Technical Note

Study on Seismic Response of Asymmetric Framed and Bundled Tube Resistant Skeletons in Near-Field Zones

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ABSTRACT

In this research, the seismic performance capabilities of both framed and bundled tube systems are studied in order to assess the dynamic response of symbolic asymmetric mid-rise steel structures subjected to both far and near-field earthquake records. For this purpose, two 10 story structural models based on framed and bundled tube skeletons were selected and designed. The main criterion considered in selecting strong earthquake records for performing nonlinear time history analyses is the existence of high amplitude and long period coherent pulse or multiple pulse features in the ground velocity time history. The mentioned powerful velocity pulse makes more seismic demands and would cause a complicated 3D dynamic response which conveys the maximum seismic drift demand from lower stories to middle or even upper ones. Yet, the participation of higher vibration modes in seismic behavior of the studied structures were also taken into account. Overall, seismic response parameters of asymmetric rigid framed tube and bundled tube skeletons are not effectively sensitive to small amounts of mass eccentricity. Moreover, this research analytical assessments show larger amplitude for the seismic nonlinearity of plastic hinges in flexible edges of the structure plan compared to stiff edges. Additionally, the floors dynamic torsional movements cause unequal yielding mechanisms, which are formed in the sided bending frames. Moreover, during the aforementioned process, the frames located at one side of the plan would reach to collapse prevention performance level (CP). Finally, it is observed that rigid framed tubes and bundled tubes can satisfy the Iranian design code restrictions for story drift.

Keywords:
Framed Tube, Bundled Tube; Irregular Bent; Mass Eccentricity; Near-Field Record

1. Introduction

Torsional irregularities in the plan caused by the actual distance between rigidity center (CR) and mass center (CM) would result in uneven demands for structural elements of the building. Assessing post-earthquake structural damages shows that, torsional effects were the major cause of severe damages and collapses of quite a few buildings during 1985 earthquakes in Mexico and Chile [1-2]. Early studies of the seismic behavior of torsionally-irregular buildings used to focus on buildings responding in an elastic range. Later researches focused more on inelastic responses of single-story and multi-story buildings, too. 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 subjected to ground motion with the lower intensity parameter [2-3]. This process would increase the structural ductility demands. Moreover, reviews of recent researches have been performed by Anagnostopoulos et al. [4], De Stefano and Pintucchi [5] and Rutenberg et al. [6].

Steel moment-resisting frames have been extensively used in regions of high seismicity for midrise and tall buildings because of their high structural efficiency and considerable ductility. In mid-rise structures when all outer and inner frames are designed as lateral load resistant system, the strong column and weak beam principle leads to an over-designation for columns when the beam design is governed by gravity loads. To achieve a more economical design, framed and bundled tube systems are used [7]. The basic structural models studied in this research are three-dimensional framed and bundled tube bents with and without a defined mass eccentricity in stories [7-9].

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 [10-11]. 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 mid-rise to tall steel buildings [12-16]. It should be noted that analysis and assessment of the parameters of asymmetric steel framed and 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. In the present study, the selected near-fault motions are characterized by forward-directivity effects, which are potentially more damaging as compared to far-field motions. Nonetheless, the analytical results denote that the studied framed tube and bundled tube structures, satisfy the performance criterion lower than the limit of seismic drift of 0.02, specified by the Iranian seismic code 2800. The existence of an eccentricity between the location of the center of mass and the center of stiffness leads to the appearance of torsion behavior in the studied models. This torsion action can cause large drift at the plan corners of the flexible face of buildings.

2. Building Description and Design Details

Two hypothetical 10-story residential building are designed in this study, according to the Iranian seismic code 2800 (fourth edition) and Iranian national building code (steel structures - Issue 10) using equivalent lateral force method [17-18]. The buildings are assumed to be on stiff soil and steel with yield strength of $F_Y = 2400\,\mathrm{Kg/cm^2}$ and ultimate strength of $F_u = 4000\,\mathrm{Kg/cm^2}$ is used for all beams and columns. The buildings configuration is stiffened framed tube and bundled tube. The buildings are $36\mathrm{m} \times 36\mathrm{m}$ in plan, with story heights of 3.5 m and column spacing of 6 m in each direction (Figure 1). The lateral loads are carried by four moment resisting frames on each side of the buildings in both systems, i.e. the stiffened framed tube and the bundled frame tube. However, the remaining elements were designed to resist gravity loads only. Figure (1) also depicts the CS (the story shear center) and CM (the floor center of mass) for 10% mass eccentric case. Table (1) lists the steel sections for both studied systems of stiffened framed tube and bundled frame tube. Floor slabs are composed of 150 mm thick light-weight concrete over thick steel deck. For gravity loads, a dead load of 0.5 ton/m^2 including self-weight of the structural

Table 1. Structural members of the studied models of Figure (1) (sizes are in cm).

Stories Groups	Columns (Rigid Frame)	Columns (Simple Frame)	Beams (Rigid Frame)	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

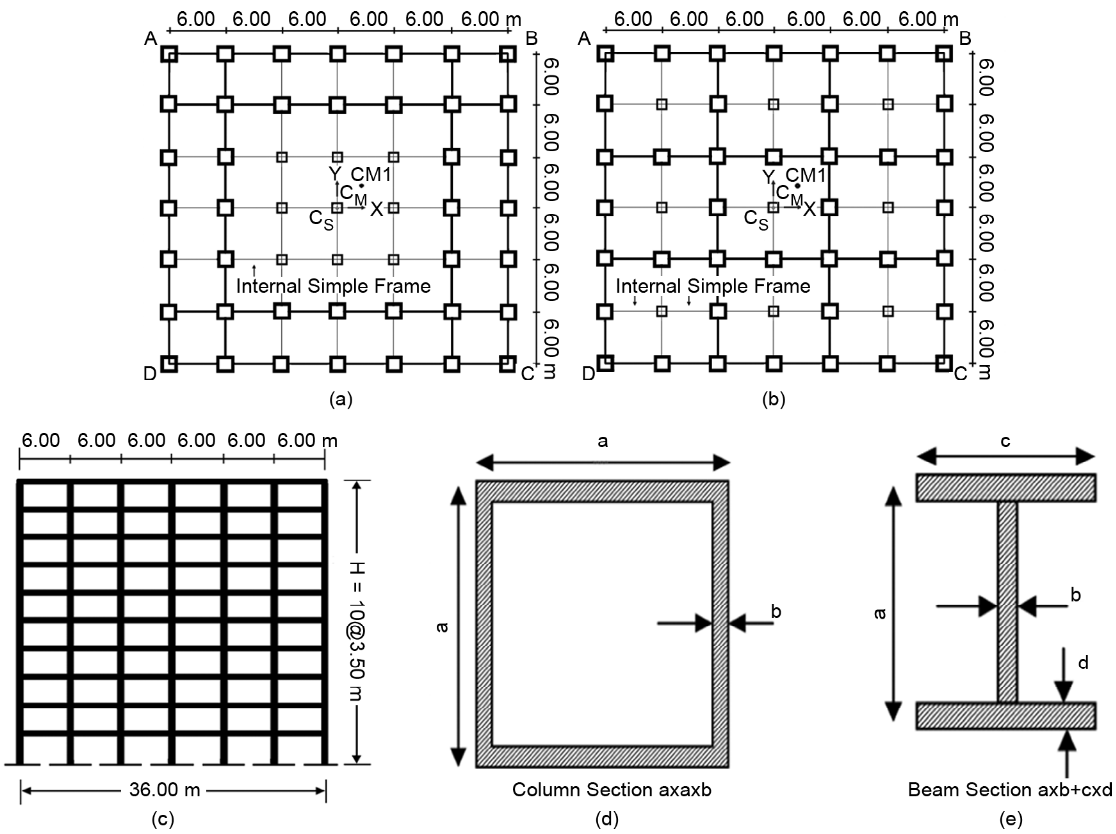

Figure 1. The studied structural models: (a) The framed tube skeleton; (b) The bundled tube skeleton; (c) Structural view (CM: the floor center of mass, CS: the story shear center); (d) Columns section property; (e) Beams section property.

Table 2. Modal vibration periods of the studied structural models.

Lateral Resistant System	Model	Base Shear Coefficient	Static Base Shear (ton)
Stiffened Framed Tube	10 story	0.093	649.64
Bundled Tube	10 story	0.093	649.64

Table 3. Modal vibration periods of the studied structural models.

Lateral Resistant System	Mass Eccentricity	T_1 (sec) First Lateral Mode (Axis X)	T_2 (sec) First Lateral Mode (Axis Y)	T_3 (sec) Initial Torsional Mode (Axis Z)
Stiffened Framed Tube	0%	1.66	1.66	0.41
	10%	1.68	1.66	0.50
Bundled Tube	0%	1.66	1.66	0.41
	10%	1.68	1.66	0.50

steel, mechanical, and electrical equipment is applied to both floors and roof. Live load is taken as 0.15 ton/m^2 for the roof and 0.2 ton/m^2 for the floors [19]. The seismic base shear coefficient and static base shears are given in Table (2).

Two detailed three-dimensional (3D) model of the buildings were developed in the CSI software computational environment [20-21]. The eccentricity of 10% of the plan dimension at angle of 45° to X principal direction was applied as the benchmark to evaluate the effects of torsion in the building. Gravity beams were modeled with moment releases at both ends. All the columns of moment resisting frames were fixed at the base, whereas gravity columns were pinned, too. A rigid diaphragm constraint was applied to account for floor slab action.

The natural periods of the three modes for all noted buildings are given in Table (3). The first two vibration modes of the buildings are at angle of -45° and +45° to X principal direction respectively. Based on the information presented in this table, it

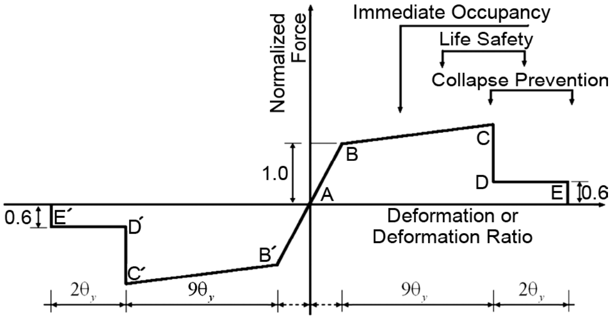

Figure 2. The FEMA 356 numerical considerations for the nonlinear limits of plastic hinges [22].

is observed that due to the longer period of the first lateral mode compared to the first torsion mode, the structures perform torsionally stiff. Moreover, in the modeling process of all 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 [22-23]. The parametric explanation of these specified plastic hinges is presented in Figure (2).

3. Ground Motion Selection

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. The chosen records involve ground motions registered in far and near-fault zones. The first group contains a few records of the Imperial Valley earthquake in 1979. Figure (3) shows the quake zone of the Imperial Valley earthquake in 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 rupture line. This rupturing process toward the Calexico station displays neutral directivity effects in the recorded time history. However, the recorded ground motions at the El Centro arrays 4, 5, 6, 7, 8 and 10 distinctly emerge forward directivity effects with various level of kinetic energy. Moreover, the illustration of forward directivity effects is relatively decreased by distancing from the fault.

The Agrarias station is in the opposite direction from the fault propagation course, and therefore, the recorded ground motion is affected by backward

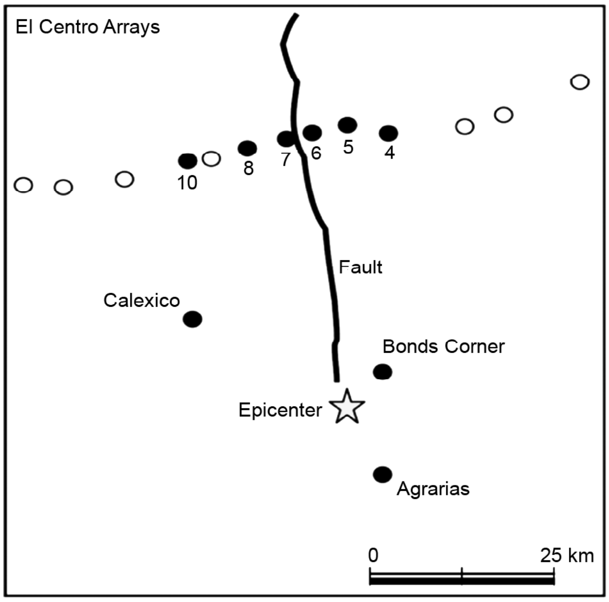

Figure 3. Record stations near San Andreas Fault in Imperial Valley territory.

directivity feature. The 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).

Since natural records demonstrate the real seismic loading caused by ground vibrations, best in the seismic assessment of the structure, thus all records in this research are applied naturally. The aforementioned process was done based on the use of three component earthquake records. However, the seismic attenuating process of vertical component of strong ground motions occurs faster than the two horizontal ones, i.e. both of fault parallel and normal components. The three components of each record are applied in X, Y and Z directions simultaneously on the resistant skeleton of the studied models (Figure 1). 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

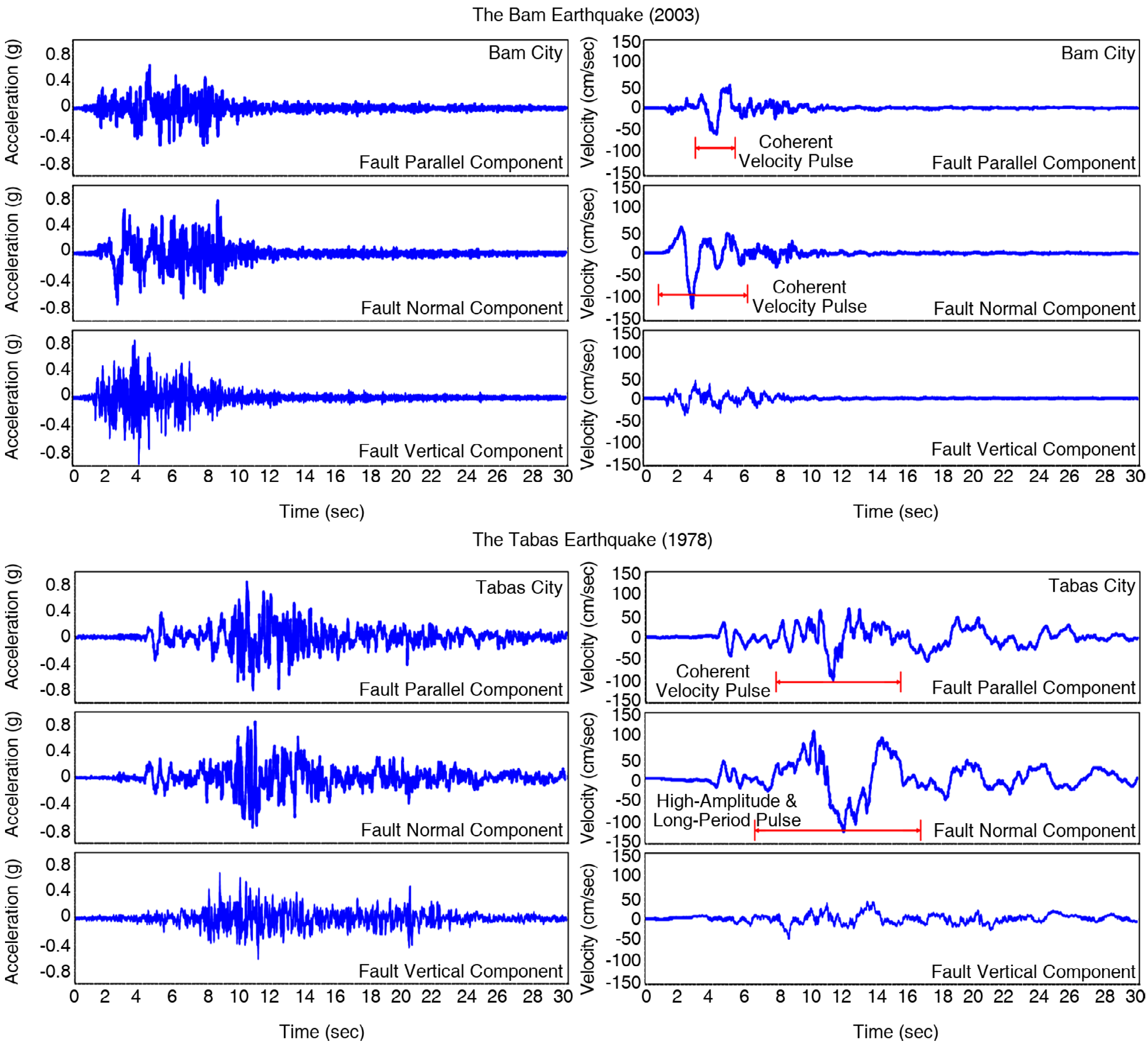

Figure 4. Three-component time history of the main shock of the Iranian earthquakes of Tabas 1978 and Bam 2003.

records including peak ground acceleration (PGA), peak ground velocity (PGV) and the momentum magnitude are displayed in Table (4) [24].

4. Nonlinear Dynamic Analysis and Response Parameters

The seismic demands and response parameters of framed tube and bundled tube models without and with mass eccentricity of 10% described above, were accurately analyzed and evaluated via employing non-linear dynamic time history procedure by CSI software [20-21]. This analytical process was accomplished subjected to the ensemble of strong ground motion listed in Table (4). It is worth men-tioning that the nonlinear response parameters of the models were determined at varying levels of ground motion intensity caused by rupture directivity effects. The illustrated variations of response parameters of the analyzed models contain the maximum base shear, the maximum absolute accel-eration, the maximum relative velocity and the maximum drift demand of stories of the studied structures.

The corresponding maximum seismic base shear is given while subjected to earthquake records in Y direction in Figures (5) and (6). As illustrated in the figures, the Bam record has caused the largest base shear value to the framed and bundled tubes (with and without mass eccentricity of 10%). Nevertheless, the Calexico record was the least destruction in Y direction under the TR component of earthquake records. However, the response parameter of dynamic base shear might be high when subjected to some near-fault earthquake records contain high-amplitude and long-period pulses. This effect is due to the presence of the aforementioned powerful directivity pulses displayed in near-fault records time history, causing the release of a large amount of energy in a short period of time during a single or few large domain excursions.

The envelop curves of maximum relative floor velocity of the studied structural models (with and

Table 4. The selected earthquake records.

Earthquake	Component	Duration (sec)	PGA (g)	PGV (cm/s)	PGD (cm)	Magnitude (M_w)	PGV / PGA (sec)	PGD / PGV (sec)
Iran - Bam 2003 Bam City (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
Iran - Tabas 1978 Tabas City (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
Imperial Valley 1979 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
Imperial Valley 1979 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
Imperial Valley 1979 Calexico (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
Imperial Valley 1979 Array 6 (E06)	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
Imperial Valley 1979 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
El Centro 1940 (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

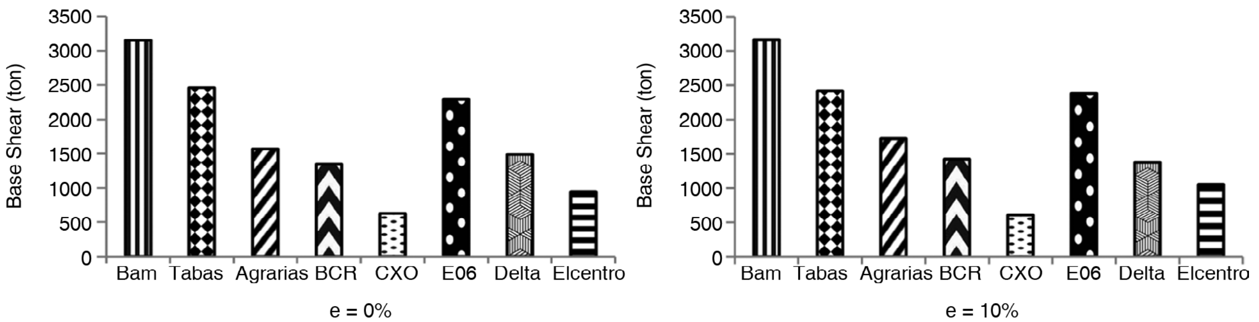

Figure 5. The calculated base shear in Y direction of the studied framed tube models.

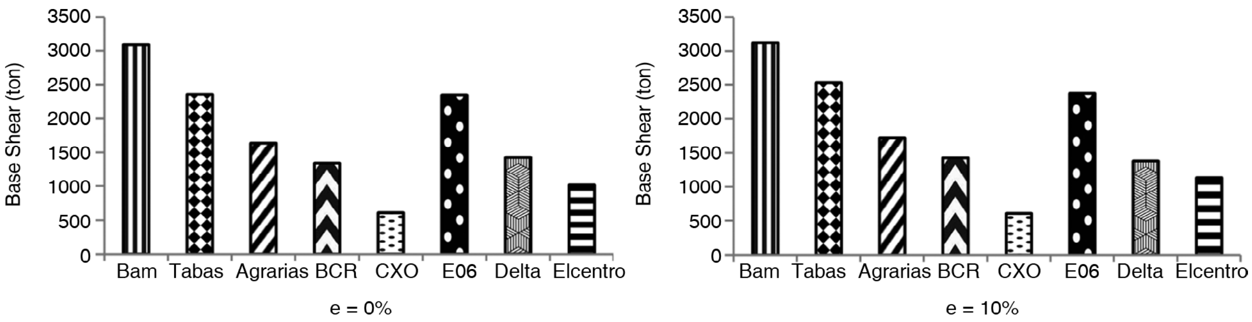

Figure 6. The calculated base shear in Y direction of the studied bundled tube models.

without mass eccentricity of 10%) are illustrated in Figure (7). As witnessed, the Bam record has caused the highest relative velocity in the buildings in Y direction. However, the Calexico record has also caused the lowest relative velocity in the framed tubes and bundled tubes in Y direction.

Maximum absolute acceleration of the studied framed tube and bundled tube levels (with and without mass eccentricity of 10%) under natural earthquake records are illustrated in Figure (8). Both of the Bam and Tabas records have caused the highest absolute acceleration in buildings along Y direction, and the Calexico record has caused the lowest absolute acceleration in framed and bundled tubes, too. The absolute seismic acceleration of levels reveals curve-shaped trends displayed in Figure (8). 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.

High values of the absolute acceleration and the relative velocity under powerful near-field earthquake records can be due to the base acceleration at the foundation, plus long-term and high-amplitude pulses in time history of the selected records. 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 subjected to far-field records. However, 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 4 and Figure 4). Additionally, the distribution of floor acceleration at the heights of the structure reveals 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

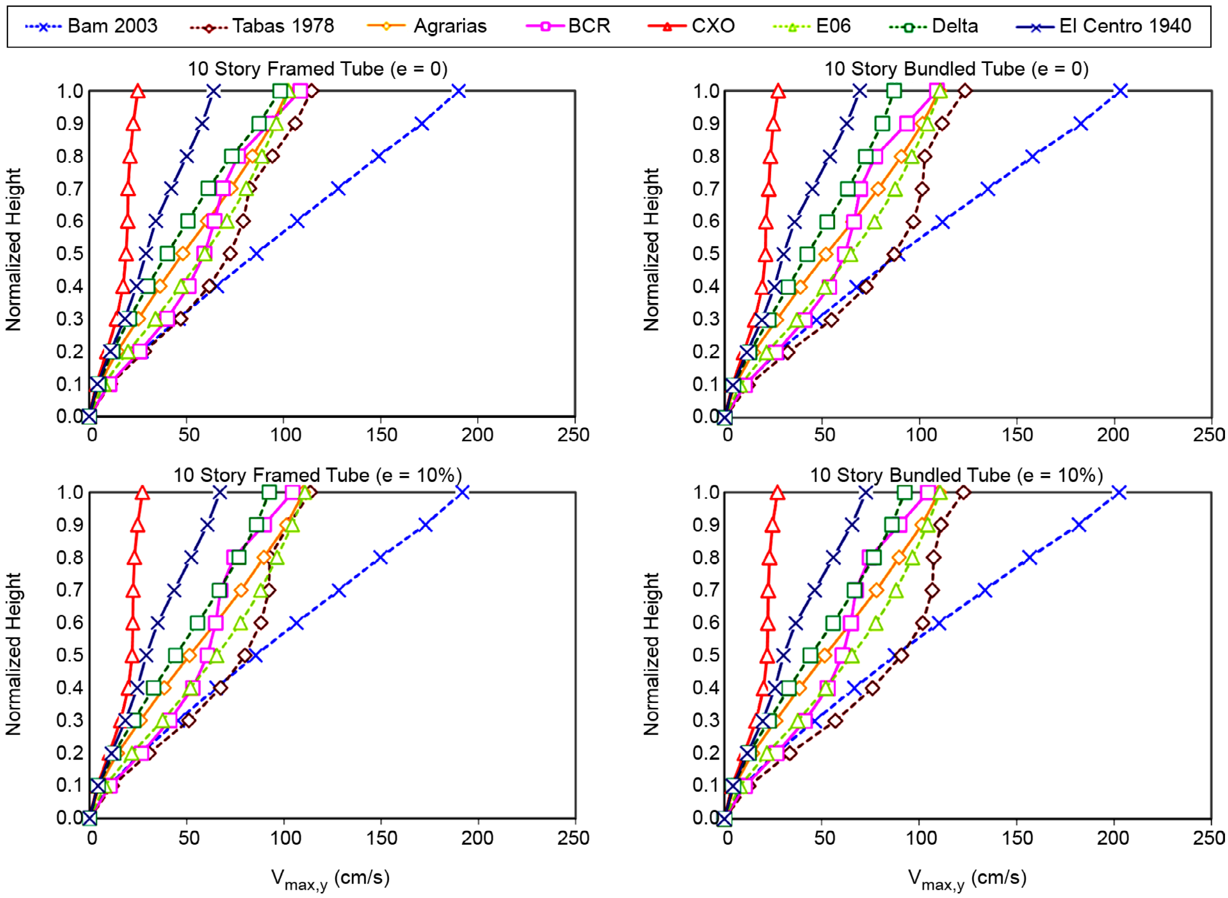

Figure 7. Envelope curves of the maximum relative velocity of floors.

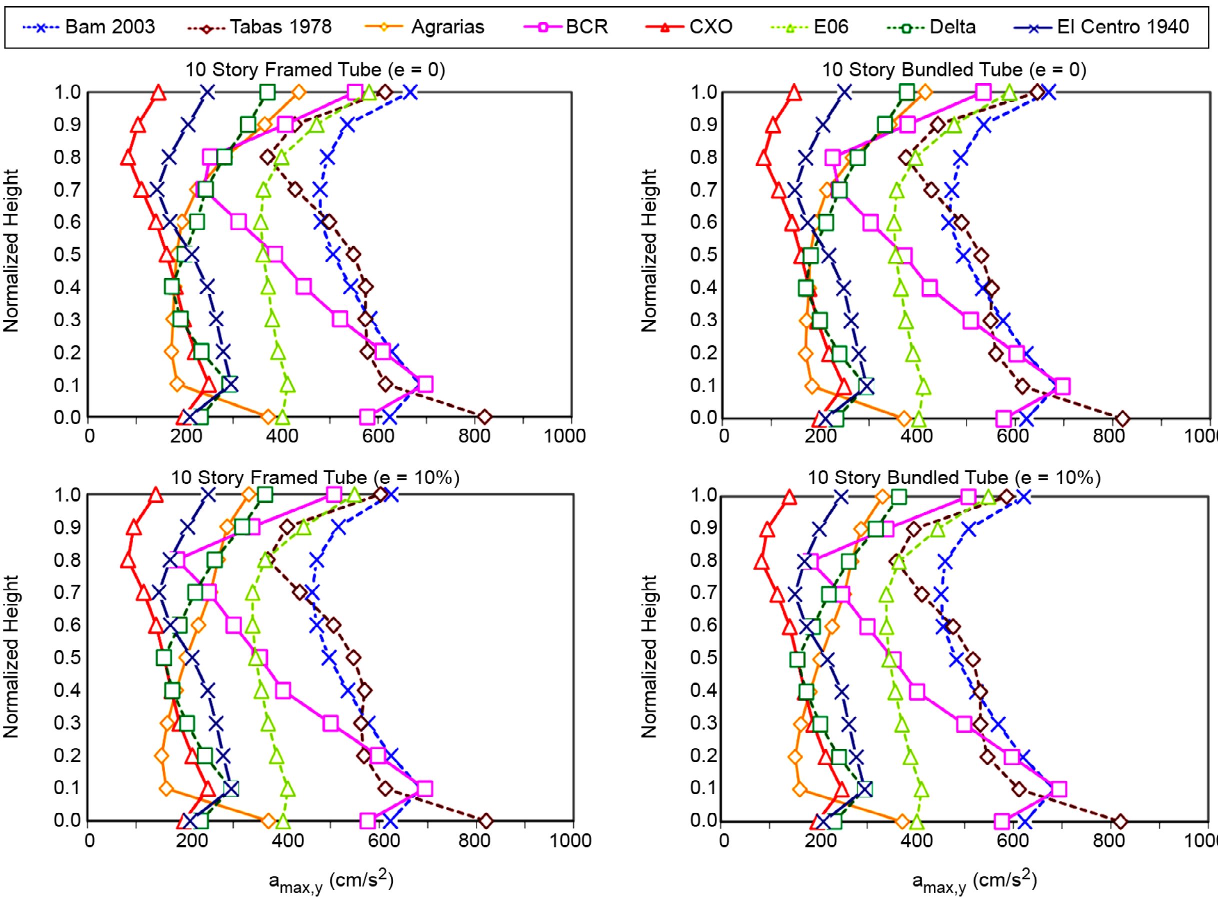

Figure 8. Envelope curves of the maximum absolute acceleration of floors in Y direction.

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 (9) and (10). 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 framed tubes and bundled tubes (with and without mass eccentricity of 10%). However, near-field records impose higher demands than far-field ones although maximum seismic drift is generally concentrated at mid-levels. The largest demand is caused by the Bam record and the lowest demand is caused by the Calexico record in Y direction of the studied structures in Figure (1). It should be noted that the calculated seismic drift values in stiff and flexible edges, subjected to most used records do not overpass the permitted amount in the Iranian seismic code 2800 that equals 0.02, but the powerful near-field record of Bam exceeds this measure.

Higher mode effects are predominant subjected to many near-fault records (e.g. Bam, Tabas, Array 6) causing a shift in the considered demand parameter 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 framed tubes and 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 (11) depicts the velocity response spectra of the applied records, which generated the demands in framed tubes and bundled tubes.

In examining spectral contents of the records, it must be noted that modal periods are gradually changing in the nonlinear range and that these alleged higher-mode periods also shift gradually as the response domain of the structure moves into an inelastic range. Three vertical bold lines shown in Figure (11) refer to modal periods of framed tubes

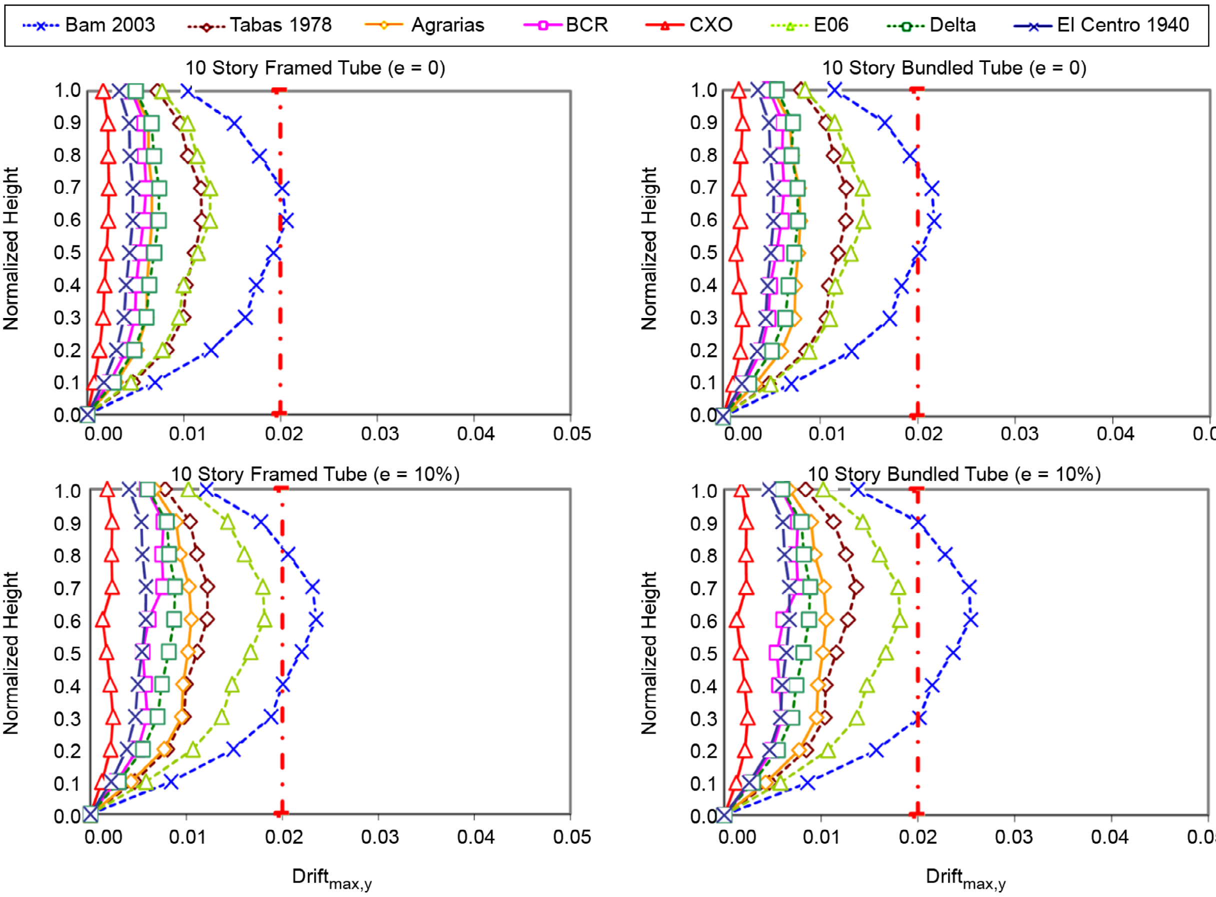

Figure 9. Seismic drift variations in the flexible edges of AB and BC in Figure (1).

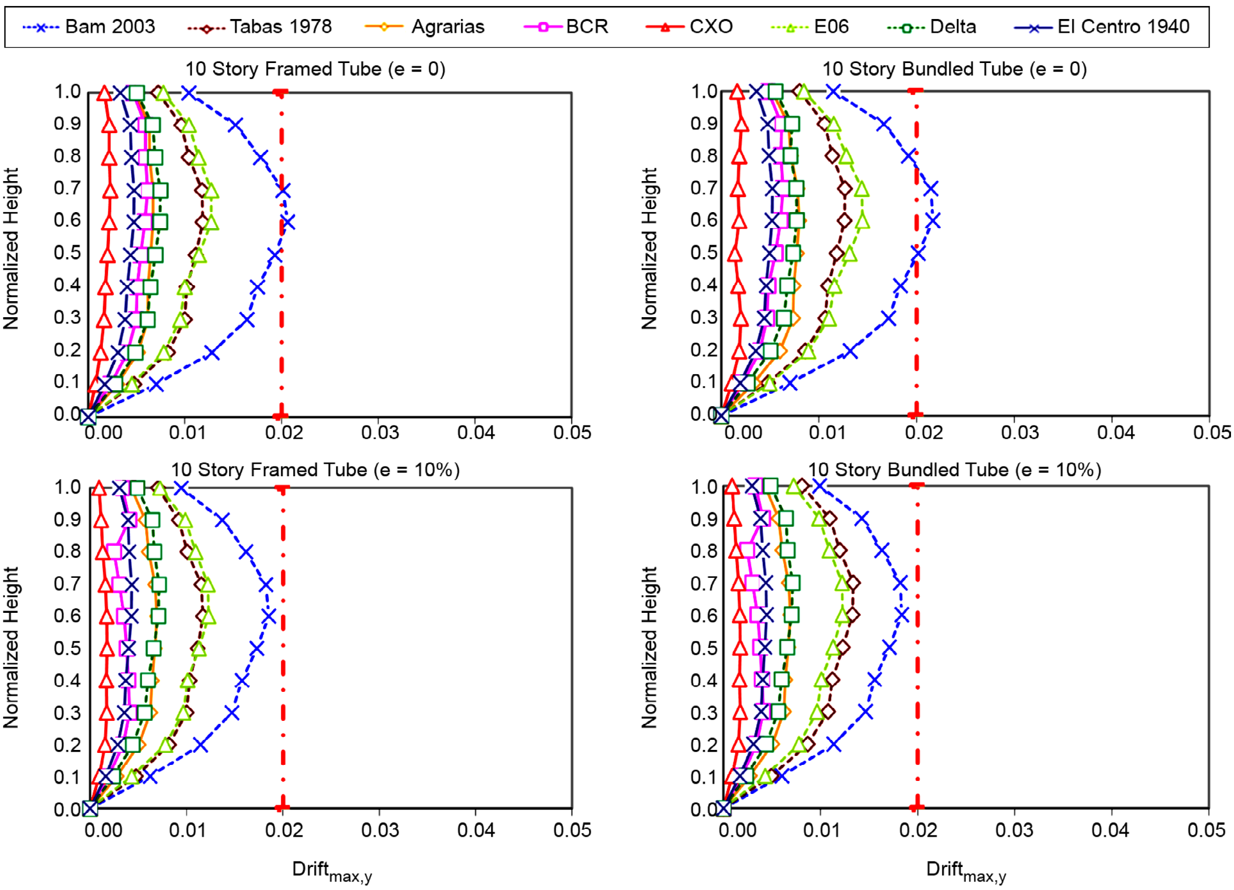

Figure 10. Seismic drift variations in the stiff edges of AD and DC in Figure (1).

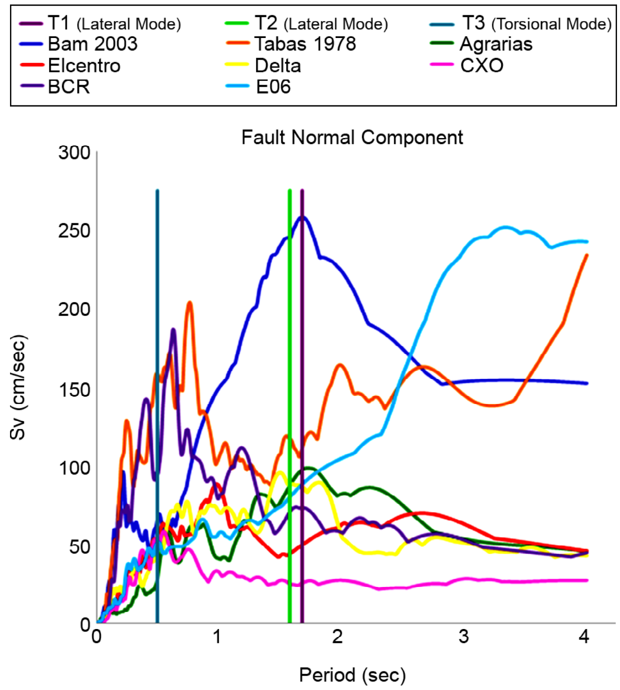

Figure 11. Velocity response spectra due to the selected records and the specified axis of the first three modal periods as noted in Table (3) related to the studied models with mass eccentricity of 10%.

and 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, the Bam and Tabas records produced larger demands at mid and top levels of framed tubes and bundled tubes (with mass eccentricity of 10%). The spectral velocity for these records at the higher-mode periods are relatively large, keeping in mind that a shift to the right of the spectra is to be expected as the intensive yielding of components occurs.

The average seismic drifts of framed tubes and bundled tubes in stiff and flexible edges are presented in Figures (12) and (13) for Y direction. The average seismic drift of flexible edges rises by an increase in mass eccentricity in framed tubes and bundled tubes. Moreover, the average seismic drift of stiff edges of framed tubes and bundled tubes declines by an increase in mass eccentricity.

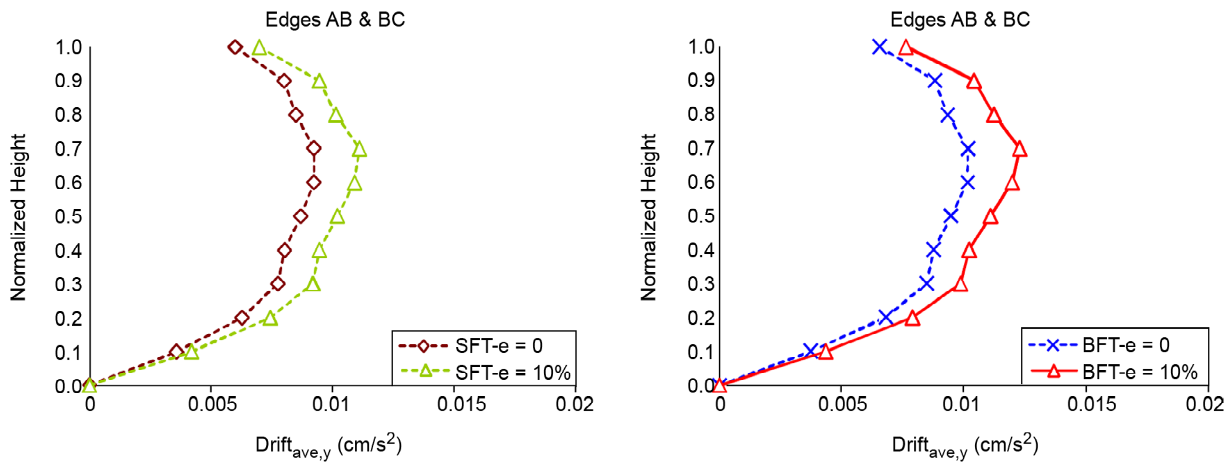

Figure 12. Variation of average seismic drift of the flexible edges of AB and BC in Figure (1).

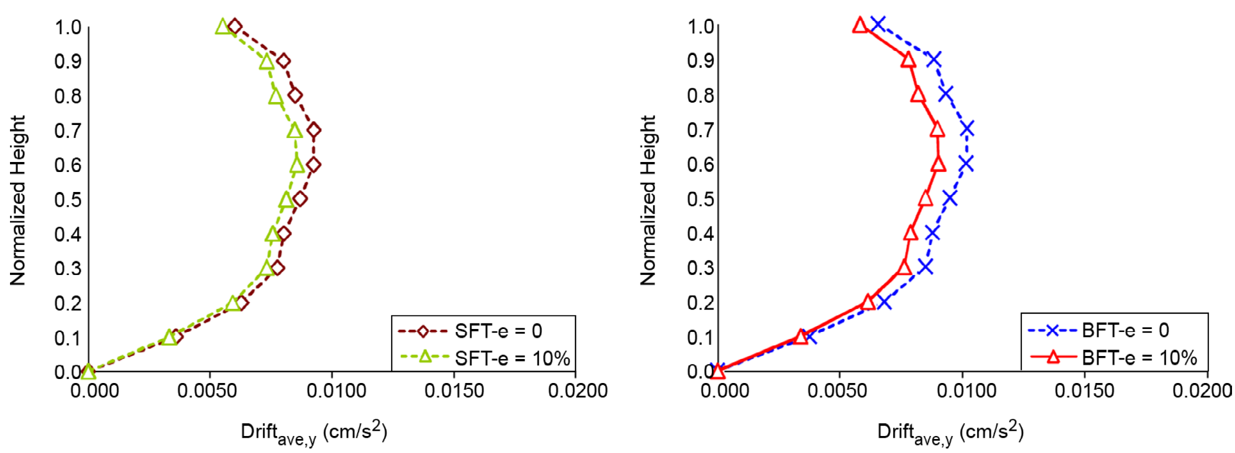

Figure 13. Variation of average seismic drift of the stiff edges of AD and DC in Figure (1).

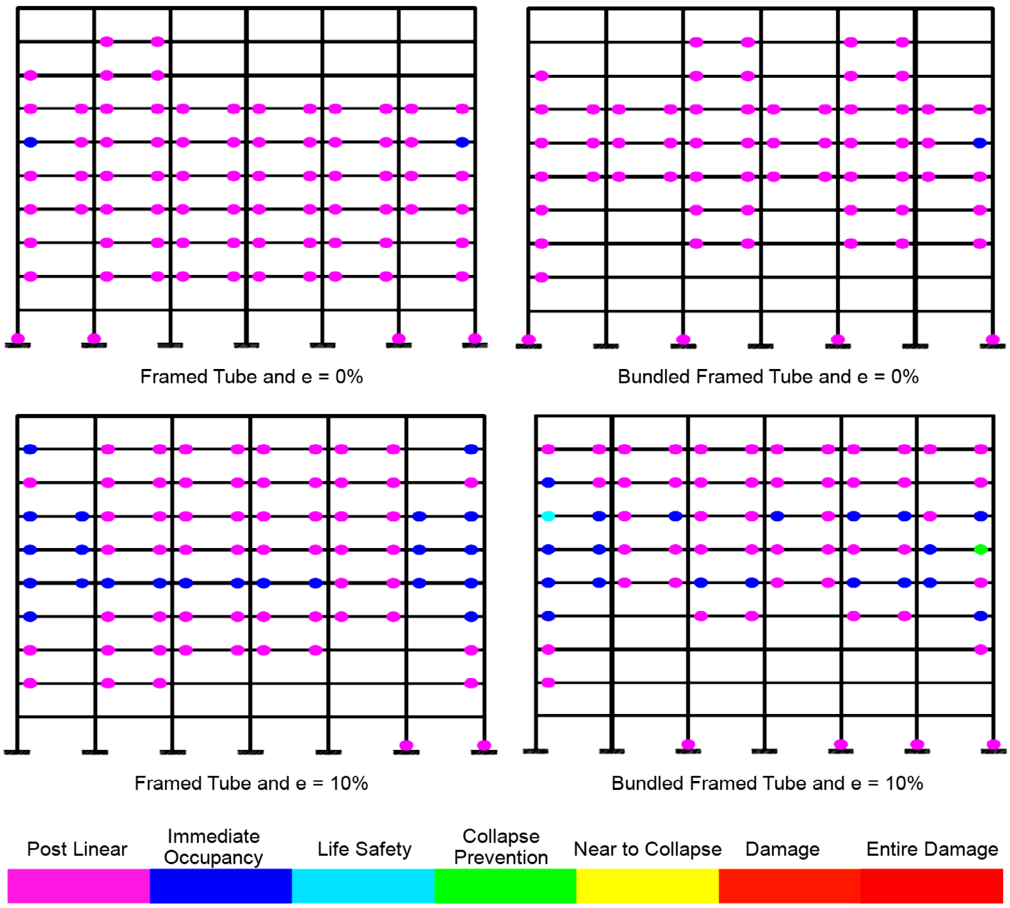

Figure 14. Final plastic hinge mechanisms formed in the studied models of Figure (1) in Y direction of plan, i.e. the frame located at BC edge, under near-field record of Tabas in 1978.

Plastic hinges mechanism created by nonlinear seismic behavior under the Tabas record are shown in Figure (14). Most plastic hinges are generally concentrated at middle levels of the framed tubes and bundled tubes resistant skeleton. Besides, analytical assessments show higher amplitude for the seismic nonlinearity of plastic hinges in flexible edges compared to stiff edges of the plan.

5. Concluding Remarks

The purpose of this research is 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 framed tube and bundled tube systems. The torsional behavior of two code-compliant ten-story framed and bundled tubes with and without mass eccentricity on levels has been studied under near-fault records. The ensemble of chosen near-field records include strong ground motions having a presence of high-amplitude and long-period pulses in the velocity time history. The existing velocity pulse make more demand and complicated seismic response with conveying seismic drift from lower story to mid-stories and high-stories and cause to participate higher vibration modes in seismic behavior of framed tubes and bundled tubes. This conclusion is evidently obtained in conjunction with the base shears, absolute acceleration, relative velocity and seismic drifts of stories, which are calculated according to performing nonlinear dynamic analyses subjected to strong earthquake records. However, seismic drift of all structural models is less than 0.5% at its highest value under far-field record and less than 2.5% subjected to near-field records. It reveals an increase of about 2% exposed to the earthquake records contain forward directivity effects.

The codified static torsional behavior of framed tubes and bundled tubes with various skeletal configurations may be significantly different from what has been observed in this study upon the seismic point of view. Hence, it needs to be rigorously investigated. The average seismic drift of flexible edges rises by an increase in mass eccentricity in framed tubes and bundled tubes. Moreover, the average seismic drift of stiff edges of framed tubes and bundled tubes declines by an increase in mass eccentricity. Dynamic twisting in the torsionally flexible framed tubes, and bundled tubes causes an increase in level of inelasticity on the moment frames located at two parallel and opposite faces of the plan. Furthermore, the plastic rotation at end of beams of moment frames would experience at or near performance level of collapse prevention (CP). Besides, analytical assessments show higher amplitude for the seismic nonlinearity 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. The contribution of higher-mode effects in the seismic response is of the main subjects, which must be considered accurately. This is resulting an increased domain for the demands in the upper and intermediate stories. Moreover, it has been observed that rigid framed tube and bundled tube systems satisfy code restrictions for seismic drift under the most of near-field earthquakes.

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