ADAPTIVE MODAL COMBINATION PROCEDURE FOR PREDICTING SEISMIC RESPONSE OF VERTICALLY IRREGULAR STRUCTURAL SYSTEMS

E. Kalkan[1] and S. K. Kunnath[2]

ABSTRACT

A new direct multi-modal pushover procedure called the Adaptive Modal Combination (AMC) procedure has been developed to estimate seismic demands in building structures. The proposed methodology is an attempt to synthesize concepts from three well-known nonlinear static methods. The basic ideas that are integrated into the procedure include: the concept of a performance or target point introduced in the Capacity Spectrum Method, recognition of the variation in the dynamic characteristics of the structural system as implemented in adaptive pushover schemes, and the modal decomposition of a multi-degree-of-freedom as suggested in the Modal Pushover Analysis (MPA). A novel feature of the AMC procedure is that the target displacement is updated dynamically during the analysis by incorporating energy based modal capacity curves in conjunction with inelastic response spectra. Hence it eliminates the need to approximate the target displacement prior to commencing the pushover analysis. The methodology has been validated for regular steel and RC moment frame buildings. In this paper, the proposed scheme is further validated for a range of buildings with vertical irregularities. It is demonstrated that the AMC procedure can reasonably estimate critical demand parameters such as interstory drift ratio for impulsive near-fault forward directivity records, and consequently provides a reliable tool for performance assessment of building structures.

Introduction

Since 1988 the Uniform Building Code started to distinguish vertically irregular structures from regular ones based on certain limits on the ratio of strength, stiffness, mass, setbacks or offsets of one story with respect to an adjacent story. These limits are based in part on analytical (e.g., Humar and Wright 1977; Costa et al. 1988; Esteva 1992; Valmundsson and Nau 1997) and experimental (e.g., Moehle 1984; Wood 1992) studies. Most previous investigations collectively pinpoint significantly altered drift and ductility demands in the vicinity of structural irregularities. Recent parametric studies on two-dimensional (2D) generic

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[1] PhD Candidate, Dept. of Civil and Env. Engineering, University of California Davis, Davis, CA 95616.

[2] Professor, Dept. of Civil and Env. Engineering, University of California Davis, Davis, CA 95616.

frames by Al-Ali and Krawinkler (1998), and code-compliant 2D special-moment-resisting-frames (SMRFs) by Das and Nau (2003) provide more insight into the influences of variation of vertical irregularity along the height on seismic performance of buildings when subjected to different types of ground motions.

In recognition of the fact that the behavior of vertically irregular structures can be significantly different compared to regular structures, seismic design provisions recommend dynamic analysis methods (i.e., modal or time-history analysis) to compute design forces in lieu of the equivalent lateral force (ELF) procedure which is essentially applicable only for regular structures with uniform distributions of mass, stiffness and strength over the height. In addition to issues related to design of vertically irregular buildings, the seismic performance assessment of such buildings also requires special attention. For regular low-rise buildings (with dominant first mode response), nonlinear static procedures (NSPs) recommended in FEMA-356, now increasingly used in engineering practice in U.S., yield reasonable approximation of critical seismic demand parameters (such as interstory drift, member plastic rotations etc.). However, for irregular structures, Chopra and Chintanapakdee (2004) have recently demonstrated that FEMA invariant load distributions (i.e., First mode, ELF, SRSS and Uniform) are systematically biased in predicting story drifts when compared to “exact” NTH analyses results. In their study, they considered generic frames having different heights and three types of irregularity resulting from stiffness, strength and stiffness-strength considerations, and demonstrated that the statistical dispersion in demand estimates compared to exact NTH simulations was lower for Modal Pushover Analysis than FEMA-based methods.

This paper examines the accuracy of the recently developed Adaptive Modal Combination (AMC) procedure to estimate critical seismic demand parameters in vertically irregular buildings. The AMC procedure is a direct multi-modal pushover methodology that integrates concepts incorporated in the capacity spectrum method recommended in the ATC-40 (1996), the direct adaptive method originally proposed by Gupta and Kunnath (2000) and the modal pushover analysis advocated by Chopra and Goel (2002). The AMC procedure eliminates the need to estimate the target displacement prior to commencing the pushover analysis by proposing the concept of a dynamic target point which is progressively updated during the process of loading. Energy-based modal capacity curves are used in conjunction with inelastic spectra to compute modal performance points (i.e., target points).

The procedure is systematically evaluated in this study for vertically irregular generic frames having different heights. The systems considered in this study are 5, 10 and 15 story SMRFs that represent mass irregularity and vertical geometric irregularity (i.e., setback) according to current IBC limitations. The buildings were designed in compliance with code requirements. A total of ten different building models were created to examine the effects of location of irregularity along the height on salient response characteristics of buildings. Each building model was subjected to a set of ten near-fault forward directivity ground motions. Comparisons of demand predictions by AMC procedure with benchmark responses obtained from NTH analyses indicate that the AMC procedure is able to provide reasonable prediction of fundamental response quantities including roof drift, interstory drift and member plastic rotations.

Description of Buildings and Analytical Models

The primary lateral load resisting system for the buildings considered in this study are steel moment frames. Generic SMRFs with heights corresponding to 5, 10 and 10 stories and each having four bays with a bay size of 5.5 m are analyzed. Except for the first floor which is 5.5 m high, the remaining floors of each frame have a height of 3.0 m. The following two types of vertical irregularities, as specified in IBC, comprise the primary variables evaluated herein.

- Mass Irregularity: is considered to exist if the effective mass of any story is more than 150 percent of an adjacent story. A roof that is lighter than the floor below is excluded from this consideration.
- Vertical Geometric Irregularity (Setback): is considered to exist where the horizontal dimension of the lateral-force-resisting system in any story is more than 130 percent of that in an adjacent story.

In order to create a system which meets the first criterion, the first and fifth story mass values were doubled respectively to generate two cases of mass irregularity for the 5-story building. In a similar fashion, the first, fifth and tenth story mass values were doubled respectively to generate 3 cases for the 10-story building. In the case of the 15-story building, mass values were magnified by a factor of 2.0 at the first, seventh and fifteenth story levels. In order to create vertical geometric irregularity, setbacks at the second and fifth story levels were introduced in the 10-story building models. As a result, a total of 10 vertically irregular frame models (i.e., 8 with mass irregularity and 2 with vertical setbacks) were generated. Figure 1 displays the different configurations considered in the study.

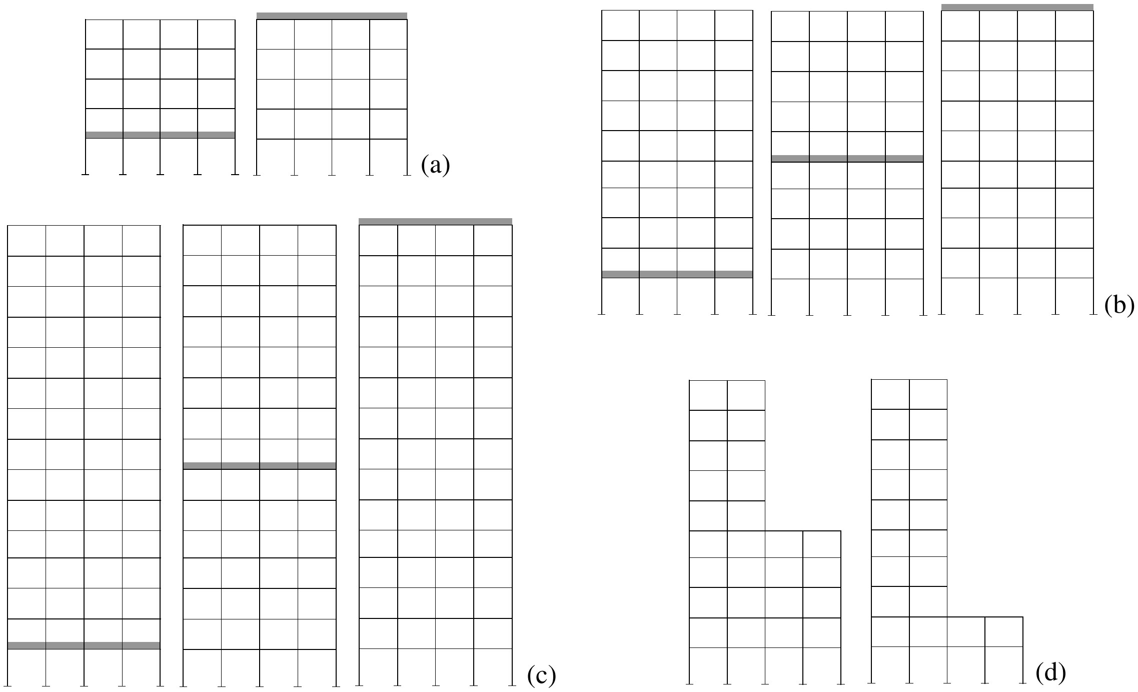
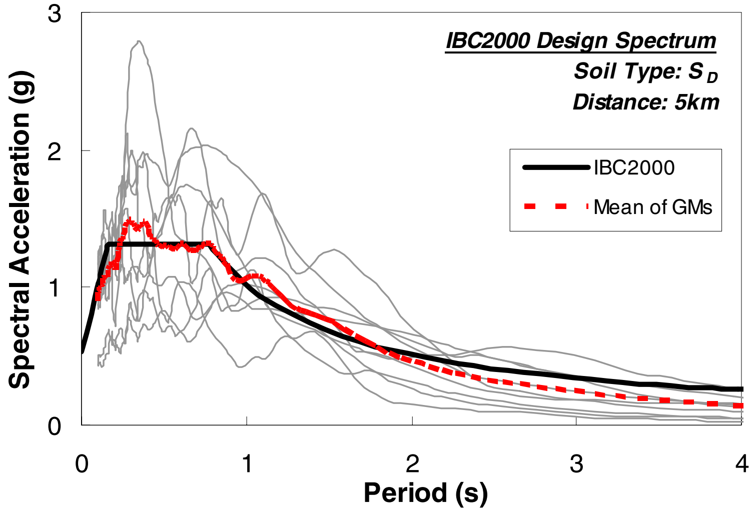


Figure 1. SMRFs used in this study: (a) 5-story, (b) 10-story, (c) 15-story (shaded floor indicates the location of mass irregularity) and (d-e) 10-story setback frames.

All frames were designed in a region of high seismicity with soil-type “D” and located about 5 km from causative fault (see Figure 2 for the respective IBC spectrum, and corresponding design coefficients to compute the base shear). The designs satisfy the strong column-weak beam requirement of the code and the size and shape of beams and columns were chosen to satisfy code drift limitations.



IBC coefficients for computing design base shear:

Z = 0.4, Source Type = A
Cv = 1.02, Ca = 0.53
Na = 1.2, Nv =1.6
I = 1.0, R = 8.5

Figure 2. IBC design spectrum together with acceleration spectra of near-fault forward directivity records, and IBC coefficients used to compute design base shear.

All frame structures were modeled as two-dimensional systems using the open source finite element platform, OpenSees (2005). Beam and columns were modeled as nonlinear elements with section properties specified using a fiber discretization at five integration points along the member length. A non-degrading bilinear material model with yield strength of 50 ksi and 2 percent strain hardening was assumed for all structural elements. Raleigh damping was assumed at 5 percent of critical for the first and third modes for the 5-story frame, and for the first and fourth modes for the remaining frames.

Ground Motion Data

Each structural model was subjected to a set of ten near-fault forward directivity motions. Acceleration time series from recent major Californian earthquakes were carefully compiled so that the mean acceleration spectrum of the selected records matches the IBC design spectrum across a wide range of spectral periods. In addition, each individual record satisfies the soil and distance constraints of the design spectrum. Records were therefore used in their original form without scaling. Relevant information on the selected ground motions is listed in Table 1, while the acceleration spectra, the mean spectrum of all records together with the IBC design spectrum are shown in Figure 2.

Table 1. Ground motion dataset

No	Year	Earthquake	M_W	Mech.[1]	Recording Station	Dist.[2] (km)	Data Source[3]	Comp.	PGA (g)	PGV (cm/sec)
1	1989	Loma Prieta	7.0	OB	Capitola	8.6	1	000	0.53	35.0
2	1994	Northridge	6.7	TH	Rinaldi Rec. Stn.	8.6	2	S49W	0.84	174.8
3	1994	Northridge	6.7	TH	Jensen Filt. Plant	6.2	1	022	0.42	106.3
4	1994	Northridge	6.7	TH	Slymar Converter Sta East	6.1	1	018	0.83	117.5
5	1994	Northridge	6.7	TH	Slymar Converter Sta.	6.2	1	142	0.90	102.2
6	1994	Northridge	6.7	TH	Sepulveda Va. Hospital	9.5	1	270	0.75	85.3
7	1994	Northridge	6.7	TH	Sylmar Olive View Hospital	6.4	1	360	0.84	130.4
8	1994	Northridge	6.7	TH	Newhall LA Fire Stn.	7.1	1	360	0.59	96.4
9	1994	Northridge	6.7	TH	Newhall Pico Canyon	7.1	1	046	0.45	92.8
10	2004	Parkfield	6.0	SS	Fault Zone 1	5.0	2	360	0.82	81.2

[1] *Faulting Mechanism = TH: Thrust; SS: Strike-slip; OB: Oblique;*

[2] *Closest distance to fault*

[3] *Data Source = 1: PEER (http://peer.berkeley.edu/smcat); 2: Cosmos (http://db.cosmos-eq.org)*

Adaptive Modal Combination (AMC) Procedure

The AMC procedure was developed in an effort to overcome some of the inherent limitations and drawbacks of current nonlinear static procedures. It integrates many features of existing pushover procedures such as the consideration of higher mode effects by combining the response of individual modal pushover analyses, and the issue of changing modal properties during the inelastic response by using adaptive load vectors as the analysis progresses. One of the more unique aspects of the procedure is that the target displacement is estimated and updated dynamically during the analysis by incorporating energy based modal capacity curves with inelastic demand measures.

The basic steps of the methodology are summarized below:

1. Compute the modal properties of the structure (i.e., natural frequencies, $\omega_n^{(i)}$, mode-shapes, $\phi_n^{(i)}$, and modal participation factors, $\Gamma_n^{(i)}$) at the current state of the system.
2. For the n^{th}-mode considered, construct the adaptive lateral load pattern, $s_n^{(i)} = \mathbf{m}\phi_n^{(i)}$, where *(i)* is the step number of the incremental adaptive pushover analysis, **m** is the mass matrix of the structure and $\phi_n^{(i)}$ is the mode shape vector. The load distribution ($s_n^{(i)}$) should be recomputed as the properties of the system change due to inelastic action.
3. Construct the capacity curve for each equivalent SDOF (ESDOF) system using the energy based approach in which the increment in the energy based displacement of the ESDOF system, $\Delta D_n^{(i)}$ can be obtained as, $\Delta D_n^{(i)} = \Delta E_n^{(i)} / V_{b,n}^{(i)}$, where $\Delta E_n^{(i)}$ is the increment of work done by lateral force pattern, $s_n^{(i)}$ acting through the displacement increment, $\Delta d_n^{(i)}$, associated with a single step of the n^{th}-mode pushover analysis. $V_{b,n}^{(i)}$ is the base shear which is equal to sum of the lateral forces at the i^{th} step. The spectral displacement, $S_{d,n}^{(i)}$ of the ESDOF system (i.e., abscissa of the ESDOF capacity curve) at any step of n^{th}-mode pushover analysis is obtained by the summation of $\Delta D_n^{(i)}$. The

ordinate of the ESDOF capacity curve is $S_{a,n}^{(i)} = V_{b,n} / (\alpha_n^{(i)} W)$, where $\alpha_n^{(i)}$ is the modal mass coefficient computed at the i^{th} step of the n^{th}-mode pushover analysis.

4. If the response is inelastic for the i^{th} step of the n^{th}-mode pushover analysis, calculate the approximate global system ductility ($\mu_n^{(i)} = S_{d,n}^{(i)} / S_{d,n}^{(yield)}$), and post-yield stiffness ratio from modal capacity curve. Post-yield stiffness ratio ($\lambda_n^{(i)}$) can be approximated using bilinear representation.
5. For the site-specific ground motion to be used for evaluation, compute the damped (ζ_n) inelastic response spectral acceleration $S_{a,n}(\mu, \zeta_n, \lambda_n)$ and spectral displacement spectra $S_{d,n}(\mu, \zeta_n, \lambda_n)$ for a series of predefined ductility levels. This step is required to calculate the energy based dynamic target displacement. If there is a significant change in spectrum parameters of λ_n and ζ_n between two inelastic consecutive steps of the pushover analysis, inelastic spectra for a series of predefined ductility levels may be re-generated considering updated parameters.
6. Plot $S_{a,n}^{(i)}$ versus $S_{d,n}^{(i)}$ (i.e., modal capacity curve from Step 3) together with the inelastic demand spectra (from Step 5) at different ductility levels. The dynamic target point, D_n^{ip} for the n^{th}-mode pushover analysis is the intersection of ESDOF modal capacity curve with the inelastic demand spectrum corresponding to the global system ductility. With the known dynamic target point for the n^{th}-mode pushover analysis, the global system roof displacement can be computed as $u_{r,n}^{(ip)} = D_n^{ip} \phi_{r,n}^{(ip)} \Gamma_n^{(ip)}$, where (*ip*) is the step-number in the incremental pushover analysis at which the dynamic target point is captured.
7. Extract the values of response parameters ($r_n^{(ip)}$) desired (e.g., displacements, story drifts, member rotations, etc.) at the ip^{th} step of the n^{th}-mode pushover analysis.
8. Repeat Steps 1-7 for as many modes as deemed essential for the system under consideration. The first few modes are typically adequate for most low to medium rise buildings. The total response is determined by combining the peak modal responses using any appropriate combination scheme such as SRSS.

Validation of the AMC Procedure for Irregular Frames

The validation process consists of comparing the peak interstory drift demands predicted by AMC procedure with those computed from nonlinear time-history analyses. The AMC procedure was applied to each of the 10 SMRF models for each of the 10 ground motions separately. This means that inelastic acceleration and displacement spectra for each record are computed and utilized in individual pushover analysis. Figure 3 presents the mean, 16 and 84 percentile response data of peak interstory drift profiles for the 5, 10 and 15-story frames with mass irregularities subjected to near-fault records. Also shown in the figure are response estimates computed using the proposed AMC procedure. In all cases, it is seen that the AMC procedure approximates the mean drift demands over the height of the frames with dispersion comparable to NTH analyses.

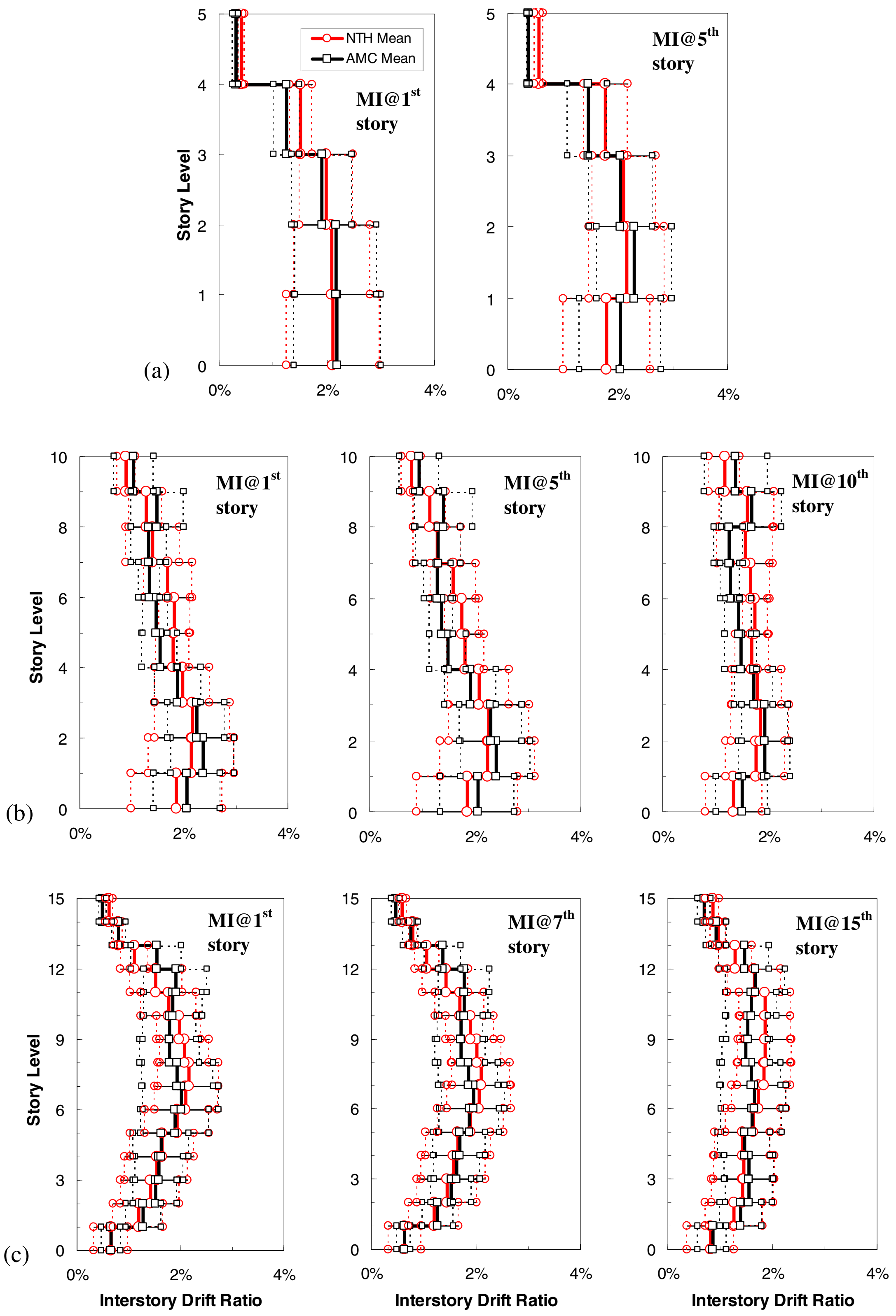


Figure 3. Comparison of AMC-predicted peak interstory drift profiles with NTH analyses (a) 5-story, (b) 10-story and (c) 15-story SMRFs with mass irregularity (MI) at various story levels.

Figure 4 compares the drift demands computed using NTH analyses with those predicted by the AMC procedure for 10-story frames having two types of setbacks. In case of setback at the second story, the AMC procedure yields almost identical drift profiles as those from NTH simulations. For the frame with the setback at fifth story, the AMC procedure overestimates the lower level drift values up to third story; however the drift profile above this level compare very favorably with NTH estimates. The dispersion in the demand estimates (indicated by the 16 and 84 percentile values) are comparable again to NTH analyses.

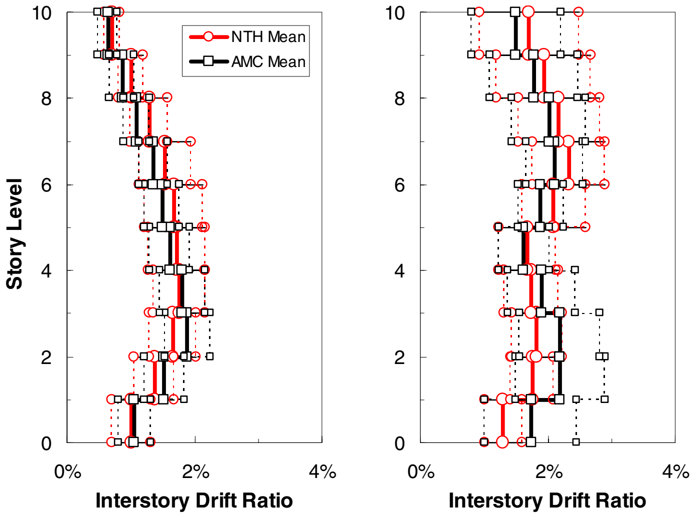


Figure 4. Peak interstory drift profiles predicted by AMC and NTH analyses for 10-story frames having setback at second story level (left) and fifth story level (right).

In the results summarized in Figures 3 and 4, the AMC procedure was applied to each frame model considering each excitation independently. Hence inelastic spectra were generated for each record and as many simulations as NTH analyses were carried out. To investigate a more practical application, the AMC procedure was applied to the structural models by considering only a single spectrum: in this case, the mean inelastic spectra of ground motions computed at pre-defined ductility levels were utilized. Figure 5 compares the difference in the predictions of these two approaches compared to NTH analyses for the 15-story frame having mass irregularity at the seventh story, and the 10-story frame with setback at the second story. Prediction errors were computed by considering the difference in inter-story drift ratios (IDR) between AMC estimates and the mean of NTH analyses. Figure 5 shows, as expected, that using inelastic spectra of individual records yield better estimates (as indicated by lower dispersion) than using a mean spectrum. However, with the objective of minimizing computational effort, the use of mean inelastic spectra of a set of records is still satisfactory and is able to predict demands without appreciable loss of accuracy compared to NTH analyses.

Results of the study indicate that increased mass at the upper story levels exacerbates the contribution of higher modes and results in migration of demands from lower stories to upper levels. Similar effects are also observed for setback buildings, wherein the setback at the fifth story results in increased drift demands concentrated at the sixth story where a sudden change in stiffness is located. Increasing the mass at the first story level for the 5, 10 and 15-story buildings does not produce appreciably larger drift at or adjacent to this story level.

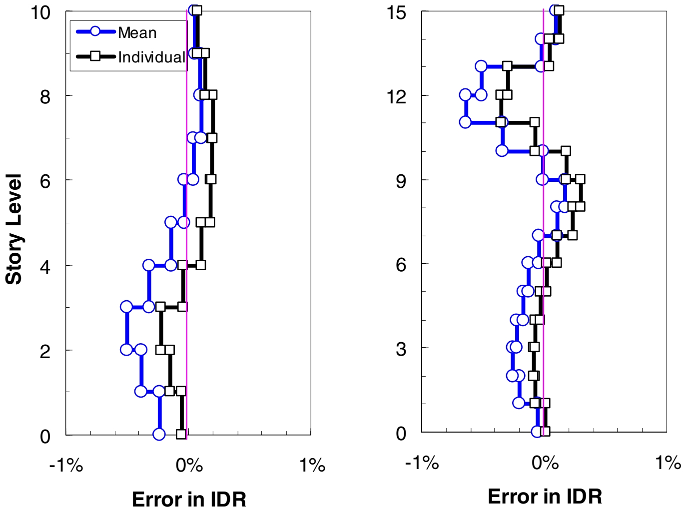


Figure 5. Comparison of error in interstory drift (IDR) demands utilizing “individual” spectrum for each record (1 simulation per record) and “mean” spectra of all records (1 simulation for all records) *LEFT: 10-story frame with setback at second story level; RIGHT: 15-story frame with mass irregularity at seventh story level.*

It should also be noted that lateral inter-story drifts are limited to 2 percent in the design of frames. Despite the fact that all records are consistent with the design spectrum in terms of soil type and fault distance parameters, many individual near-fault excitations produced demands in excess of this limit at several story levels. This raises the question on the effectiveness of the near-source amplification factors (i.e., N_a and N_v) to account for the impulsive effect of near-fault ground motions. Since these factors which are used to amplify the elastic design spectrum were originally developed using far-fault ground motions, a reexamination of these amplification factors is needed.

Conclusions

This paper evaluates the accuracy of the recently developed AMC procedure in predicting the seismic response of vertically irregular (mass irregularity or vertical setbacks) steel moment frames subjected to near-fault forward directivity records. By including the contributions of a sufficient number of modes of vibration (generally two to three), it is demonstrated that the proposed AMC procedure is able to estimate interstory drift profiles with acceptable accuracy when compared to results from NTH analyses. The validation of the AMC procedure has now been applied to both regular (see Kalkan 2005) and irregular frames and these studies suggest that the method is a promising alternative to several advanced pushover techniques for seismic assessment of moment frame structures.

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