Method of Modal Combinations for Pushover Analysis of Buildings

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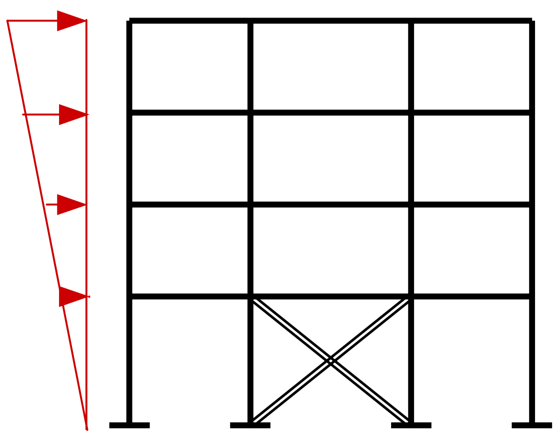
Outline

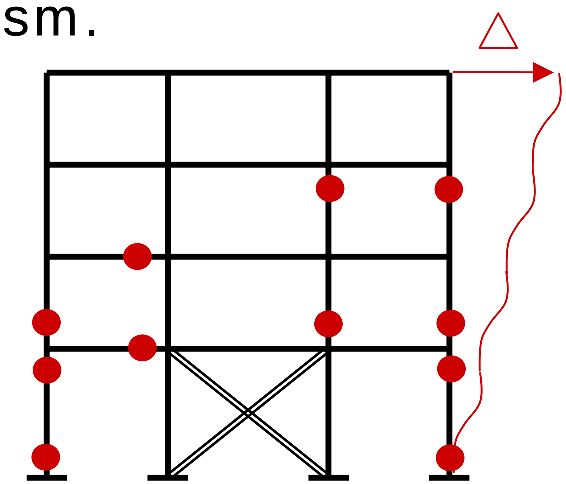
- Current FEMA pushover methodologies in Performance-Based Seismic Design
- Lateral load patterns: how they influence demand estimation in pushover analysis
- Method of Modal Combination procedure
- Summary and findings

Nonlinear Static Analysis

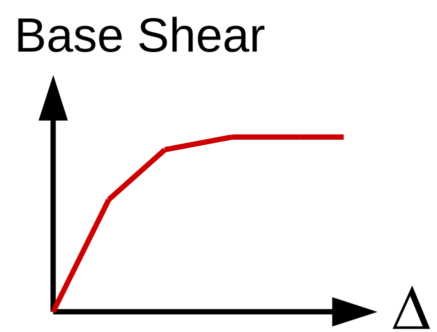
- Apply monotonically increasing lateral forces (invariant height-wise distribution) till the “control node” reaches a “target displacement” i.e., increasing load factor while fixing load pattern.

- To identify sequence and magnitudes of yielding (damage) of structural components, internal forces, deformations, and failure mechanism.



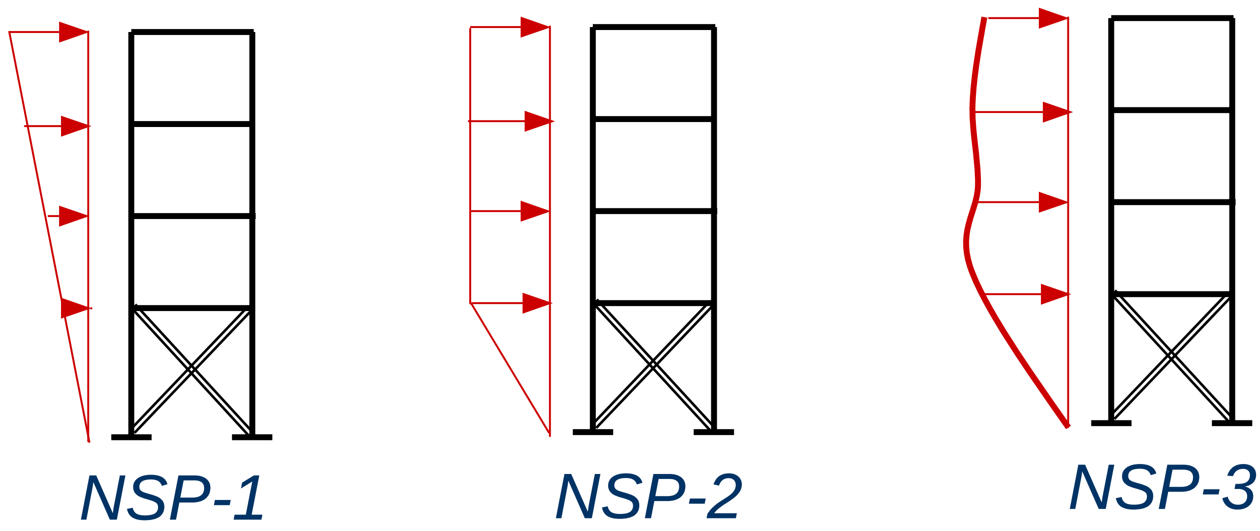


Plastic Hinge Development



Capacity Curve

FEMA-356: Nonlinear Static Procedure (NSP)



- *(NSP-1)*: *Inverted triangular pattern*
- *(NSP-2)*: Uniform pattern proportional to the floor mass
- *(NSP-3)*: Pattern proportional to the story shears obtained from a modal combination using a response spectrum analysis in conjunction with an earthquake spectra

Limitations of FEMA NSP

- Restricted to single mode response, can be reliably apply to 2D response of low-rise structures in regular plan.

- Gives erroneous results in case of:
  - Higher Mode Effects
  - Plan Irregularities (i.e., Torsion)

- No established procedure for 3D pushover analysis yet.

Understanding Modal Patterns

The dynamic load can be expressed in terms of a spatial distribution (independent of time) & a time-varying function:

$$m\ddot{\mathbf{u}} + c\dot{\mathbf{u}} + f_s(u) = p_f\, f(t)$$

$$p_f = \sum p_n = \sum \Gamma_n m \Phi_n$$

For a given response spectrum, resulting forces at level 'i' for mode 'j'

$$F_{ij} = \Gamma_j m_i \Phi_{ij}\; S_a(j)$$

Advantage of the approach: The applied lateral forces can be associated with a hazard spectrum

Select which modes are being combined:

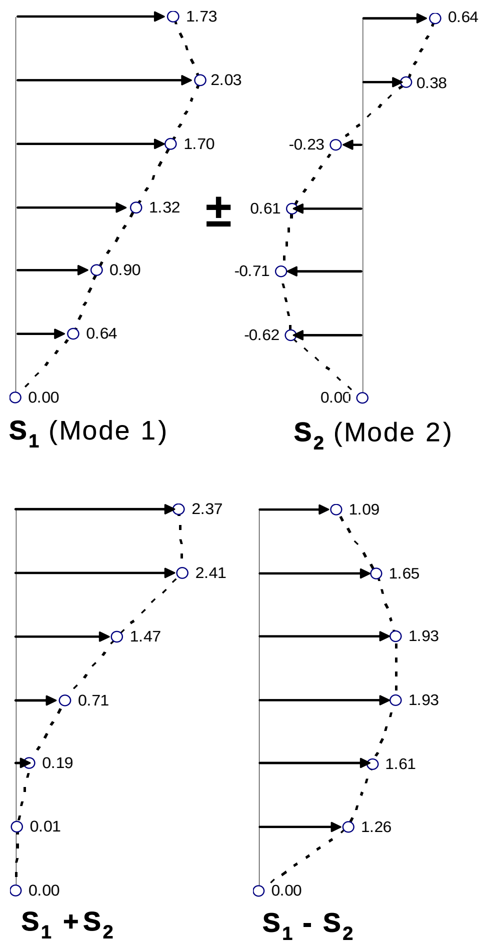
- for low to mid-rise: 1st 2 modes
- for taller structures: 1st 3 or 4 modes

$$F_j = \sum_{m=n1,n2}^{nn} \alpha_m \Gamma_m m_j \Phi_{mj} S_a(\zeta_m, T_m)$$

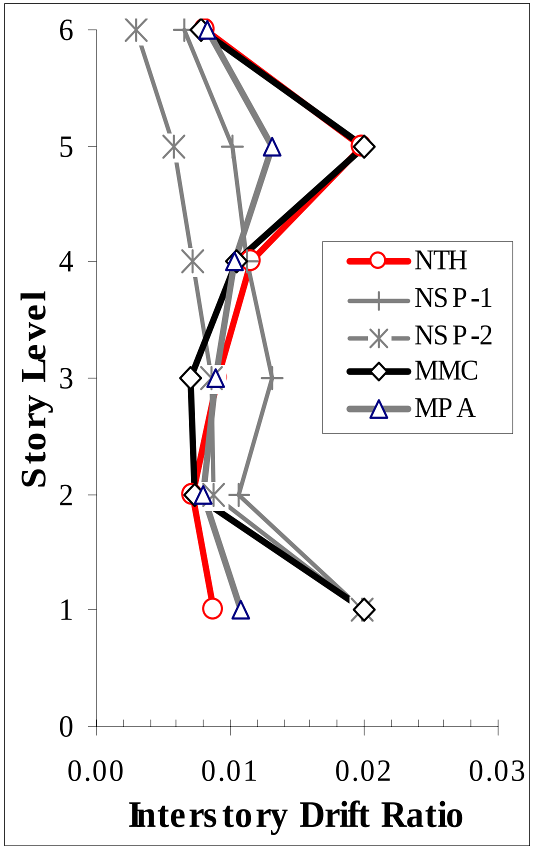
Summary of validation studies

- Several building frames of varying height were subjected to different lateral load patterns
- Each building model was also subjected to a series of ground motions
- All models were subjected to the same peak interstory drift ratio
- Demand estimates were recorded in terms of displacement and story drift profiles
- Pushover estimates were compared to nonlinear time-history global and local demands

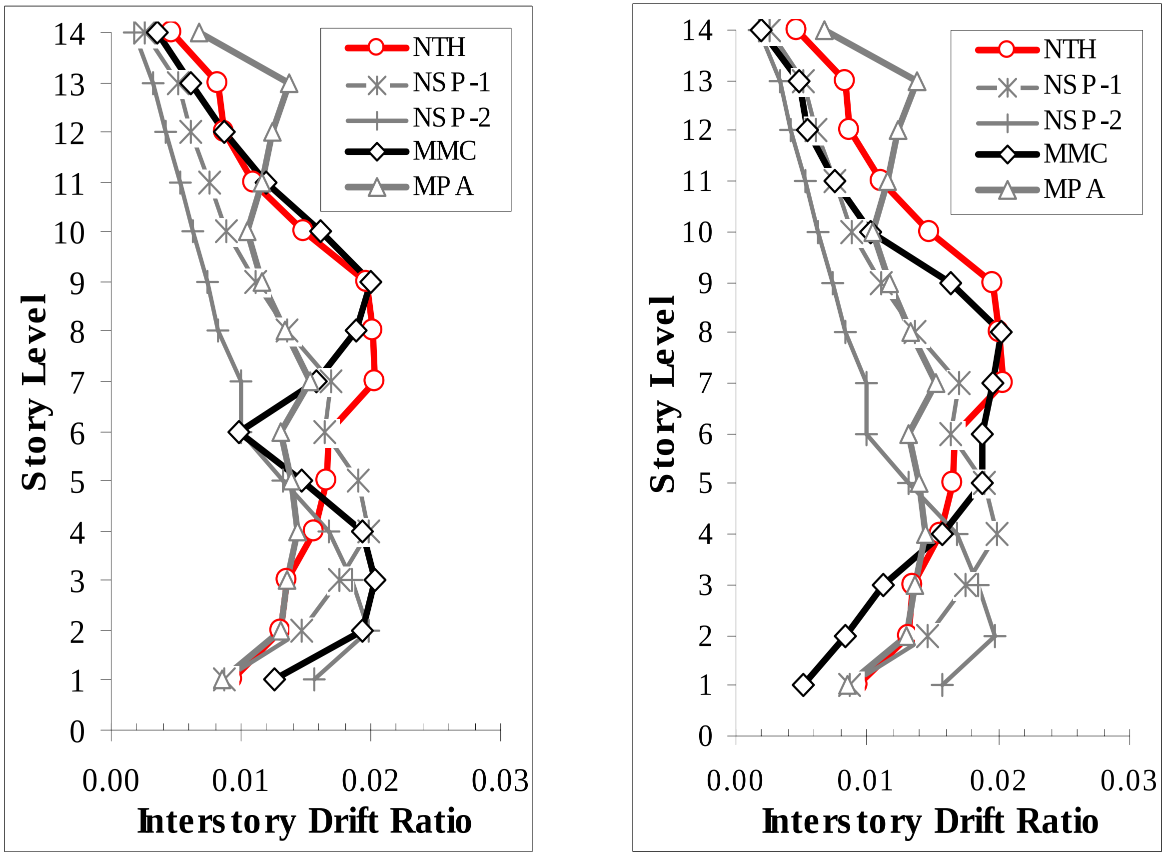
Comparison of roof and peak drift ratio (6-story building)



$$F_j = \Gamma_1 m \Phi_1 S_a(T_1) \pm \Gamma_2 m \Phi_2 S_a(T_2)$$



Comparison of roof and peak drift ratio (13-story building)



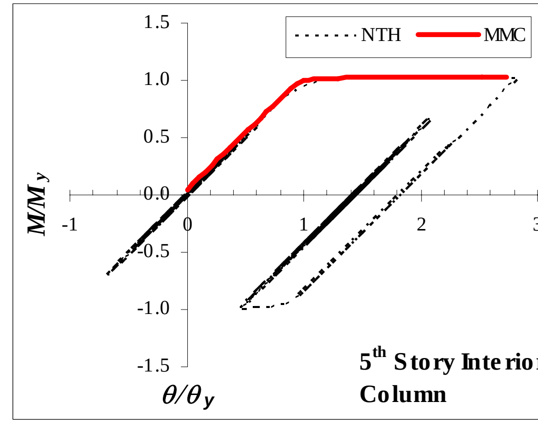
Mode1 & Mode2 Mode1 & Mode2 & Mode3

Comparison of global and local ductility demands

6-story building

	Location	NSP-1 *	NSP-2 *	NTH	MMC
Global	-	1.53		-	1.92
5th Story	-	0.0	0.0	-	2.02
5th Story Column	Interior	0.0	0.0	2.81	2.73

* NSP-1:Inverted triangle; NSP-2: Mass proportional

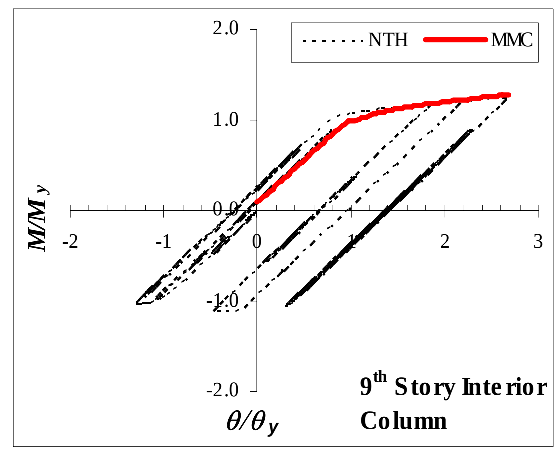


6-story building

13-story building

	Location	NSP-1 *	NSP-2 *	NTH	MMC
Global	-	2.08	2.24	-	2.05
7th Story	-	2.19	1.32	-	2.59
7th Story Column	Interior	3.28	1.67	3.69	3.74
9th Story	-	1.30	0.0	-	1.90
9th Story Column	Interior	1.61	0.0	2.60	2.70

* NSP-1:Inverted triangle; NSP-2: Mass proportional



13-story building

Summary

- The success of PBEE will depend to a large extent on our ability to predict the seismic response as accurately as possible

- The increasing popularity of pushover methods to estimate seismic demands calls for a detailed evaluation of such methods and their ability to predict nonlinear dynamic response measure

- MMC method has shown promise in predicting higher mode demands – but envelope values are usually conservative
  - Enhancements to MMC in progress

- It is unlikely that nonlinear static procedures can fully replace nonlinear time-history analyses