Adaptive Modal Combination Procedure for Nonlinear Static Analysis of Building Structures

Erol Kalkan, S.M.ASCE[1]; and Sashi K. Kunnath, M.ASCE[2]

Abstract: A new pushover analysis procedure derived through adaptive modal combinations (AMC) is proposed for evaluating the seismic performance of building structures. The methodology offers a direct multimode technique to estimate seismic demands and attempts to integrate concepts built into the capacity spectrum method recommended in ATC-40 (1996), the adaptive method originally proposed by Gupta and Kunnath (2000) and the modal pushover analysis advocated by Chopra and Goel (2002). The AMC procedure accounts for higher mode effects by combining the response of individual modal pushover analyses and incorporates the effects of varying dynamic characteristics during the inelastic response via its adaptive feature. The applied lateral forces used in the progressive pushover analysis are based on instantaneous inertia force distributions across the height of the building for each mode. A novel feature of the procedure is that the target displacement is estimated and updated dynamically during the analysis by incorporating energy-based modal capacity curves in conjunction with constant-ductility capacity spectra. Hence it eliminates the need to approximate the target displacement prior to commencing the pushover analysis. The methodology is applied to two existing steel moment-frame buildings and it is demonstrated that the AMC procedure can reasonably estimate critical demand parameters such as roof displacement and interstory drift for both far-fault and near-fault records, and consequently provides a reliable tool for performance assessment of building structures.

DOI: 10.1061/(ASCE)0733-9445(2006)132:11(1721)

CE Database subject headings: Nonlinear analysis; Seismic effects; Drift; Earthquake engineering; Model analysis.

Introduction

The introduction of performance based earthquake engineering concepts into recent guideline documents such as ATC-40 (1996) and FEMA-356 (ASCE 2000) has led to increased utilization of nonlinear static methods to estimate seismic demands. Recently, the capacity spectrum method (CSM) of ATC-40 has been adapted as a seismic evaluation method in the Japanese structural design code for buildings (Ministry of Land, Infrastructure and Transport 2001), and the N2 method (a special form of the CSM in which the demand is represented by an inelastic spectrum) has been implemented in the draft of Eurocode-8 (CEN 2001). Both CSM and the N2 method rely on a pushover analysis using invariant lateral load patterns to estimate deformation demands under seismic loading. However, these simplified approaches to predict seismic demands are known to have major drawbacks (Kunnath and Kalkan 2004; Goel and Chopra 2004). Several researchers (Chopra and Goel 2002; Jan et al. 2003) have proposed enhanced pushover procedures to account for higher mode effects while retaining the simplicity of invariant load patterns. These improved procedures utilize the concept of modal combinations either through a single pushover analysis where the load vectors reflect the contributions from each elastic mode-shape considered or through multiple pushover analyses using invariant load patterns based on elastic mode shapes where the contribution from each mode is combined at the end. Recently, a modified version of MPA (MMPA) has been proposed in which the inelastic response obtained from first-mode pushover analysis has been combined with the elastic contribution of higher modes (Chopra et al. 2004). In order to investigate alternative schemes to represent realistic lateral force demands, a new lateral load configuration using factored modal combinations has been developed by Kunnath (2004), and evaluated for various steel building structures (Kalkan and Kunnath 2004a,b). All these enhanced procedures have been shown to provide improved estimates of interstory drift values compared to conventional nonlinear static-procedures (NSPs) using inverted triangular, uniform, or other lateral load patterns based on direct modal combination rules suggested in FEMA-356 (ASCE 2000).

The invariant load patterns used in the above-referenced procedures are based on the initial elastic dynamic properties of the structure. In order to incorporate changes in the modal attributes of the structure during the inelastic phase, Gupta and Kunnath (2000) proposed an adaptive pushover procedure based on an elastic demand spectrum. In this procedure, conventional response spectrum analysis is essentially being applied at each pushover step. Several other displacement and force based pushover procedures considering progressive change in dynamic attributes of structures have also been proposed (Elnashai 2000; Antonio et al. 2002; Aydinoglu 2003; Antonio and Pinho 2004).

Finally, the estimation of target displacement in ATC-40 (1996) or FEMA-356 (ASCE 2000), or even methods used by the enhanced procedures pose numerous limitations. Although ATC-40 uses equivalent linearization and FEMA-356 uses the

[1]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, CA 95616.

[2]Professor, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, CA 95616.

Note. Associate Editor: Marvin W. Halling. Discussion open until April 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on May 31, 2005; approved on February 24, 2006. This paper is part of the ***Journal of Structural Engineering***, Vol. 132, No. 11, November 1, 2006. ©ASCE, ISSN 0733-9445/2006/11-1721–1731/$25.00.

displacement coefficient method, enhanced pushover procedures (e.g., Chopra and Goel 2002; Jan et al. 2003; Chopra et al. 2004) either use an elastic spectrum with elastic modal periods or inelastic ESDOF (equivalent single-degree-of-freedom) dynamic responses to approximate the target displacement. It has been shown that the target displacement computed using ATC-40 or FEMA-356 can be not only significantly different from each other but also significantly different from response history analysis for short period structures (Miranda and Akkar 2002). To resolve such inconsistencies, improvements have been made in CSM and displacement coefficient method which are reported in the recently released FEMA-440 (ATC 2005). Further, in the case of near-fault records these approximate methods as well as the other approaches based on the equal displacement rule may not be applicable for the period range of low- to mid-rise buildings. Another limitation stems from the assumption that the roof displacement is assumed to be representative of the ESDOF system response. The roof displacement as a parameter to convert the multiple degree-of-freedom (MDOF) system to ESDOF system is only meaningful for the first mode. It has been recently shown by Hernandez-Montes et al. (2004) that using roof displacement as the target parameter to obtain the ESDOF system properties of MDOF structure may lead to erroneous results and proceed to propose an energy-based representation of the capacity curve that overcomes some of the aforementioned problems. Though energy-based computation of the capacity curve has been implemented in MPA in their article, other issues still remain because the inelastic system properties are still obtained from elastic modal attributes, and using invariant load patterns are not compatible with the progressive yielding of the structure during the pushover analysis.

Recognizing the merits and limitations of existing methodologies, a new adaptive pushover technique referred to as the adaptive modal combination (AMC) procedure is developed in this paper. The AMC procedure derives its fundamental scheme from the adaptive pushover procedure of Gupta and Kunnath (2000) by recognizing the need to modify applied lateral loads as the system responds to the applied earthquake load. The proposed methodology also integrates the inherent advantages of the capacity spectrum method and the modal pushover procedure, and at the same time eliminating the need to pre-estimate the target displacement. The accuracy of the approach is validated by comparing predictions using the proposed method with estimates obtained from a comprehensive set of nonlinear time-history (NTH) analyses.

Development of the AMC Procedure

The primary feature of adaptive schemes is the updating of the applied story forces with respect to progressive changes in the modal properties at each step. This allows progressive system degradation due to inelastic deformations to be represented more realistically in a static framework. The original adaptive method proposed by Gupta and Kunnath (2000) is a load-controlled procedure in which load increments are scaled at each pushover step using elastic spectral accelerations ($S_{\mathrm{ae}}^{(i)}$) based on the instantaneous dynamic properties of the system. In the proposed new procedure, a displacement-controlled method is used in which the demand due to individual terms in the modal expansion of the effective earthquake forces is determined by individual adaptive pushover analyses using the inertia distribution of each mode, which is continuously updated during the process of loading. Unlike the adaptive scheme of Gupta and Kunnath (2000) where the contributions of each mode are combined at the end of each step using square-root-of-sum-of-squares (SRSS), in the proposed scheme the total seismic demand of the system is obtained at the end of the analysis by combining the individual responses using SRSS.

Basic Elements of the Procedure

The development of the AMC procedure is motivated by the need to synthesize key elements of advanced pushover methods that have independently addressed different drawbacks identified in simplified pushover procedures. The primary concepts that have been both integrated and enhanced in the proposed methodology include:

- Establishing the target displacement: An energy-based procedure is used in conjunction with inelastic displacement spectra (expressed in spectral acceleration vs. displacement format) at a set of predetermined ductility levels to progressively establish the target displacement as the modal pushover analyses proceed.
- Dynamic target point: This concept is analogous to the performance point in CSM, however, it represents a more realistic representation of demand since inelastic response measures are used to target this demand point.
- Adaptive modal combination: Finally, the method recognizes the need to alter the applied lateral load patterns as the system characteristics change yet retain the simplicity of combining the response measures at the end of the analysis.

Details of the conceptual elements of the process are described in the following sections.

Energy-Based Incremental Modal Displacement

The determination of the target displacement is a key element in a static pushover procedure. The displacement coefficient method in FEMA-356 (ASCE 2000) approximates the target displacement by modifying the elastic single degree-of-freedom demand through a set of coefficients that account for MDOF effects, inelastic behavior, degrading effects and dynamic P-delta effects. In ATC-40 (1996), the target displacement is embedded in the capacity spectrum method wherein the pushover curve is transformed into acceleration displacement response spectrum (ADRS) format (i.e., spectral acceleration versus spectral displacement). By overlapping the transformed capacity curve with an equivalent damped elastic spectrum, the performance point can be estimated in an iterative manner and converted into roof displacement of the equivalent MDOF system. The following relationships convert the MDOF capacity curve coordinates into ADRS format:

$$S_{a,n} = \frac{V_{b,n}}{W\alpha_n} \tag{1}$$

$$S_{d,n} = \frac{u_{r,n}}{\Gamma_n \phi_{r,n}} \tag{2}$$

$$\Gamma_n = \frac{\boldsymbol{\phi}_n' \mathbf{m} \boldsymbol{\iota}}{\boldsymbol{\phi}_n' \mathbf{m} \boldsymbol{\phi}_n} \tag{3}$$

where $S_{a,n}$ and $S_{d,n}$ stand for spectral acceleration and spectral displacement, respectively, corresponding to a specific period and a fixed viscous damping ratio for the nth mode considered; W=total weight; $V_{b,n}$=base shear; and α_n=modal mass coefficient ($\alpha_n=(\boldsymbol{\phi}_n'\mathbf{m}\boldsymbol{\iota})^2/[(\boldsymbol{\phi}_n'\mathbf{m}\boldsymbol{\phi}_n)\Sigma_n m_n]$). $u_{r,n}$ stands for the roof displace-

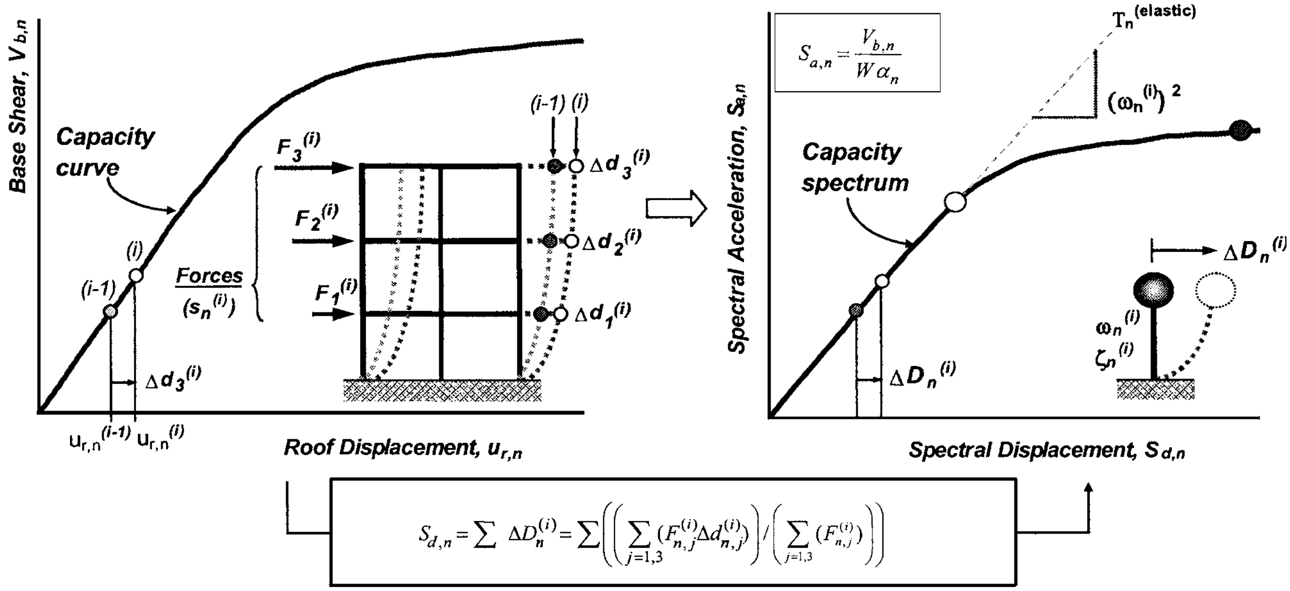

Fig. 1. Energy-based ESDOF system representation of *n*th mode MDOF system capacity curve

ment obtained from the nth-mode pushover analysis, $\phi_{r,n}$ and Γ_n are, respectively, the roof component of the nth-mode shape and the modal participation factor; $\mathbf{m}$=mass matrix; and $\boldsymbol{\iota}$=influence matrix. In ATC-40, n is restricted to the first mode only. It is therefore reasonable to conclude that the peak response quantities associated with the multimode effects cannot be correctly predicted with a conversion technique based on a single-mode response (Akkar et al. 2004).

On the other hand, in a multimode procedure such as the modal pushover analysis (MPA) introduced by Chopra and Goel (2002), the target displacement is obtained through converting the MDOF response into a series of bilinear ESDOF responses for the first n modes. It essentially extends the ATC-40 concept to multiple modes to determine the ESDOF system parameters for each mode considered. An inelastic dynamic analysis is carried out on each ESDOF system and the pertinent maximum inelastic spectral displacement demand can be obtained, and transformed back to a target displacement ($u_{n,r}$) as follows:

$$u_{r,n} = \phi_{r,n}\Gamma_n S_{d,n} \tag{4}$$

The basic limitation of this approach is that elastic modal properties are used to compute the inelastic system parameters, and the procedure may necessitate several iterations for convergence of target displacement computed from inelastic dynamic analysis. Another potential limitation arises from the fact that the roof displacement is approximated from the maximum deformation of an ESDOF system. Such an approach is only meaningful for the first mode, whereas for higher modes, the roof displacement does not proportionally change with the other story deformations, therefore use of the roof displacement as the pivotal parameter for the ESDOF representations may yield erroneous predictions of the target displacement. In recognition of this fact, an energy-based concept has been utilized to represent the MDOF system parameters in an ESDOF system corresponding to each individual mode. In the energy-based approach proposed by Hernandez-Montes et al. (2004), the abscissa of the capacity curve of the ESDOF system is determined based on the work done at each story level (j) through each incremental displacement ($\Delta d_{j,n}^{(i)}$) during the pushover analysis (see Fig. 1). The total energy increment is divided by the base shear at each step to find the incremental displacement ($\Delta D_n^{(i)}$). Hence, the sum of the incremental displacements gives the resultant displacement of the ESDOF system (i.e., spectral displacement, $S_{d,n}^{(i)}$) at any given step (i) of the pushover analysis.

For the adaptive approach proposed in this paper, it was found that the energy-based formulation results in more stable and smooth capacity curves. Another benefit of the energy formulation is that it eliminates the reversal of the higher mode capacity curves that have been observed for second and third mode pushover analyses when the roof displacement is utilized as the index parameter (Tjhin et al. 2004).

Constant-Ductility Capacity Spectra and Dynamic Target Point

A key aspect of the proposed procedure is that a set of capacity spectra based on a series of predetermined ductility levels are used for each mode to approximate the displacement demand (referred to as the *dynamic target point*). Studies conducted by the authors indicate that the increment at which the spectra should be generated is optimal at $\Delta\mu$=0.25 (meaning ductility levels of 1.0, 1.25, 1.50, etc.) though an interval of 0.5 used in many of the simulations presented in this paper was generally adequate. The peak modal inelastic spectral acceleration ($S_{a,n}^{(i)}$) and displacement ($S_{d,n}^{(i)}$) of the equivalent system associated with the instantaneous configuration of the structure is computed using the energy approach described previously. The constant-ductility capacity spectra are computed based on ESDOF system properties which can be obtained from bilinearization of modal capacity curve. As the yield displacement and postyield stiffness ratio are undetermined until the capacity curve is established, a preliminary pushover analysis using a fixed postyield stiffness (or even an elastic-perfectly plastic model) can be carried out to establish these parameters. These preanalysis estimates should be modified at the end of the next iteration of the pushover analysis and the process repeated until a stable yield point and postyield stiffness are established. In each case, it will also be necessary to regenerate the constant ductility capacity spectrum curves using updated parameters. To this extent, the proposed method is an iterative proce-

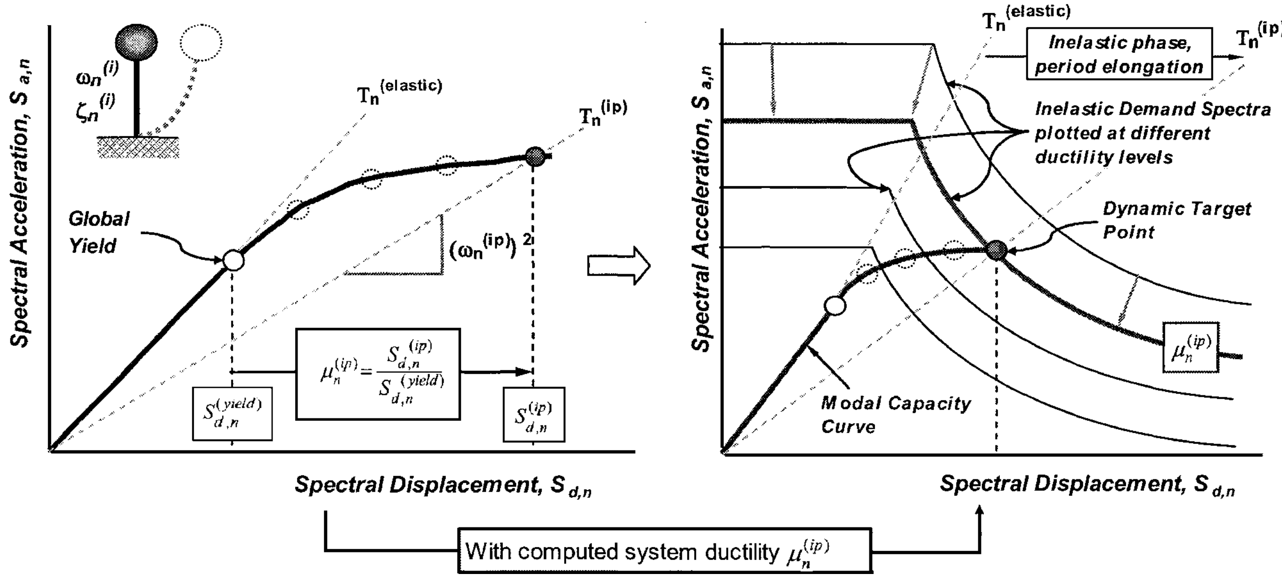

Fig. 2. Performance point evaluation using system ductility through a set of inelastic spectra

dure which requires proper calibration of the capacity curves prior to the generation of the final pushover curve.

The intersection of the modal capacity at the current state of the system and the demand spectrum (in spectral acceleration and spectral displacement format) satisfying approximately the same ductility level (as displayed in Fig. 2) represents the associated dynamic target point. This energy-based dynamic target displacement ($S_{d,n}^{(ip)}$) can be back translated from ESDOF to MDOF using the instantaneous modal properties ($\phi_{r,n}$ and Γ_n) of the system as follows:

$$u_{r,n}^{(ip)} = \phi_{r,n}^{(ip)} \Gamma_n^{(ip)} S_{d,n}^{(ip)} \tag{5}$$

Within the adaptive framework, the changing modal attributes of the inelastic system is dynamically updated during the progress of the pushover analysis, and constant-ductility capacity spectra are used to compute the dynamic target displacements for each mode considered. The dynamic target point evaluation described earlier is illustrated in Fig. 2 considering only a single mode response. At any step (i) in the modal pushover analysis (an ADRS plot for mode n is shown in Fig. 2), the equivalent ductility (identified as $\mu_n^{(i)}$ in Fig. 2) is determined. The target displacement is achieved when an intersection point is located on the constant ductility spectra. In the conceptual illustration in Fig. 2, a possible intersection at a known ductility is identified as the "dynamic target point." Such a process can be extended to as many modes as necessary.

Adaptive Modal Combination

Finally, the methodology retains the fundamental premise of adaptive methods by updating the modal vectors as often as necessary to capture the variation in the dynamic characteristics of the building. In the implementation presented in this paper, the modal vectors are updated every time an element changes state. Practically speaking, it is possible to define threshold limits during the analysis by monitoring the relative changes in modal shapes from one step to the next. Likewise, the simplicity of the modal pushover procedure is incorporated into the procedure by carrying out the response analysis of each mode separately. Peak modal quantities of interest obtained at the end of each adaptive pushover analysis for each mode are combined using a combination rule. The SRSS combination rule is typically valid if the predominant modal frequencies are well separated whereas the complete quadratic combination (CQC) may be more appropriate for systems having closer modes.

The AMC Procedure

The proposed procedure, like all pushover methods, depends on the development of an adequate simulation model of the building system. This step is a function of the analytical tool being used in the nonlinear analysis. Once a reasonable mathematical (simulation) model is developed, the earthquake loading is specified by means of a response spectrum. The procedure consists of a series of step-by-step computations with systematic updates being performed at the end of each step, as follows:

1. Compute the modal properties of the structure (i.e., natural frequencies, $\omega_n^{(i)}$, mode shapes, $\boldsymbol{\phi}_n^{(i)}$, and modal participation factors, $\Gamma_n^{(i)}$) at the current state of the system.
2. For the nth mode considered, construct the adaptive lateral load pattern as follows:

$$s_n^{(i)} = \mathbf{m}\boldsymbol{\phi}_n^{(i)} \tag{6}$$

where (i) is the step number of the incremental adaptive pushover analysis and $\mathbf{m}$=mass matrix of the structure. The load distribution ($s_n^{(i)}$) can be recomputed at every step or at a set of predefined steps following an eigenvalue analysis based on the current stiffness properties of the system. As an eigenvalue analysis can be computationally demanding, the frequency with which the load vector is updated should be established prudently with the objective of balancing computational efficiency and solution accuracy.

3. Evaluate the next incremental step of the capacity curve for each 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

$$\Delta D_n^{(i)} = \Delta E_n^{(i)} / V_{b,n}^{(i)} \tag{7}$$

where $\Delta E_n^{(i)}$=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 nth-mode pushover analysis. $V_{b,n}^{(i)}$=base shear which is equal to sum of the lateral forces at the ith step. The spectral displacement, $S_{d,n}^{(i)}$ of the ESDOF system (i.e., abscissa of the ESDOF capacity curve) at any step of nth-mode pushover analysis is obtained by the summation of $\Delta D_n^{(i)}$. The ordinate of ESDOF capacity curve is classically determined as follows:

$$S_{a,n}^{(i)} = V_{b,n}/(\alpha_n^{(i)} W) \tag{8}$$

where $\alpha_n^{(i)}$=modal mass coefficient computed at the ith step of the nth-mode pushover analysis (see Fig. 1 for exemplified computation of $S_{a,n}^{(i)}$ and $S_{d,n}^{(i)}$)

4. If the response is inelastic for the ith step of the nth-mode pushover analysis, calculate the approximate global system ductility ($\mu_n^{(i)} = S_{d,n}^{(i)} / S_{d,n}^{\text{yield}}$), and postyield stiffness ratio from modal capacity curve (see Fig. 2). Postyield stiffness ratio ($\lambda_n^{(i)}$) can be approximated using a bilinear representation. If the pushover curve exhibits negative postyield stiffness, the second stiffness of the bilinear curve would be negative. As described previously, the inelastic parameters (yield point and postyield stiffness) are yet unknown in an incremental procedure. Hence, it is typically necessary to carry out a preliminary (or dummy) pushover analysis, using adaptive force distributions and the energy-based displacement increments but not being concerned with a target displacement, to establish these parameters.
5. For the site-specific ground motion to be used for evaluation, generate the capacity spectra in ADRS format (spectral acceleration $S_{a,n}(\mu,\zeta_n,\lambda_n)$ versus spectral displacement $S_{d,n}(\mu,\zeta_n,\lambda_n)$) for a series of predefined ductility levels. This step is required to calculate the energy-based dynamic target displacement. The generation of these spectra requires the calibration of the capacity curve to establish the yield point and postyield stiffness (see discussion in Step 4 and the section on constant ductility spectra and dynamic target point).
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 nth-mode pushover analysis is the intersection of ESDOF modal capacity curve with the inelastic demand spectrum [i.e., $S_{a,n}(\mu,\zeta_n,\lambda_n)$ versus $S_{d,n}(\mu,\zeta_n,\lambda_n)$] corresponding to the global system ductility (μ). Although an exact match cannot be established unless inelastic spectral plots are pregenerated at refined ductility levels, a reasonable approximation is achieved by considering displacement spectrum plots in the ductility range of interest at ductility intervals of 0.5. With the known dynamic target point for the nth-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 stepnumber 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 ipth step of the nth-mode pushover analysis.

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. The total response given in the following expression is obtained through SRSS combination of the modal quantities:

$$r = \max\left(\left(\sum_n (r_n^{(ip)})^2\right)^{0.5}\right) \tag{9}$$

If the system remains elastic in any mode considered, the computation of the response parameters will be equal to conventional response spectrum analysis. The proposed pushover procedure can be easily implemented in any structural analysis software package that allows eigenvalue computations to be performed during the analysis phase. The results of the AMC procedure reported in this paper have been implemented using the open source finite element platform, OpenSees (2005) in conjunction with MATLAB (The MathWorks, Inc. 2001) routines.

Validation of the Proposed Methodology

The proposed AMC procedure has been verified for different structural configurations and a range of far-fault and near fault

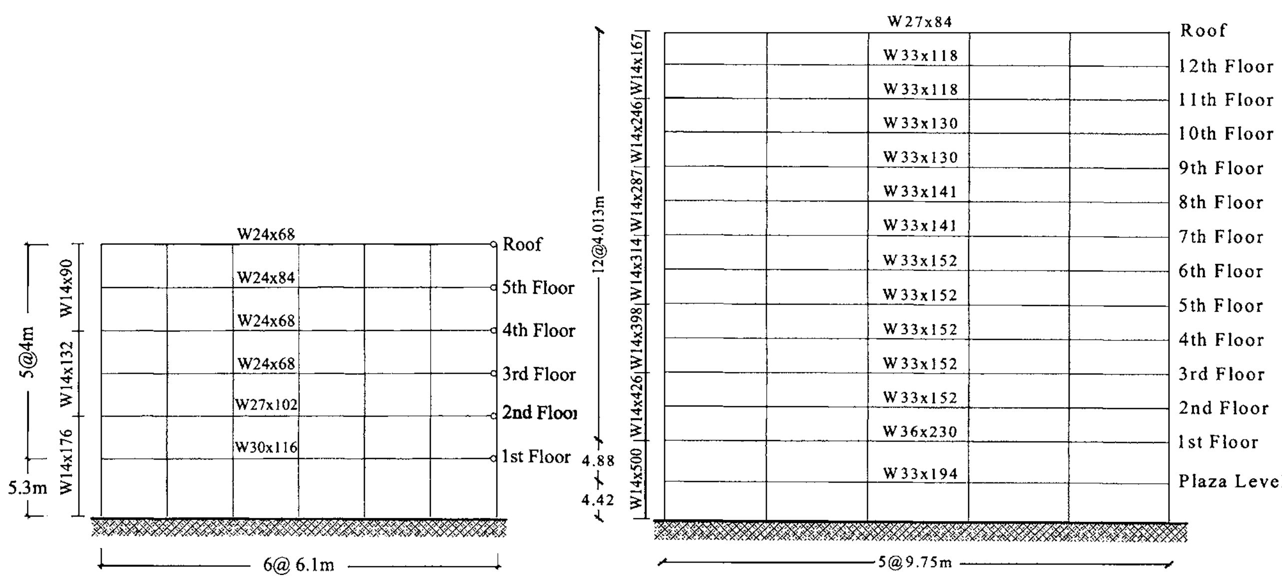

Fig. 3. Elevation views of typical perimeter frames from 6- and 13-story steel buildings

Table 1. Ground Motion Ensemble

Number	Year	Earthquake	M_w[a]	Mech.[b]	Recording station	Directivity effect	Dist.[c] (km)	Site class[d]	Data source[e]	Comp.	PGA (g)	PGV (cm/s)	Scale factors: 6-story building	Scale factors: 13-story building
Far-fault ground motions														
1	1952	Kern county	7.5	TH/REV	Taft	—	36.2	D	1	111	0.18	17.50	6.0	—
2	1992	Big Bear	6.4	SS	Desert Hot Spr. (New Fire Stn.)	—	40.1	D	2	090	0.23	19.14	4.6	4.5
3	1994	Northridge	6.7	TH	Moorpark (Ventura Fire Stn.)	—	26.4	D	2	180	0.29	20.97	—	3.9
Near-fault ground motions														
1	1992	Erzincan	6.7	SS	Erzincan	Forward	2.0	C	1	EW	0.50	64.32	1.0	1.0
2	1992	Cape Mendocino	7.1	TH	Petrolia, General Store	Forward	15.9	C	1	090	0.66	90.16	1.0	1.0
3	1989	Loma Prieta	7.0	OB	Los Gatos Parent Center	Forward	3.5	C	1	000	0.56	94.81	1.0	1.0
4	1994	Northridge	6.7	TH	Rinaldi Receiver Stn.	Forward	8.6	D	2	S49W	0.84	174.79	1.0	1.0
5	1994	Northridge	6.7	TH	Sylmar Olive View Hospital	Forward	6.4	D	1	360	0.84	130.37	1.0	1.0
6	1995	Kobe	6.9	SS	JMA	Forward	0.6	C	1	000	0.82	81.62	1.0	1.0
7	1999	Chi-Chi	7.6	TH	TCU074	Fling[f]	13.8	D	3	EW	0.59	68.90	1.0	1.0
8	1999	Chi-Chi	7.6	TH	TCU079	Fling[f]	11.0	D	3	EW	0.57	68.06	1.0	1.0

[a]Moment magnitude.

[b]Faulting mechanism: TH=thrust; REV=reverse; SS=strike-slip; and OB=oblique.

[c]Closest distance to fault.

[d]NEHRP site classifications ⇒ [C for V_s (shear-wave velocity)=360–760 m/s], (D for V_s=180–360 m/s).

[e]Data source: 1=http://peer.berkeley.edu/smcat; 2=http://db.cosmos-eq.org); and 3=http://scman.cwb.gov.tw/eqv5/special/19990921/pgadata-asci0704.htm

[f]Raw fling records were processed using a baseline correction only to conserve the true static offset.

ground motion records. Only typical findings are reported in this paper. Validation studies are presented for two steel moment frame buildings and results obtained with the AMC method are compared with MMPA and first-mode FEMA-356 lateral load pattern. The results of the different pushover analyses are then compared to benchmark results obtained from detailed NTH analyses using an array of earthquake records having both far-fault and near-fault characteristics. The records used in the NTH analyses were carefully selected so as to induce higher mode contributions.

Structural Systems and Analytical Models

The buildings considered in this evaluation study are a six-story and a thirteen-story steel special moment resisting frame systems. Both buildings represent existing structures in California and were selected for this study because the simulation models used in the analyses have been previously calibrated to observed response. Complete details of the analytical models and calibration studies can be found in Kalkan and Kunnath (2004b) and Kunnath et al. (2004). The primary lateral load resisting system in

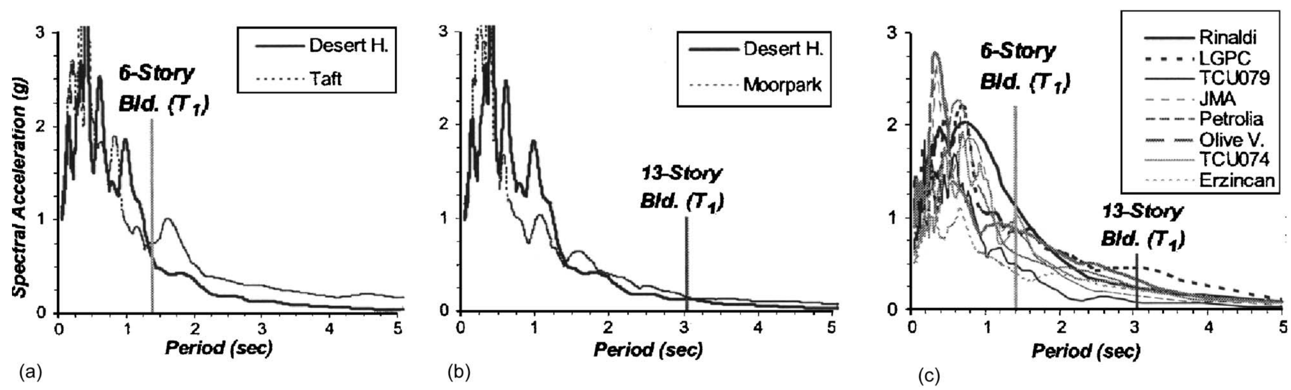

Fig. 4. Response spectra (5% damped) of (a) scaled far-fault records (for 6-story building); (b) scaled far-fault records (for 13-story building); and (c) original near-fault records (note: vertical lines indicate the fundamental periods of buildings)

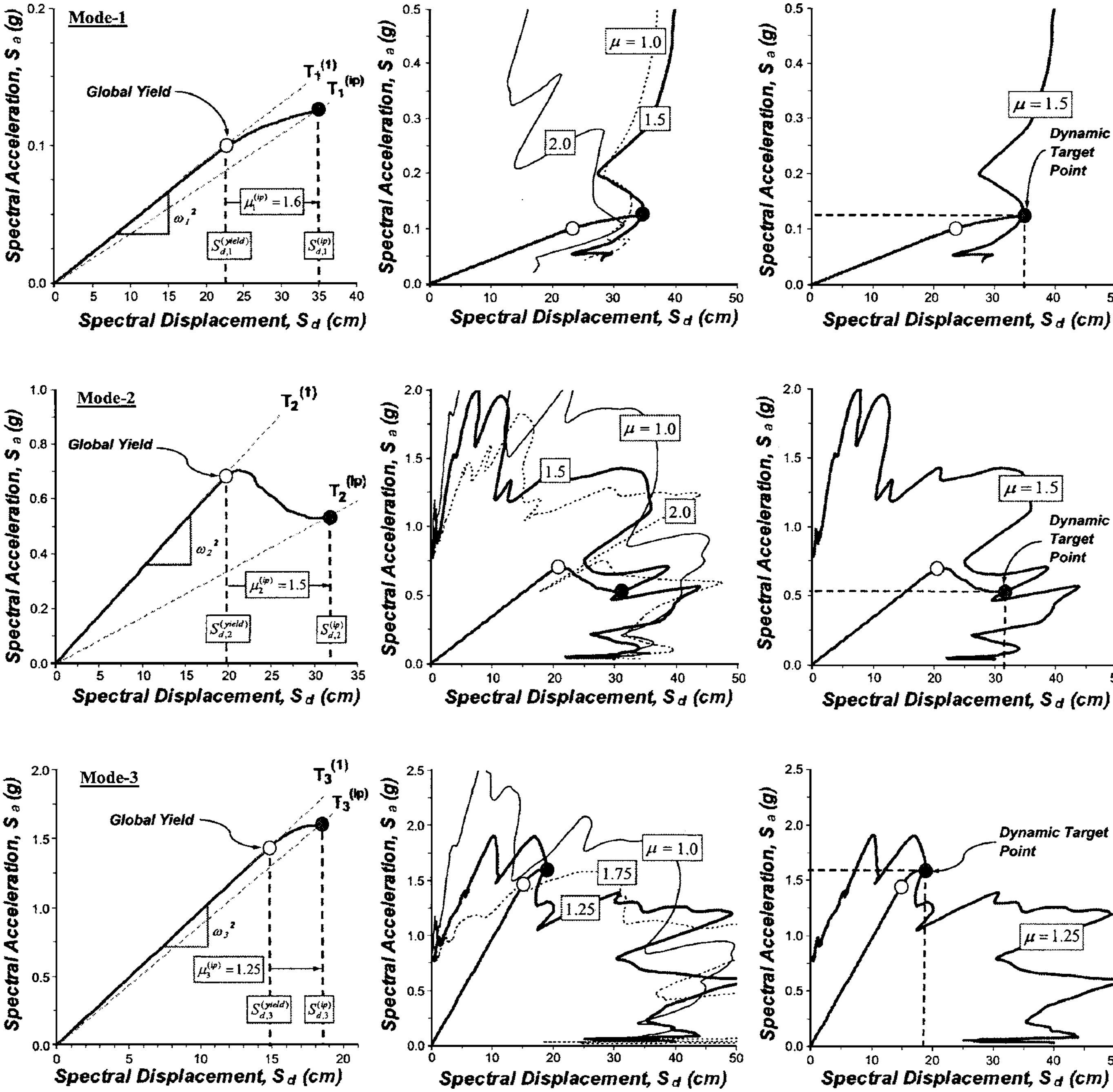

Fig. 5. Dynamic target point evaluation in the AMC procedure

both buildings is a moment frame around the perimeter of the building. Hence, the evaluation is restricted to the lateral load resisting frames. The elevation view of a typical perimeter frame for the two buildings is shown in Fig. 3.

Ground Motion Ensemble

In order to develop a set of benchmark responses against which to compare the proposed procedure, a set of records having far-fault and near-fault characteristics were compiled. These records were selected with the objective of triggering higher mode responses in the buildings. The near fault records contain either fling or forward-directivity effects with coherent long period velocity pulses. The far-fault records were amplified by a scale factor to induce inelastic response in both buildings. Such a process was not required for near-fault records. The ground motions used for evaluation study are summarized in Table 1. The response spectra of the scaled far-fault records and original near-fault records are presented in Fig. 4.

Validation Studies

The simulation model of each frame was subjected to the suite of ground motions listed in Table 1. Different scale factors were used for far fault records when analyzing the respective frames: amplification factors of 4.6 and 6.0 were used on Desert Hot and Taft records, respectively, for the 6-story building; and uniform scale factors of 3.9 and 4.5 were used on Moorpark and Desert Hot records, respectively for the 13-story building. The computed responses using nonlinear time history analyses are referred to as

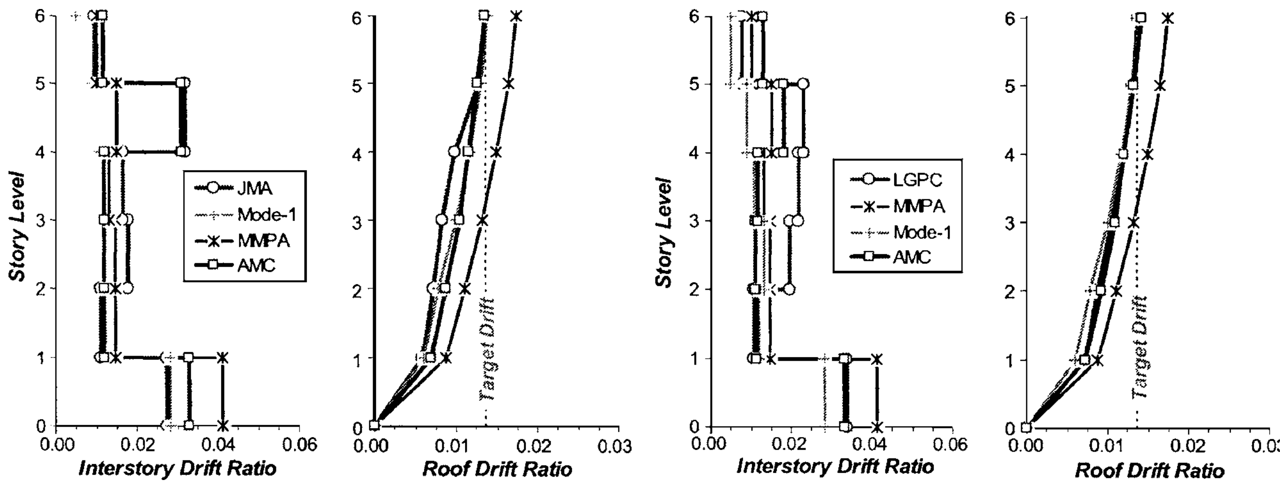

Fig. 6. Predicted peak roof drift and interstory drift ratios by nonlinear static procedures compared to NTH analyses of near-fault records for 6-story steel building

the benchmark responses. Peak inelastic response quantities for each frame predicted by AMC are compared with estimates obtained from MMPA, FEMA-356 first mode NSP and results from the NTH simulations. MMPA is considered in this study only as a comparable advanced pushover procedure. MMPA is known to produce more conservative results than MPA and studies by Chopra et al. (2004) have demonstrated that the dispersion in demand estimates using MPA are similar to NTH.

For the typical moment frames investigated in this study, only the first three modes were considered for MMPA and AMC. In the MMPA, first mode target displacements were obtained based on inelastic dynamic analyses on the ESDOF systems. ESDOF system properties were obtained through bilinear representation of the first mode capacity curve for the two buildings separately. Target displacements for the second and third modes were determined directly from the jagged elastic spectra associated with each unscaled near-fault record and scaled far-fault record using the elastic modal properties of the buildings. Target displacements for conventional first-mode pushover analyses were taken directly as the peak roof displacement computed from NTH analyses. As mentioned previously, target displacements for AMC (i.e., dynamic target points) are implicitly estimated during the analysis process without necessitating any precomputation.

Fig. 5 demonstrates an example of the dynamic target point evaluation for the 13-story steel building subjected to (JMA) motion. Fig. 5 clearly shows the global system ductility computation, and how the system parameters change as the demand exceeds the yield strength. In this particular case, the first three modal responses require a series of inelastic spectra in order to capture the intersection point (dynamic target point). For example, in the first mode, modal capacity curve yields a system ductility level of 1.6. The corresponding intersection point on the inelastic displacement spectra must match this ductility level to have reached the target point for this mode. In this particular example, the precomputed ductility spectra do not include a spectrum at a ductility of 1.6. Hence, the nearest spectrum at $\mu=1.5$ is used. This level of approximation, as suggested earlier, is adequate for practical purposes.

In Figs. 6 and 7, the peak interstory and roof drift ratio profiles are presented for the 6-story building for both earthquake sets. In all cases, higher mode effects results in larger demand at the upper (story 5) level and in one case also at the intermediate story

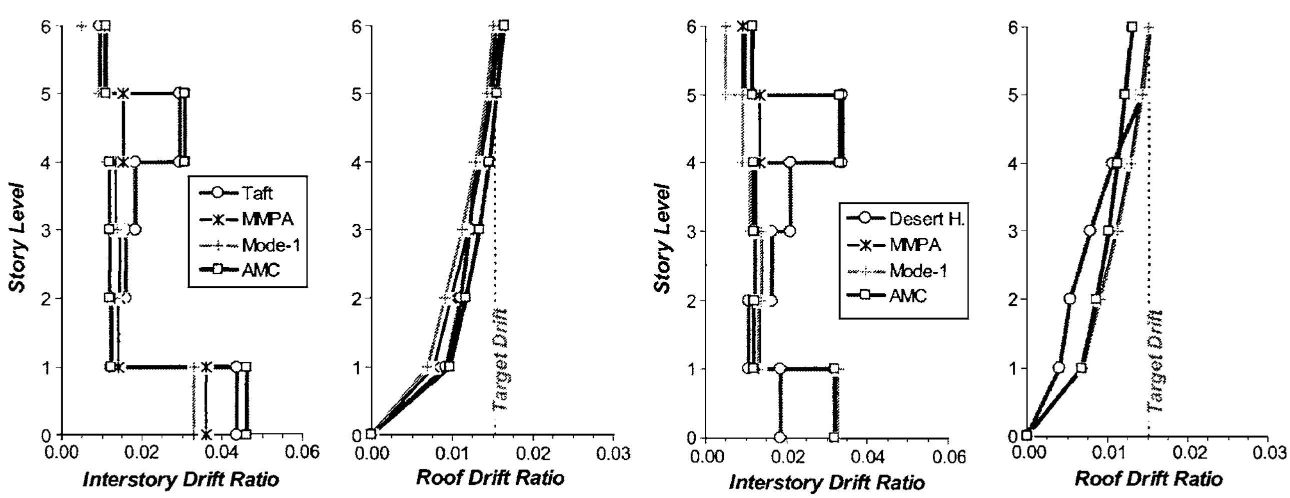

Fig. 7. Predicted peak roof drift and interstory drift ratios by nonlinear static procedures compared to NTH analyses of far-fault records for 6-story steel building

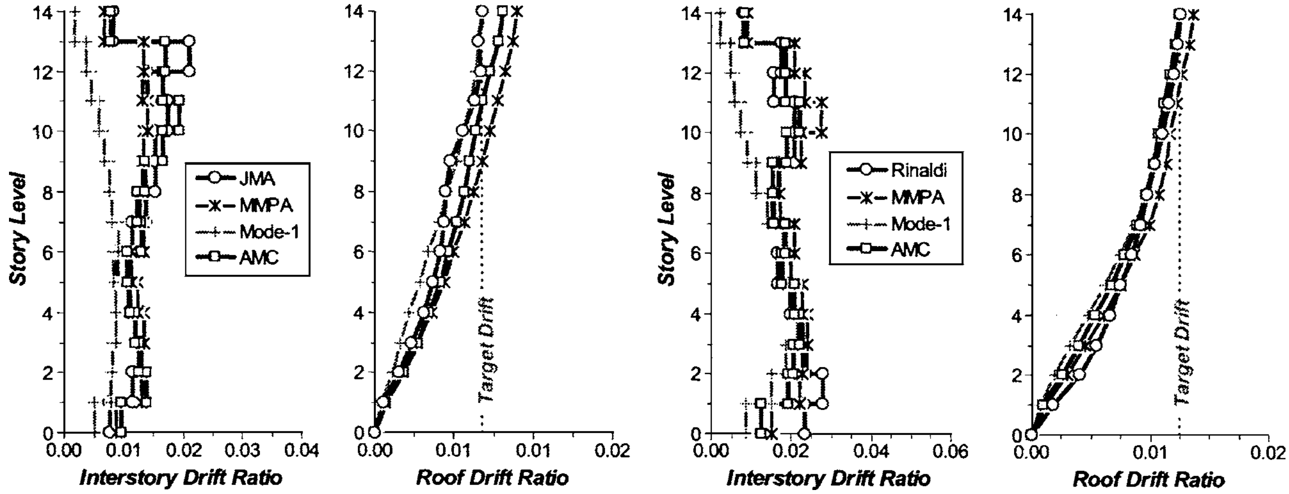

Fig. 8. Predicted peak roof drift and interstory drift ratios by nonlinear static procedures compared to NTH analyses of near-fault records for 13-story steel building

levels (stories 3 and 4). For both near-fault and far-fault ground motions, the dynamic response of the building shows significant demand at the fifth story level. The comparison of roof drift ratio shows that the AMC procedure underestimates the demand for one far-fault record but is similar to NTH predictions for the remaining far-fault record and both near-fault records. For near-fault records, roof drift ratio is overestimated by MMPA but is reasonable for far-fault records.

For the 13-story building, while MMPA captures the overall response in many cases (see Figs. 8 and 9), the proposed adaptive scheme yielded results that were generally similar to NTH results at most story levels. Nevertheless, there are cases where neither MMPA nor AMC are able to reproduce the dynamic response at some story levels. The response to LGPC and Desert Hot records (Figs. 6 and 7) are examples where the drifts at some intermediate story levels are underestimated by both methods. The dispersion serves as a reminder that complex dynamic phenomena can never be fully replaced by equivalent static schemes. Another observation, though not new, is that conventional first-mode pushover procedure not only significantly underestimates the upper story responses but also the lower story responses in some cases, even though the exact target displacements retrieved from NTH results were utilized. This implies that approximate computation of target displacement using first mode behavior may not be conservative, and may vary from record to record. The NTH results plotted in Figs. 7–9 highlight the order of underestimation of the structural response using conventional first-mode pushover analysis.

The results shown in Figs. 7–9 considered the response of typical frames to selected records so as to highlight important features of the structural response and to examine record-to-record variability. These results represent critical cases from the entire subset of simulations wherein the largest discrepancy between pushover and time-history methods was observed. Next, the effectiveness of the proposed AMC procedure to estimate story demands is investigated statistically. Results from the overall simulation study indicate that mean estimates using the AMC procedure are comparable to NTH analyses. A detailed analysis of the response data using all near-fault records generated the results displayed in Figs. 10 and 11. Shown in these figures are the mean and mean ± standard deviations (16–84 percentiles) for both NTH and AMC predictions of roof drift and interstory drift demands. The mean estimates using AMC are significantly better for

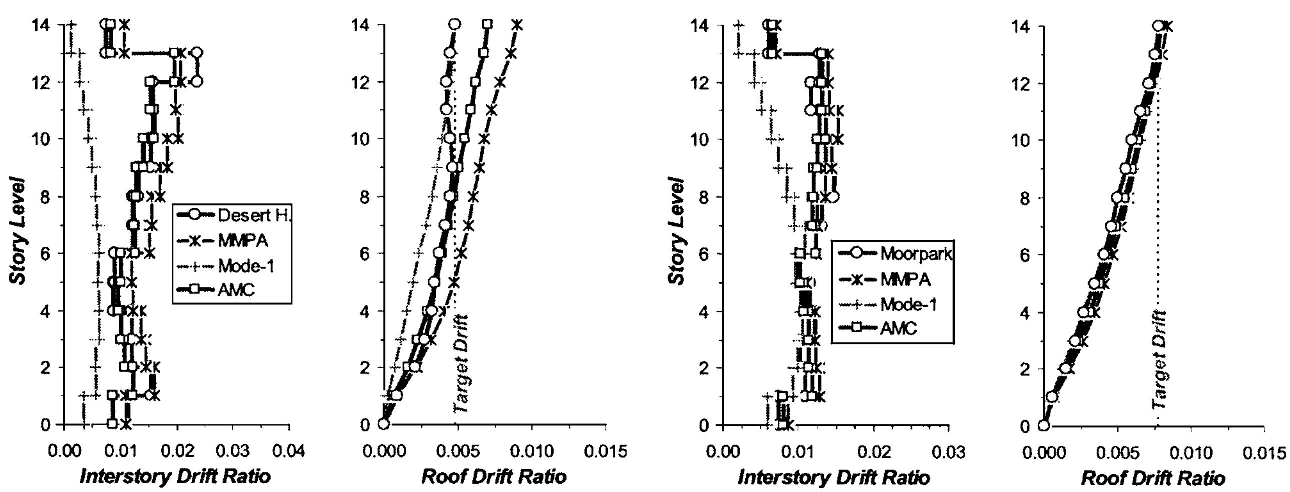

Fig. 9. Predicted peak roof drift and interstory drift ratios by nonlinear static procedures compared to NTH analyses of far-fault records for 13-story steel building

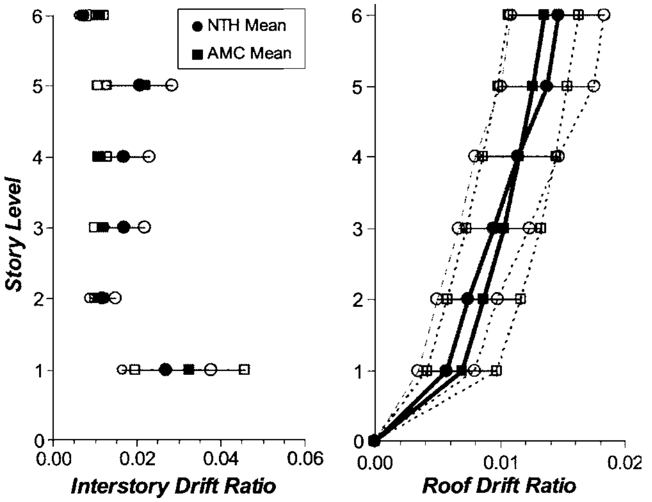

Fig. 10. Mean, 16, and 84 percentile predictions of interstory and roof drift demands for 6-story building (note: 16 and 84 percentile predictions are shown by unfilled markers)

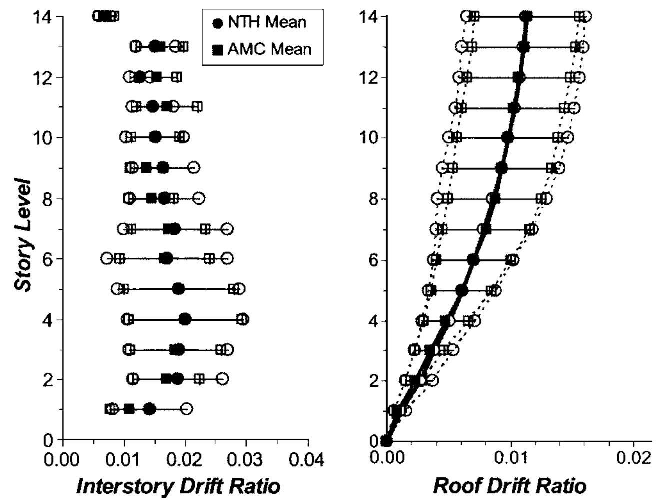

Fig. 11. Mean, 16, and percentile predictions of interstory and roof drift demands for 13-story steel building (note: 16 and 84 percentile predictions are shown by unfilled markers)

the 13-story frame because higher mode contributions in the inelastic phase of the response of this frame were limited. The dispersion using NTH is typically higher than AMC in both cases. These findings provide a measure of confidence in the general predictive abilities of the proposed pushover procedure.

Conclusions

The advancement of performance-based procedures in seismic design relies greatly on advancements in analytical methods to predict inelastic dynamic response of building structures. Since nonlinear time-history analyses are associated with greater uncertainties stemming from the choice of modeling parameters to the selection of ground motions, engineers are more likely to adopt static approaches before finally transitioning to time history methods. Hence the need to evaluate existing static methods and improve the potential for seismic response prediction remains a central issue in performance-based seismic engineering.

A new pushover technique utilizing adaptive multimodal displacement patterns is proposed in this paper with the objective of retaining the advantages of both adaptive and modal pushover procedures. The proposed adaptive modal combination procedure eliminates the need to pre-estimate the target displacement and utilizes an energy-based scheme to achieve stable estimates of the seismic demand in conjunction with constant-ductility inelastic spectra. It is shown to provide reasonable estimates of seismic demand in typical moment frame structures for both far-fault and near-fault records. By combining the contributions of sufficient number of modes, the response estimated by AMC is generally similar to the benchmark results obtained from rigorous nonlinear time-history analyses for typical steel moment frame buildings. Nonetheless, there are cases when the predictions at the some story levels do not match NTH response estimates. Additionally, the findings and conclusions are based on studies of regular moment frame buildings.

The proposed procedure is by no means more difficult to implement than any other enhanced pushover procedure, and requires primarily an eigenvalue solver that can be invoked when necessary during the progressive modal pushover analysis and an internal or external module to generate constant-ductility ADRS curves. Since the method builds on existing procedures and incorporates concepts in CSM and inelastic spectra that are already familiar to structural earthquake engineers, it attempts to provide a methodology that provides a physical basis for understanding the sensitivity of structural response to strong ground motions to structural and ground motion characteristics.

Acknowledgments

The writers wish to thank the anonymous reviewers of this paper whose comments have contributed to improving the overall methodology. Funding for this study provided by the National Science Foundation under Grant No. CMS-0296210, as part of the U.S.–Japan Cooperative Program on Urban Earthquake Disaster Mitigation, is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the writers and do not necessarily reflect the views of the National Science Foundation.

References

Akkar, S., Yazgan, U., and Gulkan, P. (2004). "Deformation limits for simple non-degrading systems subjected to near-fault ground motions." *Proc., 13th World Conf. on Earthquake Engineering*, Miracd, Vancouver, B.C., Canada, Paper No. 2276.

American Society of Civil Engineers (ASCE). (2000). "Prestandard and commentary for the seismic rehabilitation of buildings." *FEMA-356*, Washington, D.C.

Antonio, S., and Pinho, R. (2004). "Development and verification of a displacement-based adaptive pushover procedure." *J. Earthquake Eng.*, 8(5), 643–661.

Antonio, S., Rovithakis, A., and Pinho, R. (2002). "Development and verification of a fully adaptive pushover procedure." *Proc., 12th European Conf. on Eq. Engineering*, London, Paper No. 822.

Applied Technology Council (ATC). (1996). "Seismic evaluation and retrofit of concrete buildings." *Rep. No. ATC-40*, Volumes 1 and 2, Redwood City, Calif.

Applied Technology Council (ATC). (2005). "Improvement of nonlinear static seismic analysis procedures." *Rep. No. FEMA-440*, Redwood City, Calif.

Aydinoglu, M. N. (2003). "An incremental response spectrum analysis procedure based on inelastic spectral displacements for multi-mode seismic performance evaluation." *Bulletin of the Earthquake Engineering*, 1(1), 3–36.
Chopra, A. K., and Goel, R. K. (2002). "A modal pushover analysis procedure for estimating seismic demands for buildings." *Earthquake Eng. Struct. Dyn.*, 31(3), 561–582.
Chopra, A. K., Goel, R. K., and Chintanapakdee, C. (2004). "Evaluation of a modified MPA procedure assuming higher modes as elastic to estimate seismic demands." *Earthquake Spectra*, 20(3), 757–778.
Elnashai, A. S. (2000). "Advanced static inelastic (pushover) analysis for seismic design and assessment." *The George Penelis Symp. on Concrete and Masonry Structures*, Aristotle Univ. of Thessaloniki, Thessaloniki, Greece, 23–34.
European Committee for Standardization (CEN). (2001). "Eurocode 8—Design of structures for earthquake resistance, Part 1, *European Standard prEN 1998-1, Draft No. 4*, Brussels, Belgium.
Goel, R. K., and Chopra, A. K. (2004). "Evaluation of modal and FEMA pushover analyses: SAC buildings." *Earthquake Spectra*, 20(1), 225–254.
Gupta, B., and Kunnath, S. K. (2000). "Adaptive spectra-based pushover procedure for seismic evaluation of structures." *Earthquake Spectra*, 16(2), 367–391.
Hernandez-Montes, E., Kwon, O. S., and Aschheim, M. A. (2004). "An energy based formulation for first and multiple-mode nonlinear static (Pushover) analyses." *J. Earthquake Eng.*, 8(1), 69–88.
Jan, T. S., Liu, M. W., and Kao, Y. C. (2003). "An upper-bound pushover analysis procedure for estimating the seismic demands of high-rise buildings." *Eng. Struct.*, 26(1), 117–128.
Kalkan, E., and Kunnath, S. K. (2004a). "Lateral load distribution in nonlinear static procedures for seismic design." *Proc., ASCE Structures Congress*, ASCE, Reston, Va., 1–10.
Kalkan, E., and Kunnath, S. K. (2004b). "Method of modal combinations for pushover analysis of buildings." *Proc., 13th World Conference on Eq. Engineering*, Miracd, Vancouver, B.C., Canada, Paper No. 2713.
Kunnath, S. K. (2004). "Identification of modal combinations for nonlinear static analysis of building structures." *Comput. Aided Civ. Infrastruct. Eng.*, 19(4), 246–259.
Kunnath, S. K., and Kalkan, E. (2004). "Evaluation of seismic deformation demands using nonlinear procedures in multistory steel and concrete moment frames." *ISET J. Earthquake Technol.*, 41(1), 159–182.
Kunnath, S. K., Nghiem, Q., and El-Tawil, S. (2004). "Modeling and response prediction in performance-based seismic evaluation: Case studies of instrumented steel moment-frame buildings." *Earthquake Spectra*, 20(3), 883–915.
The MathWorks Inc. (2001). *MATLAB—Version 6.1*, Natick, Mass.
Ministry of Land, Infrastructure and Transport. (2001). *Design example and commentary for the calculation of response and limit strength*, Japan (in Japanese).
Miranda, E., and Akkar, S. D. (2002). "Evaluation of approximate method to estimate target displacements in PBEE." *The 4th U.S.–Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures, PEER Rep. No. 2002/21*, 75-86, Berkeley, Calif.
OpenSees. (2005). "Open system for earthquake engineering simulation." ⟨http://opensees.berkeley.edu⟩ (May 25, 2005).
Tjhin, T., Aschheim, M., and Hernandez-Montes, E. (2004). "Estimates of peak roof displacement using 'equivalent' single degree of freedom systems." *J. Struct. Eng.*, 131(3), 517–522.