1369	1440
	1	1744	**1750**	1741	**1750**	1198	1653	1825	1938

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-10. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-80 with Nonlinear Viscous Damping System to Provide 20% Viscous Damping Ratio – NF1 Fault-Normal Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	173		174		48	122	173	224
	2	204		199		74	172	312	312
	1	131		123		58	152	214	286
Interstory Velocity (mm/sec)	3	615	**719**	755	**784**	195	498	681	742
	2	725	**848**	607	**778**	276	663	885	963
	1	619	**623**	446	**512**	285	625	844	916
Damper Force (kN)	3	926	**1027**	1005	**1055**	547	875	1023	1068
	2	1006	**1116**	952	**1090**	651	1009	1166	1217
	1	908	**926**	788	**869**	661	980	1139	1186
Story Shear at Max. Disp. (kN)	3	709		927		378	555	656	690
	2	1120		1164		1237	1525	1702	1796
	1	1800		1697		1718	1965	2149	2256
Max. Story Shear (kN)	3	1205	**1276**	1388	**1434**	513	768	917	1033
	2	1740	**1826**	1748	**1838**	1415	1831	2080	2185
	1	2206	**2272**	2078	**2153**	2122	2739	3094	3257

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

Table 6-11. Comparison of Results of Simplified Methods of Analysis to Results of Nonlinear Response-History Analysis: 3-Story Frame 3S-80 with Nonlinear Viscous Damping System to Provide 20% Viscous Damping Ratio – NF1 Fault-Parallel Components

Response Quantity	STORY	SIMPLIFIED METHODS OF ANALYSIS - NEHRP (2003)				NONLINEAR TIME HISTORY ANALYSIS - IDARC2D, version 5.0			
		ELF		RSA		Min.	Average	Avg+1σ	Max.
Story Drift (mm)	3	77		79		21	46	65	72
	2	91		87		36	71	110	110
	1	62		54		28	55	79	94
Interstory Velocity (mm/sec)	3	377	**358**	468	**405**	141	306	411	438
	2	445	**423**	359	**369**	204	420	550	602
	1	392	**334**	271	**253**	207	321	409	467
Damper Force (kN)	3	817	**813**	894	**847**	466	685	795	821
	2	887	**883**	828	**850**	560	803	919	961
	1	820	**758**	693	**685**	564	702	792	847
Story Shear at Max. Disp. (kN)	3	592		701		272	424	545	652
	2	1095		1109		743	1166	1391	1424
	1	1532		1473		1069	1620	1882	1943
Max. Story Shear (kN)	3	1040	**1038**	1151	**1125**	358	594	735	778
	2	1610	**1618**	1598	**1612**	947	1365	1610	1623
	1	1917	**1899**	1825	**1826**	1369	1944	2276	2394

Values in bold indicate results obtained using the revised velocity correction factors from Table 6 of Ramirez et al. (2002a).

SECTION 7

CONCLUSIONS

Studies were conducted to investigate the effects of near-field and soft-soil ground motions on the response of single- and multi- degree-of-freedom structures with linear and nonlinear viscous damping devices. Two sets of near-field ground motions and one set of soft-soil ground motions were utilized in the analysis.

This investigation has led to the following conclusions:

(1) The damping coefficient values in 2000 NEHRP are accurate or conservative for soft-soil ground motions and for periods up to 5 seconds. Also, the 2000 NEHRP damping values are accurate or conservative for near-field motions and for periods up to 3 seconds provided that the cutoff period T_s is properly selected. For the set of near-field motions developed by Somerville (1997) and presented in Table 2-1, the appropriate values of T_s are 1.2 seconds for the fault-parallel components and 3.0 seconds for the fault-normal components.

(2) The ductility demand in damped single-degree-of-freedom structures with lower stiffness and strength is comparable to or less than the ductility demand in undamped structures for near-field and soft-soil earthquake motions. The trends and scatter in ductility demand for near-field and soft-soil motions are very similar to those previously observed for far-field motions.

(3) The 2000 NEHRP simplified method of analysis for single-degree-of-freedom systems produces results on displacement and acceleration that are generally of acceptable accuracy or conservative for near-field or soft-soil motions. The degree of accuracy is very similar to that previously observed for far-field motions. Moreover, the use of previously established correction factors for velocity on the basis of analyses with far-field motions (Ramirez et al., 2001, 2002a) produces very good estimates of peak structural velocity in near-field and soft-soil motions.

(4) The application of the simplified methods of analysis of *2000 NEHRP Recommended* Procedures to steel moment frames with linear and nonlinear

viscous damping systems, provided conservative estimates of drift and predictions for damper forces and member actions in good overall agreement with the average of results of nonlinear response-history analysis.

SECTION 8

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Phone: (716) 645-3391 ■ Fax: (716) 645-3399
E-mail: *mceer@mceermail.buffalo.edu* ■ WWW Site *http://mceer.buffalo.edu*

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