THE EFFECTS OF NEAR-FIELD AND FAR-FIELD MULTIPLE EARTHQUAKES ON SINGLE STORY RC FRAMES

Ali Reza MANAFPOUR
Assistant Professor, Urmia University, Urmia, Iran
a.manafpour@urmia.ac.ir

Parisa KAMRANI MOGHADDAM
PhD Student, Urmia University, Urmia, Iran
p.kamrani@urmia.ac.ir

Keywords: Fragility Curves, Multiple Earthquakes, Incremental Dynamic Analysis

ABSTRACT

Most of the structures situated in seismic regions experience several earthquakes during their lifetime. The majority of research studies in earthquake engineering field consider the effects of a separate earthquake on an intact structure i.e. without any initial seismic capacity deterioration. This consideration might have been justified based on the low probability of occurring two ground motions of significant effects in the lifetime of the structure, or based on the assumption that there would be sufficient time to assess and repair the structure after the first event. However, based on recent experiences, the issue of a structure to be subjected to consecutive earthquakes is real and therefore requires adequate attention. These earthquakes may be considered as from the same seismic source commonly known as foreshocks, main shocks and aftershocks, or from nearby sources affecting similar regions.

It is now well known that the seismic ground motions recorded within the near-fault region of an earthquake are qualitatively quite different from the far fault seismic ground motions. Therefore, this paper aims to investigate the effects of multiple near-field and far-field earthquakes on a SDOF system using IDA. In order to evaluate frame's behaviour under these seismic situations, the systems are considered to have a spectrum of various dynamic properties and hysteresis stiffness and strength degrading characteristics.

It is concluded that multiple near field seismic excitations may result different lateral transient and permanent deformations as compared with far field ground motions. It is also shown that the extent of these differences depends on the structural dynamic characteristics which are sensitive to ground motion frequency contents. This suggests that multiple near field and far field earthquakes would require different seismic considerations within the design procedure. Recommendations are provided on the threshold of seismic excitations as a seismic hazard level to be considered.

INTRODUCTION

Most of the structures situated in seismic regions experience several earthquakes during their lifetime. Seismic resistant design traditionally has focused on structures under single isolated design earthquake. In fact they do not consider the effects of damage accumulation during possible previous events.This was to some extent due to the complexity of seismic behaviour and the limitations in technical and computational knowledge to understand and deal with the considerable uncertainties in structural behaviour under even one single seismic event. Lack of sufficient actual data was led to accept the assumption that there would be sufficient time to assess and upgrade the structure before the next significant event.

Reinforced concrete structures due to stiffness and strength deterioration in their structural materials are more vulnerable to multiple earthquake excitations compared with steel frame structures. The damage accumulation deteriorates the stiffness and strength of structural systems in a manner that can alter their dynamic characteristics and hence their response if subjected to subsequent earthquakes. This response cannot be easily predicted from simple analysis where damage features are neglected.

Based on recent experiences (Chile (2010), Christchurch (2010, 2011), Tohoku (2011), Van (2011), Ahar-Varzeghan (2012) and Greece (2014)), it has been observed that the buildings may stay apparently intact during a main seismic event but collapse in a subsequent event. Consequently, the issue of a structure to be subjected to two or even more consecutive earthquakes is real and therefore requires adequate attention. These earthquakes may be considered as from the same seismic source commonly known as foreshocks, main shocks and aftershocks, or from nearby sources affecting similar regions.

Recently some researchers have focused on multiple earthquake excitations. Bojórquezand Ruiz-Garcia(2013) use residual drift ratio for performance objective and seismic hazard curves. Ruiz-Garcia and Miranda (2005) based on statistical analyses show that the estimation of residual deformation demands involves larger uncertainty than the estimation of maximum deformation demands. Ruiz-Garcíaand Manriquez (2011), Di Sarno (2013) estimated permanent and transient displacement demand in multiple earthquake cases. They have concluded that the demand values in terms of the both parameters increases under multiple events. In a study by Abdelnaby and Miranda (2012) it is concluded that the stiffness and strength degradation have significant effects on the final structural deformations of RC frames under the consecutive earthquakes.

Simplified SDOF systems incorporating inelastic hysteretic force-displacement relationships were studied under repeated earthquake by Aschheimand Black (1999); Amadio et al. (2003); and HatzigeorgiouLiolios (2010). Hatzigeorgiouand Beskos (2009) recommend force reduction to consider consecutive earthquakes in design process.

It is now well known that the seismic ground motions recorded within the near-fault region of an earthquake are qualitatively quite different from the usual far fault seismic ground motions. Near field seismic ground motions are frequently characterized by intense velocity and displacement pulses of relatively long period that are clearly distinguished from typical far field ground motions, (Garcia and Manriquez, 2011). Although, there has been some notable studies on the nature and effects of near field ground motions, more researches are required to achieve comprehensive estimation of these earthquakes effects on different structures.

This paper aims to investigate the effects of multiple near-field and far-field earthquakes on single story RC frames modeled as a SDOF system with various hysteretic stiffness and strength degrading characteristics. In order to evaluate frame’s behavior under these seismic situations, the structures are considered to have a spectrum of various dynamic properties and hysteresis behavior. The structures are analyzed using nonlinear incremental dynamic method (Vamvatsikos and Cornell (2002)). Maximum transient and permanent drift ratios are used as main performance indicators.

For simplicity, replicate earthquake motions are considered in this study. The response under the first (undamaged case) and second motion (taking into account the induced damage under the first motion, damaged case), is compared and conclusions are drawn.

MODEL DEVELOPMENT

In this study material level based models are introduced as opposed to conventional SDOF systems. The models are developed in the open source analysis tool, OPENSEES, which is capable of performing static and dynamic analyses of structures considering material and geometric non-linearity, and stiffness and strength degradation.

MATERIAL MODEL

Upon development of the model, Chang and Mander focused particular emphasis on the transition of the stress- strain relation upon crack opening and closure, which had not been adequately addressed in Kent & Park model. Most existing models assume sudden crack closure with rapid change in section modulus (i.e., sudden pinching behaviour). In the model by Chang and Mander, concrete in tension is modelled with a cyclic behaviour similar to that in compression. The model envelopes for compression and tension have control on the slope of the stress-strain behaviour at the origin, and the shape of both the ascending and descending (i.e., pre-peak and post-peak) branches of the stress-strain behaviour. The shape of the envelopes can be feasibly altered while keeping the values of the peak stress and the strain at peak stress constant, allowing a refined calibration for modelling.

The compressive envelope of the model by (Chang and Mander)for confined concrete complies with the generalized confinement model is applicable to RC members with either circular or rectangular cross sections and any general type and configuration of reinforcement. In OpenSEES, “Concrete07” model is an implementation of Chang and Mander concrete model with simplified unloading and reloading curve. Strain – Stress relationship for concrete model class is shown in Figure 1, (Mazzoni et al., 2006).

In reinforced concrete frames cracked section of concrete elements plays an important role in structural general behaviour. According to this effect, a reliable analytical model has to consider this parameter. In OpenSEES program cracking effects are considered in Concrete07 which include zero tensile strength in concrete fiber section once the tensile strength has been reached, (Eurocode 8, Mazzoni et al., 2006).

The stress-strain relationship of steel reinforcement bars used in this study is based on the Chang and Mander (1994) uniaxial steel model. The simulation has incorporated additional reversal memory locations to better control stress overshooting. The cycle counting method implemented in the routine achieves the same result as rain flow counting. Fatigue parameters are based on the Coffin-Manson equation for plastic strain amplitude. The buckling simulations incorporated consist of a variation on Gomes and Appleton(1997) and Dhakal and Maekawa (2002).

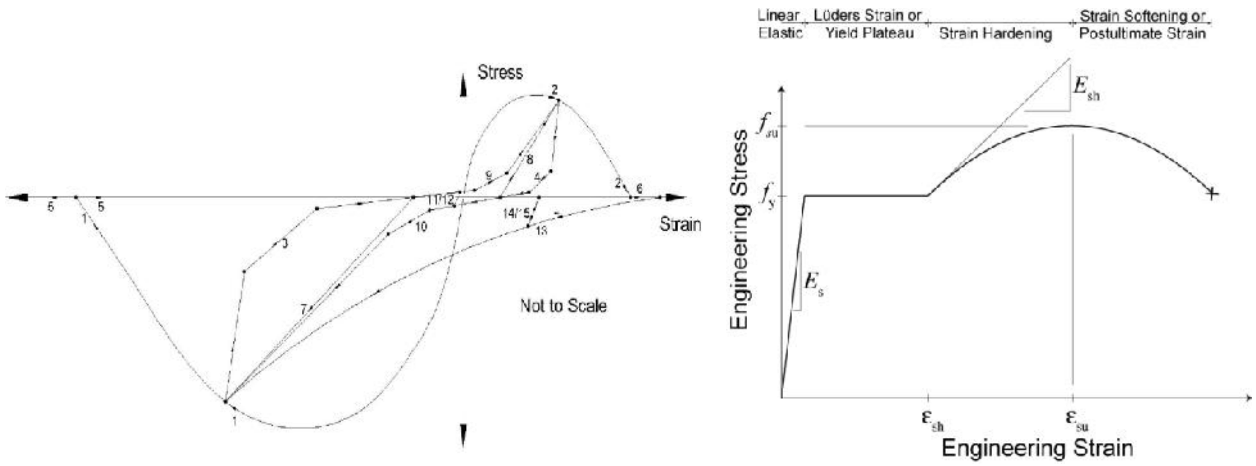

Figure 1. Steel02 Material - Material Parameters of Monotonic Envelope (right)
Concrete07 Material - Hysteretic behaviour of Concrete07 (left)

SDOF MODEL

A reinforced concrete single story frame simplified as an RC SDOF pier is studied in this section. Five SDOF systems with different periods of vibration of 0.138, 0.19, 0.28, 0.34, and 0.4 sec are considered in this study. Systems with different periods have the same pier cross sectional dimensions and height while the lumped mass value at the top of the pier is different.

The cross sections of the structural elements are modelled using fiber section model which can simulate the nonlinear behaviour of the elements. This allows for calculation of the complete flexural and axial stiffness/strength by integrating strains across the section. RC fiber sections have a general geometric configuration formed by sub-region of simpler, regular shapes and quadrilateral regions called patches. In addition, layers of reinforcement bars can be specified, (Mazzoni et al., 2006).For modelling of the elements the nonlinear displacement beam column elements are used. These elements are based on the displacement formulation and consider the spread of plasticity along the element. Integration along the element is based on Gauss – Lobatto quadrature rule. One of the advantages of OpenSEES program is the ability of performing an exact geometric transformation of the beam stiffness and resisting force from the basic system to the global coordinate system. This has become possible by using Corotational coordinate transformation tools, (Mazzoni et al., (2006), Wallace et al., (2007)).

GROUND MOTION SELECTION

Structural performance during an earthquake is greatly impacted by variability in the seismic loading. It is a great challenge to accurately predict aftershocks after a main-shock.

Ground motion record sets in this study include a set of ground motions recorded at sites located greater than or equal to 10 km from fault rupture, referred to as the “Far-Field” record set, and a set of ground motions recorded at sites less than 10 km from fault rupture, referred to as the “Near-Field” record set.The Near-Field record set includes two subsets: (1) ground motions with strong pulses, referred to as the “NF-Pulse” record subset, and (2) ground motions without such pulses, referred to as the “NF-No Pulse” record subset. Resonant or pulse-like ground motion has been observed in near-field records with directivity focusing or fling effects. Such ground motion is influenced by the rupture mechanism and possesses the following characteristics: (1) large peak ground velocities and displacements, (2) concentration of energy in one or a few pulses and (3) unusual response spectra shapes (Moustafa and Takewaki, 2010).

In FEMA P695 (ATC-63 2009), there are a suite of 22 ground motions in the far- field record set and 28 ground motions in the near-field record set. The magnitude for each of the ground motions is between M6.5 and M7.9.Available strong motion databases, such as the Pacific Earthquake Engineering NGA Database (PEER 2011) and Centre for Engineering Strong Motion Data (CESMD 2012), provide the acceleration time-histories of recorded main-shocks and their corresponding aftershocks.In this paper for detailed evaluation and conclusion, ChiChi earthquake is selected. Figure .2 and Figure3 shows earthquake time history records which are normalized for PGA = 1g.

The synthesized sequences can be generated by seeding the recorded ground motions using the repeated approach or randomized approach. In this study, the synthesized sequences by the repeating approach, termed as repeated or replicated seismic sequence, are generated to repeat a main-shock as an artificial aftershock and scale the intensity of shocks. This method can be considered as a conservative way to estimate the seismic performance of buildings on the assumption that characteristics of a main- shock and aftershocks, such as the frequency content and seismic duration, are the same. But for an initial evaluation of consecutive near field and far field earthquakes effects, this sequences are simple and easy to be used.

In this study, these given input ground motion time history are applied to the structures as a uniform excitation pattern, as defined in OpenSEES, (Mazzoni et al., 2006).

For replicate ground motions, 100 seconds time buffer between the first and second earthquakes is assigned to allow the motion of the system to go back to rest due to damping. In order to perform IDA for a mainshock-damaged building, a sequence of mainshock and aftershock records of same record was entered into the model. For a given sequence, the scale factor for a given mainshock response was unchanged while the intensity of the aftershock record was scaled until the model collapsed.

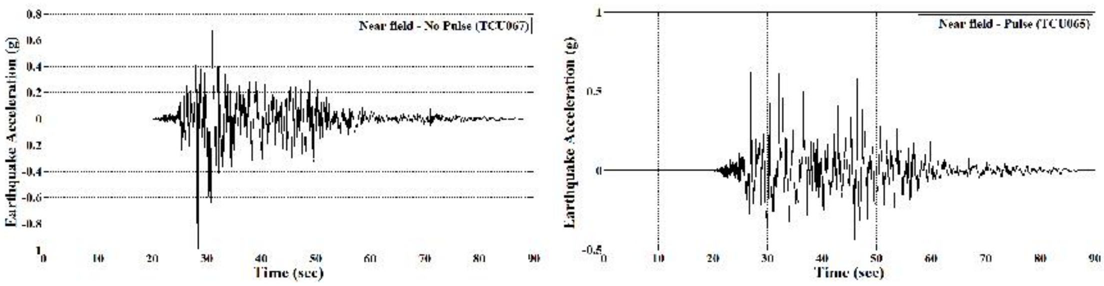

Figure 2.ChiChi time history acceleration in Near-field recorded stations

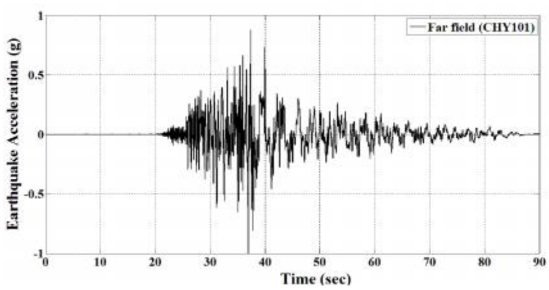

Figure 3.ChiChi time history acceleration in Far-field recorded station

NONLINEAR TIME HISTORY

This section describes SDOF system analysis results with different periods in order to examine the influence of the system vibration period and earthquake intensity on the evaluation of maximum and residual displacements. In order to investigate the effects of the near and far field ground motions in this paper SDOF system responses are studied under ChiChi earthquake with three different time history records- Far field (FF), Near field with pulse (NF-Pulse) and Near field with no pulse (NF- No Pulse) .

According to Table.1, far field, near field (pulse sub set) and near field (No-pulse subset) cases have increased residual displacement 16.9, 2.21 and 3.32 times compare with single excitation, respectively. Although, far field increases residual displacement more than two other cases, near field (No-pulse sub set) makes critical condition in both single and repeated sequence excitations for maximum transient and residual displacements.

Table 1.SDOF maximum residual and transient displacement response underChiChi earthquake

Earthquake Type	Station Name	Transient (cm)		Residual (cm)	
		Single	Sequence	Single	Sequence
FF	CHY101	3.14	4.65	0.02759	0.4671
NF-pulse	TCU065	1.85	2.39	0.04051	0.08974
NF-No pulse	TCU067	6.65	9.064	0.8077	2.68

Time history of the displacement response is shown in Fig 3 to Fig.5 for single record and repeated sequence. As it can be seen there are significant differences in three time history response under near filed and far field records. Despite the fact that these three records are from the same earthquake source, they have different epicentral distances and therefore different time histories resulting in different structural response. These figures also indicate how consecutive excitation could affect maximum structural response. In fact residual deformations resulted from nonlinear behaviour play an important role in the response of system under the next earthquake. This fact is confirmed by residual displacements at the beginning of second earthquake excitation, (see Figure4 to Figure 6).

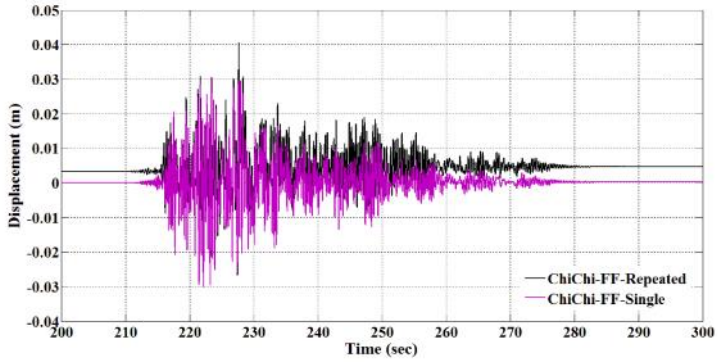

Figure 4. Time history displacement response under Chi Chi far field
(Main-Shock PGA = 1g and After-shock PGA = 0.6g in repeated sequence)

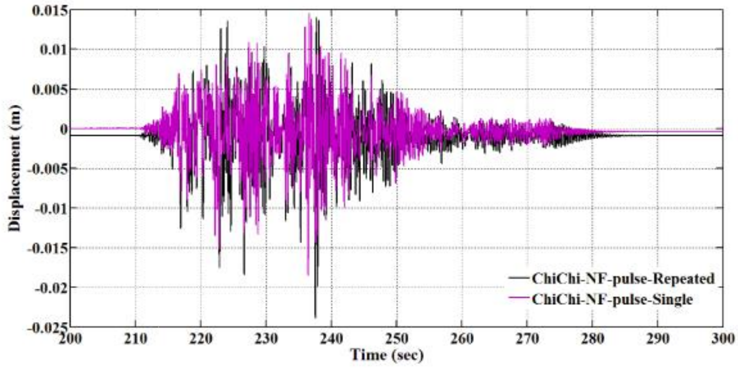

Figure 5. Time history displacement response under Chi Chi near field (with Pulse)
(Main-Shock PGA = 1g and After-shock PGA = 0.6g in repeated sequence)

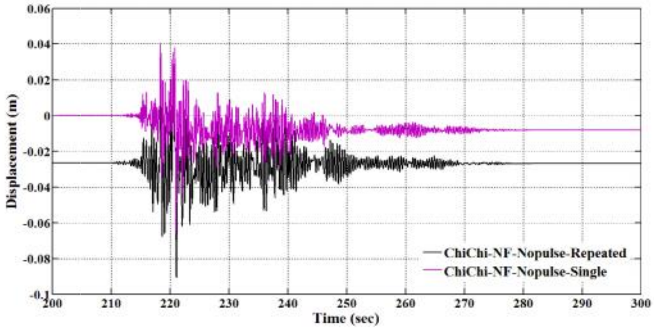

Figure 6. Time history displacement response under Chi Chi near field (with No pulse)
(Main-Shock PGA = 1g and After-shock PGA = 0.6g in repeated sequence)

INCREMENTAL DYNAMIC ANALYSIS

An IDA involves a series of nonlinear dynamics time history analyses of the structure subjected to a ground motion of increasing intensity. In addition, an ensemble of ground motion records, each record in the ensemble being scaled to multiple levels of intensity is often used and is sometimes referred to as a multi-record IDA. The scaling levels of seismic intensity are appropriately selected to force a building undergoing the entire range of behaviour, from elastic to inelastic and finally to global dynamic instability in the form of large engineering demands (e.g., interstory drift). The IDA curves present the maximum interstory drifts when the building is subjected to increasing levels of ground motion intensity.

Figure 7 and Figure 8 depict IDA results of two SDOF systems under ChiChi earthquake with three different time history records from different epicentral distances. As it was expected the structural capacities under different records have significant differences. No pulse near field excitation in both single and repeated case show lower capacity in comparison with other cases. As period of vibration decreases capacity grows up. Repeated excitation clearly reduces the structural capacity. This is due to damage accumulation in successive events which is analytically represented by inelastic behaviour of elements in combination with stiffness and strength degradation. These results are indicative of possible actual differences between far field and near field records when considered as consecutive earthquakes. It can be seen that the structures not only show reduced capacities under near field records but also are more sensitive to their consecutive application to the structure.

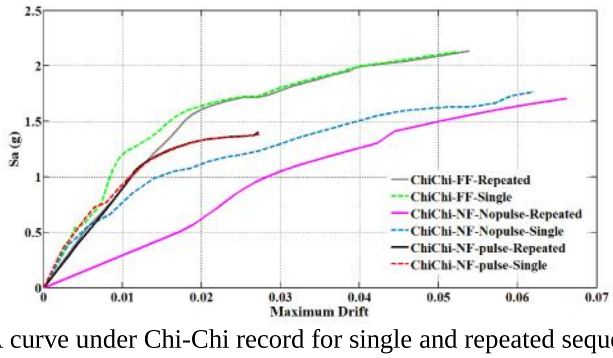

Figure 7.SDOF IDA curve under Chi-Chi record for single and repeated sequences - T = 0.28 sec

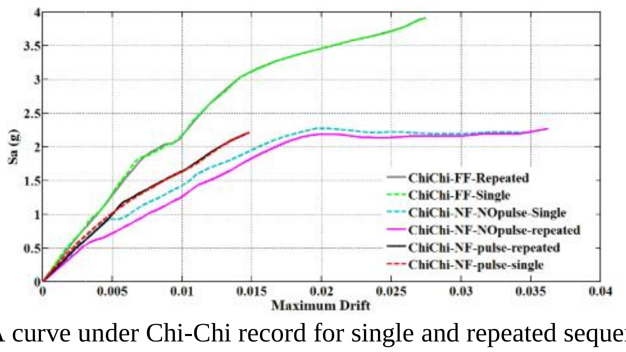

Figure8. SDOF IDA curve under Chi-Chi record for single and repeated sequences - T = 0.19 sec

CONCLUSIONS

In this study samplenear field and far field earthquakes were selected from FEMA P695 records set and the same earthquake is applied repeatedly to simplified inelastic systems that comprise a reinforced concrete pier with lumped mass on the top. The analytical model considersstiffness and strength degradation of the structure through appropriate modelling of consisting materials, i.e. concrete and steel.

Incremental dynamic analysis results show that repeated earthquakes increase the structural deformation demand as compared with single earthquake both for far-field and near-field records. Two types of near field records were used in this study. It appears that No pulse records yield more critical response compared with pulse records. It has to be pointed out that the No pulse record used in this study proves to be more demanding than other records when they applied as single earthquake. Further studies are required to generalise the initial conclusions drawn in this study. However the study clearly indicates the different characteristics of near field and far field earthquake records and warrants additional studies considering these characteristics. More specifically it appears that multiple near field may demonstrate significantly different responsethan multiple far field earthquakes. Moreover sensitivity of response to the structural characteristics were also demonstrated using five different SDOF systems.

The results presented in this study and the conclusions drawn from them point towards the importance of conducting further detailed and comprehensive analyses of different structural systems with carious properties so that to quantify the effect of multiple earthquakes on seismic response.

REFERENCES

Abdelnaby AE (2012) Multiple Earthquake Effects On Degrading Reinforced Concrete Structures, PhD Thesis, University Of Illinois at Urbana-Champaign

AbdelnabyA (2012)Response of reinforced concrete structures under multiple earthquakes. 15WCEE, Lisboa

Amadio C, Fragiacomo M and RajgeljS (2003) The effects of repeated earthquake ground motions on the non-linear response of SDOF systems, *Journal of Earthquake Engineering and Structural Dynamics*, 32, 291-308

Aschheim M and BlackE (1999) Effects of prior earthquake damage on response of simple stiffness- degrading structures, *Journal of Engineering Spectra*, 15(1), 1-24

Bojórquez E, Ruiz-Garcia J (2013) Residual Drift Demands In Moment-Resisting Steel Frames Subjected To Narrow-Band Earthquake Ground Motions, *Earthquake Engineering & Structural Dynamics*, Doi: 10.1002/Eqe.2288

Di Sarno L (2013) Effects of Multiple Earthquakes On Inelastic Structural Response, *Journal of Engineering Structures*, 673-681

Eurocode 8, Design of structures for earthquake resistance, Institution of Civil Engineers (ICE) and Institution of Structural Engineers

Fragiacomo M, Amadio C and Macorini L (2004) Seismic response of steel frames under repeated earthquake ground motions, *Journal of Engineering Structures*, 26, 2021-2035

GarciaJ and Manriquez J (2011) Evaluation of drift demands in existing steel frames as-recorded far-field and near-filed main shock-aftershock seismic sequences, *Journal of Engineering Structures*, 33, 621-634

Hatzigeorgious G (2010a) Behavior factors for nonlinear structures subjected to multiple earthquakes, *Journal of Computer and Structures*, 88, 309-321

Hatzigeorgious G and Beskos D (2009) Inelastic displacement ratios for SDOF structures subjected to repeated earthquakes, *Journal of Engineering Structures*, 31, 2744-2755

Hatzigeorgious G and Liolios A (2010b) Nonlinear behavior of RC frames under repeated strong motions, *Soil Dynamics and Earthquake Engineering*, 30, 1010-1025

Li Q and EllingwoodB (2007) Performance evaluation and damage assessment of steel frame buildings under main shock-aftershock earthquake sequences, *Journal ofEarthquake Engineering and Structural Dynamics*, 36, 405-427

Mazonni S,McKenna F, ScottH and Fenves MLG (2007) OpenSEES Command Language Manual, University of California, Berkeley

MazzoniS, McKennaF, ScottH, FenvesML, JeremicGB (2006) OpenSEES Examples Primer, University of California, Berkeley

Moustafa A and Takewaki I (2010) Deterministic and probabilistic representation of near-field pulse-like ground motion, *Soil Dynamics and Earthquake Engineering*, V(30) 412-422

Ruiz-Garcia J and Miranda E (2005)Performance Based Assessment Of Existing Structures Accounting For Residual Displacements, Blume, Department of Civil and Environmental Engineering Stanford University

Ruiz-Garcia J (2010) On the Influence of Strong-Ground Motion Duration on Residual Displacement Demands, *Journal of Earthquakes and Structures*, Vol. 1, No. 4, 1-18