Modal pushover analysis as a tool for evaluation and design of irregular frames

D.G. Lignos[a,*], C.J. Gantes[b]

[a]Stanford University, Civil and Environmental Engineering Department, Stanford, CA 94305-4020, USA
[b]National Technical University of Athens, Civil Engineering School, 9 Iroon Polytechneious Str. Athens, GR-15780, Greece

Abstract

This paper investigates the application of modal pushover analysis (MPA) as a tool to estimate seismic demands of structures with irregular mass distribution. A set of 20 ground motions is selected and median peak values of interstory drift ratios, story shears and overturning moments obtained with MPA are compared with results of nonlinear time history analysis (NL-THA). It is concluded that modal pushover analysis can be used to estimate seismic demands for practical applications in evaluation and design of frames with mass irregularity.

Keywords: Modal pushover; Mass irregularity; Pushover analysis; Nonlinear time history analysis; Higher modes; Incremental dynamic analysis; Seismic response

1. Introduction

Pushover Analysis (PA) is widely used in recent years for practical evaluation of seismic demands and for structural design. Recently, a new method of analysis, called Modal Pushover Analysis (MPA), was introduced by Chopra and Goel [1]. Based on the assumptions that the response of a structure is controlled by a single mode and the shape of that mode remains constant with time, MPA can lead to good estimates of the seismic demands of a building. Previous investigations of MPA's accuracy and efficiency dealt with regular frames [3,5]. Very recent works by Chintanapakdee and Chopra [2] and Lignos and Gantes [5] address the effects on floor displacements, story drifts and plastic hinge rotations of 'vertically' irregular frames. The present work evaluates the accuracy of MPA for interstory drift ratios, story shears and overturning moments for the case of frames with mass irregularity, by comparing results to those obtained with nonlinear time history analysis (NL-THA).

2. Ground motions

The seismic excitation that is used in the present paper is defined by a set of 20 large magnitude, small distance (LMSR) ground records with magnitude and distance from the rupture between $6.5 < Mw < 7.0$ and $13\,km < R < 30\,km$, respectively. The records are selected from the PEER (Pacific Earthquake Engineering Research) Center ground motion database (http://peer.-berkeley.edu/smcat/). Properties of this set are presented by Mendina [6]. The same ground motions have been used to evaluate seismic demands over a wide range of hazard levels, based on the Incremental Dynamic Analysis (IDA) by Vamvatsikos and Cornell [7].

Seven levels of ground motion intensity have been used and the control parameter used to 'scale' the intensity for a given structure strength, or to 'scale' the strength for a given intensity, is the parameter $[S_a(T_1)/g]/\gamma$. $S_a(T_1)$ is the 5% damped spectral acceleration at the fundamental period of the structure (without P-delta effects), and γ is the base shear coefficient, i.e. $\gamma = V_y/W$, with V_y being the yield base shear (without P-delta effects) and W the total weight of the structure. The parameter $[S_a(T_1)/g]/\gamma$ represents the ductility dependent strength reduction factor (often denoted as R_μ), which, in the context of present codes, is equal to the conventional R factor if no overstrength is present.

3. Buildings considered

In order to evaluate MPA using buildings with mass irregularities, the initial generic frame that was

* Corresponding author. Tel.: +1 (650) 723 1502; Fax: +1 (650) 723 7514; E-mail: dlignos@stanford.edu

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developed by Mendina [6] is modified to account for this source of irregularity. The building is a nine-story one-bay frame with ratio of span to story height equal to 2 and with the same moment of inertia of the columns in a story and the beam above them. Relative element stiffnesses are tuned to obtain a straight line deflected shape for the first mode. The strength design load pattern is the first mode load pattern that is determined by NEHRP provisions. Rotational springs, with 3% strain hardening for the moment – rotation hysteretic behavior, have been used to account for material nonlinearity. The nonlinear model, which has been selected to include material nonlinearity, is the peak-oriented (Clough) model, without post capping. All nonlinear analyses were performed with DRAIN-2DX analysis software [8] and global P-Δ effects are taken into consideration. The parameter γ is considered to be 0.1.

Mass irregularity at an individual floor is stipulated by a 400 kips design load, with respect to 200 kips of the other floors. Three cases are examined where mass irregularity is introduced at the second, fifth and eighth stories, respectively, and the corresponding first mode vibration periods are 0.91, 0.95 and 1.00 s. For the sake of brevity, results from the latter case are presented in this paper, but effects of the location of mass irregularity are addressed.

4. Interstory drifts

Normalized median values for interstory drifts are presented in Fig. 1 along the height of the nine-story frame for elastic behavior ($S_a(T_1)/g/\gamma = 2$). Values are normalized with respect to the first period spectral displacement over the total height of the building. MPA underestimates seismic drifts at the upper stories, while it overestimates demands at the lower stories, in comparison to NL-THA. This is not the case for intermediate and high levels of intensity ($S_a(T_1)/g/\gamma > 6$) where exactly the opposite is observed as presented in Fig. 2 for R factor equal to 8. The authors have come to the same conclusion for all cases that were examined, regardless of the position of mass discontinuity. Higher modes do not affect the error in interstory drifts at lower stories, but they contribute significantly to the correct estimation of seismic demands at upper stories.

5. Story shears

Story shears along the height of the generic frame are normalized with respect to the base shear $V_{b,NL\text{-}THA}$ as determined from NL-THA for each level of intensity. For elastic behavior ($S_a(T_1)/g/\gamma = 2$), three modes are adequate to accurately estimate demands with MPA. There is a tendency to overestimate the base shear when higher modes are included in the response, especially when mass discontinuity is located at lower stories. For higher level of intensity one mode is not adequate, and it consistently underestimates the response. MPA estimates story shears with less than 5% error when three modes are selected. The previous conclusion can clearly be verified by Fig. 3, where normalized median story shears for R = 8 are presented.

6. Overturning moments

Similar to story shears, median overturning moments

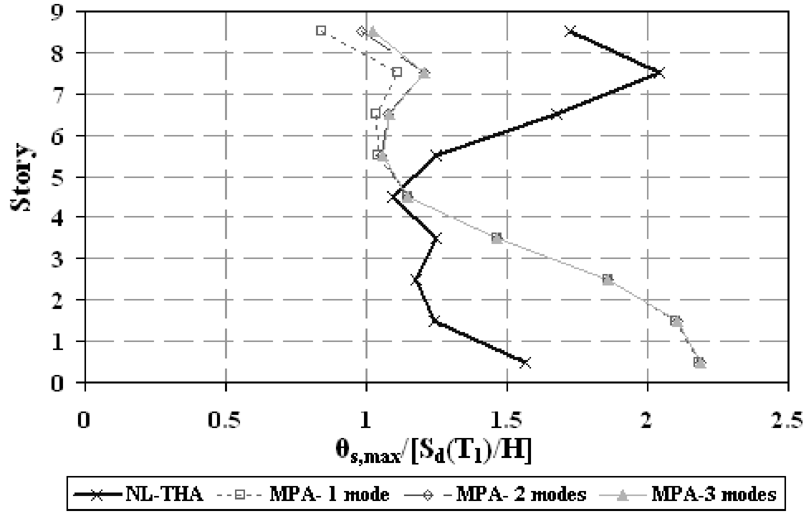

Fig. 1. Normalized median story drifts for nine-story generic frame with mass discontinuity on the eighth floor and R = 2.

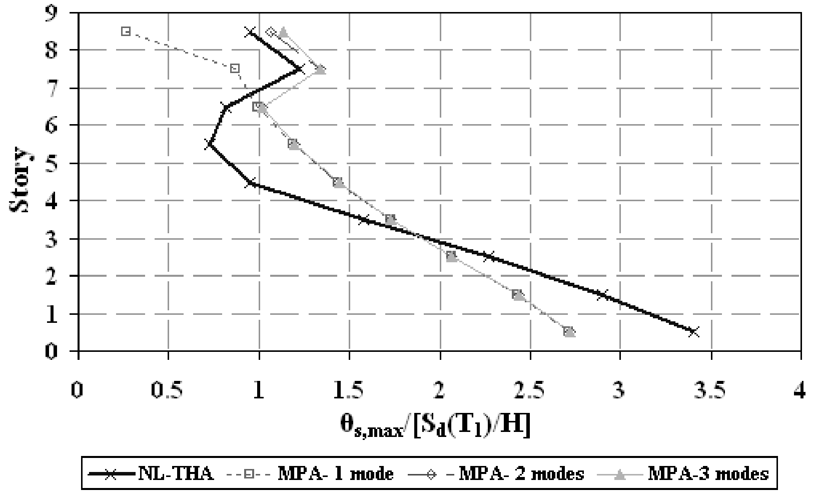

Fig. 2. Normalized median story drifts for nine-story generic frame with mass discontinuity on the eighth floor and R = 8.

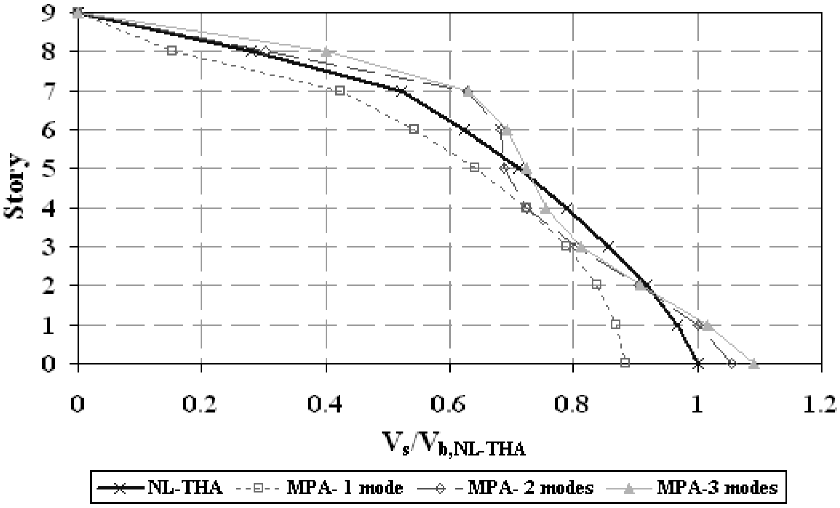

Fig. 3. Normalized median story shears for nine-story generic frame with mass discontinuity on the eighth floor and R = 8.

(OTM) are normalized with respect to the median OTM at the base of the structure, $M_{b,NL\text{-}THA}$, as determined by NL-THA for each level of intensity. For elastic response MPA estimates the demands for OTM with the desired accuracy and only one mode is necessary to capture the response, regardless of the location of mass discontinuity. This is not the case when the R factor becomes higher. Using one mode for MPA a representative picture of OTM demands is achieved, but the contribution of the second mode is important at upper stories. It is preferable to slightly overestimate OTM demands using the second mode, due to the fact that stability problems can occur if OTM is underestimated, since it is related to the axial load in the columns. Normalized median OTM along the height of the building with mass irregularity at the eighth floor are illustrated in Fig. 4 for R = 8.

7. Conclusions

The objective of the research discussed in the present paper is to evaluate modal pushover analysis in comparison to nonlinear time history analysis, for a variety of ground motions and levels of intensity, in order to estimate seismic demands of structures with mass irregularities. Using a nine-story generic frame, three cases were studied where mass irregularity was placed at the

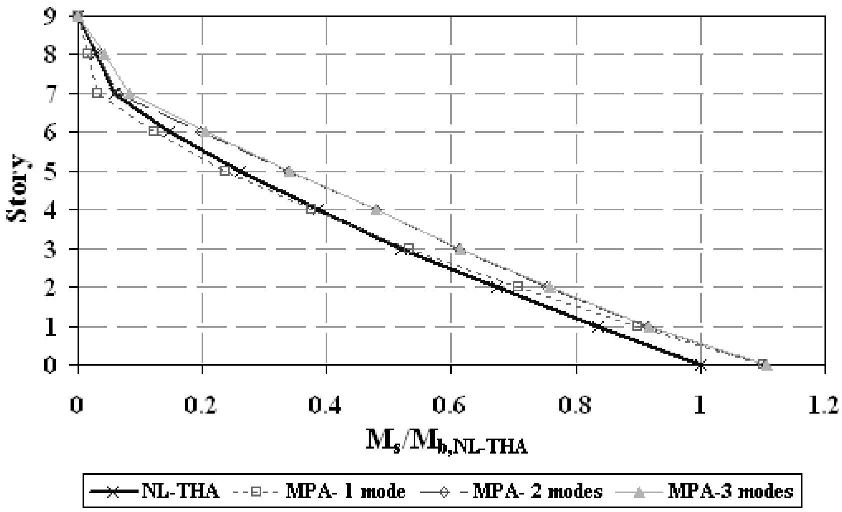

Fig. 4. Normalized median story overturning moments for nine-story generic frame with mass discontinuity on the eighth floor and R = 8.

second, fifth and eighth floors, respectively. Interstory drifts, story shears and overturning moments have been compared.

Considering story drifts, the error is significant if the response of the structure is elastic. Even if more than one mode is selected for MPA, demands are underestimated at the upper stories. For inelastic behavior, story drifts are adequately estimated by MPA in the upper stories. Higher modes do not contribute significantly to the lower stories and MPA underestimates drift demands for all the cases that were examined.

Story shears are accurately estimated for inelastic response, if three modes are selected for MPA. Including higher modes when the behavior is elastic, base shear is overestimated with an increasing tendency if mass discontinuity is located at lower stories.

MPA using only one mode determines adequately OTM demands, as long as the response of the irregular frame is elastic. For higher levels of intensity, one mode is adequate for the lower stories, but higher modes need to be considered to capture demands at the upper stories in order to avoid stability problems. This is due to the fact that higher mode effects are more critical at upper stories.

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