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On the influence of strong-ground motion duration on residual displacement demands

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Abstract. This paper summarizes results of a comprehensive analytical study aimed at evaluating the influence of strong ground motion duration on residual displacement demands of single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems. For that purpose, two sets of 20 earthquake ground motions representative of short-duration and long-duration records were considered in this investigation. While the influence of strong ground motion duration was evaluated through constant-strength residual displacement ratios, C_r, computed from the nonlinear response of elastoplastic SDOF systems, its effect on the amplitude and height-wise distribution of residual drift demands in MDOF systems was studied from the response of three one-bay two-dimensional generic frame models. In this investigation, an inelastic ground motion intensity measure was employed to scale each record, which allowed reducing the record-to-record variability in the estimation of residual drift demands. From the results obtained in this study, it was found that long strong-motion duration records might trigger larger median C_r ratios for SDOF systems having short-to-medium period of vibration than short strong-motion duration records. However, taking into account the large record-to-record variability of C_r, it was found that strong motion duration might not be statistically significant for most of the combinations of period of vibration and levels of lateral strength considered in this study. In addition, strong motion duration does not have a significant influence on the amplitude of peak residual drift demands in MDOF systems, but records having long strong-motion duration tend to increase residual drift demands in the upper stories of long-period generic frames.

Keywords: strong-motion duration; residual displacement ratios; residual drift demands.

1. Introduction

Nowadays, there is still a controversy about the influence of earthquake ground motion duration on the seismic response of structures. This controversy begins with the definition of duration of strong ground shaking of acceleration time histories recorded from earthquake events that adequately represent the time interval when the energy content of the earthquake ground shaking produce significant damage to the excited structure. Motivated by this issue, Bommer and Martinez-Pereira (1999) published a comprehensive review about the merits and pitfalls of about 30 definitions proposed in the literature. They point out that an adequate definition should have a physical significance based on a good correlation with geophysical parameters (e.g., earthquake

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magnitude, rupture history, etc.). Among several definitions, the most widely measure of strong ground motion duration for earthquake engineering purposes is due to Trifunac and Brady (1975). The authors defined significant strong motion duration, t_D, as the time interval from 5% to 95% of the *Arias intensity* computed from each single acceleration time-history. The merit of this definition is that the use of *Arias Intensity* has strong correlation with observed earthquake damage in short period structures as well as structures on soils susceptible to liquefaction, but a limitation is that it does not explicitly take into account differences in ground motion frequency content as well as the source geophysical features.

The influence of strong-ground motion duration has gained attention since researchers have found that strong motion duration is closely related to the number of inelastic cycles that structural elements suffer during earthquake excitation and, thus, with cumulative damage due to low-cycle fatigue phenomena (e.g. Mahin 1980, Fajfar and Fischinger 1990, Cosenza and Manfredi 2000, Chai 2004, Iervolino *et al.* 2006). However, other researchers (e.g. Bernal 1992, Rahnama and Krawinkler 1993, Ibarra and Krawinkler 2003, Cosenza *et al.* 2004, Iervolino *et al*. 2006) have found that t_D has small effect on the peak seismic demand parameters (e.g. maximum inelastic displacement demands, displacement ductility, or even the collapse capacity of SDOF systems). Recently, Hancock and Bommer (2006) developed a state-of-the-knowledge review of previous studies focusing on the influence of strong-motion duration on parameters related to structural damage. They reported that prior investigations that employed damage measures linked to cumulative energy usually find a positive correlation between strong-motion duration and structural damage, while studies that considered damage measures employing peak response, in general, did not find strong correlations between strong-motion duration and structural damage.

Recent seismic events have highlighted that damaged structures may need to be demolished due to excessive permanent lateral deformations at the end of the earthquake ground shaking (i.e. residual displacements), even if they did not experience severe damage or partial collapse. Furthermore, the evaluation of residual displacement demands plays a very important role in determining the technical and economical feasibility of repairing and retrofitting structures that have been damaged due to earthquake excitation. Furthermore, residual displacements might have a significant impact in earthquake-induced economic losses since structures may be demolished due to excessive permanent deformations even though they did not experience moderate-to-severe damage. In addition, an adequate estimation of residual displacement demands has shown to be critically important in evaluating the structural residual capacity and in assessing possible collapse during strong aftershocks (e.g. Luco *et al.* 2004). Thus, an adequate estimation of residual displacement demands that existing structures may experience after earthquake ground shaking should be of primary importance in modern performance-based assessment procedures.

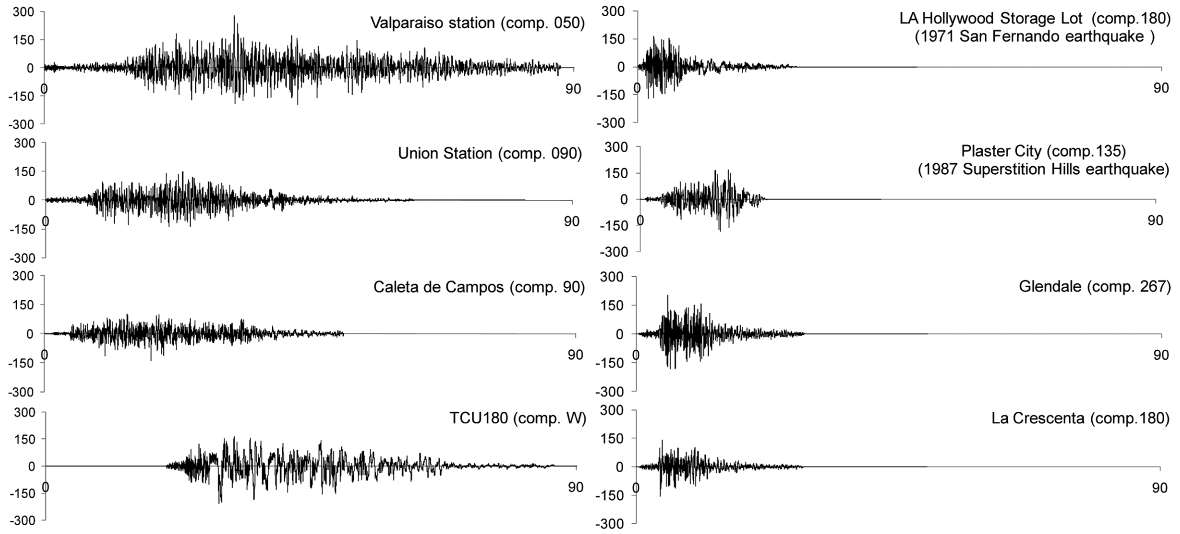
Motivated by earthquake field reconnaissance observations, researchers have performed analytical investigations recently aimed at gaining further understanding on the parameters that influence the amplitude and height-wise distribution of residual drift demands in existing multi-story buildings (e.g. Pampanin *et al.* 2003, Ruiz-García and Miranda 2006a). Previous studies have reported that the amplitude of residual drift demand and its distribution over the height depends on the component hysteretic behavior, building frame mechanism, structural overstrength as well as the ground motion intensity. Particularly, Ruiz-García and Miranda (2006a) noted that the evaluation of residual drift demands in regular moment-resisting frame models involves large levels of uncertainty (i.e. record-to-record variability) in its estimation and, moreover, this uncertainty is larger than that associated to the estimation of maximum (transient) drift demands.

The primary objective of this paper is to gain further understanding on the influence of strong motion duration on residual displacement demands of SDOF systems as well as on the amplitude and height-wise distribution of residual lateral drift demands in MDOF systems subjected to earthquake excitation. It should be noted that this study is limited to SDOF and MDOF systems subjected to earthquake ground motions recorded in free-field accelerographic stations placed on rock or stiff soil site conditions, which allows separating the influence of site conditions on the structural response. For instance, the effect of long-duration ground motions recorded on soft soil sites is beyond the scope of this study.

2. Earthquake ground motions considered in this study

In this study, the influence of strong motion duration on residual displacement demands is investigated by using the definition proposed by Trifunac and Brady (1975). Even though this definition has been criticized for lacking of correlation with the nature of the seismic event (e.g. duration of the rupture of the causative fault), it has been widely used for many researchers while evaluating the effect of strong motion duration. Therefore, two sets of 20 earthquake ground motions having short strong motion duration, ranging between 8.8 s and 15.9 s, and long strong motion duration, between 25.7 s and 51.7 s, were considered in this investigation. It should be mentioned that all records considered in this investigation were registered in accelerographic stations located on rock or stiff soil sites (i.e. with shear wave velocities greater than 180 m/s), but none was gathered in recording stations placed on soft soil sites. Both sets include ground motions recorded during 8 historical earthquake events with moment magnitude ranging from 6.5 to 8.0. Typical acceleration time-histories of records having long and short strong-motion duration are illustrated in Fig. 1.

Throughout this investigation, while ‘s20-SD’ designates the short-duration set, ‘s20-LD’ refers to



(a) (b)

Fig. 1 Examples of acceleration time-histories employed in this study: (a) long strong-duration records, (b) short strong-motion duration records

Table 1 Long strong-motion duration earthquake ground motions used in this study

Date	Magnitude [M_w]	Earthquake name	Station name	Component	D [km]	PGA [cm/s^2]	t_D [s]
19/09/85	8.0	Michoacan, Mexico	La Union	90	120.8	148.3	28.1
				180		165.6	27.1
			La Villita	90	80.3	121.5	41.8
				180		125.4	43.4
			Caleta de Campos	90	35.2	140.7	29.3
				180		139.7	25.7
03/03/85	8.0	Valparaiso, Chile	Llolleo	10	62.0	698.3	29.2
				100		436.9	30.4
			Melipilla	0	87.5	673.0	30.7
				90		518.0	27.3
			San Felipe	80	116.0	425.1	30.3
				170		303.5	31.3
			Valparaiso	50	26.5	291.5	50.0
				140		162.7	51.7
09/20/99	7.6	Chi-Chi, Taiwan	CHY15	E	43.5	142.4	37.5
			CHY25	E	18.8	156.2	33.7
			CHY46	W	29.5	139.6	30.0
			TCU120	W	8.1	220.8	32.6
			TCU123	W	15.1	160.7	35.4
			TCU138	E	10.1	191.1	34.1

D-Epicentral distance; PGA-Peak ground acceleration; t_D-strong motion duration as defined by Trifunac and Brady (1975)

Table 2 Short strong-motion duration earthquake ground motions used in this study

Date	Magnitude [M_w]	Earthquake name	Station name	D [km]	PGA [g]	t_D [s]
10/15/79	6.5	Imperial Valley, USA	El Centro Array #1	15.5	0.139	8.9
			Plaster City	31.7	0.057	10.7
09/17/89	6.9	Loma Prieta, USA	Gilroy Array #3	14.4	0.367	11.4
			Gilroy Array #7	24.2	0.226	11.5
			Palo Alto-SLAC Lab	36.3	0.112	12.5
01/17/94	6.7	Northridge, USA	LA. Centinela St.	30.9	0.322	12.4
			Canoga Park-Topanga Can	15.8	0.420	10.4
			LA. N Faring Rd.	23.9	0.273	8.8
			LA. Fletcher Dr.	29.5	0.240	11.8
			Glendale-Las Palmas	25.4	0.206	11.5
			LA-Hollywood Stor FF	25.5	0.231	12.0
			Lake Hughes #1	36.3	0.087	13.9
			Leona Valley #6	38.5	0.178	10.4
			Northridge-17645 Saticoy St.	13.3	0.159	11.0
			La Crescenta-New York	22.3	0.368	15.7
			LA.- Saturn St	30.0	0.474	11.6
			LA- Vernon Ave.	39.3	0.153	15.9
02/09/71	6.6	San Fernando, USA	LA-Hollywood Stor Lot	21.2	0.174	11.2
11/24/87	6.7	Superstition Hills, USA	Brawley	18.2	0.156	13.5
			Plaster City	21.0	0.186	11.3

D-Epicentral distance; PGA-Peak ground acceleration; t_D-strong motion duration as defined by Trifunac and Brady (1975)

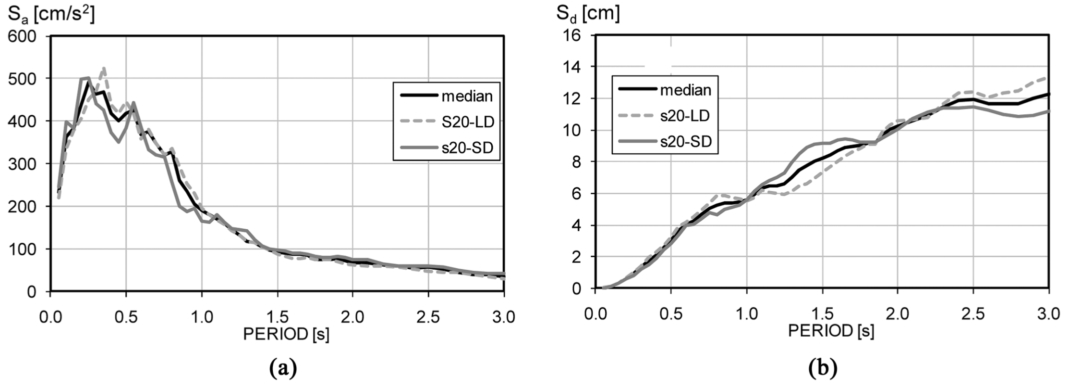


Fig. 2 Comparison of elastic spectra corresponding to the set of motions under consideration: (a) acceleration, (b) displacement

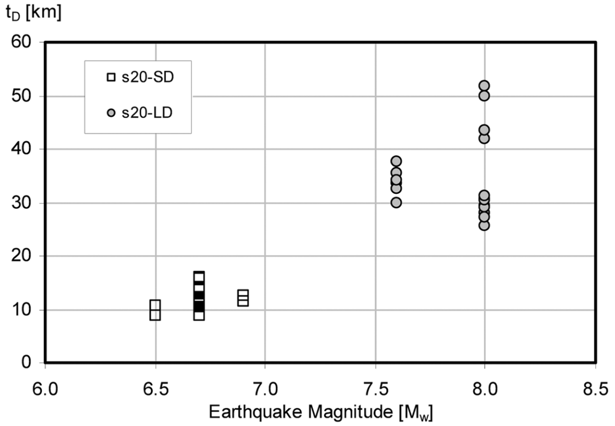


Fig. 3 Distribution of strong motion duration and earthquake magnitude for the sets s20-SD and s20-LD used in this investigation

the long-duration set. A complete list of records comprised in each set is given in Tables 1 and 2. The median elastic spectral acceleration and displacement spectra for each set are shown in Fig. 2. It can be seen that the median spectral shape of both sets is very similar, which means that the frequency content of the selected records is also similar. This is a very important issue to obtain results based only in the influence of ground motion duration without inclusion of the spectral shape effects. In addition, Fig. 3 shows the distribution of t_D and moment magnitude from all short- and long-duration records. It can be observed that t_D is closely related to earthquake magnitude, which is consistent with previous studies (e.g. Eliopoulos and Wen 1991).

3. Influence of ground motion duration on residual displacement demands of SDOF systems

3.1 Residual displacement ratios

In order to investigate residual displacement demands of SDOF systems on several structural and ground motion features, it is convenient to normalize the residual displacement demands, Δ_r, with respect to maximum elastic displacement demand, S_d, of SDOF systems having the same basic dynamic and structural properties (i.e. mass, damping ratio and fundamental period of vibration) when subjected to the same acceleration time-history, which is mathematically expressed as follows (Ruiz-García and Miranda 2006b)

$$C_r = \frac{\Delta_r}{S_d} \tag{1}$$

Statistical information of the residual displacement ratio, C_r, allows the estimation of residual displacement demands from maximum elastic displacement demands. It should be noted that a similar approach has been used by several researchers to estimate maximum inelastic displacement demands of SDOF systems from the inelastic displacement ratio, C_R, which represents the ratio of peak inelastic deformation to peak elastic deformation demand (Ruiz-García and Miranda 2003). In Eq. (1), Δ_r is computed in SDOF systems with constant yielding strength relative to the strength required to maintain the system elastic (i.e., constant relative strength). Hereafter, the relative lateral strength is measured by the lateral strength ratio R, which is defined as

$$R = \frac{mS_a}{F_y} \tag{2}$$

where m is the mass of the system, S_a is the spectral acceleration and F_y is the lateral yield strength capacity of the system. In this investigation, residual displacement ratios were computed for elastoplastic SDOF systems having a viscous damping ratio of 5%, 50 periods of vibration (from 0.5 s to 3.0 s), and experiencing 6 levels of lateral strength ratio (R = 1.5, 2, 3, 4, 5 and 6). Throughout this investigation, low levels of lateral strength ratio (e.g., $R < 3.0$) are referred to *strong* systems relative to the ground motion intensity, while large levels of lateral strength ratio (e.g. $R > 3.0$) are related to *weak* systems relative to the intensity of the ground shaking.

Previous studies developed by Ruiz-García and Miranda (2005, 2006b) using a set of 240 earthquake ground motions gathered in accelerographic stations placed on rock or stiff sites have noted that ordinates of C_r strongly depends on the period of vibration, the level of relative lateral strength, local soil site conditions (e.g. differences between rock and stiff soil sites) and the type of hysteretic behavior (e.g. the level of unloading stiffness in stiffness-degrading systems). Based on their statistical studies, the authors proposed the following simplified equation to estimate mean residual displacement ratios of elastoplastic SDOF systems

$$\hat{C}_r = \left[\frac{1}{\theta_1} + \frac{1}{41 \cdot T^{\theta_2}}\right] \cdot \alpha \tag{3}$$

$$\alpha = \theta_3 \cdot [1 - exp(-\theta_4 \cdot (R-1)^{\theta_5})] \tag{4}$$

where parameters θ_1, θ_2, θ_3, θ_4, and θ_5 are site-dependent parameters, which are reported in Ruiz-García and Miranda (2006b).

Regarding the influence of seismological parameters on residual displacement ratios, Ruiz-García and Miranda (2005) concluded that the ordinates of residual displacement ratios are not significantly influenced by the magnitude and the distance-to-the-source of the 240 earthquakes ground motions. It should be noted that the 20 short-duration earthquake ground motions represent a small sample of the set of 240 earthquakes ground motions. Therefore, it is of particular interest to investigate the effect of strong-motion duration in the ordinates of residual displacement ratios.

3.2 Results of statistical study

Central tendency and dispersion measures of residual displacement ratios were computed using the 's20-SD' and 's20-LD' ground motion sets described in the previous section. A comparison of median C_r computed from both sets and from all 40 earthquake ground motions is shown in Fig. 4 for three levels of lateral strength ratio. It can be seen that for a lateral strength ratio equal to 2, ground motion duration has slight effect on C_r. However, it seems that long-duration records could lead to larger C_r ordinates than those of short-duration records for *weaker* systems relative to the intensity of the ground motion (i.e. for higher values of R) having periods of vibration longer than about 1.0s. It should be noted that the limiting period that divides the spectral region where C_r is larger than one (i.e., residual displacement demands are larger than elastic displacement demands) might be influenced by strong ground motion duration when the system becomes *weaker*. However, it should be recognized that C_r would also slightly be influenced by local site conditions, which could be added to the effect of long strong-motion duration of the records. In order to provide information about the record-to-record variability of C_r, Fig. 5 shows the coefficient of variation of

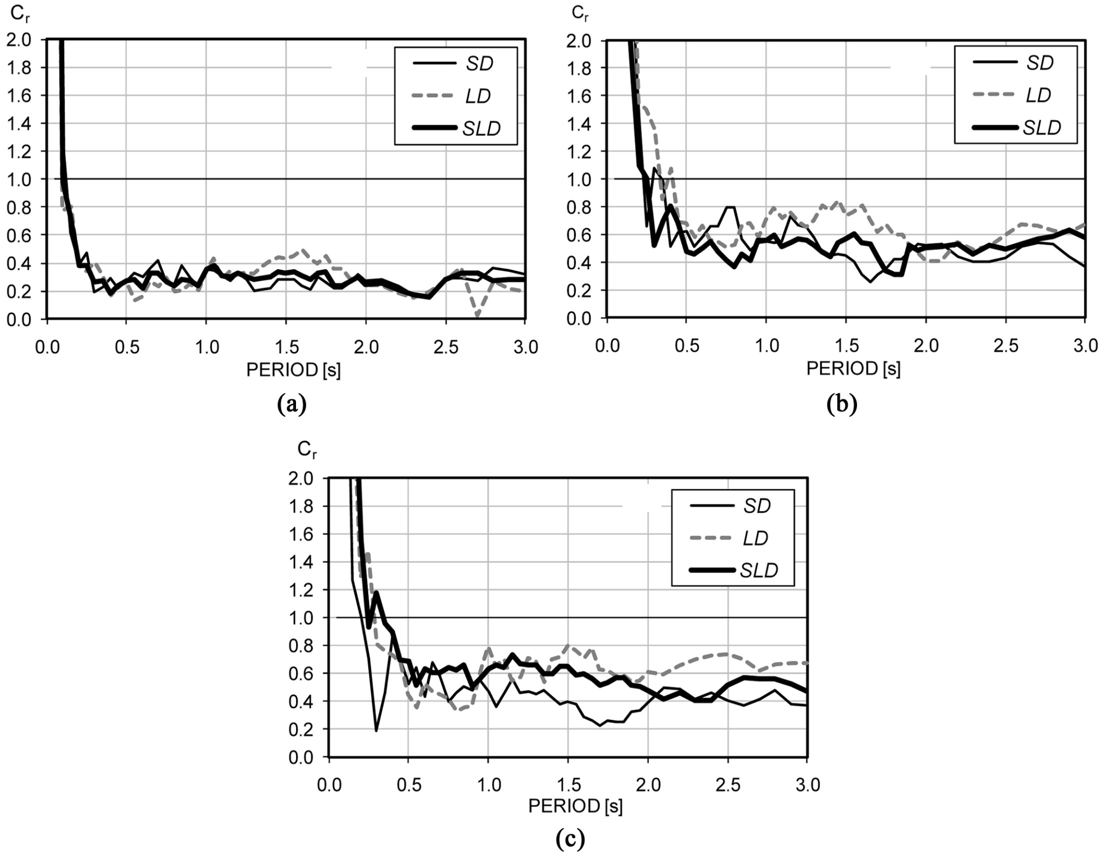
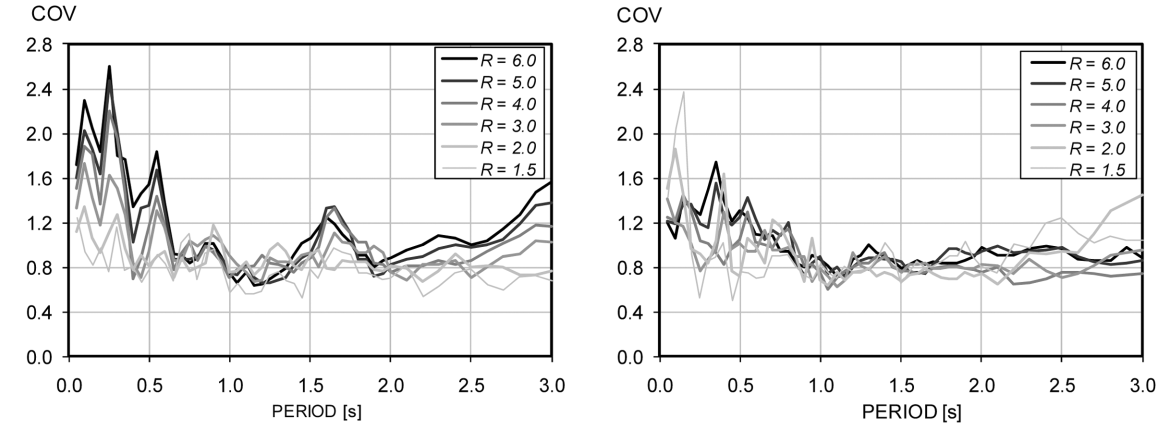
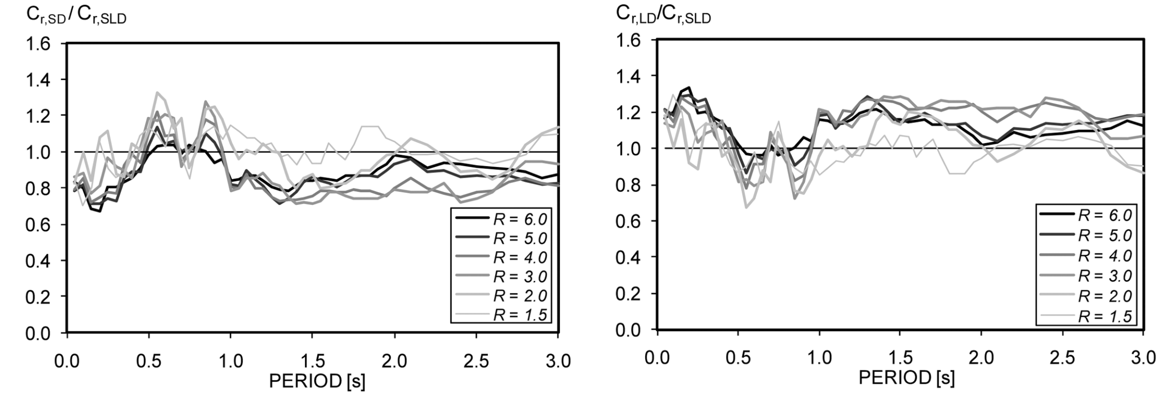


Fig. 4 Effect of strong motion duration on median residual displacement ratios for: (a) R=2, (b) R=4 and (c) R=6



(a) (b)

Fig. 5 Coefficient of variation of C_r: (a) short-duration set, (b) long-duration set



(a) (b)

Fig. 6 Mean C_r computed from each ground motion duration set normalized with respect to mean C_r from all 40 ground motions: (a) short-duration set and (b) long-duration set

C_r, which is defined as the ratio of the standard deviation to the mean, corresponding to both sets of ground motions. From the figures, it can be observed that the scatter around C_r is important, with levels of dispersion similar to those reported in Ruiz-García and Miranda (2006b). In addition, it seems that short-duration records lead to larger levels of record-to-record variability than long-duration records.

In order to quantify the effect of t_D, that is to evaluate the differences in C_r for records with different strong motion durations, ratios of mean C_r of each ground motion duration group to mean C_r computed from all 40 ground motions were computed and they are shown in Figs. 6(a) and 6(b). From the figures, it can be seen that if one neglects the effects of short t_D and uses mean C_r values, as a measure of central tendency, from all 40 ground motions instead, one would overestimate residual displacement demands for periods of vibration between about 1.0 and 2.0 s. Unlike short-duration records, the use of mean C_r from all ground motions considered here would produce, in general, underestimations of residual displacements demands for systems having $T > 1.0$ s subjected to long-duration records. It should be noted that the magnitude of underestimation or overestimation depends on the level of lateral strength ratio.

3.3 Statistical significance of strong-motion duration on C_r

To evaluate the statistical significance of strong-motion duration on C_r taking into account the large uncertainty (i.e. record-to-record variability), the hypothesis testing procedure proposed in Iervolino *et al.* (2006) was employed in this study. This procedure consists on evaluating statistically if the ratio of the medians of C_r computed from the short and long strong-motion duration ground motion sets (defined as Z > 0) is equal to one, which represents the null hypothesis (i.e. both central tendencies are the same and, thus, strong-motion duration is not significant). According to Iervolino *et al.* (2006), the null hypothesis may be accepted at a 15% significance level (i.e. strong motion duration is not statistically significant in 85% of the cases) if

$$\frac{ln(Z)}{\beta} \leq 1.5 \tag{5}$$

Where β is the is the standard error of Z, which is obtained from the standard deviation of the natural logarithms of each set. Hypothesis testing was performed for each period of vibration and each level of lateral strength considered in this investigation. For instance, a graphical representation of (5) is shown in Fig. 7 for three levels of relative lateral strength. For a given level of relative lateral strength, it can be seen that, in general, strong motion duration is not statistically significant for wide spectral regions, but any clear trend can be identified.

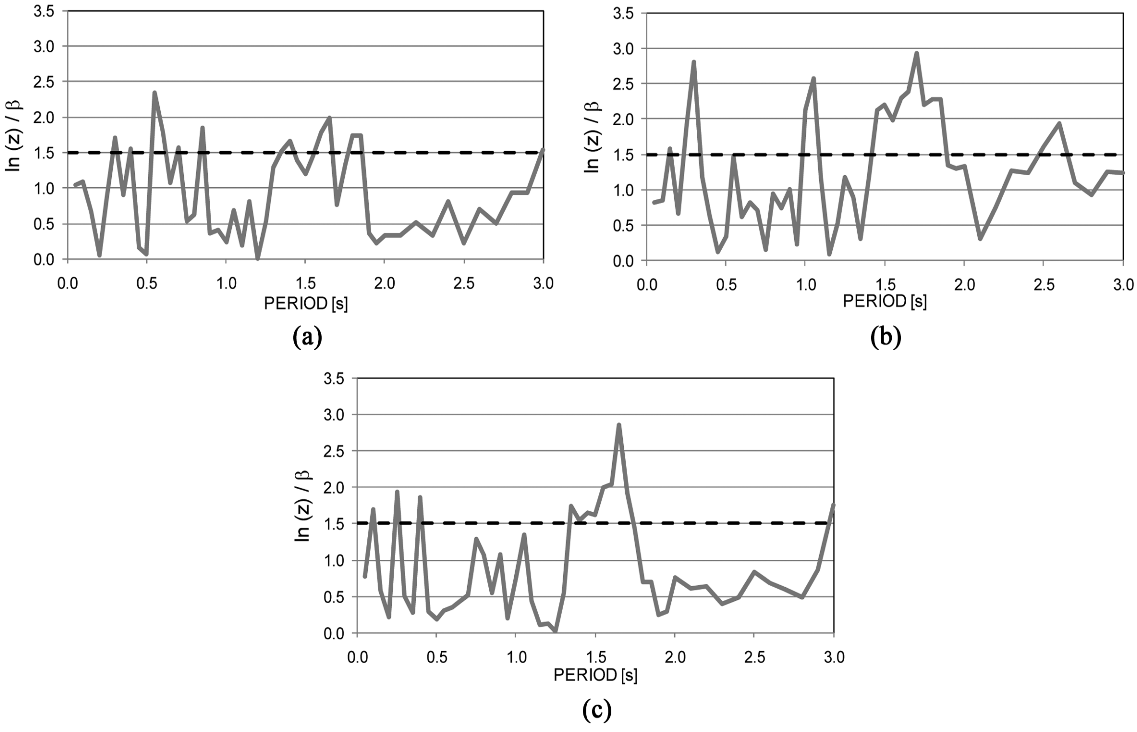


Fig. 7 Results of hypothesis testing: (a) R = 2, (b) R = 4, (c) R = 6

4. Influence of ground motion duration on residual displacement demands of MDOF systems

It should be noted that there is limited information about the influence of strong motion duration on seismic demands of MDOF systems representative of multi-story buildings. Some of the previous investigations on the effect of strong motion duration considered equivalent SDOF systems representing the dynamic properties of MDOF systems (e.g., Bernal 1992), but it is well accepted that this approach is limited to capture the global seismic response of buildings behaving in the fundamental vibration mode and, thus, higher mode effects as well as lateral stiffness and strength variation along the height, typical of existing framed multi-story buildings, are neglected using this approach. Thus, this section discusses the effect of strong-motion duration on residual drift demands of multi-degree-of-freedom systems, which are representative of existing multi-story buildings.

4.1 MDOF systems considered in this study

Primary objective of this study was to investigate the influence of strong motion duration in the amplitude and height-wise distribution of existing multi-story buildings. For the purpose, one regular one-bay generic frame building model having 3 stories and two similar frame models having 18 stories, which means a stiff and a flexible representation corresponding to the same number of stories, were considered in this investigation. The latter distinction allows studying seismic response of frame models with the same number of stories, but different fundamental periods of vibration. Therefore, all generic frames were designed according to current seismic provisions for structures located in a region of high seismicity in California (FEMA 2000). Special attention was given to providing a realistic lateral height-wise stiffness distribution, similar to that found in existing multi-story frame buildings, which controls the fundamental modal shape of each frame model. The building's fundamental period of vibration was obtained from empirical period formulas suggested by Chopra and Goel (2002), which corresponds to mean-minus and mean-plus-one-standard-deviation of periods measured in instrumented steel moment-resisting frame buildings.

The flexural yielding moment capacity in the elements was determined from story shear forces with the lateral static force distribution obtained from current seismic provisions in the United States (FEMA 2000). Inelastic deformation was restricted to plastic hinges at both ends of beam and column elements. It should be mentioned that main discussion of results is based on assuming an elastoplastic moment-curvature relationship. Each generic building was modeled as a two-dimensional centerline frame using the computer software RUAUMOKO (Carr 2008). A detailed description of the design process and modeling assumptions of the family of generic framed models is available in (Ruiz-García and Miranda 2005).

4.2 Inelastic intensity measure

Of particular interest to this investigation was the estimation of residual drift demands in the various building models under a set of ground motions at different levels of intensity. This was accomplished by using the so-called Incremental Dynamic Analysis (Vamvatsikos and Cornell 2002). An important component in this procedure is the selection of an appropriate parameter to characterize the intensity of the ground motion, which is also known as intensity measure (*IM*). Previous studies have noted that an inelastic intensity measure which consists on scaling ground motions to reach the same maximum inelastic displacement of an equivalent SDOF system having the same initial lateral stiffness (i.e. fundamental period of vibration) and yield displacement of the building of interest, Δ_y, leads to smaller record-to-record variability than other proposed *IM's* for probabilistic estimation of residual drift demands (Ruiz-García and Miranda 2010). Therefore, in this study it was decided to use a relative inelastic *IM* defined as $\eta = \Delta_i(T_1)/\Delta_y$. The yield displacement of the equivalent SDOF system can be related to the roof yield displacement of the structure, $\delta_{y,roof}$, through normalizing it by the product of the modal participation factor and the mode amplitude at the roof corresponding to the building's first-mode of vibration, $\Gamma_1\phi_1$ (i.e., $\Delta_y = \delta_{y,roof}/\Gamma_1\phi_1$). Thus, the relative inelastic *IM* used in this investigation is expressed as follows

$$\eta = \frac{\Delta_i(T_1)}{\Delta_y} = \frac{\Delta_i(T_1)}{\delta_{y,roof}/\Gamma_1\phi_1} \tag{6}$$

In this study, $\delta_{y,roof}$ for each generic building model was determined using nonlinear static (pushover) analyses using a parabolic lateral load pattern and were also performed using RUAUMOKO (Carr 2008). In addition, Table 3 contains information of T_1, $\delta_{y,roof}$ and $\Gamma_1\phi_1$ for all three generic frame models. Therefore, all acceleration time histories were scaled to produce the same maximum inelastic displacement demand of an equivalent elastoplastic SDOF system with the same fundamental period of vibration of the structure of interest and corresponding to five target relative inelastic *IM's* (η = 0.5, 1, 2, 3, 4, 6),which represents increasing levels of ground motion intensity. Each building model is expected to behave in the elastic range for relative intensities

Table 3 Fundamental period of vibration, T_1, roof yield displacement, $\delta_{y,roof}$ and normalized modal participation factor, $\Gamma_1\phi_1$ obtained for each generic frame considered in this study

N	T_1[sec]	$\delta_{y,roof}$[cm]	$\Gamma_1\phi_1$
3-R	0.50	5.1	1.23
18-R	2.00	30.5	1.37
18-F	3.33	50.8	1.37

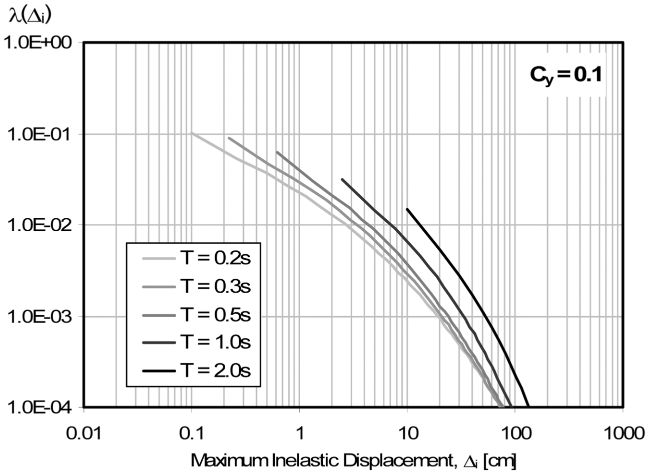


Fig. 8 Maximum inelastic displacement seismic hazard curve corresponding to $C_y = 0.1$ and five different fundamental periods of vibration (Taken from: Ruiz-Garcia and Miranda 2005)

smaller than about 0.9 and expected to experience nonlinear behavior for relative intensities larger than about 1.1. It should be mentioned that $\Delta_i(T_1)$ in Eq. (6) and, in consequence, each η corresponds to different seismic hazard levels for a specific generic frame model (i.e. having specific T_1 and $\delta_{y,roof}$, or yielding strength coefficient, C_y). To relate each $\Delta_i(T_1)$ to a seismic hazard level, a maximum inelastic displacement demand hazard curve, $\lambda(\Delta_i)$, is needed for a site-T_1-C_y-specific generic frame model. The author developed a simplified procedure to compute $\lambda(\Delta_i)$ for elastoplastic SDOF systems (Ruiz-García and Miranda 2007), which allows estimating approximately the seismic hazard level at which the records were scaled for a specific building. For instance, Fig. 8 shows $\lambda(\Delta_i)$ corresponding to C_y = 0.1 and five different fundamental periods of vibration computed from the procedure described in (Ruiz-García and Miranda 2007). Then, since the generic stiff frame having 18 stories has similar properties (i.e. T_1 = 2.0 s and $C_y \approx 0.1$), it is possible to obtain an estimate of the seismic hazard level for a given relative intensity η. For example, for η = 2 and using the values of $\delta_{y,roof}$ and $\Gamma_1\phi_1$ given in Table 1, $\Delta_i(T_1) \approx 44.4$ cm which corresponds to $\lambda(T_1) \approx 0.0011$, or approximately 1.1% probability of exceedance in 50 years (i.e. 909 year return period). In general, it should be noted that for the range of relative intensities considered in this study most buildings did not experience extremely large inelastic deformations, so no dynamic instabilities were observed.

4.3 Results of statistical study

The influence of strong motion duration on residual drift demands of MDOF systems is evaluated using the 3-story (T_1 = 0.5 s) and the 18-story stiff (T_1 = 2.0 s) generic frame models. Fig. 9 shows the profiles of median residual inter-story drift ratio, *RIDR*, along the height for increasing levels of intensity corresponding to the 18-story frame model. For comparison purposes, similar profile obtained from the response of the same frame model under a set of 40 ordinary earthquake ground motions is presented in the same figure (Ruiz-García and Miranda 2006a). Regardless of ground

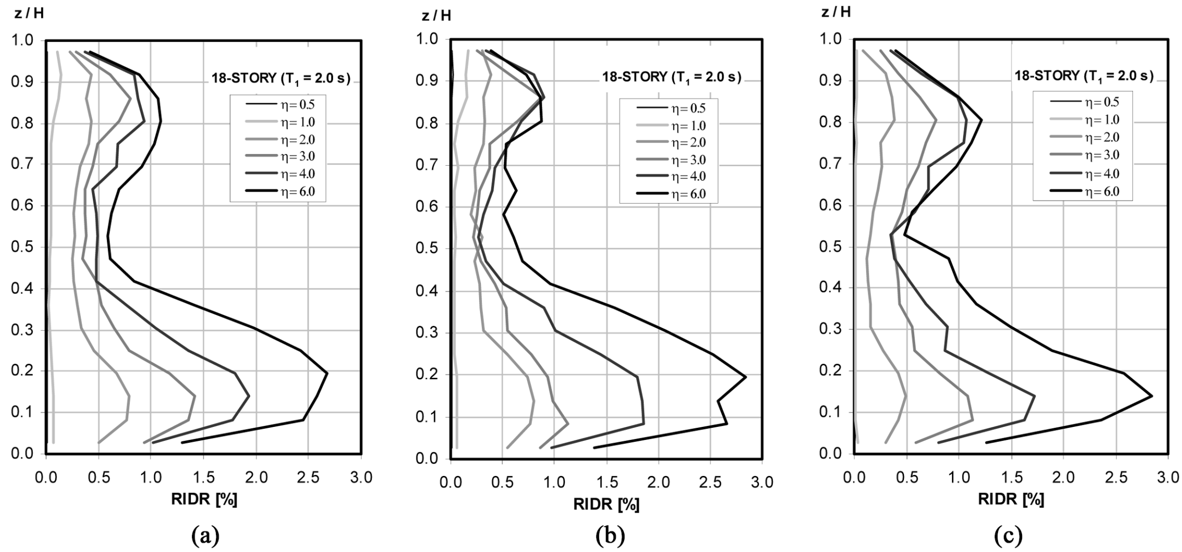


Fig. 9 Height-wise distribution of median *RIDR* for 18-R frame model obtained from three suites of ground motions: (a) s40-LMSR-N, (b) s20-SD and (c) s20-LD

motion set, it can be seen that while main concentration of median *RIDR* occurs in the lower portion, a secondary drift concentration appears in the upper portion of the frame model as the ground motion intensity increases. This effect can be attributed to the presence of higher mode effects as the building model experiences large levels of nonlinear behavior. In particular, it can be observed that long-duration ground motions lead to larger median residual drift demands in the upper stories than short-duration records.

Dispersion in the estimation of *RIDR* along the height is shown in Fig. 10. It can be seen that the dispersion does not follow a clear trend with changes in the ground motion intensity, but the amplitude is very high. This observation confirms that the estimation of residual drift demands in existing structures requires incorporating the uncertainty (i.e. record-to-record variability) through a probabilistic approach in order to obtain residual (permanent) drift demand hazard curves for performance-based assessment procedures (Ruiz-García and Miranda 2010).

To further study the influence of ground motion duration on residual drift demands, the variation of median $RIDR_{max}$ with changes in the relative ground motion intensity for the 3-story frame model (T_1 = 0.5 s) is shown in Fig. 11. For comparison purposes, the same variation obtained for maximum inter-story drift ratio, IDR_{max}, is also presented. It can be seen that, in general, strong-motion duration does not have a significant influence on the variation of median IDR_{max} and $RIDR_{max}$ for the short-period building model, which is particularly true for low levels of ground motion intensity (i.e. η < 3.0). Moreover, it seems that long-duration records lead to slightly smaller deformation demands than short-duration records for relative intensities greater than two. However, as can be seen in Fig. 12, strong motion duration has more effect on the variability of IDR_{max} and $RIDR_{max}$ as the ground motion increases.

In addition of investigating the effect of strong-ground motion duration in a short-period frame model, the variation of median lateral displacement demands for the 18-story stiff frame (T_1 = 2.0 s) is shown in Fig. 13. Again, it seems that the variation of median IDR_{max} and $RIDR_{max}$ is not significantly affected by the ground motion duration. However, as illustrated in Fig. 14, dispersion

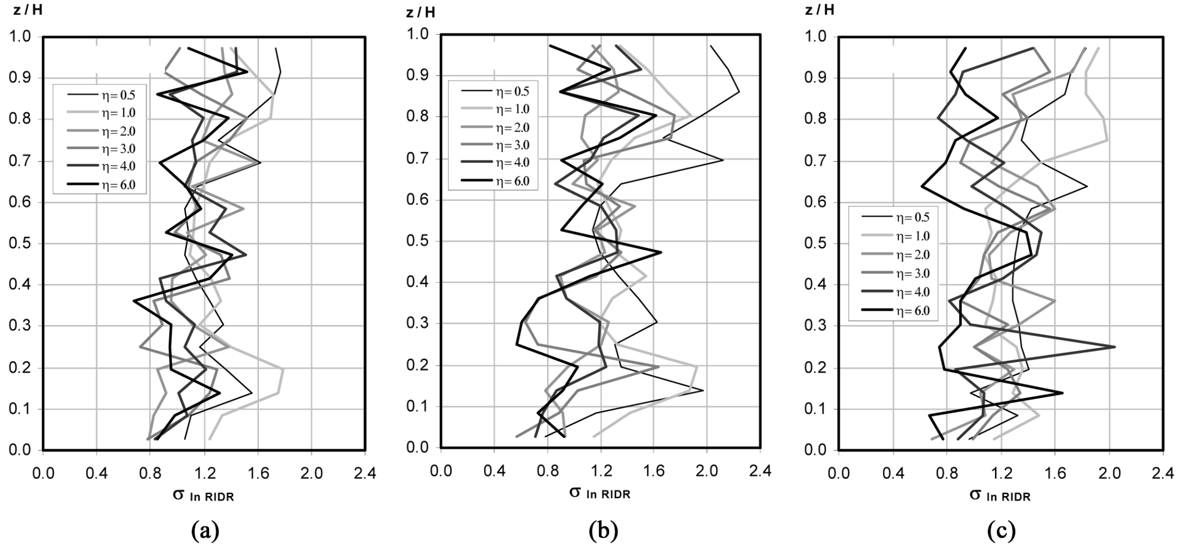
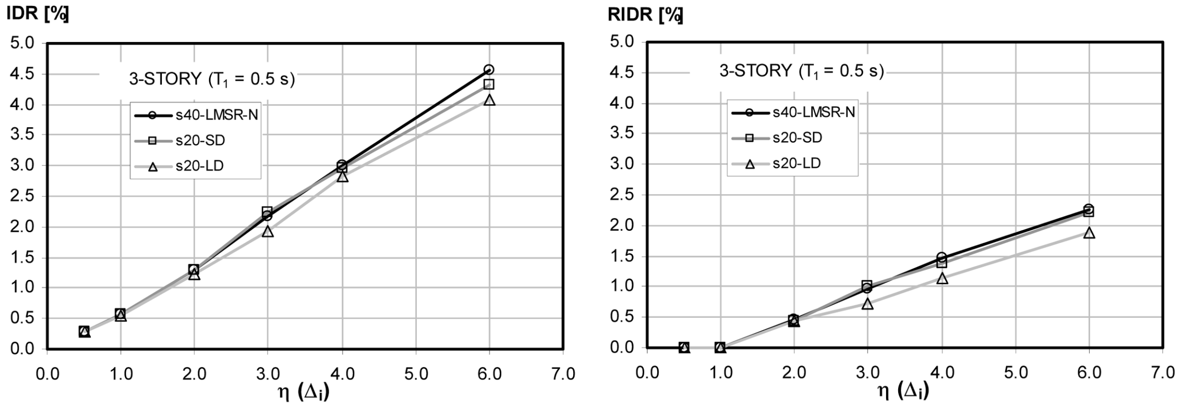
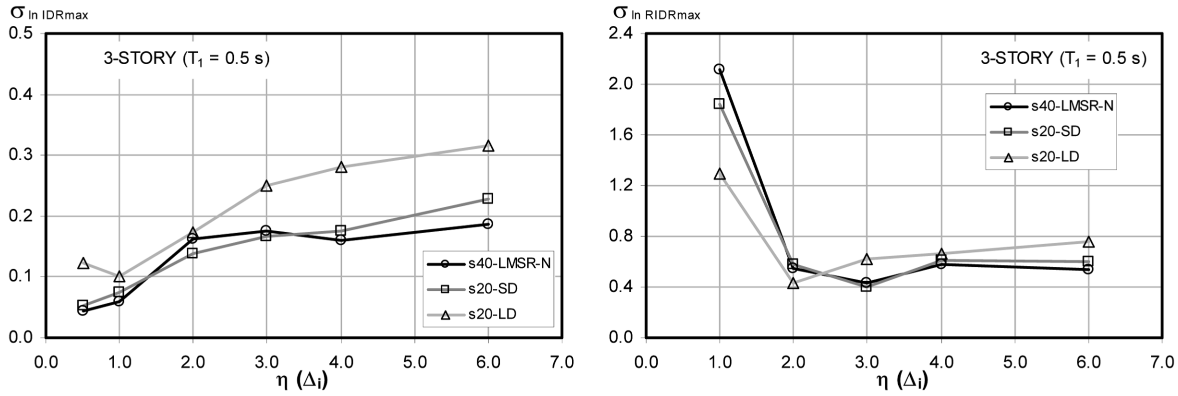


Fig. 10 Height-wise dispersion distribution of RIDR for 18-R frame model obtained from three suites of ground motions: (a) s40-LMSR-N, (b) s20-SD and (c) s20-LD



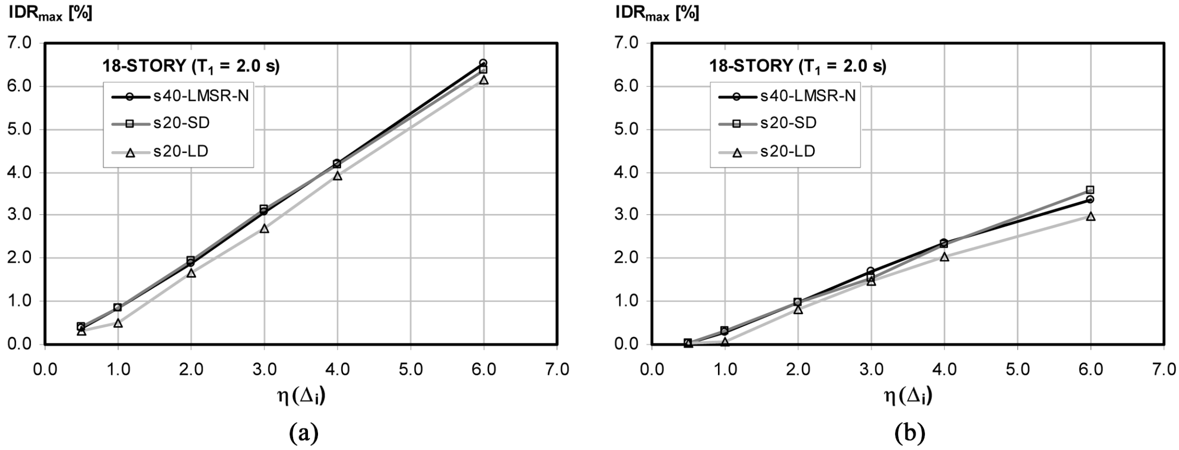
(a) (b)

Fig. 11 Effect of ground motion duration on 3-R frame model: (a) median IDR_{max} and (b) median $RIDR_{max}$



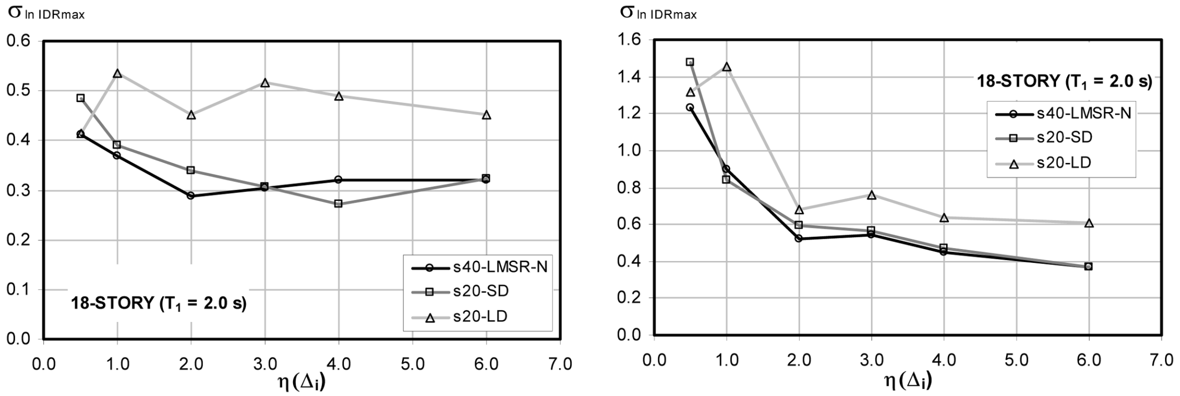
(a) (b)

Fig. 12 Effect of the ground motion duration on dispersion of 3-R frame model: (a) dispersion of IDR_{max} and (b) dispersion of $RIDR_{max}$



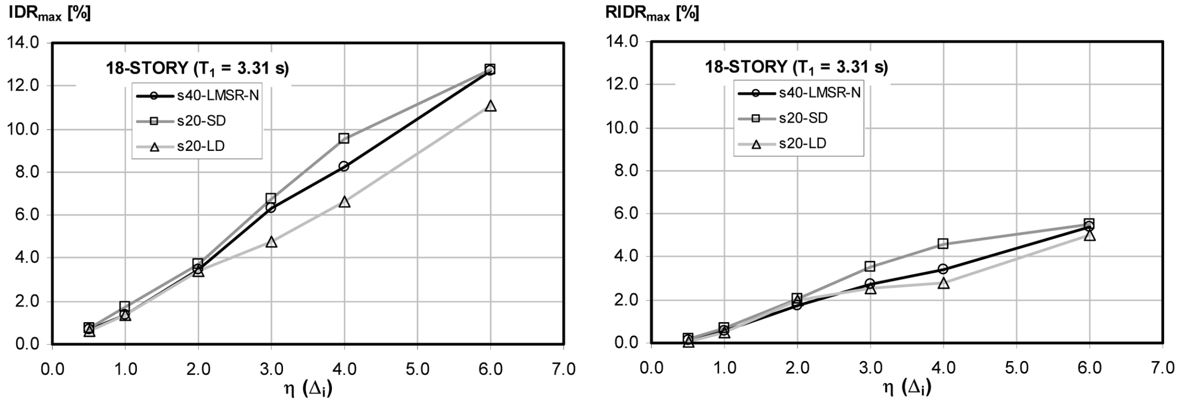
(a) (b)

Fig. 13 Effect of ground motion duration on 18-R: (a) median IDR_{max} and (b) median IDR_{max}



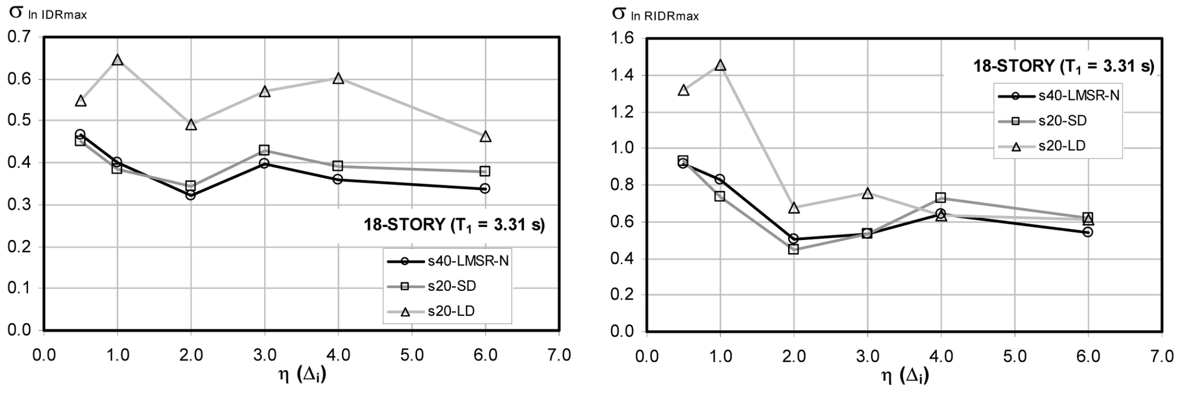
(a) (b)

Fig. 14 Effect of the ground motion duration on dispersion of 18-R frame model: (a) dispersion of IDR_{max} and (b) dispersion of $RIDR_{max}$



(a) (b)

Fig. 15 Effect of ground motion duration on 18-F frame model: (a) median IDR_{max} and (b) median $RIDR_{max}$



(a) (b)

Fig. 16 Effect of the ground motion duration on dispersion of 18-F frame model: (a) dispersion of IDR_{max} and (b) dispersion of $RIDR_{max}$

derived from the use of long-duration records is considerably higher than that of using short-duration records.

In order to investigate if building models with the same number of stories, but different period of vibration, are susceptible to strong-ground motion duration, the 18-story flexible frame model (T_1 = 3.31 s) was subjected to the same suites of ground motions and the results are shown in Fig. 15. Comparing Figs. 13 and 15, it can be seen that strong-ground motion duration has more effect on the variation of median IDR_{max} for the flexible frame model than that on its stiff counterpart. However, smaller influence of ground motion duration is appreciated in the variation of median $RIDR_{max}$. On the other hand, as was observed for the stiff long-period building model, long-duration records yields larger levels of dispersion of $RIDR_{max}$ than short-duration records for the range of ground motion intensities covered in this investigation (see Fig. 16).

Therefore, from the observations made in the this section, there is evidence to believe that strong-ground motion duration, as defined by Trifunac and Brady (1975), does not have a significant impact in the variation of median $RIDR_{max}$ of MDOF systems as the ground motion intensity increases. However, long-duration records seem to increase residual drift demands in the upper stories for flexible (i.e. long-period) structures as well as to increase levels of dispersion. This observation is very important since the frames could develop a secondary soft-story mechanism in the upper stories, which was observed in several damaged buildings located in the lake-bed zone of Mexico City when subjected to the long-duration earthquake ground motion originated from 1985 Michoacan earthquake (Villaverde 1991).

5. Conclusions

This paper summarized main results of an analytical study aimed at providing further understanding on the influence of strong-ground motion duration, measured according to the definition proposed by Trifunac and Brady (1975), on the nonlinear response of SDOF systems as well as on the amplitude and height-wise distribution of residual drift demands in frame models representative of existing moment-resisting frame buildings. The following conclusions are drawn from this investigation:

1. It was found that long-duration ground motions might lead to larger median C_r ordinates than short-duration records for systems with lateral strength ratios greater than 4 in the short- and medium-period region, which means that strong motion duration might influence the amplitude of residual deformation demands. However, taking into account the large record-to-record variability, it seems that strong motion duration may not be statistically significant for many of the periods of vibration and levels of lateral strength considered in this study.

2. Unlike previous results obtained from SDOF systems, strong-ground motion duration does not have a significant effect on median $RIDR_{max}$ for the frame models considered in this investigation.

3. Long-duration ground motions could increase the amplitude of residual drift demands in the upper stories of flexible frames as the ground motion intensity increases, which means that a secondary story mechanism could be developed in the upper stories. In addition, it seems that long-duration records lead to larger levels of record-to-record variability than short-duration records.

4. It was confirmed that the evaluation of residual drift demands involves large levels of record-to-record variability, which suggests that this variability will lead to large uncertainty in the estimation of residual drift demands during the seismic assessment of existing buildings. Therefore,

during the performance-based assessment of existing structures that include both the estimation of peak and residual (permanent) drift demands, this record-to-record variability should be taken into account through a probabilistic approach in order to obtain residual drift demand hazard curves such as that suggested in Ruiz-García and Miranda (2010).

While this study provided insight on the influence of strong-ground motion duration on residual (permanent) drift demands, it should be recognized that further studies that take into account additional MDOF effects (member structural degradation, different failure mechanism, etc.) are still needed.

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