Non-Linear Response of High Rise Buildings to Pulse Type Strong Ground Motions

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Abstract

Occurrence of strong ground motions in areas near causative faults is expectative. Studies on recorded near fault strong motions indicate that there are usually some obvious effects in the acceleration, velocity and displacement time histories. Generally, the strong ground motions recorded in near fault zones contain distinct pulses in the velocity time history. These powerful velocity pulses cause that structural system of tall building should face with considerable input energy. It should be noted that these extreme amounts of seismic energy are produced by directivity effects which have been observed in near fault earthquake records. Research results show that the maximum structural demand of a building is function of the ratio of the pulse period to the structure fundamental period. This paper includes the analytical results from non-linear dynamic analyses of two example multi-storey buildings subject to strong ground motions. These example buildings are five and thirteen storey structures which have three dimensional steel framing system. All selected earthquake records in this study, include strong ground motions recorded in Iran as well as some other downloaded records from PEER earthquake data base. According to the non linear analyses, the structural demands which are calculated subject to near field records are considerably more than those due to far field motions.

Keywords: tall building, steel structure, pulse type ground motion, near-fault area, forward directivity effects, fault rupture.

1. INTRODUCTION

Near-fault strong ground motions are usually characterized by high amplitude and short duration impulses. These powerful ground motions cause buildings to be exposed to considerable input kinetic energy. Therefore, the structural system of multi-storey buildings needs to be able to dissipate this input energy in relatively few cycles of inelastic vibration. The arrival of the strong impulsive ground motions in areas located near faults causes the structural demands to be considerably more than those due to far-fault motions. The need exists to incorporate these seismic effects in the design process of buildings located in areas near causative faults (Bozorgnia *et al* 1998, Sasani *et al* 2000, Krawinller *et al* 2003).

It is worth mentioning that the recorded time history at the station no. 2 from the 1966 Mw 6.1 Parkfield earthquake is the first ground motion which was found containing near source effects. This strong ground motion is characterized by relatively long period coherent velocity and displacement pulses. Generally there are two main seismological effects which are called rupture directivity and fling step effects cause the appearance of distinct strong pulses in the ground velocity and displacement time histories. The characteristics and propagation of ground motions in near-fault regions are strongly influenced by the fault geometry and rupture mechanism. Generally, near fault rupture directivity and fling step effects can be obviously observed in time histories of those ground motions which are recorded in the forward direction of rupture propagation. Earthquake records which contain long period and high amplitude pulses are clearly distinguished from typical far-field records (Papageorgiou *et al* 2002, Somerville 2003, Bray *et al* 2004).

The considerable and enormous destructive potential of recorded near-fault ground motions was manifested in the 1994 Mw 6.7 Northridge, 1995 Mw 6.9 Kobe and 1999 Mw 7.6 Chi Chi earthquakes. The peak ground velocities as high as 175 cm/sec and more were recorded during the main shock of these earthquakes. The period of strong velocity pulses which were observed in recorded near-fault ground motions during these earthquakes lies in the range of 1 to 2 seconds. This time domain is comparable with the natural period of tall buildings. Earthquake records which are influenced by near fault directivity pulses can generate greater structural response characteristics in high-rise buildings as compared to far field ground motions (Ventura *et al* 1995, Loh *et al* 2000, Elgamal *et al* 2004). The objective of this paper is to study the response parameters and characteristics of two example steel buildings subject to strong ground motions. These two buildings are five and thirteen storey structures. The lateral load resistant system of these two structures is a perimeter steel braced frame. A general comparison has been made between the structural response characteristics resulted from non-linear analysis subject to both far and near field earthquake records.

2. CHARACTERISTICS OF NEAR FAUT RECORDS

During a strike slip or a dip slip faulting process, forward directivity effects emerge when the rupture plane propagates towards a site at a velocity close to the seismic shear wave velocity. These faulting mechanisms cause most of the ground seismic energy due to the rupture process to arrive in a few coherent large domain pulses which occur at the beginning of the record. These impulsive waves may appear in velocity time history as well as a large fling step pulse in displacement time history of a strong ground motion. Both aforementioned impulses, i.e. a two sided dynamic velocity pulse and a one sided static displacement pulse can be observed in time histories associated with fault normal and parallel components of a strong ground motion, respectively (Somerville *et al* 1993, Durukal 2002, Ambrayseys *et al* 2003).

As an example, two high-amplitude and long-duration pulses are displayed in the time history associated with the ground motion which was recorded at the Lucerne Valley station during the 1992 Mw 7.3 Landers earthquake. On the other hand, the velocity and displacement time histories of the fault perpendicular motion which was recorded at the Joshua Tree station (JSH) from the 1992 Landers earthquake, do not display any pulses. This is because of the ground motions arrived at the JSH territory in the backward direction with respect to fault rupture propagation. However during both strike-slip and dip-slip fault rupturing, strong long-period velocity pulses corresponding to ground shear wave displacements and also a high amplitude static displacement pulse will often appear in time histories of recorded earthquake motions. These features are mostly observed in time history of fault-normal records (Heaton *et al* 1993, Iwan *et al* 1995, Somerville 1997).

Table 1: Selected far-fault earthquake records

Ground Motion	Component	Duration (sec)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	Magnitude		PGV/PGA (sec)	PGD/PGV (sec)
						M_W	M_S		
Tabas E. 1978 (Ferdous - 94.4 km)	**LN**	**40.00**	**85.3**	**5.7**	**4.6**	**7.4**	**7.4**	**0.06**	**0.81**
	TR		**105.9**	**8.6**	**9.7**			**0.08**	**1.12**
	UP		**52.0**	**7.6**	**6.7**			**0.14**	**0.89**
Landers E. 1992 (Indiana - 55.7 km)	**LN**	**60.00**	**102.0**	**9.6**	**5.0**	**7.3**	**7.4**	**0.09**	**0.52**
	TR		**106.9**	**15.2**	**9.7**			**0.14**	**0.64**
	UP		**41.2**	**6.6**	**4.0**			**0.16**	**0.60**
Chi Chi E. 1999 (CHY004 - 51.0 km)	**LN**	**150.00**	**97.1**	**20.0**	**17.5**	**7.6**	**7.6**	**0.20**	**0.87**
	TR		**98.1**	**15.8**	**15.4**			**0.16**	**0.97**
	UP		**40.2**	**6.5**	**5.3**			**0.16**	**0.82**

Fault Parallel: LN , Fault Normal: TR , Fault Vertical: UP

Table 2: Selected near-fault earthquake records

Ground Motion	Component	Duration (sec)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	Magnitude		PGV/PGA (sec)	PGD/PGV (sec)
						M_W	M_S		
Tabas E. 1978 (Tabas - 3.00km)	**LN**	**32.84**	**819.9**	**97.7**	**39.9**	**7.4**	**7.4**	**0.12**	**0.40**
	TR		**835.5**	**121.3**	**94.5**			**0.14**	**0.78**
	UP		**675.4**	**45.5**	**17.0**			**0.06**	**0.37**
Bam E. 2003 (Bam - 1.0 km)	**LN**	**66.55**	**623.4**	**59.6**	**20.7**	**6.6**	**6.8**	**0.09**	**0.34**
	TR		**778.2**	**123.7**	**37.4**			**0.15**	**0.30**
	UP		**979.5**	**39.6**	**8.6**			**0.04**	**0.21**
Landers E. 1992 (Lucerne - 1.1 km)	**LN**	**48.15**	**769.8**	**31.8**	**16.4**	**7.3**	**7.4**	**0.04**	**0.51**
	TR		**707.1**	**97.6**	**70.3**			**0.14**	**0.72**
	UP		**802.9**	**45.9**	**22.2**			**0.05**	**0.48**
Chi Chi E. 1999 (TCU068 - 1.1 km)	**LN**	**90.00**	**453.2**	**263.1**	**430.0**	**7.6**	**7.6**	**0.58**	**1.63**
	TR		**555.2**	**176.6**	**324.1**			**0.31**	**1.83**
	UP		**476.7**	**187.3**	**266.5**			**0.39**	**1.42**

Fault Parallel: LN , Fault Normal: TR , Fault Vertical: UP

Both of the fault normal and vertical components due to strong ground motions which were recorded during the main shock of the 1978 Mw 7.4 Tabas and 2003 Mw 6.6 Bam earthquakes in Iran, contain high-amplitude and long-period waveforms (Tehranizadeh *et al* 2000 & 2004, Nowroozi 2005). The general characteristics of all selected earthquake records are given in Tables 1 and 2. The near-field earthquake records in Table 2 were chosen so that their velocity time history to display strong coherent pulses. Furthermore, it can be seen that the peak ground vertical velocity due to near-field earthquake records is considerably greater than that of far-field ground motions. It is worth mentioning that both forward directivity and fling step waveforms can be observed in the time histories due to the Lucerne valley and TCU068 records from the 1992 Landers and 1999 Chi Chi earthquakes.

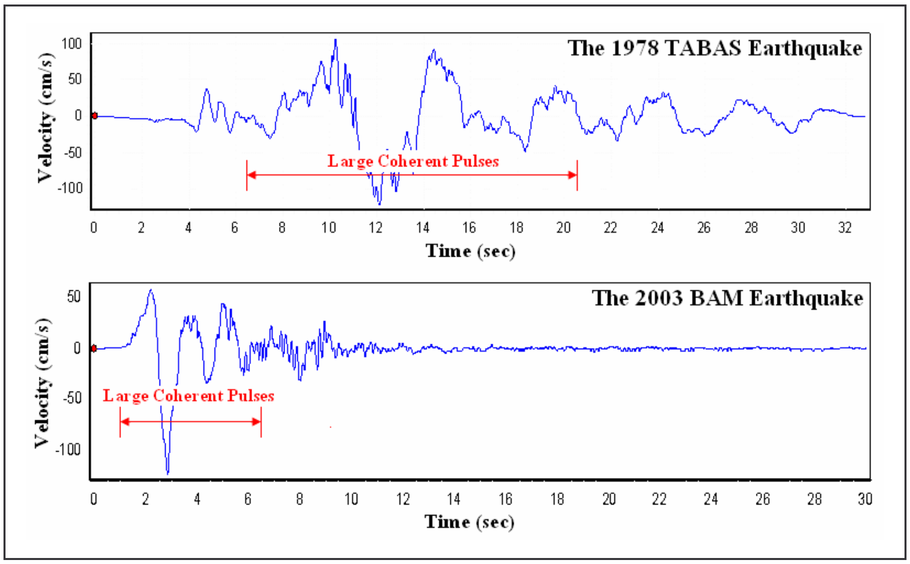

Figure 1: High amplitude and long period pulses in the velocity time history of fault normal component due to main shock of the 1978 Tabas and 2003 Bam earthquakes.

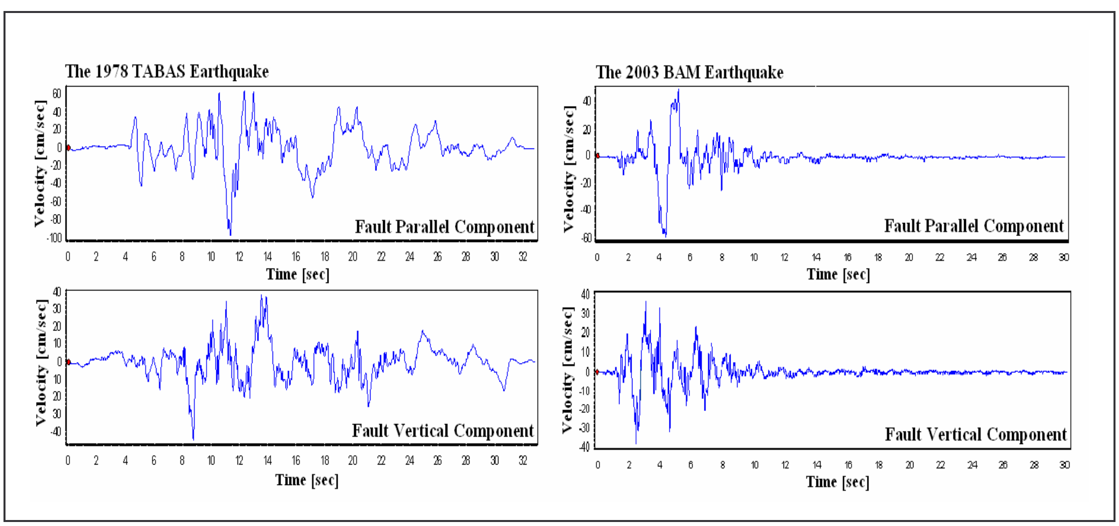

Figure 2: Coherent long-period pulses in the velocity time histories associated with the fault parallel and vertical components due to main shock of the 1978 Tabas and 2003 Bam Earthquakes

The velocity time histories associated with main shock of the 1978 Tabas and 2003 Bam earthquakes display long-period strong pulses, clearly. These velocity pulses are shown in Figure 1. These powerful pulses are also observed in velocity time histories due to the fault parallel and vertical components of both aforementioned earthquake records in addition to fault perpendicular ground motion. Figure 2 displays the velocity time histories associated with the fault parallel and vertical components due to main shock of the 1978 Tabas and 2003 Bam Earthquakes as noted in Table 2.

3. DESCRIPTION OF THE EXAMPLE STEEL BUILDINGS

Nonlinear dynamic analyses were performed for assessment of the response characteristics of two 5-storey and 13-story steel buildings. Figure 3 shows the plane and structural system of the example 13-storey building. The plane and structural system of the example 5-storey steel building is also similar to the other example building. The earthquake resistant structural system of both buildings is constructed based on eight single bay concentric braced frames which are located at the corners of plane. The storey height is uniformly 3.00m for all floors and length of all spans is 6.00m. The design dead load on all the floors is 500 kg/m^2. The effective live load was selected according to the Iranian National Standard and the structures were also designed based on the Iranian Code 2800 for very high seismic macro-zonation hazard region and soil type II (Iranian Standard 2800-5).

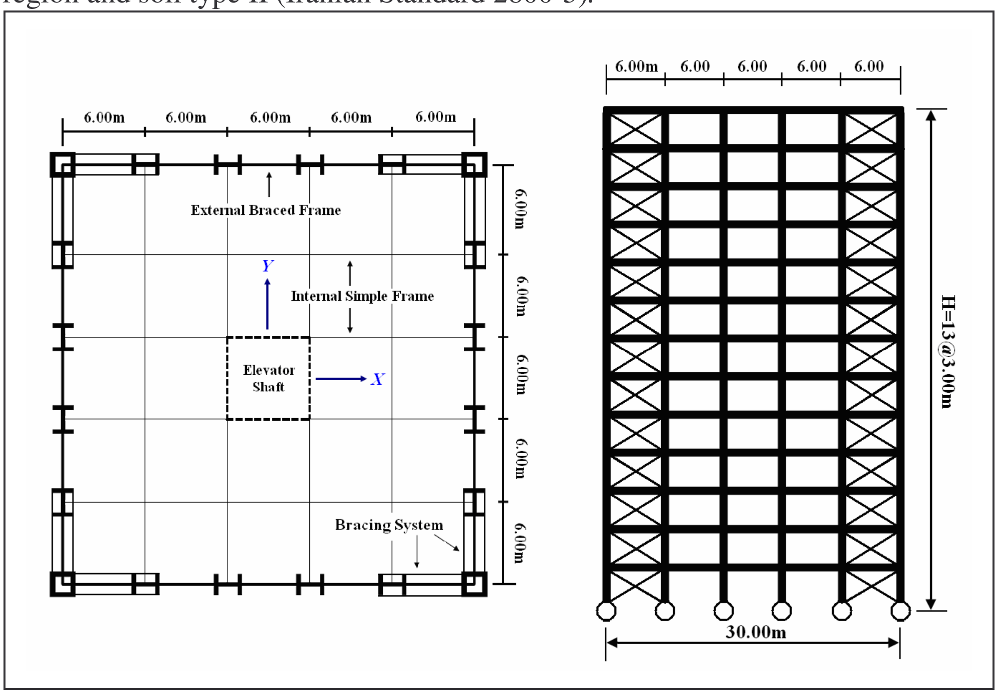

Figure 3: Structural system of the example 13-storey building

The overall behaviour of buildings under effect of forced vibrations associated with strong earthquakes will probably change from linear elastic to highly inelastic level. Hence, to provide the ability of nonlinear performance for the structural elements, the tri-linear model was utilized according to FEMA-356 (FEMA-356). Figure 4 shows the general behaviour curves which were used for the characteristics of the structural hinges. It should be noted that the nominal strength of all structural elements was calculated based on the code AISC (AISC-1994). The damping matrix of the example buildings is assumed to be classical and proportional to the stiffness and mass matrices of the structure. It is important to indicate that all selected ground motions as noted in Tables 1 and 2 were imposed to the example building as three component scaled earthquake records. The scaling procedure is based on the method which is described by the code IBC (IBC-2000).

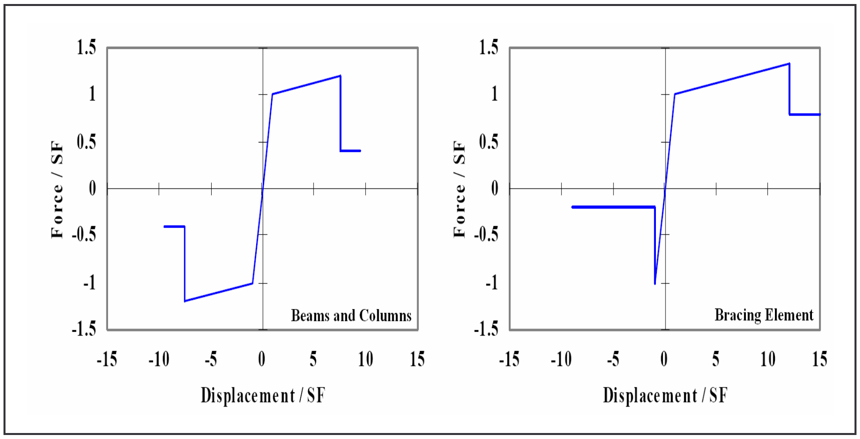

Figure 4: Assumed non-linear behavior for the structural hinges

4. DESCRIPTION OF THE EXAMPLE BUILDINGS RESPONSE

This section summarizes the calculated response characteristics due to both example steel buildings. Figure 5 displays the response velocity spectra and response acceleration-displacement spectrum associated with the fault normal component of main shock of the 1978 Tabas and 2003 Bam earthquakes. As shown in Figure 5 there are large values in time domain from 0.7sec to 2.0sec. Obviously, this time domain includes the fundamental period of medium-rise to tall building structures too. Therefore, the larger magnitudes for spectral velocity S_V will indicate that the more amounts of ground seismic energy should be imposed to multi-storey buildings with longer first mode period.

The first mode period of both five and thirteen storey example buildings is 0.5sec and 1.5sec respectively. These values are corresponding to 155cm/sec and 107cm/sec from the response velocity spectra due to the 1978 Tabas Earthquake as shown in Figure 5. The corresponding values which are resulted from the response velocity spectra due to the 2003 Bam Earthquake are also 66cm/sec and 245cm/sec, respectively. It should be noted that the spectral velocities 155cm/sec and 66cm/sec are associated with the five-storey building and the other ones are also due to thirteen-storey building. It appears that the Tabas earthquake should induce more severe effects on the five-storey building than the 2003 Bam earthquake. On the other hand, it seems that the thirteen-storey example building should be influenced by larger amount of seismic energy which is imposed by the Bam earthquake than the Tabas earthquake. From an acceleration-displacement spectrum as shown in Figure 5, it is rather easy to assess the reciprocal effects between the spectral acceleration which is introduced by base shear coefficient and the deformation demand (Iwan 1997, Malhotra 1999, Elnashi *et al* 2006).

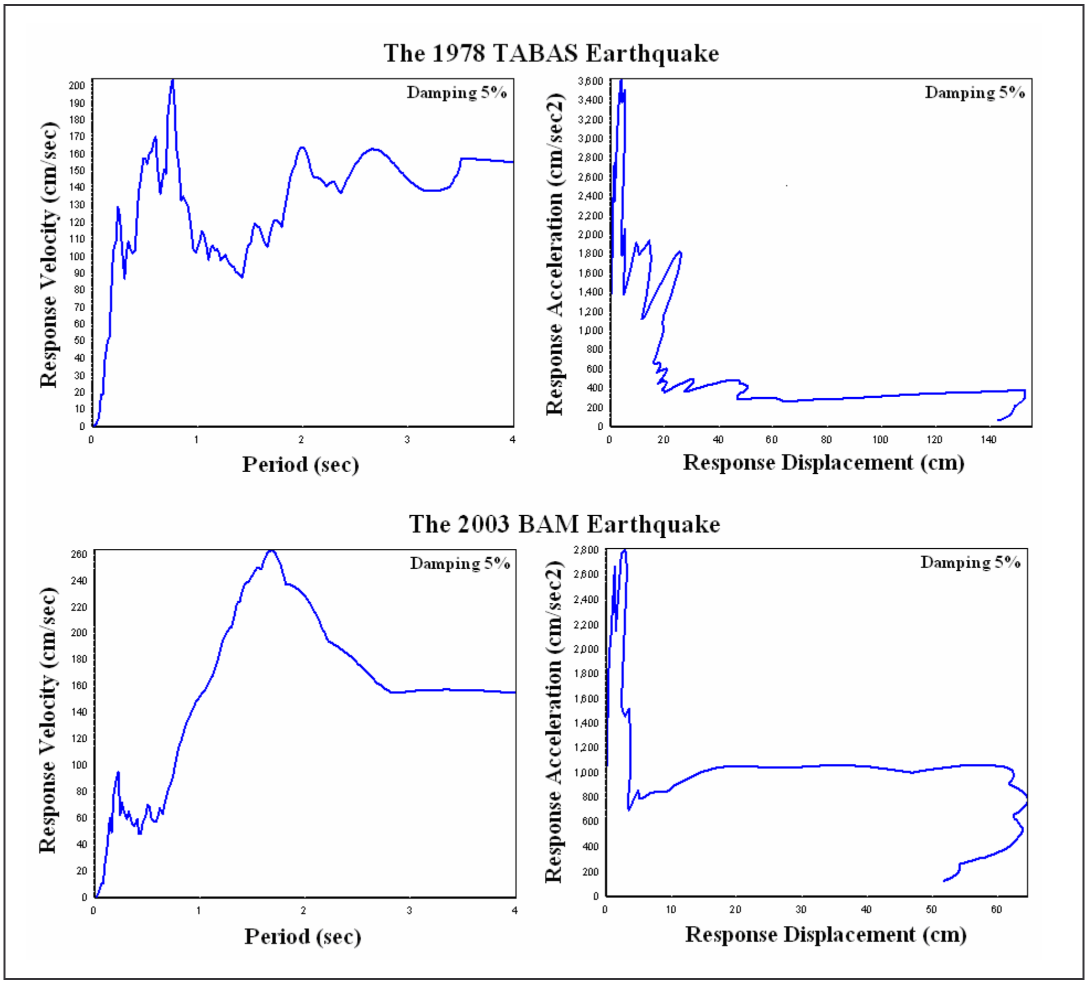

Figure 5: Response velocity spectra and acceleration-displacement spectrum due to fault normal component of main shock of the 1978 Tabas and 2003 Bam earthquakes.

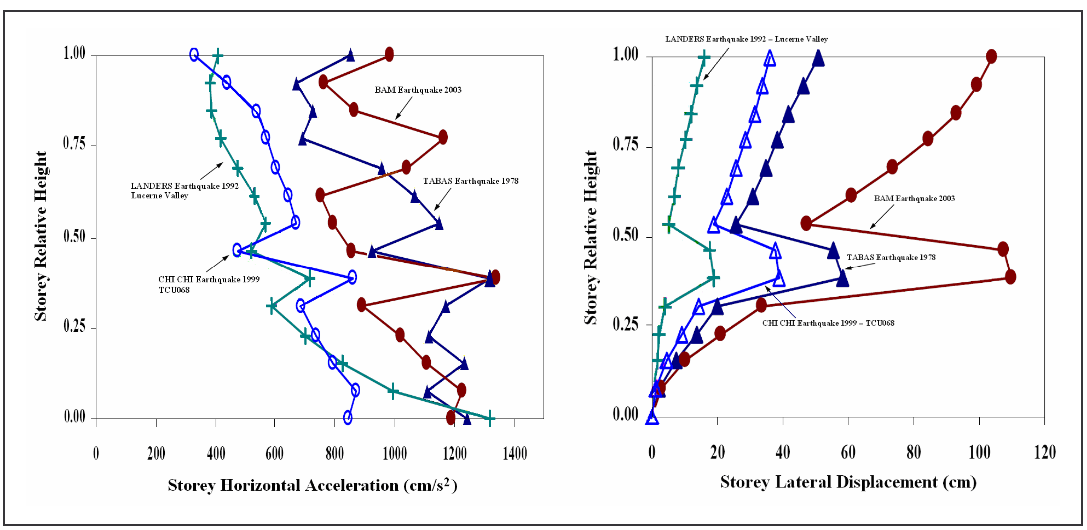

Figure 6: Total acceleration and lateral displacement results form the dynamic response of thirteen storey building to the near field records as notified in Table 2.

The presented results in this section have been obtained based on performing a number of non-linear dynamic analyses using software SAP2000 subject to far field and near field earthquake records. Storey displacement and total storey acceleration were considered as two structural response parameters which are shown in Figure 6. Furthermore, maximum values of storey drift and dynamic base shear due to both groups of selected records as notified in Tables 1 and 2 are also collected in Tables 3 and 4. These results are given versus PGA, PGV, PGD, PGV/PGA, PGD/PGV ratios.

Table 3: Response characteristics of thirteen storey building to near and far fault records

Ground Motion	**PGV** (cm/s)		**PGV/PGA** (sec)		**PGD/PGV** (sec)		**Max. of Relative Drift** (TR Dir. - cm)	**Max. of Base Shear** (TR Dir. - ton)
	TR	**UP**	**TR**	**UP**	**TR**	**UP**		
Tabas E. 1978 (Ferdous- 94.4 km)	**8.6**	**7.6**	**0.08**	**0.14**	**1.12**	**0.89**	**0.7**	**385**
Tabas E. 1978 (Tabas - 3.00km)	**121.3**	**45. 5**	**0.14**	**0.06**	**0.78**	**0.37**	**6.1**	**1885**
Bam E. 2003 (Bam-less than 1 km)	**123.7**	**39. 6**	**0.15**	**0.04**	**0.30**	**0.21**	**7.4**	**1940**
Landers E. 1992 (Indiana - 55.7 km)	**15.2**	**6.6**	**0.14**	**0.16**	**0.64**	**0.60**	**1.1**	**380**
Landers E. 1992 (Lucerne - 1.1 km)	**97.6**	**45. 9**	**0.14**	**0.05**	**0.72**	**0.48**	**5.5**	**1284**
Chi Chi E. 1999 (CHY004-51.0 km)	**15.8**	**6.5**	**0.16**	**0.16**	**0.97**	**0.82**	**1.0**	**530**

Table 4: Structural analysis results subject to near fault records

Ground Motion	**Transverse Component**			**Max. of Relative Drift** (TR Dir. - cm)		**Top Storey Velocity** (TR Dir. - cm/s)		**Top Storey Acceleration** (TR Dir. - cm/s^2)	
	PGA (cm/s^2)	**PGV** (cm/s)	**PGD** (cm)	**5-storey building**	**13storey building**	**5-storey building**	**13storey building**	**5-storey building**	**13storey building**
Tabas E. 1978 (Tabas - 3.00km)	**835.5**	**121.3**	**94.5**	**6.2**	**6.1**	**188.0**	**157.0**	**2070.0**	**830.0**
Bam E. 2003 (Bam-less than 1 km)	**778.2**	**123.7**	**37.4**	**7.2**	**7.4**	**164.0**	**238.0**	**1700.0**	**1005.0**
Landers E. 1992 (Lucerne - 1.1 km)	**707.1**	**97.6**	**70.3**	**2.2**	**5.5**	**102.0**	**79.0**	**1640.0**	**410.0**

5. CONCLUSION

Generally, the response characteristics of tall buildings subject to near field ground motions are considerably greater than those from far field earthquake records. Studies show that structural response parameters of multi-storey buildings will change from nearly elastic case to highly inelastic level. This conclusion is obviously obtained based on the increased base shears, inter-storey drifts and roof displacements which are resulted from nonlinear dynamic analyses of multi-storey buildings subject to near field earthquake records in comparison with those from far field ground motions.

Near field recorded ground motions which are characterized by forward directivity effects display coherent pulses in velocity time history. These powerful velocity pulses may be in the shape of one-sided or two-sided waveforms and contain considerable seismic energy which is released in a small time domain. Therefore, the structural system of medium-rise to tall buildings especially those which have T_N/T_P ratio close to one, must be able to dissipate extreme amounts of seismic energy in relatively few cycles of inelastic forced vibrations. It is usually observed that the existence of forward directivity effects in near fault earthquake records displays larger values for PGV and PGV/PGA ratios as well as relatively lower PGD/PGV ratios. These conditions are not always met for far-field records.

It is worth mentioning that in addition to the peak value of ground acceleration PGA both parameters of the peak ground velocity and displacement, i.e. PGV and PGD can be also used as general key parameters for preliminary assessment of medium to high-rise building response characteristics to near fault pulse-type ground motions. Furthermore, there are also two PGV/PGA and PGD/PGV ratios which can be considered as applicable parameters in order to understand the effects of near field earthquake records on multi-storey building structures.

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