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Assessment of Higher Modes Effects on Steel Moment Resisting Structures under Near-Fault Earthquakes with Forward Directivity Effect Along Strike-Parallel and Strike-Normal Components

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Abstract
Near field earthquakes with forward directivity effects have pulse in the velocity record, thus this phenomenon causes significant demands on the steel frames more than the ordinary earthquakes. Therefore, structural behavior of steel frames and the higher modes effects of structures under near fault earthquakes are essential. For this purpose 5 intermediate (ductility) steel moment resisting frames with 4, 7, 10, 15 and 20 stories under 20 far and near fault, 40 strike-parallel (SP) and strike-normal (SN) records have been investigated. Finally, the elastic responses of equivalent single degree of freedom structure (ESDOF) under mentioned records and response modification factors to convert the response of ESDOF structure to the response of MDOF structure have been presented. The results of this research show that higher modes effects under the far fault earthquakes are greater than the near fault earthquakes. Also, the inter-story drift angle of structures under near fault earthquakes with forward directivity effect is greater than far fault earthquakes for about 30–50% of structure height in upper stories. The high-rise structures demands under the SP earthquakes, because of higher modes effects, are greater than the SN earthquakes. When the ratio of the building period to the pulse period, is greater than 0.5, the effects of SP earthquakes increase more than the fault normal (SN) earthquakes.

Keywords Higher mode effect · Near fault · Forward directivity · Strike normal · Strike parallel

1 Introduction

In recent years, there are some research on the nonlinear responses of steel moment resisting frames under the near fault earthquakes. A significant amount of energy is applied to the structures under near fault earthquakes promptly. Therefore, nonlinear distribution of demands are different with the far fault earthquakes. Previous damages of near fault earthquakes showed that there are significant inter-story drift demands which decrease the safety and stability of structures.

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Structural damages due to the 1994 Northridge earthquake indicate that the present steel buildings might be highly vulnerable to pulse-like nature of ground motions. Moreover, the forward directivity effects observed during Kocaeli, Rivers, and Chi-Chi (Taiwan) earthquakes emphasized the effect of near fault earthquakes too. So, assessment of the present building's response under the near fault earthquake is an important and basic issue. The first important issue is definition of the important inherent characteristic of the near fault earthquakes, based on the last scientific findings.

Hall et al. (1995) showed that the displacement caused under the near fault earthquake pulse, applied significant structural seismic demands. Anderson and Bodin (1987), assessing the steel moment resisting frame under the near fault record, showed that the response of structure is very sensitive to the duration of acceleration pulse which is proportional to the fundamental period. Westergaard (1933) while studying the behavior of high-rise buildings under near fault earthquakes, utilizing the wave propagation theory, showed that the roof displacement of building is

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amplified due to wave deformation or reflection. He also showed that if the pulse duration be close to the fundamental period of the structure, the collision between the forward and backward waves at the middle stories, would impose significant demands on the structure. Investigations show that the difference in the distribution of maximum ductility demand of stories at the structure height depends on the characteristics of near field earthquakes and vibrational characteristics of the structure, (Sehhati et al. 2011; Soleimani Amiri et al. 2013; Özhendekci and Özhendekci 2012; Gerami and Abdollahzadeh 2015). So that in some cases the lower part of the structures and in other cases the upper parts of the structures would be critical. Some studies show that the distribution of structural deformations depends on the ratio of building period to pulse period (Sehhati et al. 2011; Alavi and Krawinkler 2001). Previous studies have demonstrated that the directivity of a fault fracture causes different effects in near field ground motions compared with far-fault earthquakes (Alavi and Krawinkler 2001, 2004; Gioncu 2000; Stewart et al. 2002; Bolt 2004; Bray and Rodriguez-Marek 2004). The forward directivity in the near fault usually has the highest effects on structures in comparison with the backward directivity (Alavi and Krawinkler 2001, 2004).

Other observations show that the main response of structures due to near fault earthquake with fling step effects (permanent displacement at strike-parallel direction of a strike-slip fault) was obtained at the first mode and wave-like vibrations without the fling effect cause main response of structure was obtained at higher modes of the structures (Kalkan and Kunnath 2006). Records with forward directivity resulted in more instances of higher-mode demand while records with fling-step displacement almost always caused the systems to respond primarily in the fundamental mode (Kalkan and Kunnath 2006). Investigating the forward directivity effect at the height of steel moment resisting frames showed that 70–90% of forward directivity affect at the bottom of structure in one-third or half of the height (Gerami and Abdollahzadeh 2015). In addition, investigating steel moment resisting frames under near fault earthquakes with pulse velocities greater than 0.70 s showed that the effects of forward directivity increased the global and local demands about 1.1–2.6 and 1.2–3.5 times, respectively (Gerami and Abdollahzadeh 2013).

Studies on Bam earthquake, Iran (2003), with more than 40,000 victims (Konagai 2004), showed that forward directivity effect of strike-normal direction (east–west) had more effects on buildings compared with the strike-parallel direction (Sanada 2004). Studying Bam City depicted that 77% of deflections and destructions in buildings were normal to the fault line (Mostafaei and Kabeyasawa 2004). Also, the nonlinear time history analysis of some buildings in Bam shows that maximum relative displacement in ground floor of moment-resisting frames occurred in strike-normal direction (Hossein and Kabeyasawa 2004). Other observations have indicated that there were more damages to poles and houses in strike-parallel direction to the fault line of Bam (Konagai 2004).

There are many practice codes adopting procedures for estimating displacement demands of building structures, which uses equivalent SDOF systems (FEMA273 1997, FEMA 356 2000, ATC40 1996, FEMA440 2004). The methodologies are resulted from of several studies on investigating the differences between the MDOFs responses and the equivalent SDOFs. After the Northridge earthquake (1994), several studies were conducted to prepare better understanding of the nonlinearity effects on structures and making a simple method to introduce these effects of the analysis and design procedures (Nassar and Krawinkler 1991; Bonowitz 1995; Miranda and Bertero 1994). Veletsos and Vann (1971) studied the relation between the responses of SDOFs and MDOFs for the first time. Seneviratna and Krawinkler (1997) showed that except for the structures with very short periods, the maximum inter-story ductility of MDOFs frame is more than the first mode of equivalent SDOFs. Humar and Rahgozar study showed that for high ductility levels, the displacement ductility demand in most stories of MDOFs might have a significant increase in comparison with ductility of the equivalent SDOFs system. They also concluded that the lowest story in most structures is critical story. However, the higher stories can show higher ductility levels due to interference of higher modes (Humar and Rahgozar 1996). Based on the previous studies, the higher modes effects of structures under near fault earthquakes and near strike-parallel (SP) and strike-normal (SN) earthquakes has not been studied yet. Also, response modification factors for ESDOF structures in estimating the seismic demands of MDOF structures under the near fault records have been less investigated. So the main purpose of this study is the assessment of higher modes effects under near fault earthquakes and presenting response modification factors (RMFs) for the response of equivalent SDOF structures to the MDOF structures under the near fault earthquakes. In Fig. 1 the flowchart of this research has been presented.

In this research, higher modes effects in steel moment resisting frames under far and near fault earthquakes (with forward directivity effect), near strike-parallel (SP), and strike-normal (SN) earthquakes would be investigated. For this purpose 5 intermediate steel moment resisting frames with 5 spans and 4, 7, 10, 15 and 20 stories under 20 far and near fault, 40 near strike-parallel (SP), and strike-normal (SN) records would be analyzed. The linear and nonlinear seismic demands discussed in this research include: stories displacement, inter-stories drift angle, stories shear and base shear. Also in this study, the response modification factors to convert elastic response of ESDOF structure (roof displacement) to the linear and nonlinear response of

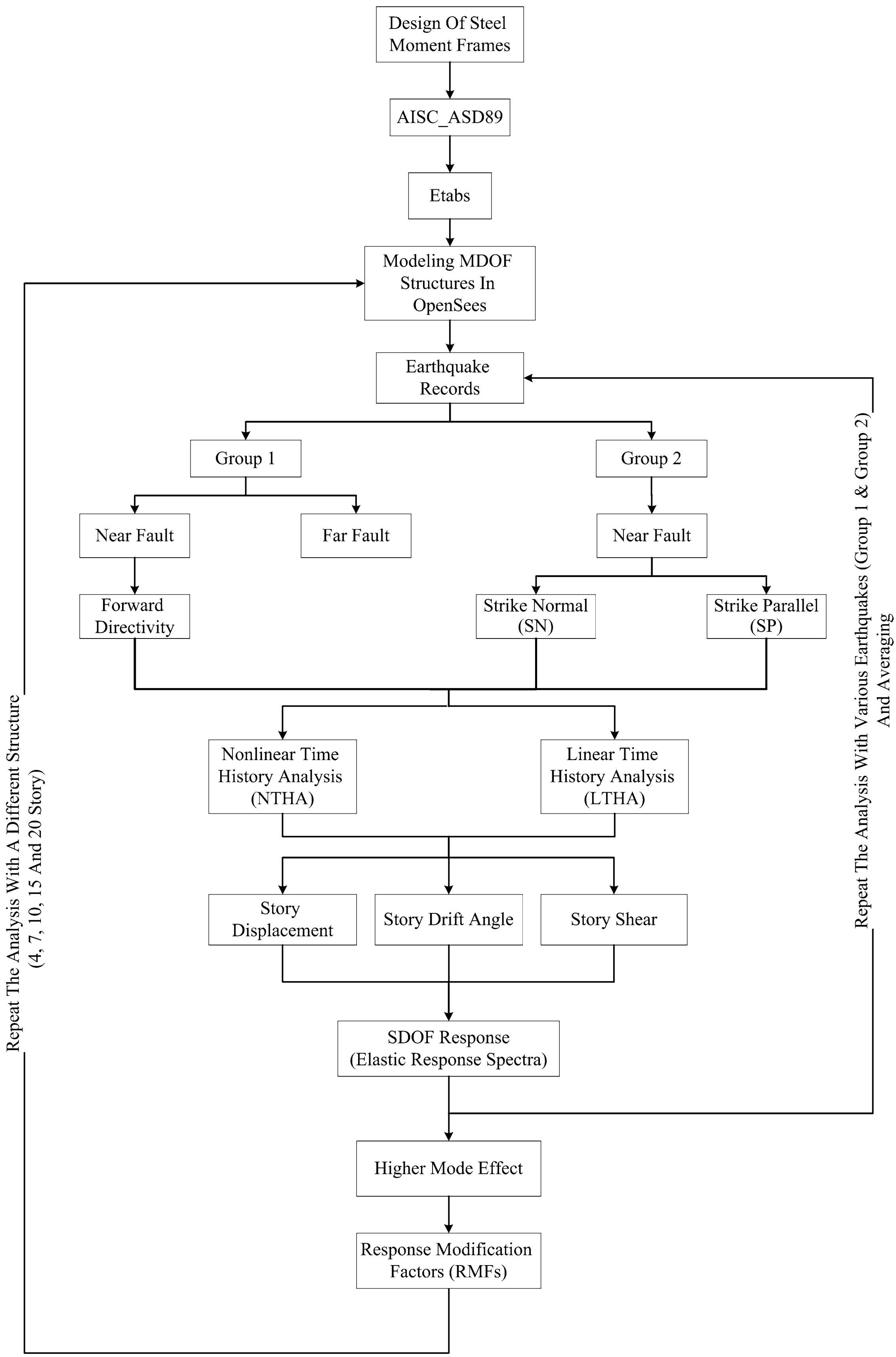


Fig. 1 General flowchart of this study

MDOF structure under various records would be presented as graphs. These graphs could be used for the preliminary estimation of seismic demands of structures under near fault earthquakes, and examining the higher modes effects. These response-modification-factors (RMFs) could be used for rapid assessment of nonlinear structural demands could be evaluated by means of elastic displacement spectrum of ESDOF structures. In addition, target displacement needed for nonlinear static analysis method under near fault earthquakes can be calculated with RMFs, which have been less considered in the previous studies.

In a simple classification the most important features of this study and differences between this research and the previous researches, could be summarized as follows:

- Comparison of the seismic demands of steel moment resisting frames under the far and near fault earthquakes with forward directivity effect.
- Investigating the seismic demands of steel moment resisting frames under near strike-parallel (SP) and strike-normal (SN) earthquakes.
- Assessment of higher modes effects under near strike-parallel (SP) and strike-normal (SN) earthquakes.
- Investigating higher modes effects with increasing the period of structure under near fault earthquakes.
- Presenting RMFs to convert the elastic response of ESDOF structures to the linear and nonlinear responses of MDOF structures under far and near fault earthquakes.
- Presenting RMFs to convert the elastic response of MDOF structures to the nonlinear response of MDOF structures under near fault earthquakes.
- Estimating the target displacement of MDOF structures used in the nonlinear static analysis under near fault earthquakes.

2 Structural Models and Verification

Verification of analytical models is one of the most important steps of a study. In numerical studies and especially when a considerable data base should be prepared for the experimental formulations, uncertainty about model verification can lead to inaccurate results. To avoid this issue, in this paper, all models have been verified based on the 9-story model shown in Fig. 2 (Gupta and Krawinkler 1999). After modeling the M1 model in the OpenSEES framework, the comparison of capacity curve in Gupta study and the 2D model created by the authors of this paper in OpenSEES framework are shown in the Fig. 3. This comparison shows the acceptable accuracy in the modeling of structures in this research.

In order to investigate the higher modes effects, there are 4, 7, 10, 15 and 20 story models with the story height of 4 m and 5 spans with 5 m length. The frames are intermediate (ductility) moment resisting frames. The frames in this research are designed completely based on the ANSI/AISC 341-05 and ASCE/SEI7-05 codes for gravity and seismic loads (ASCE 2006; ANSI/AISC 2005). The dead and live loads are $3520\frac{\text{kgf}}{\text{m}}$ and $1250\frac{\text{kgf}}{\text{m}}$, respectively. Both the equivalent static lateral force and the modal response spectrum analysis were used for the models. ST37-type steel is used in structural design with the yield stress of $2400\frac{\text{kg}}{\text{cm}^2}$ and the ultimate stress of $3600\frac{\text{kg}}{\text{cm}^2}$ and the Poisson's ratio is 0.30. The lateral drift values in all frames are compared with the allowed value in the ASCE/SEI7-05 code. The maximum drift has been considered 2.5% and 2% for the 4-story model and other frames, respectively. The sections used in the frames include box sections and plate girder. In Table 1, the sections used in various structures are presented. All elements have been chosen as compact sections (limiting local buckling) assuming enough lateral bracing. All structures studied in this research, have been modeled in OpenSEES framework by using fiber section, UniaxialMaterial Steel02 and nonlinearBeamColumn elements.

3 Seismic Records

In this study, two groups of accelerograms have been selected to be used in the nonlinear time history analysis. The first group includes 10 far-fault accelerograms and 10 near-fault accelerograms with forward directivity effect, according to Table 2. The near fault earthquakes have Forward directivity effects, low effective duration and also high velocity pulse period and have been chosen from the stations located less than 15 km from the fault. The second group has been included of 20 near fault accelerograms containing pulse-like ground motions and at strike-parallel (SP) and strike-normal (SN) directions, according to Table 3. The second group of accelerograms are derived from the Baker et al. (2007). All chosen accelerograms in this research have the moment magnitude greater than 6.5 and the soil of Class D based on the Fema356 classification guidelines and have been taken from PEER website. The elastic response spectrum of accelerograms has been made by Seismosignal software and all accelerograms have been normalized to their peak ground acceleration (PGA) before being scaled. All accelerograms in this research are scaled according to the method presented in the Iranian Seismic Code (Standard 2800). All nonlinear time history analysis (NTHA) have been performed by OpenSEES framework (Mazzoni et al. 2006).

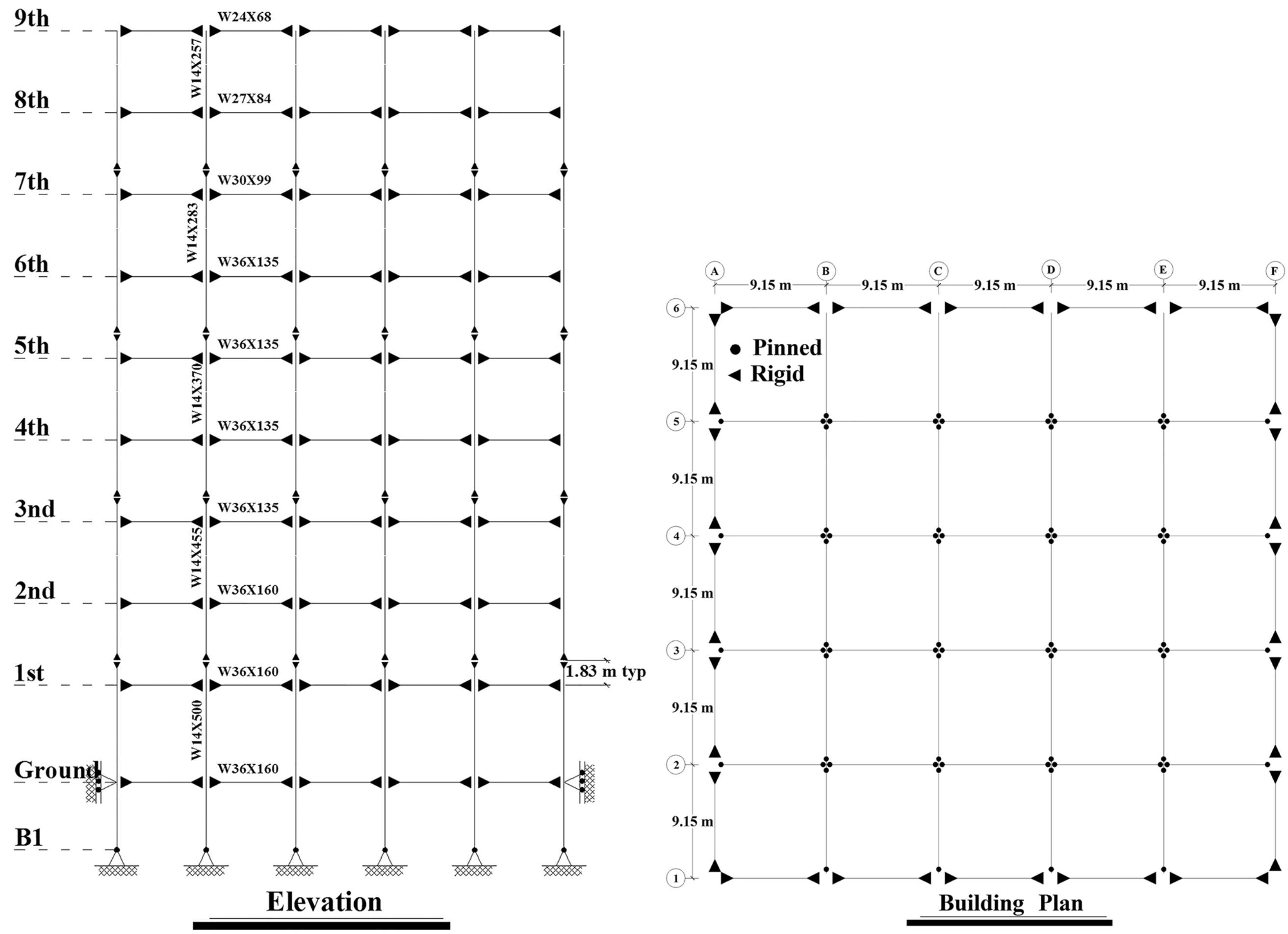


Fig. 2 Nine-story building. (Adapted from Gupta and Krawinkler 1999)

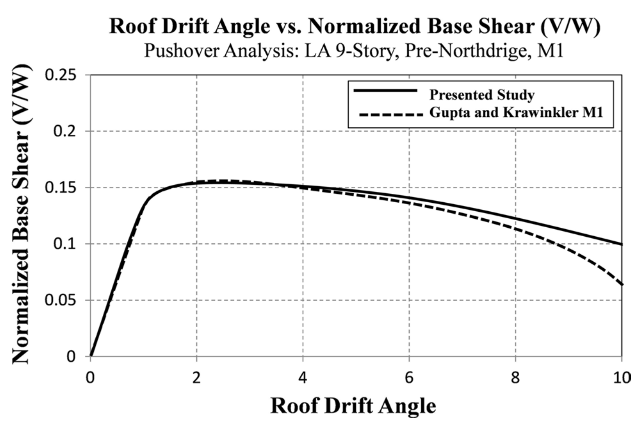


Fig. 3 Verification of models of presented study with SAC9 steel moment-resisting frame (Gupta and Krawinkler 1999; Siahpolo and Gerami 2014)

4 Assessment of Higher Modes Effects Under Near Fault Earthquakes with Forward Directivity Effect

In order to investigate higher modes effects under far fault and near fault earthquakes, two groups of accelerograms were selected. The first group including 20 far fault and near fault accelerograms with Forward directivity effect (Table 2) and the second group including 40 near fault accelerograms along the strike-parallel (SP) and strike-normal (SN) directions (Table 3). In this research, five intermediate moment resisting frames, with 4, 7, 10, 15 and 20 stories and 5 spans were designed. All nonlinear time history analyzes under the considered records are performed using OpenSEES framework. Finally, the results obtained by averaging the various record responses that will be presented at the following paragraphs.

In Figs. 4 and 5, the results of far fault and near fault earthquakes from the first group of accelerograms are presented for various structures. The results show, the story displacement of near fault records is greater than far fault

Table 1 Structural member sizes for *ISMRFs* archetypes

Storey	4-Storey *ISMRFs*		7-Storey *ISMRFs*		10-Storey *ISMRFs*		15-Storey *ISMRFs*		20-Storey *ISMRFs*	
	Columns	Beams	Columns	Beams	Columns	Beams	Columns	Beams	Columns	Beams
1	Box 40 × 10	PG 40 × 15	Box 40 × 15	PG 40 × 20	Box 40 × 20	PG 50 × 20	Box 50 × 20	PG 50 × 20	Box 50 × 25	PG 60 × 20
2	Box 40 × 10	PG 40 × 15	Box 40 × 15	PG 40 × 20	Box 40 × 20	PG 50 × 20	Box 50 × 20	PG 50 × 20	Box 50 × 25	PG 60 × 20
3	Box 30 × 10	PG 40 × 10	Box 40 × 15	PG 40 × 20	Box 40 × 20	PG 40 × 20	Box 50 × 20	PG 50 × 20	Box 50 × 25	PG 60 × 20
4	Box 30 × 10	PG 40 × 10	Box 40 × 10	PG 40 × 15	Box 40 × 15	PG 40 × 20	Box 50 × 20	PG 50 × 20	Box 50 × 25	PG 60 × 20
5			Box 30 × 10	PG 40 × 15	Box 40 × 15	PG 40 × 15	Box 50 × 20	PG 50 × 20	Box 50 × 25	PG 60 × 20
6			Box 30 × 10	PG 40 × 10	Box 40 × 15	PG 40 × 15	Box 40 × 20	PG 50 × 20	Box 50 × 25	PG 60 × 20
7			Box 30 × 10	PG 40 × 10	Box 40 × 10	PG 40 × 15	Box 40 × 20	PG 50 × 20	Box 50 × 20	PG 60 × 20
8					Box 40 × 10	PG 40 × 15	Box 40 × 20	PG 40 × 20	Box 50 × 20	PG 60 × 20
9					Box 35 × 10	PG 40 × 10	Box 40 × 20	PG 40 × 20	Box 50 × 20	PG 60 × 20
10					Box 35 × 10	PG 40 × 10	Box 40 × 15	PG 40 × 20	Box 50 × 20	PG 60 × 20
11							Box 40 × 15	PG 40 × 20	Box 40 × 20	PG 50 × 20
12							Box 40 × 15	PG 40 × 20	Box 40 × 20	PG 50 × 20
13							Box 40 × 15	PG 40 × 20	Box 40 × 20	PG 50 × 20
14							Box 40 × 10	PG 40 × 10	Box 40 × 20	PG 50 × 20
15							Box 40 × 10	PG 40 × 10	Box 40 × 15	PG 50 × 20
16									Box 40 × 15	PG 50 × 20
17									Box 40 × 15	PG 40 × 20
18									Box 40 × 10	PG 40 × 20
19									Box 40 × 10	PG 40 × 20
20									Box 40 × 10	PG 40 × 20

For the columns, the first number is the outside dimension in cm and the second one is the thickness in mm

For the beams, the first number is the Web depth in cm, and the second one is the Flange width in cm. For all beams the Flange and Web thickness is assumed as 10 mm

Table 2 The first group: used accelerograms for far and near fault earthquakes with forward directivity effect

Number	Earthquake name	Date (yy-mm-dd)	Station	R (km)	PGA (g)	PGV/PGA (s)	CAV (m/s)	Tp (s)	Tm (s)
1	Chi-Chi, Taiwan	99-09-20	CHY065	83.43	0.1	0.14	9.88	0.56	0.79
2	Chi-Chi, Taiwan	99-09-20	TAP095	109.01	0.15	0.18	56.56	0.98	0.84
3	Loma Prieta	89-10-18	CDMG58224	72.2	0.24	0.15	27.69	0.32	0.86
4	Loma Prieta	89-10-18	CDMG58472	74.26	0.26	0.16	28.35	0.64	0.85
5	Kobe, Japan	95-01-16	HIK	95.72	0.14	0.11	45.02	0.6	0.76
6	Loma Prieta	89-10-18	CDMG58223	58.65	0.23	0.11	33.26	0.3	0.53
7	Manjil, Iran	90-06-20	Qazvin	49.97	0.13	0.09	59.48	0.16	0.46
8	Northridge	94-01-17	CDMG13122	82.32	0.1	0.07	31.22	0.38	0.44
9	Tabas, Iran	78-09-16	Ferdows	91.14	0.1	0.08	48.38	0.24	0.29
10	Kocaeli, Turkey	99-08-17	Bursa Tofas	60.43	0.1	0.21	100.9	0.68	0.93
11	Denali, Alaska	02-11-03	Pump st. 10	2.74	0.32	0.43	47.83	0.94	1.52
12	Bam, Iran	03-12-26	Bam	R < 15	0.59	0.43	118.26	0.78	0.91
13	Chi-Chi, Taiwan	99-09-20	CHY101	9.96	0.44	0.27	48.15	0.9	0.98
14	Chi-Chi, Taiwan	99-09-20	TCU068	0.32	0.56	0.32	30.52	0.42	1.51
15	Imperial Valley	79-10-15	CDMG	1.35	0.43	0.26	23.33	0.24	1.31
16	Northridge	94-01-17	DWP 75	5.19	0.49	0.15	25.50	0.22	0.72
17	Silakhor, Iran	06-03-31	Chalan Cho.	R < 15	0.45	0.33	93.81	1.52	1.82
18	Kocaeli, Turkey	99-08-17	Yarimca	4.83	0.26	0.25	39.12	0.52	1.29
19	Zanjiran, Iran	94-06-20	Meymand	R < 15	0.42	0.28	123.41	1.36	1.73
20	Kobe, Japan	95-01-16	Takatori	1.47	0.61	0.21	42.52	1.22	1.10

Table 3 The second group: used accelerograms for near fault earthquakes with forward directivity effect (pulse-like) along strike-parallel (SP) and strike-normal (SN) directions

Record number	Earthquake name	Year	Station name	PGV (cm/s)	Preferred Vs30 (m/s)	Closest distance (km)	Pulse period (s)
1	Imperial Valley-06	1979	EC County Center FF	54.5	192.1	7.31	4.515
2	Imperial Valley-06	1979	EC Meloland Overpass FF	50.2	186.2	0.07	3.346
3	Imperial Valley-06	1979	El Centro Array #4	71.7	208.9	7.05	4.613
4	Imperial Valley-06	1979	El Centro Array #5	91.5	205.6	3.95	4.046
5	Imperial Valley-06	1979	El Centro Array #6	91.8	203.2	1.35	3.836
6	Imperial Valley-06	1979	El Centro Array #7	69.6	210.5	0.56	4.228
7	Imperial Valley-06	1979	El Centro Array #8	48.6	206.1	3.86	5.39
8	Imperial Valley-06	1979	El Centro Differential Array	59.6	202.3	5.09	5.859
9	Landers	1992	Yermo Fire Station	56.63	353.6	23.62	7.504
10	Northridge-01	1994	Jensen Filter Plant	67.42	373.1	5.43	3.528
11	Northridge-01	1994	Newhall-Fire Sta	120.26	269.1	5.92	1.036
12	Northridge-01	1994	Newhall-W Pico Canyon Rd.	82.88	285.9	5.48	2.408
13	Northridge-01	1994	Rinaldi Receiving Sta	167.2	282.3	6.50	1.232
14	Northridge-01	1994	Sylmar-Converter Sta	130.27	251.2	5.35	3.479
15	Northridge-01	1994	Sylmar-Converter Sta East	113.57	370.5	5.19	3.528
16	Kobe, Japan	1995	KJMA	89.1	312.0	0.96	0.952
17	Kobe, Japan	1995	Takarazuka	72.64	312.0	0.27	1.428
18	Chi-Chi, Taiwan	1999	CHY101	52.92	258.9	9.96	4.599
19	Chi-Chi, Taiwan	1999	TCU101	43.75	272.6	2.13	10.038
20	Chi-Chi, Taiwan	1999	WGK	49.33	258.9	9.96	4.396

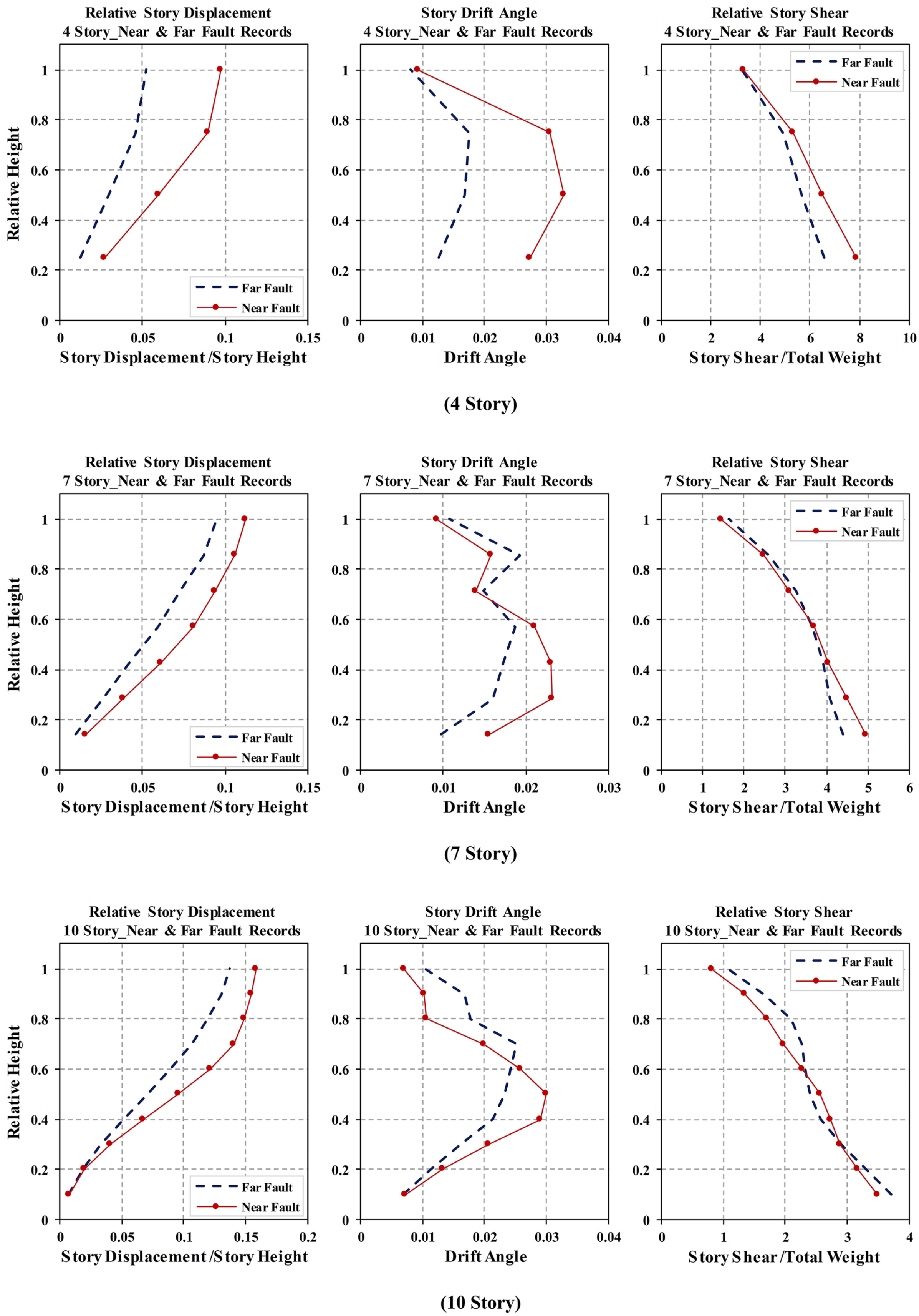


Fig. 4 Results obtained from displacement, drift angle and stories shear under the far and near fault earthquakes (the first group) for the studied structures

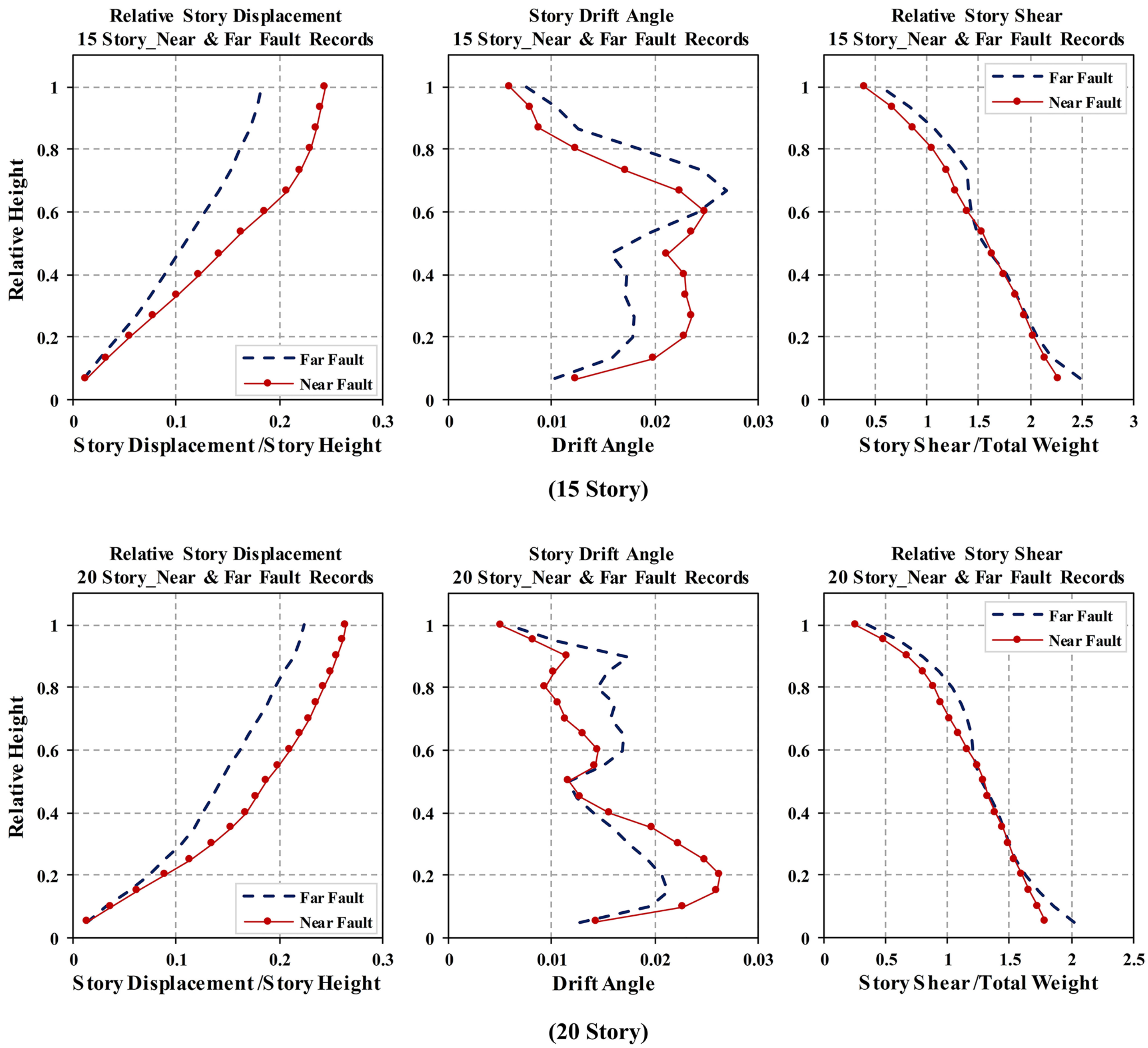


Fig. 5 Continuation of Fig. 4

records in all the investigated structures. In addition, the difference between stories displacement of far fault and near fault earthquakes decrease by increasing the period of structures. In fact, the input energy to the structure due to near fault earthquakes is higher than far fault earthquake so the story displacement of near fault earthquakes is greater than far fault earthquakes.

Also, the higher mode effect under far fault and near fault earthquakes at the upper stories of structures increases when the period of structures increases. For example, the lower stories displacement of 20-story structure are affected by the first mode while at the middle and upper stories, the behavior is due to higher modes effect. The lower stories displacement of mid-rise and high-rise structures under near fault earthquakes are affected by first mode more than far fault earthquakes. In fact, the higher modes effects in mid-rise and high-rise structures under near fault earthquakes in comparison with far fault earthquakes decrease and this decrease is observed at the lower stories of those structures.

Also, the inter-story drift angle of structures at the upper stories obtained from the far fault earthquakes are greater than near fault earthquakes due to higher modes effects.

The hysteresis curves of structures under a selected near fault earthquake, with forward directivity effect, are presented in Fig. 6. The area of hysteresis loop at different stories indicates the amount of dissipated energy by the

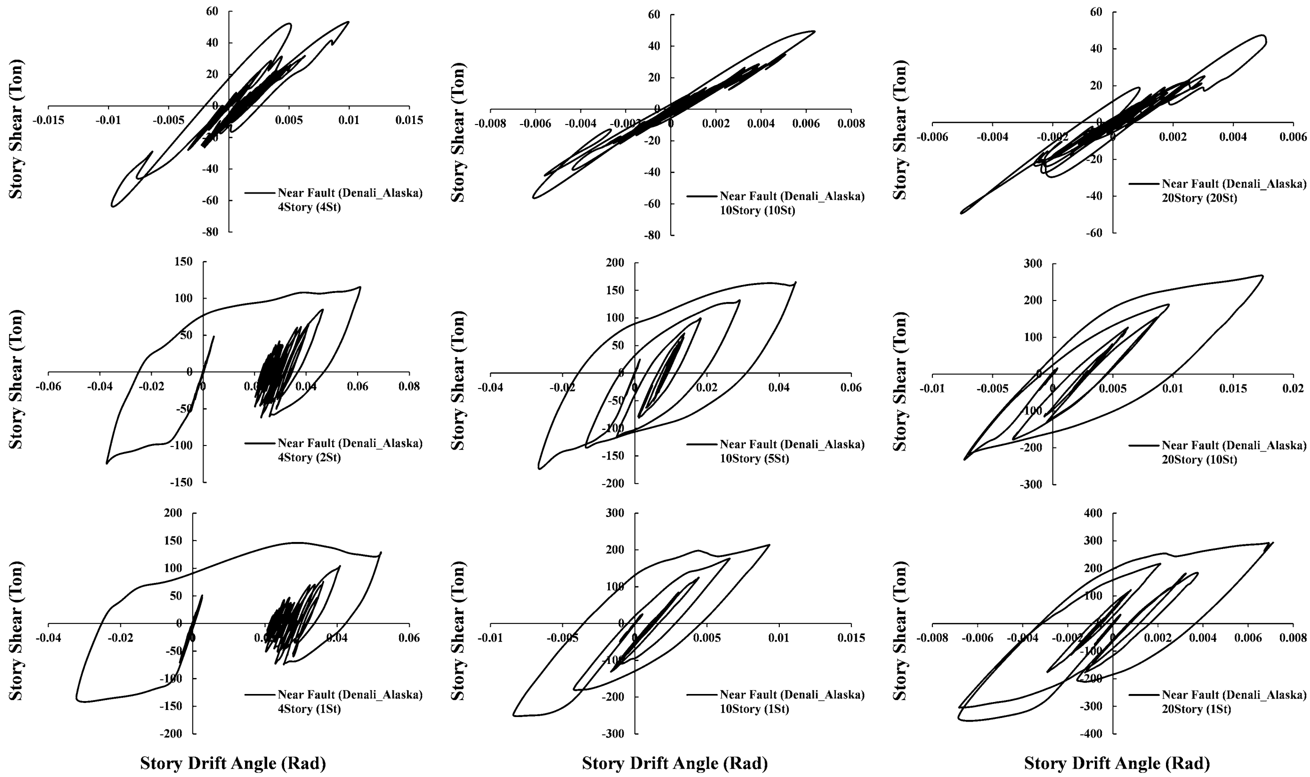


Fig. 6 Hysteresis curve for different stories (lower, middle and upper) of 4, 10 and 20 story structures under the near fault earthquake (Denali_Alaska)

structure. As it can be seen, the input energy due to near fault earthquakes is dissipated at the lower stories. Therefore, the seismic demand of upper stories is decreased. For this reason, the drift angle of upper stories, under the far fault earthquakes is greater than near fault earthquakes. This phenomenon increases if the period of structure increases. The inter-story drift angle of 4-story structure under near fault earthquakes is greater than far fault earthquakes. In addition, the inter-story drift angle of three upper stories of 7-story (30% of the total height), four upper stories of 10-story structure (40% of the total height), six upper stories of 15-story structure (40% of the total height) and ten upper stories of 20-story structure under far fault earthquakes is greater than near fault earthquakes.

The results of structures obtained from the near fault earthquakes to far fault earthquakes ratio are briefly presented in Fig. 7. The story shear results in Fig. 7 shows that at the lower and upper stories of mid-rise and high-rise structures (10, 15 and 20 story structures), the story shear of far fault earthquakes is greater than near fault earthquakes.

For simplification and preliminary estimation of the base shear values of structures under near fault earthquakes by means of the base shear obtained from the far fault earthquakes, the base shear of near fault earthquakes to far fault earthquakes ratio according to the period of structures is presented in Fig. 8. The period of various structures are 0.8, 1.22, 1.59, 2.12 and 2.44, respectively. Also, in Table 4, the values of base shear modification factor of far fault to near fault earthquakes are presented for various structures. As it can be seen, the modification factor of low-rise structures (4 and 7 story structures) is greater than 1.0. In fact, the base shear of near fault earthquake is more than far fault earthquake. On the other hand, if the period of structures increases, the base shear modification factor will decrease so that in the mid-rise and high-rise structures (10, 15 and 20 story structures) the value of this factor is less than 1.0.

The results of near fault earthquakes under the second group accelerograms for the structures are presented in Figs. 9 and 10. The stories displacement results for various structures show that if the period of structure increases, the effects of strike-parallel (SP) earthquakes increase in comparison with strike-normal (SN) earthquakes, so that for 15 and 20 story structures, the stories displacement value of the strike-parallel (SP) earthquakes is greater than strike-normal (SN) earthquakes. While, in other structures, the stories displacement due to the strike-normal earthquakes is greater.

Investigating the results of stories drift angle for various structures shows that for low-rise and mid-rise structures (4, 7 and 10 story structures), at the middle and lower stories, the effects of strike-normal earthquakes are greater

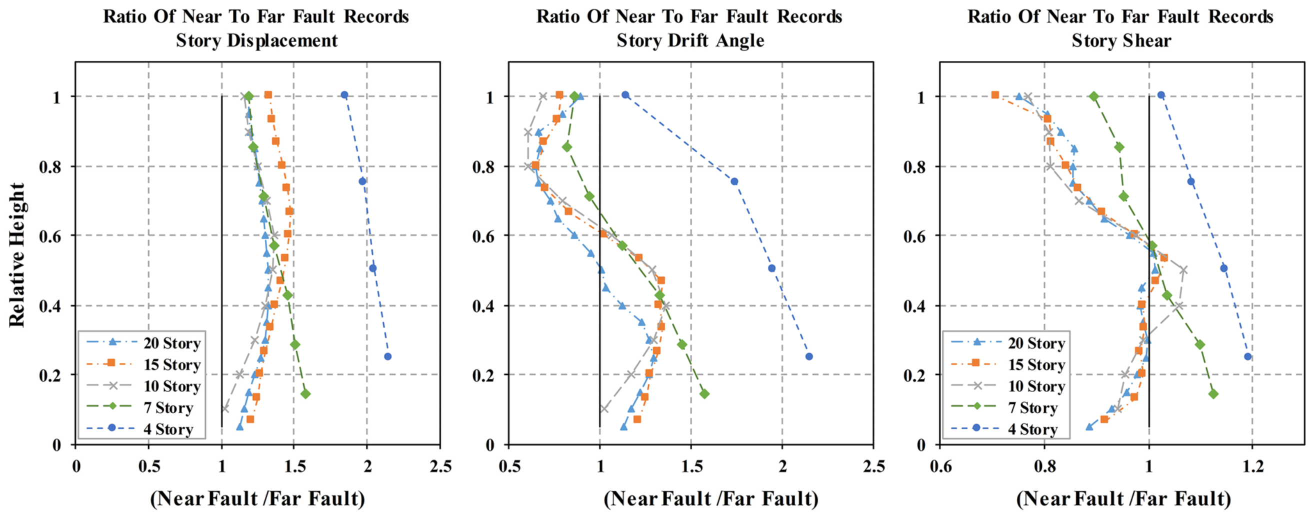


Fig. 7 Ratio of the results obtained from the near fault earthquakes to far fault earthquakes for various structures

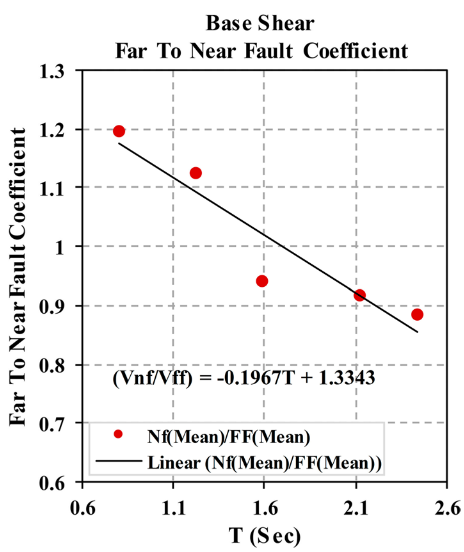


Fig. 8 Ratio of the base shear obtained from near fault to far fault earthquakes with respect to the period of the studied structures

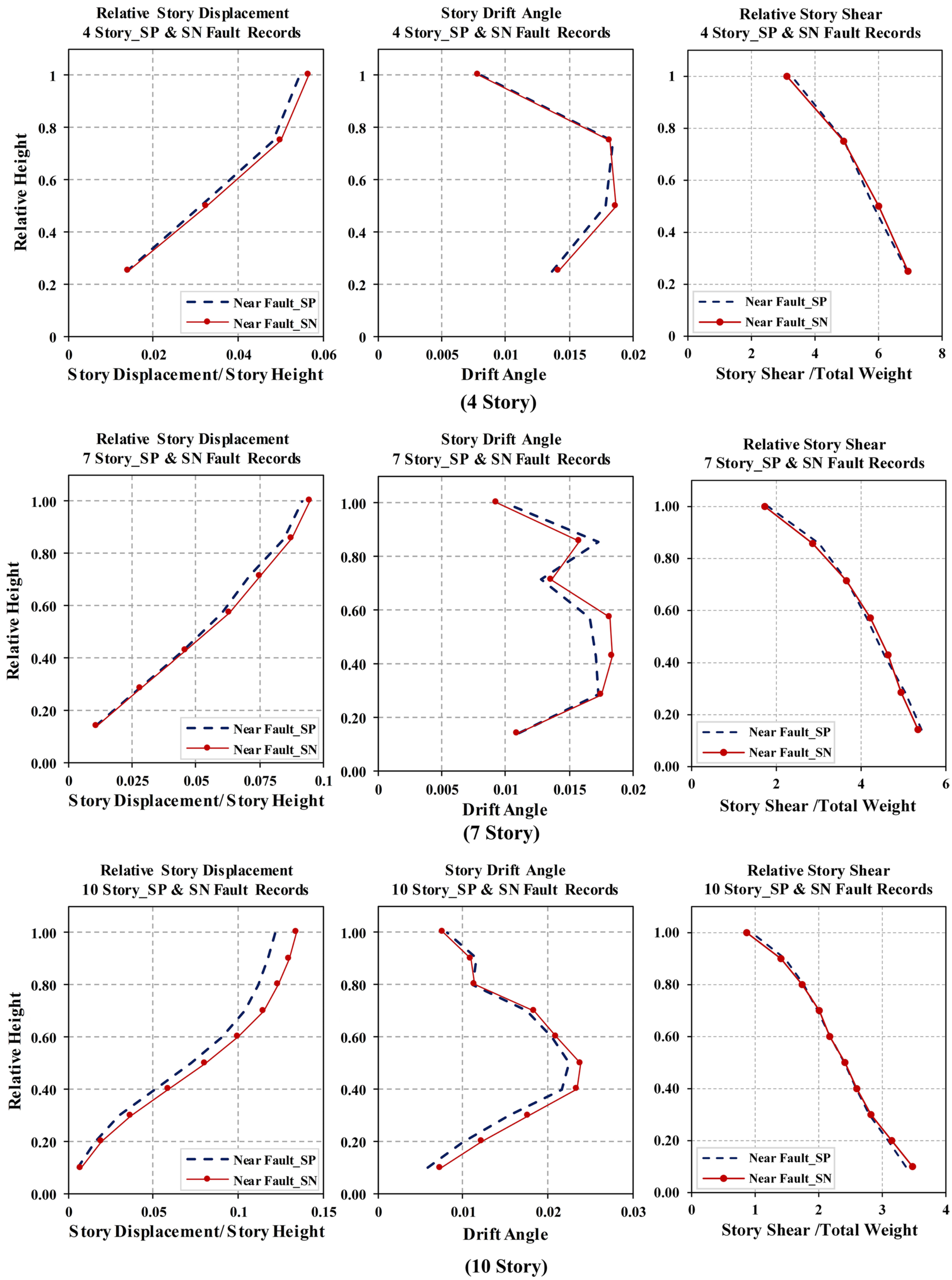
Table 4 Values of the base shear modification factors of far fault to near fault earthquakes for various structures

Coefficient	4 Story	7 Story	10 Story	15 Story	20 Story
V_{nf}/V_{ff}	1.20	1.13	0.94	0.92	0.89

than strike-parallel earthquakes. On the other hand, the stories drift angle of 15 and 20 story structures obtained from strike-parallel earthquakes are greater than strike-normal earthquakes. The main reason of this phenomenon is the higher modes effects under near strike-parallel (SP) earthquakes, especially for the high-rise structures (15 and 20 story structures).

The results of various structures period to the pulse period of the near fault earthquakes ratio show that the displacement and drift angle values obtained from the strike-parallel (SP) earthquakes increase in comparison with the strike-normal (SN) earthquakes by increasing the value of the ratio. This ratio for various structures is 0.2, 0.31, 0.4, 0.53, and 0.61, respectively. In fact when the ratio of the structure period to the velocity pulse period of the near- fault records is greater than 0.5, the effects of strike-parallel (SP) earthquakes increase in comparison with the strike-normal (SN) earthquakes. The stories shear results of various structures show that at the lower stories of 4, 7, and 10 story structures, the story of strike-normal (SP) earthquakes is greater than strike-parallel (SP) earthquakes. On the contrary, the stories shear of 15 and 20 story structures, resulted from the strike-parallel earthquakes is greater than the strike-normal earthquakes. In fact, the difference between story shear values obtained from strike-parallel and strike-normal earthquakes would increase if the period of structure increases. The main reason of this issue is that higher modes effects in strike-parallel earthquakes is higher than strike-normal earthquakes, especially for the high-rise structures.

In order to summarize the results of various structures under the second group of accelerograms, the ratio of seismic demands (displacement, drift angle and stories shear) under near strike-normal (SN) earthquakes to strike-parallel (SP) earthquakes is presented in Fig. 11. As it can be seen, the ratios of 15 and 20 story structures is less than 1.0 and for 4, 7, and 10 story structures, the ratio of drift angle and stories shear at the upper stories is less than 1.0. In fact, the 30% of the upper stories' height of low-rise and mid-rise structures (4, 7 and 10 story structures), the results obtained


Relative Story Displacement
4 Story_SP & SN Fault Records
Relative Height
Near Fault_SP
Near Fault_SN
Story Displacement/Story Height
Story Drift Angle
4 Story_SP & SN Fault Records
Drift Angle
Relative Story Shear
4 Story_SP & SN Fault Records
Story Shear /Total Weight
(4 Story)
Relative Story Displacement
7 Story_SP & SN Fault Records
Story Drift Angle
7 Story_SP & SN Fault Records
Relative Story Shear
7 Story_SP & SN Fault Records
(7 Story)
Relative Story Displacement
10 Story_SP & SN Fault Records
Story Drift Angle
10 Story_SP & SN Fault Records
Relative Story Shear
10 Story_SP & SN Fault Records
(10 Story)

◂**Fig. 9** Results of displacement, drift angle and shear of the stories, obtained from the near fault earthquakes under the second group accelerograms for the studied structures

from the strike-parallel (SP) earthquakes are greater than the strike-normal (SN) earthquakes.

In Fig. 12, the difference between the seismic demand values of far and near fault earthquakes (Fig. 12a) and also the difference of near strike-parallel and strike-normal earthquakes results (Fig. 12b) is presented for various structures. It can be seen in Fig. 12a, b, the difference between the values of story displacement, drift angle and shear will decrease if the period of structure increases. The minimum difference of story shear values obtained from far fault earthquakes in comparison with near fault earthquakes is 2.4% related to the 20 story structure. The maximum difference of this value corresponds to the 4 story structure and it is equal to 6.5%. As it can be observed from Fig. 12b, the difference between the values of stories drift angle resulted from strike-parallel and strike-normal earthquakes will increase if the period of structure increases. Also, the maximum value of this difference is 5% related to the 20 story structure. In addition, the maximum difference in stories shear value is 1.9% and corresponds to the high-rise structures (15 and 20 story structures).

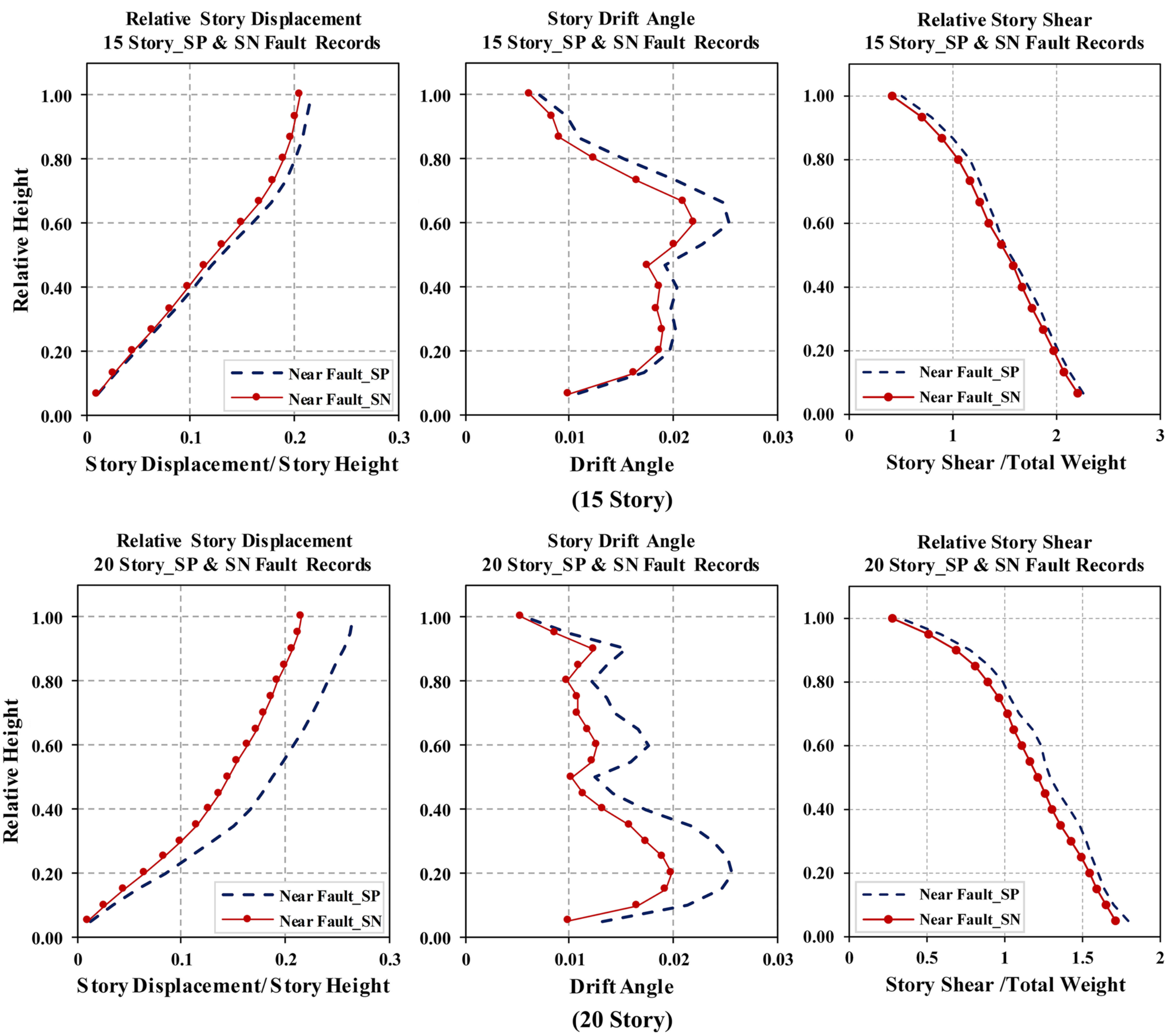


Fig. 10 Continuation of Fig. 9

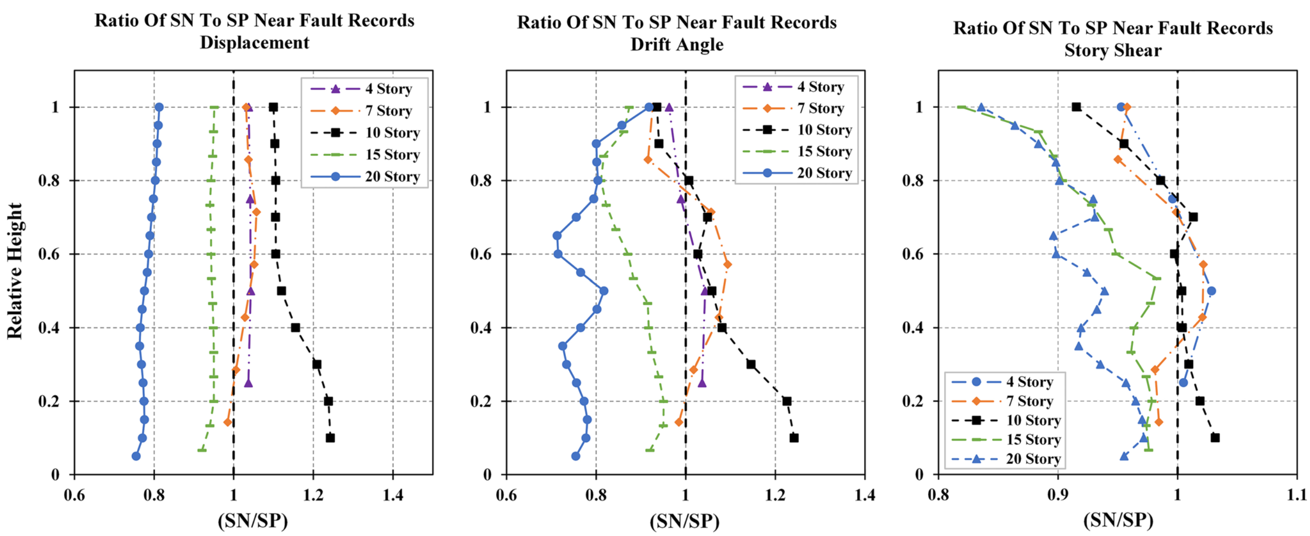


Fig. 11 Ratio of the results (displacement, drift angle and stories shear) obtained from near strike-normal (SN) to strike-parallel (SP) earthquakes for various structures

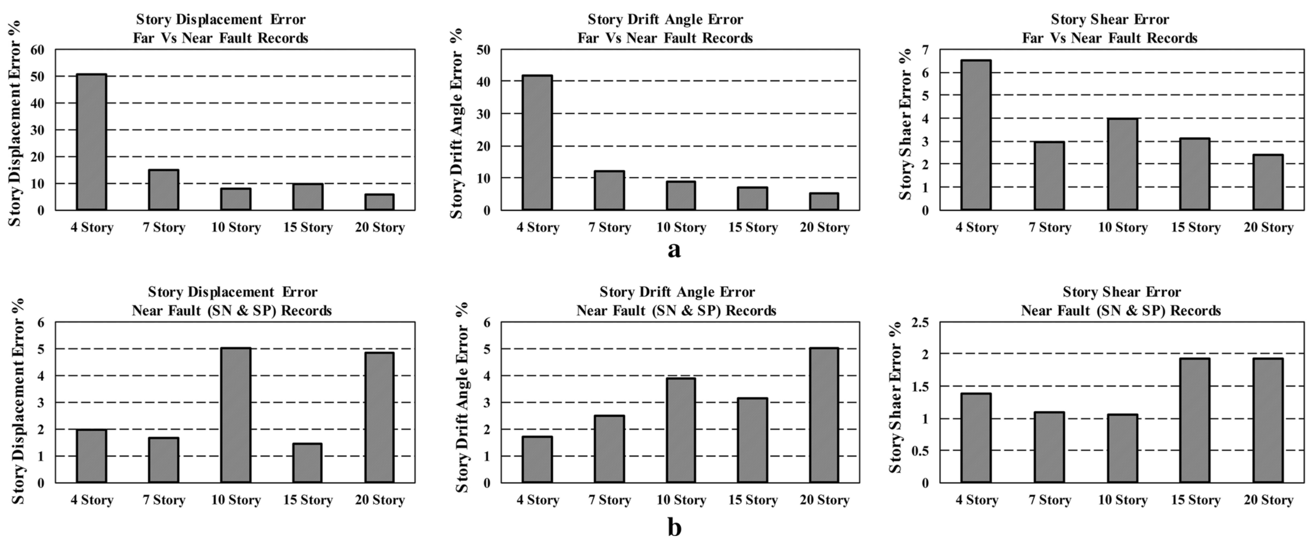


Fig. 12 Difference in response values obtained from **a** far and near fault earthquakes (the first group), **b** near strike-parallel (SP) and strike-normal (SN) earthquakes (the second group) for the studied structures

5 Response Modification Factors for Linear Time History Analysis

Nonlinear time history analysis (NTHA) is complex and time-consuming, therefore it has rarely been used by engineers. On the other hand, linear analysis methods including the linear time history analysis (LTHA) due to lacking limitations of the NTHA method have more implications in design of the structures and have been introduced in most structural design software. So, in this research, linear time history analysis (LTHA) using the OpenSEES framework and under the first and the second group of accelerograms has been performed, the results have been compared with the results of nonlinear time history analysis and finally, the response modification factors have been presented in terms of the period of various structures for far and near fault earthquakes (the first group) in Fig. 13a and for near strike-parallel and strike-normal earthquakes (the second group) in Fig. 13b. These diagrams can be used to understand the nonlinear behavior of structures and for the estimation of their responses under far and near fault earthquakes. In Table 5, the results of the linear time history

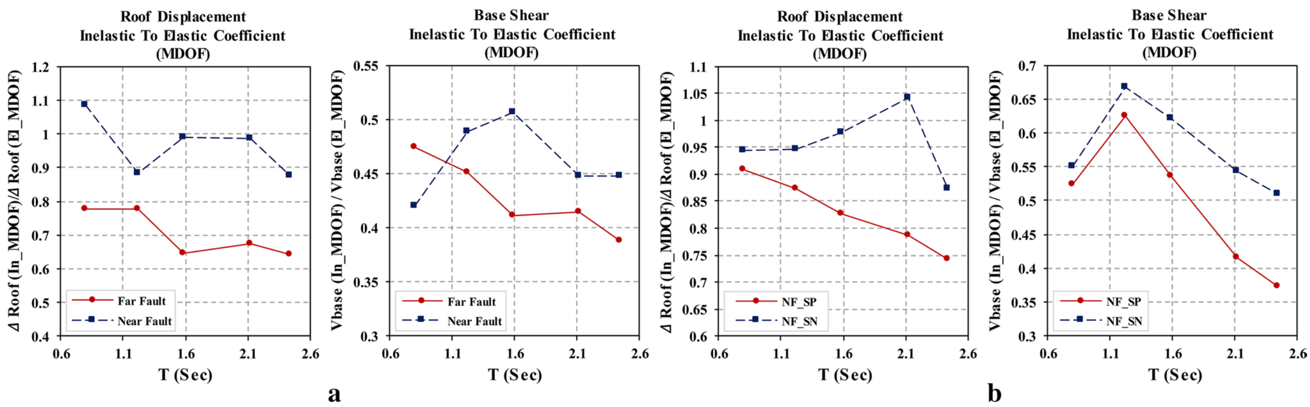


Fig. 13 Response modification factors for linear time history analyses in comparison with the nonlinear time history analyses for the MDOF structures under **a** far and near fault earthquakes (the first group), **b** near strike-parallel (SP) and strike-normal (SN) earthquakes (the second group)

Table 5 Values of linear time history analysis for the studied MDOF structures under various accelerograms

Linear response	Records	4 Story	7 Story	10 Story	15 Story	20 Story
Roof displacement (m)	Far fault	0.27	0.49	0.85	1.09	1.4
	Near fault	0.36	0.51	0.64	0.99	1.21
	SP	0.24	0.42	0.59	1.1	1.43
	SN	0.24	0.4	0.55	0.79	0.99
Maximum drift angle (rad)	Far fault	0.022	0.024	0.03	0.032	0.036
	Near fault	0.029	0.022	0.022	0.024	0.02
	SP	0.02	0.021	0.02	0.029	0.028
	SN	0.02	0.019	0.018	0.02	0.018
Base shear (Ton)	Far fault	238.03	373.56	590.06	740.94	999.38
	Near fault	321.39	388.57	450.39	628.56	767.26
	SP	225.28	333.27	411.37	673.53	923.2
	SN	215.39	307.05	365.85	502.7	644.98

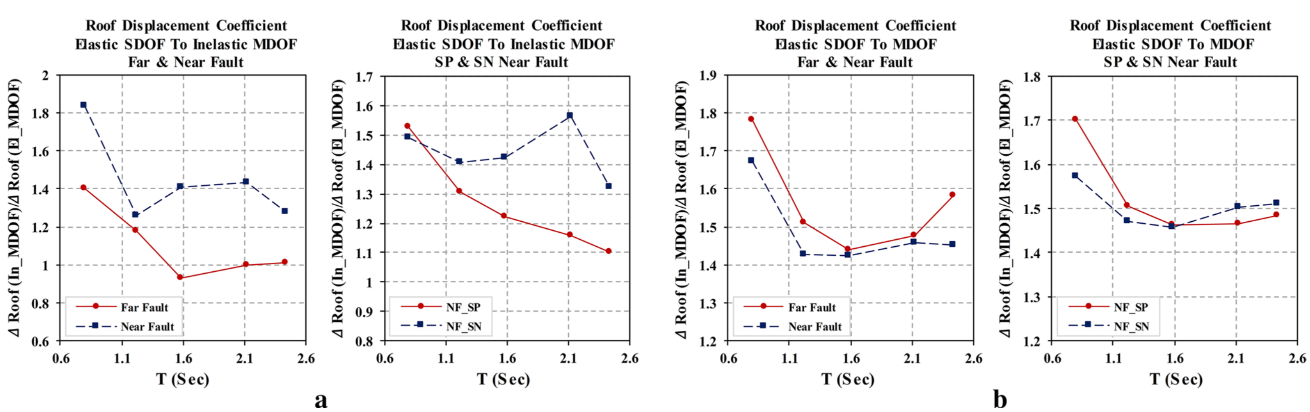


Fig. 14 **a** Response modification factors for the linear roof displacement of ESDOF structure to the nonlinear roof displacement of MDOF structure. **b** Response modification factors for the linear roof displacement of ESDOF structure to the linear roof displacement of MDOF structure according to the period of various structures

analysis for studied structures and under various accelerograms are presented.

6 Response Modification Factors for Equivalent Single Degree of Freedom (ESDOF) Structures

Equivalent SDOF structure is a kind of structure which its period is equal to the first period of MDOF structure. Also, the mass of an ESDOF structure is defined equal to the mass of the MDOF structure. The dynamic characteristics of MDOF structure are needed to model an ESDOF structure. In this research, the responses of SDOF structures corresponding to the period of MDOF structures are derived from the results of elastic response spectrum of the accelerograms with 5% damping ratio obtained from the Seismosignal software.

Figure 14a, shows the response modification factor for the linear displacement of ESDOF structure to the nonlinear roof displacement of MDOF structure, and Fig. 14b shows the response modification factor for the linear displacement of ESDOF structure to the linear roof displacement of MDOF structure in terms of the period of various structures. The periods of various structures are 0.8, 1.22, 1.59, 2.12 and 2.44 s, respectively. The most important applications of the response modification factors presented in this section, are summarized as follows:

- Simplifying the estimation of the roof displacement of MDOF structures using the ESDOF structures.
- Estimation of the target displacement of MDOF structures used in the nonlinear static analysis under near fault earthquakes.

As it can be seen, all response modification factors are greater than 1.0. This issue indicates that the MDOF effects on linear and nonlinear displacements of the structures under far and near fault earthquakes (the first and the second group) are incremental.

7 Conclusion

In this research, the higher modes effects on the seismic demands (displacement, drift angle and stories shear) of the intermediate steel moment resisting frames under far and near fault earthquakes have been investigated. For this purpose, 5 steel moment resisting frames with 4, 7, 10, 15, and 20 stories and 5 spans were designed and nonlinear analyses were performed by OpenSEES framework. Two groups of accelerograms were used in this research. The first group included 20 far and near fault accelerograms and the second group included 40 near strike-parallel (SP) and strike-normal (SN) accelerograms. Analyzing the result of nonlinear analyses, the major results of this research are presented as follows:

- The higher modes effects under far fault earthquakes are greater than the near fault earthquakes with forward directivity effect.
- The higher modes effects under near strike-parallel (SP) earthquakes are greater than strike-normal (SN) earthquakes.
- The difference between seismic demands values of structures under the far and near fault earthquakes will decrease if the period of structure increases.
- The inter-story drift angle results show that for about 30%-50% of the height of structure, at the upper stories, the response obtained from the near fault earthquakes with forward directivity effect is greater than far fault earthquakes.
- The difference of stories drift angle under strike-parallel and strike-normal earthquakes will increase if the period of structure increase. So, the maximum difference is about 5% corresponding to the 20-story structure.
- The difference between stories shear obtained from far and near fault earthquakes will decrease if the period of structure increase. So, the minimum difference is about 2.4% corresponding to the 20-story structure.

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