



DESIGN



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Analysis Procedures to Estimate Seismic Demands of Structures

Seismic Lessons Learned Panel Meeting

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Outline

Introduction

- Background
- Classification of Analysis Procedures

NSP

- Nonlinear Static Pushover

NDT

- Nonlinear Dynamic Time-history

MMP

- Multi-Mode Pushover

Conclusions

- Conclusions

Background

“The future effective use of performance-based engineering depends on the continued development of reliable and credible inelastic analysis procedures... ongoing research promises important modifications, improvements, and alternatives to current NSPs”

[FEMA 440 (2005), Improvement of Nonlinear Static Seismic Analysis Procedures]

Classification of Analysis Procedures

LSP – Linear Static Pushover

LDT – Linear Dynamic Time-history

NSP – Nonlinear Static Pushover

NDT – Nonlinear Dynamic Time-history

MMP – Multi-Mode Pushover

LSP and LDT

- LSP results can be very inaccurate for irregular structures, (FEMA 356)
- LSP can be applied to simple structures using $1.5G_{Peak}(S_a)$, (ASCE 4)
- LDT is more accurate than LSP, but can result in responses significantly different than nonlinear structural behavior.
- Nonlinear responses can approximately be accounted by F_μ , and damping.

NSP - Nonlinear Static Pushover

Advantages

- Simple analysis and has been widely used in industry.
- Can account for stiffness degradation.
- Simulates first mode behavior.
- Most validations are done for lateral behavior of tall buildings.
- Uses simplified displacement amplification factors.
- Computationally efficient
- Can use acceleration loading from prior linear dynamic analysis (Two step method).

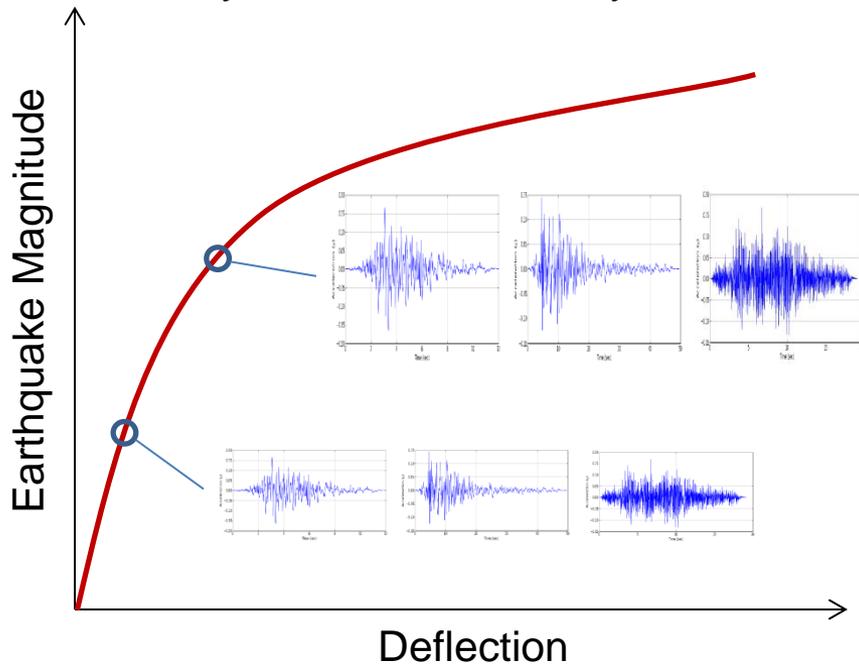
Disadvantages

- Approximate method.
- Multiple directional runs are needed.
- Inaccurate responses for irregular structures.
- Few studies are done on vertical responses.
- Doesn't account for higher mode responses.
- Inaccurate local responses such as joint rotations.
- Doesn't typically account for changes in dynamic responses due to structural degradation.
- Simplified displacement amplification factors with limiting values can result in inaccurate responses.

NDT - Nonlinear Dynamic Time-history

Advantages

- Widely recognized as the best predictive procedure to simulate nonlinear response.
- 3 directions of motions can be analyzed simultaneously



Disadvantages

- Computationally expensive.
- Requires experience to perform nonlinear analysis.
- Complexity with modeling details; material hysteresis, partial collapse.
- Can be impractical for complex structural systems.
- Limited ability to capture elastic system damping.
- Response depends on selected time history sets.
- Probabilistic or averaging of multiple sets may need to be used to address the variability.
- Evaluations may require evaluations at multiple demand levels.

Variability of Collapse as a Function of Input ground Motions

Moehle, Ghannoum, and Bozorgnia (2004)

- 3-Bay, 3-story RC frame model is subjected to seven ground accelerations recorded during the 1994 Northridge.
- Chosen records from a single earthquake to exclude the earthquake-to-earthquake variability.
- Selected record sites in the same general area to reduce spatial variability.
- Response is sensitive to the ground motions, with responses varying from almost no yielding of longitudinal steel to total collapse.

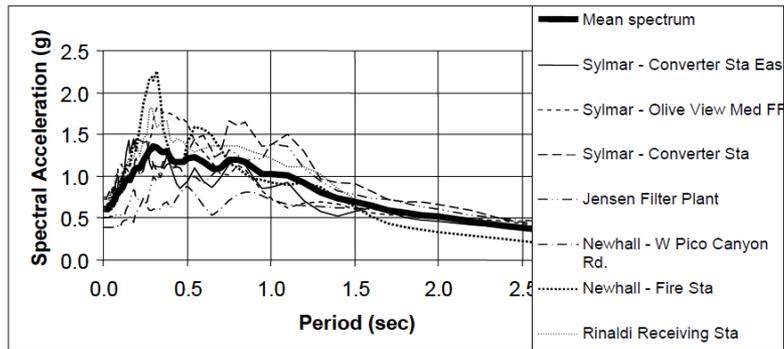
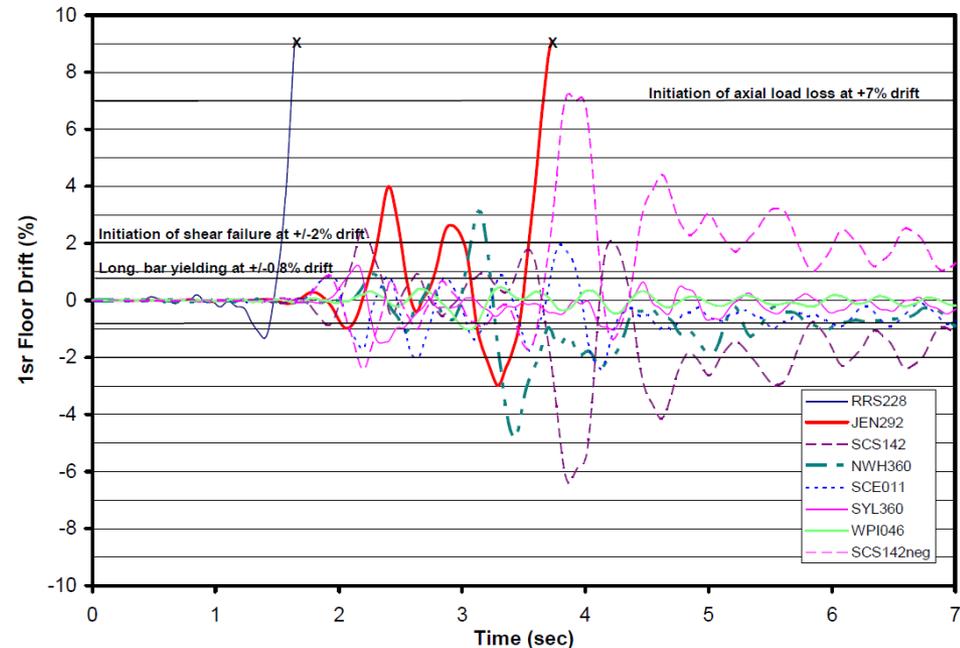


Figure 4.3 Response spectra for 5% damping of the selected 1994 Northridge records. The spectra are for the geometric mean of the two horizontal components.



MMP – Multi-Mode Pushover

Advantages

- Accounts for higher mode responses and local behaviors.
- Can simulate adaptive structural nonlinear ductile behavior.
- Can simulate site-specific displacement amplification factors.
- More accurate than NSP, and more efficient and practical than NDT for large models.
- Validations are done primarily for lateral responses of tall structures.

Disadvantages

- No single method has been accepted for general use.
- Requires validation for general use.
- Approximate method.
- Multiple directional runs are needed.
- Not many studies are done on vertical responses.
- Computationally more demanding than NSP for complex structures.

Representative Proposed MMP methods

- Elnashai (2002), Antoniou et al. (2002), FEMA 273 (1997), ATC-40 (1996) proposed a simple approach which considers a single seismic load pattern intended to capture the effect of multi-mode response by selecting the loading pattern based on a combination of multiple modes.
- Chopra and Goel (2000) proposed an equivalent SDOF time domain analyses for determination of modal demands (also acknowledge a spectral based estimation of demand).
- Gupta and Kunnath (2000), Chopra (2001), and many others proposed rigorous approaches involve calculating the response of each modal pushover separately then combining the effects.

Representative Proposed MMP methods

- Kalkan and Kunnath (2006) proposed an adaptive modal pushover analysis based on incremental loading and combination (adaptive coupled). Displacement is based on pushover with step size based on constant energy. Demand is based on matching modal pushover curves to constant ductility spectra at the pushover ductility.
- Aydinoglu (2003) proposed displacement based pushover analysis based on equal displacement / equal energy approximation (also used in ATC 40 and FEMA 440) for use in modal scaling for pushover increments
 - Modal pushover based on elastic spectral displacement scaled by mass participation (equal displacement approximation) considering amplification factors
 - Incremental loading
 - Evaluation stress state at each increment
 - Inelastic seismic demand is evaluated at the estimated spectral displacement
 - Does not rely on time history methods

Representative Proposed MMP methods

Kalkan and Kunnath (2006)

- Figure on left shows pushover curve for a mode
- Figure on right shows matching the pushover curve to inelastic demand spectra defined in acceleration-displacement space

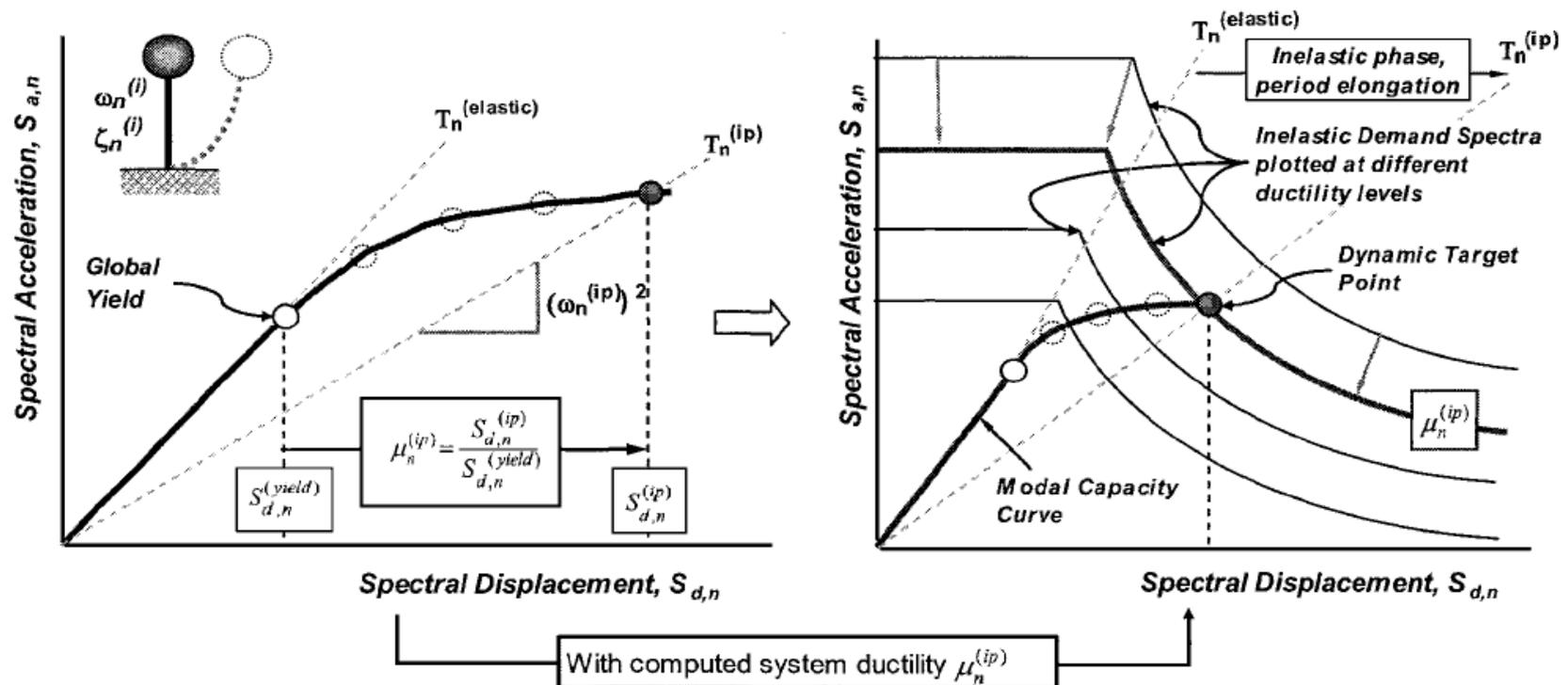


Fig. 2. Performance point evaluation using system ductility through a set of inelastic spectra

Increment Adaptive Modal Superposition

- The approach is theoretically based on incremental piecewise approach to nonlinear time history analysis.
- Assuming that increments are small and within an increment the stiffness and mass matrices are constant, the incremental motion can be resolved into incremental modal components.
- The approach relies on the assumption that the increment step size is taken small enough such that the modal matrix can be assumed to not change within the increment.
- The response is resolved similarly to a response spectrum analysis within each increment. Each increment include loading the modal load shapes for a static pushover step and recombination using the complete quadratic procedure.

Incremental MMP Pushover Methodology Implemented for PF-4

Start

Apply non-seismic loads to unstressed structure

Select pushover direction and mode shape for seismic sign to update stiffness

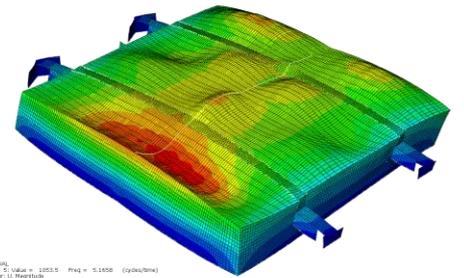
Update component stiffnesses based on latest strain state

Combined non-seismic and seismic load effects including seismic soil pressure.

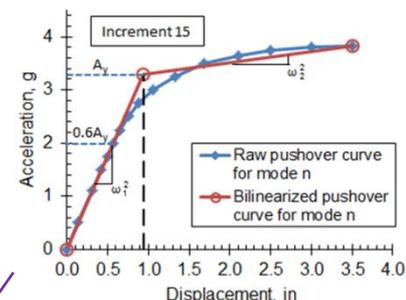
Extract natural frequencies and mode shapes and perform mode tracking

Perform response spectrum analysis, modal CQC, directional combination, & compute structural responses

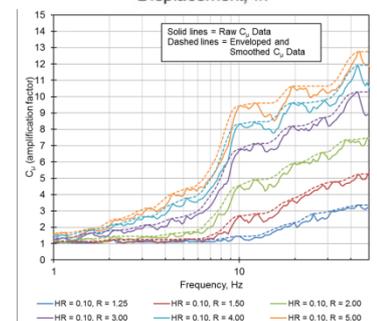
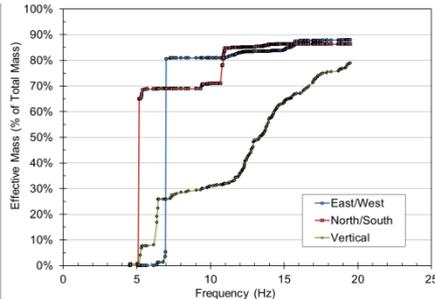
Calculate displacement amplification factor and acceleration to be applied to each mode



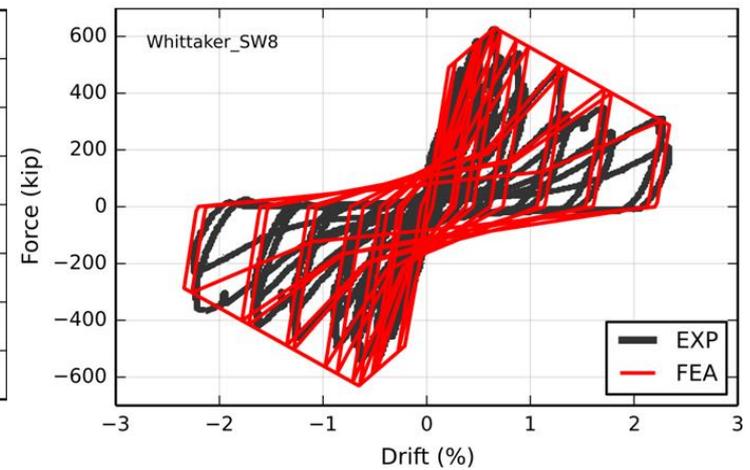
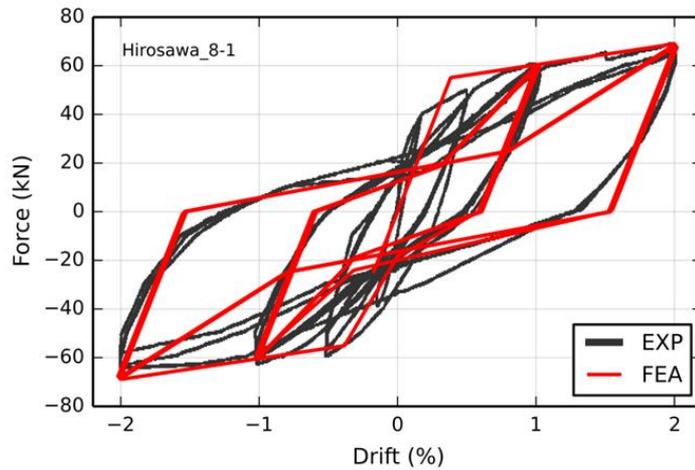
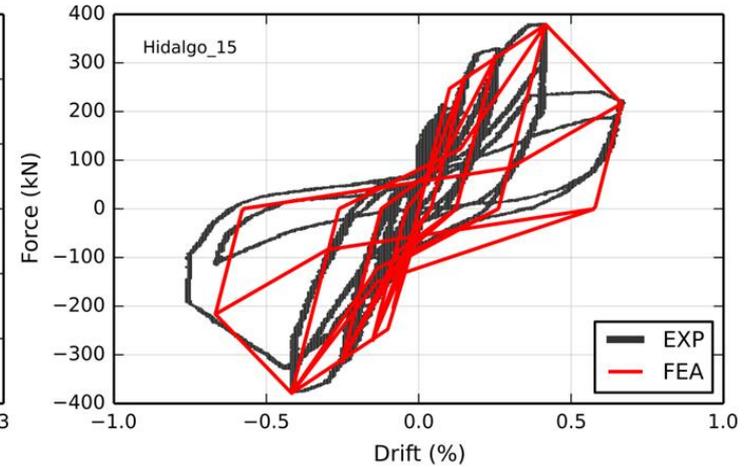
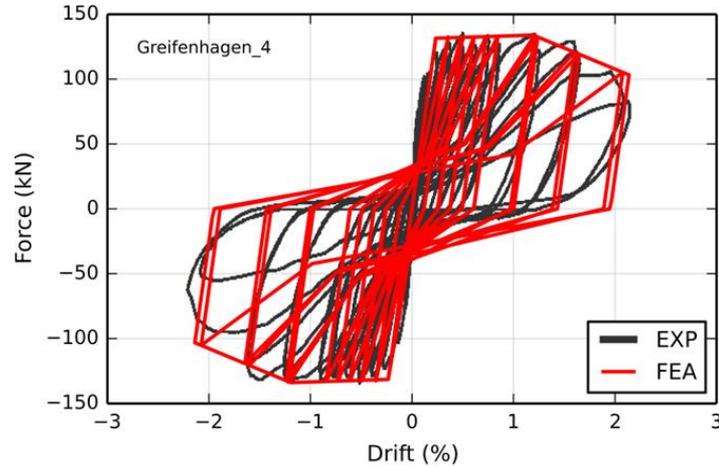
Step: MODAL, Mode: 5, Value = 1053.5, Period = 5.14588 (cycles/revs), Primary Var: U, Magnitude, Defined var: U, Displacement Scale Factor: +3.000e+02



$$R = 1.0|R_1| + 0.4|R_2| + 0.4|R_3|$$



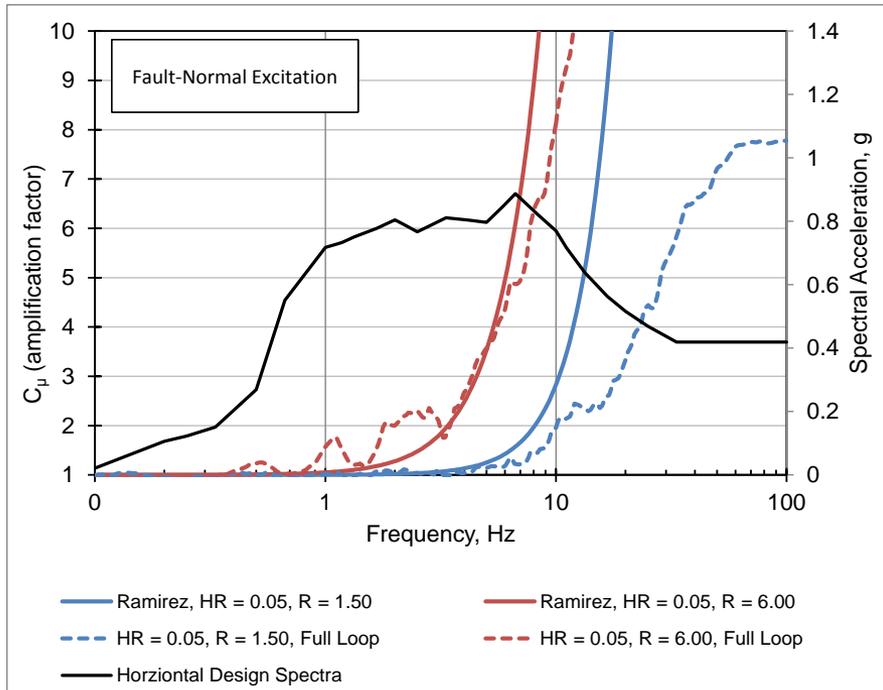
IMK Validation against test result



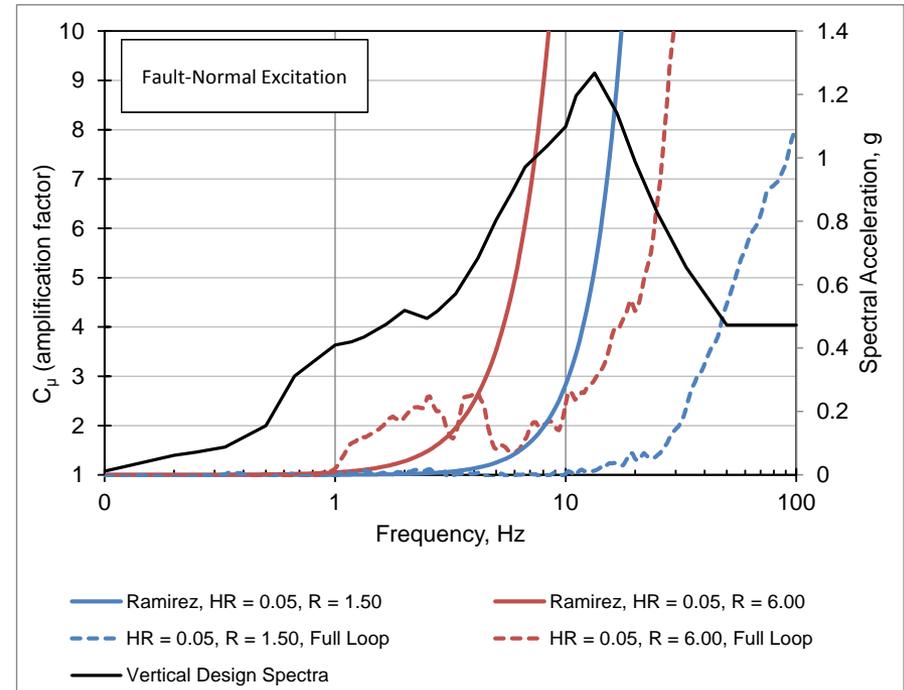
Displacement Amplification Factor

- Displacement amplification factors based on FEMA 356, FEMA 440, or alternate methods are intended to be code friendly and are based on typical design spectra.
- A site-specific and structure specific displacement amplification factors may be calculated
 - Performing time response history analyses for an elastic single degree of freedom (SDOF) model and for a nonlinear SDOF model with damaged hysteresis having the same initial stiffness but with a bilinear non-linear representation.

C_{μ} Comparisons to Ramirez



Horizontal

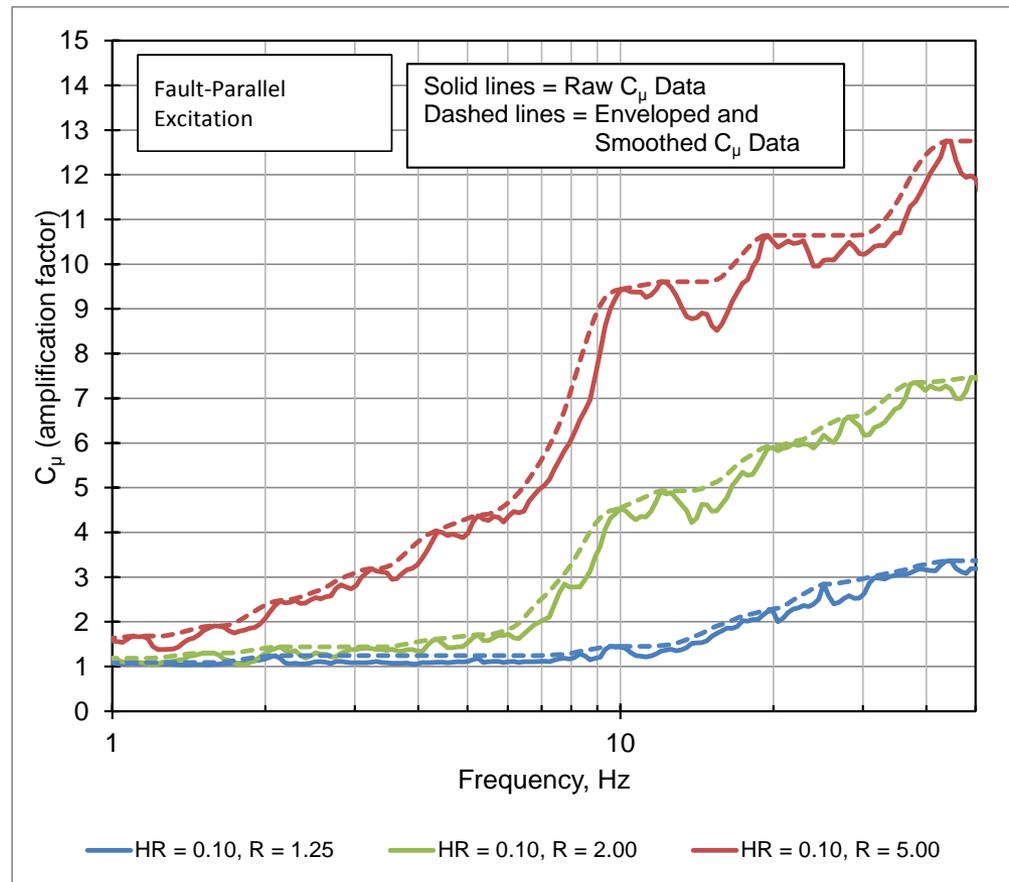


Vertical

- Ramirez C factors are derived from many time histories based on a spectra with peak accelerations between 1 and 10 Hz.
- PF-4 horizontal matches relatively well because the spectra also has a peak between 1 and 10 Hz.
- PF-4 vertical differs because the peak is around 15 Hz and no plateau.

C_{μ} Enveloping and Smoothing

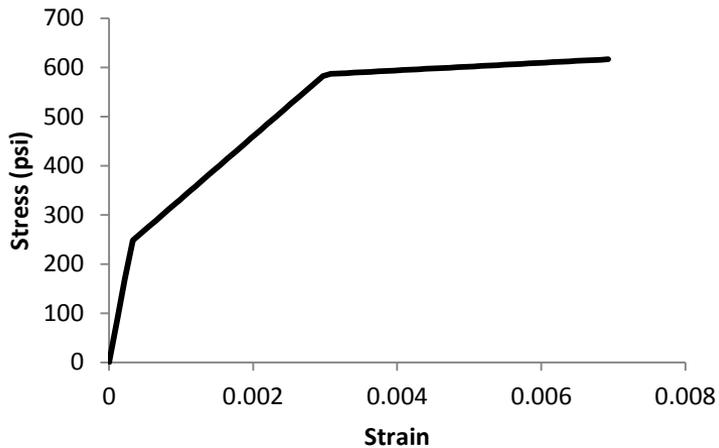
- Displacement amplification factors (C_{μ}) can have large variation between two relatively close frequencies, leading to sensitivity in response.
- C_{μ} factors have been recalculated using enveloping and smoothing.



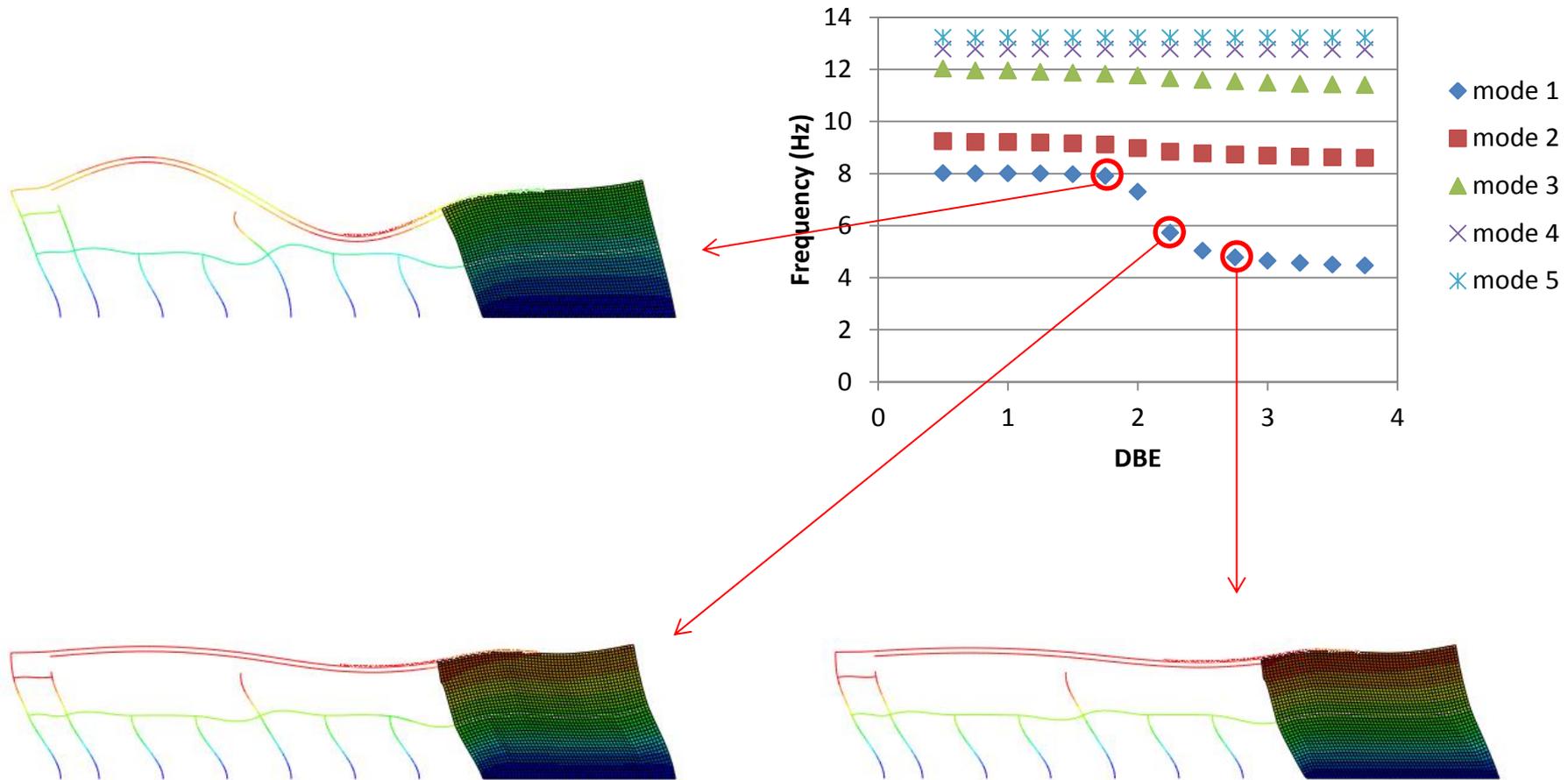
Shifting of Structural Frequencies

- Nonlinearity in shear wall
- 14 Increments (first is 0.5x remainder are 0.25x, total of 3.75x)
- 5 Modes per increment

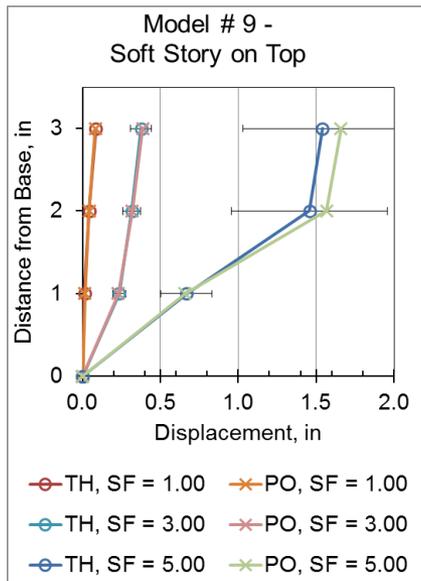
Input Shear Wall Backbone Curve



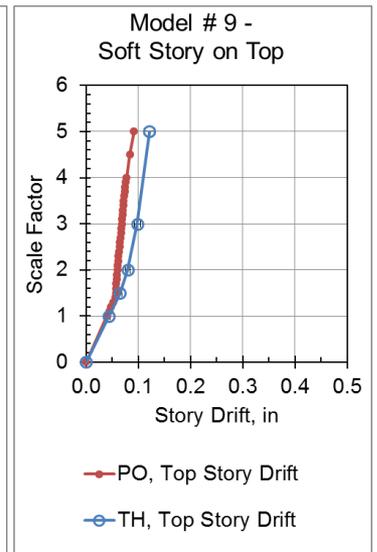
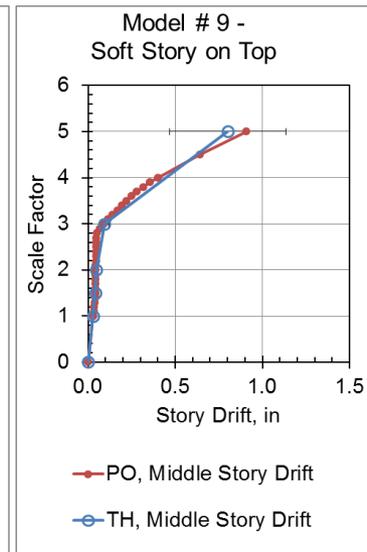
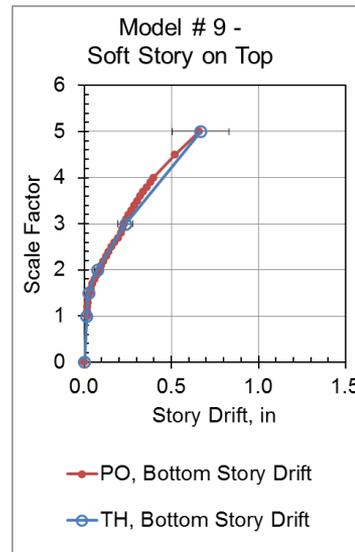
Shifting of Structural Frequencies



3 DOF Validation Example



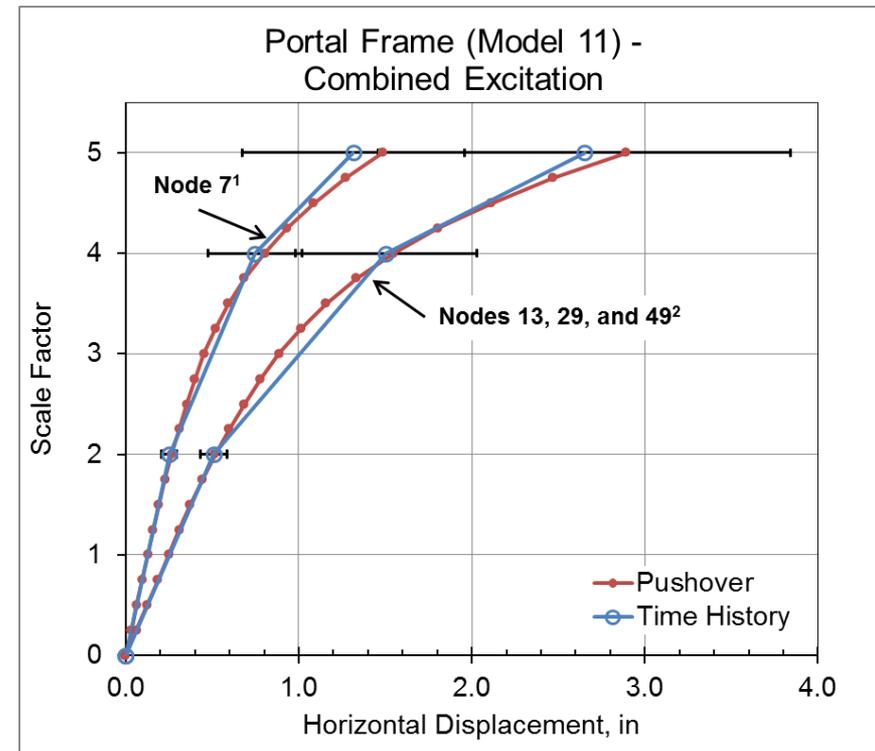
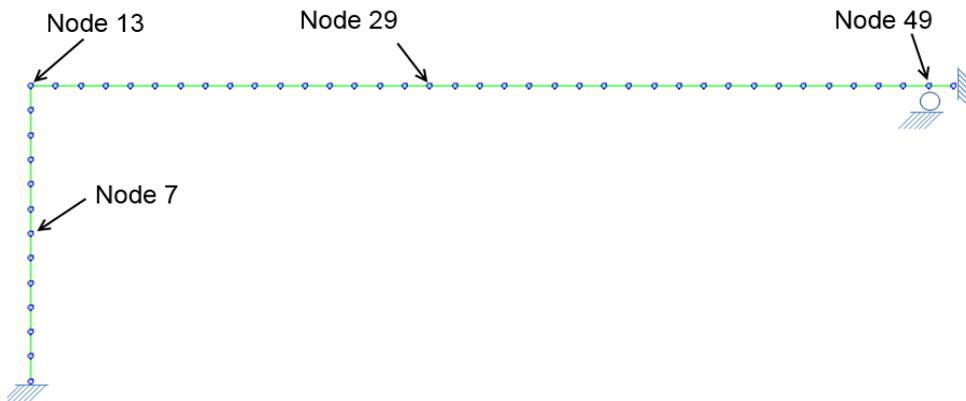
Deformed shape
comparisons at
different scale
factors



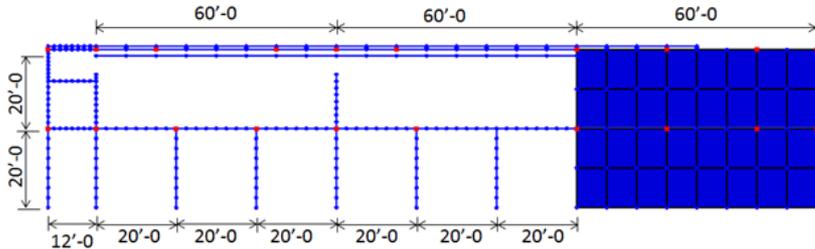
Story drift comparisons for bottom, middle, and
top story at different scale factors.

Portal Frame Validation Example

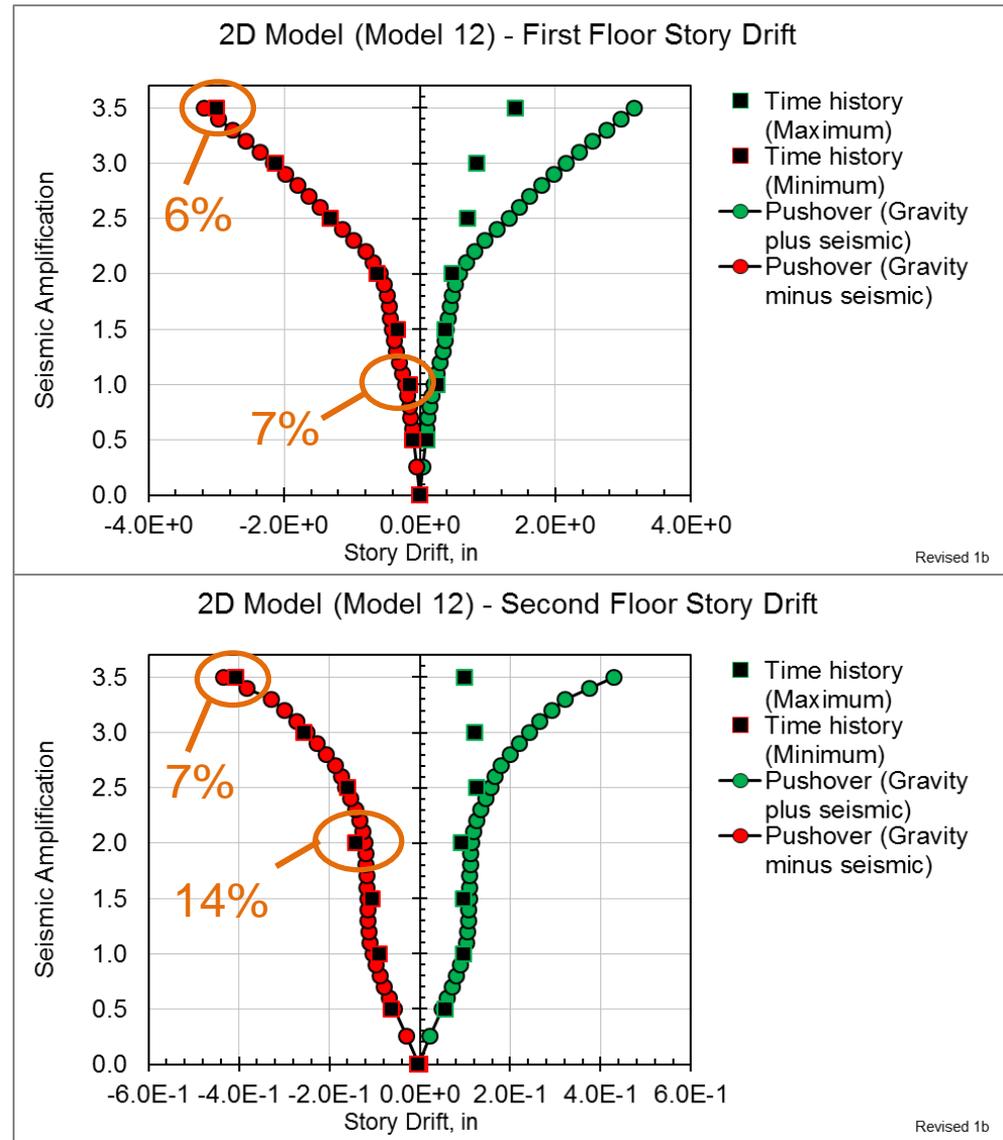
- Displacements at the mid-height of the column (Node 7) and top of the column (Node 13) are compared to time history results



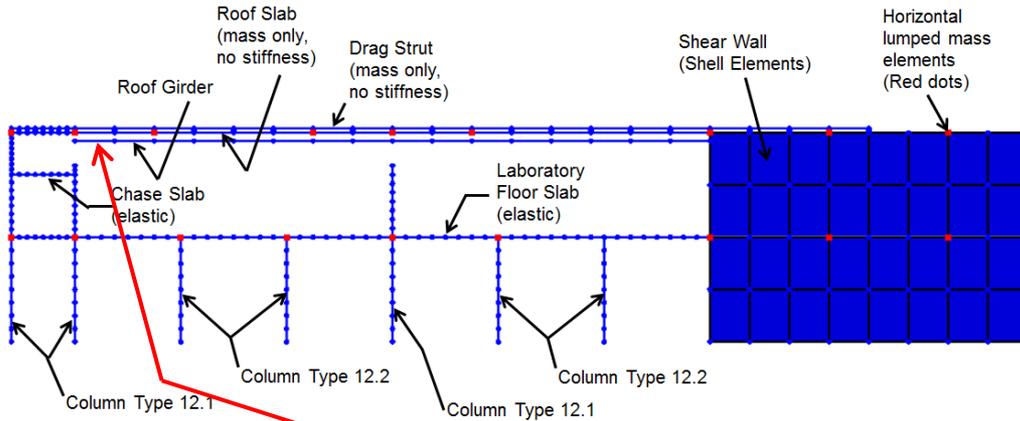
2D Model Validation Example



- The pushover matches time history story drifts with a maximum of percent difference of 7% and 14% for the first and second stories, respectively.

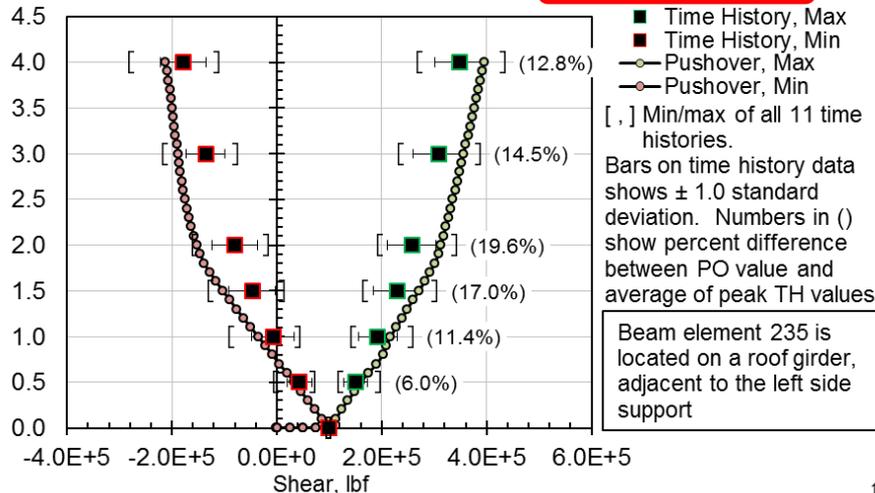


2D Model Validation Example

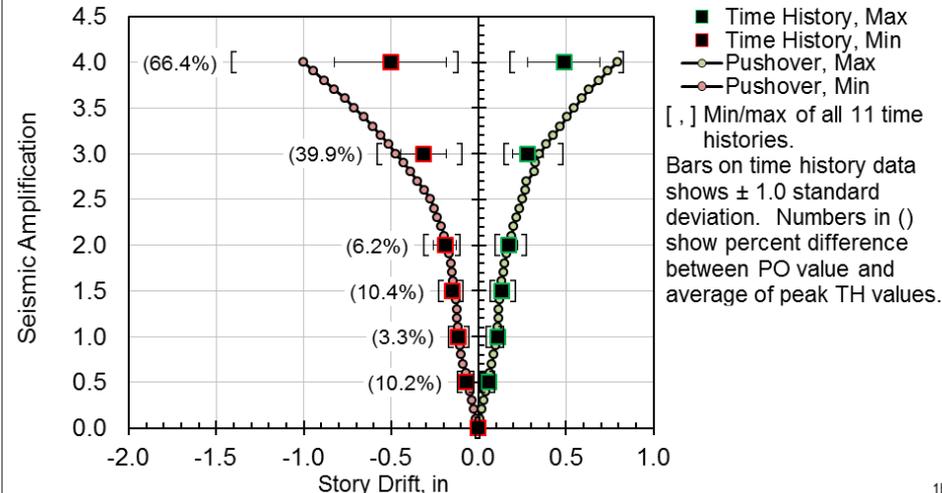


- In the linear range, the pushover matches generally matches the average of the 11 time histories.
- When the structure is nonlinear, the pushover generally meets or exceeds the mean + one standard deviation (84th percentile) of the 11 time histories.

2D Model (Model 13) - Shear Force in **Beam Element 235**



2D Model (Model 13) - Second Floor Story Drift



Conclusions

- LSP and LDT are useful design tools for new regular structures with sufficient ductile details.
- NDT can be impractical for fragility analyses for nonlinear complex structures without ductile details, even with today's high-performance computers.
- MMP is more accurate than NSP for irregular structures with higher mode effects.
- MMP with proper validation is a reliable and credible inelastic analysis procedure, and should be considered for response calculations.