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Evaluation of Story Drift under Pushover Analysis in Reinforced Concrete Moment Frames

ORIGINAL ARTICLE

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Abstract: The accurate prediction of story drift and its distribution along the height of the structure is very critical for seismic performance evaluation since the non-structural damage is directly related to the story drift. Pushover analysis is an accepted method for seismic evaluation of existing structures as well as performance-based design of new structures. Regarding assumptions and limitations in pushover analysis, there is a need to estimate the error that would affect the accuracy of story drift. This paper investigates the validity of pushover analysis to predict story drift under different lateral load patterns. For this purpose, several reinforced concrete moment frames with different heights were analyzed using pushover and nonlinear time history analyses and obtained results were compared to evaluate the error level.

Keywords: *Lateral load pattern, nonlinear time history analysis, pushover analysis, reinforced concrete moment frame, story drift.*

I. INTRODUCTION

Using experimental testing is a precise way of obtaining the structural response of the structural elements and full-scale structures [1-4]. Even though experimental methods provide an accurate simulation of the real behavior of structures, there are several inhibited limitations in its application. High construction and instrumentation costs are one of the major limitations. In addition, there are restrictions regarding the size of structure replicate under investigation. Therefore, attentions have been drawn toward the numerical methods. The numerical methods have been used for different types of structures subjected to different loading scenarios [5-8].
Lateral loading due to ground motion during earthquake is one of the major loads would be potentially imposed on the structures. Many researches have investigated the response of the structure to this loading using experimental and numerical methods [9-12]. There are two numerical methods stand out among others, which consider nonlinearity of materials during loading: nonlinear time history analysis and pushover analysis [13-16]. In nonlinear time history analysis, several earthquakes excitations records are utilized as the base-excitation forces, and then the seismic responses of the structure are calculated using a numerical method for solving the differential motion equations. Despite the accuracy of nonlinear time history analysis, it is time-consuming and sensitive to numerical and modeling parameters [17-19]. Pushover analysis is the other analysis technique that potentially would overcome the attributed problems for nonlinear time history analysis. In this method, lateral loads are increased monotonically in accordance with a predefined pattern, and then nonlinear responses and failure modes of the structure are investigated in each loading step. In pushover analysis, lateral load pattern plays a key role in the estimation of structure behavior. Therefore, a lateral load pattern should be selected in a way that the structural responses become as close to the nonlinear time history analysis results [20-25].

Previous studies have shown that uniform lateral pattern resulted in the structural global responses far from the time history analysis [21]. In this paper, other load patterns based on structural mode shapes are investigated. The accuracy of lateral load patterns for pushover analysis is investigated by determining story drift distribution along the height of structures and calculating the result deviations from the nonlinear time history analysis. Performing a nonlinear time history analysis is very time-consuming and complicated technique. Therefore, in some cases, pushover analysis can capture the nonlinear lateral response of structures accurately and it can be substituted instead of nonlinear time history analysis to determine lateral displacements, story

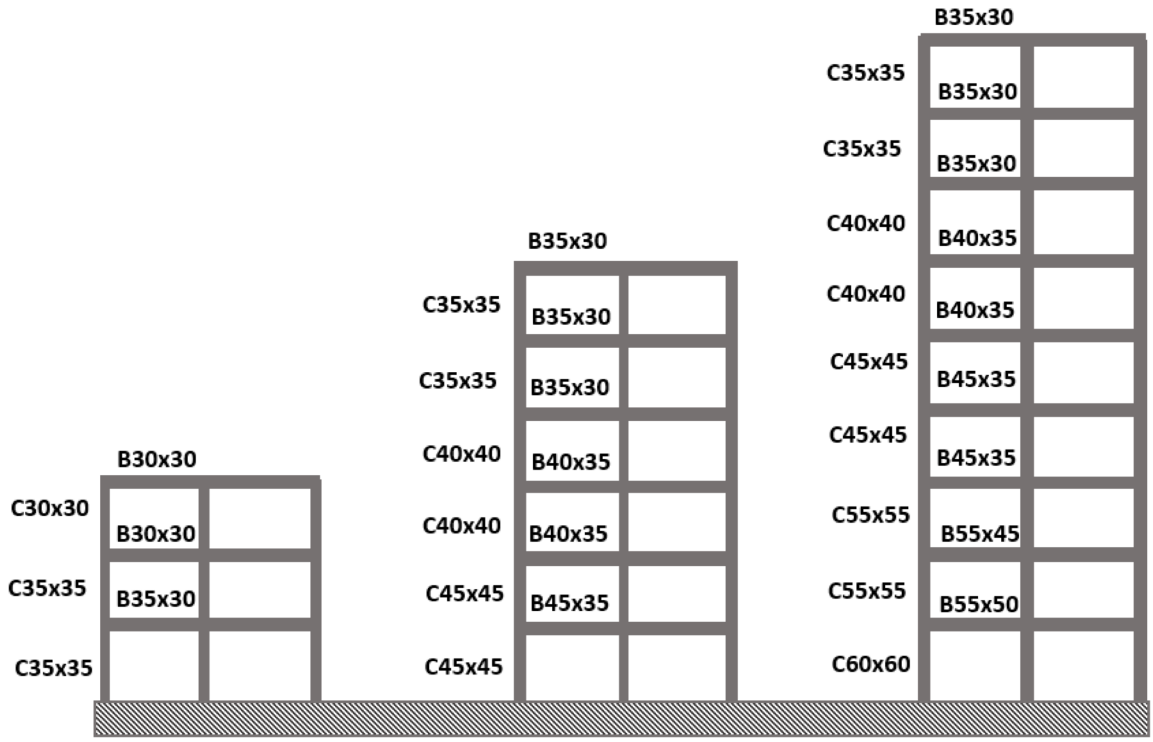

Figure 1: Cross sections of columns and beams (C=column, B=beam).

drifts, and to predict global and local seismic demands at desired performance level. Accurate estimation of target displacement for desired performance level, selection of suitable lateral load patterns, and determining the correct failure mechanism due to higher modes affect the quality of pushover results.

II. Description of Case Study Frames

Three 2-dimensional reinforced concrete frames with different heights (with 3, 6 and 9-story) were utilized to cover a broad range of fundamental periods. Rigid floor diaphragms were assigned at each story level. The effective gravity loads consisting of dead loads and 25% of live loads. The dead and live loads have been taken to be 2750 kg/m and 800 kg/m along the beam length, respectively. The reinforced concrete frame elements have been designed according to the ACI318-99 [26] using CSI SAP2000 program [27]. The span length and height of all stories are 4 m and 3.2 m, respectively. The column base connections are assumed to be fixed. Columns and beams cross sections are shown in Figure 1. To consider nonlinearity of material in the analysis, the property of plastic hinges was defined according to ASCE 41-06 [28] and assigned at the critical locations of structural elements. P-M2-M3 hinges were assigned at two ends of columns and flexural hinges were assigned at two ends of beams. Figure 2 shows Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) acceptance criteria on a force-displacement diagram for a plastic hinge.

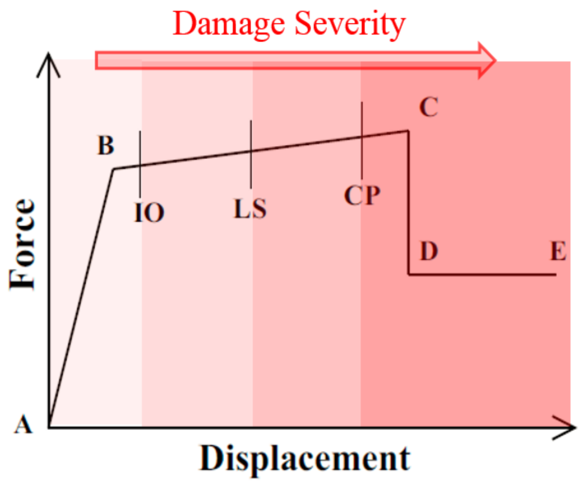

Figure 2: Deformation levels in the hinges.

III. Analysis Methods

In this section, the utilized numerical analyses are introduced, and associated procedures are explained.

A. Nonlinear time history analysis

Nonlinear responses of structures using nonlinear time history analysis are very sensitive to their modeling method and the characters of chosen earthquake excitations. Therefore, to predict the modes of deformation of the structures, a series of time history ground motions with different intensity, frequency, and various time history features were used in this research.

Earthquake Name	Scale Factor	Year	Station Name	Magnitude
San Fernando, US	4.5126	1971	Santa Felita Dam	6.61
Imperial Valley, US	2.6095	1979	Cerro Prieto	6.53
Loma Prieta, US	4.7077	1989	Anderson Dam	6.93
Northridge, US	3.3594	1994	Sunland - Mt Gleason Ave	6.69
Duzce, Turkey	4.2724	1999	Lamont 1061	7.14
Manjil, Iran	0.9641	1990	Abbar	7.37

Table 1: Summary of selected ground motion.

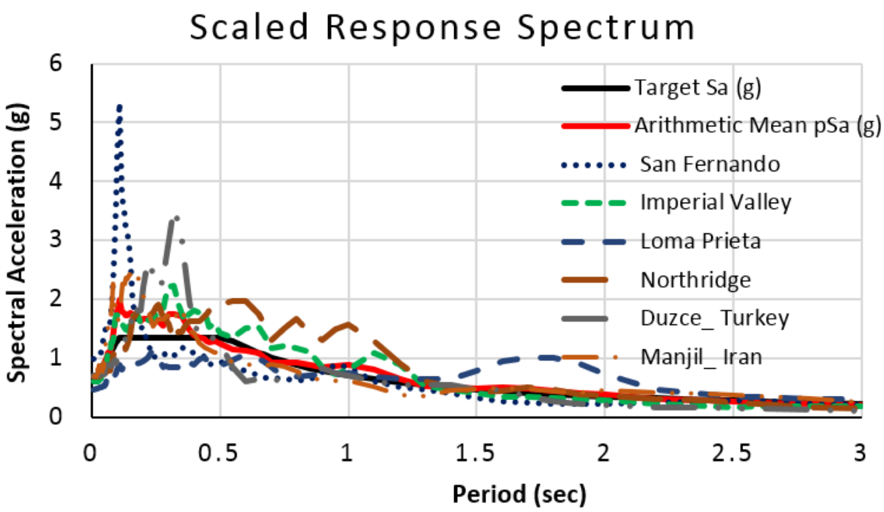

Figure 3: Target response spectrum and response spectra of scaled earthquake motions.

All the time history analyses for the different ground motion records were conducted by using CSI SAP2000 [27]. The response spectrum of selected ground motion records was scaled based on ASCE 7-10 design response spectrum for the city of Los Angeles in the United States for stiff soil and risk category III [29], [30]. Six earthquake ground motions were selected for nonlinear time history analysis (Table 1). The scaled response spectra for the selected ground motions are shown in Figure 3.

B. Pushover analysis

Pushover analysis is a nonlinear static analysis method in which the structure is subjected to gravity loads and consequently will undergo a monotonic displacement-controlled lateral load pattern which will increase to reach the ultimate condition. In pushover analysis, lateral load patterns should be selected carefully and per the recommendations of the building codes. In this research, four different lateral load patterns have been used in pushover analyses to simulate the distribution of the inertia forces through the stories. Considered lateral load patterns were described in the following:

Uniform load pattern: The lateral force in each story is proportional to the mass of the same story.

$$F_i = m_i / \sum m_i \qquad (1)$$

where F_i is the lateral force of the story i, and m_i is mass of story i.

First elastic mode load pattern: The lateral force in each story is proportional to the multiplication of the first elastic mode in the mass of that story.

$$F_i = m_i\phi_i / \sum m_i\phi_i \qquad (2)$$

where φ_i is the amplitude of elastic first mode in the story i and m_i is mass of story i.

Inverted triangular pattern based on ASCE 7-10: This lateral load pattern has been defined in the ASCE 7-10. The lateral force in each story is obtained according to Equation 3.

$$F_i = \frac{W_i h_i^k}{\sum_{i=1}^{n} W_i h_i^k} \qquad (3)$$

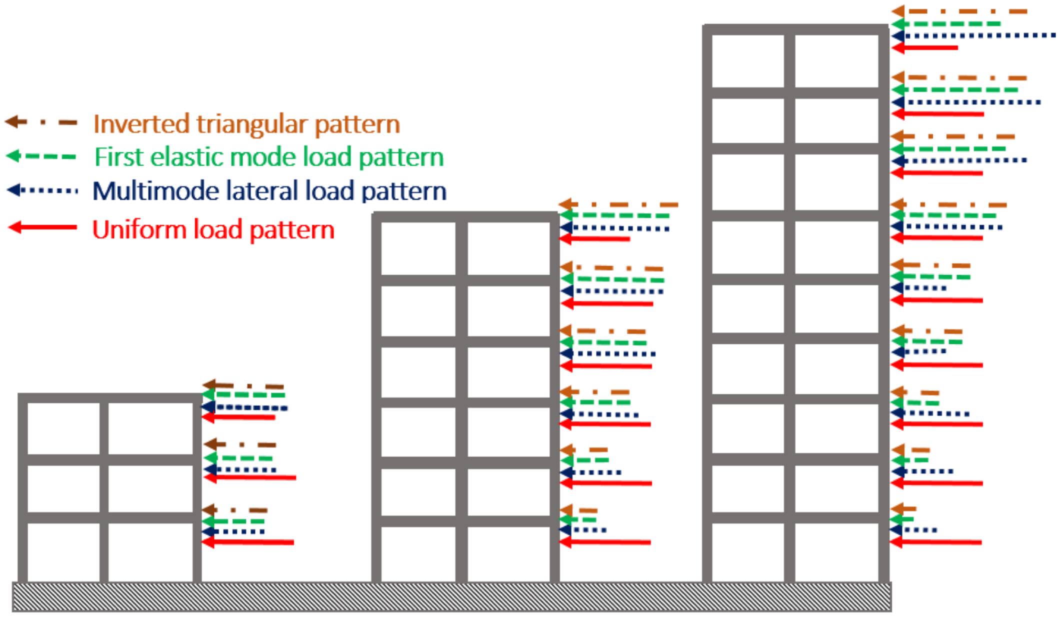

Figure 4: Distribution of the lateral load patterns along the height of frames.

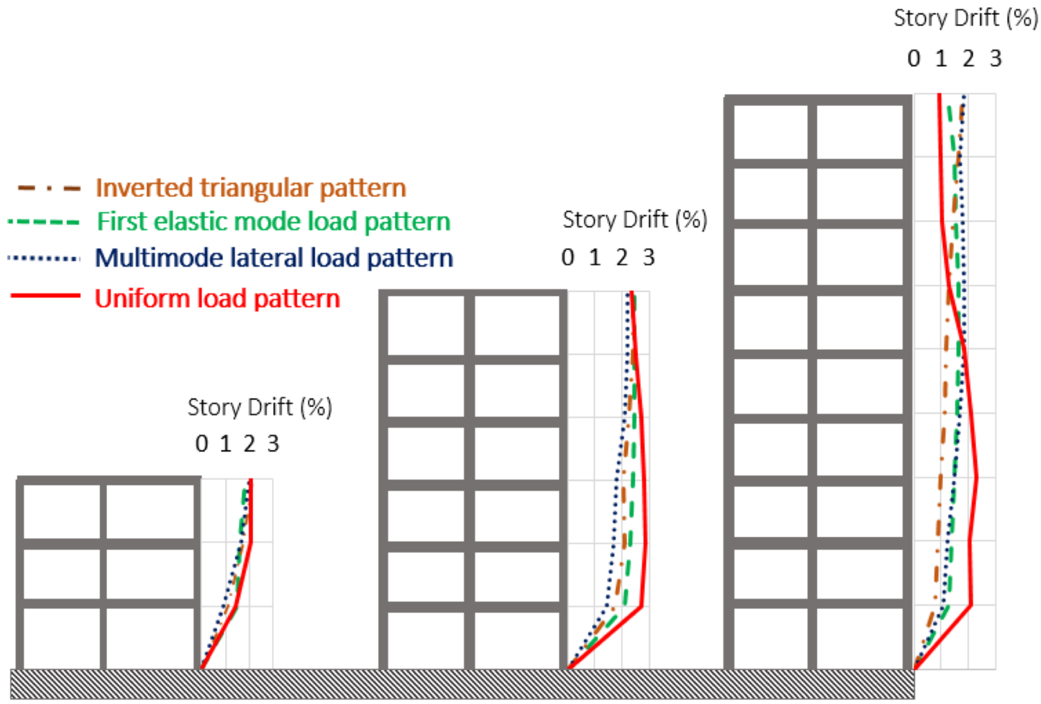

Figure 5: The story drift profile along the height of frames.

where F_i is the lateral force of the story i, h_i is the height of the story i, W_i is weight at floor level i, n is the total number of stories, k is an exponent related to structure period that is unity for the structures having a period of 0.5 seconds or less. Moreover, it is 2 for structures having a period of 2.5 seconds or more.

Multimode lateral load pattern: This lateral load pattern considers the effects of the higher elastic modes as well as the effect of potential irregularity in 3-dimensional structures [31]; and as following, the lateral force in each story is combined as the square root of the sum of the squares (SRSS) of modal responses. The steps for calculating the applied force at each story level are described below:

1. calculating the lateral force F_{in} in the story i for the mode n from the Equation 4.

$$F_{in} = \Gamma_n m_i \phi_{in} A_n \quad (4)$$

where Γ_n is the modal contribution coefficient for the mode n and $\emptyset_{in}$ is the mode shape of n in the story i, A_n is the pseudo-acceleration in the mode n from the elastic system of a single degree of freedom.

2. Calculating the story shear (V_{in}) in the story i for the mode n, where N is the total number of stories.

$$V_{in} = \sum_{j \succ i}^{N} F_{jn} \quad (5)$$

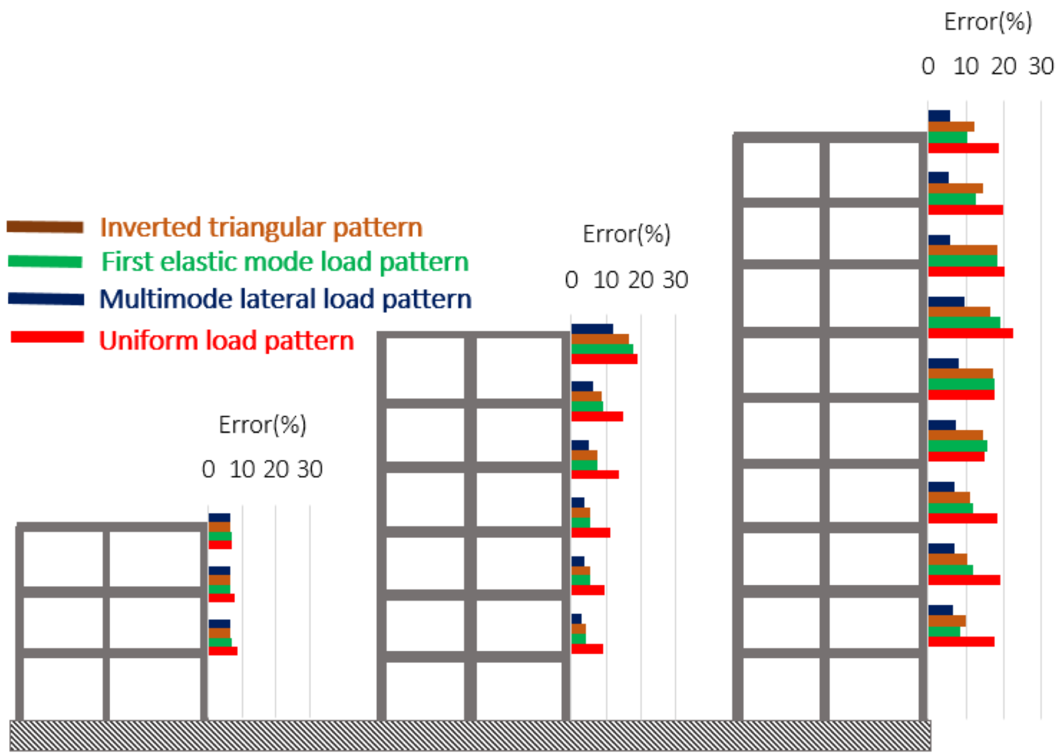

Figure 6: The percentage of error profile along the height of frames.

3. Combining the modal shear stories by using the SRSS method.

4. Recalculating lateral force of the story, F_i, in the story levels from the combination of story shears, F_{ma}, starting from the top.

In this study, three first elastic vibrational modes have been used for calculating the multimode lateral load pattern. In Figure 4, the lateral load distributions along the height were presented.

IV. DISCUSSION

The effect and accuracy of the different lateral load patterns were investigated to predict the story drift distribution in the reinforced concrete moment frames. In Figure 5, the profiles of story drift along the height of frames based on inverted triangular, first elastic mode, multimode, and uniform load patterns are presented. In addition, nonlinear time history analyses were conducted on case study frames for the selected ground motions. The maximum story drifts for each story occurred at the different times during nonlinear time history analyses. Therefore, for each ground motion, the maximum story drifts were derived for all story levels and then averaged for the considered ground motions. The story drifts calculated from each lateral load pattern in pushover analyses were compared to the average results obtained from nonlinear time history analyses to estimate the value of error. The error profiles for the lateral load patterns are illustrated in Figure 6.

V. CONCLUSION

Several reinforced concrete moment frames with different heights were modeled, designed, and analyzed. The differences between the nonlinear time history analysis, as an exact response, and pushover analysis with different lateral load patterns in term of the story drift distributions along the height of frames were investigated. The following conclusions have been made from the analytical results in this study.

1-None of the lateral load patterns can propose the story drift distribution close enough to the nonlinear time history analysis;

2-For 3-story frame, all the considered lateral load patterns resulted in a very similar story drift distribution. Their associated errors regarding the nonlinear time history analysis results were negligible. The percentage of errors was limited to maximum of 7.5%;

3-The resulted story drift from different lateral load patterns was more similar at higher story levels (for example in the 9-story frame, at top three stories);

4-Higher values of error for all frames were reported for uniform lateral load pattern compared to the other loading patterns. For example, for 3, 6 and 9-story frames, the attributed errors were 7.5%, 19.1%, and 22.6%;

5-It was observed that the errors have been increased by increasing the number of stories due to the higher mode contribution in the response;

6-The story drift resulted from uniform load pattern was about 0.021 for the first three story levels in the 9-story frame which was about 40% larger than the average reported story drift from the other considered load patterns;

7-The values of drifts for the inverted triangular load patterns are often consistent with the first elastic mode load patterns especially for 3 and 6-story frames;

8-Story drifts resulted from multimode load patterns for all frames were in good correlation with averaged story drift in nonlinear time history analyses with the lowest error values.

VI. DECLARATION

All authors have disclosed no conflicts of interest.

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