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SEISMIC BEHAVIOR OF BRB FRAMES UNDER NEAR FAULT EXCITATIONS

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ABSTRACT

For sites that are located in 10 to 15 km far from seismic source, ground motions with different properties have been recorded. Behaviors of these earthquake excitations are drastically different than far field ground motions. Distinguished characteristic of these ground motions is a high amplitude pulse like at the beginning of the seismograph. These pulse like ground motions have been obviously presented in forward directivity sites. These pulses have high amount of seismic energy released in a very short time and cause higher demands for engineering structures. Passive control of structures with hysteretic dampers is an effective method for controlling vibrations and decreasing loads on primary elements. Buckling Restrained Braces (BRBs), as hysteretic dampers with identical load-deformation behavior in both compression and tension, can dissipate most amount of seismic input energy. In this paper, performance of Buckling Restrained Braced Frames (BRBFs) under near faults excitations has been investigated. For this purpose, using OpenSees software, a series of non-linear time history analyses has been performed on 4, 8 and 12 story BRBFs. The results in terms of interstory drifts, brace hysteresis behavior, and portion of seismic input energy dissipated in BRBs were compared. In this research, desirable performance for BRBFs under near fault excitation was obtained due to absorption of high amount of seismic input energy (about 64%) in BRBs.

Introduction

In recent decades, destructive earthquakes such as the Northridge, Kobe, Izmit, Dozce and Chi-Chi in near fault zones have been reported. These earthquakes that had special effects on structures caused starting widely investigations on their characteristics. Near fault is not a new expression and after the 1966 Parkfield, California, and the 1971 Pacoima, San Fernando earthquakes in 1975, Bolt used this expression for the first time (Bruce A. Bolt, 2004). But those days, importance of this subject in design of new structures was not understood yet. After recent earthquakes and large damage of structures designed with earthquake codes, it was proven to the investigators that nonlinear response of structures subjected to near and far field earthquakes are

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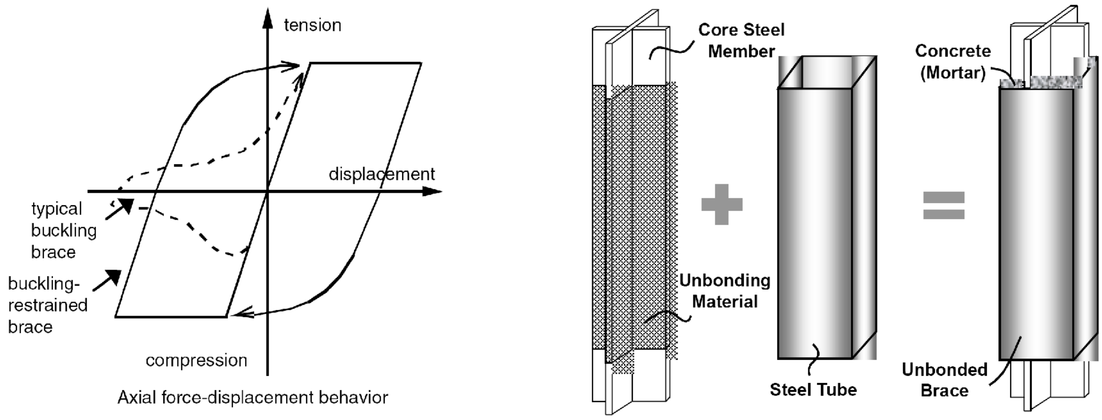
different and thus the codes must be revised. Distinguished characteristic of near fault records is pulse like motion at the beginning of the record. These pulses in velocity and displacement records are well detected. Some effects of pulse like motions in records are increased of high period accelerations ratio in their response spectrum or creation of one or some peak velocities. These motions applied high amount of seismic energy to be dissipated by structures in limited cycles. Thus, big deformations would likely occur in structures and potential of fatigue and brittle damage will be increased. Although effects of near fault ground motions specially forward directivity effect are partially known, but due to indetermination of actual dynamic behavior of kinds of structures in these zones, limited codes have special provisions for design purpose in these areas.

In 2001, Alavi and Krawinkler assessed elastic and plastic behavior of steel moment resisting frames (SMRFs) under near fault excitations. According to their research, if natural period of structure was bigger than pulse period, stories elastic shear forces would depend on the ratio of structure to pulse periods. In 2006 Krishnan performed some case studies on 19 SMRF buildings, designed per UBC 1997, under strong ground motion records from near-source earthquakes. The study mentioned that earthquakes with magnitudes in the range of 6.7–7.3, create drift demands of the order of 0.05 and plastic rotation demands of the order of 0.04–0.05 radian in the beam to column connections; while past experiments on large beam sections with pre-Northridge beam to column connections realize plastic rotations of less than 0.03 radian only before fracturing (Engelhardt MD, Husain AS, 1992). Also tests reported by FEMA-355D indicate that very few specimens could develop plastic rotations up to 0.05 radian. Based on this study, near-source earthquakes have such an effect that if it is not considered, then serious damages in beam to column connections are expected. In 2006 Kalkan et al. investigated different characteristics of near fault ground motions and their effects on SMRFs. 21 ground motions, 7 with forward effect, 7 with fling step effect and 7 far field records were considered to create a comprehensive research on SMRFs. To gain further insight into the effects of high-amplitude pulses on structural demands, they also used idealized pulses in a separate study. From last research it was obtained that under near fault records, use of systems with high ductility and high ability of absorbing energy is inevitable. For this purpose, in recent years, many different control systems have been developed. BRBs as hysteretic dampers are one of most applicable systems for passive control of structures. Regular and stable hysteresis curves cause big amount of energy absorption.

The present study focuses on the evaluation seismic performance of BRBs under near fault excitations. For this purpose, three frames with different heights were designed for a high seismically active area, zone 4. Design of BRBs was done according to the seismic provisions of AISC2005. Nonlinear dynamic analyses have been done with OpenSees software.

Buckling Restrained Brace Frames

During the earthquakes happened in recent decades, especially those in the Kobe 1995, Northridge 1994 and Mexico 1985, Concentrically Brace Frames (CBFs) didn’t show acceptable performance, since most beams and columns had been damaged. Researchers replaced them with an alternative called Buckling Restrained Brace Frame (BRBF). BRBFs are a new steel seismic-load-resisting system used in the western United States and Japan because of its efficiency and its promise of seismic performance far superior to that of conventional braced frames.



(a) (b)

Figure 1. (a) Behavior of conventional brace versus BRB (Uang, C. M., Nakashima, M., 2004), (b) Typical BRB (Tsai, K.C., 2004)

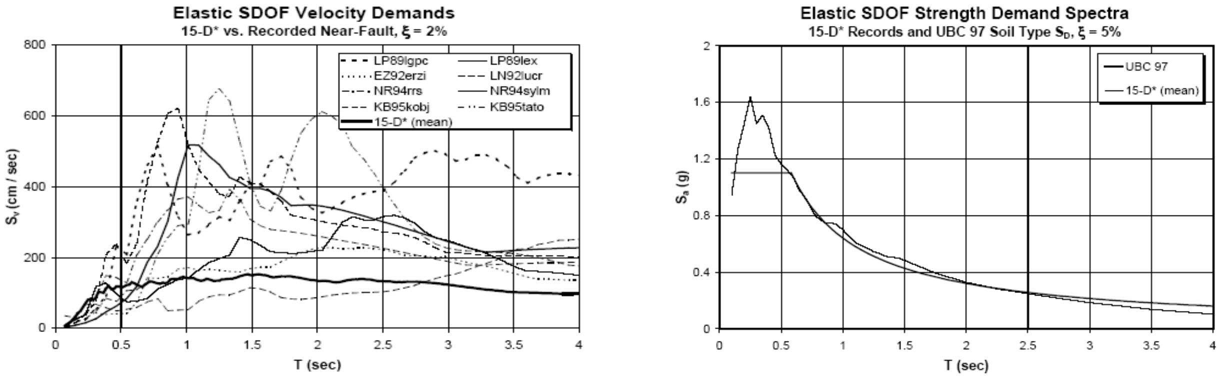
Since near-fault ground motions have high content of input energy compared to far-fault ground motions, it is necessary to utilize a system with great ductility. With prevention of brace buckling in BRBFs, more stable and ductile behavior can be achieved in the structural system. The principal rule of BRB is that in compression, stress resistance and flexural buckling resistance should be separated. Most of the BRBs developed to date have similar concepts. The brace is composed of a steel core, which is designed to yield during both tension and compression (Uang, C. M., Nakashima, M., 2004). To preclude global buckling in compression, the steel core is placed inside a steel casing (usually a hollow structure shape) and casing is filled with mortar or concrete.

Near-Fault Ground Motions

Earthquakes in which their origin is less than about 15.0 km from their recording site are near-fault ground motions. Till today, it is distinguished that many building that had been designed according to existing earthquake codes showed poor behavior under near-fault ground motions, so required to consider near-fault effects. Even in the case of one earthquake, far records versus near records are completely different and two characteristics of near-fault: 1- Forward-Directivity 2- Fling Step, are the main cause.

The effect of earthquakes in near fault strongly depends on their direction of propagation. Forward directivity will be appeared if the rupture propagates towards the site. When a site is located at one end of the fault and rupture initiates at the other end of the fault and travels towards the site, the arrival of the wave front is seen as a large pulse of motion (a shock wave effect) that occurs at the beginning of the record (Bray, J. D., Mark, A. R., 2004). Forward directivity can amplify amplitude of near-fault ground accelerations, velocities, and displacements even for moderate magnitude earthquakes. Peak accelerations may exceed 1.0 g, while peak velocities may exceed 2.0 m/ sec, and peak displacements can go beyond 2.0 m (Kalkan, E. et al., 2006). Fling step is created because of permanent ground displacements due to tectonic deformations. Its results are high velocity pulses and a uniform step in the displacement time history that cause large permanent displacements in the structure.

In 2001, Alavi and Krawinkler scaled a set of 15 far-fault records in a way such that the spectrum of each individual record matches the UBC 97 (Fig. 2a), and then they are compared with several near-fault ground motion records with forward directivity (Fig. 2b). Figures result in: 1- They are large variations in the near-fault response spectra. 2- In some cases amplitude of near-fault response spectra is several times greater than design spectra. So it's clear that special effects of near-fault ground motions should be considered in design purposes.



(a) Velocity Spectra (b) Mean Acceleration Spectrum

Figure 2. (a) Velocity response spectra of near-fault ground motions and reference ordinary ground motions, (b) mean acceleration spectrum of reference set of records (Alavi and Krawinkler 2001)

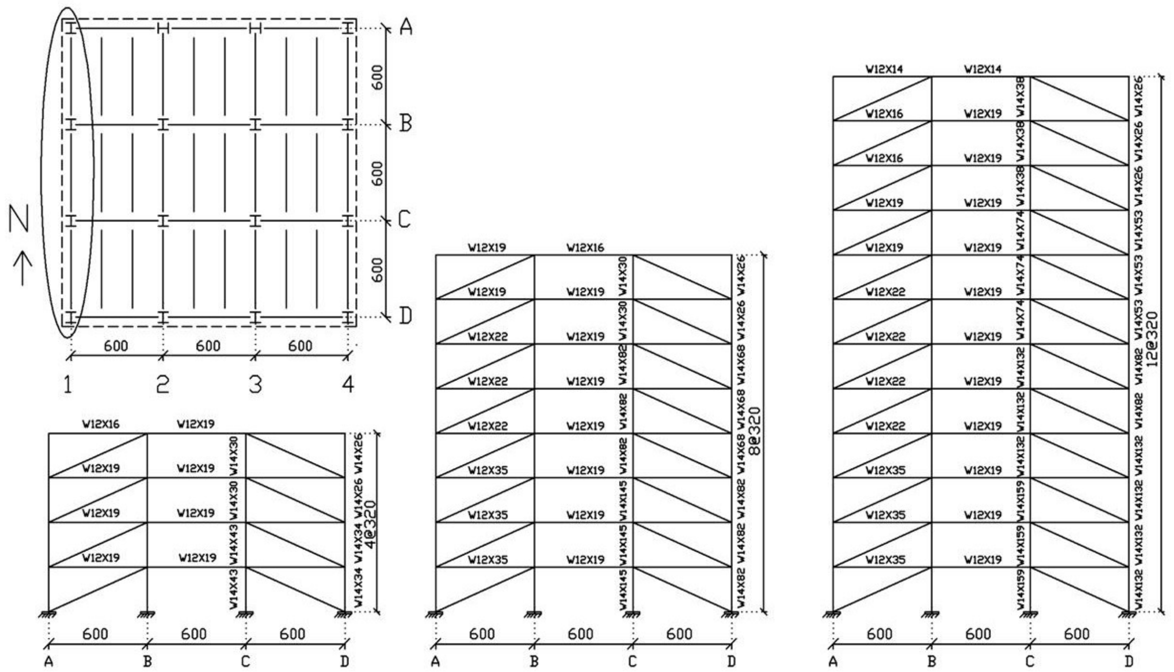


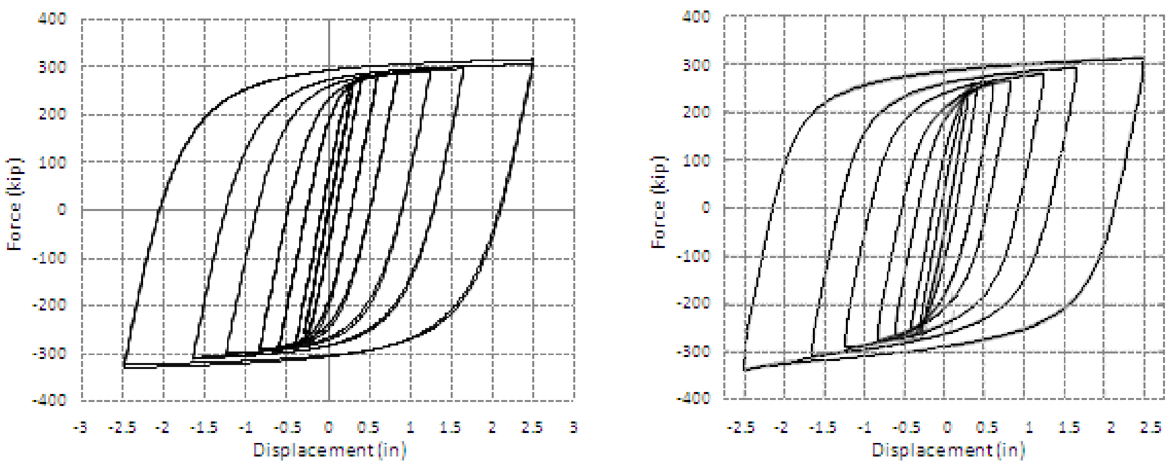
Figure 3. Structural configuration of 4, 8 and 12 story buildings

Characteristics of the Models

To evaluate the seismic behavior of BRBFs, 4, 8 and 12 story buildings with the bay length of 6 m and story height of 3.2 m with diagonal bracing were designed. The buildings were designed in accordance with the seismic provisions of the AISC2005, and use of Steel Tips 2004 recommendations. Frames are assumed located in Los Angeles in a site with distance of less than 5 km of an active fault (Na=1.2, Nv=1.6). Near fault provisions of UBC97 have been considered in design of frames. The gravity dead and live (or snow) loads assumed for the frame design were 83 and 30 psf for the roof level and 96 and 40 psf for the second floors. The floor plan and elevation view of the buildings with beam and column sections are shown in Fig. 3. Nominal yield strength equal to 50 ksi was used for columns and girders. Designed BRBs with steel core material of JIS SN400B and yield stress equal to 41.1 ksi are product of Nippon Steel Company. In design of frames, beam to column connections in braced bays and mid bay assumed rigid and pin respectively. Braces were assumed to be pinned at both ends and the column-to-base connections are assumed fully restrained.

Structural Modeling

Modeling and nonlinear dynamic analyses were carried out through OpenSees software that is an object-oriented framework for finite element analysis (Mazzoni S., et al., 2006). Modeling of elements, i.e. beam and columns, has been done with nonlinear beam-column element. For modeling of braces, nonlinear beam-column element with the material of Steel02 was used. The parameters of this material were calibrated with experimental hysteretic curve of specimen 99-1 in PEER Report 2002/08 (Black, C., et al., 2002). The analytical and experimental models are shown in Fig. 4.



(a) (b)

Figure 4. Analytical model of BRB (a), Experimental model of BRB (b)

The used section for each member is the fiber section. The strain hardening of 2% was considered for the beams and columns behavior in inelastic range of deformation. Story masses were lumped in each story level. Geometric nonlinearities, i.e. P-Δ effects, were included in the elastic and inelastic analyses. An initial mid-span imperfection of 1/800 for all columns was considered for buckling prediction in columns. The Newmark method with integration parameters of γ = 0.5 and β= 0.25 was utilized to solve the equations of motion. 5% Rayleigh damping was assumed in the dynamic analyses. Modal frequencies of modeled frames are listed in Table 1.

Table 1. Modal properties of the frames

No. of stories	Periods (s)		
	1	2	3
4 story	0.63	0.23	0.14
8 story	1.01	0.34	0.19
12 story	1.53	0.49	0.26

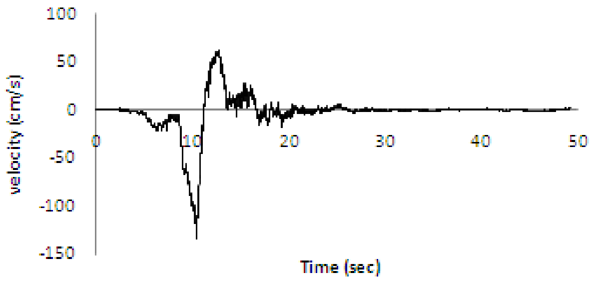
Earthquake Acceleration Selection and Scaling

For dynamic analysis, 7 near fault ground motions were selected. These ground motion histories were developed for the near fault area as part of the SAC project. Earthquakes in the magnitude (Mw) range of 6.7 to 7.5 and source-to-site distance range of 1.1 to 8.5 km were selected. These ground motions recorded on soil or rock converted to soil. Main characteristic of the whole ground motions are forward directivity effect, but Landers earthquake have fling step effect too. In Fig. 5 velocity and displacement time histories of Landers earthquake are shown. In Table 2, the seismological properties of the records used for this study are summarized (Krawinkler, H., 2000). In order to possibly compare seismic response of frames under these records, the entire ground motions were scaled with a unique method. For this purpose, the spectrum of each record matches the 5 percent damped UBC 1997 design spectrum with minimum error in the period range of 0.6 sec to 4.0 sec. Acceleration response spectrums of the 7 scaled records with mean spectrum are shown in Fig. 6 together with the UBC97 spectrum.

Table 2. seismological properties of Near-Fault Records

No.	SAC Name	Year	Earthquake	M_W	Station	Mech.[1]	R, (km)	Site[2]	PGA (g)	PGV (cm/s)	PGD (cm)
1	NF01	1978	Tabas	7.4	Tabas	th	1.2	D	0.9	107.9	50.3
2	NF03	1989	Loma Prieta	7	Los Gatos	ob	3.5	D1	0.72	169.5	63. 9
3	NF07	1992	C. Mendocino	7.1	Petrolia	th	8.5	D1	0.64	123.3	55.4
4	NF09	1992	Erzincan	6.7	Erzincan	ss	2	D	0.43	116.9	41.5
5	NF11	1992	Landers	7.3	Lucerne	ss	1.1	D1	0.71	133.4	225.4
6	NF15	1994	Northridge	6.7	Olive View	th	6.4	D	0.73	119.8	30.5
7	NF19	1995	Kobe	6.9	Takatori	ss	4.3	D	0.79	170.4	54.9

1. Codes for mechanism: ss- strike-slip; ob- oblique; th- thrust
2. Codes for site: D- soil; D1- rock converted to soil



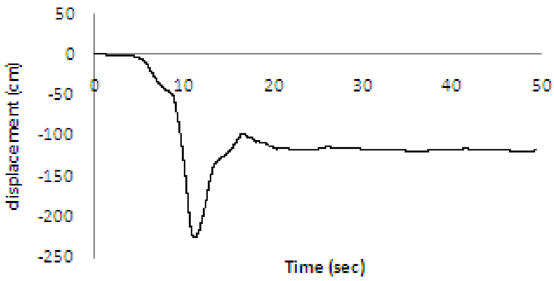


Figure 5. Velocity and displacement time histories of Landers earthquake

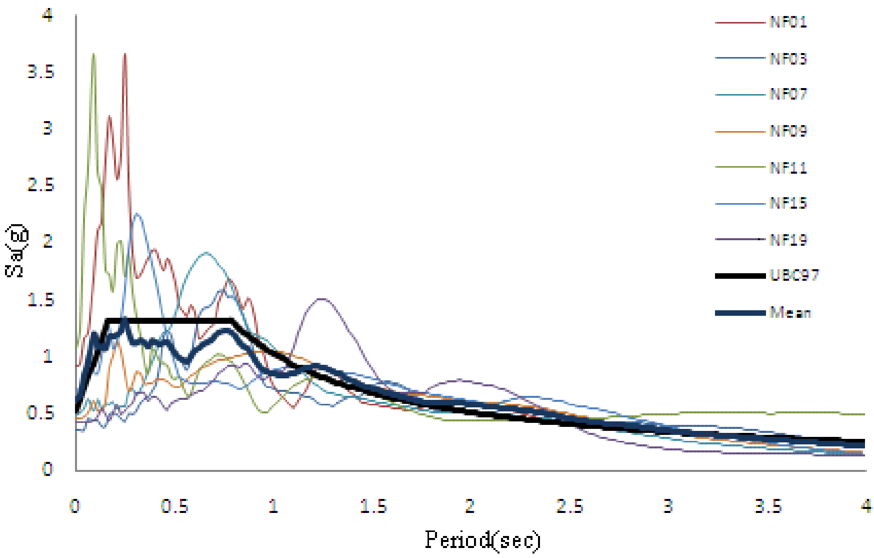


Figure 6. Response spectrum of the selected records with mean and UBC97 spectrums (5% damping)

Structural performance assessment

The results of 21 nonlinear time history analyses of BRBFs are evaluated in terms of interstory drift, braces hysteresis behavior, and portion of seismic input energy dissipated in BRBs. In Fig. 7 max interstory drift ratio (IDR) of 4, 8 and 12 story frames are shown. Due to more effect of first mode in response of 4 and 8 story frames, the max IDR was occurred in bottom floors but in 12 story frame, higher modes effect caused max IDR in mid and top floors. According to IDR values it is observed that these values are in acceptable range which is conducive to lower damages in nonstructural components.

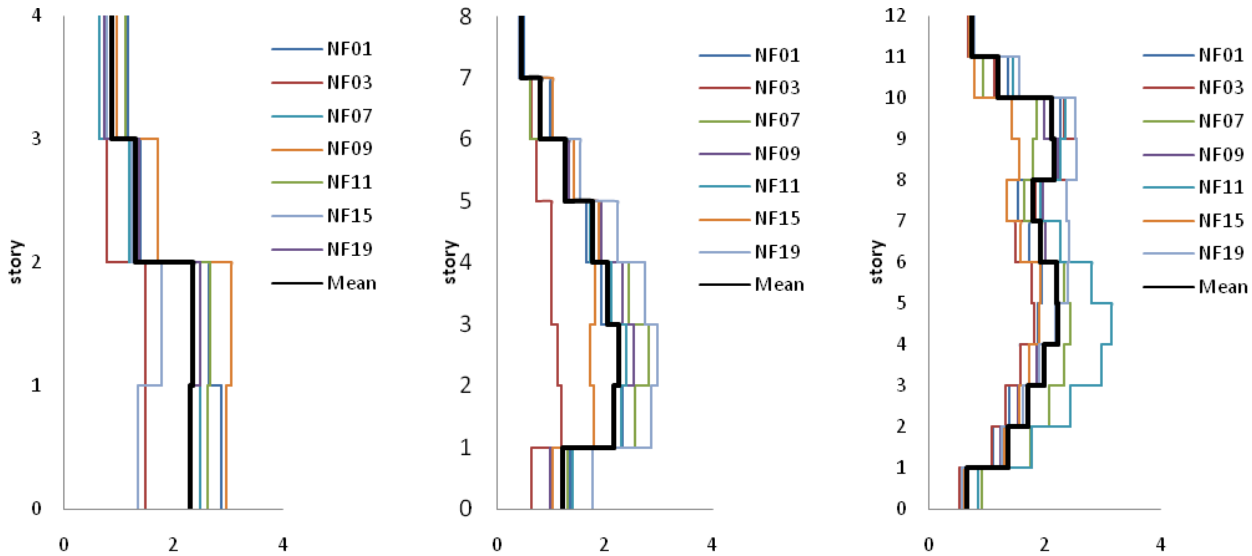


Figure 7. Max interstory drift of 4, 8 and 12 story frames

One of the important factors for performance evaluation of dampers is seismic absorbed energy. Seismic input energy versus braces absorbed energy is displayed in Fig. 8. The mean value of absorbed to input energy ratio (Fig. 8d) for all frames is approximately the same (64%), and therefore, it is independent from number of stories.

With assessment of seismic response of frames and their performance, it was resulted that seismic energy content was affected by structural period and high amplitude pulse period. It was obtained, when pulse period was close to structural period, high portion of energy was imposed to the structure. Since these high amplitude pulse like motions, have long periods (about 2-6 sec), they are more effective on taller structures.

The Tabas earthquake with high frequency content has had approximately same effect on 3 frames. Assessment of velocity record of this earthquake shows the existence of high amplitude pulses, with periods close to those of the frames. In terms of input energy, more relative shifts were observed with increasing the number of stories for the other records compared to the Tabas. This results from lack of pulses with periods close to that of the short frame in such records. In case of the Kobe earthquake, an abrupt change in input energy content from 4 story frame to 8 story was found. Assessing velocity record of this earthquake, it was shown that major pulse periods in the Kobe record were in periods with range of 1 to 2 sec. Therefore, 8 and 12 story frames were more influenced by these pulses.

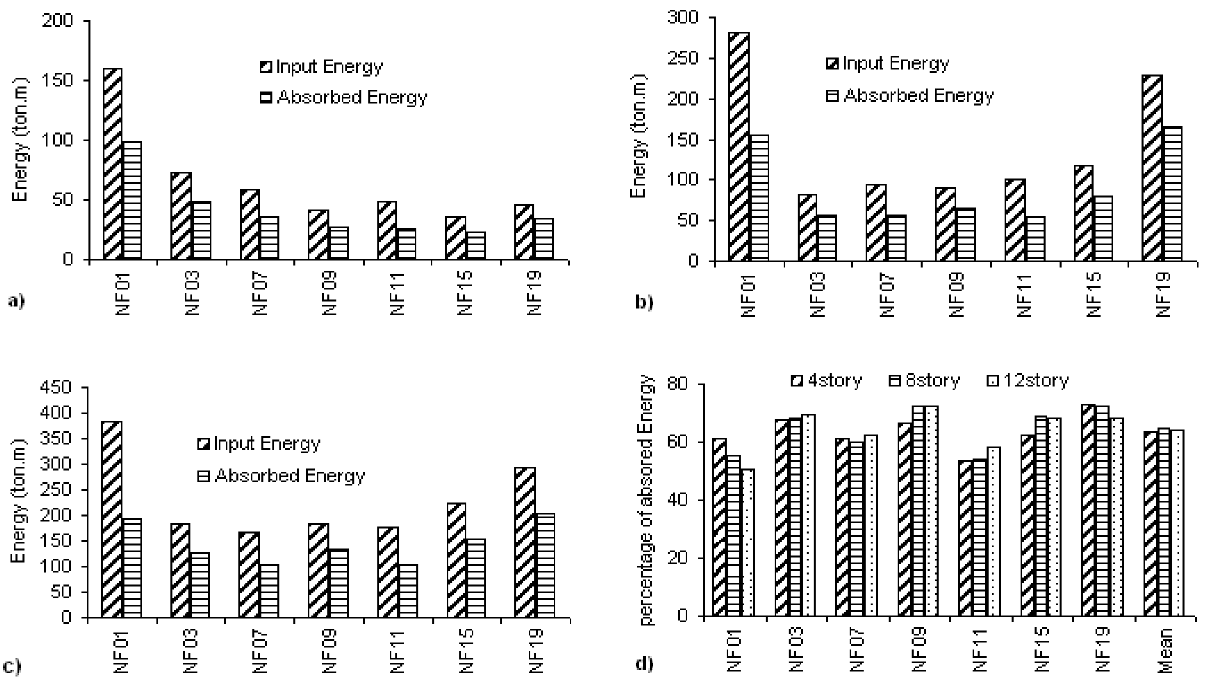
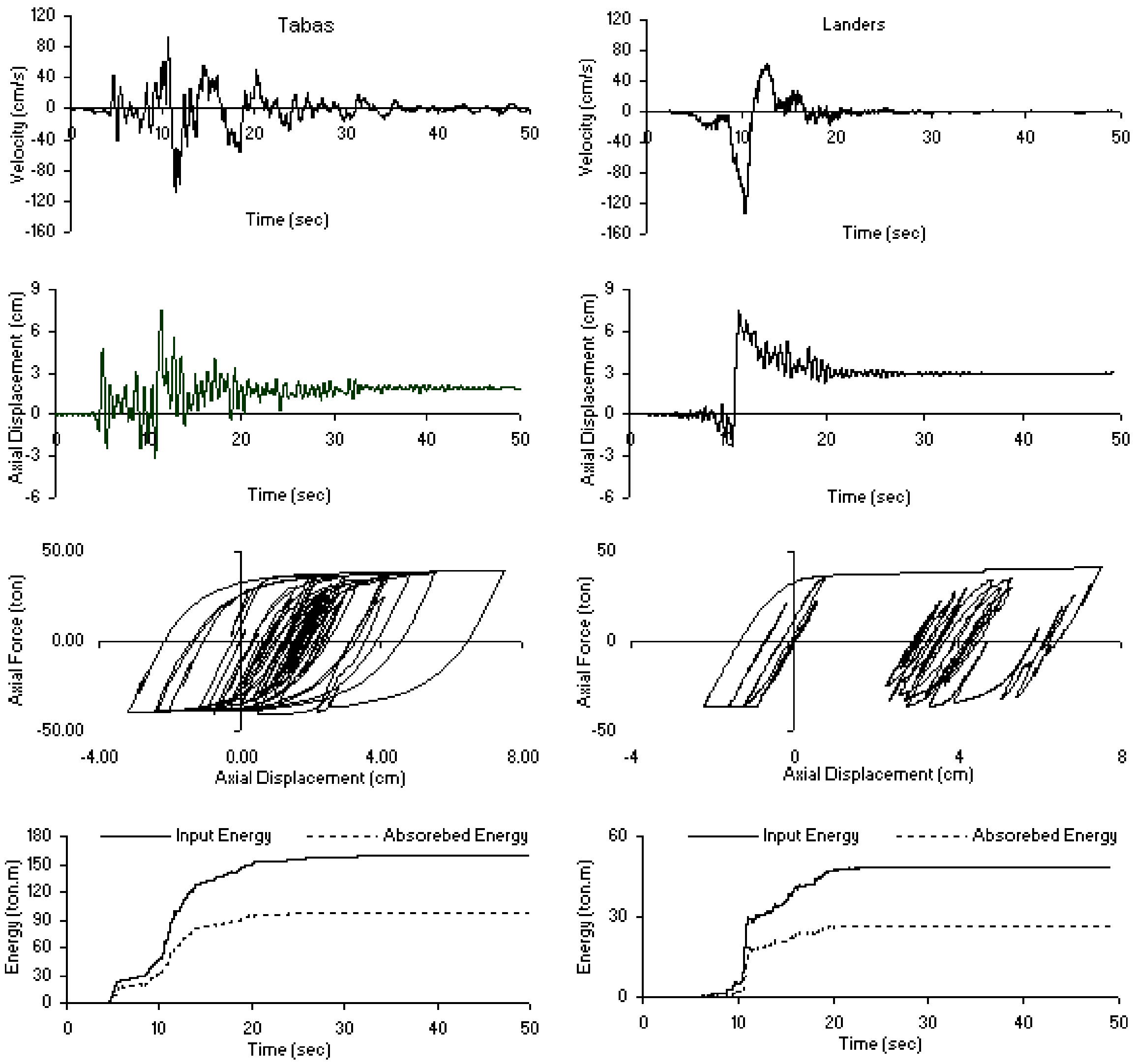


Figure 8. Seismic input energy vs. braces absorbed energy for a) 4 story frame, b) 8 story frame, c) 12 story frame; d) percentage of braces absorbed energy, subjected to different near fault earthquake records

Behavior of one of the second floor braces in 4 story frame for the Tabas and Landers earthquakes are displayed in Fig. 9. High-velocity pulses in velocity time histories of these ground motions cause sudden displacements in braces; for instance, in the Landers Earthquake, when peak of velocity was occurred (at 11th sec), a considerable deformation in a short time is observed (from -3 cm to 8 cm within about 3 sec).



(a) (b)

Figure 9. Behavior of a typical brace under (a) the Tabas, (b) the Landers excitations for 4 story BRB frame

Conclusions

An Analytical study on 3 BRBFs under near-fault ground motions is presented. Analyses showed that because of pulse like motion effects, high amount of input energy is imposed to the structures. Due to its high ductility, BRBs dissipate a large portion of input energy as a hysteretic damper; therefore, it is no major damage in beams and columns. As the results showed, Effects of pulse like motions increase with the increase in the height of structures, but the ratio of BRB absorbed energy to total input energy is still constant. In other words, this ratio is independent of frame height. Although low inelastic stiffness of BRBs induced some concern about large interstory drifts, analyses result in acceptable values. Based on near-fault records, it is revealed that the characteristic periods of these pulse like motions is typically in the range of 2–6 s which corresponds to the fundamental natural period of 15–50 story structures. So these structures should be designed with near-fault earthquake considerations.

Present research with limited case studies, only investigated some characteristics of the near-fault ground motions on BRBs. It is suggested that future studies focus on high buildings to evaluate long period pulse like motions' effects more accurately, other configurations of BRBFs such as V and V-inverted bracing can also be studied.

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