ISBN 978-93-84422-56-1
Proceedings of International Conference on Architecture, Structure and Civil Engineering (ICASCE'15)
Antalya (Turkey) Sept. 7-8, 2015 pp. 1-7

Using Spectral Acceleration Area as an Intensity Measure Parameter for Accurate Estimation of Seismic Demand

Mehdi Mahdavi Adeli
Department of Civil Engineering, College of Engineering, Shoushtar Branch, Islamic Azad University, Shoushtar, Iran

Abstract: *In probabilistic seismic demand analysis, Intensity Measure (IM) parameter plays an important role; thus, its selection should be precisely done based on various studies. The results of recent studies have shown that first mode spectral acceleration as the current IM parameter is not suitable for estimation of seismic demand for all types of structures with varying heights. Thus, it seems necessary to introduce a new intensity measure parameter for estimation of seismic demand of steel moment-resisting frames which constitutes the main aim of this study. In so far as it is almost impossible that any of spectral accelerations could be solely considered and used as seismic demand estimator for all frames with various heights because of nonlinear behavior of structure and the effects of various modes, the area under spectral acceleration curve has been introduced here as a new IM. The results of incremental dynamic analysis of frames subjected to 80 selected ground motion records indicate that if an appropriate period and interval is selected, this new IM can effectively reduce the standard deviation of demand model and increase the accuracy of estimated demand consequently.*

Keywords: *Probabilistic Seismic Demand Analysis, Intensity Measure, Spectral Acceleration Area, Incremental Dynamic Analysis, Steel Moment-Resisting Frames*

1. Introduction

In recently developed performance based design engineering frameworks, estimation of seismic demand is an essential part to describe the performance of structure. The most challenging in this estimation is the large uncertainty associated with the seismic events and structural response demands. Because of this uncertainty, can be described in term of those originating from randomness and modelling errors, using a probabilistic method to treatment of both randomness and uncertainty is required in estimation of seismic demand [1]. This method is generally known as Probabilistic Seismic Demand Analysis (PSDA). PSDA is an approach for calculating the mean annual frequency of exceeding a specified seismic demand for given structure at a designated site [2]. PSDA combines a ground motion Intensity Measure (IM) hazard curves for designated site with the demand results from Nonlinear Dynamic Analysis (NDA) of the given structure under a suite of earthquake ground motion records through the application of the total probability theorem [3]. If the maximum inter story Drift Ratio (denoted by DR) is selected as the demand parameter, the following mathematical expression can be used to calculate the probability that the drift exceeds the value x, P[DR >x]:

$$P[\mathrm{DR} > x] = \int P[\mathrm{DR} > x \mid \mathrm{IM} = y].\left| d\lambda_{\mathrm{IM}}(y) \right| \tag{1}$$

Where $\lambda_{\mathrm{IM}}(y)$ means the mean annual frequency of IM exceeding the value y, which is also known as the ground motion hazard in terms of IM evaluated at y and |d…| denotes absolute value of its differential with respect to IM also evaluated at y. The term, P[DR > x| IM = y], which means the probability of DR exceeding the value x given that IM equals y, is the main issue concerned here. As a common practice this term is determined by NDA of a rigorous nonlinear model of structure under the ground motion records that are incrementally scaled to different levels of intensity measure, through a method called Incremental Dynamic Analysis, (IDA). By using IDA, i.e., scaling the amplitudes of ground motion records to a target IM level (e.g., here IM = y), and performing the NDA of a structure to obtain the structural response of interest, the variation of responses due to earthquake excitations at each IM level is obtained.

The results of various studies show that for this conditional response at any intensity measure level follow a lognormal distribution. In other words, the probability of a DR exceeding a given level x at a given intensity level, e.g., y, can be expressed as follow [3]:

$$P[\mathrm{DR} > x \mid \mathrm{IM} = y] = 1 - \Phi\left(\frac{\ln(x) - \mu}{\sigma}\right) \tag{2}$$

Where Φ(…) denotes the standard Gaussian cumulative distribution function and μ and σ are its mean and standard deviation, calculated by introducing the Probabilistic Seismic Demand Model (PSDM). A PSDM is a mathematical expression relates structure specific demand to the specific IM. The selection of PSDMs is based on several inherent properties such as practicality, sufficiency, effectiveness and efficiency [4]. In spite of these difficulties, based on extensive regression analysis of response of steel structures, the following form is accepted for the defining the seismic demand model in Steel Moment-Resisting Frames (SMRFs) [5]:

$$\ln(\mathrm{DR}) = a.\ln(\mathrm{IM}) + w + \sigma.\varepsilon \tag{3}$$

Where ε is a standard normal random variable with zero mean and unit standard deviation, σ is the unknown standard deviation of model and a and w are the unknown model parameters. In fact σ in eq.2 is the estimated standard deviation for the model and μ will be the product of eq.3 when the value of ε is zero.

Having above introductory explanation, the main object of this article can be now elaborated in more details. In fact IM parameter plays the most significant role in the problem of estimating the seismic demand. A proper IM parameter would result in less dispersion in response which in turns can be related to a decrease in standard deviation of PSDM. It is to say that the selection of a proper IM parameter can increase the accuracy in estimation of seismic demand value. The selection of such parameter for SMRFs is the focus of this article. In other words, it is tried to find out a parameter among different spectral parameters which is the best estimator of seismic demand in SMRFs. Considering the results of recent studies, which show that the current IM parameter i.e. the spectral acceleration at the first mode of vibration, Sa1, is not a appropriate seismic demand estimator for all of the SMRFs with different heights [6], it seems introducing this new IM is unavoidable in performance based earthquake engineering frameworks.

In this article the nonlinear model of a series of generic frames is used to represent the SMRFs. It has been shown that the maximum inter-storey Drift Ratio (DR), which is the peak in drift ratio response time histories over all stories in the frame, is an appropriate displacement-based structural demand to predict the behaviour of SMRFs, particularly overall collapse cases and non-structural damages [1]. Therefore this parameter has been selected as demand parameter. Furthermore, in order to avoid biasness of the result to the number of ground motion records, a large number of records are employed for NDA.to 2014 International Conference on Architecture and Civil Engineering (ICAACE 2014). The Conference is a primary international forum for scientists and technicians working on topics relating to Civil and Architecture Engineering.

2. Generic Archetype Steel Moment-Resisting Frames

The results of this study would be useful when they can be applied to all types of SMRFs not just to a special model of these structures. In order to reach this end and cast a reliable archetype of SMRFs, the concept of generic frames is adopted in this paper. NDA is carried out using a family of two-dimensional single-bay generic SMRFs for 3, 6, 9, 12 and 15-storey structures, and the first mode period equals to 0.3, 0.6, 0.9, 1.2 and 1.5 second. The results of different studies show that using a single-bay generic frame can properly demonstrate the behaviour of multi-bay frames [7]. Nonlinear beam-column elements with concentrated plastic hinges in two ends, connected by an elastic element, are adopted for modeling the frames. The nonlinear behaviour in plastic hinges is modelled implementing rotational springs (with stiffness and strength deterioration). The peak-oriented model is then applied to specify the hysteretic behaviour. Also, in order to consider the cyclic deterioration, the modified model suggested by Ibarra and co-workers have been used. In this model, cyclic deterioration parameter is accounted for deterioration criterion within the concept of hysteretic energy dissipation [8]. Main characteristics of this family of frames are as follows, more details can be found in [7]:

- The same mass is used at all floor levels.

- The frames have constant storey height equal to 3.66 m and beam span equal to 7.32m.
- The same moment of inertia is assigned to the columns in a storey and the above beam.
- Relative stiffness is tuned so that the first mode is straight line.
- Plasticization just occurs at the end of the beams and the bottom of the first storey columns.
- Frames are designed so that simultaneous yielding at all plastic hinge locations is attained under a parabolic (NEHRP, k=2) load pattern.
- Global (structure) P-delta is included (member P-delta is ignored).
- Moment-rotation hysteretic behaviour is modelled by using rotational springs with peak-oriented hysteretic rules and cyclic deterioration parameter equals to 30.
- For the NDA, 5% Rayleigh damping is assigned to the first mode and the mode at which the cumulative mass participation exceeds 95%.

3. Selection of Ground Motion Records

In this article, using a bin strategy, 80 ground motion records have been selected from the PEER Centre Ground Motion Database (http://peer.berkeley.edu/smcat/) and classified into four magnitude-distance bins for the purpose of NDA of SMRFs [9]. The record bins are as follows:

- Large Magnitude-Short Distance Bin, LMSR, (6.5 < Mw < 7.0, 13 km < R < 30 km)
- Large Magnitude-Long Distance Bin, LMLR, (6.5 < Mw <7.0, 30 km < R < 60 km)
- Small Magnitude-Short Distance Bin, SMSR, (5.8 < Mw < 6.5, 13 km < R < 30 km)
- Small Magnitude-Long Distance Bin, SMLR, (5.8 < Mw < 6.5, 30 km < R < 60 km)

4. Incremental Dynamic Analysis Of Modelled Frames

As it was mentioned, the IDA is utilized in order to produce the date needed for introducing a new IM parameter. Generally, IDA is done by conducting a series of NDA. In this process the IM of ground motion increases incrementally and the selected seismic demand parameter is monitored during each analysis [10]. The extreme values of demand parameter are plotted against the corresponding value of the IM for each level to produce a database and consequently the unknown model parameters are estimated based on this database. In this article, the spectral acceleration of the first mode (Sa1) of the ground motion records is scaled from a small value to a to a high level which may lead to overall collapse of the modelled frames by a scale factor which can be less or more than one. Here overall collapse is identified either via detecting by non-convergence of dynamic analysis, or a large increment in structural deformations with a small increment in intensity or the demand response reaches a certain value which is defined as collapse limit. In fact each record is scaled from Sa1=0.05g to the larger possible value in vicinity of collapse with 0.05g steps incrementally and each time a NDA is performed.

The results obtained from above procedure are collected for performing statistical process. Here, only the points, in which no collapse has occurred, are used for selecting the best IM parameter and the collapse data points are removed from database [11]. The number of these points for 3, 6, 9, 12 and 15-storey frames were observed as 4929, 5035, 3769, 2823 and 2206, respectively. In Figure 1 an example of these data points resulted from IDA with two different IMs (Sa1 & Sa2) in 3, 9 and 15-storey frames are shown.

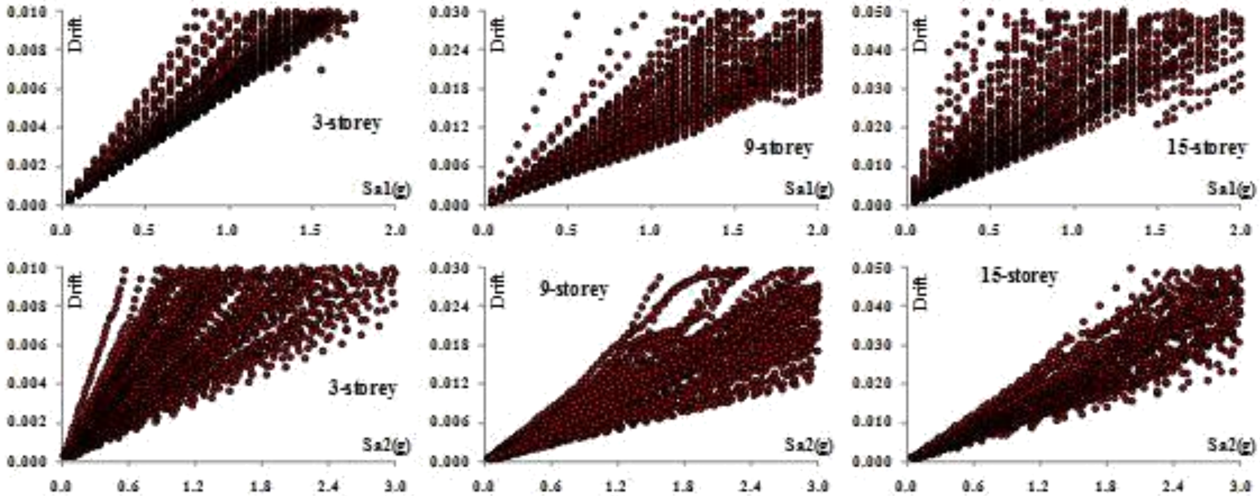

Fig. 1: An example of data points resulted from IDA with two different IMs (Sa1 & Sa2) in 3, 9 and 15-storey frames.

5. Single Spectral Acceleration As IM Parameter

Although using a single spectral acceleration as IM parameter, especially Sa1, is currently practicing the main IM parameter in estimation of seismic demand of SMRFs, some recent studies show that these IM parameters may have not the same accuracy in estimation of seismic demands of all frames with different height [6]. The standard deviation of PSDM of eq. 3 is the best criterion to evaluate the accuracy of single spectral acceleration as IM parameter. Consequently, in order to evaluate the accuracy of single spectral acceleration as IM parameter by using the statistical calculations, the standard deviation of this model, when one of the four usual value (Peak Ground Acceleration, PGA and spectral acceleration at first, second and third mode of vibration, Sa1, Sa2 and Sa3 respectively) is used as IM, estimated and shown in Table 1 [12].

TABLE I: Estimated Standard Deviation of PSDM eq 3 Using Four Different IM Parameters

	IM	PGA	Sa1	Sa2	Sa3
Frame	3-storey	0.2837	0.1860	0.4240	0.3479
	6-storey	0.3151	0.1933	0.3934	0.4467
	9-storey	0.3083	0.2495	0.2724	0.4228
	12-storey	0.3294	0.3249	0.2576	0.3802
	15-storey	0.3558	0.3862	0.2139	0.3377

It is clear that the standard deviations of PSDMs with one of these four quantities as IM parameters strongly depend on the number of stories of frames, which is not a good sign at all. In other words, although Sa1, which is the current IM in estimation of seismic demand, in low-rise and stiff structures, 3 and 6-storey frames, is the best IM parameter for estimation of seismic demand in absolute terms In these structures, this IM is not a appropriate estimator in high-rise and deformable structures, 12 and 15-sorey frames. Also the second mode spectral acceleration, Sa2, which is the best IM in 12 and 15-storey frames, becomes the weakest estimator in low rise-frames. As a general rule of this section, it is clear that there is no single spectral acceleration to introduce as the best IM parameter of all frames with different number of stories.

6. Spectral Acceleration Area As IM Parameter

After unsuccessful finding an appropriate IM parameter between single spectral accelerations, as a new attempt the area under the spectrum in acceleration diagram is targeted as to be an IM. In order to evaluate the accuracy of this new IM, first the area under the spectrum-acceleration diagram has been calculated for a wide range of periodical intervals of a minimum value 0.05 second in the period range of 0-2 second (totally 820 intervals) and then all these areas have been treated as IM parameter. After identification of areas of the spectrum which have the best accuracy in the estimation of seismic demand of each frame based on the lowest standard deviation, these areas have been evaluated in more details, so that the areas of all possible intervals with at least 0.01 second length have been calculated and treated as IM parameter.

The estimated standard deviations resulted from these new IM parameters in PSDM eq.3 are shown in Figure 3. From this figure it can be easily concluded that there are regions in spectral area that if treated as an IM parameters will be able to decrease standard deviation and consequently increase the accuracy in estimation of demand. In 3 and 6-storey frames, the best area of spectral acceleration, which is identified in [0.27-0.35] and [0.48-0.67] second, will be able to estimate the seismic demand in the format of eq. 3 with a reduction in the standard deviation of 10% comparing to the case when Sa1 is used as IM. This reduction in 9, 12 and 15-storey frames is more tangible and has been about 33%, 32% and 18%. The best period intervals for calculation of the area under the spectrum-acceleration in these frame are [0.21-1.31], [0.19-1.64] and [0.23-1.58] second, respectively. In fact the main reason of this reduction is the ability of these new IM parameters to reduce the dispersion of the data points which resulted from IDA. As a result one can say that in case of selecting one proper periodical interval, implementation of the area under the spectrum-acceleration diagram in estimation of seismic demand can be more accurate comparing to using a single spectral acceleration, nevertheless the problem in terms of lacking the generality of the intervals for all frames is steal remains. In table 2, the final results of this section and previous one, which consist of the best IM parameters in PSDM and their corresponding standard deviations, are summarized for different frames.

TABLE II: The best IM parameters and their corresponding standard deviation in different frames

Number of Stories	Periods (sec.)	Probabilistic Seismic Demand Model T	σ	$[T_D-T_U]$	σ	Collapse Fragility Curve T	Error	$[T_D-T_U]$	Error
3	T_1=0.30 T_2=0.10	0.30	0.184	[0.27-0.35]	0.165	0.12	1.05%	[0.21-0.33]	1.17%
6	T_1=0.60 T_2=0.23	0.60	0.190	[0.48-0.67]	0.170	0.60	1.10%	[0.44-0.81]	1.13%
9	T_1=0.90 T_2=0.35	0.88	0.248	[0.21-1.31]	0.168	0.04	1.02%	[0.15-1.31]	1.01%
12	T_1=1.20 T_2=0.48	0.48	0.234	[0.19-1.64]	0.163	0.03	1.02%	[0.10-1.45]	1.10%
15	T_1=1.50 T_2=0.60	0.60	0.210	[0.23-1.58]	0.172	0.17	1.10%	[0.23-1.60]	1.09%

T: Period of spectral acceleration at which the minimum σ and error are observed.
$[T_D-T_U]$: Interval of Periods of spectral acceleration area at which the minimum σ and error are observed.

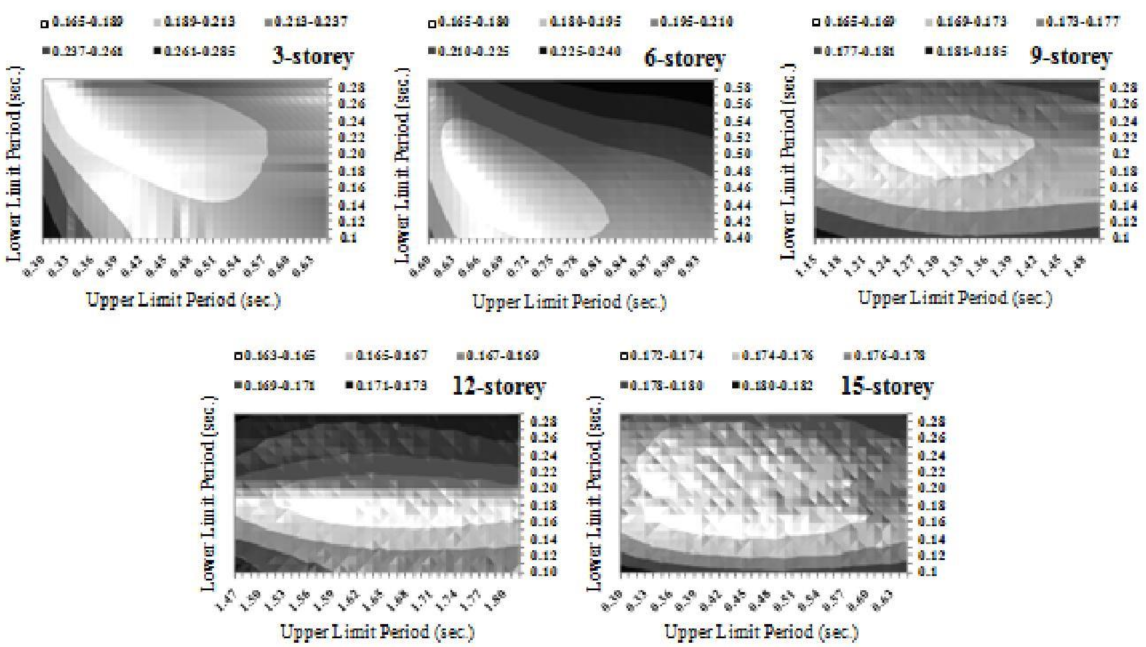

Fig. 2: The best interval of periods for using their spectral area as IM parameter and the estimated standard deviation for different frames.

7. Introducing A Unique Spectral Area As IM Parameter

In previous section the best area under spectrum-acceleration diagram have been determined for estimation of seismic demand in different frames, but as it has been observed that, these best estimators have not been the same for frames with different heights, while the main objective of this research is to introduce a unique parameter as IM parameter in all frames with different heights in such a way that all cases have an acceptable accuracy in estimation of seismic demand. In this research it has been observed that, if the area under the spectral acceleration diagram has been chosen as IM parameter, a unique parameter can be introduced as the proper estimator in all frames. The main reason in supporting of the above notion is the fact that those intervals, which have been introduced as the best spectral area, have common and overlapping limits which can be used toward satisfying the aim of introducing a unique IM. So the aim is to find an interval from periods, in which if the area under the spectral accelerations diagram is used as IM parameter in PSDM of eq.3, the calculated mean standard deviation in different frames be the minimum. In order to define the lower limit of this interval, that period of the mode in which the cumulative mass participation exceeds 95% is used (denotes by Tm and for 3, 6, 9, 12 and 15-storey frames, this mode is the 2nd, 3rd, 3rd, 4th and 4th mode respectively) and in order to define the upper limit, T1 would be used. So this interval will be defined as [αTm – βT1]. In order to determine the optimum value of α and β based on the least possible mean value of the PSDM standard deviation in different frames, the area of spectral acceleration is calculated corresponding to the considered interval for all possible values of α and β and applied in the PSDM as IM parameter. Then the standard deviation was calculated for each frame and it has been used for determining the mean value of standard deviations which are shown in Figure 3.

It can be seen that there is a region in the spectrum whose area can be used as IM parameter for the estimation of seismic demand in all frames. This region can be defined as $0.95 \leq \alpha \leq 1.5$ and $1.35 \leq \beta \leq 1.65$. The mean value of standard deviations in this interval is less than 0.185. Also it can be concluded the best interval is [1.2Tm – 1.5T1] for all frames. So the area under spectral acceleration diagram in this interval of periods can be defined as the best estimator of seismic demand in steel moment-resisting frames.

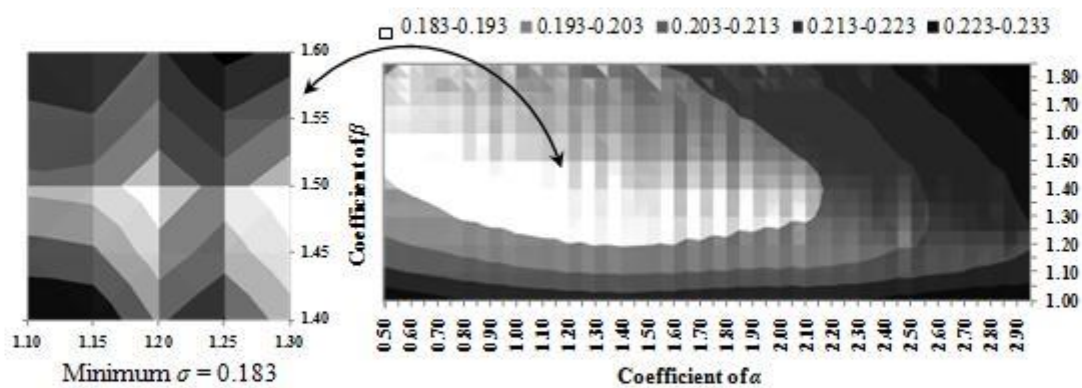

Fig 3: The best interval of periods defined in the form of [αTm – βT1] for using their spectral area as IM parameter and the mean of estimated standard deviation

8. Conclusions

This paper aimed at finding a proper spectral intensity measure parameter for estimation of the seismic demand of steel moment-resisting frames with different number of stories. The modelling of frames was done based on the concept of generic frames for generation of generalized results; moreover, various ground motion records including 80 bin strategy selected records was used for nonlinear dynamic analysis. Furthermore, in order to generate the required databases, a rigorously incremental dynamic analysis was used for selection of IM parameter. The results obtained in this study are as follow:

- If a suitable interval of periods is selected, this new IM parameter effectively reduces PSDM standard deviation and increases the accuracy of estimated demand. This reduction is mainly due to the ability of this new IM parameter in reduction of the dispersion of data points induced from IDA.

- Although the intervals, that are used for calculation of the spectral acceleration area produce the best estimation of seismic demand, are not the same in different frames, it is possible to find uniform interval with T1 that is the first mode period for upper limit and Tm that is the period of the mode at which the cumulative mass participation exceeds 95%.
- This new IM parameter introduced in this study is spectral acceleration area at the interval of [αTm – βT1]. The reason for the use of different periods in range of T1 to Tm for determination of the interval is to contribute all of the effective modes and the reason for the use of two modification coefficients, α and β is to consider the effect of nonlinear behaviour of the structure on seismic demand.
- The results indicate that spectral acceleration area in [αTm – βT1] defined by $0.95 \leq \alpha \leq 1.5$ and $1.35 \leq \beta \leq 1.65$ is precise enough to be used as IM parameter. More strictly, the area under the spectral acceleration in interval [1.2Tm-1.5T1] is introduced as the spectral intensity measure parameter to estimate the seismic demand.

9. References

[1] F. Jalayer, and C. A. Cornell. "A Technical Framework for Probability-based Demand and Capacity Factor Design (DCFD) Seismic Formats," Report No. 2003/08 PEER, Uni. of California at Berkeley, Berkeley, California, 2003.

[2] P. Tothong and N. Luco, "Probabilistic seismic demand analysis using advanced ground motion intensity measures", *Earthquake Engineering & Structural Dynamics*, vol. 36, Issue 13, pp. 1837–1860, 25, 2007.

[3] N. Luco. "Probabilistic seismic demand analysis, SMRF connection fractures, and near source effects," Ph.D. thesis, Dept. of Civil and Environmental Eng., Stanford University, Stanford, 2002.

[4] K. Mackie and B. Stojadinovic, "Probabilistic seismic demand model for California highway bridges," *Journal of Bridge Eng.*, Vol. 6 (6), pp. 468-481, 2001. http://dx.doi.org/10.1061/(ASCE)1084-0702(2001)6:6(468)

[5] R. Sehhati, "Probabilistic seismic demand analysis for near-fault zone," Ph.D. thesis, Dept. Civil and Environmental Eng., Washington State University, Washington, 2008.

[6] M. Mahdavi Adeli, M. Alinia, A. Deylami, and M. Banazadeh, "The comparison of probabilistic seismic demand models estimated through the incremental dynamic analysis and the use of scaled ground motion records," *ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING)* Vol. 12, No. 3 (2011), pp. 319-335.

[7] R. A. Medina and H. Krawinkler, "Evaluation of drift demands for the seismic performance assessment of frames," *Journal of Str. Eng.*, Vol. 131 (7), pp.1003-1013, 2005. http://dx.doi.org/10.1061/(ASCE)0733-9445(2005)131:7(1003)

[8] L.F. Ibarra and H. Krawinkler, "Global Collapse of Frame Structures under Seismic Excitations," Report No. 2005/05 PEER, Uni. of California at Berkeley, California, 2005.

[9] R. A. Medina and H. Krawinkler, "Seismic demands for non-deteriorating frame structures and their dependence on ground motions," Report No. 144, Stanford University, 2003.

[10] D. Vamvatsikos and C.A. Cornell, "Incremental dynamic analysis," *Earthquake Engineering & Structural Dynamics*, Vol. 31 (3), pp. 491-514, 2002. http://dx.doi.org/10.1002/eqe.141

[11] M. Mahdavi Adeli, A. Deylami, M. Banazadeh and M. Alinia "A Bayesian Approach to Construction of the Probabilistic Seismic Demand Models for Steel Moment-Resisting Frames," *Scientia Iranica*, Vol. 18, No 4 (2011), pp. 885-894 http://dx.doi.org/10.1016/j.scient.2011.07.019

[12] M. Mahdavi Adeli, M. Banazadeh and A. Deylami, "Bayesian Approach for Determination of Drift Hazard Curves for Steel Moment-Resisting Frames in Territory of Tehran," *International Journal of Civil Engineering*, Vol. 9, No 3 (September 2011), pp. 145-154.