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Extension of the Consecutive Modal Pushover Analysis (CMP) to Asymmetric Concrete Moment Resistance Frame Buildings

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Abstract- The Nonlinear Static Procedure (Nsp) Based On Pushover Analysis Is Usually Restricted With A Single Mode Response. The Nsp Is Valid Mainly For Low-Rise Buildings Where The Behavior Is Dominated By Fundamental Vibration Modes. It Is Of Significance To Take Into Account Of Higher Mode Effects In Pushover Analysis Of Such Structures As Tall Buildings Or Asymmetric Structures. Consecutive Modal Pushover (Cmp) Procedure Is Recently Proposed To Consider Higher Mode Effects In 2d Models. This Paper Deals With The Extension Of The Cmp Method To Asymmetric Building Structures. The Asymmetric Models Of This Study Are Reinforced Concrete Moment Resisting Frame Buildings. The Results Are Compared With Results Of Nonlinear Dynamic Time-History Analyses. Promising Compatibility Is Found In Both Local And Global Responses.

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I. Introduction

According to the nonlinear static procedure (NSP), also known as pushover analysis, seismic demands of a building can be computed by pushing the building with a specific height wise distribution lateral load pattern to reach a predetermined target displacement. NSP's suffer from some shortages. Among them, invariant load pattern is one of the most important limits and it causes higher modes effects being neglected during pushover analysis. Besides, in original NSP's, all methods were limited to planar structural models and so, torsional effects are not considered directly and effectively. Recently, attempts have been made to overcome these limits and extend the applicability of simplified methods to asymmetric structures, which require a 3D analysis and consider higher modes effects in the analysis *e.g.* (Ayala and Tavera 2002), (Aydinoglu, 2003), (Chopra and Goel, 2004), (Fujii et al., 2004), (Yu et al., 2004) and (Zárate and Ayala, 2004).

This paper deals with the extension of the consecutive modal pushover (CMP) analysis which was proposed by (Poursha et al., 2009). The CMP procedure contains multi-stage and single-stage pushover analysis and is able to take higher modes effects into account. In the original version of the CMP method, 2D models were used and so, torsional effects were neglected. In the paper, the extended CMP method is summarized and applied to four ten story buildings with 0%, 5%, 10% and 20% eccentricities in Y direction. The results are compared with results of nonlinear response history analysis (NL-RHA).

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II. Discription of the Consecutive Modal Pushover (CMP)

The CMP procedure benefits from consecutive implementation of modal pushover analysis and uses limited number of modes to develop results (Poursha et al., 2009). This procedure contains a multi-stage and a single-stage pushover analysis. When the first stage of the multi-stage pushover analysis is performed completely, the next stage starts with initial structural state which is the same as the state at the end of the first stage. Numbers of modes which are considered in the multi-stage pushover analysis depend on the fundamental period of the structure. If the fundamental period of the structure exceeds 2.2 seconds, then, three modes shapes being used in analysis otherwise, two modes shapes would be enough. The displacement increment at the roof in each stage of multi-stage pushover analysis, u_{ri}, is calculated as follows:

$$u_{rn} = \beta_n \delta_t \qquad (2.1)$$

In which,

$$\beta_n = \alpha_n \text{, for stages before the last stage} \qquad (2.2)$$

and,

$$\beta_n = 1 - \sum_{j=1}^{Ns-1} \alpha_n \text{, for the last stage} \qquad (2.3)$$

Where δ_t is the total target displacement at the roof, and N_s is the number of stages considered in the multi-stage pushover analysis. Also, α_n is the effective modal mass ratio for the n^{th} mode, which is defined as the ratio between the effective modal participating mass for the n^{th} mode divided by total mass of the structure. The target displacement can be obtained through different methods e.g. capacity spectrum method (ATC-40, 1996), displacement coefficient approach (FEMA356, 2000), N2 method (Fajfar, 2000) and dynamic analysis of the structure (Moghadam, 2002). As mentioned before, the CMP procedure uses single – stage pushover analysis to develop results. Hence, a pushover analysis with a triangular or a uniform load distribution is performed separately. Seismic demands can be obtained by enveloping the peak responses derived from the multi-stage and the single-stage pushover analysis. The CMP procedure as proposed by Poursha (2009) is summarized below in a sequence of steps:

a) Calculate natural frequencies, ω_n and mode-shapes, ϕ_n. These properties are computed by Eigen values obtained from linearly elastic building analysis. Mode-shapes are normalized so that the roof component of ϕ_n equals unity ($\phi_{rn}=1$).

b) Compute $s_n^* = m\phi_n$ (Chopra and Goel, 2004), where s_n^* shows the distribution of incremental lateral forces over the height of the structure for the n^{th} mode.

c) Compute the total target displacement of the structure at the roof, δ_t.

d) The CMP procedure consists of single-stage and multi-stage pushover analysis. First, Gravity analysis should be implemented and then, pushover analyses are performed according to the following sub-steps

   i. Perform the single-stage pushover analysis with the triangular load pattern for low to mid-rise building and the uniform load pattern for high-rise building until the control node at the roof of the building reaches the predetermined target displacement.

   ii. Perform two-stage pushover analysis for those buildings which their fundamental periods are less than 2.2s. In the first stage, a pushover analysis is performed by using the incremental lateral forces, $s_1^* = m\phi_1$, until the control node reaches $u_{r1} = \beta_1\delta_t$, (Eqn. 2.1, for i=1). Then, second stage should be performed. In this stage, a pushover analysis is implemented by using the incremental lateral forces, $s_2^* = m\phi_2$, until the control node reaches $u_{r2} = \beta_2\delta_t$, (Eqn. 2.3, for N_s=2 and i=2).

   iii. Perform three-stage pushover analysis for those buildings which have fundamental period more than 2.2s. The first stage are exactly is the same with the first stage of the two-stage pushover analysis. Next pushover analysis is performed by using, $s_2^* = m\phi_2$, until the control node reaches $u_{r2} = \beta_2\delta_t$ (Eqn. 2.1, for i=2). Then, last pushover analysis is implemented by using $s_3^* = m\phi_3$ until the control node reaches $u_{r3} = \beta_3\delta_t$, (Eqn. 2.3, for N_s=3 and i=3).

e) Calculate peak responses of desired values in each pushover analysis. In the paper the one-, two-and three-stage pushover response are denoted by r_1, r_2 and r_3 respectively.

f) Calculate the ultimate responses as follows:

$$r = Max\{r_1, r_2\} \quad , for T < 2.2s \qquad (2.4)$$

$$r = Max\{r_1, r_2, r_3\} \quad , for T \geq 2.2s \qquad (2.5)$$

III. Analytical Models, Assumptions and Types of Analysis

Four ten-story reinforced concrete building with 0%, 5%, 10% and 20% eccentricity in Y direction are considered as models as shown in Fig. 3.1. Lateral load resisting systems of buildings are concrete moment resistant frame with medium ductility. All frames consist of 4*5m bays in each direction and a story height of 3.0m is assumed. Some brief characteristics of buildings are listed in Table 3.

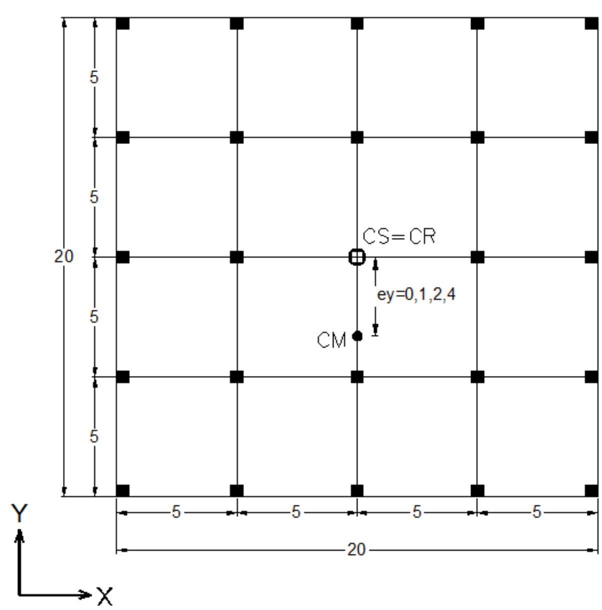

Figure 3.1 : Typical Plan of buildings considered (units in meters)

Table 3.1 : Models Characteristics

No.	No. of story	h(m)	b(m)	Eccentricity (%)	Periods (s)		
					T_1	T_2	T_3
S1	10	30	20	0%	1.23	1.23	0.99
S2				5%	1.25	1.23	0.98
S3				10%	1.29	1.23	0.97
S4				20%	1.45	1.25	0.94

The OpenSEES program is used to create and analyze models. The DD+50%LL load combination are assumed in gravity analysis where DD, is the dead load and LL, is the live load. The CMP procedure is carried out for models. The P-Δ effects are neglected in all pushover analyses. Two modes are considered in the CMP procedure to develop responses and pushover analyses are implemented in X direction only. Each mode-shapes consists of two transitional (X,Y) and a rotational (rotation about Z) components. Since, models have eccentricities in Y direction as shown in Fig. 3.1., only X and rotational component of each mode-shape is considered and mode-shapes are normalized to 1 at top in X component. The target displacements are obtained as the maximum top floor displacement computed by NL-RHA. Seven far field ground motion records are selected from the ground motion database of the Pacific Earthquake Engineering Research Center (PEER) to run NL-RHA. A minimum 15 km distance from the station to surface rupture is considered to select record and soil type is B according to USGS classification system. All records are normalized to 0.35g before processing. Some detail characteristics of ground motion are listed in Table 3.2. The Dist. values stands for closest distance to surface projection of rupture in the table. The responses obtained from pushover analyses are compared with the mean of maximum responses computed by NL-RHA.

Table 3.2 : Characteristics of Ground Motions

No.	Name	Year	M	Recording Station	Dist.[1] (km)	Component	PGA(g)	PGV(cm/s)
1	Chichi	1999	7.6	TCU047	33.01	N	0.413	40.2
2	Imperial	1979	6.5	6604 Cerro Prieto	23.5	H-CPE147	0.169	11.6
3	Kocaali	1999	7.4	Arcelik	17	ARC000	0.218	17.7
4	Landers	1992	7.3	23 Coolwater	22.8	CLW-LN	0.283	25.6
5	Loma Prieta	1989	6.9	Anderson Dam	20	AND270	0.224	20.3
6	Northridge	1994	6.7	24000 LA	35.9	OBR090	0.335	16.7
7	Sanfernando	1971	6.6	24278 Castaic	24.2	OPR021	0.324	15.6

IV. Discussion of Results

The drift ratio is defined as the ratio between relative displacements of two story divided by height of the story and calculated as follows:

$$DR = \frac{d_{i+1} - d_i}{H} \quad (4.1)$$

Where, d_i, d_{1+1} and H are the displacement of the i^{th}, $(i+1)^{th}$ story and the height of the story respectively.

Story drift ratios are computed by the CMP, Triangular load pattern and NL-RHA and shown in Fig. 4.1 to 4.4. Figures illustrate that the CMP procedures estimate drift ratios for 10 story buildings well in comparison with NL-RHA results. As seen in Fig 4.1. to 4.4., the height-wise distribution of story drifts derived from the CMP is similar to NL-RHA. Additionally, the pushover analysis by using triangular lateral load pattern, underestimates drift ratios in higher levels in comparison with NL-RHA results.

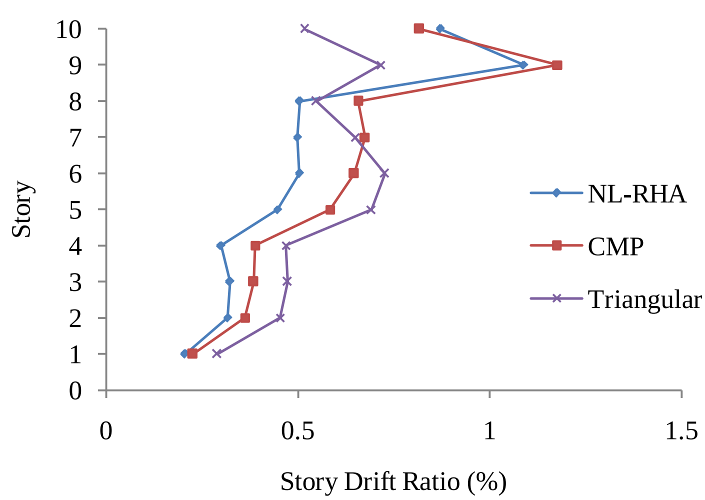

Figure 4.1 : Height-wise distribution of drift ratio for symmetric model

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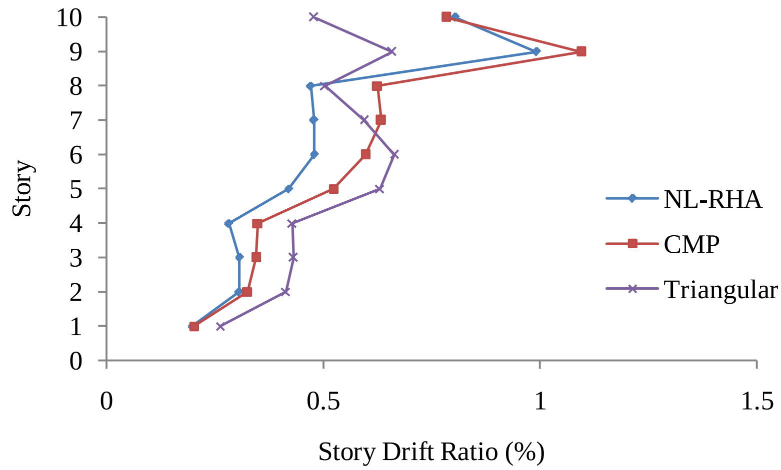

Figure 4.2 : Height-wise distribution of drift ratio for asymmetric model with 5% eccentricity

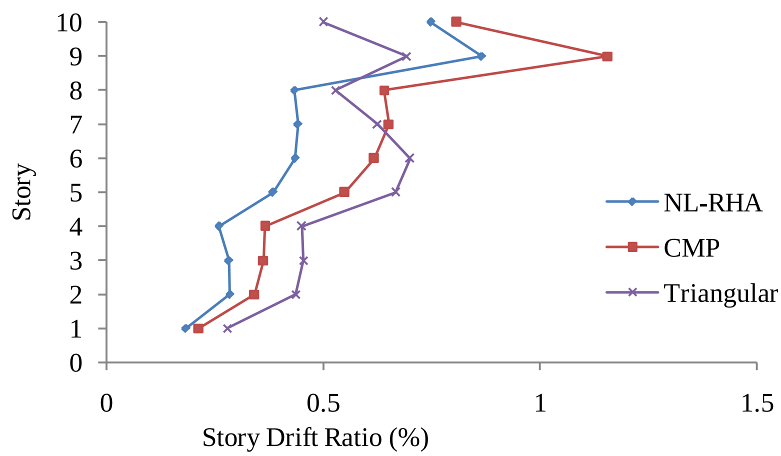

Figure 4.2 : Height-wise distribution of drift ratio for asymmetric model with 10% eccentricity

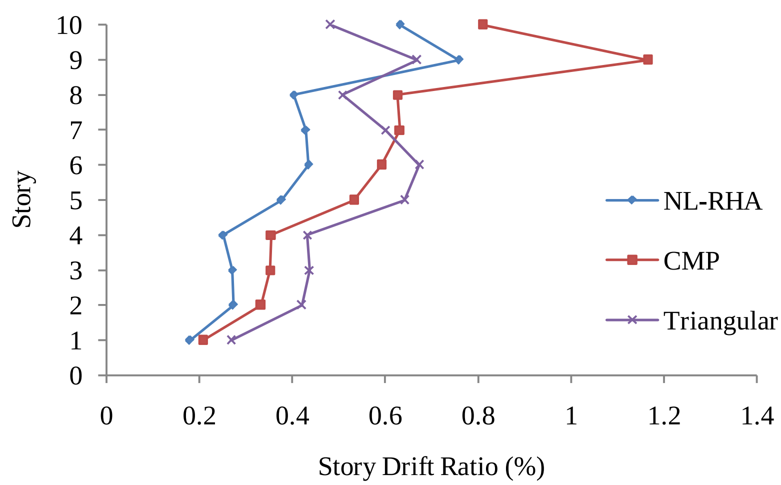

Figure 4.4 : Height-wise distribution of drift ratio for asymmetric model with 20% eccentricity

V. Conclusion

Since higher-modes play significant role in tall building, The Consecutive Modal Pushover (CMP) procedure is proposed to consider higher-mode effects in the pushover analysis. It is assumed that dynamic characteristic of a structure are invariable during analysis and so, they are obtained through linearly-elastic analysis. The CMP procedure employs force distribution load pattern and consists of single-stage and multi-stage pushover analysis. The single–stage pushover analysis can be performed either by triangular or uniform load pattern. The multi-stage pushover analysis can be performed in two or three stages based on the height of the structure. Both single-stage and multi-stage pushover analysis are considered to develop results. The CMP procedure benefits from consecutive implementation of modal pushover analysis and uses limited number of modes to develop results. The CMP procedure estimates the height-wise distribution of drift ratio well, and their results are similar to results obtained by NL-RHA.

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