Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

SEISMIC BEHAVIOR OF REGULAR AND IRREGULAR REINFORCED CONCRETE BUILDINGS USING ADAPTIVE PUSHOVER PROCEDURE

A. Shooshtari[1]and H. R. Vejdani-Noghreiyan[2]

ABSTRACT

Reinforced concrete structures exhibit nonlinear behavior in seismic loads. Modeling of these structures under seismic loads is one of the most demanding aspects in recent decades. Very robust models for RC plane frames are available in DRAIN-RC code. This package is able to analyze RC plane frames with conventional pushover and nonlinear time history analyses. In this study, DRAIN-RC code is developed to be able to analyze RC plane frames with adaptive pushover procedure. Using this software, a comparative study is carried out to evaluate the reliability of adaptive pushover analysis for regular and irregular buildings. Numerical examples show that for regular buildings adaptive response is very close to triangular distribution of lateral load. But, for irregular buildings, adaptive pushover response is completely different from triangular and uniform pattern response.

Introduction

The use of linear static analysis for seismic design of structures is often questioned among researchers. Nonlinear time history analysis of multi-degree of freedom structures, on the other hand, is not practical for everyday design and may require specialized expertise on the topic. Therefore, nonlinear static analysis under monotonically increasing lateral load (pushover analysis) has been gaining momentum as a rational and yet reasonably strait forward procedure.

Pushover is an alternative method for seismic analysis of structures. In this method, lateral static loads are gradually imposed on the structure. This requires consideration of inelasticity under increasing lateral loading. The pushover analysis has been evaluated in several studies. The most serious deficiency inherent in the conventional pushover method is that it is limited to a single-mode response and hence, only buildings with a dominant mode shape may be evaluated reliably. In the conventional pushover method, analyst should determine the lateral load pattern prior to analysis. Since, actual loading pattern especially during analysis changes, conventional pushover yields approximate results.

As mentioned above, static inelastic analysis (pushover analysis) of structures for seismic evaluation of buildings has been gaining recognition as an alternative to dynamic time history analysis. While there is sufficient incentive to pursue static analysis, in view of its simplicity and the uncertainties associated with earthquake records needed for dynamic analysis, the usefulness of pushover analysis is often questioned by researchers. The pushover analysis may provide the following information for seismic evaluation of structures:

1-Overall strength and available over-strength (strength relative to design base shear) under a given lateral load distribution.

[1]Assistant professor, Dept. of Civil Engineering, Ferdowsi University of Mashhad, IRAN, ashoosht@ferdowsi.um.ac.ir
[2]PhD. Candidate, Dept. of Civil Engineering, Ferdowsi University of Mashhad, IRAN, hamid_vejdani@yahoo.com

2-Overall drift and inter-storey drift capacities.
3-Distribution of plastification within the structure and identification of potentially critical regions for improved design and detailing.
4-Ductility demands.

(Gulkan and Sozen 1974) are probably the first researchers who suggested pushover for representing the response of multi-degree of freedom system by a single degree of freedom equivalent. (Saiidi and Sozen 1981) introduced a simple analytical model to estimate the displacement histories of multi-storey reinforced concrete structures subjected to strong ground motions. In developing this model they made two major simplifications. First, they replaced a multi-degree-of-freedom (MDOF) model of a structure by a single degree-of-freedom (SDOF) oscillator. Secondly they approximated the variation of incremental stiffness properties of the whole structure by a single nonlinear spring. The specifications of SDOF oscillator were determined based on a calculated relationship between based moment and lateral displacement under monotonically increasing load. These researchers compared displacements of eight small-scale reinforced concrete structures which were tested under strong ground motions with those obtained analytically. The results showed that the method produced good correlations in both high and low amplitude ranges. (Moghadam and Tso 1995) conducted nonlinear static pushover analysis of asymmetric buildings. They designed two 7-storey reinforced concrete ductile moment resisting frame buildings, one symmetric and the other one asymmetric. A 3-D analysis was carried out using computer program CANNY-C. They investigated displacements; inter storey drift, ductility and hinging patterns. It was shown that for the same level of lateral load, the exterior frame of the asymmetrical building experienced significantly larger inter-storey drift and larger ductility demands for both columns and beams.

As mentioned above, conventional pushover analysis obtains very valuable information about structures. Despite its usefulness, it suffers from many fundamental deficiencies compared to inelastic time history analysis. Some of them are as follows:
1-Pushover analysis implies a separation between structural capacity and earthquake ground motion.
2-Damage in pushover analysis is just related to the lateral deformation of the structure. Results obtained by nonlinear time history analysis show that, earthquake duration has an effective role in the response of structures. In other words, cumulative damage caused by the reversal loading is one of the most important parameter in the response of structures.
3-Inelastic dynamic analysis shows that height distribution of mass influence the response of structures that can not take into account in conventional pushover analysis.
4-Conventional pushover analysis can not consider the changes in dynamic characteristics of structures during analysis.

For the above reasons, possible developments to conventional pushover are suggested by researchers (Antonio 2004a, b). Among the publications in this area, adaptive pushover analysis accounts for the changes in dynamic characteristics of structures during analysis. In other words, adaptive pushover analysis takes into account the current stiffness of the structure and updates lateral load distribution in every step. The first paper that utilizes adaptive procedure is drawback to the work of (Bracci 1997). Afterward, (Lefort 2000) developed the method to consider higher mode contributions. (Gupta and Kunnath 2000) proposed a different methodology for adaptive pushover analysis. In their methodology, site-specific spectrum can be used to define the loading pattern. In this procedure, the spectral estimates become the basis for determining the incremental lateral forces to be applied in the pushover analysis. Also, for defining load pattern in this procedure, as many modes as deemed important can be considered in the analysis. (Elnashai 2001) proposed an adaptive pushover procedure that seemed to encompass all advanced features. This procedure is a single-run and multi modal analysis. It also accounts for the variation of dynamic properties of the structure in updating lateral load pattern. Site specific spectrum can also be considered in the scaling of lateral load forces.

In this study, adaptive pushover method is implemented in DRAIN-RC program (Saatcioglu 1997). After that, a comparative study is carried out to compare the results of analysis from conventional and adaptive pushover.

Conventional Pushover

In conventional pushover analysis, a predetermined lateral load is assumed to push the structure until failure occurs. Therefore, a reference load vector should first assumed by analyst. Usually triangular, uniform and static code distributions can yield a rational response for the structure. Fig. 1 shows these kinds of lateral loads.

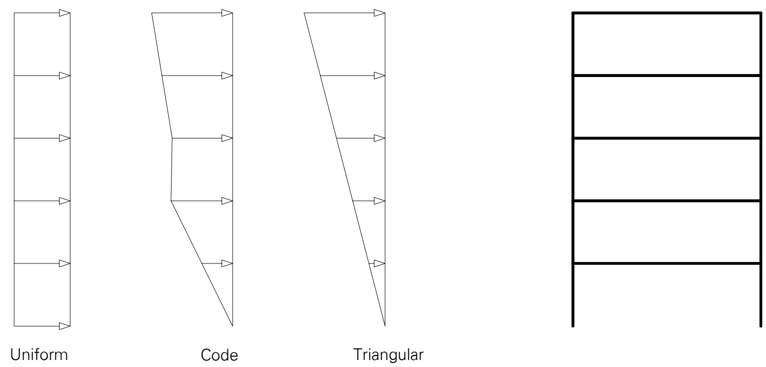

Figure 1. Lateral load patterns in conventional pushover analysis.

Base shear is the sum of the entries of load vector. The reference load vector $(\{P_0\})$ is chosen such that the sum of the entries of it becomes the ultimate base shear. A scale factor (λ) is used to trace the interval of $[0,1]$ to obtain the response of the structure incrementally. After each step, the load factor (λ) and displacement vector $(\{D\})$ are updated as follows:

$$[K_T]_i \{\Delta D\}_i = \Delta\lambda_i \{P_0\} \quad (1)$$

$$\lambda_{i+1} = \lambda_i + \Delta\lambda_i \quad (2)$$

$$\{D\}_{i+1} = \{D\}_i + \{\Delta D\}_i \quad (3)$$

In these equations, $[K_T]_i$ is the tangent stiffness matrix in step (i) and $\{\Delta D\}_i$ represents the increment of the displacement. Tangent stiffness matrix $([K_T])$ is updated before each step to be able to account for the nonlinear behavior of the structure. Because of linearizing the response of structure during each step (by assuming constant stiffness matrix) drift error is unavoidable. For decreasing the cumulative error, an additional term is added to the right side of the Eq. 1 to draw back the response of the structure to the equilibrium path. This vector is called unbalanced force vector and may be obtained by the following equation:

$$\{q\}_i = R(\{D\}_i) - \lambda_i \{P_0\} \quad (4)$$

In this equation, $(\{q\}_i)$ represents unbalanced force vector obtained from the previous step and $R(\{D\})$ is the internal resistance vector due to nodal displacement. Fig. 2 shows unbalanced force vector in nodal displacement versus load parameter axes.

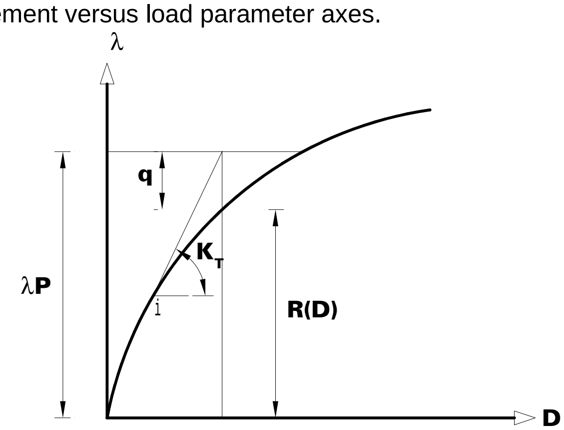

Figure 2. Equilibrium path and unbalanced load vector.

Therefore, following equation is solved for obtaining the increment response of the structure.

$$\left[K_T\right]_i \left\{\Delta D\right\}_i = \Delta\lambda_i \left\{P_0\right\} + \left\{q\right\}_i \quad (5)$$

Total displacement vector after each step is calculated by adding displacement increment obtained from Eq. 5 to the total displacement vector of previous step.

Adaptive Pushover

As mentioned above, in conventional pushover method, a predefined lateral load pattern is used to push the structure. This vector is usually triangular or uniform. But, in adaptive pushover technique, lateral load pattern is a variable vector during analysis. It is updated in every step to account for current dynamic properties of the structure. Therefore, an eigenvalue problem is solved before each step. Modal shapes are combined (using SRSS, CQC or ABS method) to yield the load pattern. After that, the lateral load vector is normalized such that the sum of its entries becomes the ultimate base shear. For performing eigenvalue problem, mass distribution of the structure is needed. In the other words, mass matrix should be defined to obtain lateral load pattern. In the case of using lumped mass method, there are several zero diagonal entries in mass matrix. Therefore, static condensation should be applied to make stiffness matrix compatible with mass matrix for eigenvalue problem.

In this paper, (Elnashai 2001) technique is implemented in DRAIN-RC program and SRSS method is used to combine the modal shapes.

DRAIN-RC Program

DRAIN-RC is a computer software developed at the University of Ottawa by (Saatcioglu 1997). This computer program is a modified version of a general dynamic analysis program called DRAIN-2D by (Kanaan and Powell 1973). In DRAIN-RC program, inelasticity was modeled as hinge plasticity model. Therefore, user should specify sectional characteristics of members as an input file. The flexural primary curve can be established by conducting a sectional moment-curvature analysis. Computer software, COLA (Yalcin 2000), developed at the University of Ottawa, was used for this purpose. This program also provides the primary moment rotation relationship for deformations caused by anchorage slip. In this study, the sectional moment-curvature relationship was determined for each frame member through sectional analysis by COLA program. The initial linear portion of the relationship, prior to cracking, was determined by beam theory and by considering a transformed section. Strain compatibility analysis was employed for post cracking regions with the usual assumption of plane sections before bending remains plane after bending. Although moment-curvature relationship showed a smoothed curve with distinct points for significant changes in slope at cracking and yielding points, it was idealized as a bi-linear relationship where the initial line segment represented the elastic branch and the second line segment represented the post-yield region. This idealization was necessary to be consistent with the flexural hysteretic model incorporated in DRAIN-RC. The analytic way to find the two lines is explained in the next section. From the idealized curve one can find effective flexural rigidity (EI) and strain hardening ratio r (post-yield stiffness ratio) as well as yielding moment (My) to be specified as input for DRAIN-RC.

Idealizing Moment-Curvature Response

There are several methods for idealizing moment-curvature response. In this paper, moment-curvature curve is idealized as a bi-linear relationship. According to the method, two segment lines are defined such that, the area under two lines is equal to that of the original curve. In addition, the first line intersects original curve at a point which has nearly %75 of yielding moment. Therefore, its curvature is also %75 of yielding curvature. Another condition that is used for defining two segment lines is the magnitude of ultimate curvature. On the basis of this method, the curvature of the ultimate point is chosen to be μ times of the yielding curvature. In this research ductility ratio μ is assumed to be equal to 6. Fig. 3 shows a schematically diagram for idealizing the moment-curvature response by this method.

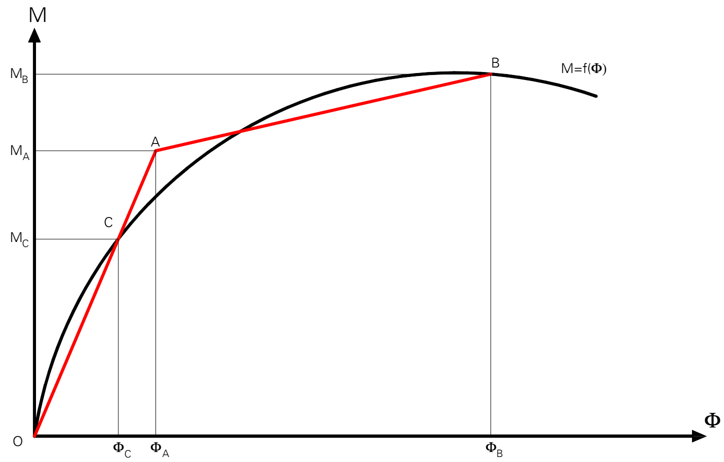

Figure 3. Idealizing the moment-curvature response.

According to what is mentioned above, following equations may be used to determine the location of point A and point B in moment-curvature axes.

$$\begin{cases} \int_0^{\Phi_B} f(\Phi)d\Phi = \frac{1}{2}\left(\Phi_A M_A + (M_A + M_B)(\Phi_B - \Phi_A)\right) \\ f(0.75\Phi_A) = 0.75M_A \\ f(\Phi_B) = M_B \\ \Phi_B = \mu\Phi_A \end{cases} \quad (6)$$

According to the observations of the authors, real moment-curvature response can be fitted by two functions. The first function is a line which starts from reference point to a point of abrupt change in slope. The other part of the curve may be fitted best by a logarithmic function. Therefore, one can easily substitute M_A, M_B and Φ_B in the first equation of the above system by Φ_A from other equations of the system.

Numerical Examples

In this section, a comparative study is carried out to compare adaptive pushover and conventional pushover analysis implemented in DRAIN-RC program. As was mentioned before, models developed in DRAIN-RC are for plane RC frames. Therefore, two kinds of plane RC frames (regular and irregular buildings) are investigated. For each kind, two buildings (4 and 8 storey buildings) are considered. Before pushover analysis, these buildings were designed based on ACI 318-99 and then, column and beam sections were analyzed by COLA to obtain moment-curvature response. After that, bi-linear responses of sections were obtained. For the sake of comparison, in conventional analysis, two lateral load patterns (Uniform pattern and triangular load pattern) are explored. Adaptive pushover analysis with SRSS combination of modal shapes is also investigated. Units used in these examples are (kN-m). Material properties are assumed to be 21 MPa for the concrete compressive strength and 240 MPa for the yield strength of both longitudinal and transverse reinforcement.

4-Storey Regular Building

4-storey RC building illustrated in Fig. 3 is explored. Sections used in this building are shown in Fig.4. Vertical loads are exerted on the structure by point loads on each node of the structure. These loads are important for considering $P-\Delta$ effects on columns and stability of the whole structure. Roof lateral displacement versus lateral load using adaptive and conventional pushover analyses are compared in Fig. 5. As is observed, adaptive pushover response is between triangular pattern and uniform pattern of conventional pushover analysis.

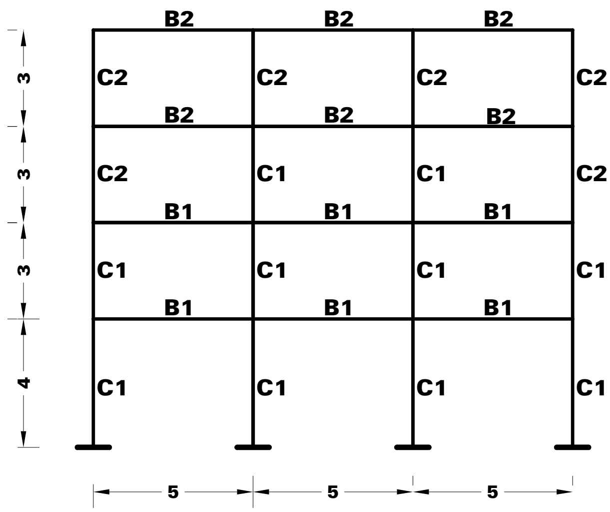

Figure 4. 4-Storey regular building.

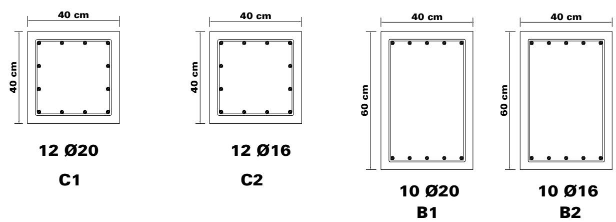

Figure 5. Column and beam sections.

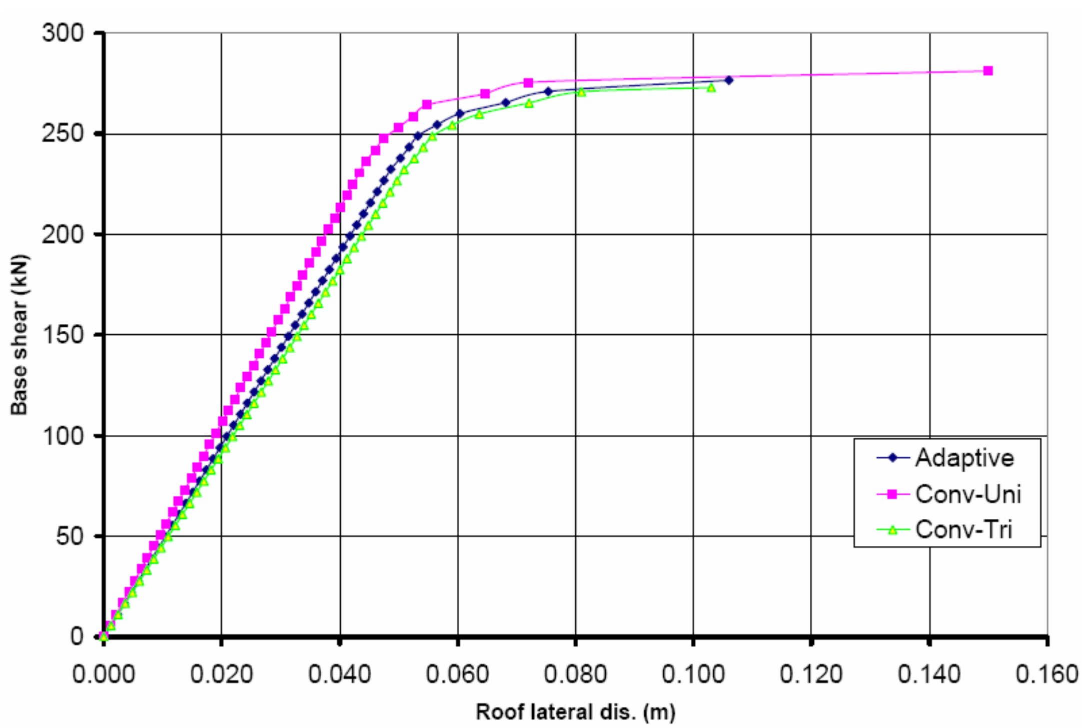

Figure 6. Responses of pushover analyses of 4-storey RC building.

8-Storey Regular Building

Another example explored in this paper is an 8-storey RC building illustrated in Fig. 7 Column and beam sections used in this building are shown in Fig. 8. Dead loads and fraction of live loads are also exerted on the structure by point loads on each node of the structure. Like 4-storey regular building, the results obtained from adaptive and conventional pushover analyses are shown in Fig. 9. In this structure, again adaptive pushover response is between triangular and uniform pattern of conventional pushover analysis. Discrepancy between uniform response and triangular response in conventional pushover analysis is significant for 8-storey regular building. Adaptive response is very close to triangular load pattern.

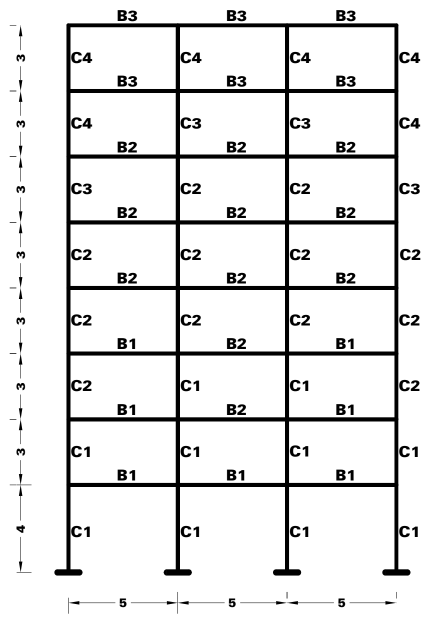

Figure 7. 8-Storey building.

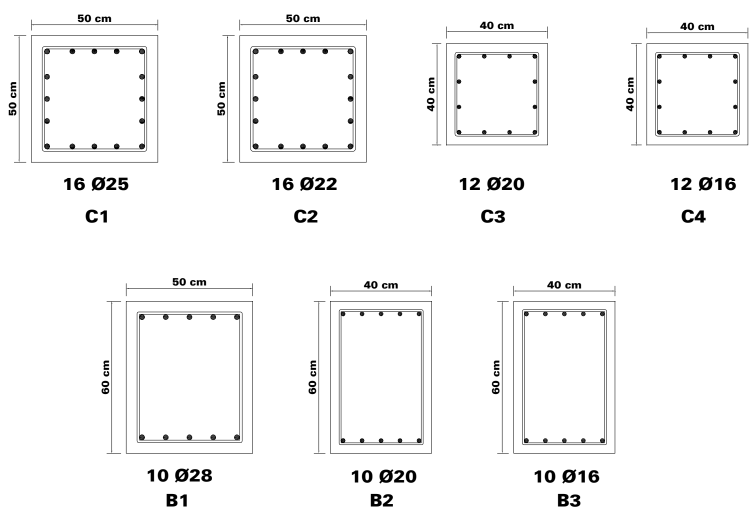

Figure 8. Column sections and beam sections of the 8-storey building.

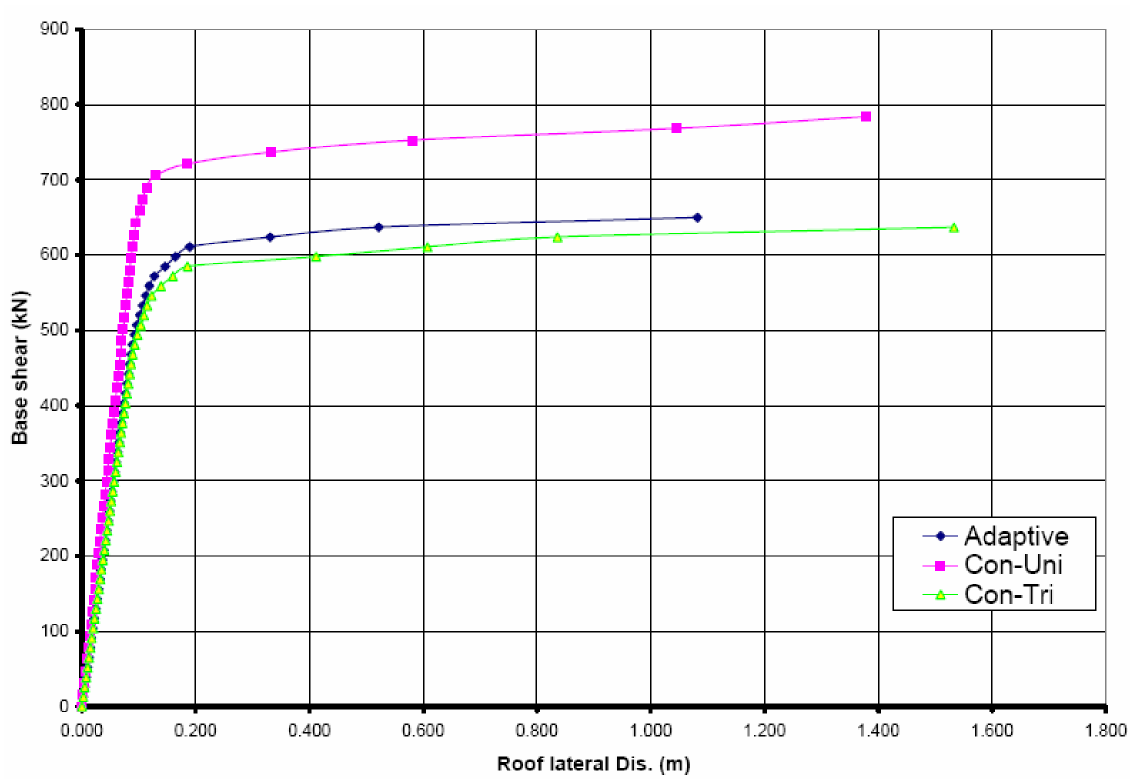

Figure 9. Responses of pushover analyses of 8-storey RC building.

4-Storey Irregular Building

The structure shown in Fig. 10 is another example explored here. This 4-storey building is irregular. Like other examples, this structure was first designed. Column and beam sections are as shown in Fig. 5 for regular frame. Pushover responses from conventional and adaptive methods are shown in Fig. 11. As can be seen in the figure, adaptive response is very close to uniform distribution of conventional pushover. This is predictable since, mass distribution and stiffness distribution is not proportional along the height of the building. Therefore, triangular distribution may not yield to a rational response. In this case, code distribution may provide a better estimate of actual response of the structure.

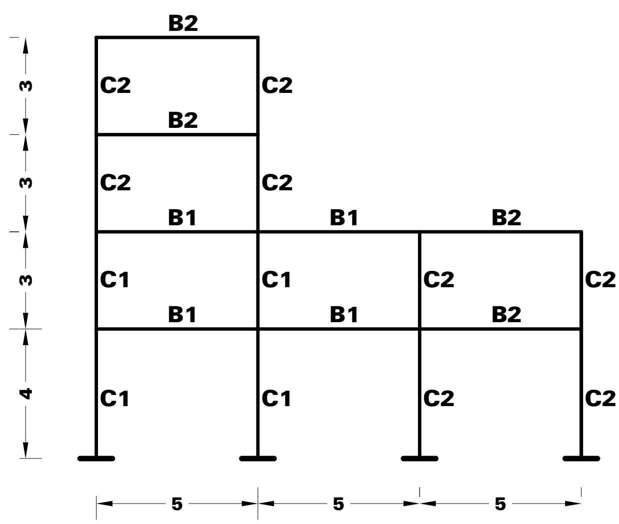

Figure 10. 4-storey irregular frame.

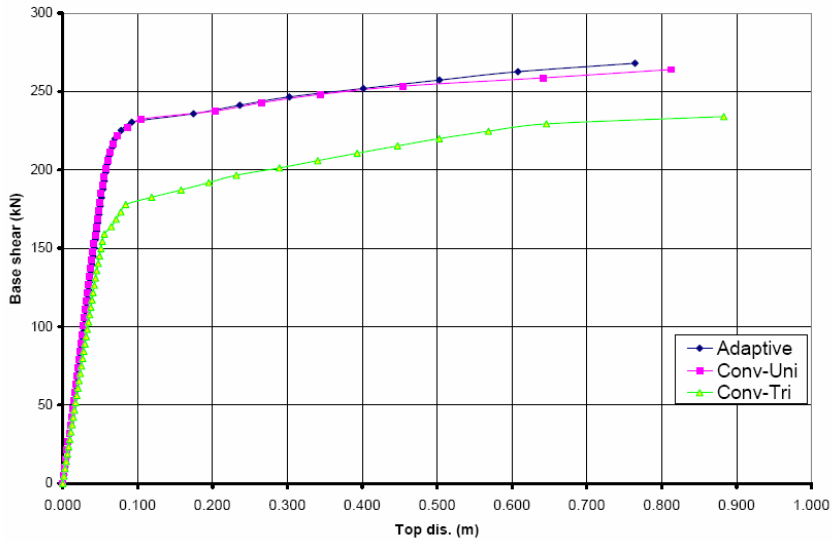

Figure 11. Responses of 4-storey irregular building.

8-Storey Irregular Building

For the sake of comparison an 8-storey irregular frame is also investigated. The structure and its beams and columns are illustrated in Fig. 12. Sections of beams and columns are the same as 8-storey regular frame shown in Fig. 8. Adaptive response of this structure is beyond the interval of uniform and triangular distribution of conventional pushover analysis.

Conclusions

In this paper, adaptive pushover analysis was implemented in DRAIN-RC program. After that, a comparative study was carried out to evaluate the response of adaptive pushover analysis. Numerical examples in this study show that adaptive pushover response is between responses from uniform lateral load pattern and triangular lateral load pattern from conventional pushover analysis for regular buildings. In addition, in regular frames, adaptive response is closer to triangular load pattern than uniform load pattern. This result is rational and is predictable for regular buildings. On the other hand, for irregular frames, adaptive response is closer to uniform pattern than triangular pattern. As it can be concluded from numerical examples, triangular distribution is a good lateral load pattern for regular buildings for conventional pushover analysis. For irregular buildings, on the other hand, it is better to use adaptive pushover instead of conventional pushover analysis.

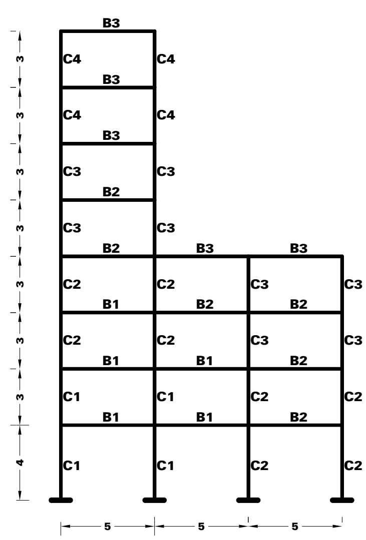

Figure 12. 8-storey irregular building.

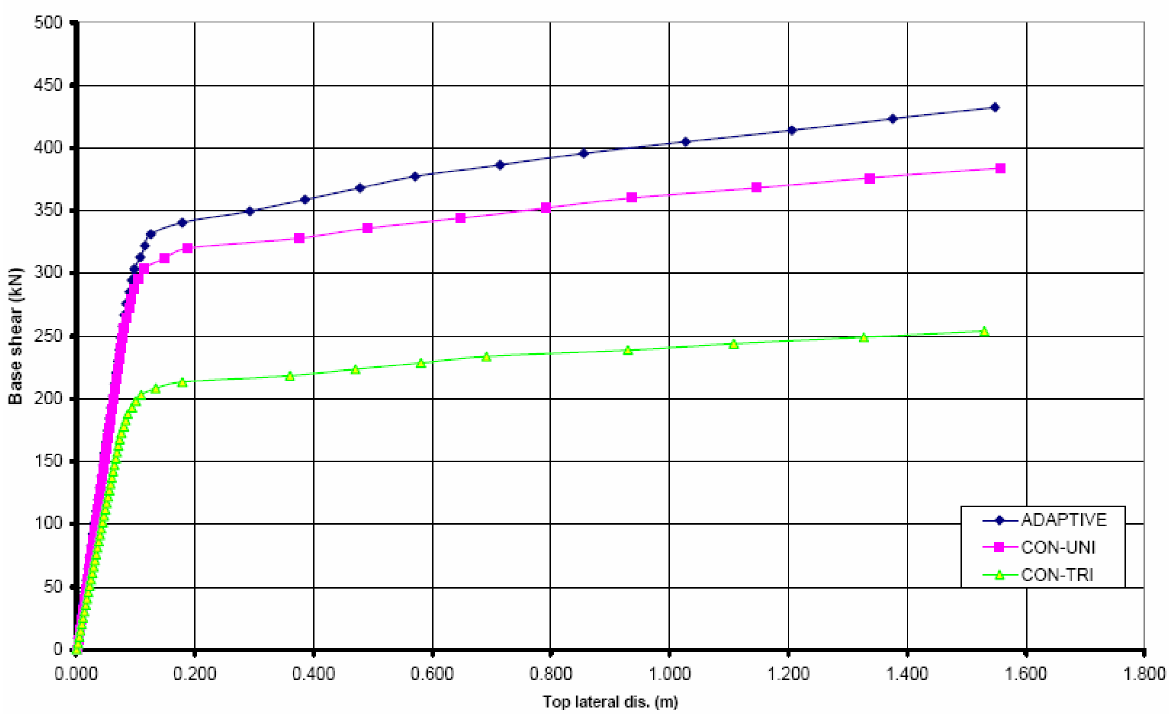

Figure 13. Responses of pushover analysis of 8-storey irregular frame.

References

Antonio, S. and R. Pinho, 2004a. Development and verification of a force-based adaptive pushover procedure, *Journal of Earthquake Engineering* 8(5), 643-661.

Antonio, S. and R. Pinho, 2004b. Advantages and limitations of adaptive and non-adaptive force-based pushover procedures, *Journal of Earthquake Engineering* 8(4), 497-522.

Bracci, J. M., S. K. Kunnath, and A. M. Reinhorn, 1997. Seismic performance and retrofit evaluation of RC structures, *ASCE, ST Division* 123(1), 3-10.

Chopra, A. K. and R. K. Goel, 2002. A modal pushover analysis procedure for estimating seismic demands for buildings, *Earthquake Engineering & Structural Dynamics* 31, 561-582.

Elnashai, A. S., 2001. Advanced inelastic static (pushover) analysis for earthquake applications, *Structural Engineering and Mechanics* 12(1), 51-69.

Gupta, B. and S. K. Kunnath, 2000. Adaptive spectra-based pushover procedure for seismic evaluation of structures, *Earthquake Spectra* 16(2), 367-391.

Gulkan, P. and M. Sozen, 1974. Inelastic response of reinforced concrete structures to earthquake motions, *ACI Journal* 71(6), 604-610.

Kannan, A. E. and G. H. Powell, 1973. General purpose computer program for dynamic analysis of inelastic plane structures, *Earthquake Engineering Research Centre*, University of California, Berkeley, California, USA.

Lefort, T., 2000. Advanced pushover of RC multi-storey buildings, *MSc Dissertation*, Imperial College London, United Kingdom.

Moghadam, A. S. and W. K. Tso, 1995. 3-D pushover analysis for eccentric buildings, *Proc. 7th Canadian conference on earthquake engineering*, Montreal, 381-388.

Saiidi, M. and M. A. Sozen, 1981. Simple nonlinear seismic analysis of RC structures, *Journal of Structural Engineering*, ASCE 107, 937-952.

Saatcioglu, M., A. Shooshtari and J. Alsiwat, 1997. Computer program for dynamic inelastic response history analysis of reinforced concrete structures; DRAIN-RC, Report No. OCEERC 97-18, Ottawa-Carleton Earthquake Engineering Research Center, University of Ottawa, Ottawa,Canada.

Yalcin, C. and M. Saatcioglu, 2000. Inelastic analysis of reinforced concrete columns, *Computers and Structures* 77(5), 539-555.