ON THE IMPROVEMENT OF NONLINEARSTATIC PROCEDURES FOR STRUCTURES SUBJECTED TO NEAR-FAULTGROUNDMOTIONS CONSIDERINGVARIOUS FAULTING MECHANISMS

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Keywords: Pulse-Like Ground Motion , Near-Fault Earthquakes, Nonlinear Static Procedure, Displacement Coefficient Method, Lateral Load Pattern

ABSTRACT

This paper investigates inelastic seismic demands of the normal component of near-fault (NF) pulse-like ground motions, which differ considerably from those of far-fault (FF) ground motions and also parallel component of near-fault ones. The results are utilized to improve the nonlinear static procedure (NSP) called Displacement Coefficient Method (DCM). 96 NF and 20 FF ground motions and the responses of various SDOF systems constitute the dataset. A comprehensive set of Nonlinear Time-history (NTH) analyses are conducted to produce benchmark responses against the predictions of NSPs are compared. Considerable influences of different faulting mechanisms are observed on inelastic seismic demands. The demands are functions of the strength ratio and also the ratio of pulse period to structural period. Simple mathematical expressions are developed to consider the effects of NF motion and fault type on nonlinear responses. Modifications are presented for the DCM by introducing a NF modification factor, C_N. In locations, where the fault type is known, the modifications proposed in this paper help to obtain a more precise estimate of seismic demands in structures. The second objective is the verification of the probable differences in seismic demands of MDOF structures, including steel moment-resisting frames, and also inefficiencies of current lateral load patterns. The family of structural models used in this study is composed of nine and twenty-story 2-D moment resisting steel frames, considering medium to tall frame models. Two basic types of ground motions are used as the input: 10 FF and 10 NF ground motions. NTH analyses as the output, which are utilized to demonstrate the differences in seismic demands for each set, including interstory drift ratios and peak roof displacement ratios.

INTRODUCTION

Performance-based engineering methods that rely on NSPs for prediction of structural demands have been introduced in recent decades. FEMA 440 (2005) presents the results of a comprehensive study on this subject. This document reviews the related documents, namely FEMA 356 (2000) and ATC-40 (1996), and proposes improvements in calculating the inelastic displacement demand for a given ground motion. FEMA 440 includes descriptions of the two NSPs that were recommended by above-mentioned codes and used in practice. FEMA 356 utilized DCM, in which several empirically derived factors were used to modify the response of an elastic SDOF model of the structure to account for inelastic effects. The alternative Capacity Spectrum Method (CSM) of ATC-40 used empirically derived relationships for the effective period and damping as a function of ductility to estimate the response of an equivalent linear SDOF oscillator in an iterative procedure. Recommendations of FEMA 440 have been implemented in some recent codes of practice such as ASCE41-06 (2007). Approximate NSPs are commonly used in engineering practice as an advanced analysis technique to estimate seismic demands. Although seismic demands are best estimated using NTH analyses, NSPs are frequently used in engineering applications to avoid the intrinsic complexity and additional computational effort required by the former. Although many beneficial improvements have been presented for DCM and CSM in FEMA 440, but a review of the data used for this purpose shows that improvements consider FF ground motions mainly, and less data have been produced for NF earthquakes.

NF ground motions differ from FF ground motions in that they often contain strong coherent dynamic long period pulses and/or permanent ground displacements. Out of the two kinds of NF ground motions, i.e. pulse-like and non-pulse-like ones, ground motions with velocity pulses caused by NF directivity effects have received a great deal of attention because of their potential to cause severe damage to structures. Inelastic to elastic seismic spectral displacement ratio for FN pulse-like records may virtually depart from the equal displacement rule, and can be higher than that of FF ground motions (Iervolino et. al. 2012) and is the focus of this paper. NF ground motion with directivity or fling effects is significantly influenced by the rupture mechanism and is substantially different from FF records. This class of ground motion has large amplitude and long period, exhibits unusual response spectra shapes, possesses high PGV/PGA and PGD/PGA ratios and is best characterized in the velocity and the displacement time-histories. Such ground motion is also characterized by its energy being contained in a single or very few pulses, thus capable of causing severe damage to structures. Many studies in recent years have investigated the dynamic response of structures to these pulse-like ground motions (Iervolino et. al. 2012, Iwan et al. 2000, Baker 2007). In order to identify pulse-like NF ground motions not by a mere judgment, a systematic procedure was proposed by Baker (2007). This approach uses wavelet analysis to extract the largest velocity pulse from a given ground motion, which mostly occurs in the FN component of records.

It is well-known that in addition to other factors such as earthquake magnitude, epicentral distance and soil type, the ground motions in a location are also a function of fault mechanism. Seismologists use the angle of the fault with respect to the surface (known as the dip) and the direction of slip along the fault to classify faults. They categorize faults into three main groups based on the sense of slip: a fault where the relative movement (or slip) on the fault plane is approximately vertical is known as a *dip-slip* fault (DS) where the slip is approximately horizontal, the fault is known as a *strike-slip* (SS) fault and finally an *oblique-slip* (OS) or *combined* fault has non-zero components of both strike and dip slip. For all mentioned distinctions, it is the orientation of the net dip and sense of slip of the fault which must be considered; not the present-day orientation, which may have been altered by local or regional folding or tilting.

NSPs for MDOF structures are based on monotonically increasing predefined load patterns until some target displacement is achieved. However, it is now well-known that these simplified procedures based on invariant load patterns are inadequate to predict inelastic seismic demands in buildings when higher modes contribute to the response and inelastic effects alter the height-wise distribution of inertia forces (e.g., Gupta and Kunnath 2000; Kalkan and Kunnath 2004; Goel and Chopra 2004). In order to overcome some of these shortcomings, a number of enhanced procedures considering different loading vectors (derived from mode shapes) were proposed. These procedures try to account for higher mode effects and use elastic modal combination rules while still utilizing invariant load vectors. The Modal Pushover Analysis (MPA) of Chopra and Goel (2002), Modified Modal Pushover Analysis (MMPA) of Chopra et al. (2004), and Upper-bound Pushover Analysis (UBPA) procedure of Jan *et al*. (2004) are examples of this approach. A new Adaptive Modal Combination (AMC) procedure, whereby a set of adaptive mode-shape based inertia force patterns is applied to the structure, has been recently developed by Kalkan and Kunnath (2007). This methodology is an attempt to synthesize concepts from three well-known nonlinear static methods. With the increase in the number of alternative pushover procedures proposed in recent years, it is useful to identify the potential limitations of these methods and compare their effectiveness in simulating seismic demands at the structure, story and component level.

Based on above, this paper tries to suggest improvements for nonlinear static analysis procedures to accounts for the effects of NF pulse-like ground motions. The fault type influence on the inelastic response of structures is also studied. Improvements are presented for the current DCM for SDOF and the differences of seismic demands in MDOF systems subjected to various ground motions are investigated.

A REVIEW OF DISPLACEMENT COEFFICIENT METHOD

In the DCM, as presented in FEMA 356, the target displacement, which corresponds to the displacement at roof level of a building, can be estimated using Eq.(1). The coefficients of this equation are defined in detail in FEMA 356.

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \qquad (1)$$

FEMA 440 recommends that the limitations (capping) imposed by FEMA 356 on the coefficient C_1 be abandoned. In addition, a distinction was recognized between two different types of strength degradation that have different effects on system response and performance, which led to recommendations for the coefficient C_2 to account for cyclic degradation in strength and stiffness. It was also suggested that the coefficient C_3 be eliminated and replaced with a limitation on strength. Although there have been some advantageous improvements for these coefficients in FEMA 440, no specific improvement was presented for the NF effects. For a SDOF system, the inelastic to elastic displacement ratio, as presented in Eq.(2), is expressed as the maximum inelastic displacement demand divided by the maximum elastic displacement demand, for a system with the same properties, including the same stiffness and mass, subjected to the same earthquake ground motion. This coefficient is used as C_1 coefficient in FEMA, to relate expected maximum inelastic displacements to displacements calculated for linear elastic system.

$$C_R = \frac{\delta_{inelastic}}{\delta_{elastic}} \qquad (2)$$

MacRae and Tagawa (2001) recommended an *R*-*μ*-*T* relation for NF motions that change with directivity. Ruiz-Garcìa and Miranda (2006) investigated the inelastic displacement demands for structures built on soft soils and presented an analytical expression for the ratio of inelastic to elastic displacements for soft soils. They also developed inelastic displacement ratios (IDRs) for structures on firm sites (Miranda 2000). Baez and Miranda (2000) also studied amplification factors to estimate inelastic displacement demands for the design of structures in the near-field. Miranda (2000) also studied inelastic displacement ratios for displacement-based earthquake resistant design, and derived a simplified expression from nonlinear regression analyses in order to estimate mean IDRs of sites with average shear wave velocities higher than 180 m/sec. Later, Ruiz-Garcìa and Miranda (2012) supplemented the above-mentioned studies by evaluation of seismic displacement demands from ground motions recorded in recent earthquakes. Enderami*et al.* (2014) proposed a new energy-based approach for predicting seismic demands of steel structures at the near-fault sites by introducing the concept of dissipated hysteretic input energy during largest yield excursion. Many studies investigated the functional form for prediction of NF pulse-like inelastic displacement ratio and derived analytical-form relationship for the inelastic displacement ratio (Iervolino*et. al.*2012, Baltzopoulos *et. al.*2013, Ruiz-Garcia 2011, Wen *et. al.* 2014). Many other researchers also focused on this issue from different aspects (Akkar et al. 2004, Chioccarelli and Iervolino 2010, Ruiz-Garcìa 2011, Zhai et al. 2013), but they did not consider the fault type influence on inelastic displacement ratios in their studies.

CONSIDERED GROUND MOTIONS

In this paper, wavelet analysis method, presented by Baker (2007, 2008) is used for selecting pulse-like NF ground motions. Based on this, a set of 96 records (most of them identified earlier by Baker *et. al.* 2007) from the NGA (Next Generation Attenuation project) database (http://peer.berkeley.edu/nga/) has been collected. Moment magnitude of records ranges from 5.0 to 7.6 and the vast majority of them are associated with C and D NEHRP site classification. On the other hand, for the purpose of verification and comparison, a set of 20 non-pulse-like (ordinary) records, all from type C soil condition, are also selected from the NGA database. Datasets, in terms of number of records from each faulting mechanisms are summarized in Table 1.

Table 1. Pulse-like and ordinary datasets

Mechanism	Records	Pulse-like records	ordinary records
Strike-slip	40	34	6
Dip-slip (Reverse & Normal)	33	25	8
Oblique-slip (Combined)	47	37	6
Total	116	96	20

Forward directivity results when the fault rupture propagates toward the site at a velocity nearly equal to the propagation velocity of the shear waves and it eventually produces velocity pulses. But it should be noted that not all identified pulses are from directivity effects. The period of detected velocity pulse (T_p), a parameter of interest in NF ground motions, is easily determined by velocity response spectra and more precisely by wavelet algorithm. Table 2 shows the distribution of pulse-like records in differentT_p bins. The distribution of velocity pulses for each faulting mechanisms demonstrates that OS faults cover wider range of T_p, in comparison to SS and DS faults, which have narrower scattering range in T_p, respectively.

Table 2. Distribution of pulse-like records in T_p bins

T_p	[0, 1s]	[1, 2s]	[2, 3s]	[3, 4s]	[4, 5s]	[5, 6s]	[6, 12s]
Number of records	9	17	8	11	11	8	32

INELASTIC DISPLACEMENT RATIO (IDR)

In this paper NDAs has been carried out for a variety of SDOF systems, when subjected to sets of NF pulse-like records and ordinary ground motions. The SDOF systems were designed to cover practical range of periods of vibration and different levels of nonlinearity. Periods of vibration ranged from T=0.1 s to T=3 *s*. These periods were selected by an increment of 0.1*s* from T=0 to T=1, an increment of 0.2s from T=1 to T=2, and an increment of 0.5s from T=2 to T=3. Nonlinearity level is measured by means of strength ratio R. In this research, R=2,3,4,5 and 6 were considered. It should be noted that all of the considered ground motions in this study are used in their unscaled form, because the yield strength of the SDOF systems were adjusted in the way that the desired strength ratio, R, be attained. Elastically Perfectly Plastic (EPP) hysteretic model was considered here in this study. After carrying out NTH analysis for the linear and nonlinear systems, the inelastic to elastic displacement ratio, C_R, were determined. Therefore, a total of 9,806 IDRs were computed with the open source finite element platform, OpenSees (2005) corresponding to 116 ground motions, 17 periods of vibration, and 5 levels of strength ratio. Mean IDRs were then computed for each period and each strength ratio, the results of which will be presented hereafter. Several studies have revealed that pulse-like motions in FN direction are generally stronger than both FP components and non-pulse-like ground motions; yet, not enough is known about the probable influence of fault type on nonlinear response of structures. Results of NDAs in this study are illustrated in Fig. 1, which shows mean IDRs of SDOF systems versus the periods of vibration for different strength ratios, corresponding to all FF and NF ground motions, regardless of their faulting mechanism.

The differences of IDRs for the two types of ground motion are obvious from Fig.1. The equal displacement rule is applicable for periods of vibration more than 1.3*s* in FF records and for periods more than about 3*s* in NF records. From Fig. 1(a), it can be seen that mean IDRs are characterized by being larger than 1 in the short-period spectral region, but they reach about 1 for periods longer than about 3.0 *s*. For periods smaller than 2.0 *s*, IDRs are strongly dependent on the period of vibration and on the level of nonlinearity. In general, in this spectral region maximum inelastic displacements become much larger than maximum elastic displacements as the strength ratio increases and as the period decreases. It is noteworthy that there are obvious bumps, representing a peak in C_R for period of about 0.6 *s* for all R values. Besides, the C_R coefficient for NF ground motions is observed to be at least 50 percent higher compared to that of FF ground motions in the considered period range. Also, these differences become more pronounced by increasing the nonlinearity level and decreasing the period. Therefore, the inefficiency of utilizing C_R of FF records for NF ones is obvious and some modifications are needed in order to use this coefficient for NF ground motions. It means that the C_1 coefficient of FEMA 440 is not capable of predicting the nonlinear response of structures subjected to NF earthquakes correctly.

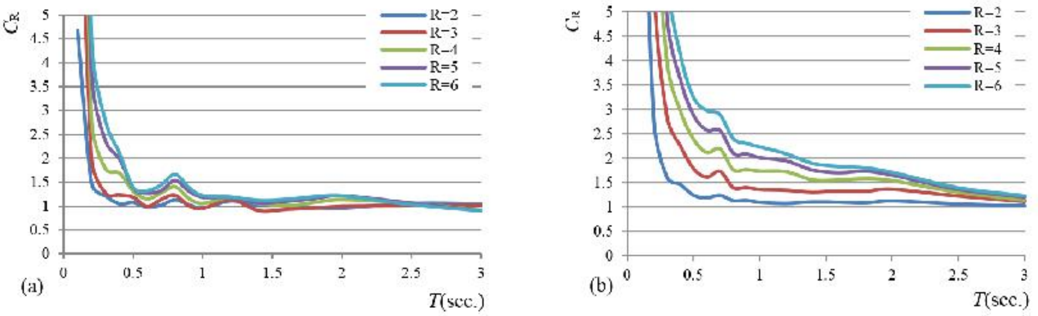

Figure 1. Mean IDRs for different R values vs. period for: (a) All FF Ground Motions, (b) All NF Ground Motions

Ma and Archuleta (2006) studied the mechanism dependence of radiated seismic energy from three hypothetical crustal events by modeling spontaneous ruptures and concluded that the reverse fault has the largest apparent stress compared to that of the strike-slip fault and normal fault. It means that T_p is somehow representative of fault's radiated seismic energy and the larger the value of T_p, the higher C_R values would be. Therefore, in order to reduce the scatters in results of Fig.1 and also for better comparison, periods of vibration were normalized with respect to the pulse period. These results are represented in Fig. 2, demonstrating that the faulting mechanism directly affects the value of the pulse period. This method is vastly used in similar studies in the literature and also in FEMA 440.

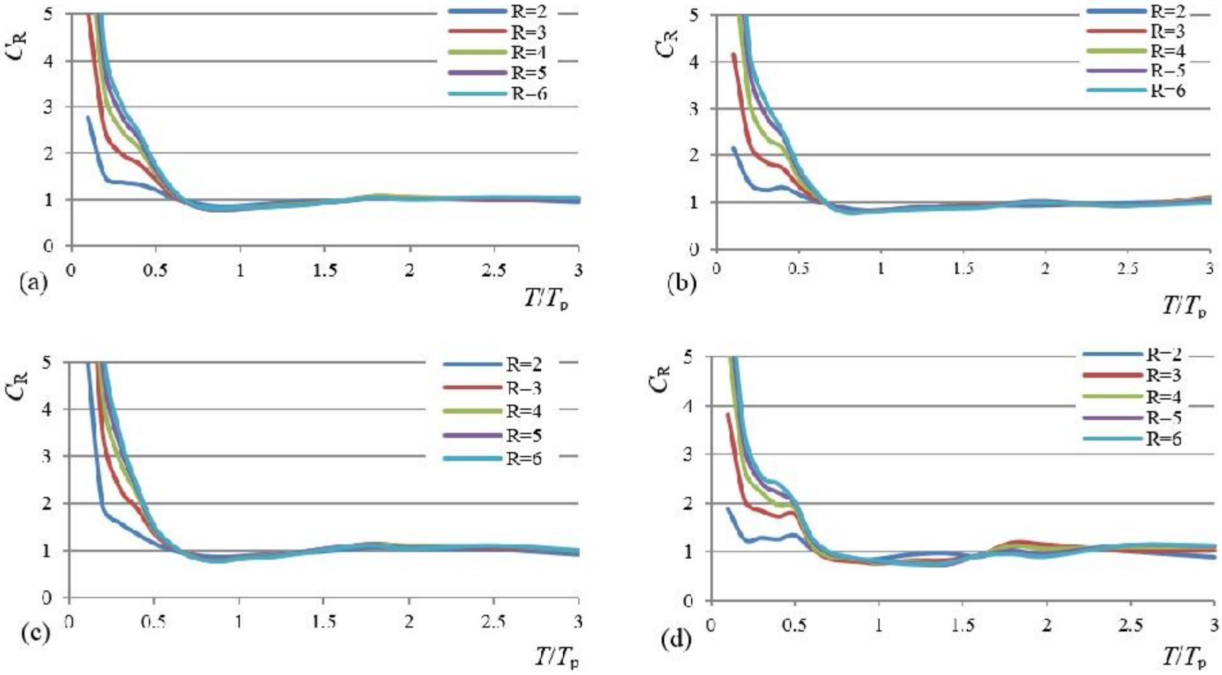

Figure2. Mean IDRs for different R values vs. normalized period for: (a) All NF Ground Motions, (b) SS fault type NF Ground Motions, (c) DS fault type, (d) OS fault type

In Figs. 2(b)-(c)-(d), considerable differences are obvious for various faulting mechanisms which demonstrate the fact that fault type can have considerable influences on nonlinear response of structures. From this figure, OS fault seems to create larger demands compared to SS and DS faults.

REGRESSION ANALYSIS

As the inelastic to elastic displacement ratio, C_R, for pulse-like NF ground motions are not compatible with those of FF ones, the C_1 coefficient presented in FEMA 440 may not be capable of covering pulse-like NF ground motions. Therefore, for application to NF ground motions, a modification should be carried out on C_1, which is done here in the form of a modification factor, C_N. By multiplying this factor by C_1, results would take into account the NF effects. In order to achieve this goal, the C_1 coefficients of FEMA 440 were calculated for each inelastic SDOF system and they were compared with NDA. The modification factor, C_N, is then defined as follows:

$$C_N == \left[\frac{(C_R)_{ex}}{(C_1)_{app}}\right]_{T,R} = \begin{cases} -_1\cdot\left(\frac{T}{T_p}\right)^4 + -_2\cdot\left(\frac{T}{T_p}\right)^3 + -_3\cdot\left(\frac{T}{T_p}\right)^2 + -_4\left(\frac{T}{T_p}\right) + -_5 & \frac{T}{T_p} \le 0.6 \\ -_6\cdot\left(\frac{T}{T_p}\right)^5 + -_7\cdot\left(\frac{T}{T_p}\right)^4 + -_8\left(\frac{T}{T_p}\right)^3 + -_9\left(\frac{T}{T_p}\right)^2 + -_{10}\left(\frac{T}{T_p}\right) + -_{11} & 0.6 < \frac{T}{T_p} \le 2.0 \\ 1 & \frac{T}{T_p} > 2.0 \end{cases} \quad (3)$$

aving created such data for all levels of nonlinearity, it was tried to derive a parametric equation describing C_N using nonlinear regression analysis in order to determine the coefficients of Eq. (6). In this equation, the influences of faulting mechanism may also be considered. The polynomial functions of order 4 and 5 have been able to estimate the C_N coefficient for T/T_p<0.6 and 0.6< T/T_p<2.0, respectively. The goal is now to find constant factorsθ_i (for i=1,2,3, 4, 5, 6, 7, 8, 9, 10, 11) that best fit the data. If all the NF data are considered, these constants are found as presented in Table 3. The results demonstrate good correspondence between actual modification factor and the estimated ones. Once appropriate values for θ_i for different levels of R were found, it was tired to derive a relationship between θ_i and R in terms of polynomial functions. Similar expressions were also derived considering various faulting mechanisms.

Table 3. Coefficient estimates for Eq. (6) for all NF records

	R=2	R=3	R=4	R=5	R=6
θ_1	56.906	31.056	56.038	65.453	61.594
θ_2	-94.409	- 50.151	- 74.323	- 84.355	- 76.594
θ_3	52.397	23.072	25.042	26.468	20.604
θ_4	-11.439	- 3.7251	1.1121	0.0929	1.9105
θ_5	2.0175	1.7586	1.4801	1.3118	1.0482
θ_6	-0.6166	-2.0747	-3.0002	-2.9062	-3.011
θ_7	4.5088	14.017	20.252	19.666	20.26
θ_8	- 13.159	- 37.378	- 53.608	- 52.28	- 53.562
θ_9	19.09	49.282	69.609	68.293	69.622
θ_{10}	- 13.515	- 31.88	- 44.089	- 43.582	- 44.274
θ_{11}	4.5492	8.8348	11.624	11.581	11.726

SEISMIC DEMANDS FOR MDOF SYSTEMS

Most of the researches on the lateral load influence in pushover analyses methods, utilize both NF and FF earthquake records and compare the NTH analysis results by different pushover load patterns, but they do not directly compare results of NF and FF ground motions to demonstrate any probable differences for each data sets in seismic demands of structures. In this section, two SAC model buildings, including 9-story and 20 story buildings are selected from FEMA 355-c report (2000). These buildings were designed following the local code requirements in Los Angeles city. Descriptions of the buildings (member sections, design basis, plan dimensions and story heights, etc.) are described in FEMA 355-c in detail.

In the 9-story building, one of the exterior bays has only one moment-resisting connection to avoid bi-axial bending in the corner column. In the 20-story buildings, all the exterior connections are moment-resisting connections, and box columns are used at the corners to resist bi-axial bending. The design yield strength of the beams and girders is 36 *ksi* and that of the columns is 50 *ksi*. In order to consider ground motions with diverse characteristics, 10 ordinary FF records and 10 NF ground motions having forward directivity effects were used. Therefore, a total of twenty records were compiled for the NTH analyses.

In order to facilitate a rational basis for comparison of the different ground motions, the previously mentioned ground motions were scaled by two different methods: (a) a peak roof drift ratio of 2 percent was achieved for each of the two steel buildings (b) the average response spectrum of each ensemble scaled by the requirements of Iranian code for seismic resistant design of buildings (2005) for soil type II was utilized. The differences of each data set are evaluated by comparing the maximum story displacement profiles and interstory drift ratio (relative drift between two consecutive stories normalized by story height). These demands are presented in Figs. 3 and 4 along the height of the buildings, respectively. Comparing the NTH responses for the different ground motions indicates that NF and FF records generally produce different demands. The total displacements of the structures are higher in case of NF records, as demonstrated previously for SDOF systems. Also, larger interstory drift ratios are induced by NF records compared to FF ones.

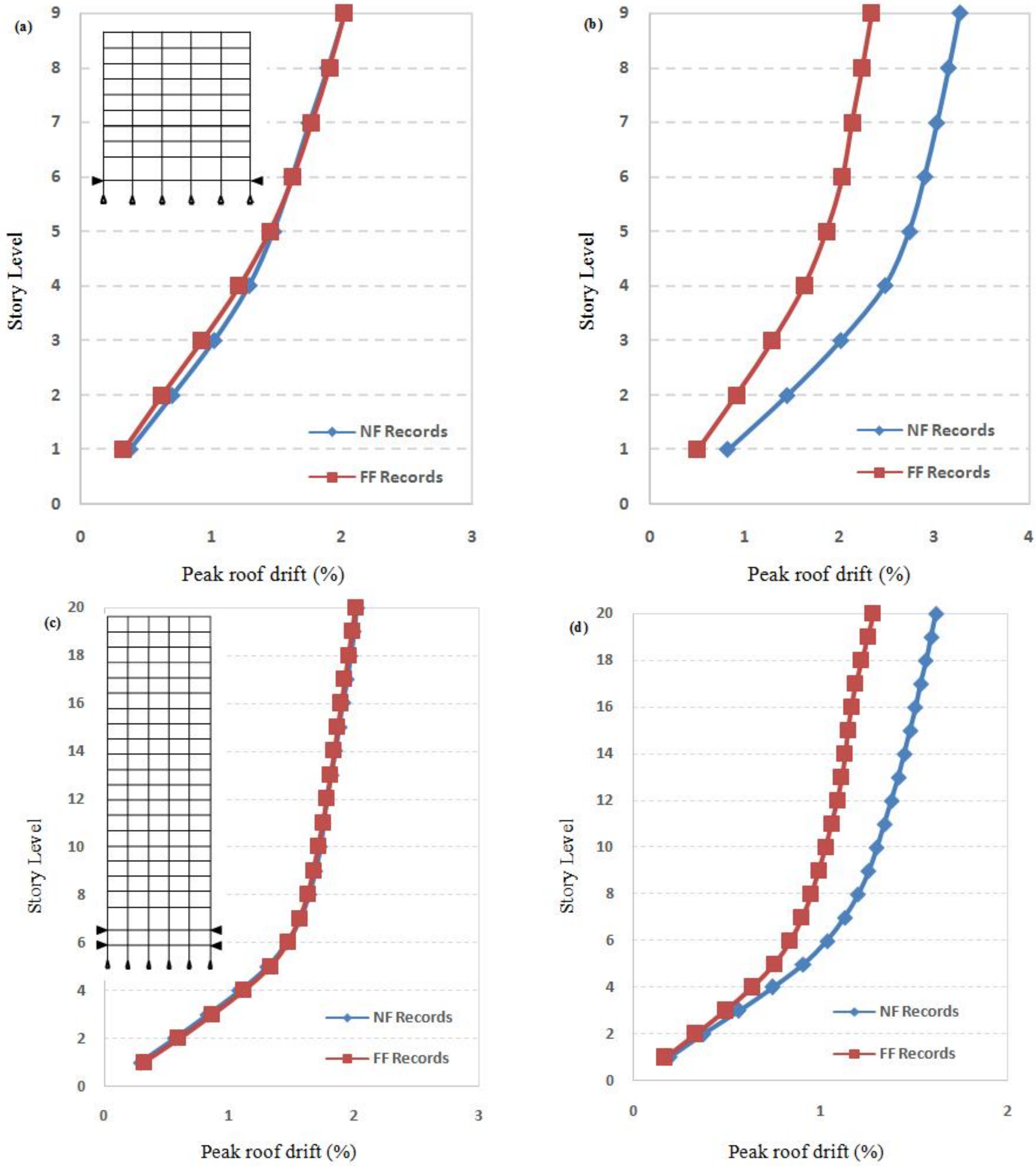

Figure 3. Estimated peak displacement ratio profiles by NTH analyses for: (a) 9-story building scaled by method a; (b) 9-story building scaled by method b;(c) 20-story building scaled by method a; (d) 20-story building scaled by method b

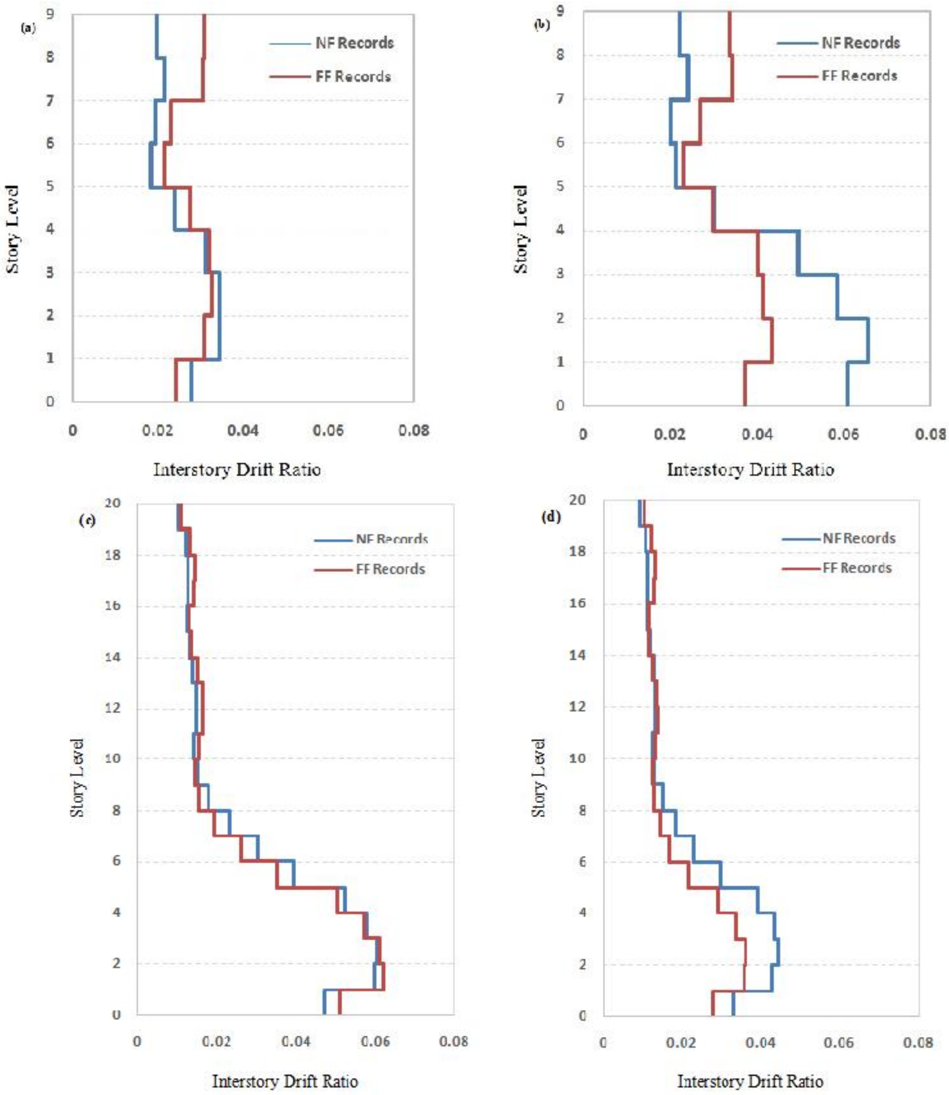

Figure 4. Estimated peak interstory drift profiles by NTH analyses for: (a) 9-story building scaled by method a; (b) 9-story building scaled by method b;(c) 20-story building scaled by method a; (d) 20-story building scaled by method b

SUMMARY AND CONCLUDING REMARKS

The following conclusions can be drawn from the results of this study.

- The effects of NF earthquake ground motions on the response of structures are higher than FF earthquakes, in the whole region of periods.Limiting periods at which mean IDRs become equal to 1 depend on the level of inelastic deformation. Although these limiting periods increase with increasing strength ratios, equal displacement rule is applicable for periods longer than 3 *s* for NF strong motions.
- Various faulting mechanisms produce different values for the pulse period.
- The equal displacement rule is applicable for T/T_p ratios larger than about 0.6 for all strength ratios, regardless of their faulting mechanism. For smaller values of T/T_p, the equal displacement rule is not applicable as displacements ratios vary by R. For OS faults, this limiting ratio of T/T_p is about 0.65.
- Considerable differences in nonlinear seismic demand are obvious for various faulting mechanisms which demonstrate the fact that this parameter can have considerable influences on nonlinear response of structures. The results demonstrate that OS fault typecan cause larger demands compared to SS and DS fault types.
- The coefficient C_1 used in DCM of FEMA 440 underestimates the NF ground motion responses in T/T_p<0.6 range and it overestimates the results in 0.6<T/T_p<2.0 range. Therefore, a NF modification factor, C_N, is presented in this paper. Polynomial functions of order 4 and 5 have been found to be able to estimate this modification coefficient for T/T_p<0.6 and 0.6<T/T_p<2.0, respectively. These

equations do not change the format of IDR in FEMA 440 and only modifies the C_1coefficient by multiplying a modification factor in order to consider NF effects. Also they allow the effects of various faulting mechanism to be taken into account

- Comparing the results of NF and FF ground motions, demonstrates that the total displacement of the MDOF structures are higher in case of NF records, similar to that of SDOF systems. NF records also introduce larger inter-story drift ratios.

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