NONLINEAR PERFORMANCE OF A TEN-STORY REINFORCED CONCRETE SPECIAL MOMENT RESISTING FRAME (SMRF)

Houssam Mohammad Agha[1], Li Yingmin[2], Oday Asal Salih[1] and A'ssim Al-Jbori[1]

[1] *Doctoral Candidate, College of Civil Engineering, Chongqing University, Chongqing, 400045, P.R.China*
[2] *Professor, College of Civil Engineering, Chongqing University, Chongqing, 400045, P.R.China*
Email: Houssam_79@hotmail.com

ABSTRACT :

The basic aim of this study is to investigate the nonlinear performance of a ten story special moment resisting frame (SMRF). The elements are designed based on the 1997 edition of the Uniform Building Code for seismic zone 2A. The global and local nonlinear behaviors of the frame are studied under several earthquake ground motions. For this purpose, an inelastic dynamic analysis is performed using three artificial time histories functions generated using SIMQKE_GR program. Nonlinear Static "Pushover" Analyses using various invariant lateral load patterns was also performed. The seismic performance of the structure is determined on the basis of its damage state under an earthquake ground motion. For this purpose, inelastic dynamic and nonlinear static analyses are used to calculate the damage state "drift profiles and inter-storey drifts". Damage Index from the nonlinear time history analysis is compared with those obtained by pushover analysis procedure. In general, the case study explores variations in the results; it was found that estimates of building response from the nonlinear static analysis are generally insensitive to the pattern of lateral load used to perform the pushover analysis. On the other hand, it was found that building structure's dynamic response characteristics depend strongly on the load path, properties of the structure and the characteristics of the ground motion.

KEYWORDS: Nonlinear performance, seismic performance, pushover analysis, moment resisting frame, Uniform Building Code

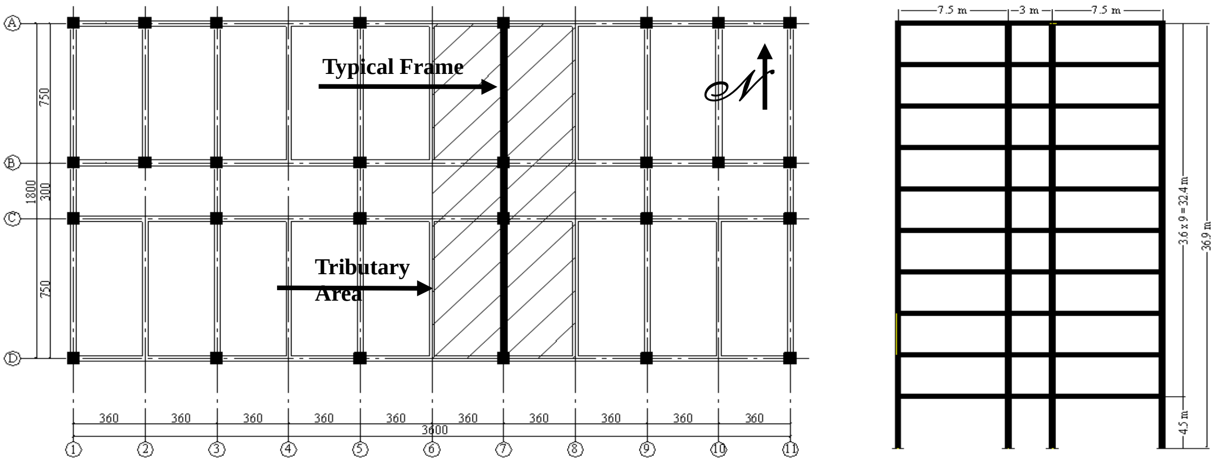
1. INTRODUCTION

The design of buildings is fundamentally concerned with ensuring that the components of the building, e.g. lateral force resisting system, can adequately serve their intended function. In the case of seismic design of the lateral force resisting system, the design problem can be reduced simply to the problem of providing adequate force and deformation capacity to resist the seismic demands. The ATC40 (ATC, 1996) and FEMA 273 (ATC, 1997) documents provide guidelines for the rehabilitation of existing buildings in a performance-based seismic design framework. The ATC40 document emphasizes the use of Nonlinear Static analysis (NSA) methods to predict building demands, whereas, FEMA 273 addresses the use of both linear and nonlinear analysis methods.

Recently, the NSA method has emerged as an attractive method for evaluating the performance of new and existing buildings. This is primarily because of the ability of the NSA method to provide estimates of the expected inelastic deformation demands and to help identify design flaws that would be otherwise obscured in a linear analysis of the building. In addition, the features of the NSA method are available to the structural engineer without the modeling and computational effort of a nonlinear time history analysis. Krawinkler (1996) stressed the importance of evaluating the accuracy of demands predicted using the pushover analysis. The focus of this paper is on the prediction of the nonlinear performance of a ten-story reinforced concrete Special Moment Resisting Frame (SMRF) using the NSA and time history method.

2. EXAMPLE BUILDING

Figure 1 shows the plan and elevation of a 10 story building used for this investigation. The building utilizes a structural system with moment resisting frames in both directions. The frame elements are sized and detailed on the basis of the 1997 UBC Zone 2A (Z = 0.15) requirements. The beam size of 60 by 30 cm is chosen as initial element dimensions for all beams. And the column sizes are of 60×60 cm for the first, second and third stories, 50×50 cm for the fourth, fifth and sixth stories and 40×40 cm for the rest stories. Normal weight concrete is used for all elements. Concrete compressive strength of 35 Mpa for columns and 30 Mpa for beams is used. Grade 60 steel is used for all longitudinal reinforcements and the transverse reinforcements.



(a) Plan (b) Elevation

Figure 1 Example building, typical floor plan and elevation

The case study frame designed using the Uniform Building Code-1997. Structural system is identified as a SMRF (R=8.5, Ω_0 =2.8). The soil profile is assumed to be soft rock (SD). The seismic source type is 'C' because the faults are considered to have a relatively low rate of seismic activity. The distance to seismic source is more than 10 km from the fault. The near source factor for the long period building (N_V) is 1.2 and for the short period building Na is 1.0. The resulting seismic coefficients C_V and Ca are 0.25 and 0.18 respectively. Structural fundamental period according to the Method A of the Section 1630.2.2 of the 1997 UBC is 1.095 sec and this structure belong to the velocity-controlled region in the design response spectra. Effective stiffness of the frame is simulated by assuming one-half the gross section properties for the beams and full gross section properties for the columns. The gravity loads due to the tributary dead and live load are input for columns at each floor level in order to consider the axial load effect on their flexural capacity. The analysis assumes rigid floor diaphragms, with each node having three degrees-of-freedom. The analysis of the building is carried out using the SAP2000 program. The building is assumed to have 5% damping in its first three deformation modes. The strain-hardening stiffness is assumed to be 5% of the elastic stiffness. The fundamental period of the elastic building, initially determined by code prescribed method, was verified by analyses as 1.15 s.

Both pushover and nonlinear time history analyses were performed using gross section properties and P-Delta effects were considered. Nonlinear member behavior of reinforced concrete sections was modeled as in SAP2000. The potential hinges at beam ends are idealized using the default moment hinges M3 of the SAP2000 program and default P-M2-M3 hinges assigned to all columns' ends have same plastic rotation capacities regardless of the section dimensions. The effects of lateral load patterns on global structural behavior were studied on moment resisting frames.

3. NONLINEAR TIME HISTORY ANALYSES

The nonlinear response of structures is very sensitive to the structural modeling and ground motion characteristics. Therefore, a set of representative ground motion records that accounts for uncertainties and differences in frequency and duration characteristics has used to predict the possible deformation modes of the structures for seismic performance evaluation purposes. The ground motion records used in this study include three Spectrum-Compatible time histories TH1, TH2 and TH3 generated using SIMQKE_GR program (Gasparini and Vanmarcke, 1976).

The spectrum adopted was the Eurocode 8 (2003) Type 3 spectrum for low events, soil type C (dense sand or gravel, or stiff clay). After generating an initial three accelerograms, the corresponding spectra were computed and the degree to which they matched the target spectrum was assessed by eye until an acceptable fit was achieved. 5% damped elastic pseudo-acceleration response spectra of ground motions is given in Figure 2. The acceleration- time histories of ground motion records are also shown in Figure 3.

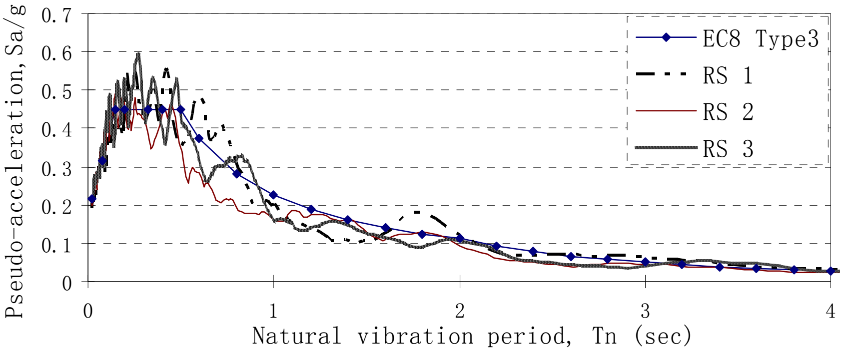


Figure 2 Pseudo-acceleration response spectrum of ground motion (5% damped)

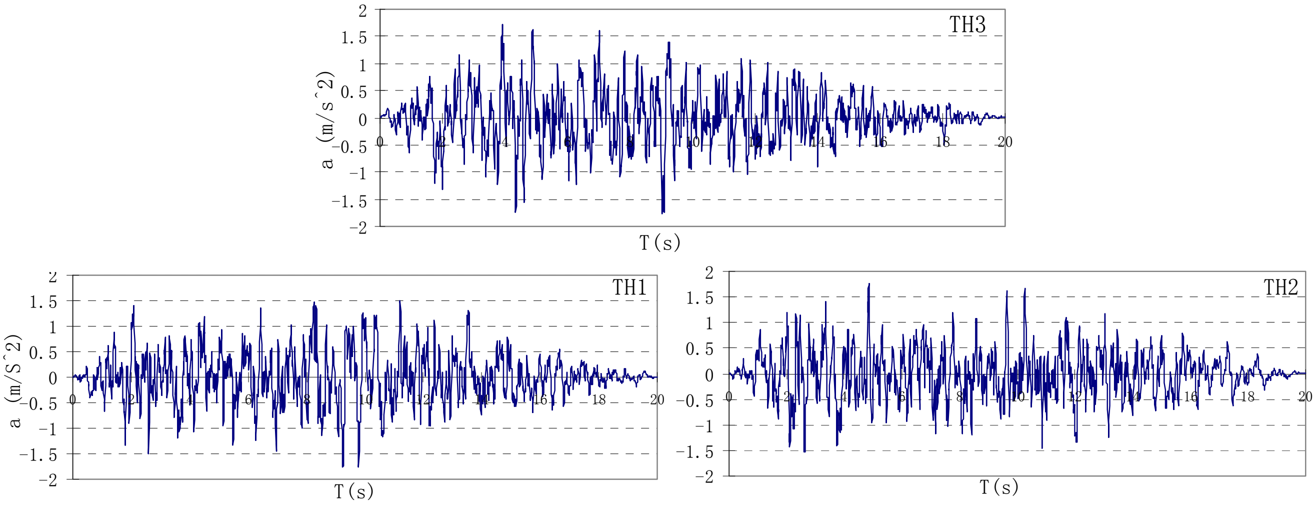


Figure 3 Acceleration-time histories of ground motion records

Nonlinear time history analyses were performed by using SAP2000 for the ground motion records. Maximum absolute values of response parameters such as story displacements, inter-story drift ratios and story shears were determined at the considered deformation level for each ground motion record. It is also worth mentioning that the maximum values of any response parameter over the height of the frames generally occurred at different instants of time. Also, plastic hinge locations were identified in nonlinear time history analyses.

4. CONVENTIONAL PUSHOVER ANALYSES

Since the nonlinear behavior may vary with the pattern of lateral loads, it has been suggested (Krawinkler, 1996; ATC, 1997) that multiple patterns to be investigated when performing a pushover analysis. Pushover analyses were performed on RC SMRF using SAP2000. Five common types of lateral load patterns were utilized to represent the likely distribution of inertia forces imposed on the frames during an earthquake. The utilized lateral load patterns are uniform lateral load pattern, modal load pattern, code lateral load pattern, FEMA-273 lateral load pattern and multi-modal (or SRSS) lateral load pattern. The contribution of first three elastic modes of vibration was considered to calculate the 'Multi-Modal (or SRSS)' lateral load pattern in this study. The height-wise distribution of lateral load patterns for case study frames is illustrated in figure 4.

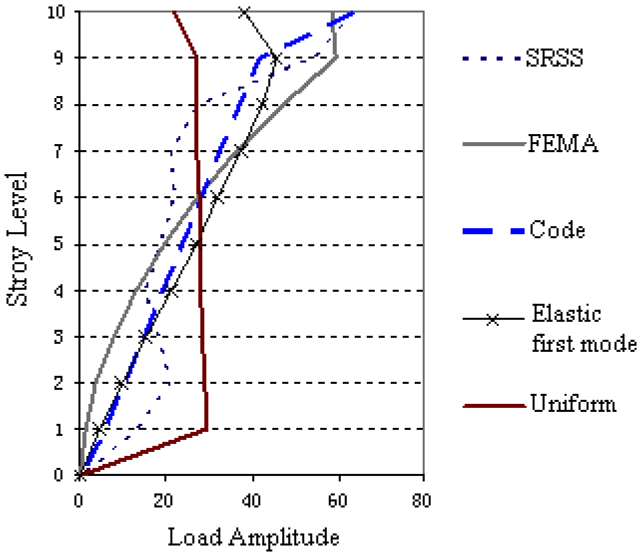


Figure 4 Distributions of lateral load patterns

5. INTERPRETATION OF ANALYSIS RESULTS

The effects and the accuracy of invariant lateral load patterns utilized in pushover analysis were evaluated in this study. For this purpose, global structure behavior, inter-story drift ratios, story shears and plastic hinge locations were selected as response parameters and compared with those parameters of nonlinear time history analyses.

5.1. Global Structure Behavior and story Pushover Curves

Capacity curves (base shear versus roof displacement) are the load-displacement envelopes of the structures and represent the global response of the structures. Capacity curves of aforementioned lateral load patterns are shown in figure 5.

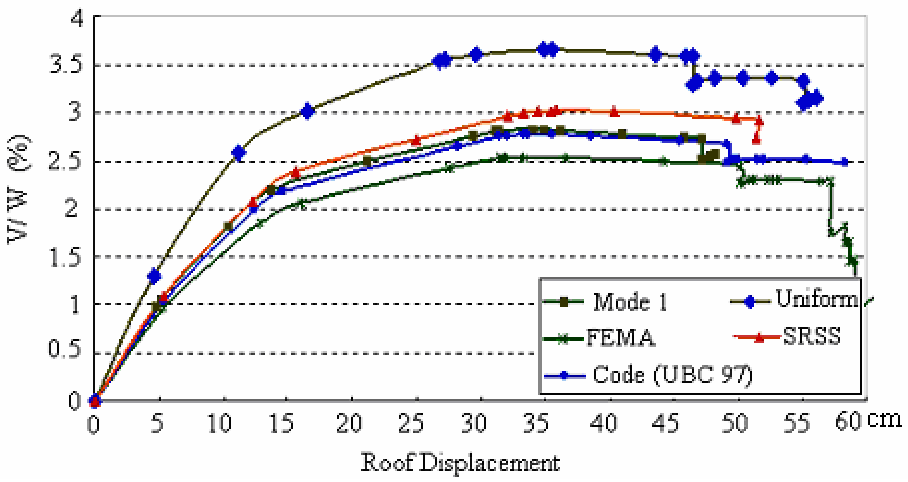


Figure 5 Capacity (pushover) curves for 10 story UBC 97 RC frames

In this capacity cures, base shear is normalized with respect to the total seismic weight of the frame. The height-wise distribution of lateral load patterns together with the capacity curves reveals that the shape of capacity curve depends on the height-wise distribution of lateral load pattern as well as the nonlinear structural characteristics. Pushover analyses using uniform lateral load pattern yielded capacity curves with higher initial stiffness and base shear capacity but lower maximum roof displacement than those of the triangular lateral load patterns.

All triangular lateral load patterns yielded almost same capacity curves, the difference in the point of application of the resultant triangular load patterns are negligible. Elastic first mode and FEMA-273 lateral load patterns yielded the lower and upper bounds of base shear capacities obtained from triangular lateral load patterns, respectively. The use of SRSS or code lateral load patterns is better to represent an average capacity curve determined by triangular lateral load patterns for the frames. Uniform lateral load pattern is mostly unconservative that it *overestimates base shear capacity and underestimates the maximum global displacement demand with respect to triangular lateral load patterns.* The global structural behavior predicted by triangular lateral load patterns is better than Uniform lateral load pattern with respect to the dynamic behavior and the overall structural response. The uniform and triangular lateral load patterns seem to be the upper and the lower bounds of the approximate dynamic global behavior, respectively.

The variation in the shape of story pushover curves is a function of base shear capacity of the frames and the height-wise distribution of story forces. But the variation in the height-wise distribution of triangular lateral load patterns for this mid-rise frame is negligible and the difference in story shears is only significant for uppermost stories due to the significant difference in the amplitude of story forces developed at uppermost stories.

5.2. Inter-Story Drift Ratios

The structural damage is directly related to the inter-story drift ratio. The accurate estimation of inter-story drift ratio and its distribution along the height of the structure is very critical for seismic performance evaluation purposes. The inter-story drift ratios of case study frame are presented in figures 6. As this is the case, the overall interpretation on the accuracy of the inter-story drift ratio yields the following observations:

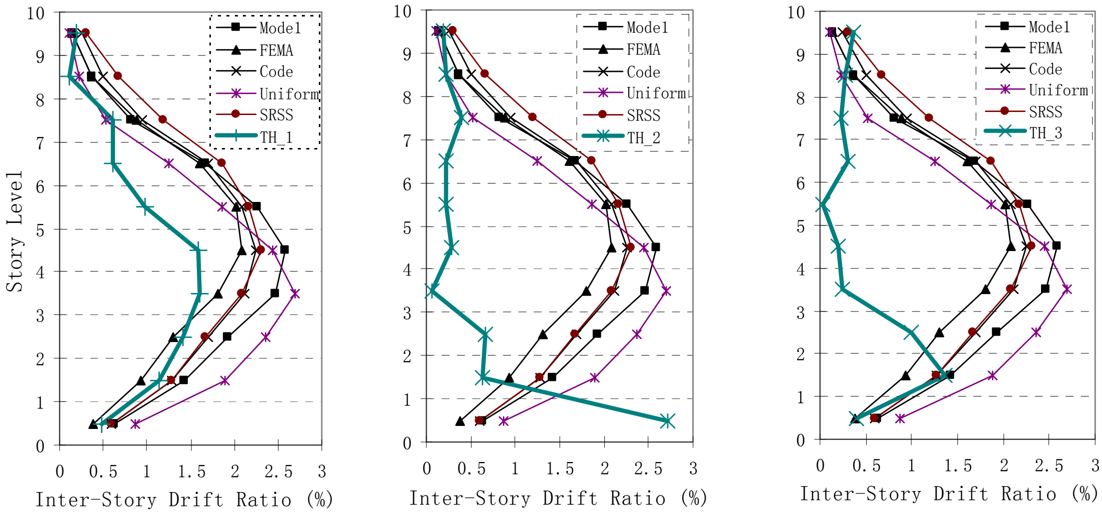


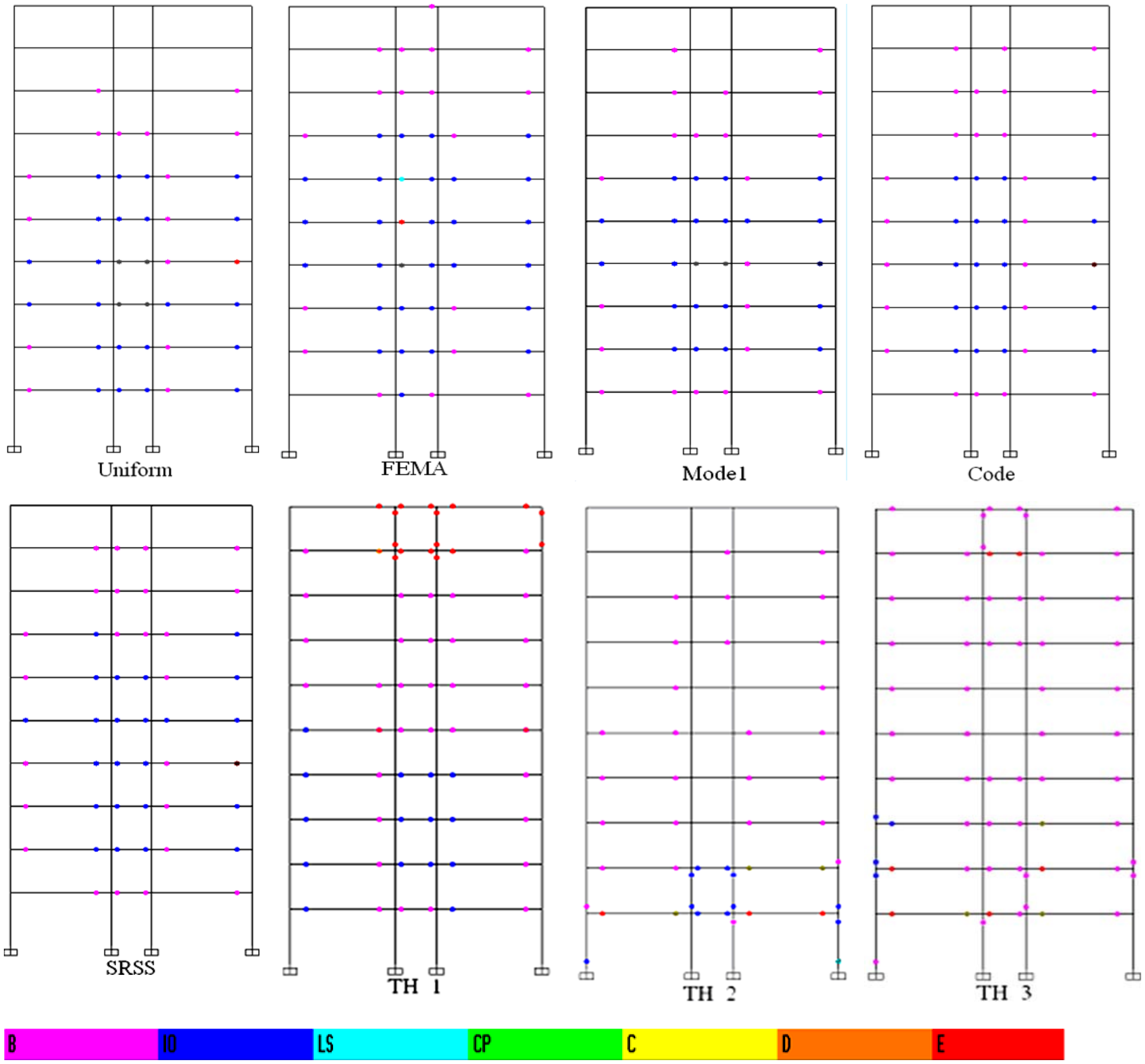
Figure 6 Inter-story drift ratio profile for a 10 story UBC 97 RC frame

- Each ground motion excites different structural response.
- None of the lateral load patterns could capture adequately the exact inter-story drift profile obtained from nonlinear time history analysis for any ground motion record.
- The differences involved in inter-story drift were observed to be larger in nonlinear time history analysis for the first soft story. In contrary, the differences in upper stories inter-story drift are larger.

- The discrepancies in inter-story drift profiles for triangular lateral load patterns were observed to be larger in nonlinear range.
- All lateral load patterns including the uniform lateral load underestimated the inter-story drift ratios at the lower tall story (soft story) and overestimated the response at higher stories.
- The distribution and the magnitude of maximum inter-story drift ratio over the frame height for all three ground motions show the effects of the soft story at nonlinear deformation levels.

5.3 Plastic Hinge Locations

Weak points' location and potential failure modes that structure would experience in case of a seismic event are identified. The locations of plastic hinges are predicted by pushover and nonlinear time history analyses for each ground motion and presented in figure 7.



IO: Immediate occupancy, **LS**: Life safety, **CP**: Collapse prevention, **C**: Collapsed.

Figure 7 Plastic hinges locations for 10 story UBC 97 RC frame

The comparison of plastic hinge locations determined by pushover analyses and nonlinear time history analyses lead to the following observations:

- Plastic hinges' "PH" locations obtained from nonlinear time history analyses are generally different for each ground motion.
- None of the lateral load patterns used in pushover analysis could capture adequately the exact plastic hinge locations of nonlinear time history analyses in the columns while the discrepancies in the locations in the beams' ends are acceptable.
- Uniform lateral load pattern mostly predicts the damage at lower beams but could not produce any damage at upper stories.
- Triangular lateral load patterns yield similar PH locations but no significant damage in the columns.
- The occurrence order and position of the plastic hinges obtained from nonlinear time history analyses at the critical column (first story) revealed that the bottom story is apt to be the weak story. This phenomenon presents clearly the effect of the first tall and soft story.
- PH patterns of nonlinear time history analyses reveal the effects of higher modes on structural behavior. However, none of the lateral load patterns capture this effect even the 'Multi-Modal (SRSS)' lateral load pattern. Also, the early collapse of the soft story underestimated this effect.

The analysis carried out showed that the response is very sensitive to the mechanical characteristics of the system and to the dynamic input. A great care must be posed on the dimensioning of the elements, avoiding that the system, protecting the lower stories, moves the collapse mechanisms toward the weaker high stories.

Lateral load patterns utilized in traditional pushover analyses give some idea about the locations where inelastic behavior is expected but their prediction of plastic hinge locations is generally inadequate. Although these lateral load patterns miss important weak points, the predictions of triangular lateral load patterns were observed to be a bit better than uniform loading predictions but the difference in the accuracy of any triangular lateral load pattern was observed to be insignificant.

6. CONCLUSIONS

The main conclusion derived from the observations on the response prediction of pushover method is that the variation of lateral load patterns in the height-wise distribution is not very significant for such kind of ten story frame and none of the invariant lateral load patterns could capture the approximate dynamic behavior globally and at story levels. The uniform and triangular lateral load patterns seem to be the upper and lower bounds of approximate dynamic global behavior. All invariant lateral load patterns underestimated the dynamic behavior at almost all story levels as illustrated in story pushover curves. Similarly, none of the invariant lateral load patterns could predict the 'exact' plastic hinge locations. The plastic hinge locations prediction of each pushover method was observed to be inadequate and non-conservative. The plastic hinge patterns that result from the seismic excitations showed variations among the ground motions even at the same roof displacements due to characteristics of the ground motions and the frame.

For this mid-rise frame, any triangular lateral load pattern could be used in practice to predict response parameters as the difference in the accuracy of any triangular lateral load pattern demand prediction was observed to be insignificant. Uniform lateral load pattern mostly emphasized demands in lower stories over demands in upper stories. Also, plastic hinge locations predictions of triangular lateral load patterns were observed to be better than those of uniform load pattern. The difference in the accuracy of any triangular loading prediction was observed to be insignificant.

Although pushover analyses gives an insight about nonlinear behavior imposed on structure by seismic action, pushover analyses were not able to reasonably capture neither the exact sequence of hinging nor their locations. Therefore, design and seismic evaluation process should be performed by keeping in mind that some amount of

variation always exists in seismic demand prediction of pushover analysis.
Tall first may result in the partial or total collapse of the story. This can result in a significant change in the deformation pattern of the building and abrupt change in inter-story drift with most earthquake induced displacement occurring within the tall first storey. This can result in extensive damage within the ground floor and even instability and collapse of structures.

Finally, more systematic and complete parametric studies, considering different periods, strength ratios, and earthquake ground motions, however, will be required to establish definite criteria for efficient design of reinforced concrete special moment resisting frame system.

REFERENCES

American Concrete Institute (ACI). (1999). Building Code Requirements for Reinforced Concrete (ACI 318-99), Detroit, Michigan, U.S.A.

Applied Technology Council, ATC-40. (1996). Seismic evaluation and retrofit of concrete buildings, Vols. 1 and 2, California, U.S.A.

Chopra, A.K. and Goel, R.K. (1999), Capacity-Demand-Diagram Methods Based on Inelastic Design Spectrum. *Journal of Earthquake Spectra* **15:4**, 637-656.

Computers and Structures. (2000). SAP2000: Three Dimensional Static and Dynamic Finite Element Analysis and Design of Structures, Computers and Structures Inc., Berkeley, California, U.S.A.

Gasparini, D.A. and Vanmarcke E.H. (1976). Simulated Earthquake Motions Compatible with Prescribed Response Spectra. Research Report R76-4, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Fajfar, P. and Fischinger, M. (1987). Nonlinear Seismic Analysis of R/C Buildings: Implications of a Case Study, *Europian Earthquake Engineering* ***1:1***, 31-43.

Fajfar, P. and Fischinger, M. (1988), N2 – A Method for Non-Linear Seismic Analysis of Regular Structures. Proc. 9th World Conf. on Earthquake Engineering, Tokyo/Kyoto **5**, 111-116.

Federal Emergency Management Agency. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356), Washington DC, U.S.A.

ICBO. (1997). Uniform Building Code - 1997 Edition, Vol. 2: Structural Engineering Design Provisions, International Conference of Building Officials, Whittier, California, U.S.A.

Houssam, M.A (2007). Comparison of GB50011-2001 and UBC 1997 Code for Seismic Design of Building Based on RC Frames. MSc Thesis, Chongqing University, Chongqing, P.R.China.

Oguz, S. (2005). Evaluation of Pushover Analysis Procedures for Frame Structures. MSc Thesis, Middle East Technical University, Turkey.

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**, 452-64.