A comparative study of the traditional performance and The Incremental Dynamic Analysis approaches (IDA)

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ABSTRACT:
In this study, the applicability of different load patterns in traditional pushover for seismic response assessment is investigated. At first Cornel UPSHA approach is used for estimating response spectra with probability of exceedance PE=10% and a time histories compatible with those of estimated response spectra were determined to be used in IDA method. Following this, three steel MRF frames (3, 9 and 15-story) according to IBC-ASD have been selected and designed, then the frames loaded under different load patterns (inverted triangular, uniform and first mode-based) that is frequently used in traditional pushover analysis methods. The outputs of the structural analysis, in the forms of, story shear versus story drift ratios of upper, middle and lower portions of structural heights were depicted and compared with those of IDA method and standard error of selected frames were calculated.
KEYWORDS: Pushover, Load pattern, Incremental dynamic analysis (IDA)

1. INTRODUCTIN

With in the last years, the use of nonlinear analysis in performance method has been widely performed for vulnerability assessment of the structures in engineering community. The main objective in performance method is evaluating the capacity structures and finding the earthquake demand or performance point (p.p.). The most commonly used analysis approach in the performance method is pushover. The use of pushover in earthquake engineering is base on the work of Gulkan and Sozen (1974) or earlier, where a single degree of freedom system is derived to represent the multi degree of freedom structure via an equivalent or substituted structure. The purpose of the pushover analysis is to access the structural performance by estimating the strength and deformation capacities using a static, non-linear analysis algorithm and compare these capacities with the demands at the corresponding performance levels. The assessment is based on the estimation of important structural parameters, such as interstory drift and element deformation and forces. The analysis accounts for the geometrical nonlinearities and material inelasticities, as well as the redistribution of internal forces, hence it provides crucial information on response parameters that cannot be obtained with traditional elastic method.

The simplicity of pushover analysis approach and its capability in providing structural nonlinear response information served well as an alternative to time-history analysis method. This method can be employed to identify the seismic resisting components in which inelastic deformation are expected to be high or might cause important changes in inelastic dynamic structural response characteristics (Krawinkler and Seneviratna).

The pushover is an approximate analysis method through which an increasing lateral load with an invariant high-wise distribution is applied to a mathematical model of structure until a target displacement is reached and/or the structure is collapsed. In this method lateral load pattern represents the likely distribution of inertia forces imposed over the height of structure during an earthquake. The distribution of inertia forces vary with the severity of the earthquake and time through out its duration. However, in traditional pushover analysis approaches, generally, an invariant lateral load pattern is used. Generally speaking, two different non-linear static analysis approaches (pushover) are found in literature:
* Constantly fixed applied load increment.
* Instantaneously updated applied load increment.

The first family of non-linear static method consists of non-adaptive analysis approaches, which are based on incremental lateral load in the forms of triangular, uniform and those compatible with the first mode shape pattern. Traditional push over approach is an example of this family (ATC-40, FEMA 273, FEMA 356). The second family of static non-linear analysis (pushover) method is those in which the applied load is constantly updated, depending upon the instantaneous dynamic characteristics of the structure. Adaptive first mode (SDOF) pushover method and adaptive full modes (MDOF) are samples of this family.

1.1. Traditional Pushover Analysis

Traditional pushover analysis, commonly used for assessment of building structures, is a nonlinear-iterative solution of the well known static equilibrium equation KU=P, where K is the nonlinear stiffness matrix (tangent stiffness), U is the displacement vector and P is a predefined load vector (triangular, uniform) applied laterally over the height of structure in a small load increment forms. This lateral load is a fixed pattern with constant ratio throughout the analysis procedure. In such methods, inelastic static is traced to the single degree of freedom system (SDOF), derived by Gulkan and Sozen to represent the multi-degree of freedom via an equivalent structure. Saiidi and Sozen and Fajfar and Fischinger proposed a simplified inelastic analyses approach for multi-degree of freedom systems (MDOF).

The above mentioned procedure continues until a predefined limit state such as immediately occupancy, life safety or collapse prevention is reached or until structural collapse is detected. It is worth mentioning that this target limit state may be that of expected for designing a new structure or for calculating the drift for assessment purpose. The pushover analysis may be performed using force-control or displacement-control approach. In the former fashion, the structure is subjected to an incremental lateral load pattern and corresponding displacements are calculated while in the latter, the structure is subjected to a deformation profile and lateral forces necessary to generate such displacements are computed. The first option is commonly preferred due to the reason that the displacement is not known. FEMA 356 requires the pushover plot to be performed by applying monotonically increasing lateral force vectors with a constant vertical profile in the forms of triangular or uniform distribution.

1.2. Incremental Dynamic Analysis Approach (IDA)

Several methods are being proposed to tackle the accurate estimation of the seismic demand and capacity of structures. One of the promising candidates is IDA (Vamvatsikos & Cornell, FEMA440). IDA is a procedure that offers demand and capacity prediction capability, in regions ranging from elasticity to global dynamic instability, by using a series of non-linear dynamic analysing under suitably multiply-scaled ground motion records (Vamvatsikos & Cornell). This approach needs time-histories to be scaled and applied to the structure. For this purpose, the uniform response spectra, corresponding to the probability of exceedence, PE=10%, of the selected region were estimated through a site specific hazard analysis using the well known PSHA method. Further, two time histories compatible with the estimated uniform response spectra were calculated to be used in IDA approach and will be explained in the next section.

2. Specific Site Earthquake Input:

A probabilistic Seismic Hazard Analysis (PSHA) was performed on the basis of Cornell-McGuire method (Cornell; McGuire) and the uniform hazard spectra corresponding to the probability of exceedence 10%, (PE=10%), of the site were estimated. According to Cornell and McGuire, modern PSHA is based on the following equation:

$$\gamma(y)=\sum \upsilon p[Y\geq y]=\sum \upsilon \int\int \left\{1-\int_0^y \frac{1}{\sqrt{2\pi}\delta_{\ln,y}}\exp\left[-\frac{(\ln y-\ln y_{mr})^2}{2\delta_{\ln,y}^2}\right]d(\ln y)\right\} f_m(m)f_R(r)dmdr \tag{1}$$

Where *v* is the activity rate, *fM*(*m*) and *fR*(*r*) are the probability density function (**PDF**) of earthquake magnitude *M* and *R* epicenteral or focal distance respectively. *ymr* and *σln,y* are the median and standard deviation at *m* and *r*. *fM*(*m*) and *fR*(*r*) were introduced to account for the variability of earthquake magnitude in the selected region and the corresponding epicenteral or focal distance respectively (Cornell; McGuire). *ymr* and *σln,y* are determined by the ground motion attenuation relationship (Campbell, Joyner and Boore Abrahamson and Silva, Toro and others, EPRI, Atkinson and Boore, Akkar and Bommer). The peak ground accelerations (PGA) and the elastic response spectra with 5% damping ratio corresponding to the probability of exceedenses 10% with the well known computer program SEISRISK III (Bender and Perkins) were estimated to be used in performance assessment of the selected structures. The time-histories compatible with the estimated uniform response spectra were determined. Figures 1 present the estimated response spectra and corresponding compatible time-histories.

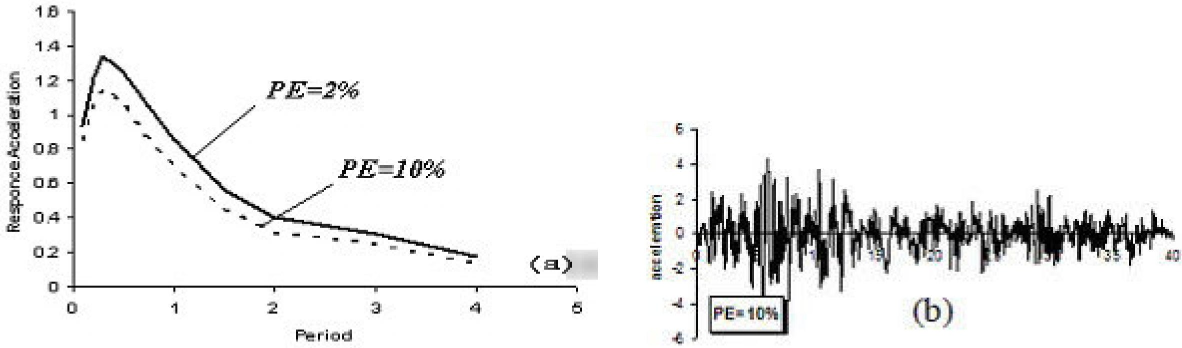

Figure 1 (a) Estimated response spectra for the selected site, (b) Compatible time-histories corresponding the estimated Response spectra with probability of exceedance 10%

3. Lateral load patterns

The lateral load patterns should approximate the inertial forces expected in the building during an earthquake. Although the inertia force distributions will vary with severity of the earthquake and with time, in traditional pushover analysis an invariant load pattern is used. Three different load patterns (inverted triangular, uniform and first mode-based) that is frequently used in traditional pushover analysis methods, is used and compared.

3.1. Triangular lateral load pattern

The vertical distribution of base shear, V, in this method is given by:

$$F_i = c_{vi} . V \tag{2}$$

$$c_{vi} = \frac{w_i h_i^k}{\sum_{i=1}^{n} w_i h_i^k} \tag{3}$$

$$k = 0.5T + 0.75 \tag{4}$$

Where V is the pseudo lateral load, c_{vx} is the vertical distribution factor, w_i is the portion of the total building weight W located on or assigned to i^{th} floor, h_i is the height from the base to floor i^{th} level and T is the fundamental period of the building in the direction under consideration.

3.2. Uniform lateral load pattern

The uniform distribution consisting of lateral forces proportional to the total mass at each level is in the following form where m_i is the mass value for the i^{th} story.

$$F_i = c_{vi}.V \tag{5}$$

$$c_{vi} = \frac{m_i}{\sum_{i=1}^{n} m_i} \tag{6}$$

3.3. First mode lateral load pattern

A vertical distribution proportion to the shape of fundamental mode, in the direction under consideration, is in the following fashion where ϕ_i is the first mode shape value for the i^{th} story

$$F_i = c_{vi}.V \tag{7}$$

$$c_{vi} = \frac{\phi_i m_i}{\sum_{i=1}^{n} \phi_i m_i} \tag{8}$$

4. Studied models

Three symmetric and regular 3, 9, 15 stories steel MRF frames with the span-ratio ranges of H/B<1.5, 1.5<H/B<3 and 3<H/B have been selected and designed, based on IBC-ASD. Configuration and section properties of the frames are shown in Figure 2 and Tables 2 to 3 respectively. The material properties are stated in Table 1. The analyses were performed using ZeusNL version 1.7.2 (A.S. Elnashai et al.) and the results are shown through four different graphs for each frame.

Table 1 Material properties of selected structures

Material properties	*Yield strength*	*Tensile strength*	*Modulus of elasticity*
Beams and columns	235.4 (MPa)	392 (MPa)	2*10e5 (MPa)

Table 2 Natural periods of structures

Building types	MRF	*T1*	*T2*	*T3*	*T4*
H/B<1.5	*3-story*	0.70	0.23	0.15	-
1.5<H/B<3	*9-story*	1.48	0.49	0.28	0.19
H/B≥3	*15-story*	1.84	0.72	0.42	0.30

Table 3 Section specification of frames

		Exterior columns	*Interior columns*	*Beams*
3-story	Story1	IPB20	IPB20	IPE40
	Story2	IPB20	IPB20	IPE40
9-story	Story1,2,3	IPB34	IPB34	IPE40
	Story4,5,6	IPB30	IPB30	IPE40
	Story7,8,9	IPB28	IPB28	IPE40
15-story	Story1	Pl35x40x3	Pl35x40x3	IPE45
	Story2,3	Pl35x35x3	Pl35x35x3	IPE45
	Story4,5	Pl35x35x3	Pl30x30x3	IPE45
	Story6,7	Pl30x30x2.5	Pl35x35x3	IPE45

Story8	Pl30x30x2.5	Pl30x30x2.5	IPE40
Story9,10	Pl25x25x2.5	Pl30x30x2.5	IPE40
Story11,12	Pl25x25x1.5	Pl25x25x2.5	IPE40
Story13	Pl25x25x1.5	Pl25x25x1.5	IPE40
Story14	Pl20x20x1.5	Pl25x25x1.5	IPE40
Story15	Pl20x20x1.5	Pl20x20x1.5	IPE40

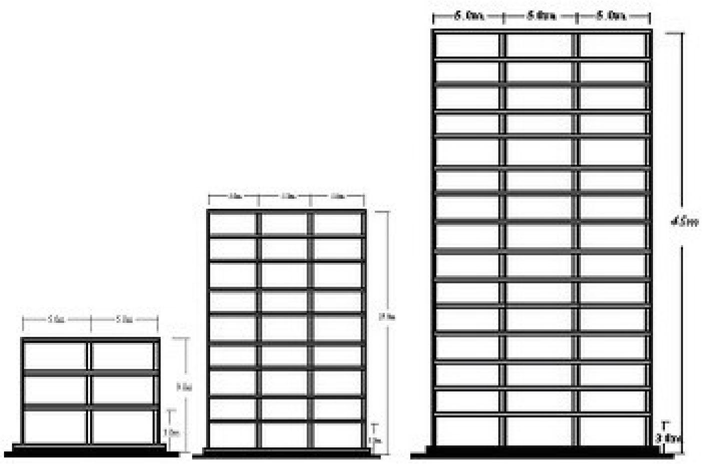

Figure 2 View of studied frames

5. Comparing the Traditional Non-linear (Pushover) Analysis Approaches with Those of IDA

In this section, the non-linear (pushover) analysis responses of steel MRF structures in three frames 3, 9, 15 stories are calculated and compared with those of incremental dynamic analysis method. The uniform response spectrum, estimated from a specific site study with probability of exceedence, PE=10%, was used in static analysis methods while its compatible time-history was used in IDA approach. The comparison of Traditional approaches with those of IDA are performed and demonstrated in three steps. Consequently, apart from the usual practice of monitoring base shear versus global drift (so called General level), also story shear versus interstory drift were included in the evaluation of pushover and IDA of the frames. The story shears versus interstory drifts are depicted for three levels of structures, first-storey ratio, middle-storey ratio and top-storey ratio. The results are shown and discussed in the next sections.

6. Comparison of force-displacements

It is quite postulated that, the capacity curve (base shear versus roof displacement) represents the global non-linear response of structures subjected to strong motions. To make a comparison between the capacity curves (pushover) obtained form the above mentioned three load patterns and those of IDA approach, with probability of exceedance of 10% (PE=10%), three steel frames were designed. The nonlinear static (pushover) analyses of the designed structures were performed using the aforementioned methods.

The storey shears versus storey drift ratios of upper, lower and middle stories were depicted for comparison purpose and demonstrating their response differences with those of non-linear static IDA approach (see figures 3 to 6). The comparison process was extended to the second performance indicator, the story shear versus interstory drift. The story force was derived by adding all individual element shear forces and three levels were selected: first, middle and top.

7. Capacity Curves Diagrams

7.1. Capacity Curves Diagrams for General Level

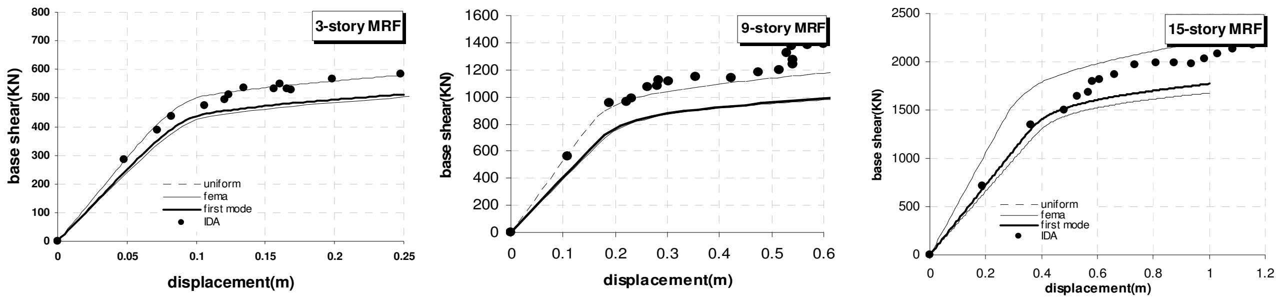

Figure 3 Non-linear response comparison of frames in global level

7.2. Capacity Curves Diagrams for First Level

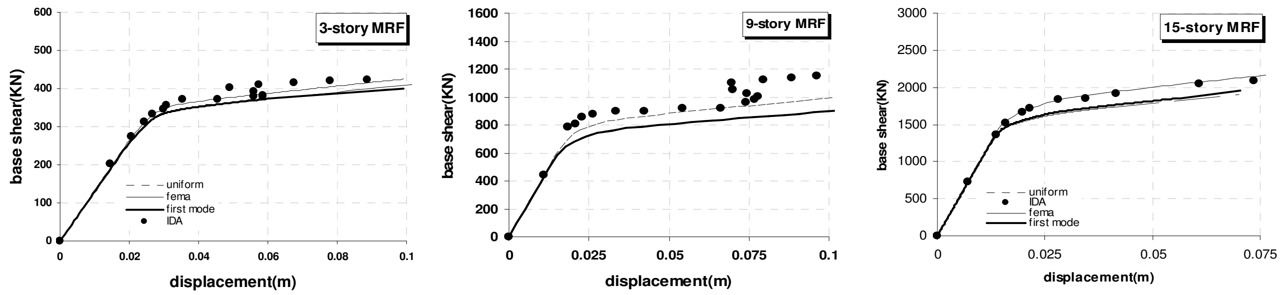

Figure 4 Non-linear response comparison of frames in first level

7.3. Capacity Curves Diagrams for Middle Level

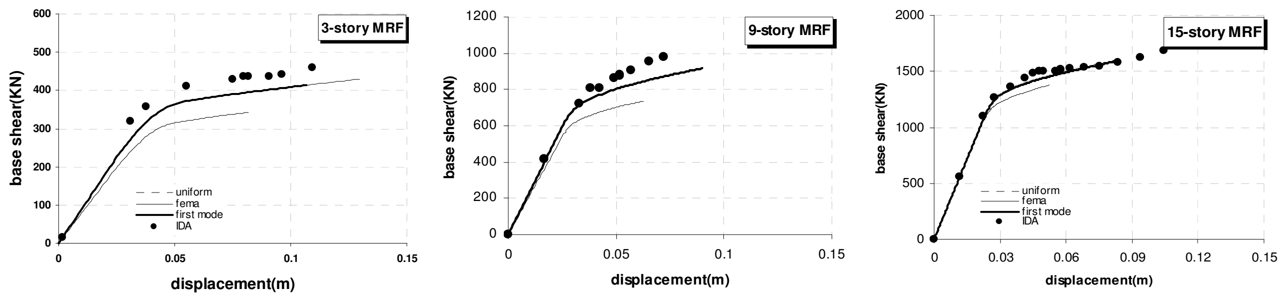

Figure 5 Non-linear response comparison of frames in middle level

7.4. Capacity Curves Diagrams for Top Level

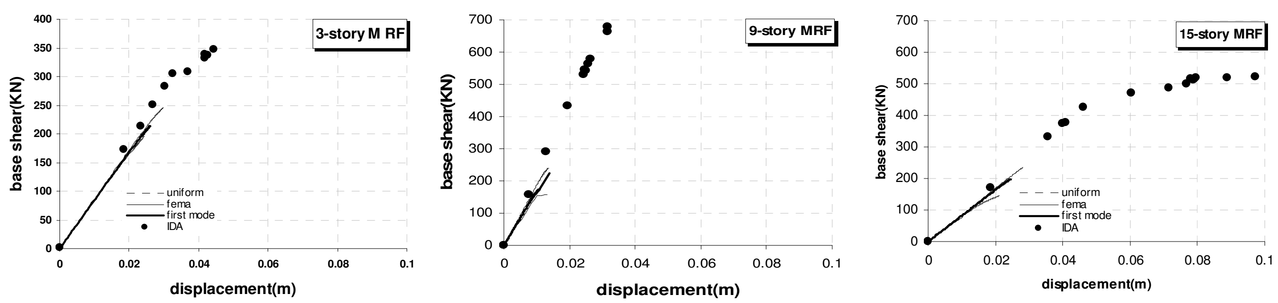

Figure 6 Non-linear response comparison of frames in top level

8. Measuring the Used Pushover Techniques Accuracies

Since the damage of structures is directly related to local deformations, the inter-story drifts can be used as comparison criteria for different schemes. The standard error (S.E.) through the whole nonlinear deformation may be defined in the following form (Papanikolaou et al.):

$$Error(\%) = 100\left[\frac{1}{n}\sum_{i=1}^{n}\left|\frac{\Delta_{iD} - \Delta_{iP}}{\Delta_{iD}}\right|\right] \tag{9}$$

Where, Δ_{iD} is the inter-storey drift at a given level *i* from the IDA, Δ_{iP} is the corresponding inter-storey drift from the pushover analysis and *n* is the number of the IDA steps. More accurate response is obtained as the standard error tends to Zero. The standard errors for three lateral load patterns used in traditional pushover approached are calculated and showed in Table 4.

Table 4 Presentation of the used pushover techniques accuracies

	General level			*First story*			*Middle story*			*Top story*		
MRF	Triangular	First mode	Uniform	Triangular	First mode	Uniform	Triangular	First mode	Uniform	Triangular	First mode	Uniform
3-story	2.28	2.52	4.17	2.16	2.24	2.78	2.13	2.20	5.51	7.89	9.22	11.42
9-story	21.57	20.21	7.04	14.79	14.92	7.81	6.58	6.42	11.67	13.7	17.5	22.80
15-story	14.56	16.20	9.44	6.57	5.75	2.28	15.70	18.01	20.40	25.1	49.6	44.10

9. Conclusion

The main objective in this study was to compare the applicability of different load patterns in traditional pushover for seismic response assessment. The methodology that is used for evaluating performance of different load patterns is based on a quantitative measure for the difference in response between traditional pushover and incremental dynamic analysis (IDA) that is deemed to be the most accurate. This methodology is applied on a set of three steel MRF frames that is covered various span-ratio ranges. A series of pushover analysis results on various structural levels is presented and compared to incremental dynamic analysis (IDA). With respect to the limited number of tested structures, the following conclusions can be conducted.

In general level in H/B<1.5 the responses obtained from IDA are between triangular load pattern and uniform one and it converge to uniform load pattern capacity curve with the increasing of H/B ratio and going in nonlinear region.

At the First Story Level in all span ratios, uniform load pattern is more effective and has the smallest S.E in first level.

In middle level triangular, uniform and elastic first mode pattern diverge from IDA. In all of patterns the S.E. values are considerable with the more S.E. in uniform and smallest values in triangular load pattern.

In top level, all load patters lead to poor predictions and have considerable differences with IDA responses therefore the S.E. values in all lateral load patterns are more than acceptable values. However in this level the S.E. involves in uniform load pattern has the largest values.

REFERENCES

Gulkan, P. and Sozen, M.A. (1974). Inelastic of reinforced concrete structures to earthquake motions. *ACI Journal* 71, 604-610.

Krawinkler H. and Seneviratna, G.D.P.K. (1998). Pros and cons of a pushover analysis of seismic performance evaluation. *Engineering Structures* 20(4–6), 452–464.

Antoniou, S. and Pinho, R. (2004a). Advantage and Limitations of Adaptive and Non-Adaptive Forced-Based Pushover Procedure. *Journal of Earthquake Engineering* 8(4), 497-522.
Antoniou, S. and Pinho, R. (2004b). Development and Verification of Displacement-Based Pushover Procedure. *Journal of Earthquake Engineering* 8(5), 643-661.
Papanikolaou, K.V., Elnashai, A.S. and Pareja, J.F. (2005). Limits of applicability of traditional and adaptive pushover analysis for seismic response assessment. Report 05-02, Mid-America Earthquake Center, University of Illinois at Urbana-Champaign, USA.
Applied Technology Council (1996). Seismic Evaluation and Retrofit of Concrete Building. Report ATC40, Redwood City, USA.
FEMA (1997). NEHRP guidelines for the seismic rehabilitation of building. Report FEMA 273, Federal Emergency Management Agency, Washington, D.C., USA.
FEMA (2000). Prestandard and commentary for the seismic rehabilitation of building. Report FEMA 356, Federal Emergency Management Agency, Washington, D.C., USA.
Saiidi M. and Sozen, M.A. (1981). Simple nonlinear analysis of RC structures. *ASCE, ST Division* 107(ST5), 937-951.
Fajfar P. and Fischinger, M. (1988). N2 method for nonlinear seismic analysis of regular structures. *Proceedings of the ninth world conference on Earthquake Engineering* 5, 111-116, Tokyo-Kyoto, Japan.
Vamvatsikos D. and Cornell, C.A. (2005). Seismic Performance, Capacity and Reliability of Structures as Seen Through Incremental Dynamic Analysis. Report No. 151, Department of Civil and Environmental Engineering, Stanford University, USA.
FEMA (2005). Improvement of nonlinear static seismic analysis procedures. Report FEMA 440, Federal Emergency Management Agency, Washington, D.C., USA.
Cornell, C.A. (1968). Engineering seismic risk analysis, *Bulletin of Seismological Society of America* 58, 1583–1606.
Cornell, C.A. (1971). Probabilistic analysis of damage to structures under seismic loads. in D.A. Howells, I.P. Haigh, and C. Taylor, eds., Dynamic waves in civil engineering: *Proceedings of a conference organized by the Society for Earthquake and Civil Engineering Dynamics* New York, John Wiley, 473–493.
McGuire, R.K. (1995). Probabilistic seismic hazard analysis and design earthquakes: Closing the loop. *Bulletin of Seismological Society of America* 85, 1275–1284.
McGuire, R.K. (2004). Seismic hazard and risk analysis, Earthquake Engineering Research Institute, MNO-10, 240, USA.
Campbell, K.W. (1981). Near-source attenuation of peak horizontal acceleration, *Bulletin of Seismological Society of America* 71(6), 2039–2070.
Joyner, W.B. and Boore, D.M. (1981). Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley. *Bulletin of Seismological Society of America* 71, 2011–2038.
Abrahamson, N.A. and Silva, W.J. (1997). Empirical response spectral attenuation relations for shallow crustal earthquake, *Seismological Research Letters* 68(1), 94–127.
Toro, G.R., Abrahamson, N.A. and Schneider, F. (1997). Model of strong ground motions from earthquakes in central and eastern north America: Best estimates and uncertainties, *Seismological Research Letters* 68(1), 41–57.
Electric Power Research Institute (EPRI) (2003). CEUS ground motion project, model development and results: Report 1008910.
Atkinson, G.M., and Boore, D.M. (2006). Earthquake ground-motion predictions for eastern North America, *Bulletin of Seismological Society of America* 96, 2181–2205.
Akkar, S. and Bommer, J.J. (2007). Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East. *Bulletin of Seismological Society of America* 97, 511-532.
Bender B. and Perkins, D.M. (1987). SEISRISK III, A computer program for seismic hazard estimation. US Geological Survey, Bulletin 1772.
International Building Code (IBC) (2000). International Code Council, Virginia, USA.
Elnashai, A.S., Papanikolaou, K.V. and Lee, D.H. (2002-2007). ZEUS-NL A program for inelastic static and dynamic analysis of structures. user manual, Mid-America Earthquake Center, University of Illinois at Urbana-Champaign, USA.