

Evaluation of Current NSP Using Strong-Motion Records

Rakesh K. Goel, PhD, PE, F.ASCE
Professor

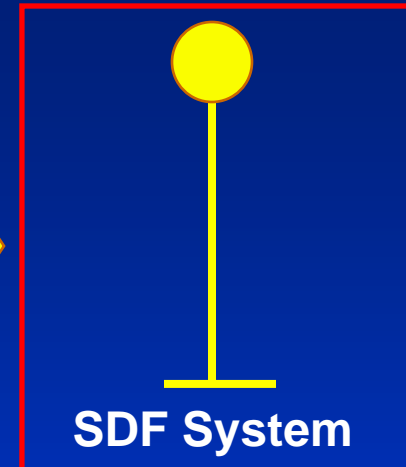
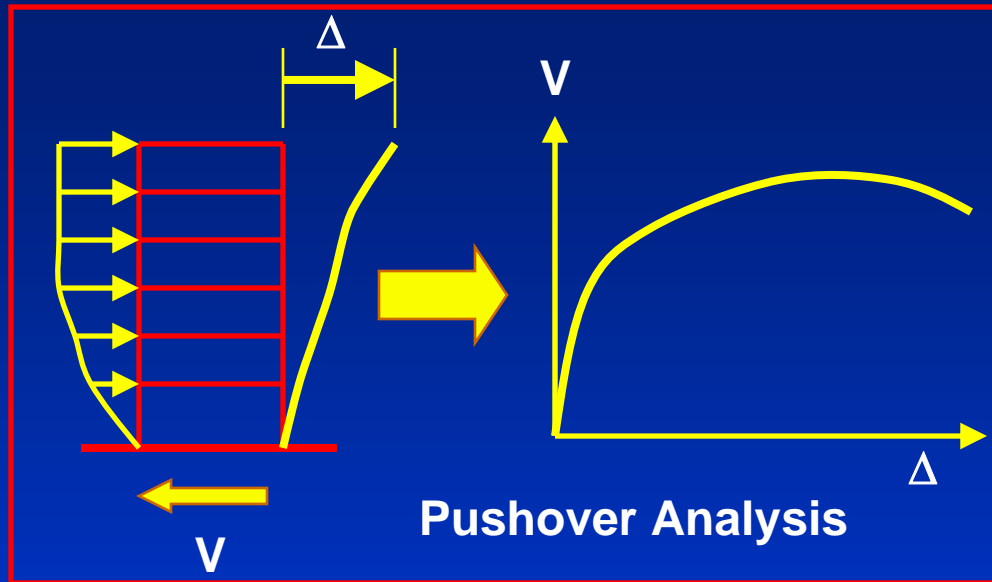
California Polytechnic State University,
San Luis Obispo, CA 93407

Presented at
2007 Structures Congress, Long Beach, CA
May 16-20, 2007

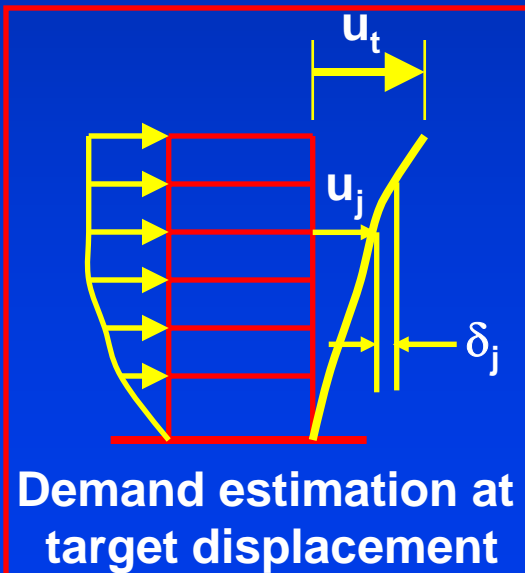
Objectives

- To evaluate current NSP to estimate target displacement
 - FEMA-356 Coefficient Method (CM)
 - FEMA-440/ASCE-41 CM
 - ATC-40 Capacity Spectrum Method (CSM)
 - FEMA-440 Improved CSM
- Using recorded motions of buildings
 - Imperial County Services Building
 - Motions from 1979 Imperial Valley earthquake
 - Sherman Oaks 13-Story Commercial Building
 - Motions from 1994 Northridge earthquake

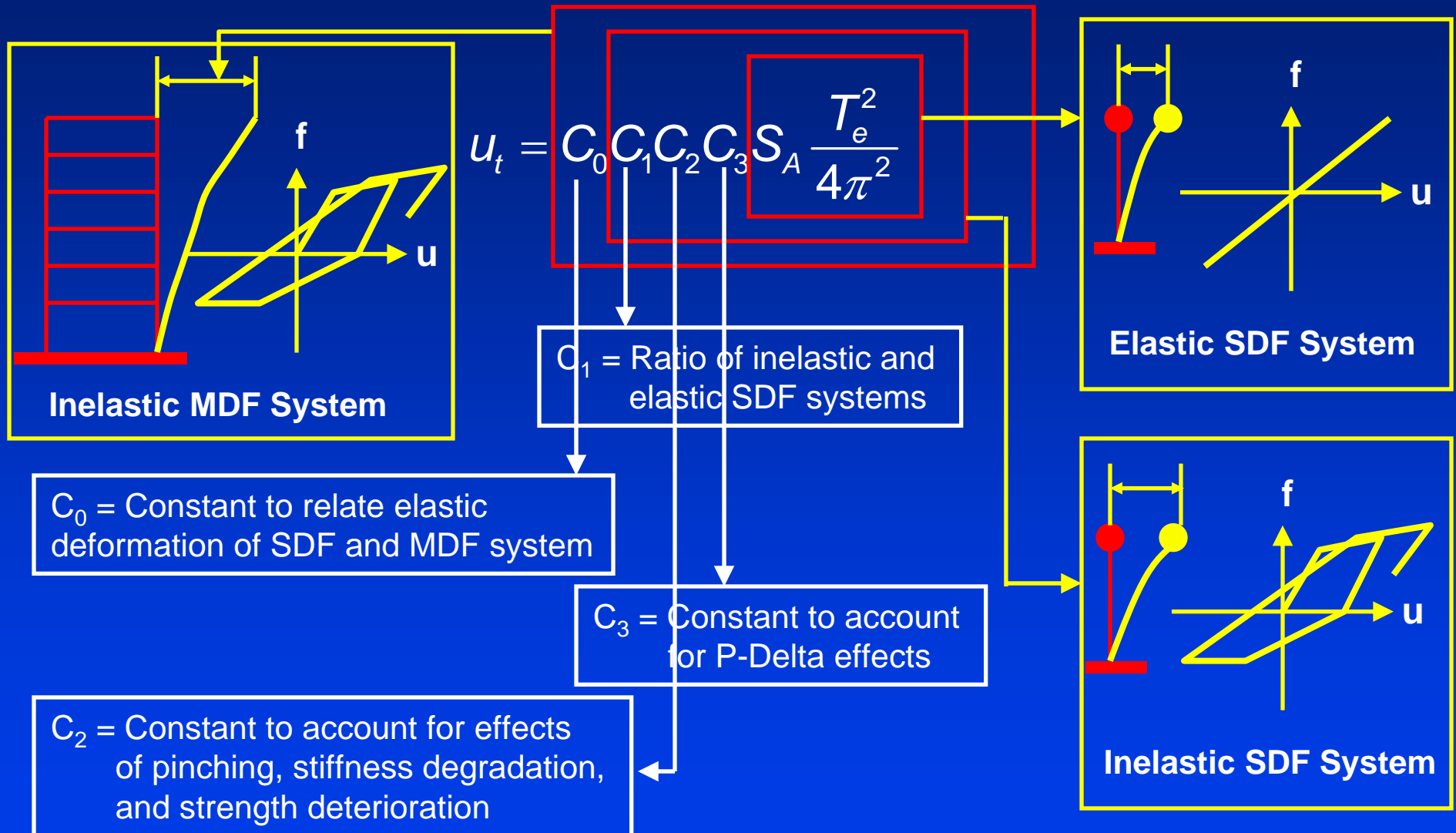
Summary of NSP



Target Displacement
of MDF System u_t



FEMA-356 CM



FEMA-356: C_1 and C_3

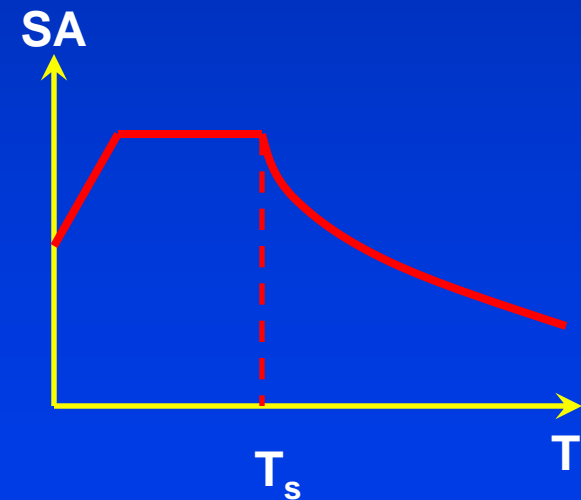
$$C_1 = \begin{cases} 1.0; & T_e \geq T_s \\ \frac{1.0 + (R-1)T_s/T_e}{R}; & T_e < T_s \end{cases}$$

Cap on C_1 : 1.5 for $T_e < 0.1$ sec

R = Ratio of elastic and yield strength

$$C_3 = 1.0 + \frac{|\alpha|(R-1)^{3/2}}{T_e}$$

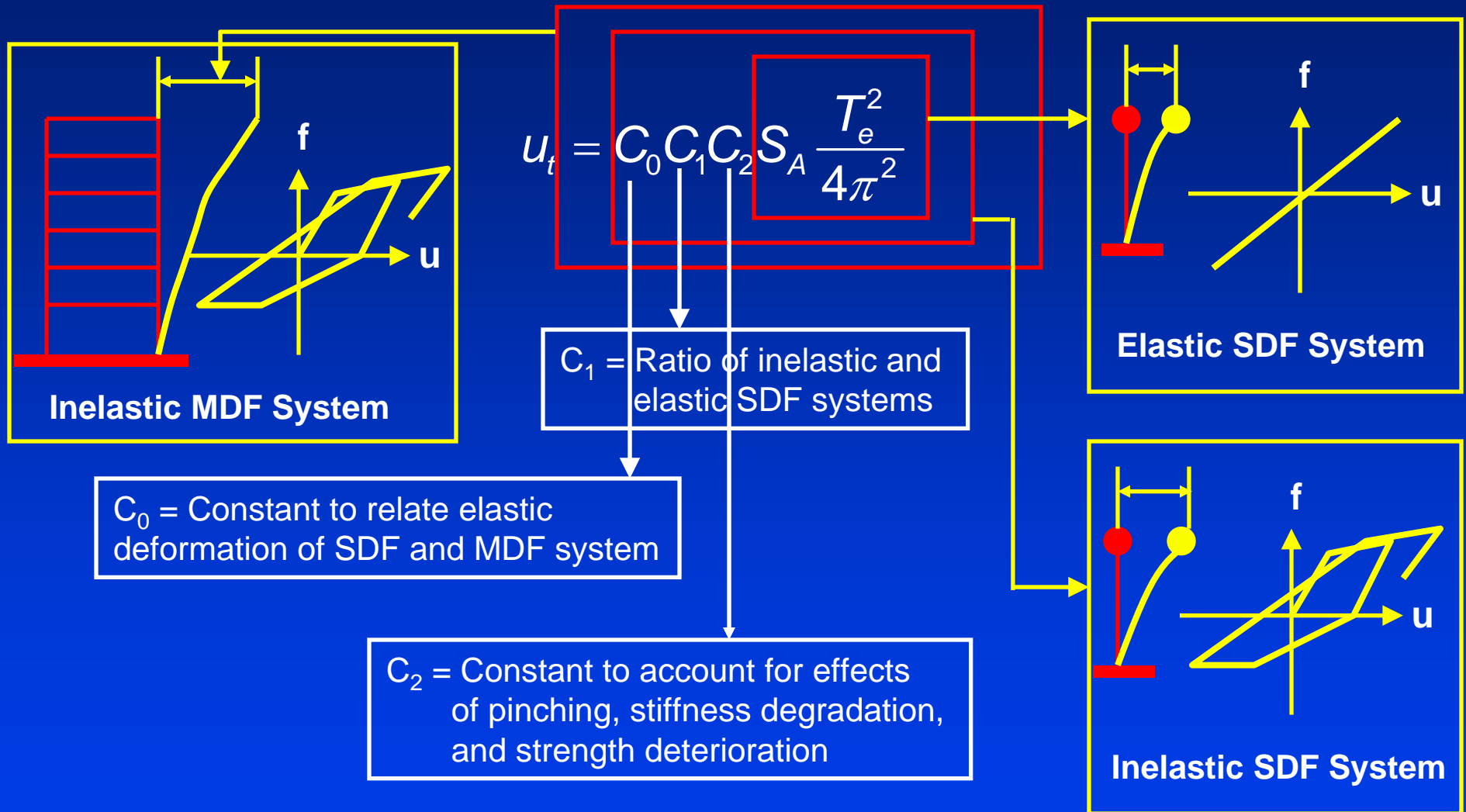
α = Post-yield stiffness ratio



FEMA-356: C_2

Structural Performance Level	$T_e < 0.1$ sec		$T_e > T_s$	
	Framing Type 1	Framing Type 2	Framing Type 1	Framing Type 2
Immediate Occupancy	1.0	1.0	1.0	1.0
Life safety	1.3	1.0	1.1	1.0
Collapse Prevention	1.5	1.0	1.2	1.0

FEMA-440/ASCE-41 CM



FEMA-440/ASCE-41: C_1 and C_2

$$C_1 = \begin{cases} 1.0 + \frac{R-1}{0.04\alpha}; & T_e \leq 0.2s \\ 1.0 + \frac{R-1}{\alpha T_e^2}; & 0.2s < T_e \leq 1s \\ 1.0; & T_e > 1s \end{cases} \quad C_2 = \begin{cases} 1.0 + \frac{1}{800} \left(\frac{R-1}{T_e} \right)^2; & T_e \leq 0.7s \\ 1.0; & T_e > 0.7s \end{cases}$$

R = Ratio of elastic and yield strength

α = is equal to 130 for site class A and B

= 90 for site class

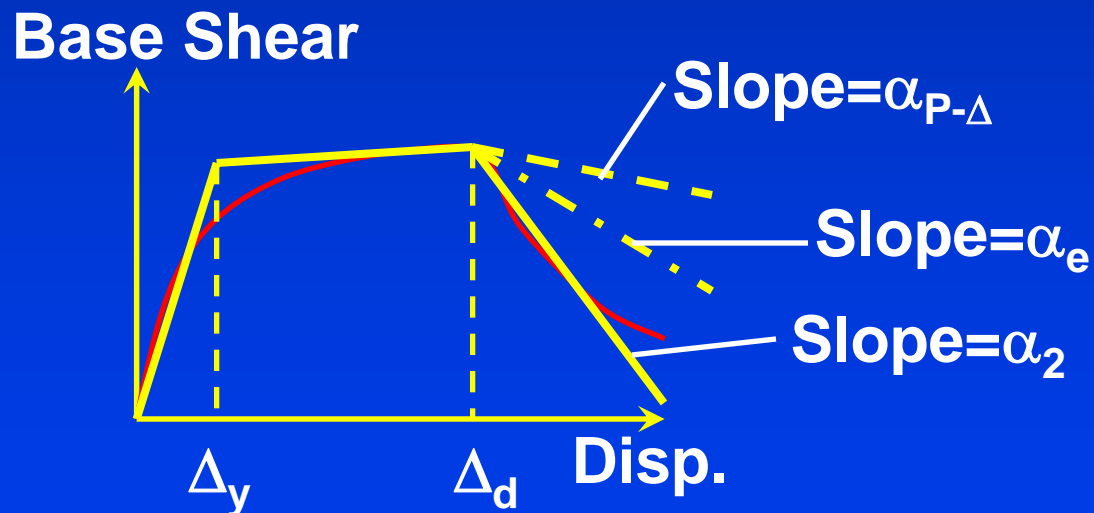
= 60 for site class D, E, and F

FEMA-440/ASCE-41: Cap on R

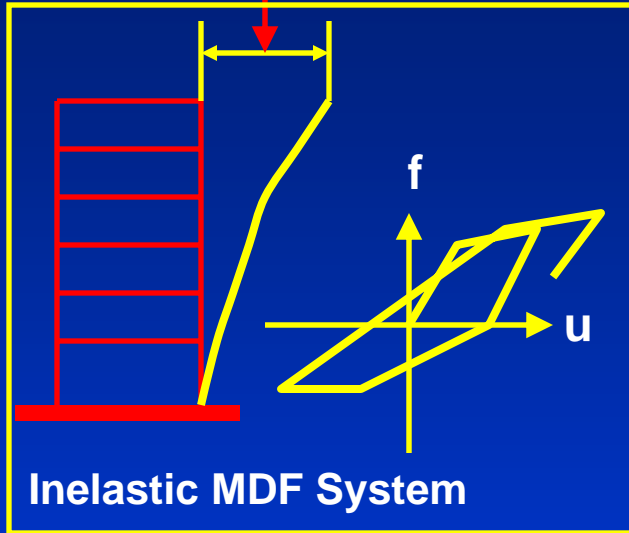
$$R_{\max} = \frac{\Delta_d}{\Delta_y} + \frac{\alpha_e^{-h}}{4}; \quad h = 1.0 + 0.15 \ln(T_e)$$

$$\alpha_e = \alpha_{P-\Delta} + \lambda (\alpha_2 - \alpha_{P-\Delta})$$

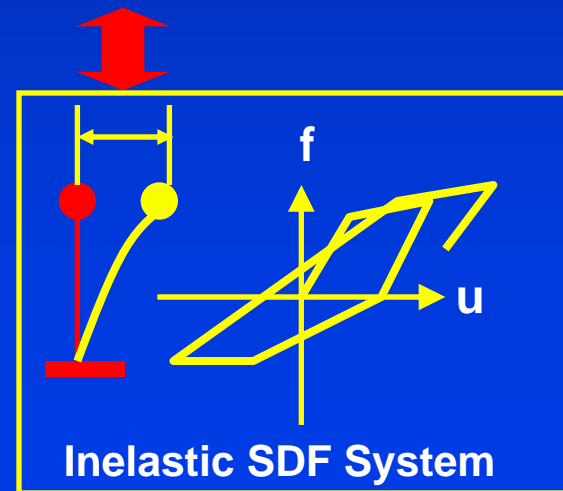
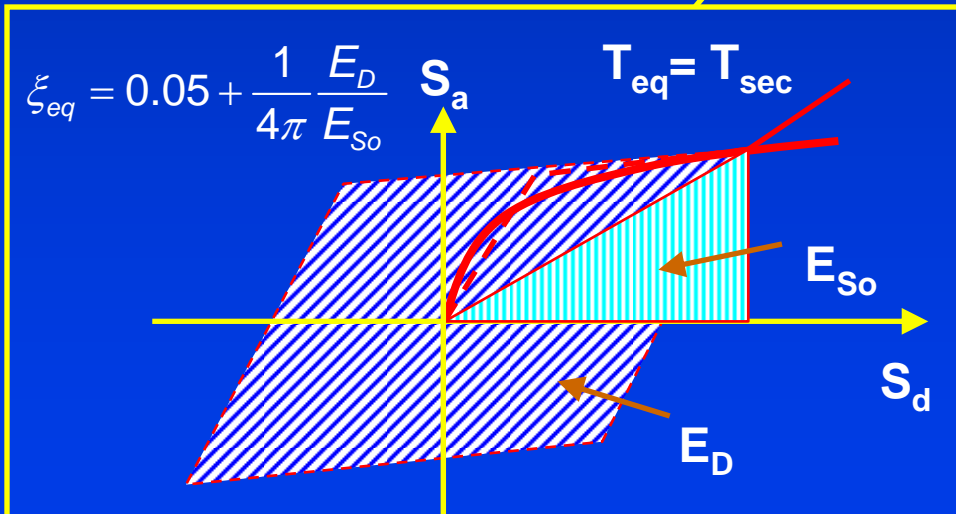
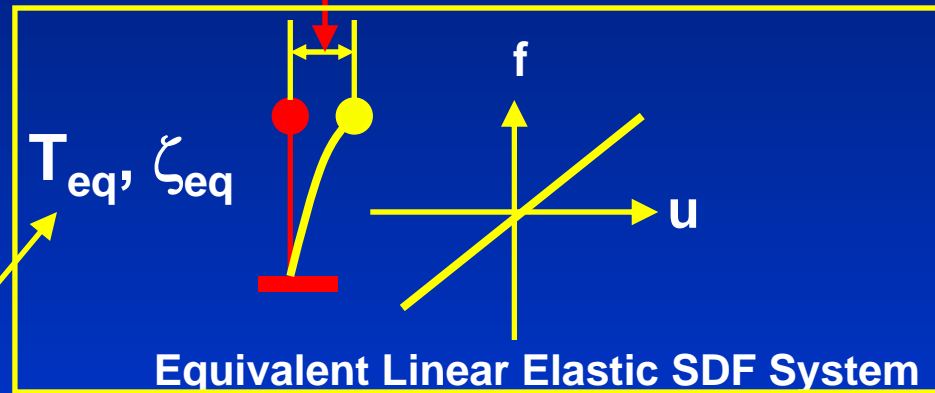
λ = Near field effect factor
= 0.8 if $S_1 \geq 0.6$ (MCE)
= 0.2 if $S_1 < 0.6$ (MCE)



ATC-40 CSM



$$u_t = C_0 S_D(T_{eq}, \xi_{eq})$$



ATC-40

For bilinear systems

$$T_{eq} = T_o \sqrt{\frac{\mu}{1 + \alpha\mu - \alpha}}$$

$$\zeta_{eq} = 0.05 + \kappa \frac{1}{\pi} \frac{(\mu - 1)(1 - \alpha)}{\mu(1 + \alpha\mu - \alpha)}$$

Requires iterations to compute T_{eq} and ζ_{eq}
because of ductility μ

FEMA-440 CSM

$$\zeta_{eff} = \begin{cases} A(\mu-1)^2 + B(\mu-1)^3 + \zeta_o; & \mu < 4.0 \\ C + D(\mu-1) + \zeta_o; & 4.0 \leq \mu \leq 6.5 \\ E \left[\frac{F(\mu-1) - 1}{F(\mu-1)^2} \right] \left(\frac{T_{eq}}{T_o} \right)^2 + \zeta_o; & \mu > 6.5 \end{cases}$$

A to E = Constants that depend on hysteretic behavior and post-yield stiffness ratio

Requires iterations because of ductility μ

FEMA-440 CSM

$$T_{eff} = \begin{cases} \left[G(\mu - 1)^2 + H(\mu - 1)^3 + 1 \right] T_o; & \mu < 4.0 \\ \left[I + J(\mu - 1) + 1 \right] T_o; & 4.0 \leq \mu \leq 6.5 \\ \left[K \left(\sqrt{\frac{(\mu - 1)}{1 + L(\mu - 2)}} - 1 \right) + 1 \right] T_o; & \mu > 6.5 \end{cases}$$

G to K = Constants that depend on hysteretic behavior and post-yield stiffness ratio

Requires iterations because of ductility μ

NSP Using Recorded Motions of Building: Modifications

- Pushover curve for fundamental mode of the building in the direction under consideration
 - ASCE-41 proposes using only the fundamental mode
- Modifications to target displacement computation
 - FEMA-356, FEMA-440, ASCE-41 CM
 - S_A for SDF system due to motions recorded at the building base with $\zeta = 5\%$ and $T = T_e$
 - ATC-40 and FEMA-440 CSM
 - S_D for SDF system due to motions recorded at the building base with ζ_{eff} and T_{eff}

Computer Models

- Three-dimensional model of each selected building
 - Flexural and axial behavior modeled with detailed fiber-sections
 - Shear and torsion behavior modeled as linear-elastic
- OpenSees computer program used for modeling

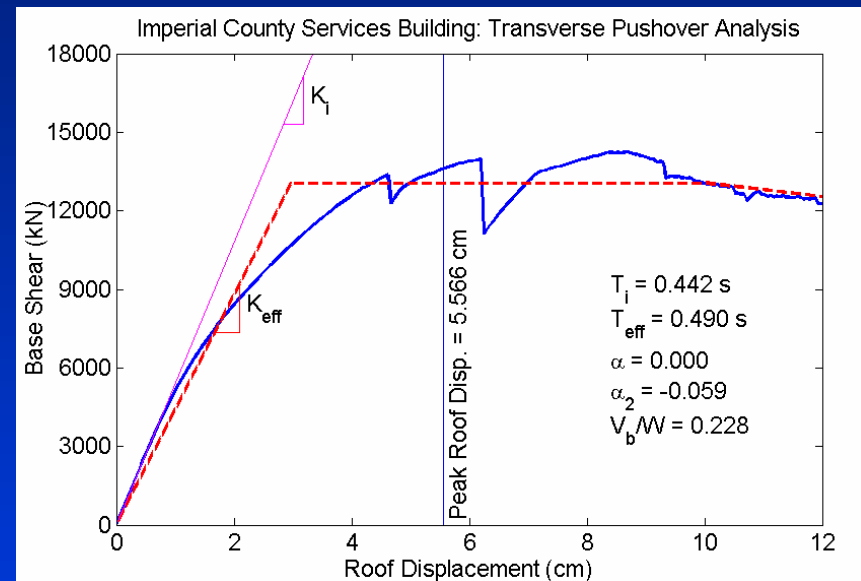
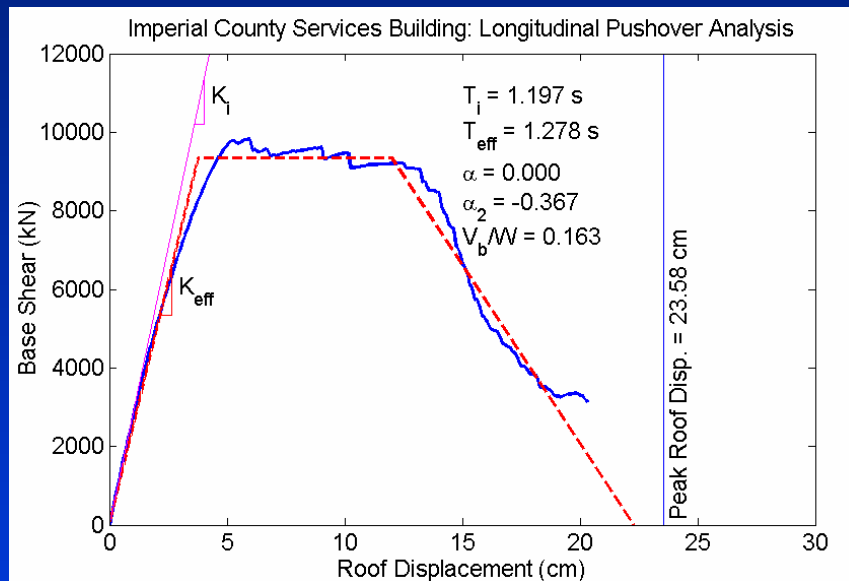
Results from NSP

Imperial County Services Building

- Longitudinal (E-W) direction:
Moment-resisting frame
- Transverse (N-S) direction:
Single-bay shear walls/moment-resisting frame in first story and end shear walls in upper stories
- Recorded motions available from 1979 Imperial Valley earthquake
- Building damaged during 1979 Imperial Valley earthquake and subsequently demolished



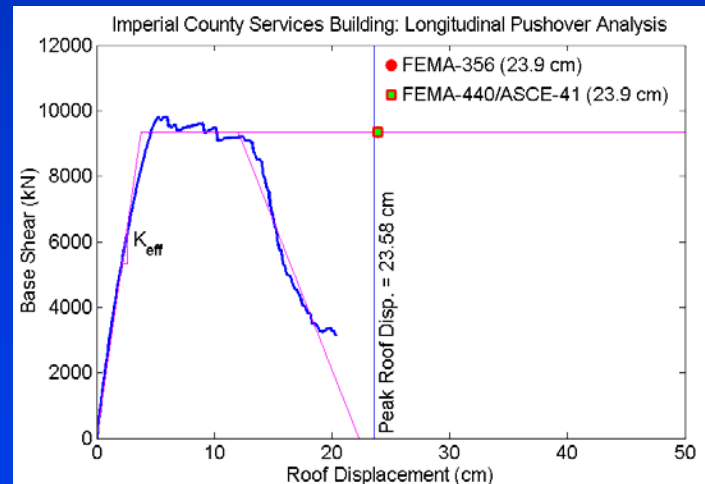
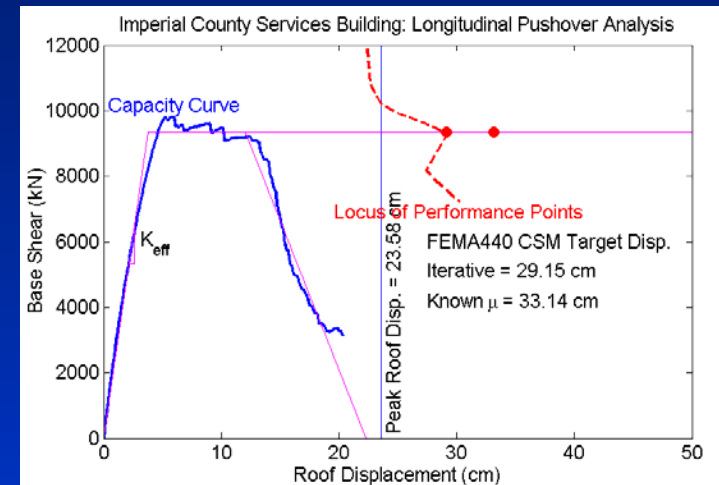
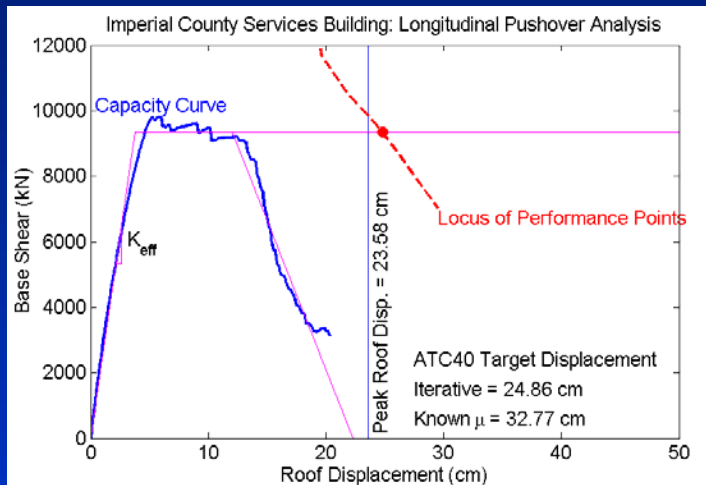
Pushover Curves and Recorded Peak Motions



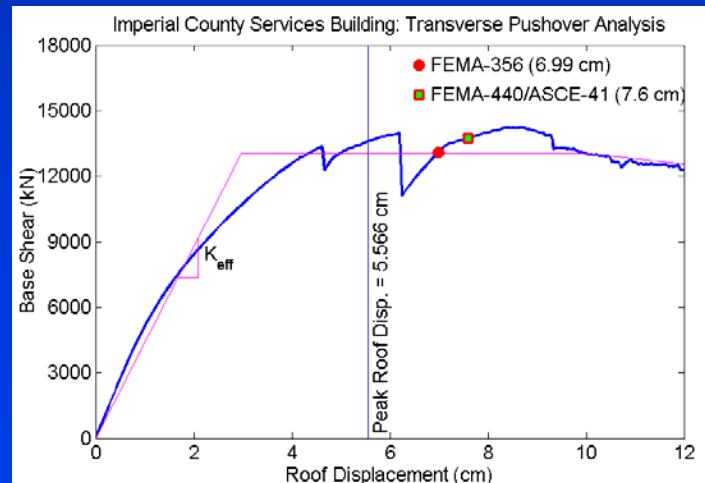
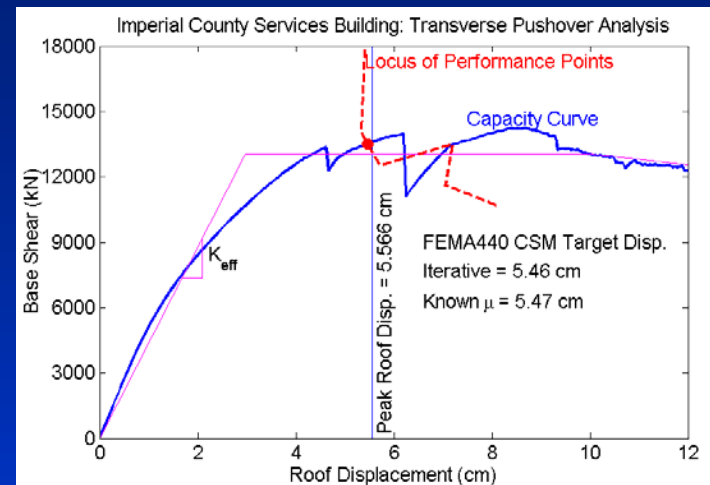
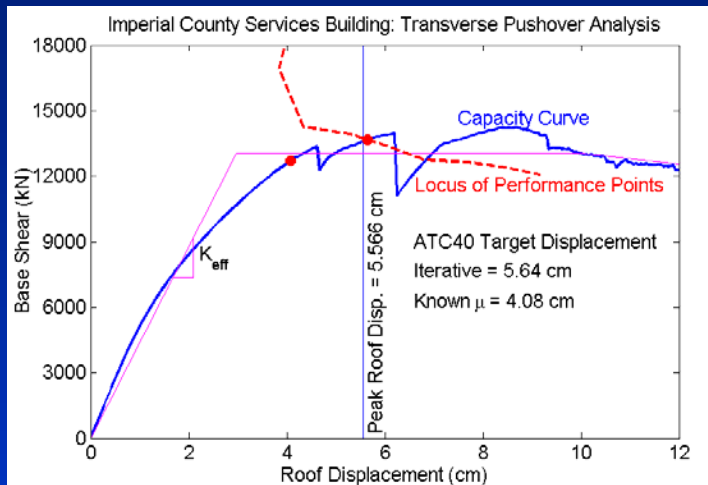
Pushover analysis indicates building collapse in longitudinal direction

ATC-9 report concluded that building collapsed due to motions in E-W (longitudinal) direction

NSP in Longitudinal Direction



NSP in Transverse Direction

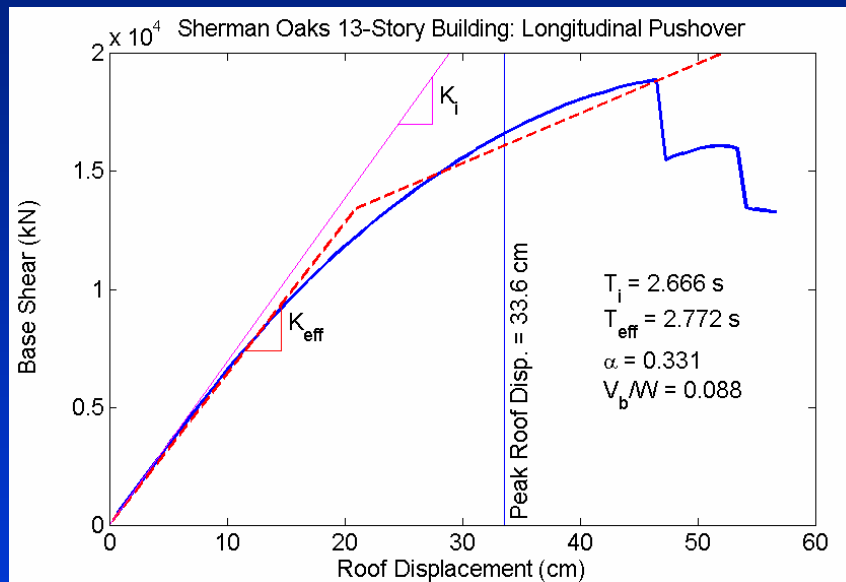


Sherman Oaks: 13-Story Commercial Building

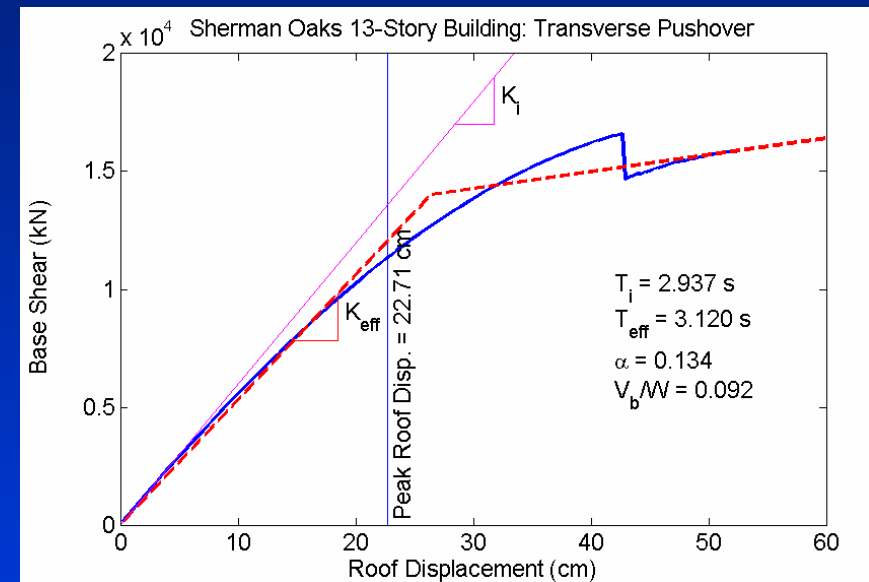
- Moment-resisting frame in both longitudinal (E-W) and transverse (N-S) directions
- Additional shear walls in basement in both directions
- Recorded motions available from 1994 Northridge earthquake
- Building damaged during 1994 Northridge earthquake and subsequently strengthened with friction dampers



Pushover Curves and recorded Motions

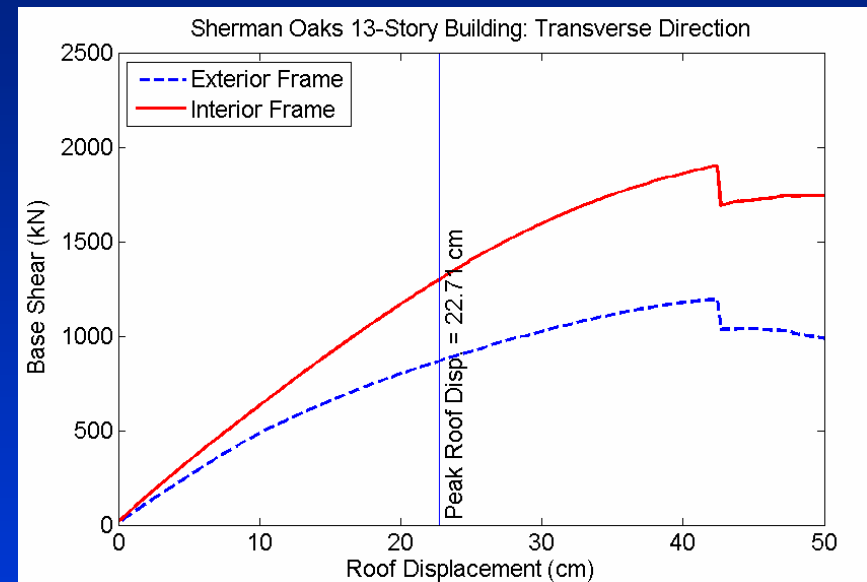
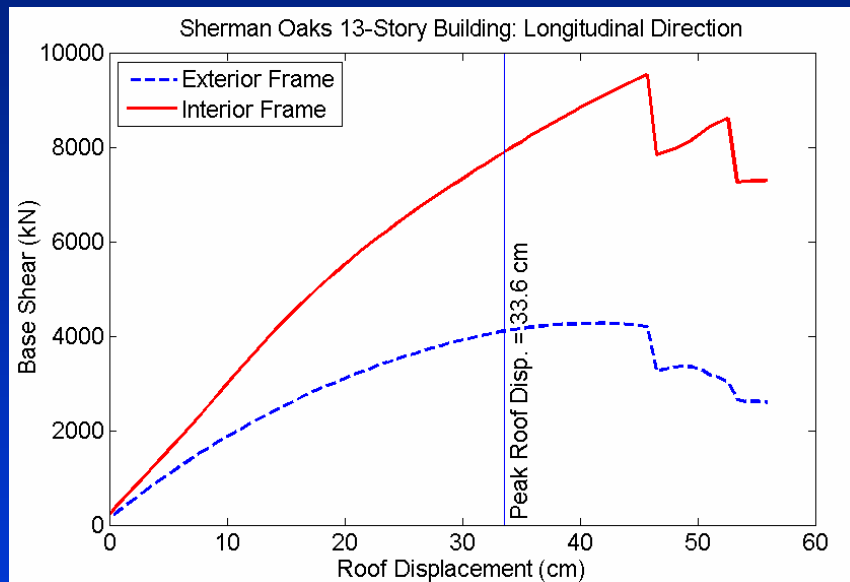


Building deformed beyond linear-elastic limit in E-W (longitudinal) direction



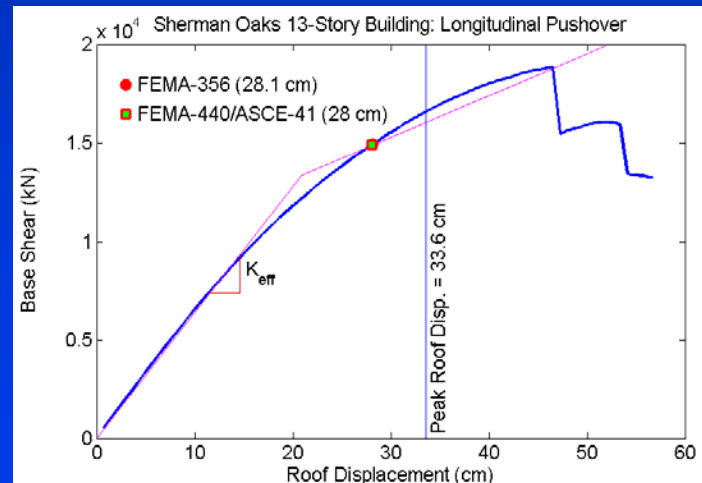
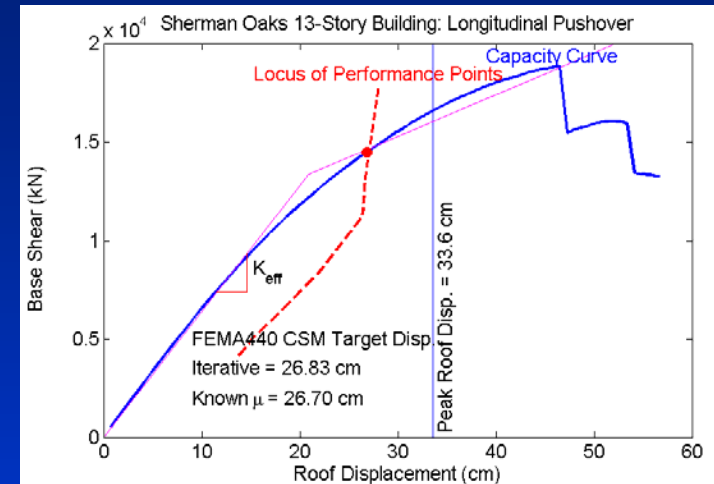
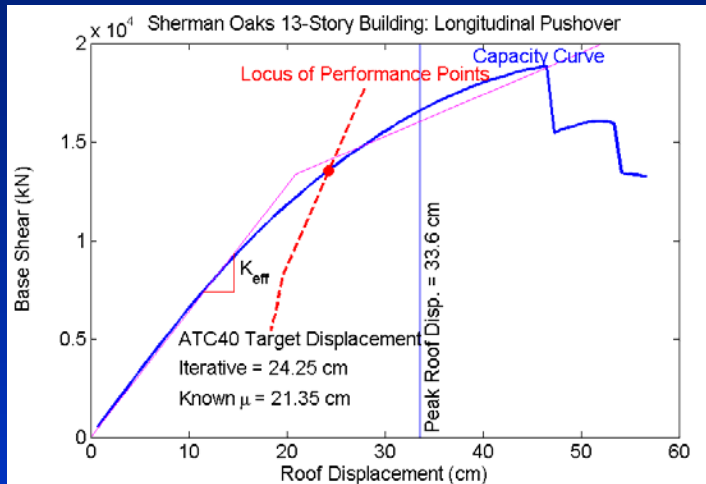
Building remained essentially elastic in N-S (transverse) direction

Relative Strength of Frames

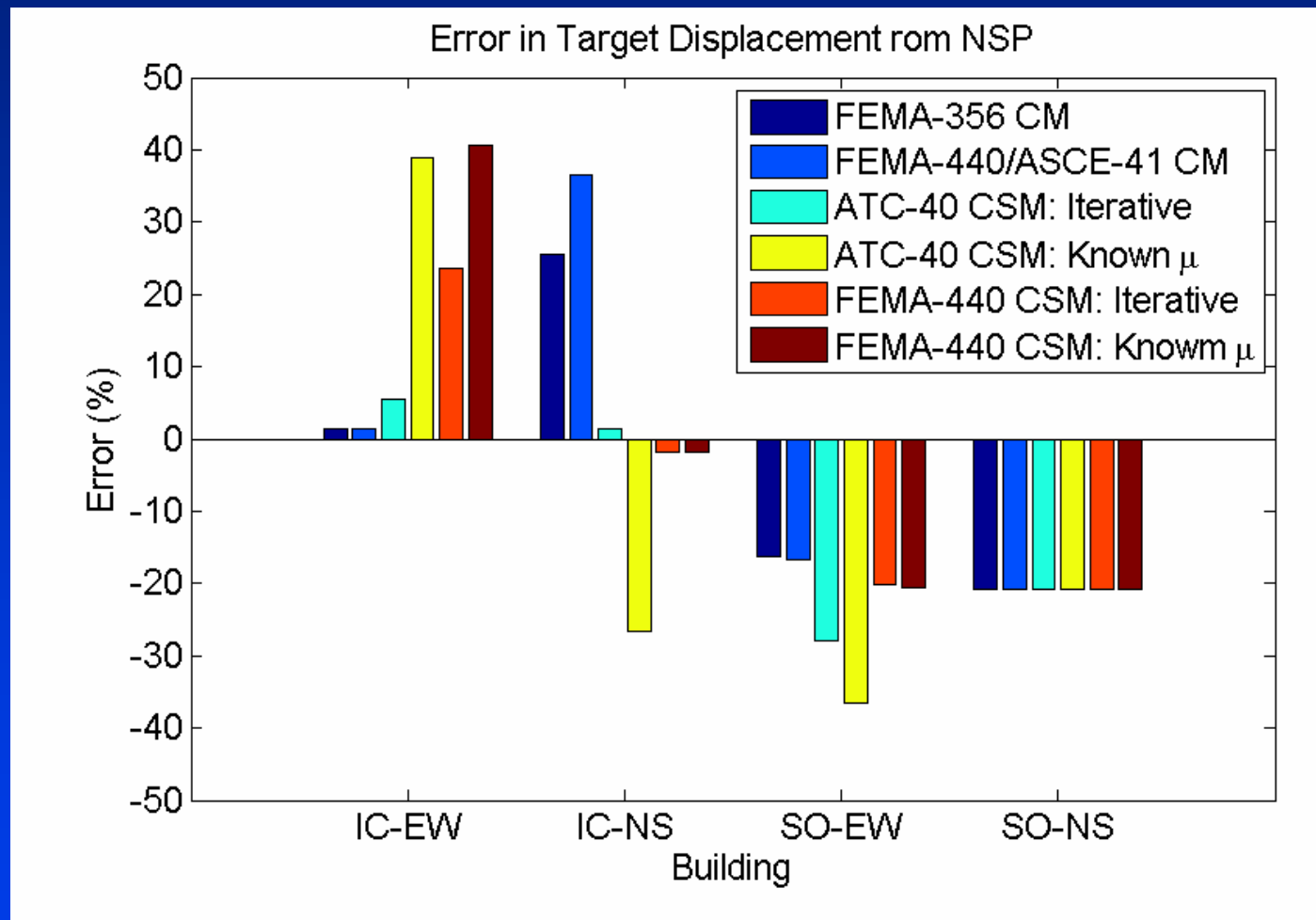


Exterior frames are much weaker in both direction and expected to experience some damage

NSP in Longitudinal Direction



Error in Target Displacement from NSP Compared to Recorded Motions



Summary

- Most NSP may lead to under- or overestimation of target displacement by twenty-percent compared to recorded motions
- FEMA-356 and FEMA-440/ASCE-41 CM provide generally similar target displacement
- ATC-40 and FEMA-440 CSM iterative procedure may provide different target displacement compared to that based on known ductility demand in buildings with recorded motions
- Pushover curve of the entire building may not reveal the level of inelastic behavior in all frames if the frame strength differs
- Analysis of additional buildings with recorded motions underway to add to the database