EVALUATION OF SEISMIC RESPONSE OFTALL BUILDINGS WITH FRAMED TUBESKELETONS IN HIGH SEISMIC AREAS

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ABSTRACT

In this research, the performance abilities associated with tube type lateral load resistant framed systems are studied in order to assess the seismic response parameters of steel tall buildings subjected to both far and near-field earthquake records. For this purpose, four 30 story structural models with framed tube based skeletons were selected and designed. The plans of models are squared shape. The structural response parameters have been computed and obtained by conducting a number of non-linear dynamic time history analyses. The structural models have been designed according to the Iranian seismic code 2800(third edition). Findings from this study reveal that, mean maximum demands and the dispersion in the peak values were extremely higher for near-fault records than far-fault motions. The maximum story drift for the studied models was determined and compared with the “life safety” and “collapse prevention” performance limits, as recommended by FEMA 356.

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. The subject of building resistance to the wind and earthquake loadshas been the main point in the designation of new structural systems.Moreover, increasing building height as well as keeping its deflection within an appropriate restriction, is another crucial point which would lead to minimizing materials usages. Structures response parameters under earthquakesare fundamentally different from those caused by wind or gravity loads. It is obvious thatmuch more detailed analyses and conceptual explanations would be faced when subjected to strong earthquake loads(Coull and Bose 1975, Bungaleand Taranah 2005).

One of the systems used in the construction of tall buildings are rigid tubular forms whichcan provide the structural efficiency for different levels. Generally, a framed tube skeleton can be defined as a three-dimensional system that providesvery stiff structural bentswhich form a "tube" around the perimeter of the building. 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 (Smith and Coull 1976, Ali and Moon 2007).

Is should be noted that height to width ratio, plan dimensions, spacing and the size of columns and spandrels of structural skeletoncan directly affect the efficiency of the framed tube systems. In the case of lateral load at the lower floors, especially at the ground level, the axial force in the corner columns is much larger than that of the center column of the flange frames. This can be due to the flexibility of the spandrel beams which imposes the shear lag effects, thenthe axial stress resultants in the corner columns should be greater than that of the inner columns of the web frames. Additionally, the major interactions between two types of frameswhich construct the webs and the flanges of a framed tube structure,are the vertical shear transfer forces at the corners (Gunel and Ilgin2007,Coull 1988).

It is noticeable that the general seismological issues with this research should be summarized as follows; (1),Characterization of near-fault ground motions in terms of their directivity effects, kinetic energy and frequency content in addition to notifications caused by acceleration spikesand velocity pulses (2),Quantification of the damaging potential of near-fault ground motions in comparison with far-fault records through nonlinear time history analyses conducted on the four 30-story steel structural models with framed tube based skeletons. This process should be completed by performing the analytical determinations and graphical illustrations of the seismic response parameters of the studied structures namely, steel framed, bundled, castled, and cellular tube skeletal systems.

The aforementioned models have been designed using the lateral load distribution which isspecified in the Iranian seismic code 2800 (Third edition).The section profiles of members and connections of all structural models have been designed based onthe 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 main characteristic 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-LIKEGROUNDMOTIONS

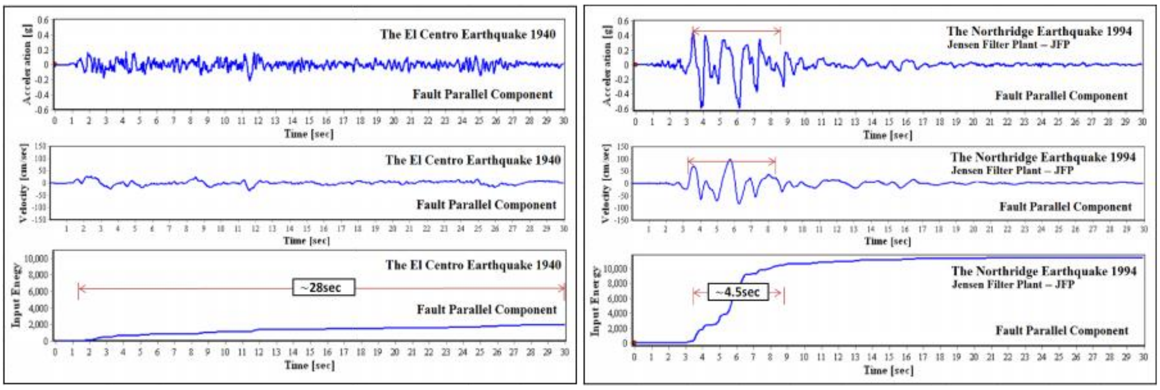
One of the most distinctive features that can be observed in the nature of strong near-fault records is the ability to generate a relatively long-duration and high-energy pulses in the both of acceleration and velocity time histories. When the fault rupture propagationexpanded toward the site,the forward rupture directivity effects willgenerally occur. Pulse-like near-fault ground motions resulting from directivity effects, undoubtedly are a special class of ground motions which have been particularly challenging to characterize the codified seismic consistency assessments (Somerville et al 1997, Somerville 2003, Stewart 2001).

The arrival of the velocity pulse in a near-fault record causes the structure to dissipate considerable input energy in relatively few plastic cycles, whereas cumulative effects from increased cyclic demands are more pronounced than far-fault records. These kinds of near-source quake tremors cause most of the seismic energy from the rupture process to arrive in one coherent long-period pulse of motion.Yet, the records which affected by backward-directivity faulting process typically do not exhibit any obvious and great pulse-like features. Most of the kinetic energy related to powerful earthquake recordswith forward-directivity effectsisreleased during a short limited period within the pulse configuration(Kalkan et al 2006, Baker 2008).

According to studies on the seismic response parameters of special moment resisting frames, the seismic demands are extremely increased by the earthquake records containingvelocity pulses (Movahed et al 2014). Furthermore, the Fourier amplitude spectra and both acceleration and velocity response spectrums of the near-field earthquake records which contain forward directivity effects are completely different from the records at far-field stations (Kalkan 2006, Bray and Marek 2004, Alavi and Krawinkler 2000).

Conversely, the releasing process of the kinetic energy of a far-fault motion would often be occurred on the longer duration, causing agradually incremental build-up regarding to the structural response parameters. The overall kinetic energy variation pertaining two records is also shown in Figure 1, in whichthe JFP station is located near to the epicenter of the Northridge earthquake 1994 and the MRP station takes place in the far zone.According to Figure 1about 90 percent of the input energy of the near-field ground motion i.e. the Jensen-Filter (JFP)record expose to structure within about 4.5 seconds.This case for the El Centro 1940 record has a domain of near to 28 secondsin which the releasing of the kinetic energy is more balanced and occurs in a longer range of time.

Those pulse-like ground motions i.e. the near-fault records which display wave-like features in one or both of the fault-parallel and normal directions respect to rupture plate, are usually particular concern of engineers due to holding the potential to cause high levels of structural responses. These motions are more intense as compared to ordinary far-fault records as well as a shorter effective duration (Bray et al 2009, Hall et al 1995, Trifunac and Todorovska 2014).



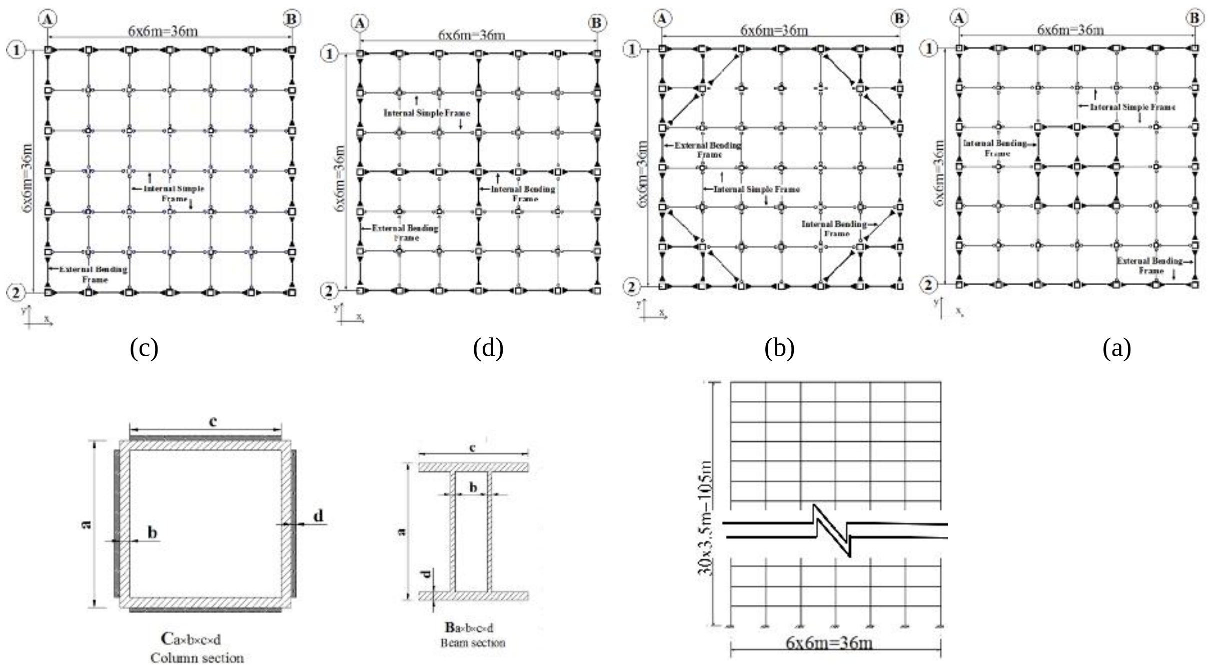
(a) (b)

Figure 1. Input energy for two records (a) far-fault ground motion (El Centro 1940), (b) near-fault ground motion with forward directivity effects (Jensen-filter 1994)

The conducted research shows that high-velocity pulseswhich emerged in the time history of the Jensen-Filter 1994 recordare able to impose severe inelastic demands in seismic response of tall framed tube structures. Furthermore, the seismological characteristics of strong near-fault records such aseffective duration, long-period pulses and energized cycles of ground motion are in higher degrees of importance, especiallyin the subject of preparation of codified design criterions. In this regards the current design approachesmaybe inadequate conceptually(Krawinkler 1995, Tremblay et al, 1995, Moehle et al, 2010).

DESCRIPTION OF STUDIED MODELS

The studied models in this research consist of four steel structural systems i.e. framed, bundled, castled and cellulartubes in 30-story formsas shown in Figure 2.All of the floor diaphragmsare assumed to be infinitely rigid in plane as compared to the vertical elements of the structural skeleton. This manner implies the assumption of rigid body motion for all floor slabs.There are six bays in the X and Y directions of the plans, respectively. Additionally, all stories have the height of 3.5m.



(g) (f) (e)

Figure 2. 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 30-storey models; (f) Beams section property of 30-story models; (g) 30-story configuration.

The applied dead load is 0.5 ton/m^2 for all floors. The live load was set equal to 0.2 ton/m^2 for the floors and 0.15 ton/m^2 on the roof. The columns have been assumed being fixed at the base level. Centerline dimensions were utilized in the element modeling for all case studies. The design lateral load coefficients related to the seismic lateral load have been calculated in compliance with the Iranian seismic code 2800 [8] and are shown in Table 1. The structures modal vibration periods related to the X direction are shown in Table 2. The sections, members and connections of all structural models have been designed based on the Iranian national building code (steel structures - part 10) and they have moderated ductility parameter.

It should be noted that, based on the above noted codes, three main issues must be controlled in the seismic design of every steel moment resisting frame. These considerations contain the evaluation of the seismic drift limits of stories, the confirmation of the principle of strong column and weak beam in all connections and the assessment of adequate strength of panel zones, which have been accurately considered in the designation process. The members of structural resistant frames of all studied models and their section properties are presented in Figure 2 and Table 3, respectively.

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	30-story	0.041	1042

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	4.47	2.62	1.67
Bundled Tube	3.7	2.62	1.39
Castled Tube	3.82	2.37	1.41
Cellular Tube	3.87	2.56	1.42

Table 3. Structural members of the Models

Stories Groups	Exterior columns (External Rigid Bents)	Interior Columns (Internal Rigid Bents)	Beams (Rigid Bents)
1-5	C750x30x650x25	C750x30x650x25	B500x20x500x25
6-10	C700x30	C700x30	B500x20x500x25
11-15	C650x30	C650x30	B500x20x500x25
16-20	C600x30	C600x30	B500x20x450x25
21-25	C550x25	C550x25	B450x20x400x25
26-30	C500x15	C500x15	B350x15x400x20

THE ENSEMBLE OF CHOSEN EARTHQUAKE RECORDS

The compiled ground motion database for non-linear dynamic time history analyses constitutes a representative number of far-fault and near-fault ground motions from a variety of tectonic events. The main criterion which was considered to choose strong ground motions for performing non-linear time history analyses, is the presence of high amplitude and long period pulse or a multiple pulse system in the velocity time history of each earthquake record. 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].

The chosen earthquake records are categorized in two sets. The first set includes six near-fault ground motions characterized with forward-directivity effects as well as long period coherent velocity pulses. These six ground motions include the three component records of the Sylmar (SCS), Rinaldi (RRS), Jensen Filter Plant (JFP)and Newhall W.Pico (WPI), all due to the 1994 Northridge earthquake. The main shock of the two so-called Iranian earthquakes which were happened in the Tabas and Bam territories in 1978 and 2003 respectively, are classified the same as four aforementioned records of the 1994 Northridge earthquake. The second set contains an ordinary far-fault ground motion, named the El Centro 1940 three component record which does not display any velocity pulse or acceleration spike in its time history.

A number of seismological characteristics of the chosen earthquake records as well as the peak ground acceleration (PGA), the peak ground velocity (PGV) and the peak ground displacement (PGD) are shown in

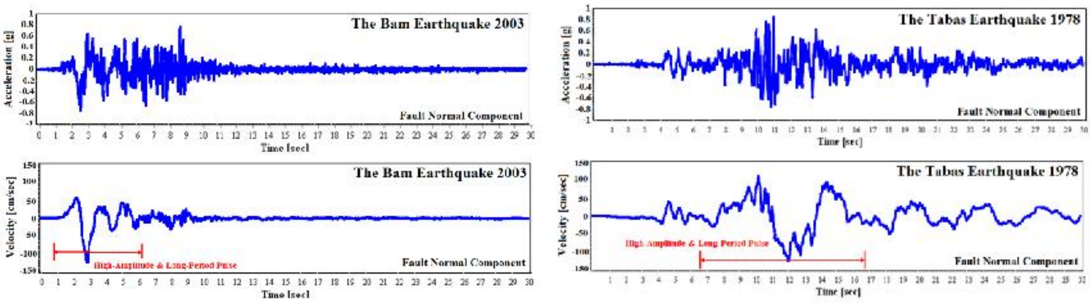
1.http://peer.berkeley.edu/

Table 4. The acceleration and velocity time histories corresponding to the fault normal component of the two Iranian records are also shown in Figure 3.

Table 4. 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
El Centro 1940 Array 9 – 8.30km	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

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



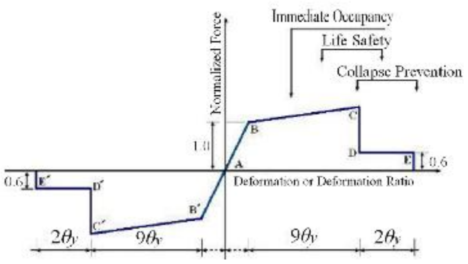
(a) (b)

Figure 3.The acceleration and velocity time histories of (a) Bam 2003 (BAM-TR); (b)Tabas-1978 (TAB-TR)

RESPONSE PARAMETERS OF THE STUDIED MODELS

The four buildings described in the earlier section are generally evaluated employing non-linear dynamic time history procedures to compare the resulting structural demands.Nonlinear response history analysis is the best tool currently available for predicting building response at varying levels of ground motion intensity. In all, 28 nonlinear time-history (NTH) simulations were conducted on the four buildings. The illustrated outputs of the analyzed models contain the maximum base shear of structure, the maximum velocity and the maximum probable drift of each story, respectively.

In modeling process of all structures, the ability of accomplishing non-linear behavior for all beams and columns were assigned based on introducing both, the interacting P-M2-M3 and the moment M3 hinges based on the report FEMA 356 as shown in Figure 4.The response parameters for the all 30-story models are illustrated in Figure 5-7. The calculated maximum base shears and also the static base shear that has been considered in the designation of the studied models are presented in Figure 5. According to the presented results, it is confirmed forthe structural models which are affected by near-field earthquake records, the response of base shears are relatively higher than those ones were evaluated subjected to the far-field earthquakes.



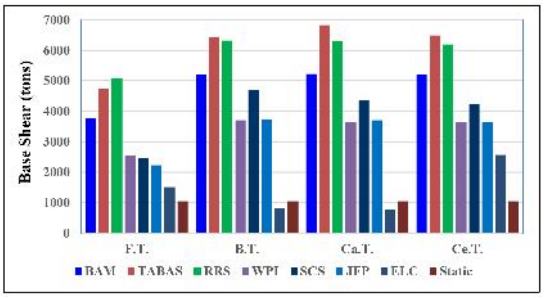
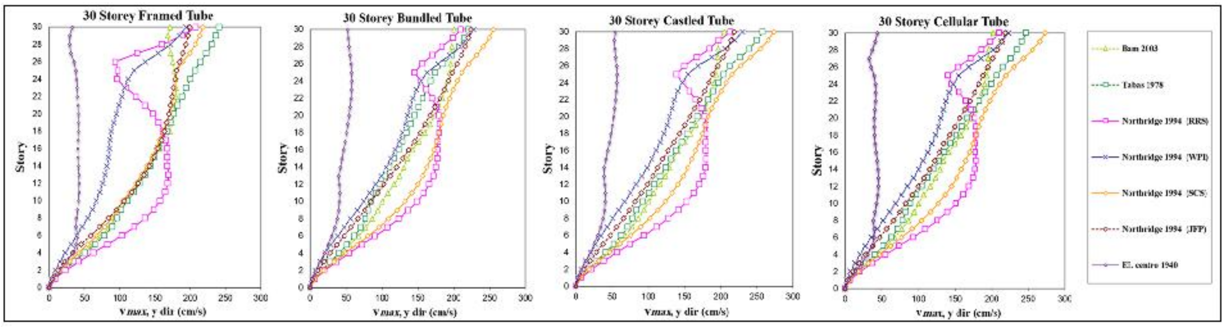


Figure4.Model of nonlinear behavior of the beam-column Figure 5. Maximum seismic base shear

The variations of the maximum relative velocity of all stories are illustrated in Figure6. Based on the result of this research, the earthquake records enable to display wave-like features in their time histories, especially in the form of high amplitude coherent velocity pulses (Table 4, Figure 3), the distribution of the floors velocity in the height of the structures contains larger values of this parameter in comparison with the results of the far-fault tremor.

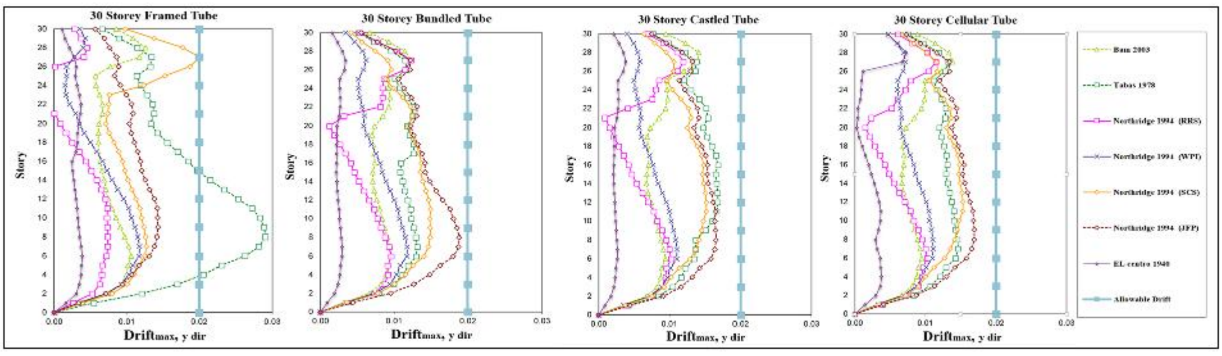


(c) (d) (b) (a)

Figure 6.The maximum relativefloors velocity of (a) 30-story F.T.; (b) 30-story B.T.; (c) 30-story Ca.T.; (d) 30-story Ce.T.

The peak interstory drift profiles obtained from NTH analyses of the studied models subjected to two sets of ground motions are presented in Figure 7. For the all 30-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 at the middle and upper stories levels.

The largest demand is caused by theTabasrecord 1978which produced aboutthree percent interstory drift at about middle height of F.T. model and the Jensen Filter record imposes about two percent drift in B.T., Ca.T. andCe.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 [8].The variation in story demand parameter for the far-fault record is less significant. It is important noting, the probability of existence higher values and the larger distribution forms the maximum drift for all stories of the studied structures which are designed and constructed in near causative fault areas. Therefore, this notification point should be better to consider in performance-based design criterions.



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

Figure 7. Stories maximum seismic drift of (a) 30-story F.T.; (b) 30-story B.T.; (c) 30-story Ca.T.; (d) 30-story Ce.T.

CONCLUSIONS

The major objective of this presented research is describing important capabilities and special characteristics of the near-fault ground motions and their effects on the dynamic responses of steel framed tube based structural systems.Specifically, these systems are more suitable for the lateral resistant system of tall buildings.Nevertheless, the results of this study show that large velocity pulses displayed in the time history of the energized records of the Northridge earthquake 1994 can impose severe inelastic demands in the seismic response parameters of high-rise steel structures. Furthermore, the general drift demand is less than 0.02 and the maximum value for velocity of stories is greater than 250 cm/sec in the Y direction of the studied models.

The illustrated outputs of the analyzed models indicate that 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 may lead to the case of dynamic instability in the main column elements of high-rise buildings. Furthermore, while the ratio of the velocity pulse period to the structure natural period is greater than unit ($Tp/T1 \geq 1$), it can cause the formation of a plastic mechanism with high levels of nonlinear performance, especially in the middle and upper stories of all four studied tall structures. It is obvious that the notified severity of the structural demands is extremely influenced by the ratio of the two aforementioned periods.

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