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COMPARISON OF MODAL PUSHOVER ANALYSIS AND NONLINEAR TIME HISTORY ANALYSIS USING PRECEDENCE LIST RECORD SELECTION METHOD

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Performance based seismic engineering is a rather new concept in earthquake engineering. Evaluation of structural response is the key element to future decision making. Modal Pushover Analysis (MPA) has been introduced to increase the accuracy of Pushover analysis; but it fails in some cases of the irregular structural systems (i.e. stiffer lower stories). The objective of this paper is to present the use of Load Dependent Ritz vectors (LDR) which takes into account the spatial distribution of dynamic force; instead of commonly used eigen-mode shape in the MPA in order to improve the accuracy of calculated response of irregular systems, when limited number of modes is to be considered, especially for stiff systems. First, a 16-story irregular system is analyzed for a set of ground motion records then precedence list record selection method is used to lessen the numerical effort needed for evaluation of response. Results of full Nonlinear time history analysis and reduced set will be compared with response estimated from enhanced MPA. The numerical results have indicated that using LDR vectors, in case of stiffer lower stories, increase the accuracy of force response. Also using precedence list method can reduce the analysis time and provide relatively accurate responses.

KEYWORDS: Modal Pushover Analysis, Ritz vectors, LDR, Nonlinear Static Analysis, Stiffness Irregularity

INTRODUCTION

Evaluation of structural response is a key concept in performance based seismic engineering. Structures can be analyzed using either linear or nonlinear methods. Nonlinear dynamic analysis is considered as ‘exact’ method, however, it is very time consuming and may not be suitable for everyday engineering practice; this favors the use of NSP in engineering practice [Building Seismic Safety Council. (1997)]. Although it may provide good approximation for some types of structures (mainly regular structures), due to limitations in its fundamental concepts like the first mode distribution of load, good estimates would not be promised for all types of structures especially for structures with considerable higher-mode contribution to response.

In order to overcome this limitation, MPA procedure has been proposed by Chopra Chopra AK, Goel RK. (2002), which offers several attractive features, for instance, it retains the conceptual simplicity and computational ease of current pushover procedures with invariant force distributions. In the MPA procedure, the seismic demand due to individual terms in the modal expansion of the effective earthquake forces is determined by nonlinear static analysis using the inertia force distribution for each mode. These “modal” demands due to the first few terms of the modal expansion are then combined by the CQC rule to obtain an estimate of the total seismic demand for inelastic systems. A step-by-step summary of the MPA procedure to estimate the seismic demands for a multistory building is presented in Chintanapakdee, C. and Chopra, A.K. (2003) and Chopra AK, Goel RK. (2002).

The accuracy of MPA must be evaluated for a wide range of structural systems and ground motions to identify the conditions under which it is applicable for seismic evaluation of structures. By studying the bias of this approximate procedure, MPA has been shown to be

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accurate enough in estimating seismic demands for seismic evaluation of “regular” buildings. Because vertical irregularities significantly influence the seismic demands on buildings, the next step is to determine whether or not the MPA can estimate seismic demands of irregular buildings to a degree of accuracy which is considered sufficient for practical application? Chopra and Chintanapakdee (2003) have shown that: “The MPA procedure is less accurate relative to the reference regular frame in estimating the seismic demands of frames with strong or stiff-and-strong first story; soft, weak, or soft-and-weak lower half; stiff, strong, or stiff-and-strong lower half”. As this method considers the first few modes it is susceptible to lack of accuracy for the cases in which higher-mode contribution cannot be neglected.

Incremental dynamic analysis (IDA)—a procedure developed for accurate estimation of seismic demand and capacity of structures—requires non-linear response history analysis of the structure for an ensemble of ground motions, each scaled to many intensity levels, selected to cover the entire range of structural response—all the way from elastic behavior to global dynamic instability. Recognizing that IDA of practical structures is computationally extremely demanding , some researchers [Baker JW, Cornell CA (2006a), Watson-Lamprey, J.A. and N.A. Abrahamson (2006), Shantz T (2006)] has developed procedures to use Nonlinear Time-History Analysis (NTHA) reducing the number of ground motions, while keeping the accuracy and considering the randomness of response. In this research, the method proposed by Azarbakht and Dolšek (2007), along with NTHA will also be considered for comparison of obtained results. This method would lead to a precedence list of record to be used through following steps:

1. Select a set of ground motion records based on the earthquake scenario. This is the same step as in an IDA analysis. The number of records within the given set can, if so desired, be high, since, when using the methodology, there is no need to compute the seismic response of the MDOF model for all records in order to obtain a good prediction of the median IDA curve.
2. Create a MDOF mathematical model that can be used for the simulation of the realistic seismic response of the structure under investigation.
3. Define a simple mathematical model, e.g. a SDOF model. This model should be a good representative of the linear and nonlinear characteristics of the MDOF mathematical model, yet simple enough for it to be possible to perform a large number of nonlinear time-history analyses, without the need for very time-consuming calculations.
4. Compute single-record IDA curves for the simple model, for all the ground motion records within the given set. Because of the simplicity of the chosen simple model, this should not be a time-consuming task.
5. Based on the results obtained in step 4, arrange the ground motion records within the given set in order to obtain a good precedence list. This is an optimization problem. The objective of the optimization is to minimize the differences between the ‘original’ and the ‘selected’ median IDA curves. The ‘original’ median IDA curve is obtained from all the single-record IDA curves (step 4), whereas the ‘selected’ median IDA curves are obtained only for the first s ground motion records from the precedence list, where s is the number of ‘selected’ ground motion records. The number of median IDA curves, based on the s ground motion records, is thus equal to the number of ground motion records in the set being used.
6. Compute a single-record IDA curve for the MDOF model, starting with the first record from the precedence list. After computation of the single-record IDA curves for the sth record from the precedence list (where s is a number greater than or equal to two), compute the ‘selected’ median IDA curve and compare it with the ‘selected’ median IDA curve obtained from the (s − 1)th records.

The objective of the proposed method is to improve the accuracy of MPA for the vertically irregular frames with stiffer lower stories for the estimation of the seismic demands.

PROPOSED METHOD: MPA USING LDR OR PSUEDO STATIC VECTOR INSTEAD OF EIGENVECTOR

Wilson et al. (1982) introduced a new dynamic analysis method based on Rayleigh-Ritz method, which took into account the effects of spatial distribution of the dynamic loading and yielded much better results in less computational time than the use of exact eigenvectors known as WYD Ritz vectors (Wilson, Yuan and Dickens) or LDR (Load Dependent Ritz) vectors. Consider the input force as $F(s,t)=\{f(s)\}.g(t)$ ($\{f(s)\}$ is the spatial distribution of excitation), the first Ritz vector, which is the static response of the time independent portion of load vector, $\{f(s)\}$ can be computed as: $\{X_1\}=[K]^{-1}\{f\}$ (which is known as pseudo static vector in mode-acceleration procedure). Since this vector will be used for extraction of other vectors, it would be impossible to generate vectors that are not excited by the assumed loading. The obtained response format is analogous to pseudo static vector used in the “mode-acceleration” based response spectrum approach Ghafory-Ashtiany, M. (1989).

– Static correction

$$\{U(t)\} = \sum_{i=1}^{r} \{\varphi_i\} y_i(t) + ([K]^{-1} - [K_r]^{-1})\{f(s)\}g(t)$$

- Pseudo static vector

$$\{U(t)\} = \sum_{i=1}^{r} \{\varphi_i\} y_i(t) + ([K]^{-1} - [K_r]^{-1})\{f(s)\}g(t)$$

$$\{U_s\} = [K]^{-1}\{f(s)\}$$

- LDR vectors

$$\{U(t)\} = \sum_{i=2}^{r} \{X_i\} y^*_i(t) + \frac{\bar{X}_1}{(\bar{X}_1^T [M] \bar{X}_1)^{1/2}} y^*_1(t)$$

In each of the first two summation methods, the full loading vector has been accounted for either in the dynamic manner by first term or in a static manner by the second term, which is not the case for LDR vectors; since the first vector corresponds to static solution and additional vectors represent dynamic contribution neglected by the static solution. This is the major benefit of using LDR vectors in MPA approach where first few modes are usually considered, and implementing LDR vectors ensures the consideration of higher-mode participation in force or displacement response calculation (displacement response converges faster than force response so accurate displacement response do not guarantee accurate force responses due to higher modes). It should be noted that the first pseudo static vector, $\{U_s\}$, is identical to the starting vector of LDR vector approach. Thus in the continuation of the paper, only the results for LDR has been presented.

NUMERICAL ANALYSIS

To evaluate the effectiveness of using LDR or $\{U_s\}$ vectors; two types of structural systems were considered in this research: 1) Regular moment resisting frame systems and 2) Irregular frame systems with stiffer lower stories. Both type of systems were designed according to Iranian National Building code which is similar to AISC-89 (ASD method) for PGA=0.3g, soil type III and Response reduction factor R=6. In this article, we will focus only on the 16-story irregular frame as this is an ongoing project to consider uncertainties of precedence list method to be used along MPA. The properties of the mentioned frame and its respective periods for the first three modes are shown in Figure 1.

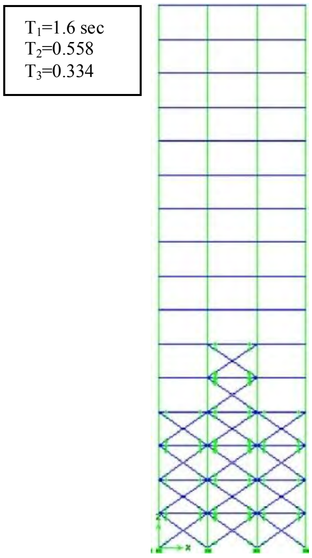


Figure 1 Irregular 16-stroey frame model that has been used in the application of MPA with LDR

For the input ground motion, a set of near-field ground motions recorded on soft soil (type 3) scaled to PGA of 0.7g (to ensure the nonlinear response) with impulsive character which can cause considerable response and contribution of higher modes has been used. Figure 2 shows spectral acceleration of records used in this research, full set mean and mean of selected ground motions using precedence list method (Bam, Duzce, Loma-Prieta).

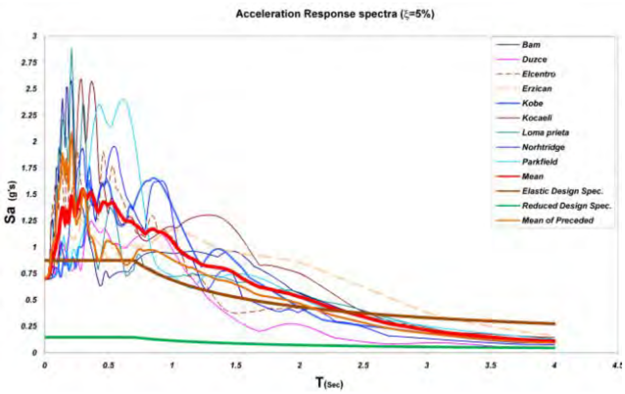


Figure 2 Spectral accelerations for selected ground motions and mean spectrum

Considering the effect of higher modes on response for the case of stiffer lower stories, the use of LDR vectors and pseudo static vector for such irregular systems (also for regular systems for measuring the accuracy, in line with nonlinear time history analysis which is assumed to be exact response) have been examined.

Using Precedence list Method and employing nonlinear time history analyses, three records were selected from 9 used records (Bam, Duzce and Loma-Prieta) in order to compare results obtained from reduced set of ground motions and results of full data set. Fig. 3 shows 16%, 50% and 84% percentiles of full data set and reduced or "selected" data set. IDA curves were derived for spectral acceleration at firs structural period vs. maximum inter-story drift (θ_{max}).

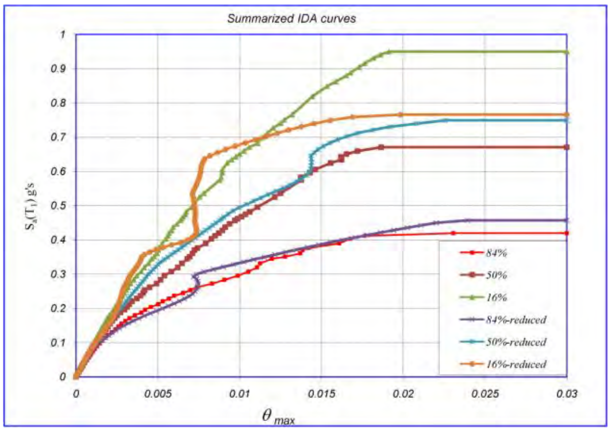


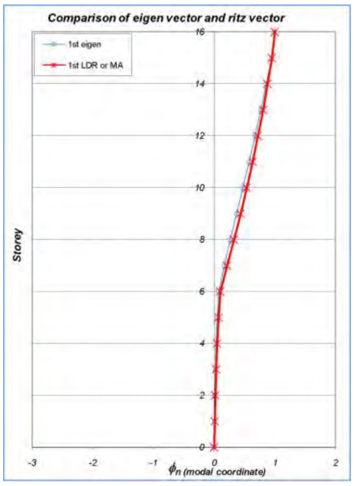
Fig. 3 Comparison of full and reduced data set summarized IDA curves: first spectral acceleration vs. maximum inter-story drift.

Fig. 4 shows modal properties of the 16-story irregular frame that have been obtained and used for the evaluation of two approaches (LDR vectors and eigenvectors). Rayleigh damping ratio has been used for calculating damping in each mode for the analysis of SDOF (Single Degree of freedom) systems that are required in MPA approach. It is important to consider rational damping ratios since it is not known whether the properties are in the velocity sensitive region or not. Different systems have been coded according to the number of stories, regularity, type of vectors (LDR or eigenvector) and number of modes that have been used; For example 16sIr-e(2) represent the results for a 16 story Irregular-frame, using 2 eigen-modes). It should be noted that since spectral content of the first vector in LDR vector approach is spread among all the basis vectors, shape of each computed vector depends on the requested number of LDR vectors. Appropriate selection of required number of LDR vectors is crucial.

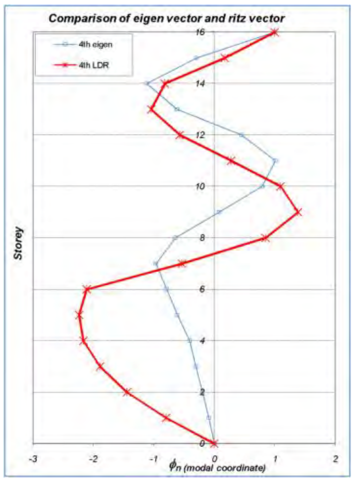
Figure 5(a) shows the difference between First LDR vector or Pseudo static vector and first eigenvector. As it can be seen there is no significant participation of lower stories in either case. Figure 5(b) shows the comparison between fourth eigenvector and fourth LDR vector (in a set of four vectors). It is apparent that LDR vectors have activated the stiffer part of the structure and as a result, their contribution to the final response can be captured by using only first few modes.

Story	Eigen vectors				Story Mass	LDR vectors (set of 4)			
	Mode1	Mode2	Mode3	Mode4		Mode1	Mode2	Mode3	Mode4
16	1.0000	1.0000	1.0000	1.0000	2.9540	1.0000	1.0000	1.0000	1.0000
15	0.9455	0.7025	0.2494	-0.2943	3.3107	0.9455	0.7059	0.3334	0.1735
14	0.8573	0.2086	-0.6646	-1.1209	3.3212	0.8573	0.2146	-0.5628	-0.8168
13	0.7698	-0.1796	-0.9657	-0.6178	3.3648	0.7698	-0.1752	-0.9880	-1.0446
12	0.6722	-0.4908	-0.7404	0.4482	3.3701	0.6722	-0.4914	-0.9427	-0.5729
11	0.5734	-0.6736	-0.2283	1.0102	3.3807	0.5734	-0.6792	-0.5039	0.2782
10	0.4707	-0.7402	0.3344	0.7888	3.4031	0.4707	-0.7485	0.1641	1.0971
9	0.3692	-0.6970	0.7184	0.0775	3.4375	0.3692	-0.7046	0.7868	1.3842
8	0.2668	-0.5638	0.8362	-0.6436	3.4546	0.2668	-0.5680	1.1579	0.8509
7	0.1627	-0.3606	0.6762	-0.9686	3.4546	0.1627	-0.3610	1.1086	-0.5327
6	0.0719	-0.1486	0.3558	-0.7905	3.4905	0.0719	-0.1473	0.6728	-2.1134
5	0.0485	-0.0974	0.2492	-0.6109	3.5264	0.0485	-0.0967	0.4637	-2.2377
4	0.0295	-0.0547	0.1510	-0.4075	6.6652	0.0295	-0.0549	0.2508	-2.1639
3	0.0190	-0.0389	0.1085	-0.3057	6.7449	0.0190	-0.0394	0.1614	-1.8894
2	0.0105	-0.0243	0.0680	-0.1982	6.7449	0.0105	-0.0250	0.0816	-1.4431
1	0.0040	-0.0107	0.0301	-0.0907	6.7449	0.0040	-0.0114	0.0223	-0.7981
T_n	1.6044	0.5580	0.3341	0.2373		1.6044	0.5579	0.3204	0.1841
ω_n	3.9162	11.2604	18.8079	26.4767		3.9162	11.2613	19.6128	34.1357
Γ_n	1.4354	-0.6763	0.4985	-0.5222		1.4354	-0.6762	0.4833	-0.4275
Mass Participation%	44.5865	8.4291	6.2215	10.1979		44.5865	8.4398	9.0947	30.1470
Cumulative MP	44.5865	53.0156	59.2371	69.4350		44.5865	53.0263	62.1209	92.2679

Fig. 4 Modal properties for 16-story irregular frame



(a)



(b)

Fig. 5 Comparison of Eigenvectors and LDR vectors (a) First LDR vector vs. 1st eigenvector (b) 4th vector comparison

Story Shear and Moments

In the case of shear response of irregular structure, to satisfy 90% of mass participation requirement, 8 eigen-modes should be considered for 16-story irregular frame but in case of using LDR vectors, 3 vectors would be sufficient. Figure 6 and Table 1 show the advantage of MPA analysis with LDR vectors over eigenvector with respect to nonlinear time history analysis (NLTHA). The first story shear of 16 story irregular structure after using 4 eigen-modes will have 40% error while using 3 LDR vectors only cause 10% error. This trend can be seen for stiffer part of structures because these parts are not excited till the higher modes. On the other hand, using records selected based on record selection scheme defined earlier tends to overestimate the story shears which may not be desired economically but considering the computational efficiency it seems quite appropriate with only using 3 ground motions this results can be seen in all the parameters studied here like force responses or displacement response. In case of the regular structures (that are not presented here), use of LDR vectors does not cause significant improvement but still fewer vectors would be needed to satisfy 90% participation of mass.

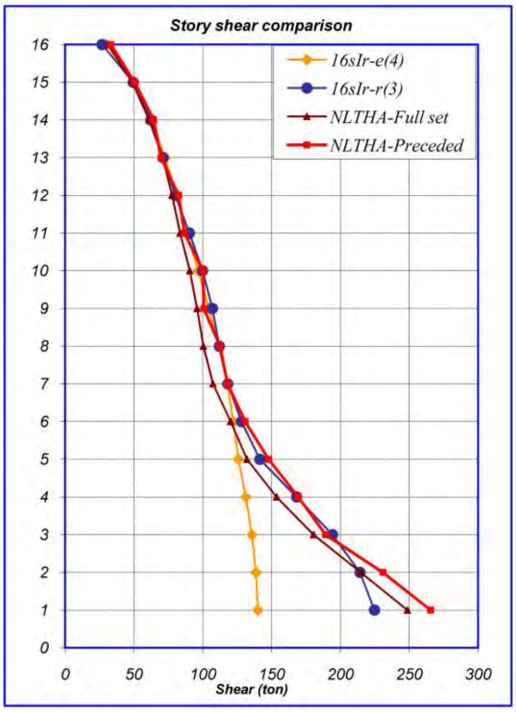


Fig. 6 Comparison of story shear between NLTHA for full and selected record set and MPA using eigenvectors and LDR vectors

Table 1 MPA error percentage in Story Shear response using LDR vectors or eigenvectors

Story	16 Story-Irregular	
	Eigen	LDR
16	-4.48	-14.16
15	2.47	1.58
14	1.57	2.38
13	2.76	0.45
12	3.97	3.06
11	5.79	8.14
10	6.84	10.38
9	9.12	11.71
8	11.08	11.56
7	9.72	10.01
6	1.63	6.55
5	-4.64	7.12
4	-14.55	9.49
3	-24.86	7.56
2	-35.42	-0.26
1	-43.67	-9.59

Figure 7 shows the similar results for the story moments. Using LDR vectors for low-rise regular structures has no noticeable benefit because LDR vectors for these kinds of structures rapidly converge to exact eigenvectors. As the structures get taller, more accurate results can be obtained by using less number of LDR vectors than eigen-modes, still there is no significant difference. In the case of irregular frames considered the superiority of LDR vectors is noticeable because using only 3 LDR vectors not only satisfy 90% mass participation but also provides proper estimates where 8 eigen-vectors were needed for 90% mass participation.

Drift Response

Figure 8 and Table 2 show the results for drift ratio ($\Delta_i - \Delta_{i-1}/h_i$) of the studied frame. As the height of structure increases, the use of LDR vectors will lead to better estimates of exact values. In the case of regular structures there is no important difference in using either LDR vectors vs. eigenvectors.

Table 3 shows the accuracy of the proposed method for the "Overall Drift Index (Δ_{TOP}/H)" where H is overall height of structure. However, it should be noted that higher modes have little influence on displacement response of a structure, but in some irregularities (like the one considered here) they may become more important. Use of LDR vectors for regular frames, does not have any superiority over the use of eigenvectors in the obtained results (except for the time of calculations and number of vectors required). However, like other parameters, hitherto studied, for irregular frames especially for taller frames LDR vectors will produce more accurate results, even with smaller number of LDR vectors used for the analysis. This is mainly due to the benefits of including higher mode responses (via static correction concept) in the starting vector for LDR vectors algorithm. Precedence list method NLTHA reduction scheme (using first three records from list) provides overestimates of studied parameters.

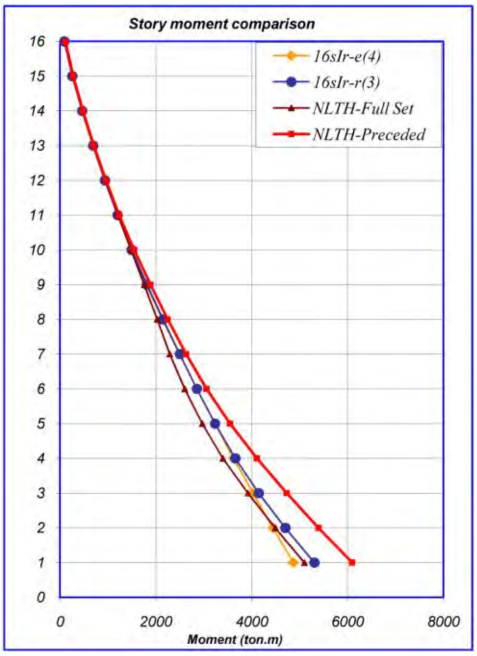


Fig. 7 Comparison of story moment between NLRHA and MPA using eigenvectors and LDR vectors

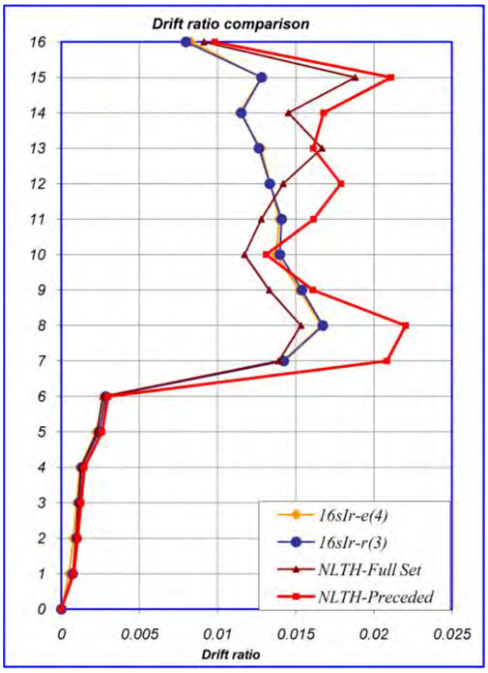


Fig. 8 Comparison of drift ratio between NLRHA and MPA using eigen-vectors and LDR vectors

Table 2 MPA error percentage in drift ratio using LDR vectors or eigenvectors

Story	16 Story-Irregular	
	Eigen	LDR
16	-9.08	-12.66
15	-32.01	-31.86
14	-21.42	-20.71
13	-23.45	-24.19
12	-5.80	-6.08
11	8.92	10.08
10	17.39	19.27
9	14.46	15.71
8	8.61	9.12
7	1.91	2.39
6	2.77	6.77
5	-2.06	5.84
4	-4.30	4.53
3	-9.48	5.27
2	-17.16	5.28
1	-32.40	-2.47

Table 3 MPA error percentage in drift index using LDR vectors or eigenvectors

Story	16 Story-Irregular	
	Eigen	LDR
16	2.71	2.95
15	2.56	2.81
14	6.72	6.97
13	8.29	8.61
12	10.90	11.31
11	12.15	12.58
10	12.13	12.50
9	9.76	10.21
8	7.10	7.96
7	4.26	6.72
6	-4.79	5.22
5	-8.06	5.23
4	-12.39	4.50
3	-16.56	4.56
2	-22.58	3.95
1	-32.28	-1.48

From the mentioned results, the following observation can be made for regular and irregular structures:

Regular structures:

- Best results are obtained using first set of LDR vectors with more than 90% cumulative mass participation.
- For most of low rise to medium rise regular models ($H/B \leq 3$) first mode is dominant for response calculation. As the height of structure increases, neglecting upper modes may cause

serious errors in estimation of the response parameters. For this group of models using LDR vectors has no meaningful superiority over eigenvectors (except for the number of vectors required in some cases).

- Use of LDR vectors (because of their nature) usually leads to over estimated results for lower stories but slightly underestimated results for higher stories comparing to use of eigenvectors.
- For the case of low rise to medium rise regular models, using more than 2 or 3 LDR vectors would not lead to better results. Since, at the end of LDR vectors algorithm an eigen-value problem is solved and first few LDR vectors (depending on the size of the system) will converge to the exact eigenvectors.

Irregular structures:

- Best response estimates are obtained using the first set of LDR vectors with less than 90% cumulative mass participation. One should keep in mind that the shapes of LDR vectors are dependent on number of vectors requested, as this number increases shapes of first few vectors will be the same as eigenvectors, so it is important to choose adequate number of LDR vectors.
- Use of LDR vectors provides better estimates of response calculation in comparison with use of eigen-modes, since the starting vector in LDR vector generation algorithm is equivalent to the static correction concept. Considering the effect of higher (rigid) modes to the response of the irregular frames, their effects can be compensated by the first vector of LDR.
- In the case of using single ground motion, results are more scattered. Best results are obtained using first set of LDR vectors with more than 90% cumulative mass participation.
- Use of precedence list method can result in considerable reduction of computational effort required for evaluation of structures (3 records instead of 9 records) and still provides good approximates of response. However, it tends to overestimate the response.

CONCLUSION

The paper proposed an MPA procedure using LDR vectors. Use of the LDR vectors, was investigated for structures with stiffer lower stories. From the numerical results, it can be seen that for this type of irregularity, use of LDR vectors is superior to use of exact eigenvectors based modal properties. As the simplicity and speed, besides accuracy, are the most important factors in selecting an approach, use of LDR vectors can supersede the use of exact eigenvectors for this special kind of irregularity. For the case of regular structures there were no meaningful differences in using either set of vectors. It should be kept in mind that the rule proposed here for selecting the number of required Ritz vectors is a rule of thumb and it needs more investigation. Precedence list method is a rather new concept which may provide proper approximate using less ground motions.

REFERENCES

Azarbakht A, Dolšek M. (2007) Prediction of the median IDA curve by employing a limited number of ground motion records. Earthquake Engineering & Structural Dynamics ; DOI: 10.1002/eqe740.

Baker JW, Cornell CA (2006a). Spectral shape, epsilon and record selection. Earthquake Engineering & Structural Dynamics, 35(9): 1077 95.

Building Seismic Safety Council. (1997). *NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA-273.* Federal Emergency Management Agency: Washington, DC.

Chintanapakdee, C. and Chopra, A.K. (2003). “Evaluation of The Modal Pushover Analysis Procedure Using Vertically “Regular” and Irregular Generic Frames” *Report No.PEER-2003/03, Pacific Earthquake Engineering Research Center*, University of California, Berkeley.

Chopra AK, Goel RK. (2002) “A modal pushover analysis procedure for estimating seismic demands for buildings.” *EQ. Eng. and Structural Dynamics*; **31(3)**: 561-582.

Chopra AK. (2001). Dynamics of Structures: Theory and Applications to Earthquake Engineering. 2nd Ed., Prentice Hall, Englewood Cliffs, New Jersey.

Ghafory-Ashtiany, M. (1989). "Seismic Response of Six Correlated Earthquake Components by Mode Acceleration Approach"; *Iranian Journal of Science and Technology: Earthquake Engineering Issue*, **Vol. 13**, No. 2 and 3.

Shantz T (2006). Selection and Scaling of Earthquake Records for Nonlinear Dynamic Analysis of First Mode Dominate Bridge Structures, Proceedings of the 8th National Conference on Earthquake Engineering, San

Francisco, Earthquake Engineering Research Institute. Oakland, California.

Watson-Lamprey, J.A. and N.A. Abrahamson (2006), "Selection of Ground Motion Time Series and Limits on Scaling", Soil Dynamics and Earthquake Engineering, 26(5) 477-482.

Wilson, E. L., (2002), Three Dimensional Static and Dynamic Analysis of Structures. Computers and Structures, Inc. Berkeley, California, USA.

Wilson, E.L., Yuan, M.W., Dickens, J.M. (1982). "Dynamic Analysis by Direct Superposition of Ritz Vectors", *EQ. Eng. and Structural Dynamics*, **vol. 10**, pp 813-821.