16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2444

Registration Code: S-C1461952849

Seismic Response of Asymmetric Steel Bundled Tube Resistant Skeletons under Near-Field Earthquake Records

S. Sohrabifard [1], M.R. Mansoori [2], A. Meshkat-Dini [3], A.S. Moghadam[4]

[1] *Msc. Student of Earthquake Engineering, Science and Research Branch, IAU, Tehran, Iran, S.Sohrabifard@gmail.com*
[2] *Assistant Professor, Science and Research Branch, IAU, Tehran, Iran, M.Mansoori@srbiau.ac.ir*
[3] *Assistant Professor, Kharazmi University, Tehran, Iran, Meshkat@khu.ac.ir*
[4] *Associate Professor, International Institute of Earthquake Engineering and Seismology ,Tehran, Iran, Moghadam@iiees.ac.ir*

Abstract

Physical characteristics of various recorded ground motions during earthquakes are naturally very different based on various types of fault mechanisms. Generally, to determine different characteristics of two groups of far and near-field records, frequency content as well as long period pulse features in the velocity time history and great values of PGV and PGA parameters must be referred too. Major ground motions recorded during Tabas 1978 and Bam 2003 earthquakes in Iran are some of the best samples of strong and destructive wave-like motions containing a great deal of kinetic energy. Due to displaying pulse-like features in their velocity time history corresponding to the emergence of spike-shaped wavelets in their recorded ground acceleration, near-field records containing forward directivity effects are strongly capable of forcing huge kinetic energy on structures in a relatively short period of time. In this paper, the seismic behavior of a particular type of resistant structure called a rigid bundled tube under near-field ground motions is analyzed and studied. The studied skeleton is a ten-story rigid bundled tube with a value of mass eccentricity. The results are calculated and analyzed after conducting several nonlinear time history analyses under a number of three-component near-field records. Overall, the results of this research explain that seismic response parameters of asymmetric rigid bundled tube skeletons are not effectively sensitive to small amounts of mass eccentricity. Moreover, analytical assessments show larger amplitude for the seismic performance of plastic hinges in flexible edges of the plan compared to stiff edges. Finally, it is observed that rigid bundled tubes can satisfy the Iranian design code restrictions for story drift.

Keywords: Bundled Tube; Near-field Record; Irregular Building; Seismic Behavior; Mass Eccentricity

1. Introduction

Torsional irregularities in the plan of a building caused by the actual distance between centers of rigidity (CR) and mass (CM) would result in uneven demands from the structural elements of the building. Assessing post-earthquake structural damages shows that, this uneven distribution of the demand in torsionally irregular buildings leads to an increased vulnerability compared to torsionally regular buildings. Yet, torsional effects were reported to be the major cause of severe damages and the collapse of several buildings during 1985 earthquakes in Mexico and Chile (Meli et al 1985; Mitchell et al 1986; Wood et al 1991). Therefore, understanding the behavior of torsionally irregular buildings is of significant importance and has drawn interest for several decades. Early studies of the seismic behavior of torsionally irregular buildings used to focus on buildings responding in an elastic range (Erdik 1975; Kan et al 1977; Hejal et al 1989). Later researches focused on inelastic responses of single-story (Tso et al 1985 and 1990; Goel et al 1990; Perus et al 2005) and multi-story buildings (Delaliera et al 1994 and 1995; Tso et al 2002; Marusic et al 2005; Kosmopoulos et al 2007). A common conclusion was that the normalized story drift in inelastic systems does not exceed the corresponding normalized drift in elastic systems, and that the relative torsional component of deformation decreases with ground motion intensity and hence, ductility demands increase (Perus et al 2005; Marusic et al 2005; Kosmopoulos et al 2007). Recently, more studies are focusing on understanding the influence of biaxial excitation on the behavior of torsionally irregular buildings. Reviews of a recent research have been performed by Rutenberg 2002; De Stefano et al 2002; Anagnostopoulos et al 2015 [1,2,3,4,5].

The basic structural models studied in this research are three-dimensional bundled tube moment frames with and without a defined mass eccentricity in stories. It must be considered that the shear lag effect shall appear in a framed tube system made solely of four planar rigid frames located at the edges of the plan. Shear lag effect appears due to the formation of a displacement field at the fixed end of deep girders connected to wide circumferential columns and is in fact caused by a huge shear force. The use of bundled tube structures consisting of some smaller rigid tube frames reduces the shear lag effect considerably. A bundled tube system consists of several perpendicularly interconnected rigid frames which include a set of framed tube structures with a smaller framework. Considering the fact that each of these framed tubes has a high lateral resistance, they can be arranged in any desirable shape or cut at any desirable height [6].

One of the most remarkable characteristics observed in near-field records is the presence of powerful and high-amplitude velocity pulses as well as distinct displacement waveforms in their time history [6,7,8,9,10]. Earlier study results reveal that the existence of powerful pulses in the velocity time history of strong records imposes intense nonlinear demands on the seismic response of tall steel buildings [11,12,13,14,15]. It should be noted that analysis and assessment of the parameters of asymmetric steel bundled tube responses subjected to far and near-field records can provide more accurate knowledge on the behavioral nature of these types of structures under intensive and strong ground vibrations.

2. Structural Models and Design Considerations

The studied structures in this research are bundled tubes with and without mass eccentricity in stories. The eccentricity of 10% of the plan dimension at the 45° angle with respect to the X axis was applied as a benchmark to evaluate the effects of torsion in studied structures. They are designed according to the Iranian seismic code 2800 (fourth edition) and also the Iranian national building code (steel structures - division 10) [16,17]. The buildings are 36m×36m in plan with a story height of 3.5m and a column spacing of 6m in each direction. Details of the plan and facade as well as the designed section properties are displayed in Figure 1. The site soil is of type 2 and the location of the project is assumed in a high-level earthquake hazard zone. The definition of design loads of the structure is done according to the Iranian national building code (design loads for buildings - division 6) [18]. Dead and live loads applied at all floor levels are respectively 0.5 t/m^2, 0.2 t/m^2 and 0.5 t/m^2 and 0.15 t/m^2 for the roof. Yet, the base shear coefficient is specified according to the standard lateral load defined in the Iranian seismic code 2800 (fourth edition) [14]. The section characteristics of structural elements are designed according to the Iranian national building code (steel structures - division 10) and are shown in Table1. Moreover, two design criteria are closely considered and checked which include the limitations in the seismic story drift and also considerations for the strong-column/weak-beam principle in all connections and joints [16, 17]. The first three periods of modal vibrations in the studied structures are sequentially presented in Table2. Based on the information presented in this table, it is observed that due to longer periods of the first lateral modes compared to the first torsional modes, structures perform torsionally stiff. Moreover, in the modeling process of the two studied structures and in order to define the nonlinear behavior of beam and column elements, the flexural plastic hinge M3 and the interactive nonlinear hinges P-M2-M3 are sequentially used based on FEMA-356 and 440 defined numerical recommendations [19,20]. The parametric explanation of these specified plastic hinges is presented in Figure 2.

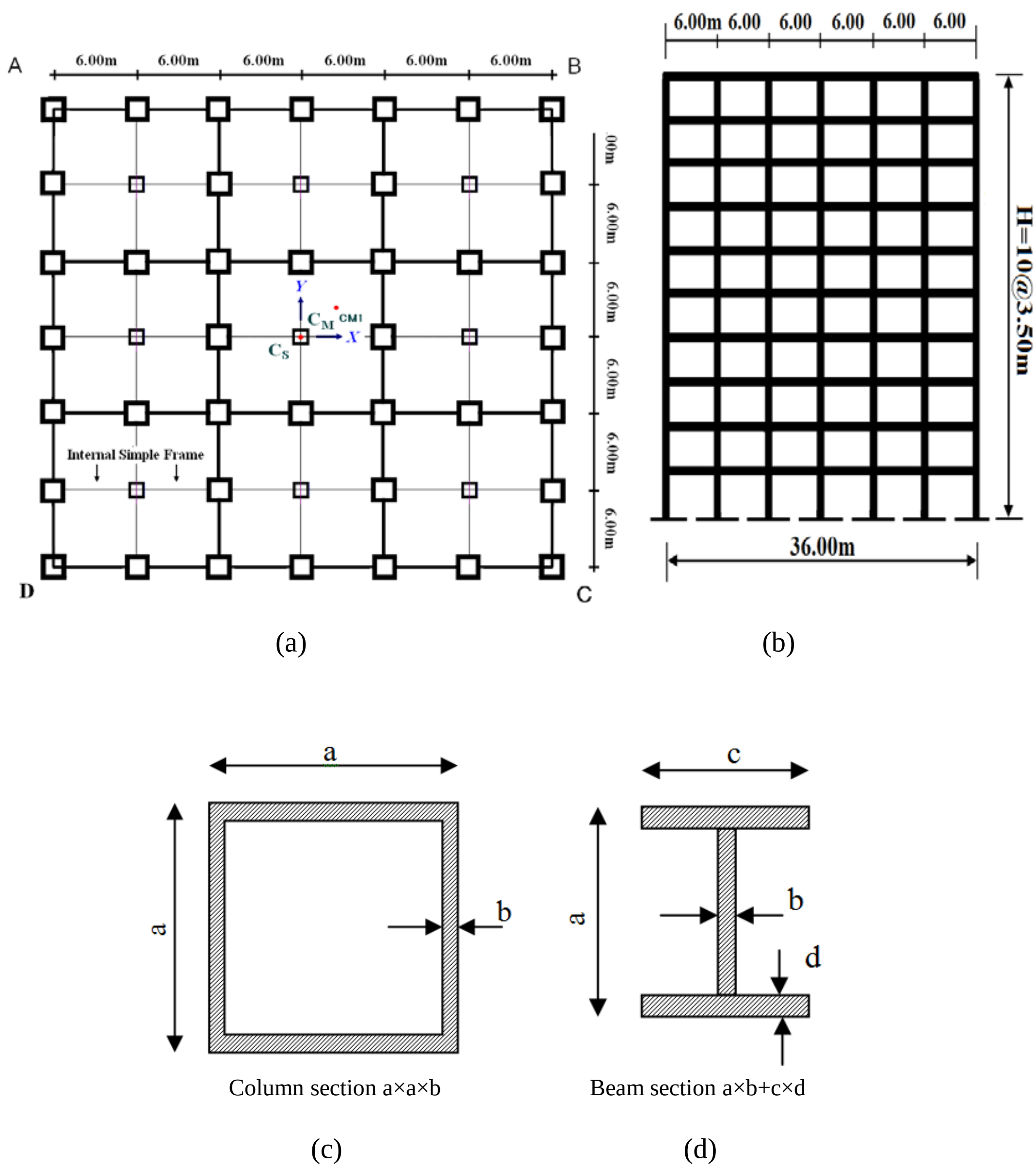


Fig. 1- Studied bundled tube structural models: (a) Plan configuration; (b) structural view (C_M: center of mass, C_S: shear center); (c) Columns section property of 10-storey models; (d) Beams section property of 10-story models

Table 1 - Structural members of the studied structural models

Stoeies Groups	Columns (Rigid Bents)	Columns (Simple Frame)	Beams (Rigid Bents)	Beams (Simple Frame)
1- 2	BOX 53×53×2.5	BOX 41×41×2	PL 45×2 + 45×2	PL 40×0.8 + 20×1.5
3 - 4	BOX 47×47×2	BOX 35×35×1.2	PL 45×2 + 45×2	PL 40×0.8 + 20×1.5
5 - 6	BOX 47×47×2	BOX 26×26×1.2	PL 40×1.5 + 35×2	PL 40×0.8 + 20×1.5
7 - 8	BOX 44×44×2	BOX 23×23×1	PL 40×1.5 + 25×2	PL 40×0.8 + 20×1.5
9 - 10	BOX35×35×2	BOX 20×20×1	PL 40×1 + 20×1.2	PL 40×0.8 + 20×1.5

Table 2 - Modal periods of the studied structural models

Lateral Resistant System	Mass Eccentricity	T_1 (sec) First Lateral Mode respect to X	T_2 (sec) Second Lateral Mode respect to Y	T_3 (sec) Initial Torsional Mode
Bundled Tube	0%	1.66	1.66	0.41
	10%	1.68	1.68	0.50

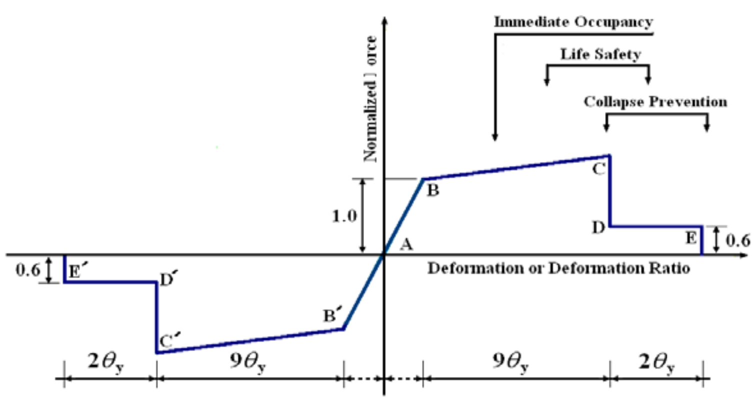


Fig. 2 - The FEMA 356 numerical considerations for the nonlinear limits of plastic hinges [19]

3. Chosen Earthquake Records

The existence of high-amplitude and long period pulses in the velocity time history is the main criterion for selecting earthquake records for the purpose of conducting nonlinear time history analyses. Chosen records involve ground motions registered in far and near-fault zones. The first group contains a few records of the Imperial Valley earthquake 1979. Figure 3 shows the quake zone of the Imperial Valley earthquake 1979 where the epicenter location is specified by a star.

As observed in the quake zone, the rupture process initiates near the earthquake epicenter in figure 3 and propagates along the fault line and also toward Calexico station (displays neutral directivity effects) and El

Centro arrays 4,5,6,7,8 and 10 which emerges strong forward directivity effects. Moreover, the illustration of forward directivity effects is relatively decreased by distancing from the fault. Agrarias station is in the opposite direction from the fault propagation course and therefore, the recorded ground motion is affected by backward directivity feature. Bonds Corner station is located near the epicenter of the earthquake, but it was observed weak directivity effects in the recorded time history. This group is important, since all the stations in it are relatively near the earthquake's epicenter and have the same soil class and near-field specifications too. The second group involves powerful records of Bam 2003 and Tabas 1979 that have high-amplitude and long period pulses in their time history. The acceleration and velocity time history of these records are shown in Figure 4.

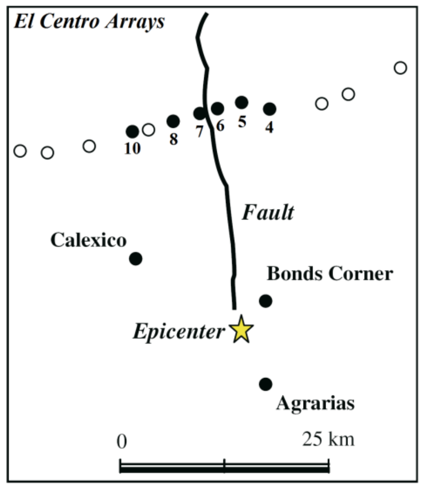
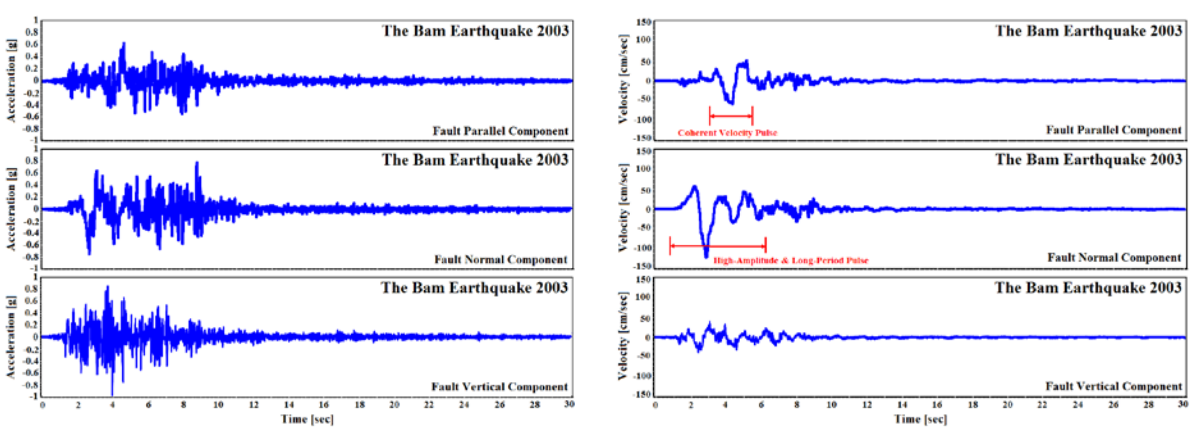


Fig. 3 - Record stations near San Andreas fault in Imperial Valley territory

Since natural records demonstrate the real seismic loading, best in the assessment and design of the structure, and since attenuating process of vertical ground motions occurs faster than the two horizontal ones, all records in this research are applied naturally. The three components of each record are applied in X, Y and Z directions simultaneously on the resistant skeleton of the studied structures. The component parallel to the fault rupture surface is applied in the X direction, the stronger perpendicular component corresponding to the rupture surface is applied in the Y direction of the structure's plan and the vertical component is applied in the Z direction too. The most important physical parameters of the chosen records including peak ground acceleration (PGA), peak ground velocity (PGV) and the momentum magnitude are displayed in Table 3 [21].



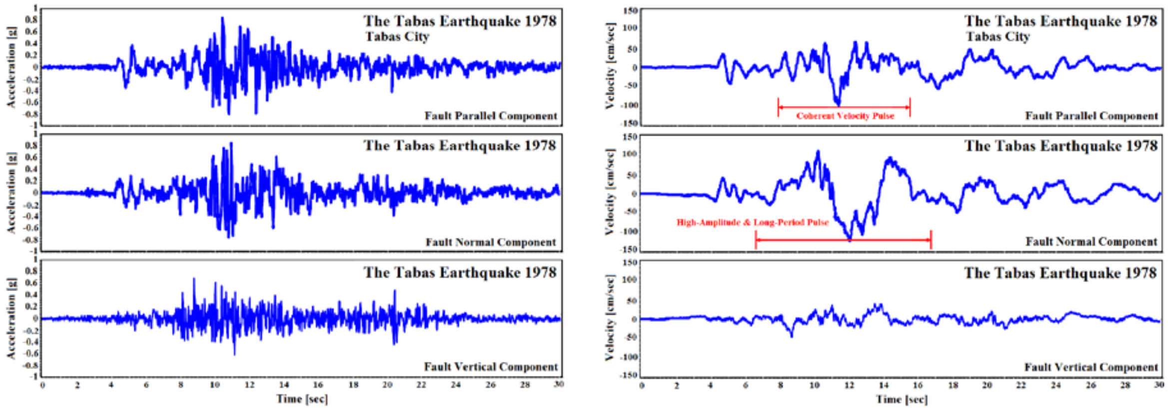


Fig.4- Three-component time history of main shock in Iranian earthquakes of Tabas 1978 and Bam 2003

Table 3 - The selected earthquake records

Earthquake	Component	Duration (sec)	PGA g	PGV cm/s	PGD cm	Magnitude M_w	PGV / PGA (sec)	PGD / PGV (sec)
The IRANIAN 2003 - Bam Earthquake (BAM)	LN	30	0.635	59.6	20.7	6.6	0.09	0.34
	TR		0.793	123.7	37.4		0.16	0.30
	UP		0.999	37.66	10.11		0.03	0.26
The IRANIAN 1978 - Tabas Earthquake (TAB)	LN	30	0.836	97.7	39.9	7.4	0.12	0.40
	TR		0.851	121.3	94.5		0.14	0.78
	UP		0.688	45.5	17		0.06	0.37
The 1979 Imperial Valley Earthquake - Agrarias (AGR)	LN	30	0.37	35.22	9.73	6.5	0.09	0.27
	TR		0.21	42.19	11.47		0.2	0.27
	UP		0.835	10.18	4.94		0.01	0.48
The 1979 Imperial Valley Earthquake - Bonds Corner (BCR)	LN	30	0.59	45.15	16.06	6.5	0.07	0.35
	TR		0.77	45.81	15.44		0.06	0.33
	UP		0.42	12.18	3.98		0.03	0.32
The 1979 Imperial Valley Earthquake - Calexico Fire Station (CXO)	LN	30	0.201	15.94	8.58	6.5	0.08	0.53
	TR		0.274	21.02	8.34		0.07	0.39
	UP		0.178	6.64	2.52		0.03	0.38
The 1979 Imperial Valley Earthquake - El Centro Array 6	LN	30	0.41	64.88	27.69	6.5	0.16	0.43
	TR		0.44	109.7	65.89		0.25	0.6
	UP		1.65	57.5	26.41		0.03	0.46
The 1979 Imperial Valley E. - Delta (DLT) - (Far Field)	LN	30	0.237	24.9	9.17	6.5	0.1	0.36
	TR		0.35	30.45	10.34		0.08	0.34
	UP		0.145	5.27	3.24		0.03	0.61
The 1940 El Centro (Far Field)	LN	30	0.215	30.2	23.91	7	0.14	0.79
	TR		0.313	29.8	13.32		0.1	0.45
	UP		0.205	10.7	9.16		0.05	0.85

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

4. Nonlinear Dynamic Analysis and Response Parameters

The seismic demands and response parameters of bundled tube models with and without mass eccentricity of 10% as described earlier, were accurately analyzed and evaluated through the application of nonlinear dynamic time history analyses by CSI software [22, 23]. This analytical process was accomplished by applying a group of strong records listed in Table 3. It is worth mentioning that nonlinear response parameters of the studied structural models were determined at various levels of ground motion intensity caused by rupture directivity effects. The illustrated variations of response parameters of analyzed models contain maximum base shear, maximum absolute acceleration, maximum relative velocity and maximum seismic story drift of the studied structures.

The corresponding maximum seismic base shear is given while subjected to earthquake records in Y direction in Figure 5. As illustrated in the figure, Bam record has caused the largest base shear value to the bundled tube (with and without mass eccentricity of 10%), while Calexico record was the least destructive in Y direction under the TR component of earthquake records. Yet, the response parameter of dynamic base shear might be high when subjected to some near-fault earthquake records. This effect is due to the presence of long-term and high-amplitude pulses in near-fault records time history, causing the release of sudden energy in a short period of time during a single or few large domain excursions.

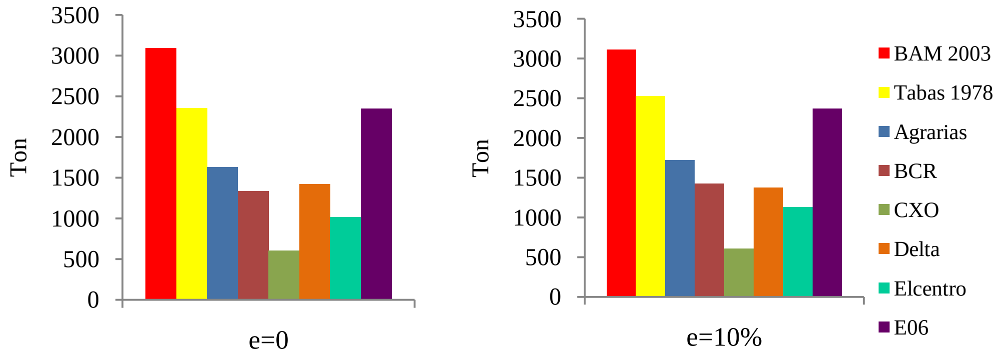


Fig. 5 - Calculated base shear in Y direction of studied bundled tube models

The envelop curves of maximum relative velocity of bundled tube floors (with and without mass eccentricity of 10%) are illustrated in Figure 6. As witnessed, Bam record has caused the highest relative velocity in buildings in Y direction. However, Calexico record has also caused the lowest relative velocity in bundled tubes in Y direction.

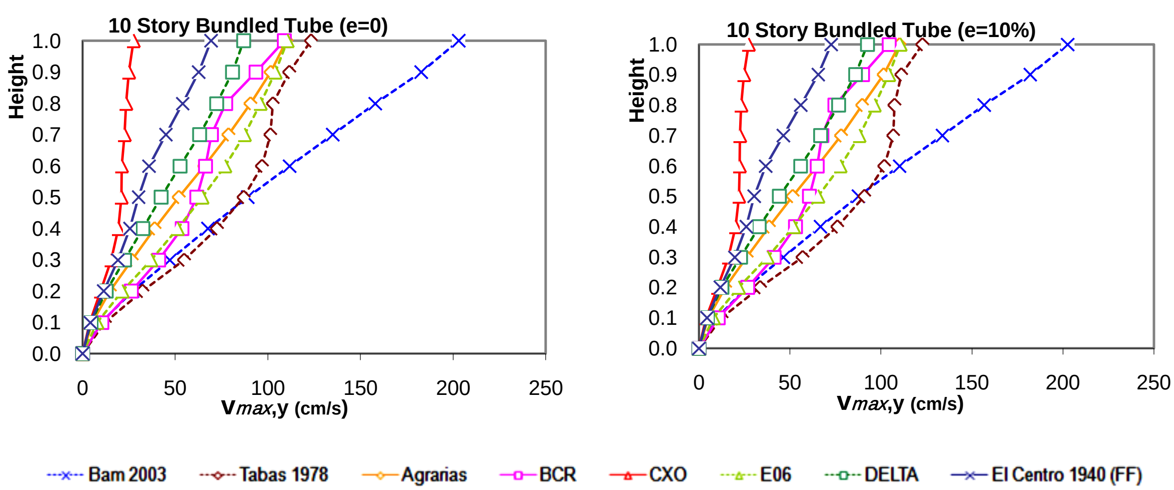


Fig. 6 - Envelope curves of maximum relative velocity of floors

Maximum absolute acceleration of bundled tube levels (with and without mass eccentricity of 10%) under natural earthquake records are illustrated in Figure 7. Bam and Tabas records have caused the highest absolute acceleration in buildings along Y direction and Calexico record has caused the lowest absolute acceleration in bundled tubes in Y direction. The absolute seismic acceleration of levels reveals curve-shaped trends displayed in Figure7. The parameter of absolute acceleration of the floor was high on lower levels because of extreme inertial forces. This demand parameter would decline in mid-levels and finally increase again at top levels because of higher-mode effects.

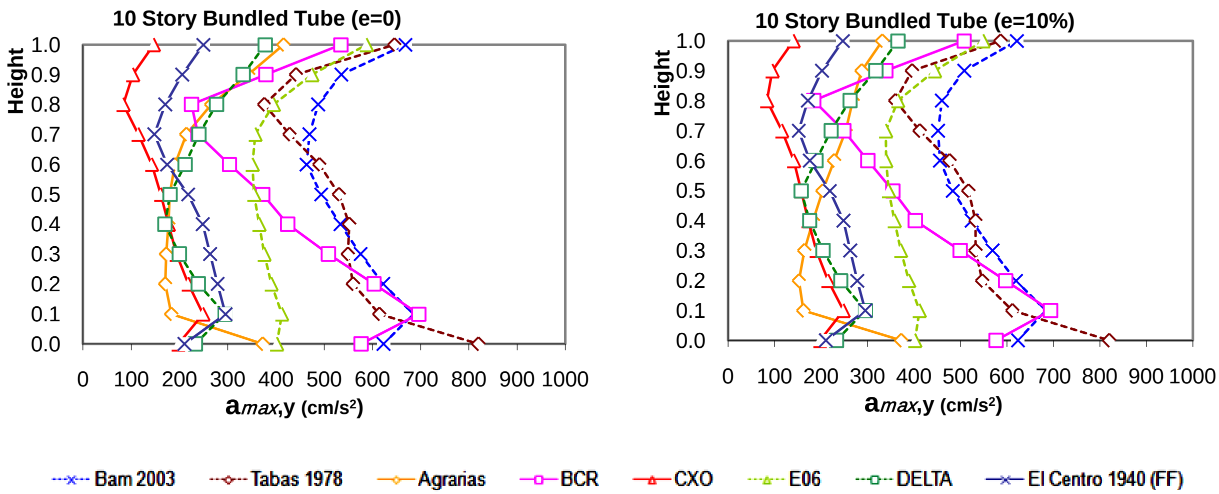


Fig. 7 - Envelope curves of maximum absolute acceleration of floors

High values of absolute acceleration and relative velocity under powerful near-field earthquake records are due to base acceleration at the foundation, plus long-term and high-amplitude pulses in their time history. Based on the results of this research, maximum absolute acceleration and maximum relative velocity of levels in models under near-field earthquake records are considerably higher than the same values obtained under far-field records. These results can refer to the nature of strong ground motions containing forward directivity effects. These earthquake records are capable of displaying wave-like features in their time history, especially in the form of coherent high-amplitude velocity pulses (Table 3, Figure 4). Additionally, the distribution of floor acceleration at the heights of the structure reveal larger values of this parameter in comparison with the results under far-field records and those near-field earthquakes which do not display velocity pulses or even velocity spikes.

Seismic drift or relative displacement between two consecutive levels normalized by height is defined as a main parameter of seismic demand, since there is a rational relationship between seismic drift and ductility demand of each level. The seismic drift of Y direction in stiff and flexible edges resulted from nonlinear time history analyses of the studied structures subjected to two sets of ground motions are presented in Figures 8 and 9. Based on Figure 1, two lines of AB and BC show the flexible edges of the structure plan. Far-field motions like the El Centro (ELC) record produce quite a consistent seismic drift in bundled tubes (with and without mass eccentricity of 10%). However, near-field records impose higher demands than far-field records although maximum seismic drift is generally concentrated at mid levels. The largest demand is caused by Bam record and the lowest demand is caused by Calexico record in Y direction of the studied bundled tubes. It should be noted that the calculated seismic drift values in stiff and flexible edges in most used records do not overpass the permitted amount in the Iranian seismic code 2800 which equals 0.02, but the powerful near-field record of Bam exceeds this measure.

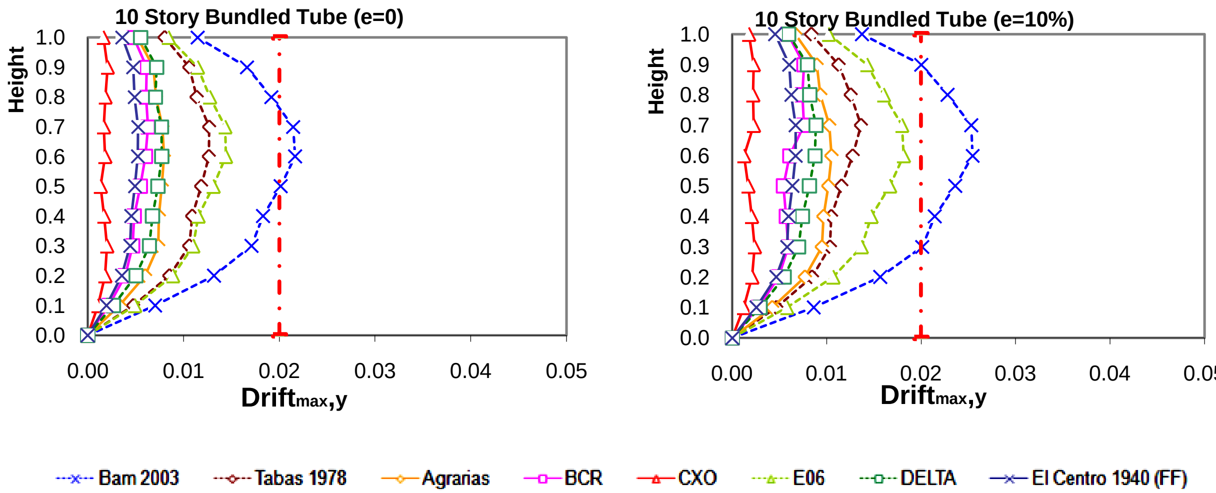


Fig. 8 Seismic drift variations in flexible edges of AB and BC in Figure 1

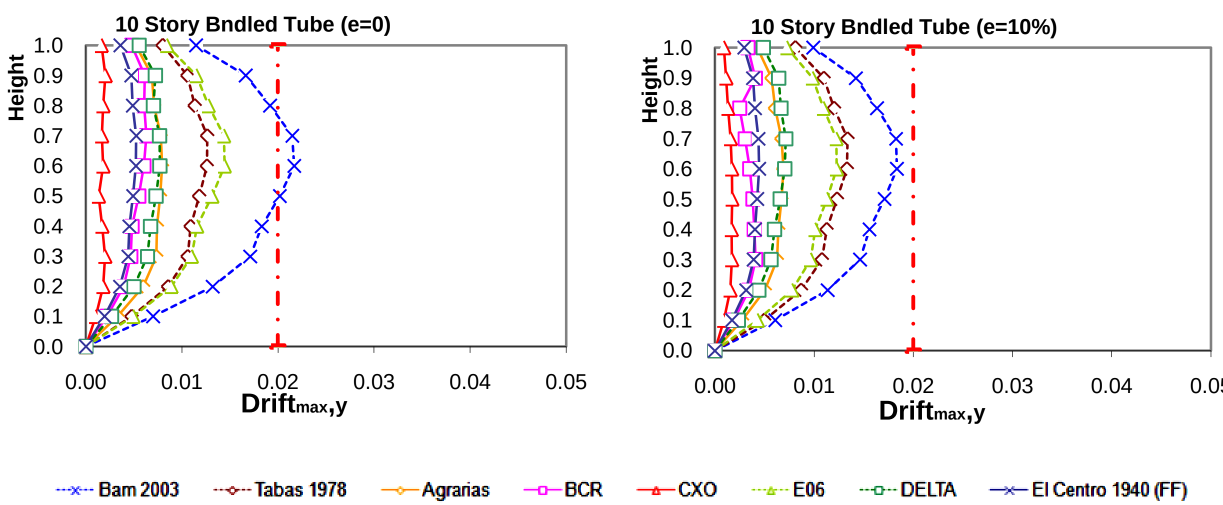


Fig. 9 - Seismic drift variations in stiff edges of AD and DC in Figure 1

Higher mode effects are predominant subjected to many near-fault records (e.g., Bam, Tabas, Array6) causing a shift in demand from lower to upper levels. Variations in story demand for far-field records are less significant. To put it in another way, higher mode effects could play a role in seismic responses of bundled tubes (with and without mass eccentricity of 10%). In order to determine the contribution of higher modes, it is necessary to inspect both acceleration and velocity response spectra of the selected ground motions, collectively. Figure 10 depicts the velocity response spectra of applied records which generated the demands in bundled tubes. In examining spectral contents of records, it must be noted that modal periods are gradually changing in a nonlinear manner and that these alleged higher-mode periods also shift as the response domain of the structure moves into an inelastic range. Three vertical bold lines shown in Figure 10 refer to modal periods of bundled tubes (with mass eccentricity of 10%) in the elastic range. All these lines will gradually move to the right as the yielding component progresses. In order to correlate the information on spectral demands with the observed behavior, the building responses were re-examined. As observed, Bam and Tabas records produced larger demands at mid and top levels of bundled tubes (with mass eccentricity of 10%). The spectral velocity for these records at the higher-mode periods are large, keeping in mind that a shift to the right of the spectra is to be expected as the intensive yielding of components occurs.

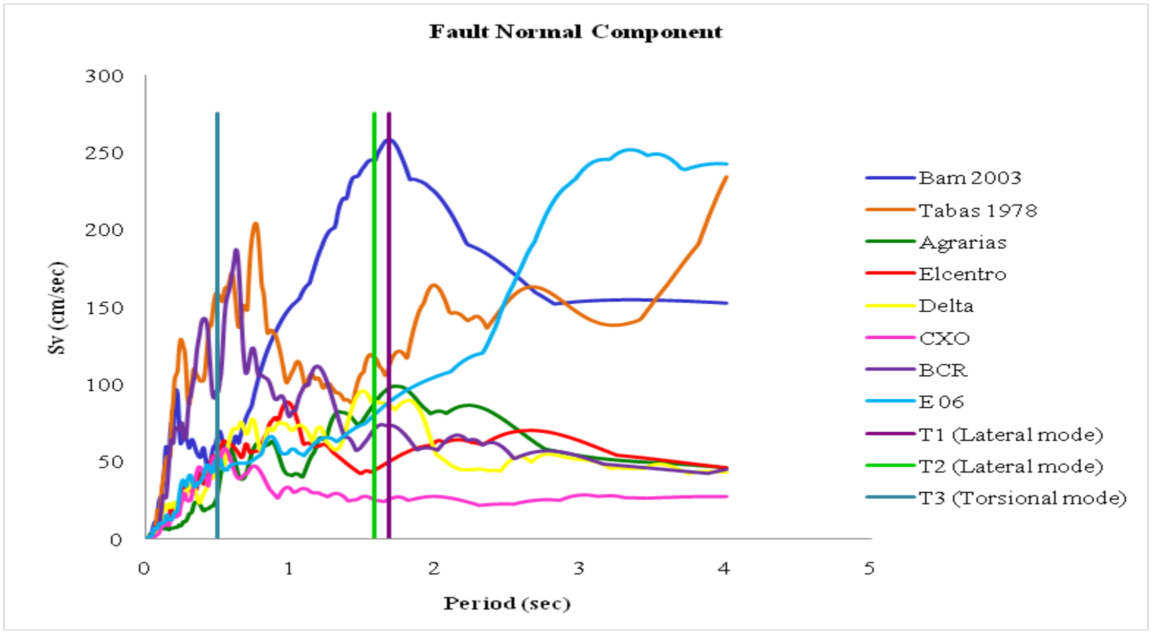


Fig. 10 - Velocity response spectra due to selected records and the specified axis of the first three modal periods as noted in Table 2 related to bundled tube model with mass eccentricity of 10%

The average seismic drifts of bundled tubes in stiff and flexible edges are presented in Figures 11 and 12 for Y direction. The average seismic drift of flexible edges rises by an increase in mass eccentricity in bundled tubes. Moreover, the average seismic drift of stiff edges of bundled tubes declines by an increase in mass eccentricity.

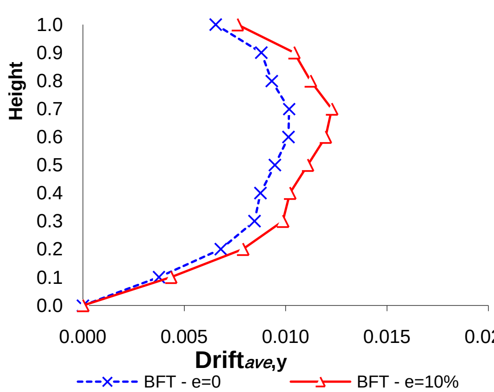


Fig. 11 – Variations of average seismic drift of flexible edges of AB and BC in Figure 1

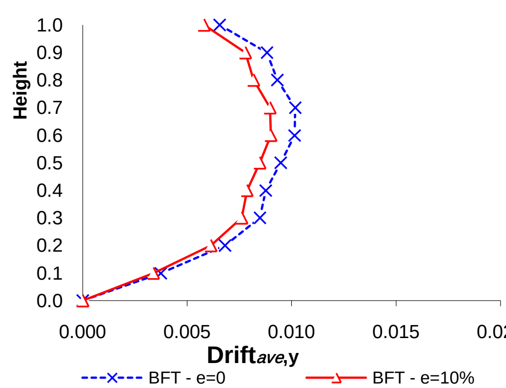


Fig. 12 – Variations of average seismic drift of stiff edges of AD and DC in Figure 1

Plastic hinges mechanism created by nonlinear seismic behavior under Tabas record is shown in Figure 13. Most plastic hinges are generally concentrated at mid levels of the bundled tube resistant skeleton. Also, analytical assessments show higher amplitude for the seismic performance of plastic hinges in flexible edges compared to stiff edges of the plan.

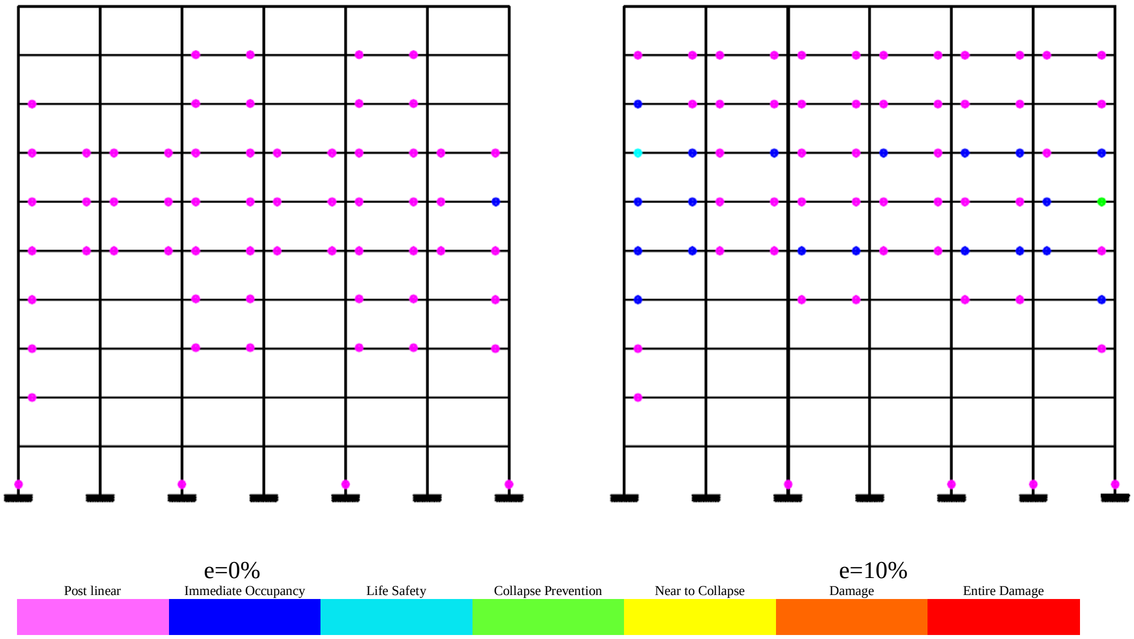


Fig. 13 -Final plastic hinge mechanisms formed in studied models of Figure 1 in Y direction of plan (frame located on BC edge) under near-field record of Tabas 1978

5. Concluding Remarks

The purpose of this research has been to conduct a more thorough study on important physical characteristics of recorded ground motions near to and far from the fault rupture plate, as well as their effects on the seismic response parameters of asymmetric steel bundled tube systems. The torsional behavior of a code-compliant ten-story bundled tube with and without mass eccentricity on levels has been studied under near-fault records. This conclusion is evidently obtained considering the base shear, absolute acceleration, relative velocity and seismic story drift and according to nonlinear dynamic analyses under strong earthquake records. The group of chosen near-field records includes strong ground motions containing high-amplitude and long term pulses in their velocity time history. The existing velocity pulse creates higher demand and more intensive seismic responses specially for seismic story drift from lower to mid and top floor levels and therefore, results in the participation of higher vibration modes in the seismic behavior of the studied bundled tube models.

Torsional behavior of bundled tubes with different configurations against torsion may be significantly different from what has been observed in this study and therefore, needs to be rigorously investigated. The average seismic story drift rises by an increase in mass eccentricity in flexible edges and declines with an increase in mass eccentricity in Stiff edges. Also, analytical assessments show higher amplitude for the seismic performance of plastic hinges in flexible edges of the plan compared to stiff edges. Finally, it can also be concluded that a careful examination of velocity response spectra can provide engineers with a reasonable assessment of potential damages caused by near-fault records. Moreover, it has been observed that rigid bundled tube systems satisfy code restrictions for seismic story drift subjected to the most near-filed earthquake records.

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