ASSESSMENT OF SEISMIC RESPONSE OF MID-RISE STEEL BUILDINGS WITH STRUCTURAL CONFIGURATION OF FRAMED TUBE SKELETONS

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ABSTRACT

In this research, the performance abilities of tube type lateral load resistant framed systems are studied in order to assess the dynamic response of mid-rise steel structures subjected to both far and near-field earthquake records. For this purpose, four 10 story structural models with separated framed tube based skeletons were selected and designed. The structural models have been designed according to the Iranian seismic code 2800 (third edition). The main criterion which was considered to select strong ground motions for performing nonlinear time history analysis is the existence of high amplitude and long period pulse or a multiple pulse feature in the velocity time history of each earthquake record. Assessment of the analytical results should emphasize on the importance of both lateral displacement and drift of all stories which must be considered exactly during the design process. Additionally, it was concluded that the maximum drift demand is about 0.035. The upper level of rotation of rigid connecting zones was calculated higher than seven percent of a radian. Generally, it was concluded that, the seismic response of mid-rise steel structures with framed tube skeleton is dramatically influenced by those strong earthquake records which are able to display energized long period pulses in their time histories.

INTRODUCTION

According to the engineering buildings observations associated with structural failures during the last earthquake tremors, there are some absolute uncertainties about the risks of near-fault ground motions on structures with conventional constructions. Structures response parameters under earthquakes are fundamentally different from those caused by wind or gravity loads. It is obvious that, much more detailed analysis and conceptual explanations would be faced while subjected to strong earthquake loads (Coull and Bose 1975, Bungale and Taranah 2005).

One of the systems used in the construction of mid and high-rise buildings are rigid tubular forms which can provide the structural efficiency for different performance levels. A framed tube skeleton can be defined as a three-dimensional system that provides very stiff structural bents which form a "tube" around the perimeter of the building. It is quite desirable to concentrate as much lateral load-resisting system components as possible on the perimeter of tall buildings to increase their structural depth and in turn, their resistance to lateral loads. This system consists of closely spaced exterior columns tied at each floor level by spandrel beams to produce a huge bent containing orthogonal rigidly frame panels which entirely forms a rectangular tube type cantilever system. The behavior of a framed-tube structure is more complex than a simple closed tube element. This concept was approved in regards to combined shear-flexure behavior of framed tube structures. Although, the traditional use of tubular structures are most commonly of square platform, but they have also been employed in circular, triangular and trapezoidal shaped plans. The tubular structures has the architectural advantage of allowing freedom in planning the interior zone. It should be noted that, height to width ratio, plan dimensions, spacing and the size of columns and spandrels of structural skeleton can directly affect the efficiency of the framed tube systems. Especially when buildingڔs height increase, the forces of nature begin to dominate the structural system and take on increasing importance in the overall building system. Other arrangements are available that are more amenable to allowing openings, as such can be note to bundled-tube systems, that it is one of the most useful structural systems for construction mid-rise and high-rise and considered more advanced form of framed tube systems. The efficiency of these kind of systems in being able to produce a laterally high stiffness for a minimum of additional material makes it an economic structural system for taller buildings (Smith and Coull 1976, Ali and Moon 2007).

It is noticeable that the general seismological issues with this research should be summarized as follows. Firstly, characterization of near-fault ground motions in terms of their directivity effects, kinetic energy and frequency content in addition to notifications caused by acceleration spikes and velocity pulses. Secondly, quantification of the damaging potential of near-fault ground motions in comparison with far-fault records through nonlinear time history analyses, which have been conducted on the four 10-story steel structural models with framed tube skeletons. This process should be completed by performing the analytical determinations and graphical illustrations of the seismic response parameters of the studied structures named steel framed, bundled, castled, and cellular tube skeletal systems.

The aforementioned models have been designed using the lateral load distribution which is specified in the Iranian seismic code 2800 (third edition). The section profiles of members and connections of all structural models have been designed based on the Iranian national building code (steel structures - part 10). The chosen records involve two groups of strong earthquake tremors which are recorded in far and near-fault areas. The characteristic criterion in selection of strong ground motions for performing non-linear time history analyses is the existence of high amplitude and long period pulse configurations in the velocity time history of each earthquake record.

PULSE-LIKE GROUND MOTIONS

The near-fault large velocity pulses and forward/backward directivity effects were recognized as early as 1966 and clearly demonstrated by the ground motions obtained from the earthquakes of Tabas in 1978, Imperial Valley in 1979 and Landers in 1992. By the way, the Northridge earthquake 1994 has been focused on attention of structural engineers and code writers on detailed aspects of strong ground motions (Naeim 2004). The earthquake record parameters, such as the acceleration and velocity time histories, the input kinetic energy and the Fourier amplitude spectra are generally plotted as shown in Figures 1 and 2. Moreover, the special illustration of both obvious types of ground vibration processes, i.e. the forward directivity and far-field motions are identified functionally.

One of the most distinctive features that can be observed in the nature of strong near-fault records is long-duration and high-energy pulse generation ability in both acceleration and velocity time histories as shown in Figures 1a and 1b. Meanwhile, it can be seen for the far-fault record namely Moor-park (MRP) that it does not display any velocity pulses or acceleration spikes in its time history as shown in Figure 2a and 2b. While the fault rupture propagation expands toward the site, the forward directivity effects will generally take place. Pulse-like near-fault ground motions resulted from directivity effects are essentially a special class of ground motions. They have been particularly challenging to specify the codified seismic consistency assessments (Somerville et al 1997, Somerville 2003, Stewart 2001).

The majority of the kinetic energy related to powerful earthquake records with forward-directivity effects usually get released during a short limited period of time together with pulse configuration. Interestingly, the kinetic energy releasing process of a far-fault motion would often be occurred in the longer time duration, causing a gradually incremental build-up with respect to the structural response parameters (Kalkan et al 2006, Baker 2008, Trifunac et al 2013). The overall kinetic energy variation pertaining two records is shown in Figures 1c and 2c. Regarding to aforementioned figures, the Tabas station is located near to the epicenter of the Tabas earthquake 1978 whereas the MRP station of Northridge earthquake 1994 takes place in the far zone. By taking the Figure 1 into account, around 90 percent of the input energy in the case of the near-field ground motion, expose to structure within around less than 15 seconds such as Tabas record that, it is about three times bigger than the energy which produced by MRP record. This case for the MRP 1994 record has a domain near to 25 seconds in such a way that, its kinetic energy releasing is more balanced and occurs in a wider time interval.

The Fourier spectrum of most of pulse type records instead of spread over a wide range of the frequency content, set in a small temporal domain and sometimes its maximum value is placed at a particular frequency. Also in the Fourier spectrum of these records, it can be seen that in the range of short frequencies corresponding to the natural period of mid to high-rise buildings, the related velocity based values of the Fourier spectrum are increased to considerably large amounts. Yet, the high frequency band corresponding to the low periods i.e. the period of the higher modes, has relatively short height components at the same time. This implies that the effective kinetic energy is usually low, corresponding to the domain of high frequencies (Kalkan 2006, Bray and Marek 2004, Alavi and Krawinkler 2000). This subject is denoted in Figures 1d and 2d. From an interactive pseudo acceleration-displacement spectrum as shown in Figure 1e and 2e, it is rather easy to assess the mutual effects between the spectral acceleration which stand for base shear coefficient and the deformation demand (Iwan 1997, Malhotra 1999, Elnashi et al 2006).

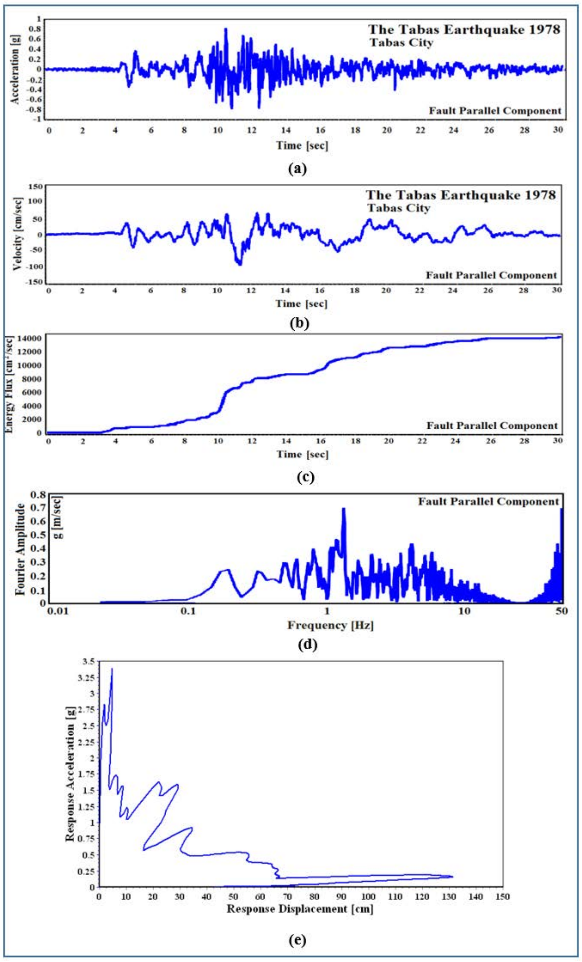


Figure 1. The near-fault ground motion with forward directivity effects of Tabas 1978

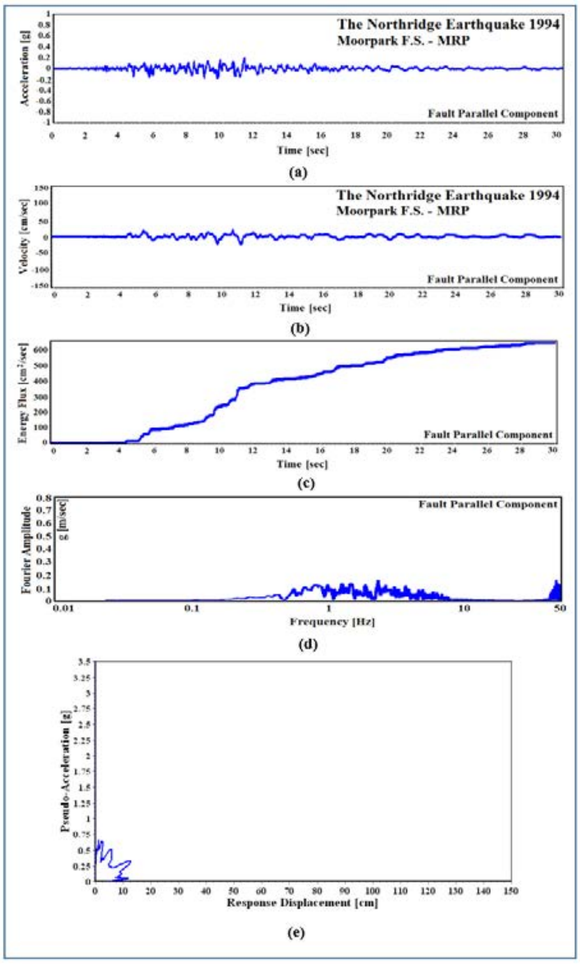
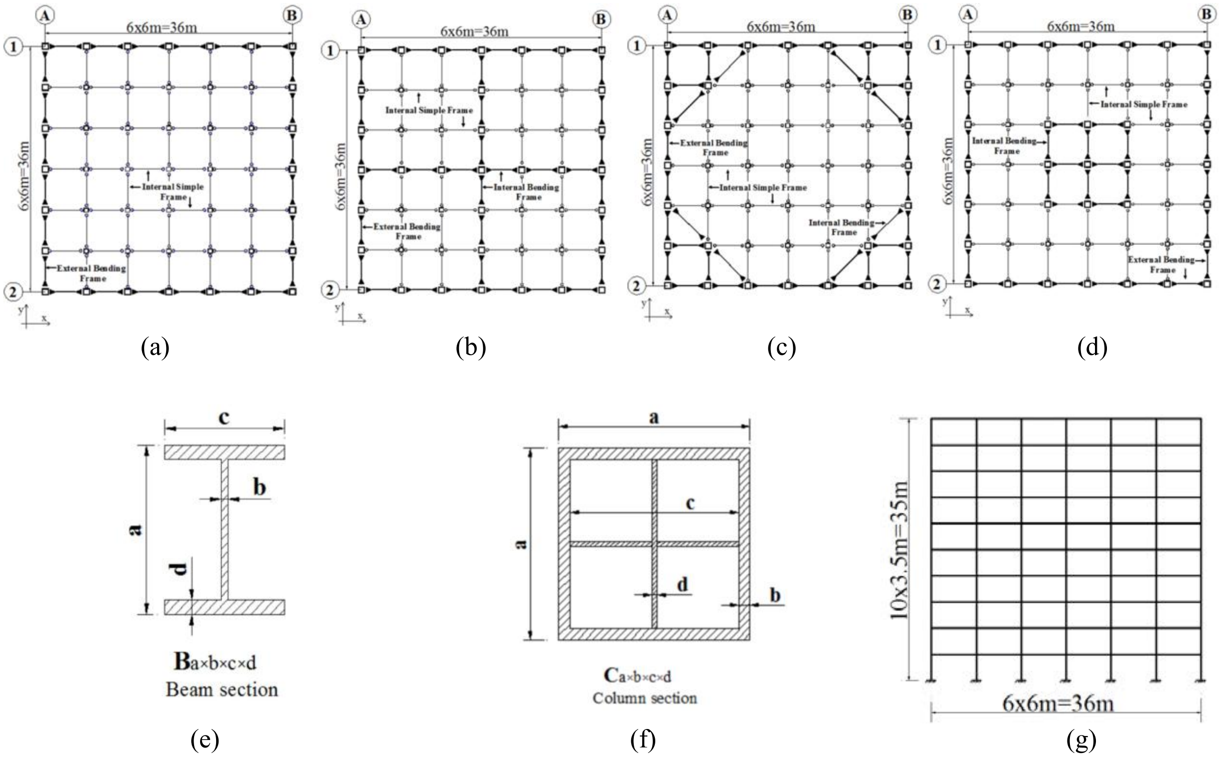


Figure 2. The far-fault ground motion of Moor-Park 1994

EXPLANATION OF THE STUDIED MODELS

The studied models in this research are consisted of four steel structural systems, notified as framed, bundled, castled and cellular tubes in 10-story forms as shown in Figure 3. All of the floor diaphragms are assumed to be infinitely rigid in plane as compared to the vertical elements of the structural skeletons. This criterion implies the assumption of total rigid body motion for all floor slabs. The plan configuration includes six bays in both of the X and Y axises. Additionally, the height of all stories is constant and equal to 3.5m. The 3D computer models of these four studied structures were created using SAP2000 (Version 14.2.2). Centerline dimensions were used in the element modeling, and the columns were assumed to be fixed at the base level. For the structural response evaluations, the floors masses were applied to frame models based on the floor tributary area and distributed proportionally to the floor nodes. The applied dead load is 0.5 ton/m^2 for all floors. Yet, the live load was set 0.2 ton/m^2 for the floors and 0.15 ton/m^2 on the roof. The design base shear coefficients related to the codified seismic lateral load have been calculated based on the Iranian code 2800 (third version). The final values are shown in Table 1. Table 2 shows the modal vibration periods associated with all four studied models related to the X direction. The design process of all members and panel zones were accomplished according to the Iranian national building code (steel structures - part 10). All of the main structural members were assigned to moderated ductility parameter.

It is noticeable that three main issues have to be assessed accurately in the seismic design of steel moment resisting frames. There are some basic considerations which have to be evaluated carefully. The aforementioned codified provisions are the evaluation of the seismic drift limits of stories, the parametric assessment of adequate strength of panel zones as well as to meet the approval of the principle of strong column and weak beam in all connections. These provisions have been accurately considered in the designation process. The structural and the plan configuration of all studied models as well as the designed section properties are presented in Figure 3 and Table 3, respectively.



(a) (b) (c) (d)

(e) (f) (g)

Figure 3. The structural models: (a) Plan of Framed tube; (b) Plan of Bundled tube; (c) Plan of Castled tube; (d) Plan of Cellular tube; (e) Columns section property of 10-storey models; (f) Beams section property of 10-story models; (g) The 10-story configuration.

Table 1. The seismic base shear coefficient and static base shears

Lateral Resistant System	Model	Base Shear Coefficient	Static Base Shear (Tons)
Framed/Bundled/Castled/Cellular Tubes	10-story	0.071	578

Table 2. Modal vibration periods of structural models

Lateral Resistant System	T1 (sec) First Lateral Mode	T2 (sec) Second Lateral Mode	T3 (sec) Initial Torsional Mode
Framed Tube	2.2	1.33	0.83
Bundled Tube	1.81	1.33	0.692
Castled Tube	1.8	1.19	0.687
Cellular Tube	1.81	1.32	0.686

Table 3. Structural members of the studied models

Stories Groups	Exterior columns (External Rigid Bents)	Interior Columns (Internal Rigid Bents)	Beams (Rigid Bents)
1-2	C500x30	C500x30x440x25	B500x15x250x25
3-4	C450x30	C450x30	B500x15x350x25
5-6	C400x30	C400x30	B450x15x350x25
7-8	C350x30	C350x30	B450x15x350x20
9-10	C300x20	C300x20	B400x10x250x20

THE SELECTED EARTHQUAKE RECORDS

The strong ground vibrations that have been used in this research include a number of far-fault and near-fault ground motions from different tectonic tremors. The selected earthquake records have been applied with ground accelerations recorded in three orthogonal directions, i.e. two horizontal and one vertical components. The examined near-fault ground motions, which have been recorded at a distance less than 20 Km from the fault rupture plate, may be characterized by intense velocity pulses of relatively long period. This factor causes that to distinguish them from typical far-field ground motions. It is notified that the near-fault records which contain forward directivity effects were selected from the strong motion database of the Pacific Earthquake Engineering Research Center[1].

Table 4. The selected earthquake records

Ground Motion	Component	Duration (sec)	PGA (g)	PGV (cm/s)	PGD (cm)	Magnitude	PGV/PGA (sec)	PGD/PGV (sec)
						M_W		
Tabas 1978 Tabas City - 3.0km	LN	30.00	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		0.06	0.37
Bam 2003 Bam City - 1.0km	LN	30.00	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
Northridge 1994 Sylmar (SCS) - 6.40km	LN	30.00	0.897	102.23	45.28	6.7	0.11	0.44
	TR		0.612	117.47	54.16		0.19	0.46
	UP		0.586	34.59	25.63		0.06	0.74
Northridge 1994 Newhall (WPI) - 7.10km	LN	30.00	0.325	67.4	16.1	6.7	0.21	0.23
	TR		0.455	92.8	56.6		0.20	0.61
	UP		0.290	37.2	13.3		0.13	0.35
Northridge 1994 Jensen Filter Plant (JFP) -6.10km	LN	30.00	0.593	99.10	23.96	6.7	0.16	0.24
	TR		0.424	105.95	50.69		0.25	0.47
	UP		0.399	33.91	8.89		0.08	0.26
Northridge 1994 Rinaldi (RRS) - 7.10km	LN	30.00	0.472	72.72	19.82	6.7	0.15	0.27
	TR		0.838	166.87	29.79		0.19	0.17
	UP		0.852	51.01	11.71		0.06	0.22
Northridge 1994 Tarzana (TAR) - 7.10km	LN	30.00	0.99	76.77	29.21	6.4	0.07	0.38
	TR		1.77	109.67	36.56		0.06	0.33
	UP		1.04	73.69	20.52		0.07	0.27
El Centro 1940 Array 9 ت8.30km	LN	30.00	0.215	30.2	23.91	7.0	0.14	0.79
	TR		0.313	29.8	13.32		0.10	0.45
	UP		0.205	10.7	9.16		0.05	0.85

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[1] http://peer.berkeley.edu/

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

The ensemble of earthquake records is categorized in two sets. The first set includes seven near-fault ground motions which are influenced by intensive forward-directivity effects and contain energized high amplitude velocity pulses. These five ground motions include the Sylmar (SCS), Rinaldi (RRS), Jensen Filter Plant (JFP), Newhall W. Pico (WPI) and Tarzana (TAR) which are all due to the 1994 Northridge earthquake. The main ground shock of the two most powerful Iranian earthquakes namely the Tabas in 1978 and Bam in 2003, are classified the same as aforementioned records of the 1994 Northridge earthquake. The second set contains an relatively strong far-fault ground motion, named the El Centro 1940 record which no distinct acceleration spike or coherent velocity pulse would not appear in its three component time history. It is generally observed based on Table 4 that, the existence of forward directivity effects in near fault earthquake records may display larger values for PGV and PGV/PGA ratios as well as relatively lower PGD/PGV ratios.

RESPONSE PARAMETERS OF THE STUDIED MODELS

The seismic demands and response parameters of the four studied models described above, were accurately analyzed and evaluated via employing non-linear dynamic time history procedure. This analytical process was accomplished subjected to the ensemble of strong ground motion listed in Table 4. It is worth mentioning 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 relative base shear i.e. the ratio of calculated base shear versus total seismic mass of structure, the maximum probable drift of each story and configuration of plastic hinges along the height of models, respectively.

The codified modelings of all four studied models were completed through assigning the normalized force/moment - deformation/rotation relation such as the one shown in Figure 4 that provided in the FEMA-356. The basic nonlinear response parameters for the all 10-story models are displayed in Figure 5-7. The analytical ratios of the calculated base shear versus total seismic mass of structure as well as the codified static base shear due to the studied models are presented in Figure 5.

It is evident that the dynamic base shear values for the studied models which are affected by powerful near-field records are distinctly greater than those ones subjected to the far-field ground motions.

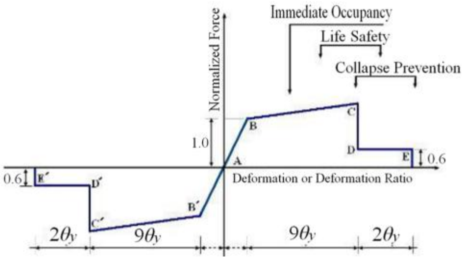
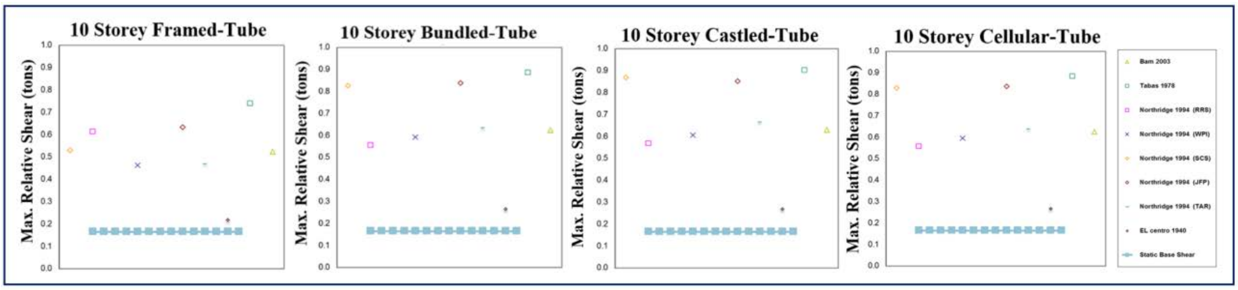


Figure 4. The Fema 356 model of nonlinear behavior of beam-column element



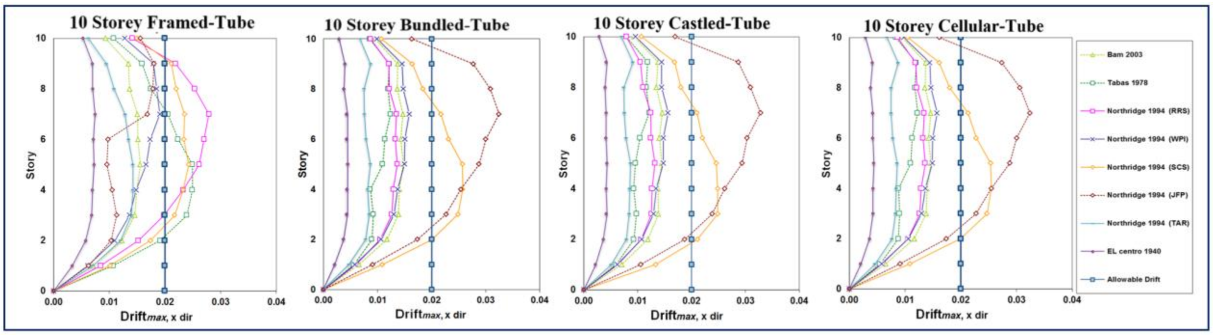
(a) (b) (c) (d)

Figure 5. The maximum relative seismic base shear of (a) 10-story F.T.; (b) 10-story B.T.; (c) 10-story Ca.T.; (d) 10-story Ce.T. model.

The peak interstory drift profiles obtained from NTH analyses of the studied models subjected to two sets of ground motions are presented in Figure 6. For the all 10-story buildings, far-fault motions produce nearly uniform interstory drift demands. Meanwhile, the near-fault records impose extremely higher demands than far-fault records. Moreover, the maximum drift is generally concentrated on the middle and upper stories levels. The largest demand is caused by the Rinaldi (RRS) record 1994 which produced about three percent interstory drift at about middle height of F.T. model and the Jensen Filter record imposes higher than 3.5 percent drift in B.T., Ca.T. and Ce.T. models.

It should be noted that these evaluated drift parameters of all studied structures are comparable with allowable drift level i.e. 0.02, that is notified in the Iranian seismic code 2800. The analytical variation in story drift demand corresponding to the far-fault El Centro record 1940 is less significant. It is important noting, the extreme probability of existence higher values and the larger distribution forms of the maximum drift for all stories of the studied structures which are designed and constructed in near causative fault areas. Yet, far-fault ground motions produce nearly uniform interstory drift demands for most records of this category. Therefore, this notification point should be better to consider in performance-based design criterions.

As illustrated in Figure 6, the influence of the higher modes of vibration can results in significantly higher flexural demands. As illustrated, for B.T., Ca.T. and Ce.T. models, the JFP record would result in increased demand especially in the upper stories while the RRS record for F.T. model does. Furthermore, the structural demands are generally greater than those anticipated by a typical prescriptive design. The analytical schemes of the formation of plastic hinges and corresponding rotations in all studied models affected by the Jensen-Filter (JFP) record are provided in Figure 7. Additionally, the conducted research shows that coherent velocity pulses which emerged in the time history of these records e.g. the JFP, are able to impose severe inelastic demands in seismic response as can be observed in Figure 7.



(a) (b) (c) (d)

Figure 6. The stories maximum seismic drift of (a) 10-story F.T.; (b) 10-story B.T.; (c) 10-story Ca.T.; (d) 10-story Ce.T. model.

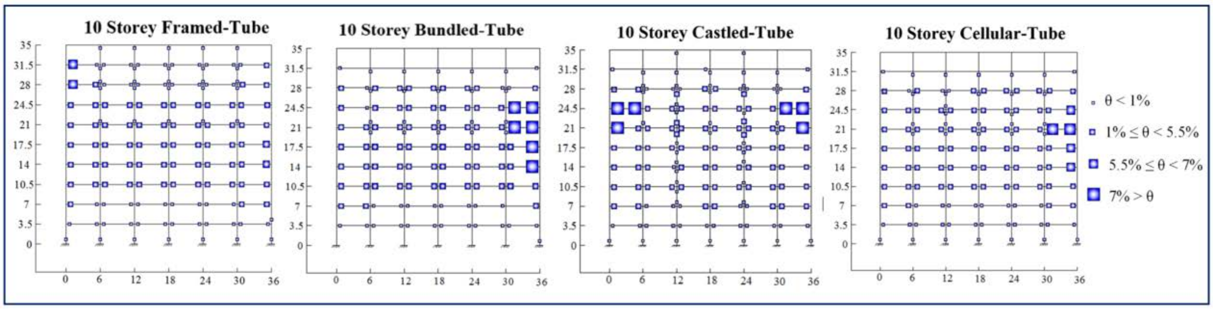


Figure 7. The configuration of plastic hinges and corresponding rotations in the rigid frame 1-2 of Figure 3, (a) 10-story F.T.; (b) 10-story B.T.; (c) 10-story Ca.T.; (d) 10-story Ce.T. model.

CONCLUSION

The major objective of the current research is to develop a fundamental understanding on the important capabilities of the characterize near-fault ground motions and their effects on the response of mid-rise tubular rigid framed systems. For this purpose, four 10-storey structures with the framed tube skeleton have been designed based on the Iranian codes and analyzed through non-linear time history procedures. The research process was pursued via influencing the selective ensemble of both near and far-fault records on the proposed models. The analytical results were illustrated according to the special characteristics of those selected earthquake records which contain velocity pulses and strong spike type features. The presence of large coherent velocity pulses that displayed in the time history of the energized records of the Northridge earthquake 1994 as well as two main shocks of the Tabas 1978 and Bam 2003 powerful ground quakes, can strongly impose severe inelastic demands in the seismic response parameters of mid-rise steel framed tube structures.

The maximum drift story, seismic base shear as well as the schematic forming of plastic mechanism in all of studied structural skeletons have been compared and evaluated. Analytical results indicate that the general drift demand may be higher than 0.035 and would lead to increasing levels of response parameters as compared to the permissible limits. This analytical manner may result that the basic structural members would not provide the required level of seismic performance. The existence of high-amplitude coherent velocity pulses as well as powerful acceleration spikes in time history of damaging near-field records causes a series of intensive severe inelastic seismic demands which are able to form a plastic mechanism with high levels of nonlinear performance, especially in the middle and upper stories of all four studied models. It is common for higher modes of vibration to heavily influence the mid-rise buildings seismic response subjected to strong ground shakings. In this regards, the second or even third modes of vibration can be taken into account in the overall design process.

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