Earthquakes and Structures, *Vol. 7, No. 6 (2014) 1283-1301*
DOI: http://dx.doi.org/10.12989/eas.2014.7.6.1283

Impact of time and frequency domain ground motion modification on the response of a SDOF system

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(Received February 20, 2014, Revised October 1, 2014, Accepted October 8, 2014)

Abstract. Ground motion modification is extensively used in seismic design of civil infrastructure, especially where few or no recorded ground motions representative of the design scenario are available. A site in Los Angeles, California is used as a study site and 28 ground motions consistent with the design earthquake scenario are selected. The suite of 28 ground motions is scaled and modified in the time domain (TD) and frequency domain (FD) before being used as input to a bilinear SDOF system. The median structural responses to the suites of scaled, TD-modified, and FD-modified motions, along with ratios of he modified-to-scaled responses, are investigated for SDOF systems with different periods, strength ratios, and post-yield stiffness ratios. Overall, little difference (less than 20%) is observed in the peak structural accelerations, velocities, and displacements; displacement ductility; and absolute accelerations caused by the TD-modified and FD-modified motions when compared to the responses caused by the scaled motions. The energy absorbed by the system when the modified motions are used as input is more than 20% greater than when scaled motions are used as input. The observed trends in the structural response are predominantly the result of changes in the ground motion characteristics caused by modification.

Keywords: time domain modification; frequency domain modification; ground motion characteristics; bilinear SDOF system; structural seismic response analyses

1. Introduction

Seismic design of critical infrastructure requires nonlinear time history analyses using input ground motions (ASCE 2010, ATC 2011). Ideally, recorded ground motions from earthquake events consistent with the design scenario are selected so that their average response spectrum is equal to or greater than the target response spectrum. This can be problematic for design scenarios where few or no recorded ground motions from similar earthquake events are available; in which case, ground motion modification can be implemented to modify recorded ground motions so that their response spectra match the target spectrum.

There are two main techniques for ground motion modification:

- In the time domain (TD) modification process, the difference between the spectral

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http://www.techno-press.org/?journal=eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

acceleration of the recorded ground motion and the target spectral acceleration for a given period is used to calculate the amplitude, frequency, and duration of a time history "wavelet" (Lilhanand and Tseng 1988). The "wavelet" is then added to the recorded acceleration time history and the process is repeated for all periods of interest until the acceleration response spectrum of the recorded motion matches the target spectrum within a specified tolerance. RSPMatch (Abrahamson 1992) is an example of a program that uses TD modification. More recent versions of RSPMatch (Hancock *et al.* 2006, Al Atik and Abrahamson 2010) have made improvements to the "wavelet" function in order to prevent permanent displacements from developing in the time history during modification.

- In the frequency domain (FD) modification process, the Fourier amplitude spectrum of the recorded ground motion for a given frequency is multiplied by the ratio of the target spectral acceleration to the spectral acceleration of the recorded motion for the corresponding period (Rizzo *et al.* 1975). This process is repeated for all periods of interest until the response spectrum of the recorded motion matches the target spectrum within a specified tolerance. Scaling the Fourier amplitude spectrum by some ratio at a given frequency has the same effect as adding to the acceleration time history a harmonic motion with a corresponding frequency and amplitude equal to the scaling ratio. The resulting acceleration time history typically undergoes post-processing steps (e.g., tapering, filtering, baseline correction) to remove any permanent displacements. FD modification has been accused of introducing unrealistic amounts of energy (Naeim and Lew 1995) to the ground motions, although subsequent work has shown that this is not always the case (Zekkos *et al.* 2012).

Recent studies have focused on finding an appropriate ground motion selection or modification technique for predicting the median seismic responses of a structural system (Haselton 2009, Huang *et al.* 2011, Heo *et al.* 2011, O'Donnell *et al.* 2012, Grant and Diaferia 2013). Huang *et al.* (2011) used TD-modified motions, matched to the median acceleration response spectrum of scaled ground motions, as input to bilinear single degree-of-freedom (SDOF) models with varying yield strengths and periods. The TD-modified motions were observed to have smaller variability in the structural responses and produce smaller peak structural displacements than those produced by the scaled motions. Heo *et al.* (2011) compared the accuracy of responses due to scaled and TD-modified motions in matching the median estimate of maximum inter-story drift ratios for four-story and 12-story reinforced concrete frames. A more accurate prediction, with smaller variability, of the "true" maximum inter-story drift ratio was produced by using the TD-modified motions as input for the nonlinear time history analysis. Grant and Diaferia (2013) used maximum inter-story drift ratios for 12-story and 20-story reinforced concrete frames predicted by a benchmark study (Haselton 2009) as a point of comparison to assess the accuracy of responses caused by unscaled and TD-modified motions. Overall, the unscaled and TD-modified motions produced responses somewhat smaller than the point of comparison. Despite these advances, there is still a need to understand the effects of both TD and FD modification on structural response. Although the effects of TD modification on structural response have been studied, limited research for FD modification has been conducted. A comparison between the structural response when using scaled, TD-modified, and FD-modified motions as input is needed to investigate whether one technique leads to consistently biased results and why.

This study compares the impact that TD and FD modification techniques have on the response of a bilinear hysteretic SDOF system with varying periods, strength ratios, and post-yield stiffness ratios. Responses examined include peak structural acceleration, peak structural velocity, peak structural displacement, normalized maximum absorbed energy, maximum displacement ductility, normalized maximum absolute acceleration, and normalized residual displacement. The intent of this study is to identify observed biases in the structural response caused by TD or FD modification for the selected design scenario and attempt to provide an explanation for any biases.

2. Methodology

A suite of ground motions consistent with an earthquake scenario in Los Angeles, California was selected and applied to a bilinear hysteretic SDOF model with varying structural properties. The ground motions in the suite were scaled, TD-modified, and FD-modified before being used as input to the SDOF model.

2.1 Structural model

To consider the effects of ground motion modification on the response of a structure, a numerical model of a SDOF system was developed. The bilinear hysteretic model, similar to that used by Christopoulos *et al.* (2002), considered in this study is shown in Fig. 1. The nonlinear pseudo-restoring force, plotted on the y-axis, was represented by the nonlinear restoring force of the system, $F(x)$, normalized by the initial stiffness of the system, k_0. The yield force, f_y, and post-yield stiffness, kh_1, were normalized by the weight of the system and initial stiffness to produce the strength ratio, η, and post-yield stiffness ratio, α, respectively. Eqs. (1)-(4) describe the initial period, T_0, η, α, and yield displacement, x_y, of the system (Christopoulos *et al.* 2002).

$$T_0 = 2\pi\sqrt{\frac{m}{k_0}} \tag{1}$$

$$\eta = \frac{f_y}{mg} \tag{2}$$

$$\alpha = \frac{kh_1}{k_0} \tag{3}$$

$$x_y = \frac{T_0^2 \eta g}{4\pi^2} \tag{4}$$

where m and g represent the mass of the system and gravitational acceleration, respectively. The values for the SDOF system properties (i.e., T_0, η, and α) used in this study are shown in Table 1, with damping held constant at 5% (which is typical for systems with the properties examined in this study) for all combinations. The combination of these properties results in x_y values ranging from 0.01 to 100 cm.

Overall, 108 different SDOF systems were investigated. The period and strength ratio control the behavior of the system in the elastic regime while the post-yield stiffness ratio controls the behavior of the system after yielding. The range of periods was selected to represent very stiff to flexible structures. SDOF systems with longer periods (i.e., T_0 greater than 2 seconds) were not

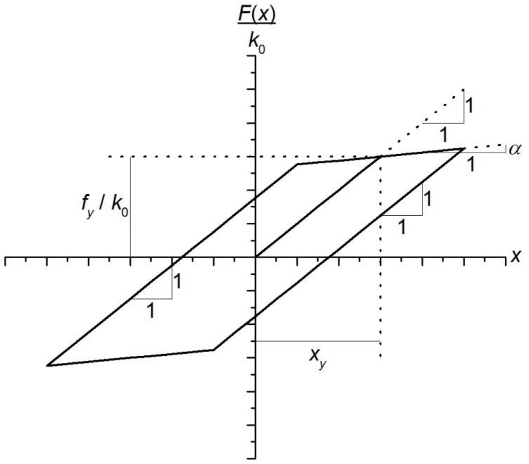

Fig. 1 Pseudo force-displacement relationship used for the bilinear hysteretic SDOF system (adapted from Christopoulos *et al.* 2002).

Table 1 SDOF system parameters used in this study.

T_0 (s)	η	α
0.10	0.05	0.00
0.25	0.10	0.02
0.50	0.20	0.05
1.00	0.30	
1.50	0.50	
2.00	1.00	

considered because they cannot account for contributions from higher modes (Krawinkler and Seneviratna 1998) and, as a consequence, may not accurately represent the behavior of real structural systems. The range of post-yield stiffness ratios was used to represent systems that respond perfectly plastic and systems that experience some strain hardening. The model did not account for strength deterioration and collapse to more easily identify trends due to the different modification processes and minimize effects due to structural complexity. Although a SDOF system is considered, it is expected that the results would also be valid for a multiple degree-of-freedom (MDOF) system that vibrates primarily in its first mode.

2.2 Ground motion selection and modification

A site near the Los Angeles International Airport (33.9° N, 118.4° W) was selected as a case study. A median acceleration response spectrum for a 7.1 magnitude (M_w) event on a rock site at a distance of 12.5 km ($R_{hypocentral}$) was generated using the Next Generation Attenuation (NGA) relationships (Abrahamson and Silva 2008, Boore and Atkinson 2008, Campbell and Bozorgnia 2008, Chiou and Youngs 2008). The median response spectrum was then conditioned on a uniform hazard spectrum (UHS) with a 2% probability of exceedance in 50 years at a target period of 1 second to produce the conditional mean spectrum (CMS) (Baker 2011). The CMS ($\exp(\mu_{\ln(Sa)})$) and its plus and minus one standard deviation ($\exp(\mu_{\ln(Sa)} \pm \sigma_{\ln(Sa)})$) spectra are shown in Fig. 2. A target period of 1 second was selected because it is the average period of the structural configurations considered in this study. Although multiple CMS conditioned on each period of the different SDOF systems considered could have been generated, a single CMS allows the same suite of ground motions to be used for all systems. Using the same suite of ground motions allows for a direct comparison between TD and FD modification effects using the same seed motions for all structural systems.

Motions recorded during similar earthquake events (10 km < $R_{hypocentral}$ < 35 km; 7 km < $R_{Joyner\text{-}Boore}$ < 35 km; 6.6 < M_w < 7.6; NEHRP site class C or higher (FEMA 2004)) were selected from the Pacific Earthquake Engineering Research Center's (PEER) database of ground motions (Chiou *et al*. 2008). This initial selection resulted in 54 pairs of ground motions (i.e., both horizontal components of motion). The root mean squared error (RMSE) for all of these motions was calculated using Eq. (5), which was adapted from the work by Kottke and Rathje (2008).

$$RMSE = \sqrt{\frac{\sum_{i}^{n}\left[\ln\left(Sa_{tar}(T_i)\right) - \ln\left(Sa_{rec}(T_i)\right)\right]^2}{n}} \tag{5}$$

$Sa_{tar}(T_i)$ and $Sa_{rec}(T_i)$ represent the spectral accelerations of the target and recorded motion at the *i*th period, respectively. *n* represents the total number of spectral points used in the calculation.

Of the 108 motions, the 28 motions with the smallest RMSE were selected so that the initial motions have response spectra that are relatively close to the target response spectrum. This suite of 28 motions was then divided into four sets of seven ground motions (since sets of seven ground motions are commonly used in engineering practice) with the RMSE values increasing from set one to set four. Some changes were made to the rankings of the ground motions to ensure that each set did not contain motions recorded at the same station or more than three motions from the same earthquake event. In order for the median acceleration response spectrum of the suite of 28 motions to be equal to or greater than the target spectrum, each set of seven ground motions was scaled by applying a single scale factor to all motions in the set. The scale factor of each set was gradually increased until the median response spectrum of the set was approximately equal to the target spectrum. This resulted in small scale factors ranging from 1 to 1.2. The scale factors and ground motion characteristics for the suite of 28 scaled motions are listed in Table 2. The original suite of unscaled motions was then modified using TD and FD techniques to create suites of 28 TD-modified and 28 FD-modified ground motions.

The median ($\exp(m_{\ln(Sa)})$) and the plus and minus one standard deviation ($\exp(m_{\ln(Sa)} \pm \sigma_{\ln(Sa)})$) acceleration response spectra of the scaled, TD-modified, and FD-modified suites are compared with the target spectra in Figs. 2(a)-(c), respectively. The median acceleration response spectra for the suites of TD- and FD-modified motions closely match the target spectrum (as shown in Figs. 2(b)-(c)) and have little variability as illustrated by the small range of spectral accelerations between their median plus and minus one standard deviation spectra. For design scenarios where ground motion variability is an important consideration, matching to the standard deviation target response spectra may be performed (Jayaram *et al.* 2012), but was not performed here since the focus is on comparing median response using TD and FD modification.

Table 2 Scale factors and ground motion characteristics, including peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), Arias intensity (I_a), and significant duration (D_{5-95}), of the scaled ground motions.

Set	Scale Factor	No	Earthquake	Station	Comp.	PGA (g)	PGV (cm/s)	PGD (cm)	I_a (cm/s)	D_{5-95} (s)
1	1.1	1	Hector Mine 1999	Hector	90	0.37	45.9	15.4	226	9.7
		2	Northridge-01 1994	N Hollywood-Coldwater Can	270	0.30	24.4	12.7	143	16.4
		3	Loma Prieta 1989	Saratoga-Aloha Ave	0	0.56	45.3	17.9	176	9.4
		4	Northridge-01 1994	LA-Wadsworth VA Hospital S	235	0.33	36.3	11.1	104	13.5
		5	Loma Prieta 1989	Saratoga-W Valley Coll	0	0.28	46.7	21.5	131	11.1
		6	Chi-Chi, Taiwan 1999	TCU122	North	0.29	37.5	39.7	186	30.3
		7	Landers 1992	Joshua Tree	0	0.30	30.2	10.5	199	27.2
2	1.0	8	Loma Prieta 1989	Saratoga-Aloha Ave	90	0.32	42.6	27.6	109	8.3
		9	Loma Prieta 1989	Saratoga-W Valley Coll	270	0.33	61.5	36.3	124	10.7
		10	Landers 1992	Joshua Tree	90	0.28	43.1	14.3	235	26.1
		11	Kobe, Japan 1995	Nishi-Akashi	90	0.50	36.6	11.3	227	11.2
		12	Northridge-01 1994	LA-Wadsworth VA Hospital N	235	0.25	32.8	11.3	82	15.0
		13	Northridge-01 1994	LA-UCLA Grounds	360	0.47	22.0	7.3	165	10.2
		14	Chi-Chi, Taiwan 1999	CHY024	East	0.28	52.9	43.6	183	24.1
3	1.2	15	Northridge-01 1994	LA-Wadsworth VA Hospital S	325	0.46	25.5	5.6	155	10.5
		16	Hector Mine 1999	Hector	0	0.32	34.3	27.0	120	11.7
		17	Northridge-01 1994	N Hollywood-Coldwater Can	180	0.36	30.0	7.6	173	15.0
		18	New Zealand-02 1987	Matahina Dam	83	0.31	26.0	7.7	94	6.2
		19	Chi-Chi, Taiwan 1999	TCU138	West	0.23	49.2	43.7	231	33.9
		20	Loma Prieta 1989	Gilroy Gavilan Coll	67	0.43	34.3	7.6	130	5.0
		21	Chi-Chi, Taiwan 1999	TCU120	North	0.23	44.3	40.0	192	32.4
4	1.2	22	Chi-Chi, Taiwan 1999	TCU122	East	0.26	51.0	51.7	207	30.8
		23	Loma Prieta 1989	Anderson Dam (Down)	250	0.29	24.3	9.2	115	10.5
		24	Northridge-01 1994	Beverly Hills-12520 Mulhol	35	0.74	48.9	10.3	431	8.9
		25	Chi-Chi, Taiwan 1999	TCU116	East	0.22	58.5	59.1	225	32.5
		26	Northridge-01 1994	LA 00	90	0.47	45.6	5.5	154	10.1
		27	Loma Prieta 1989	San Jose-Santa Teresa Hills	315	0.27	25.0	7.5	144	11.4
		28	Northridge-01 1994	LA-Chalon Rd	160	0.22	32.5	6.9	93	10.9

Table 3 Medians (m) and standard deviations (σ) of the TD-modified-to-scaled and FD-modified-to-scaled ratios of peak ground velocity (PGV), peak ground displacement (PGD), Arias intensity (I_a), and significant duration ($D_{5\text{-}95}$)

Characteristic		TD/Scaled	FD/Scaled
PGV	m	0.96	0.84
	σ	0.28	0.28
PGD	m	1.08	0.73
	σ	0.43	0.44
I_a	m	1.22	1.15
	σ	0.41	0.38
$D_{5\text{-}95}$	m	1.00	1.15
	σ	0.16	0.24

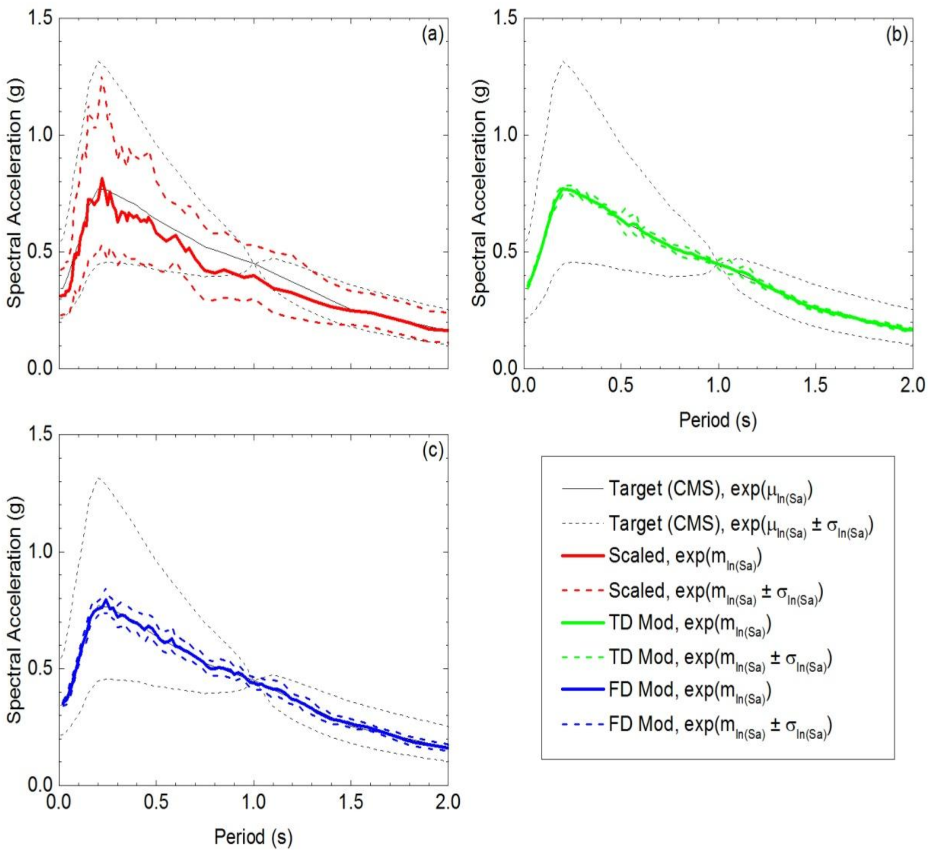

Fig. 2 Median ($\exp(m_{\ln(Sa)})$) and plus and minus one standard deviation ($\exp(m_{\ln(Sa)} \pm \sigma_{\ln(Sa)})$) acceleration response spectra of the (a) scaled, (b) TD-modified, and (c) FD-modified suites of motions compared with the target (CMS, $\exp(\mu_{\ln(Sa)})$) and its plus and minus one standard deviation ($\exp(\mu_{\ln(Sa)} \pm \sigma_{\ln(Sa)})$) spectra developed for this case study.

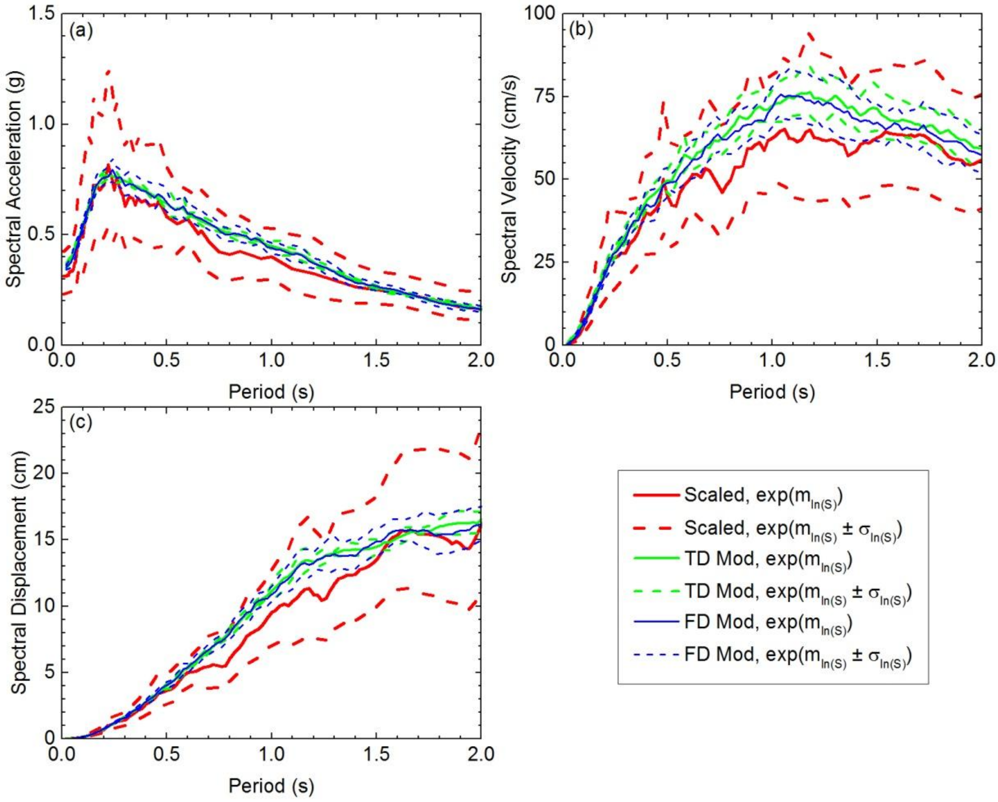

Fig. 3 Median ($\exp(m_{\ln(S)})$) and median plus and minus one standard deviation ($\exp(m_{\ln(S)} \pm \sigma_{\ln(S)})$) (a) acceleration, (b) velocity, and (c) displacement response spectra for the suites of 28 scaled, TD-modified, and FD-modified ground motions.

The median acceleration, velocity, and displacement response spectra for the suites of scaled, TD-modified, and FD-modified ground motions are plotted in Fig. 3. The median spectral accelerations, velocities, and displacements of the TD- and FD-modified motions are somewhat larger than those of the scaled motions for periods between 0.5 and 1.5 seconds. Since the CMS was conditioned on the 2% UHS at a period of 1 second, it has a slight "bump" at 1 second. Because the recorded ground motions generally did not have acceleration response spectra with this "bump", the median spectral accelerations of the scaled motions are somewhat smaller than the target values and the modified motions' spectral accelerations near a period of 1 second (Fig. 3(a)). This also results in the modified motions having larger spectral velocities (Fig. 3(b)) and displacements (Fig. 3(c)) than the scaled motions near 1 second.

TD-modified-to-scaled and FD-modified-to-scaled ratios were calculated for the ground motion characteristics of each motion. The medians (m) and standard deviations (σ) of the ratios are presented in Table 3. FD modification resulted in motions with peak ground velocities (PGV) and peak ground displacements (PGD) that were less than those of the scaled motions. TD modification produced motions with slightly larger peak ground displacements than the scaled motions. Arias intensity (I_a) (Arias 1970) of the TD- and FD-modified motions was greater than the Arias intensity of the scaled motions (20% and 15%, respectively). The increase in Arias intensity is the result of modifying motions to match the somewhat larger spectral values of the target spectrum. The significant duration ($D_{5\text{-}95}$) (Trifunac and Brady 1975) of the motions, on average, increased by 15% due to FD modification, but was not impacted by TD modification. This is a consequence of the mathematical manipulations by which the recorded acceleration time history is modified using each technique. FD modification adds harmonic motions to the recorded acceleration time history, thus adding energy throughout the time history and increasing significant duration.

2.3 Analysis approach

For each of the 108 SDOF systems, a nonlinear time history analysis was conducted using the three suites of 28 ground motions (i.e., scaled, TD-modified, FD-modified) as input to the system. Newmark's method with Newton-Raphson iterations (Chopra 2007) was used to compute the response of the SDOF system. The response parameters investigated were: peak structural acceleration (A), peak structural velocity (V), peak structural displacement (D), normalized maximum absorbed energy (E_{abs}), maximum displacement ductility (μ_Δ), normalized maximum absolute acceleration (a_{max}), and normalized residual displacement (x_{res}). These response parameters are indicative of damage sustained to the structure or non-structural elements, provide an understanding of the effect of ground motion duration on structural response, and signify potential residual deformations (Christopoulos *et al.* 2002, Chopra 2007). Normalized maximum absorbed energy, maximum displacement ductility, normalized maximum absolute acceleration, and normalized residual displacement are defined in Eqs. (6)-(9) (Christopoulos *et al.* 2002).

$$E_{abs} = \frac{\max_{0\le t\le t_D} \left|E_s(t)\right|}{x_y g} \tag{6}$$

$$\mu_\Delta = \frac{\max_{0\le t\le t_D} \left|x(t)\right|}{x_y} \tag{7}$$

$$a_{\max} = \frac{\max_{0\le t\le t_D} \left|a(t) + a_g(t)\right|}{g} \tag{8}$$

$$x_{res} = \frac{\left|x(t_D)\right|}{x_y} \tag{9}$$

where t_D represents the duration of the time history, $x(t)$ represents the displacement of the structure at time t, $a(t)$ represents the acceleration of the structure at time t, and $a_g(t)$ represents the ground motion acceleration at time t. $E_s(t)$ represents the mass-normalized strain energy of the structure at time t as defined by Eq. (10) (Christopoulos *et al.* 2002).

$$E_s(t) = \left(\frac{2\pi}{T_0}\right)^2 \int_0^{x(t)} \frac{F(t)}{k_0} dx \tag{10}$$

3. Structural response

For each structural configuration, the median and standard deviation of each response parameter were calculated for the suites of motions (i.e., scaled, TD-modified, FD-modified), as well as their modified-to-scaled ratios.

3.1 Scaled and modified response

The responses to the suite of scaled ground motions provided a baseline understanding of the influence of the structural properties on the SDOF system response. The median peak structural acceleration, peak structural velocity, and peak structural displacement are shown in Figs. 4(a)-(c) as a function of the period and strength ratio of the structure. The peak structural accelerations are larger at short periods (0.5 seconds), the peak structural velocities are larger at intermediate

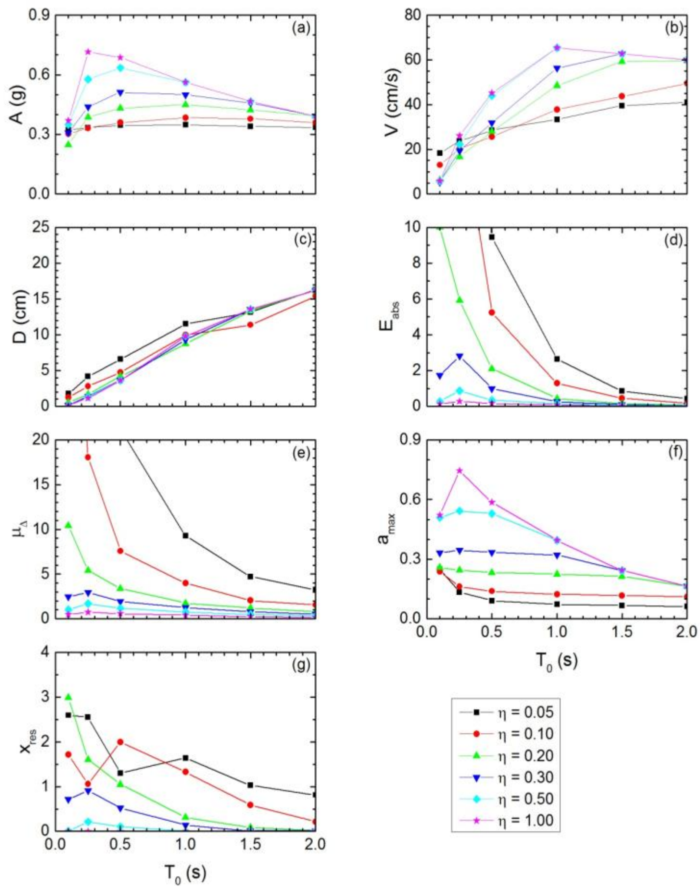

Fig. 4 Median (a) peak structural acceleration, (b) peak structural velocity, (c) peak structural displacement, (d) normalized maximum absorbed energy, (e) maximum displacement ductility, (f) normalized maximum absolute acceleration, and (g) normalized residual displacement caused by the suite of scaled motions (post-yield stiffness ratio equals 0.02).

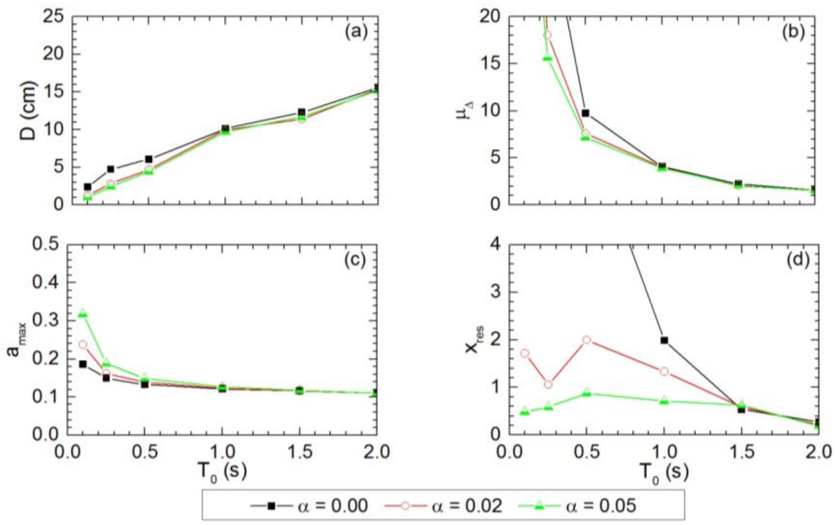

Fig. 5 Effects of the post-yield stiffness ratio (α) on median (a) peak structural displacement, (b) maximum displacement ductility, (c) normalized maximum absolute acceleration, and (d) normalized residual displacement caused by the suite of scaled motions (strength ratio equals 0.1).

periods (1 or 1.5 seconds), and the peak structural displacements are larger at long periods (2 seconds), as expected. For short, intermediate, and long periods the system is more sensitive to acceleration, velocity, and displacement, respectively (Chopra 2007). This observation is more apparent as the strength ratio increases because the system tends to remain elastic. The normalized maximum absorbed energy (Fig. 4(d)), maximum displacement ductility (Fig. 4(e)), and normalized residual displacement (Fig. 4(g)) decrease significantly as the structural period and strength ratio increase due to the system remaining in the elastic regime. The normalized maximum absolute acceleration (Fig. 4(f)) decreases for systems with smaller strength ratios because of yielding. For larger strength ratios, the normalized maximum absolute acceleration is similar in shape to the peak structural acceleration because the system remains elastic.

Fig. 5 shows the effects of the post-yield stiffness ratio on peak structural displacement, maximum displacement ductility, normalized maximum absolute acceleration, and normalized residual displacement. For structures with a period less than 1 second and a strength ratio of 0.05 or 0.1, increasing the post-yield stiffness ratio reduces the peak structural displacement (Fig. 5(a)) and maximum displacement ductility (Fig. 5(b)) by over 30%. For systems with larger post-yield stiffness ratios, smaller structural displacements are caused by a given applied force. The normalized maximum absolute acceleration increases for short periods as the post-yield stiffness ratio increases, which was similarly observed in Christopoulos *et al*. (2002), due to the smaller displacements associated with stiffer structures. The normalized residual displacement (Fig. 5(d)) is reduced by over 50% as post-yield stiffness increases for structures with strength ratios less than 0.2 and a period less than 1 second. Larger post-yield stiffness ratios limit the amount of inelastic or permanent deformation in the system, thus reducing the normalized residual displacement. The responses of structures with larger strength ratios are not affected by the post-yield stiffness ratio because fewer motions cause the system to yield. The remaining structural responses are not significantly impacted by a change in the post-yield stiffness ratio. In the case of normalized maximum absorbed energy, although there is an increase in the force acting on the structure as the post-yield stiffness ratio increases, a corresponding decrease in displacement results in an area under the hysteretic curve (i.e., absorbed energy) that is similar to the case with zero post-yield stiffness.

The median responses caused by the suites of scaled, TD-modified, and FD-modified ground motions for SDOF systems with a strength ratio of 0.2 and a post-yield stiffness ratio of 0.02 are plotted in Fig. 6. For varying period, strength ratio, and post-yield stiffness ratio, the TD- and FD-

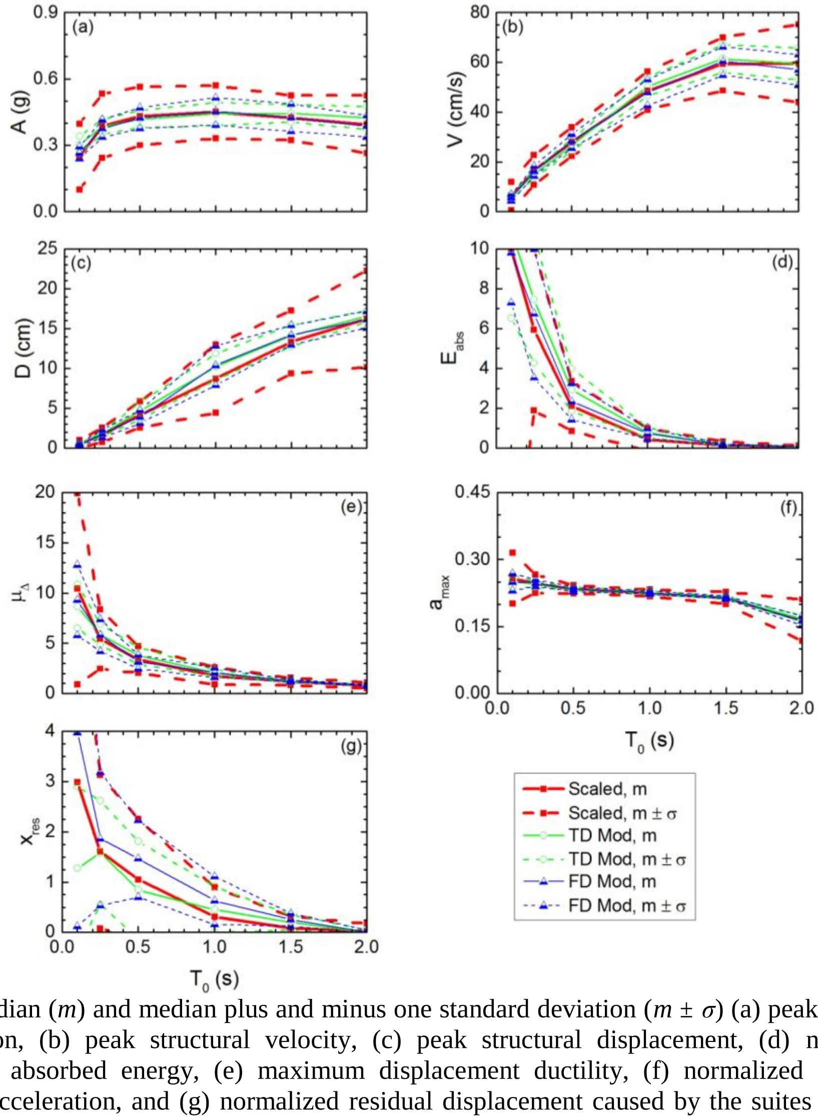

Fig. 6 Median (m) and median plus and minus one standard deviation ($m \pm \sigma$) (a) peak structural acceleration, (b) peak structural velocity, (c) peak structural displacement, (d) normalized maximum absorbed energy, (e) maximum displacement ductility, (f) normalized maximum absolute acceleration, and (g) normalized residual displacement caused by the suites of scaled, TD-modified, and FD-modified motions (strength ratio equals 0.2; post-yield stiffness ratio equals 0.02).

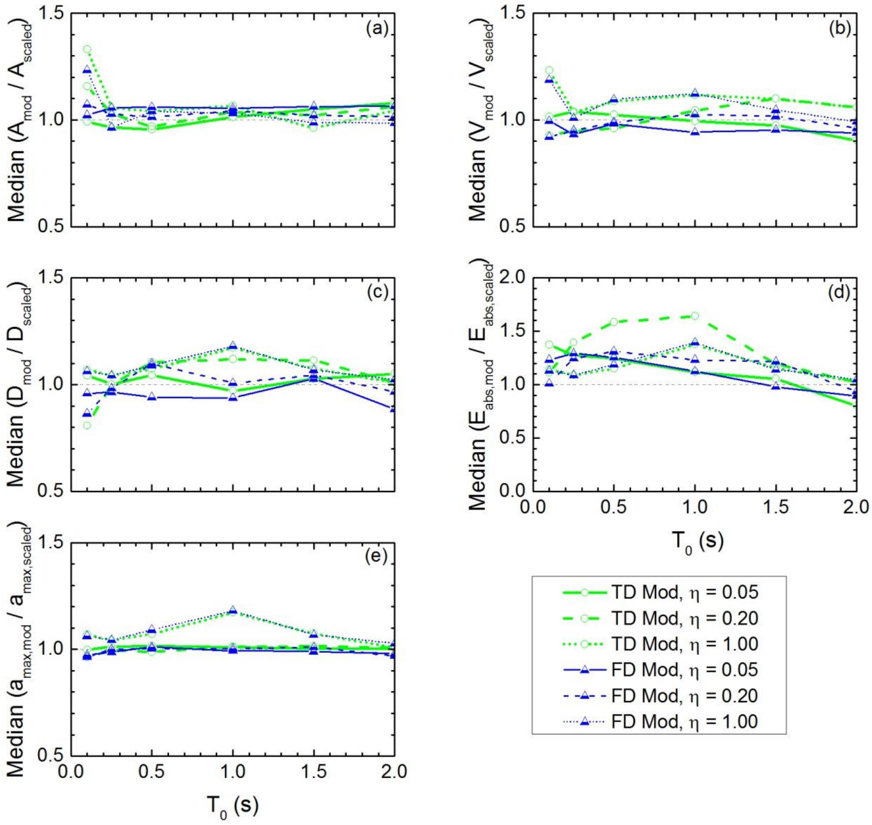

Fig. 7 Median ratios of modified-to-scaled response for (a) peak structural acceleration, (b) peak structural velocity, (c) peak structural displacement, (d) normalized maximum absorbed energy, and (e) normalized maximum absolute acceleration for the suite of motions (post-yield stiffness ratio equals 0.02).

modified ground motions produce median responses with trends similar to those observed for the median responses produced by the scaled motions. However, there are some notable differences in the magnitudes of the medians produced by the different suites of motions:

- For SDOF systems with periods between 0.5 and 1.5 seconds, the median peak structural acceleration (Fig. 6(a)) and peak structural velocity (Fig. 6(b)) resulting from using the modified motions as input are generally equal to or somewhat larger (less than 10% larger) than the same responses resulting from using the scaled motions as input. Similarly, the median peak structural displacement (Fig. 6(c)) and maximum displacement ductility (Fig. 6(e)) are 5 to 20% larger for SDOF systems with periods between 0.5 and 1.5 seconds when the modified motions are used as input as opposed to the scaled motions. The increases observed for peak structural acceleration, peak structural velocity, peak structural displacement, and maximum displacement ductility for systems subjected to the modified motions are the result of the modified motions having larger spectral accelerations, velocities, and displacements than the scaled motions between periods of 0.5 and 1.5 seconds.

- It is observed that the energy absorbed by the SDOF systems increases by more than 20%, and as much as 80%, when the modified motions are used as input instead of the scaled motions (Fig. 6(d)). During the modification process, the Arias intensity of the ground motions was increased by 22% and 15% for the TD and FD techniques, respectively. The increase in Arias intensity is indicative of the modified ground motions containing more energy that is dissipated by the system.
- Note also that the variability in the structural responses due to the modified motions is much smaller than the variability in the structural responses due to the scaled motions as indicated by the median plus and minus one standard deviation shown in Fig. 6. The smaller variability is the result of the modified motions having acceleration response spectra that very closely match the target spectrum as shown in Figs. 2(b)-(c). On the other hand, in Fig. 6(g), it is observed that the normalized residual displacements caused by the scaled, TD-modified, and FD-modified motions have similar amounts of dispersion. This observation is the result of the highly variable nature of normalized residual displacement (e.g., its dependence on the time when yielding occurs) and also explains why the normalized residual displacement has the most noticeable differences when using a scaled ground motion as opposed to a TD- or FD-modified motion.

3.2 Modified-to-scaled ratios

For each response parameter, the ratio of the system response using the TD- or FD-modified motion as input to that caused by the scaled motion was calculated. This calculation was performed for each individual motion in the suites of TD- and FD-modified ground motions. The medians of the ratios for each response parameter are shown in Fig. 7 for SDOF systems with strength ratios of 0.05, 0.2, and 1 and a post-yield stiffness ratio of 0.02. Note that the medians of the ratios shown in Fig. 7 are different than the overall median of the suites shown in Figs. 4 and 6. The medians of the ratios show the impact that modification has on an individual motion. If modification results in a motion producing a larger response than that of the scaled motion, the ratio is greater than 1. Conversely, if the response due to the modified motion is smaller than the response due to the scaled ground motion, the ratio is less than 1. Ratios for normalized residual displacement are highly variable due to some scaled motions producing very small residual displacements, so these results are not shown in Fig. 7. Standard deviations of the ratios for the TD- and FD-modified motions are also not shown in Fig. 7, but are overall similar to each other.

The peak structural acceleration (Fig. 7(a)) is significantly impacted by modification for SDOF systems with a period of 0.1 seconds because structures with small periods are more sensitive to accelerations. A majority of the scaled motions have spectral accelerations that are less than the target at a period of 0.1 seconds. Therefore, the spectral accelerations of these motions are increased during modification leading to the larger ratios. For SDOF systems with a period of 0.1 seconds, the median ratios for the TD- and FD-modified motions reach or exceed values of 1.3. For a constant period of 0.1 seconds, as the strength ratio of the structure increases, the ratios increase from approximately 1.0 to approximately 1.3 for both modification techniques because the system remains in the elastic regime. Slight increases (ratios between 1.0 and 1.1) in the peak structural accelerations resulting from the modified motions are observed for SDOF systems with periods between 0.5 and 1.5 seconds. Again, this is the result of the scaled motions having smaller spectral accelerations than the target in this range of periods and the modification process increasing these spectral accelerations to match the target. Neither modification technique consistently results in larger responses than the other since both techniques result in motions with very similar acceleration response spectra.

The peak structural velocity (Fig. 7(b)) is slightly impacted by modification (ratios between 0.9 and 1.1). For SDOF systems with periods between 0.5 and 1.5 seconds, the peak structural velocities resulting from using the modified motions as input is 5 to 10% larger than the peak structural velocities caused by the scaled motions. The spectral velocities of the modified motions are larger than those of the scaled motions between periods of 0.5 and 1.5 seconds. TD modification appears to produce ground motions that result in slightly larger peak structural velocities than those of the FD-modified motions (ratios of 1.1 compared to 1.0) for SDOF systems with a period between 1 and 2 seconds and strength ratios greater than 0.1. In this range of periods, the TD-modified motions have spectral velocities that are slightly larger than those of the FD-modified motions. For a strength ratio of 0.05, the FD-modified motions lead to peak structural velocities that are less than the resulting peak structural velocities caused by the scaled motions.

There is some impact from modification on peak structural displacement (Fig. 7(c)), with ratios ranging from 0.8 to 1.2 for TD modification and 0.9 to 1.2 for FD modification. For systems with intermediate periods (0.5 to 1.5 seconds) and larger strength ratios (greater than 0.1), peak structural displacement generally increases when the structure is subjected to the modified motions. This is a result of the modified motions having larger spectral displacements than the scaled motions in this period range. Since the spectral displacements of the TD-modified and FD-modified motions are very similar, no significant difference is observed between the ratios for the two modification techniques. For structures with a strength ratio of 0.05, the median ratios for the FD-modified motions are less than 1. The ratios for ductility will be the same as the ratios for peak displacement, so they are not shown in Fig. 7.

Modification has the largest impact on the normalized maximum absorbed energy (Fig. 7(d)), where the ratios range from 0.8 to 1.8 for the TD-modified motions and from 0.9 to 1.4 for the FD-modified motions. The low ratios are observed only for structures with a period of 2 seconds, for which none of the modified motions caused the system to yield, yet some of the scaled motions did cause yielding. Typically, the modified motions lead to the system absorbing a noticeably larger amount of energy (ratios greater than 1.2). The increase in the energy absorbed by the system when subjected to modified motions rather than scaled motions is at least partially attributed to the modified motions having larger Arias intensities. A larger Arias intensity signifies that the motion contains more energy in its acceleration time history, a large portion of which will be dissipated by the system during shaking. The TD-modified motions result in the systems absorbing larger amounts of energy than the FD-modified motions partially due to the Arias intensity of the TD-modified motions being 5% larger.

The impact of both modification techniques is minimal when considering normalized maximum absolute acceleration (Fig. 7(e)). Only structures with a period of 1 second and a strength ratio greater than 0.5 are somewhat impacted by modification, with ratios being 1.2 for the TD- and FD-modified motions. Structures with larger strength ratios respond in the elastic regime leading to normalized maximum absolute accelerations with values similar to the spectral accelerations of the ground motions. For a period of 1 second, the modified ground motions are observed to have larger spectral accelerations than the scaled ground motions. This increase is observed for the normalized maximum absolute acceleration, but not for the peak structural acceleration (Fig. 7(a)) because the normalized maximum absolute acceleration is a function of the structural and ground acceleration.

Varying the post-yield stiffness ratio has no significant impact on the medians of the ratios. As stated before, the median peak structural acceleration, peak structural velocity, and normalized maximum absorbed energy resulting from the scaled and modified motions do not experience any changes as the post-yield stiffness ratio is varied. For structures with a period of 0.1 seconds, there is a 50% increase in the median normalized maximum absolute acceleration as the post-yield stiffness ratio increases, but no such increase is observed for the other structural configurations. The median peak structural displacements were impacted by changes in the post-yield stiffness ratio. However, the peak structural displacements produced by the suites of scaled, TD-modified, and FD-modified motions were all impacted similarly by changing the post-yield stiffness ratio. Therefore, no change due to varying the post-yield stiffness ratio is observed in the ratios for peak structural displacement.

4. Discussion

Based on the results for this scenario, both modification techniques generally have minimal impact on the resulting peak structural acceleration, peak structural velocity, peak structural displacement (and maximum displacement ductility), and normalized maximum absolute acceleration. Slight increases (10-20%) in these responses are observed when the modified motions are applied to SDOF systems with periods between 0.5 and 1.5 seconds. In the same period range, the modified motions have larger spectral accelerations, velocities, and displacements than the scaled motions. Large increases (changes of greater than 20%) are observed in the energy absorbed by the system when the modified motions are applied instead of the scaled motions due to the larger Arias intensities of the modified motions. When compared to the scaled motions, TD- and FD-modified motions generally result in slight increases in the peak structural velocities and peak structural displacements; however, FD-modified motions result in a decrease in these responses for systems with a strength ratio of 0.05. Table 4 summarizes the general trends in the impact of modification on the structural responses observed in this study and provides exceptions where those trends do not apply.

Table 4 Summary of the general trends observed for the response parameters and exceptions

Response Parameter	General Trend	Exceptions
Peak structural acceleration	TD ≈ FD ≈ Scaled	For T_0 = 0.1 s and $\eta \geq 0.3$, TD ≈ FD > Scaled For T_0 = 0.5 to 1.5 s, TD ≈ FD ≳ Scaled
Peak structural velocity	TD ≈ FD ≳ Scaled	For T_0 > 1 s and $\eta \geq 0.3$, TD > FD > Scaled For η = 0.05, TD ≈ Scaled > FD
Peak structural displacement and displacement ductility	TD ≈ FD > Scaled	For η = 0.05, TD ≈ Scaled > FD
Normalized maximum absorbed energy	TD > FD > Scaled	For T_0 = 2 s, Scaled > TD ≈ FD
Normalized maximum absolute acceleration	TD ≈ FD ≈ Scaled	For T_0 = 1 s and $\eta \geq 0.5$, TD ≈ FD > Scaled

Selecting which modification technique to use is dependent on the response parameter of interest. For many of the response parameters, both modification techniques have limited impact when compared to the responses caused by the scaled motions. For the normalized maximum absorbed energy, the modified motions of both techniques lead to larger responses than those of the scaled motions. For this response parameter, FD modification may be preferable if the objective is to produce responses closer to those of the scaled motions. However, TD modification would be preferable if the objective is to produce the largest demand on the system.

Likewise, structural properties play an important role in the selection of which technique to use. For structures with periods of 0.5 to 1.5 seconds and strength ratios greater than 0.3, the responses caused by the modified motions are slightly larger than the responses caused by the scaled motions. Both modification techniques produce ground motions that result in peak structural velocities and peak structural displacements equal to or smaller than those produced by the scaled motions for SDOF systems with strength ratios of 0.05. If the goal is to produce the largest structural responses, the scaled ground motions may be more desirable for this scenario. Therefore, it is important to understand the structure and the key response parameters before selecting the modification technique to be used.

5. Summary and conclusions

The effects of ground motion modification on the structural response of a SDOF system for a suite of 28 ground motions were examined considering TD and FD modification techniques and varying structural properties. Response parameters, such as peak structural displacement and normalized maximum absorbed energy, were calculated for suites of scaled, TD-modified, and FD-modified ground motions along with their medians. Ratios of modified-to-scaled responses were also calculated for each ground motion along with the medians of those ratios for each technique.

The following observations are made for this scenario:

- Modification using either technique (TD or FD) has only a small impact (changes of less than 20%) on the peak structural acceleration, peak structural velocity, peak structural displacement (and maximum displacement ductility), and normalized maximum absolute acceleration.
- Modification has a more significant impact on the normalized maximum absorbed energy with changes as large as 80%. The modified motions generally have larger Arias intensities than the scaled motions, which, at least partially, leads to the observed increase in the normalized maximum absorbed energy.
- For SDOF systems with periods between 0.5 and 1.5 seconds, the responses caused by the modified motions are somewhat larger than those caused by the scaled motions. In this period range, the modified motions have larger spectral accelerations, velocities, and displacements than the scaled motions.
- For systems with strength ratios of 0.05, peak structural velocities and peak structural displacements resulting from the FD-modified motions are about 10% less than those resulting from the scaled motions.
- TD-modified motions produce somewhat larger peak structural velocities (10% larger) than the FD-modified motions for systems with periods greater than 1 second. The TD-modified

motions also lead to the system absorbing more energy (30% larger) than the FD-modified motions. The differences in the peak structural velocity and normalized maximum absorbed energy are the result of the TD-modified motions having slightly larger spectral velocities and Arias intensities than the FD-modified motions.

- The variability in the responses caused by the modified motions is significantly smaller than the variability in the responses caused by the scaled motions as a result of the modified motions having response spectra that closely match the target spectrum.
- The post-yield stiffness ratio has a slight impact on the peak structural displacements, maximum displacement ductility, normalized maximum absolute acceleration, and normalized residual displacements caused by the motions. The impact on these responses is similar for the scaled, TD-modified, and FD-modified motions.
- The observed effects of modification on the structural response are predominantly caused by the impact of modification on the ground motion characteristics.

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