Fast Nonlinear Seismic SSI Analysis of Nuclear Structures in Complex Frequency Domain
- A Breakthrough Development -

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October 1, 2013

Purpose of This Presentation:

The presentation shows a novel nonlinear SSI approach for modeling of nonlinear hysteretic behaviors of reinforced concrete structures in the complex frequency domain.

The new approach can be used to perform fast and accurate nonlinear SSI analyses, including sophisticated nonlinear hysteretic models, at a small fraction of the runtime of a time domain nonlinear SSI analysis.

A case study of a nuclear shearwall building is presented in relative detail.

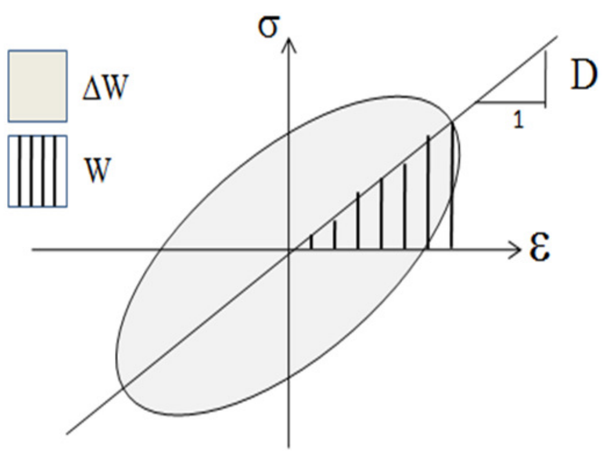
ACS SASSI Option N was used for nonlinear SSI analysis.

Equivalent-Linear System in Complex Frequency

Based on the up-to-date literature, the nonlinear behavior of dynamic structural systems can be captured only by nonlinear time history analyses.

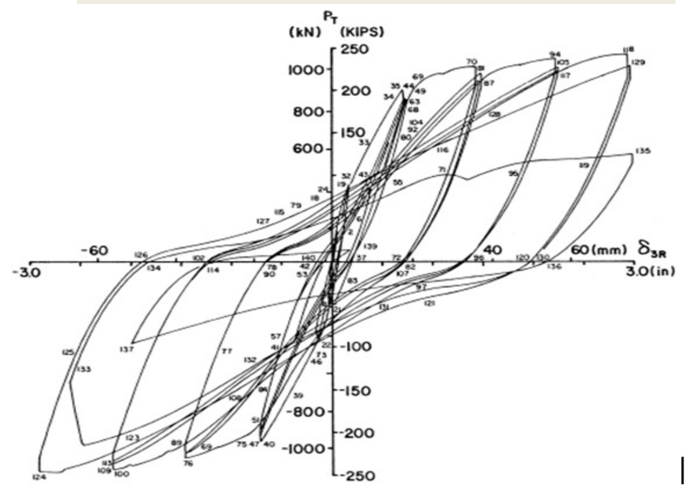
Only simple equivalent linear (EQL) approaches were applied in frequency domain. As a result of the EQL model *time invariant behavior*, the SSI response could be either over or under estimated at different time moments.

Linear Hysteretic Model



Frequency Domain
(Time-Invariant System)
(Frequency-Invariant)

Non-Linear Hysteretic Model



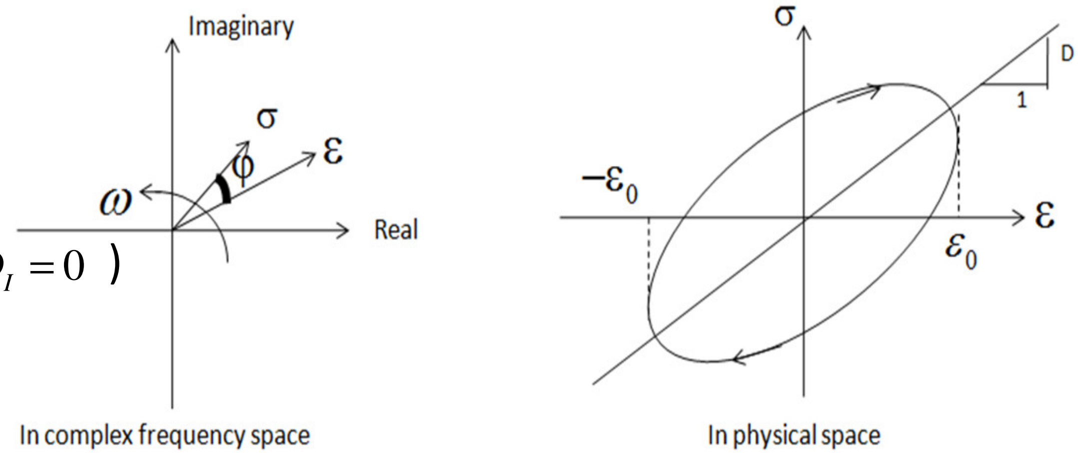
Time Domain
(Time-Dependent System)
(Frequency-Dependent)

Linear Hysteretic (Voigt) Model in Complex Frequency

In complex frequency, Hooke Law is:

$$\sigma^*(\omega) = D^*(\omega)\varepsilon^*(\omega)$$

$$D^*(\omega) = D_R + iD_I$$ (for elastic solid $D_I = 0$)



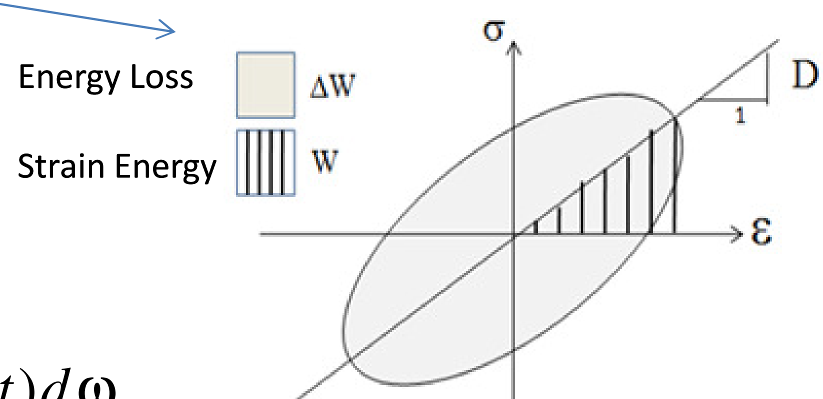
Visco-Elastic Material Model

Linear Hysteretic Model Parameters:

$$\beta = \frac{1}{4\pi}\frac{\Delta W}{W}$$

$$D^* = D_R\left(1 - 2\beta^2 + 2i\beta\sqrt{1-\beta^2}\right)$$

real part imag part



In time domain, using Fourier duality:

$$\sigma(t) = \sigma_{elast}(t) + \sigma_{diss}(t)$$

$$\sigma_{elast}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} D_R(\omega)\varepsilon^*(\omega)\exp(-i\omega t)\,d\omega$$

$$\sigma_{diss}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} D_I(\omega)\varepsilon^*(\omega)\exp(-i\omega t)\,d\omega$$

Using Fourier duality linear (nonlinear) time response can be mapped in a complex frequency response and vice-versa.

Nonlinear Hysteretic Models in Time and Frequency

To map a linear system response time history we need a linear (frequency-independent) hysteretic model.

To map a nonlinear system response time history we need a nonlinear(frequency-dependent) hysteretic model.

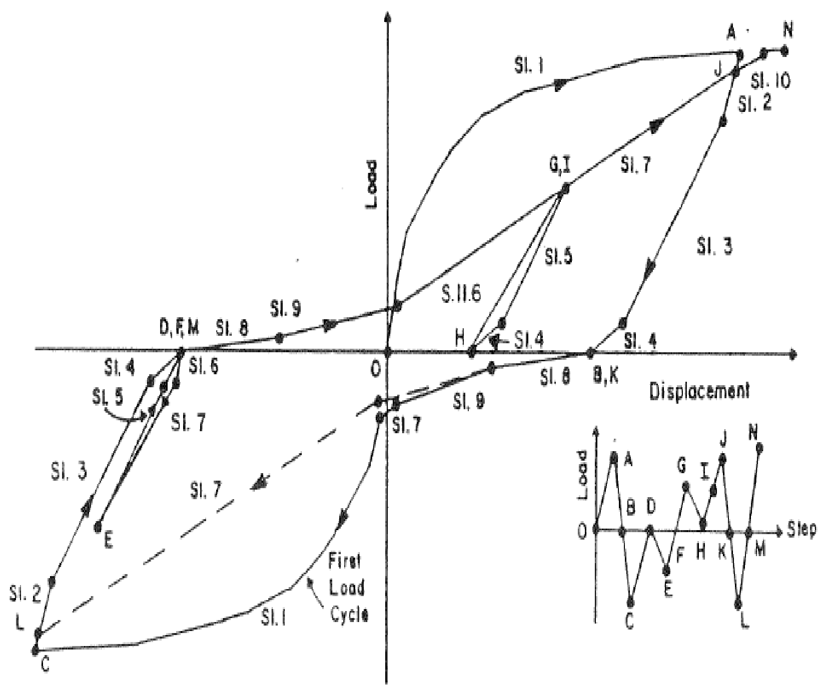
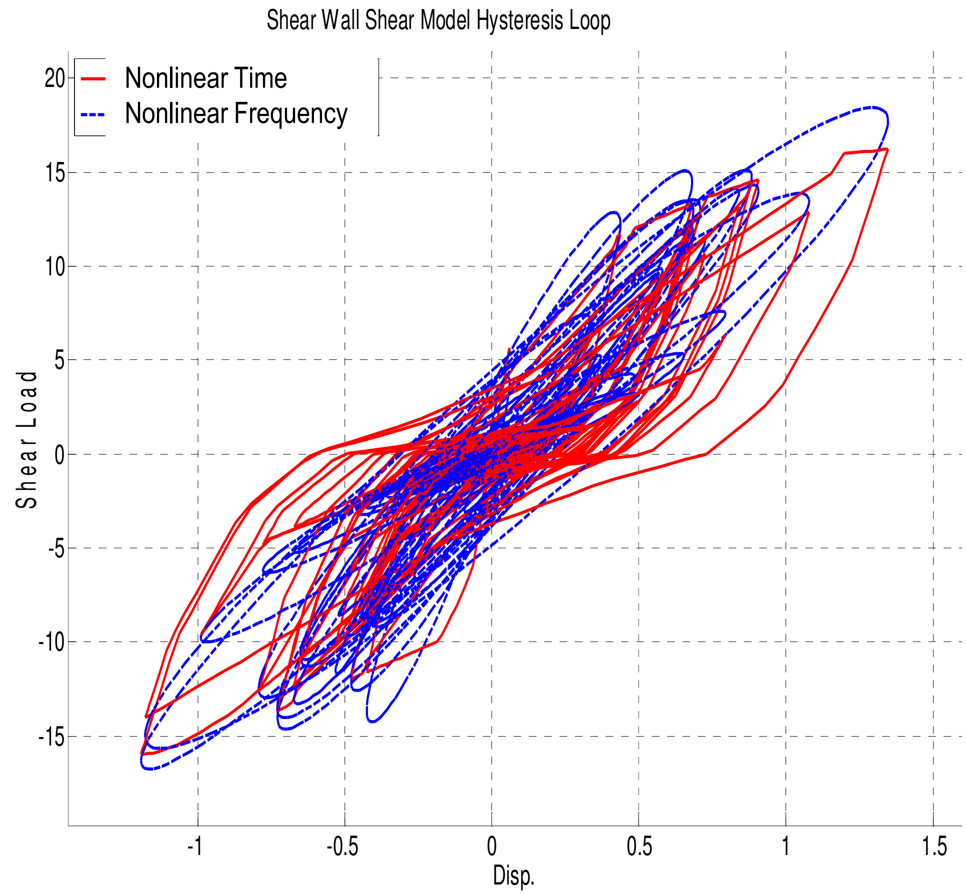
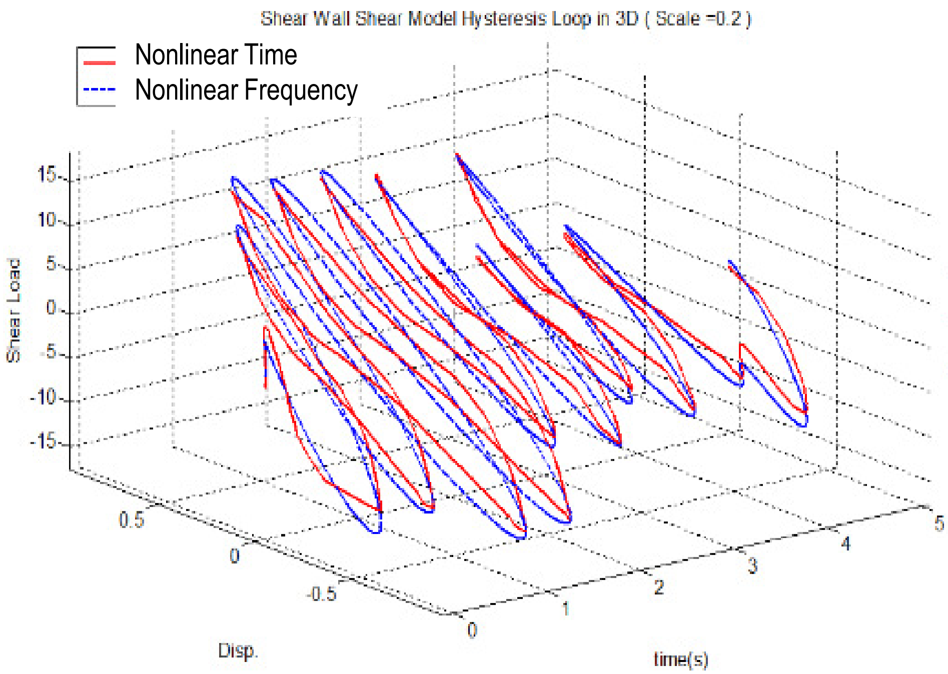


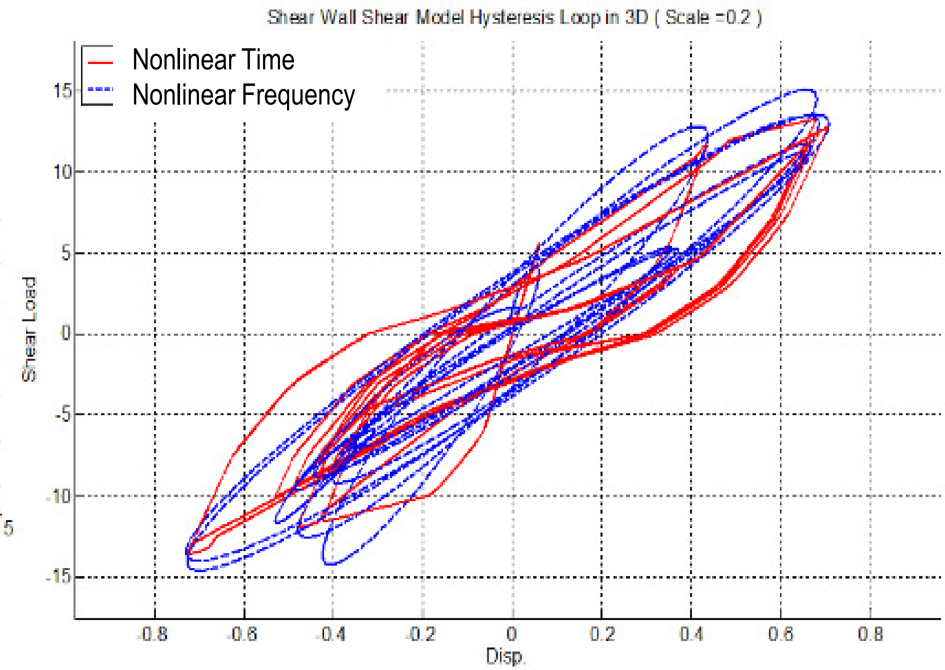
Figure 5b. Shear hysteresis model



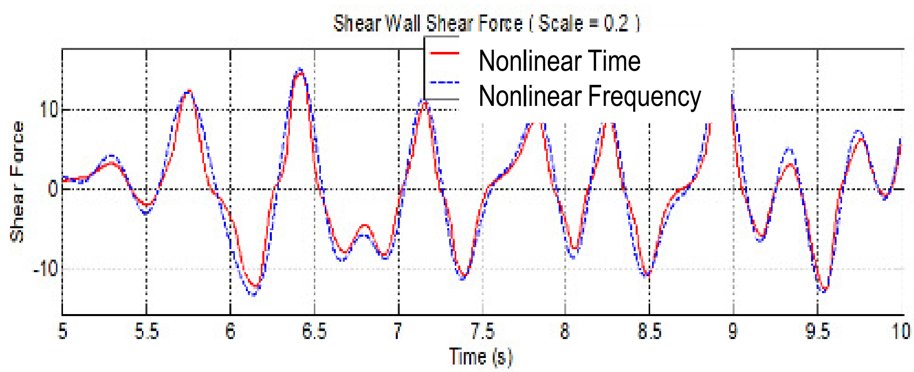
Nonlinear Hysteretic Model in Complex Frequency



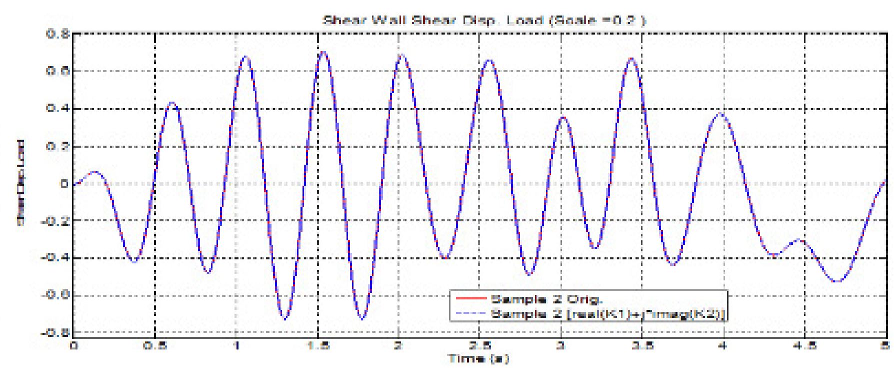
Comparison Hysteretic Loops in Time-Domain



Comparison of the Two Nonlinear Hysteretic Models



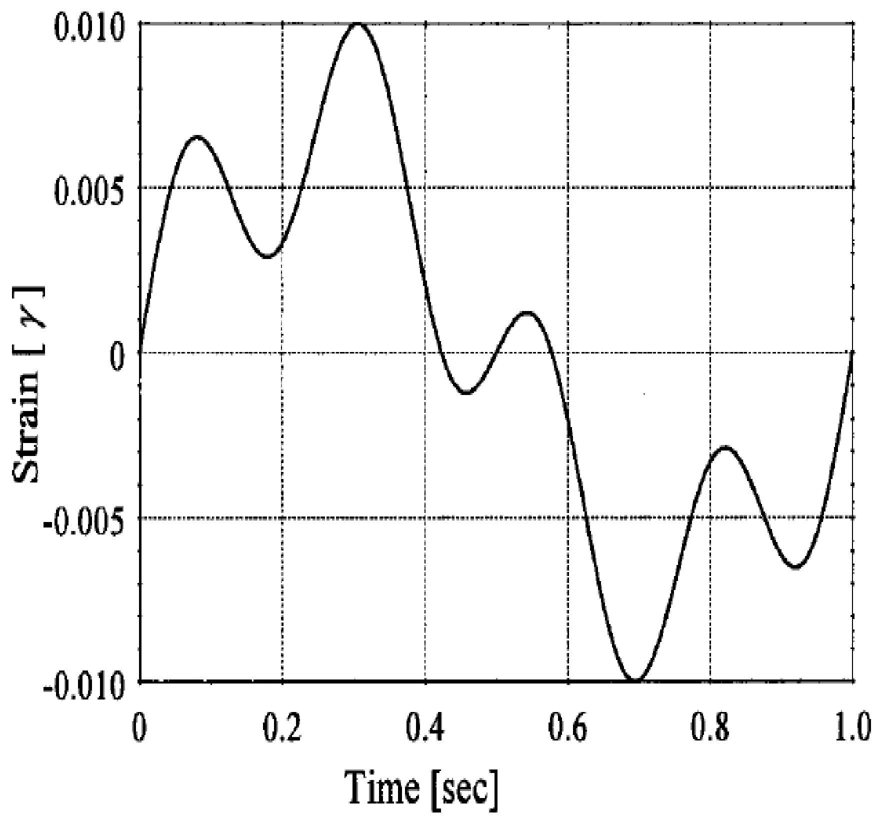
Shear force in time



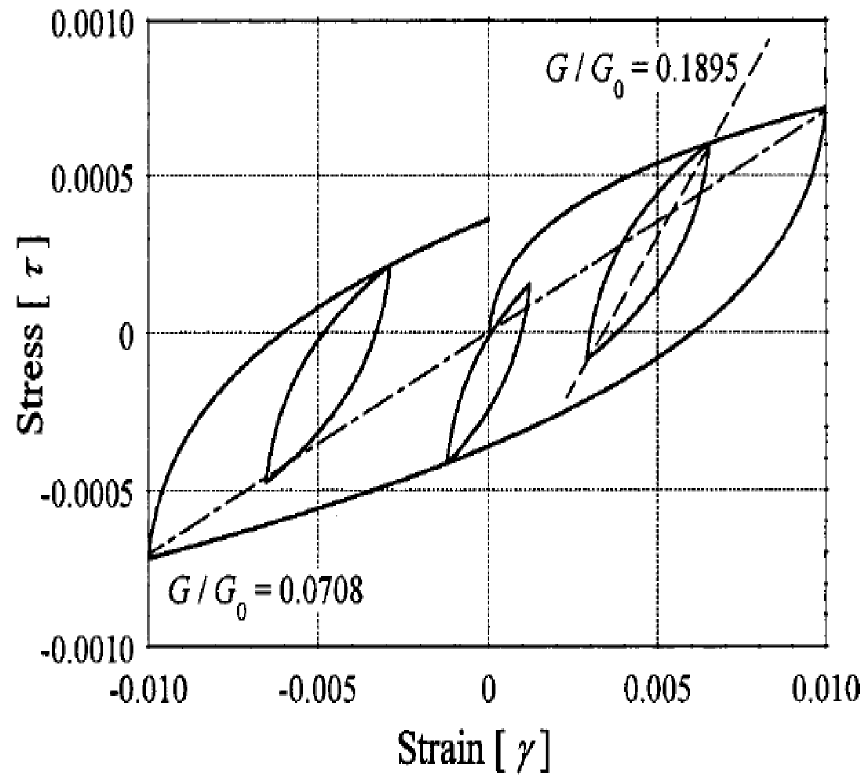
Displacement

Frequency-Dependent Linearized Hysteretic Models in Complex Frequency: Kausel-Assimaki Model

Time Response

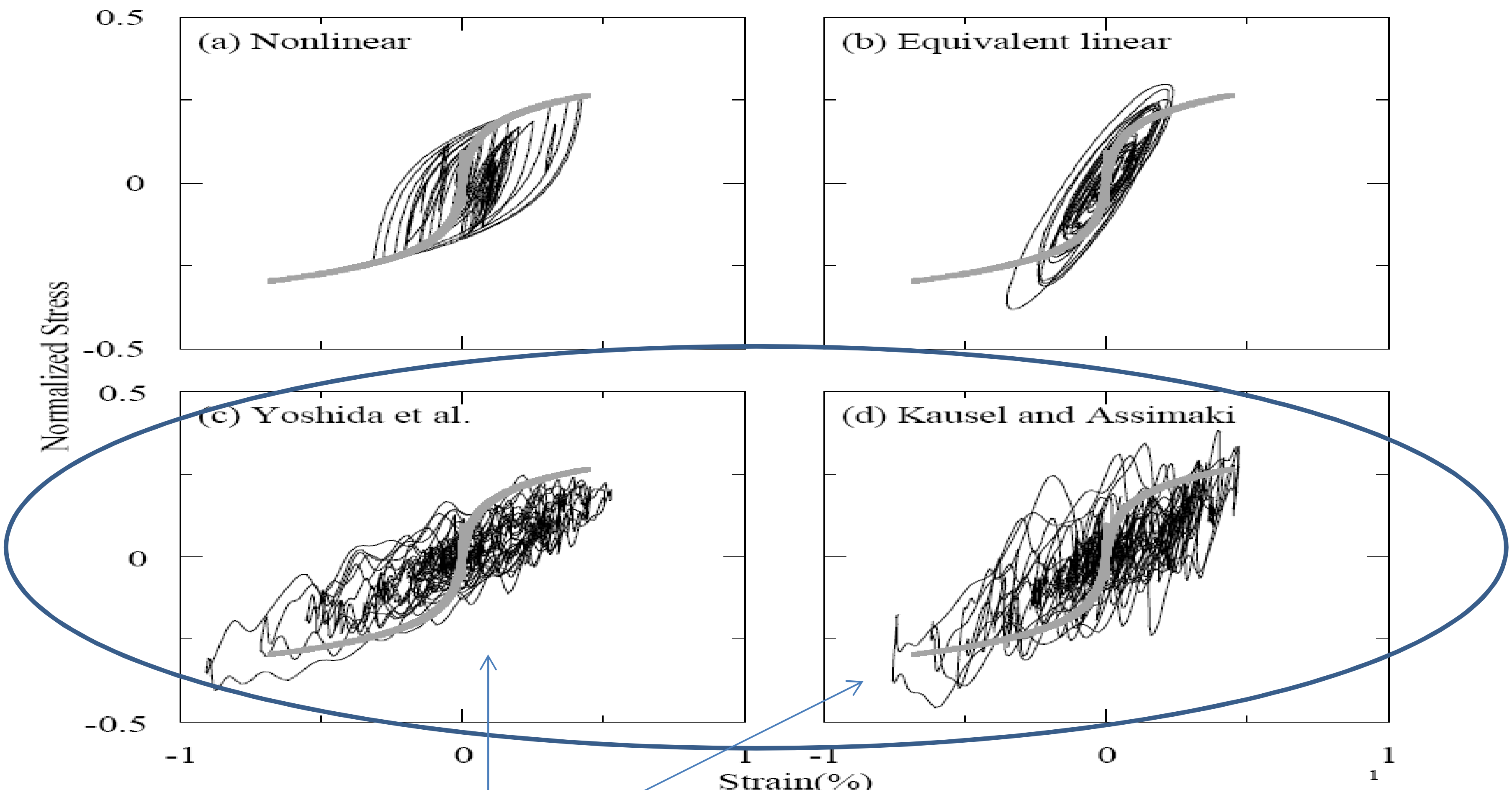


Hysteretic Loops



Kausel, E. and Assimaki, D. ,2002

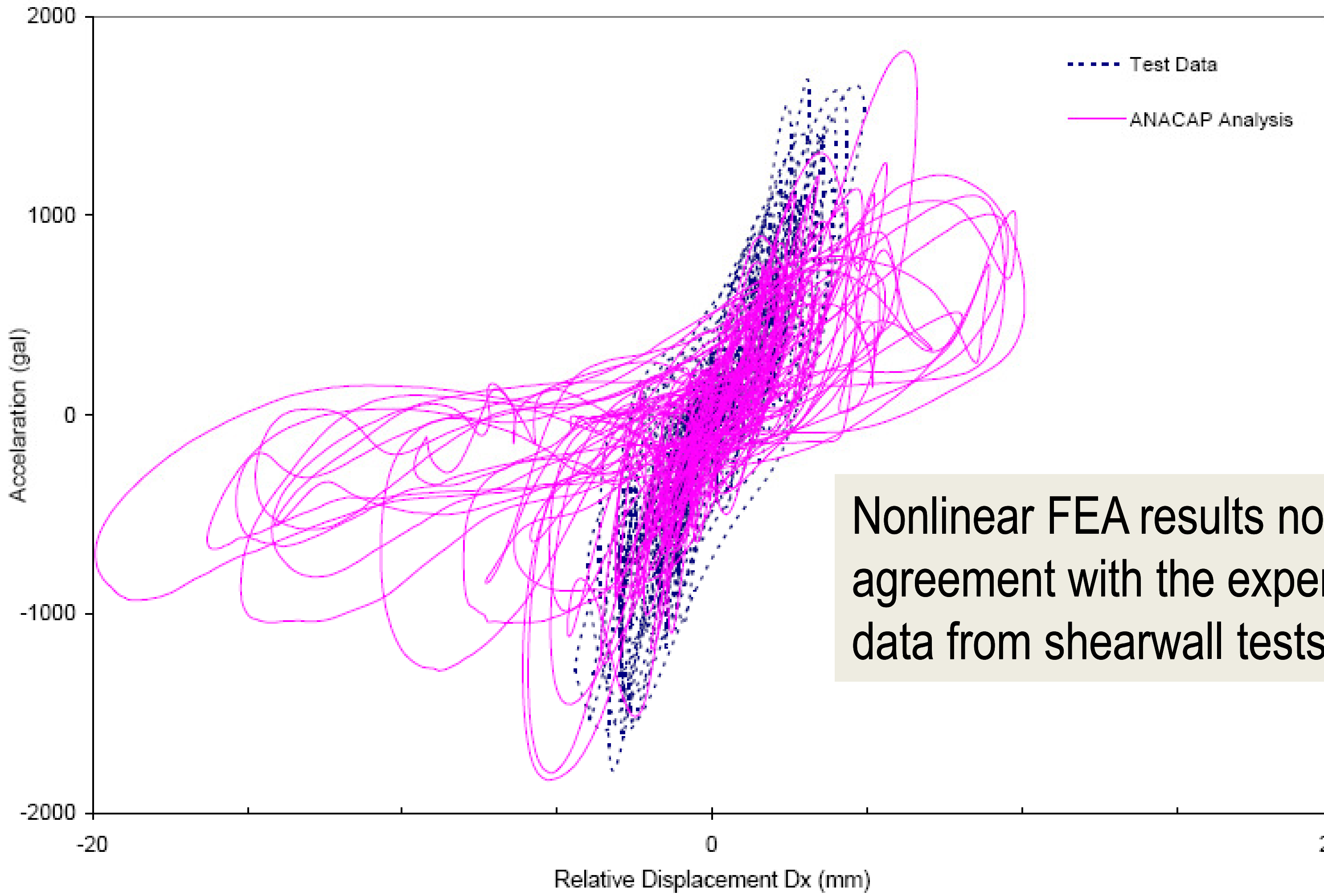
Frequency-Dependent Hysteretic Model Results



Kwak, D.Y.K., Jeong, C.G., Park, D. and Park, S. ,2008

REMARK: *Kausel and Assimaki (2002) and Yoshida et al. (2002) implementations lacked in the compatibility between the frequency and the time domain representations.*

Nonlinear Plasticity FEA Models: ANACAP Model



Nonlinear FEA results not fully in agreement with the experimental data from shearwall tests…..

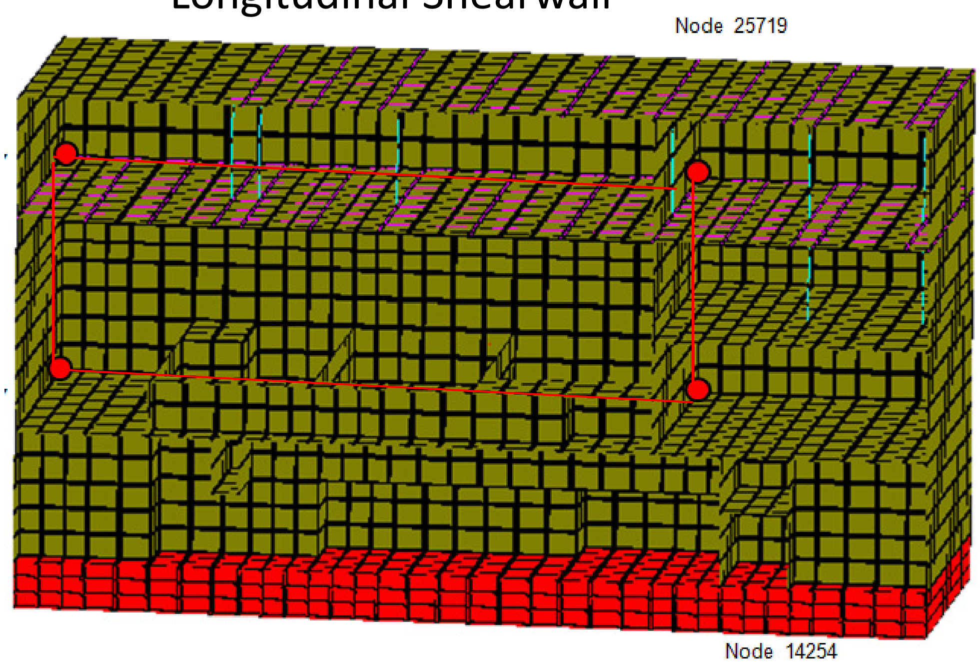
Figure 5-86 Comparison of X-Direction Hysteresis from ANACAP Analysis Considering Prior Damages but with X-Input Motion only and Test Result for Run-6

NUREG/CR-6925, BNL-NUREG-77370, 2006

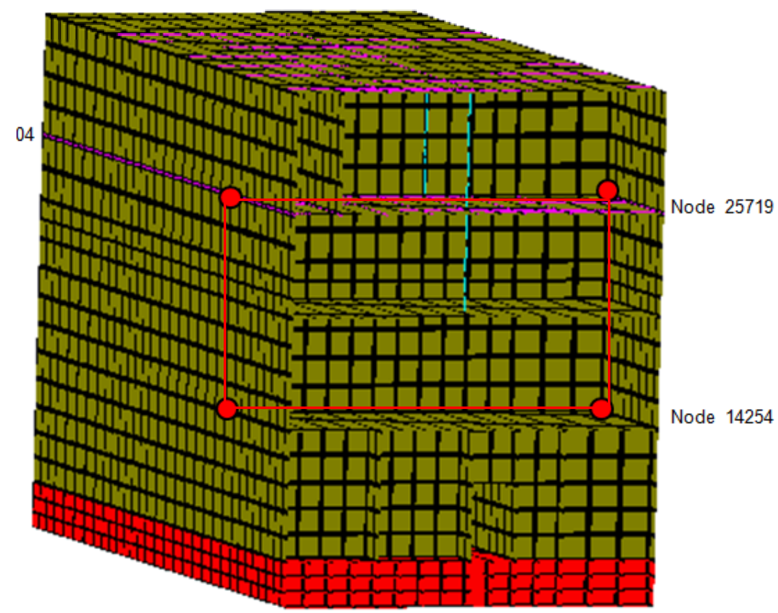
Nonlinear SSI Analysis of Low-Rise Shearwall Buildings

- Define shearwall panels between floors that will behave nonlinear.
- Define shearwall panel back-bone curves and hysteretic models based on experimental evidence, in accordance with recommendations of ASCE 43-2005 and ASCE 41-06.

Longitudinal Shearwall



Transverse Shearwall



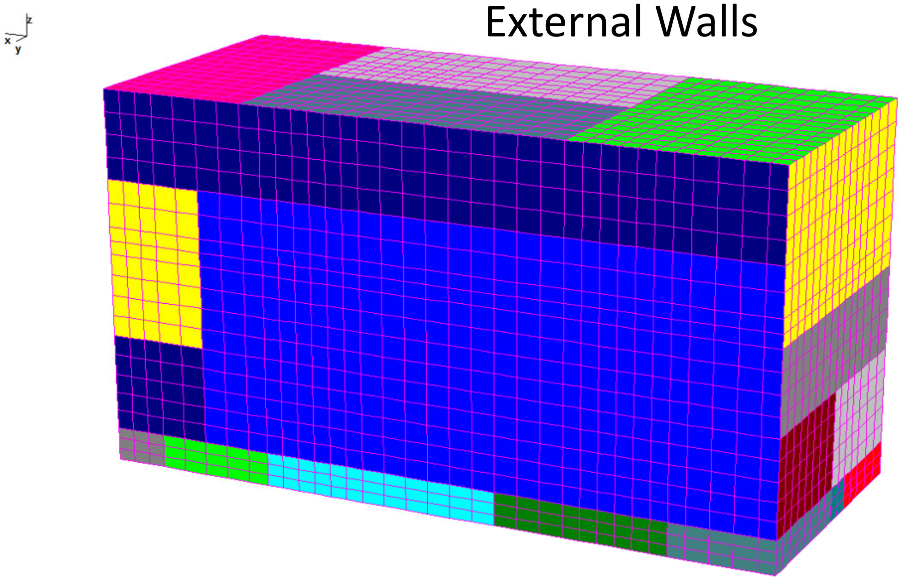
Nonlinear SSI Analysis in Complex Frequency:

Computational Steps:

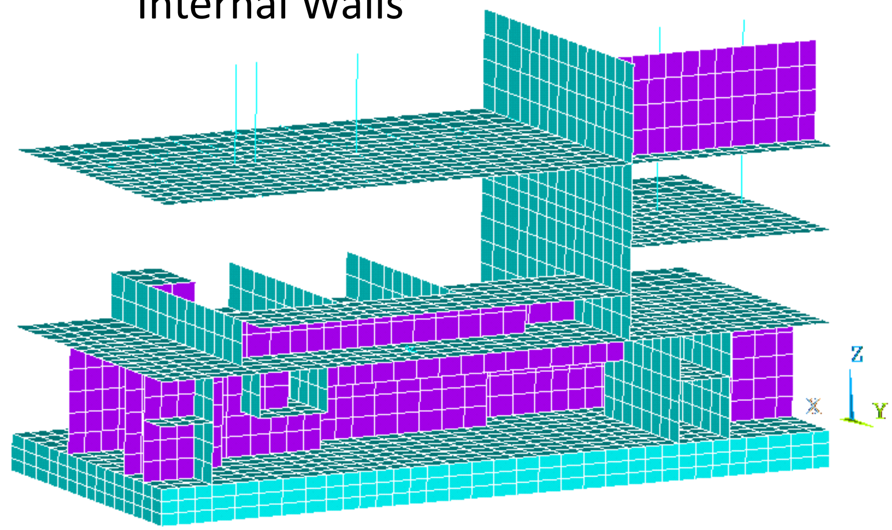
- For the initial iteration, perform a linear SSI analysis using the elastic properties for the selected shearwall panels
- Compute the reinforced concrete shearwall panel behavior in time domain and frequency domain using the hysteretic model associated to each selected panel
- Perform a new SSI analysis iteration using a fast SSI reanalysis (restart analysis) in the complex frequency domain using the hysteretic models computed in Step 2 for all selected panels
- Check convergence of the nonlinear SSI response after new SSI iteration, and go back to Step 2 if the convergence was not achieved.

Nuclear Shearwall Building on A Rock Site

External Walls

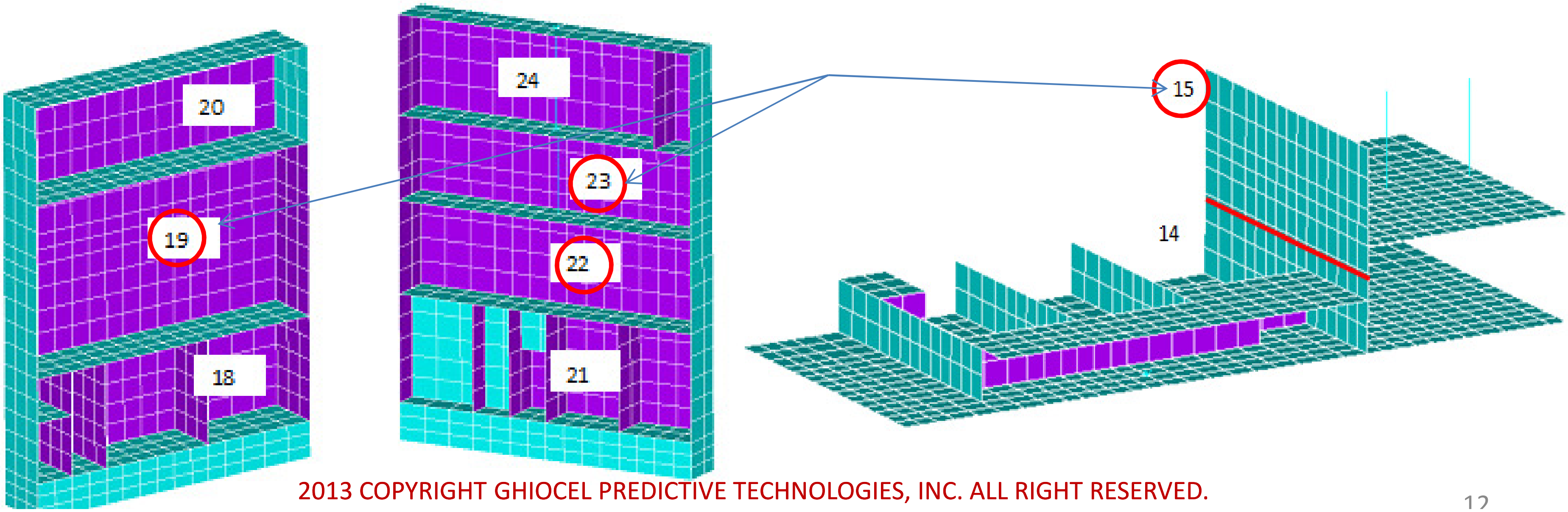


Internal Walls



Transverse External Walls

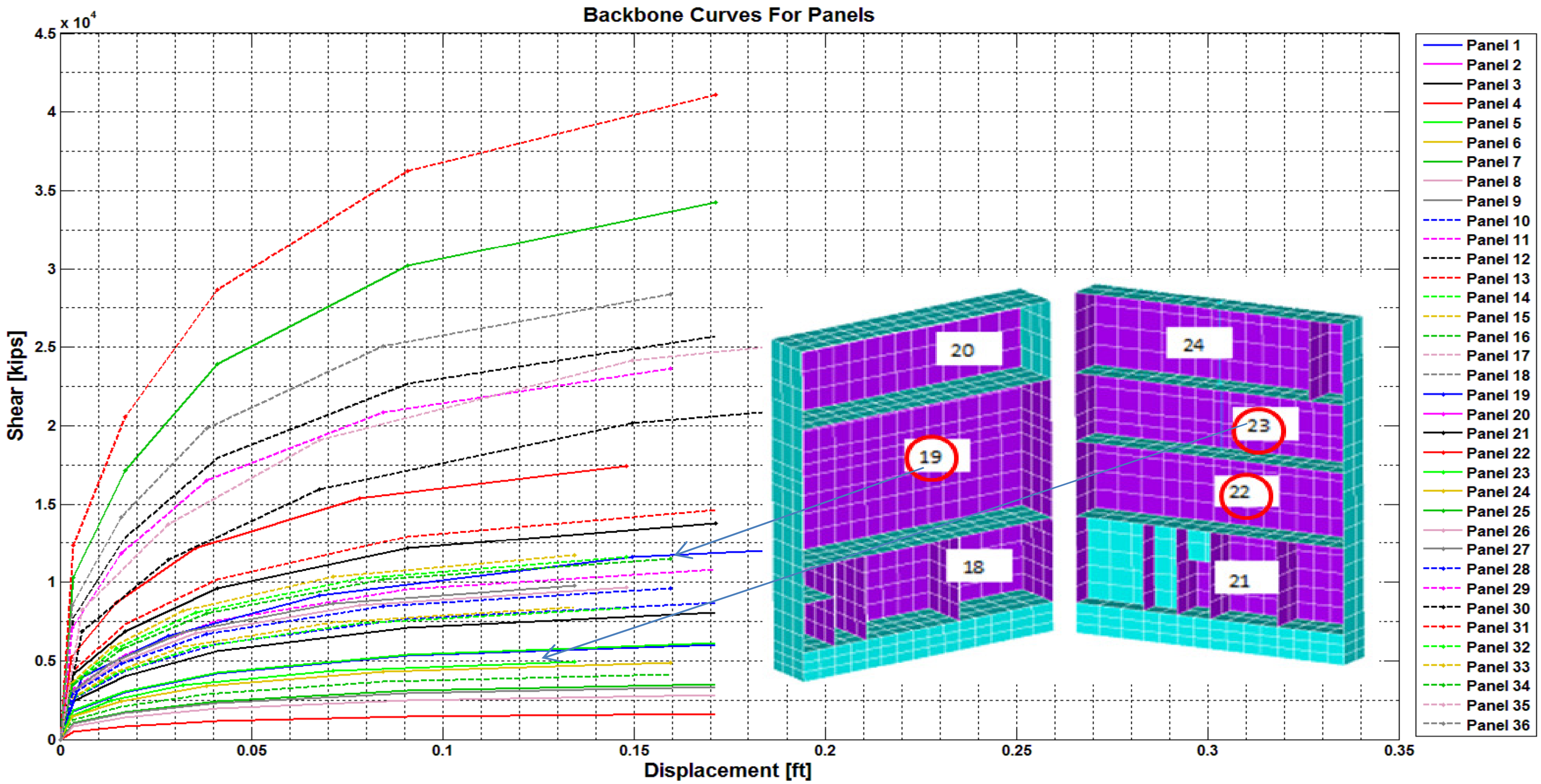
Transverse Internal Walls



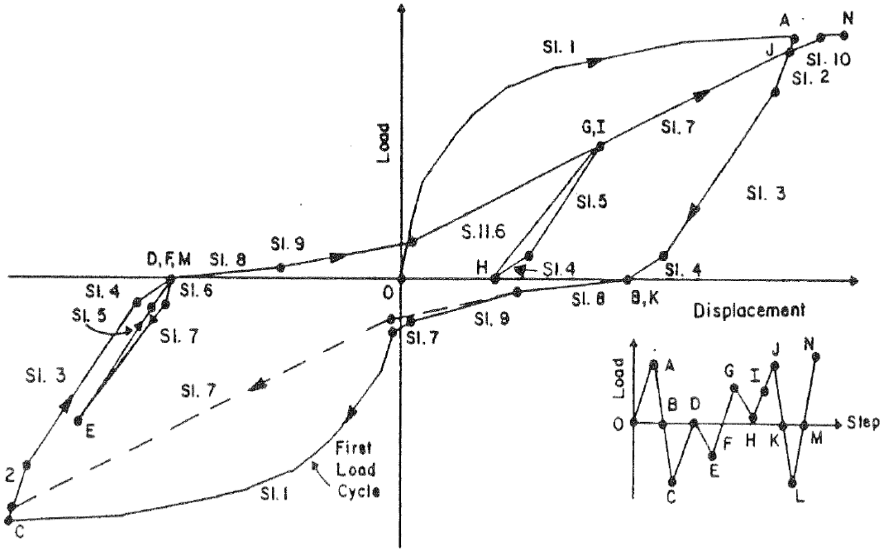
Shearwall Back Bone Curves (BBC) for All Shearwalls

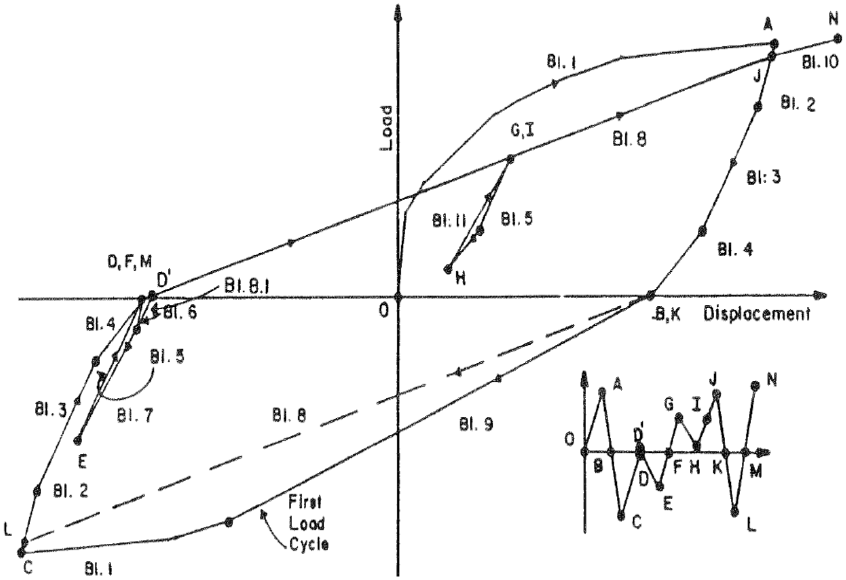
A number of 36 wall panels were modeled for nonlinear SSI analysis.
For each BBC were determined based on ASCE 04-2013 and ASCE 43-05.

Focus of the weak story (results shown for the panels #19 and 23)

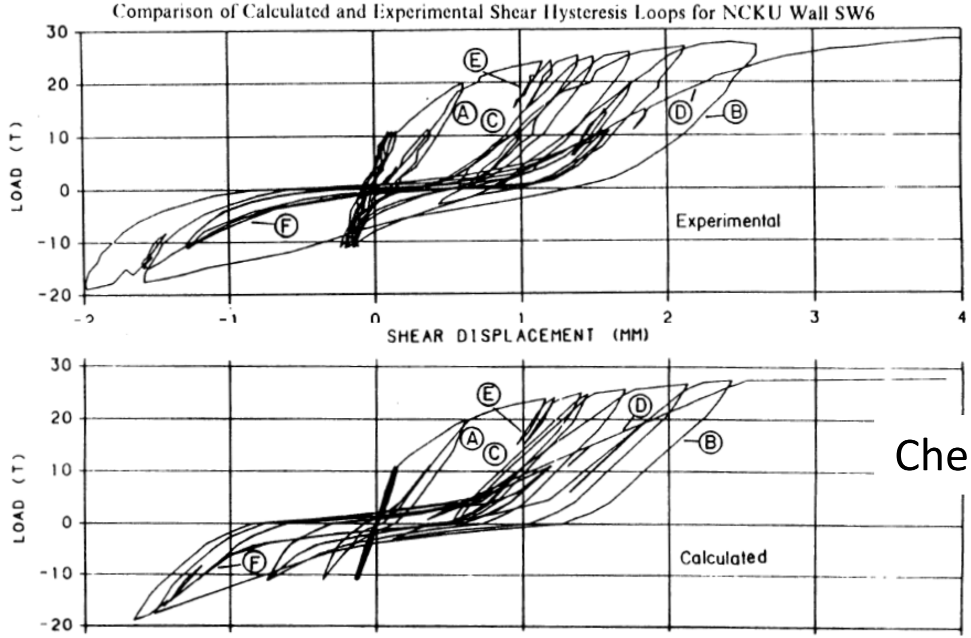


Chen-Mertz Hysteretic Model for Low-Rise Shearwalls





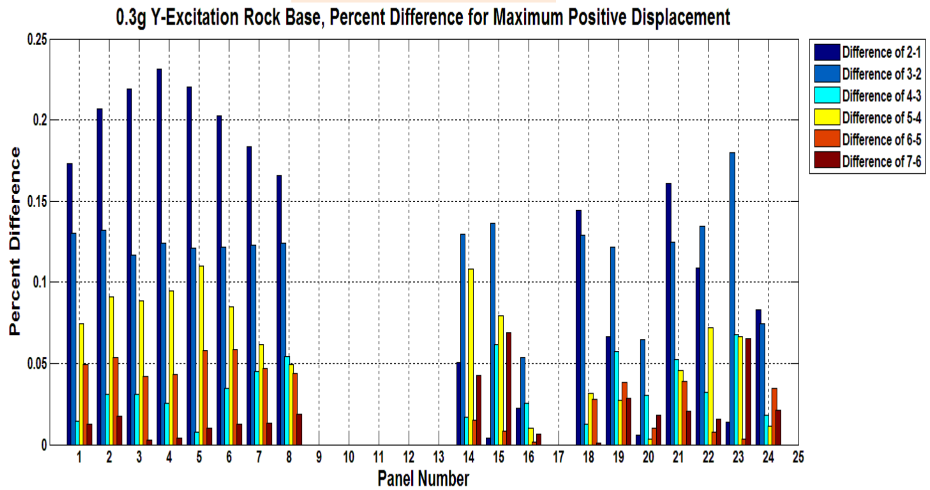
Comparison of Calculated and Experimental Shear Hysteresis Loops for NCKU Wall SW6



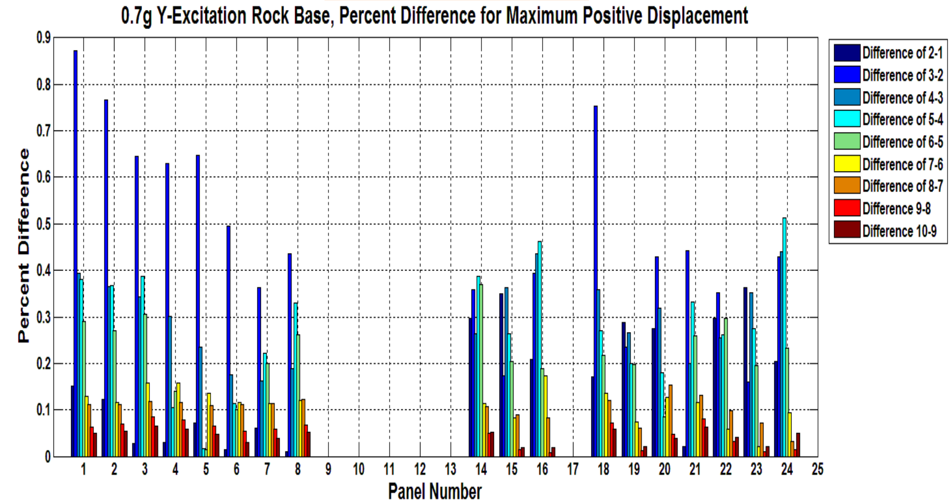
Cheng and Mertz, 1989

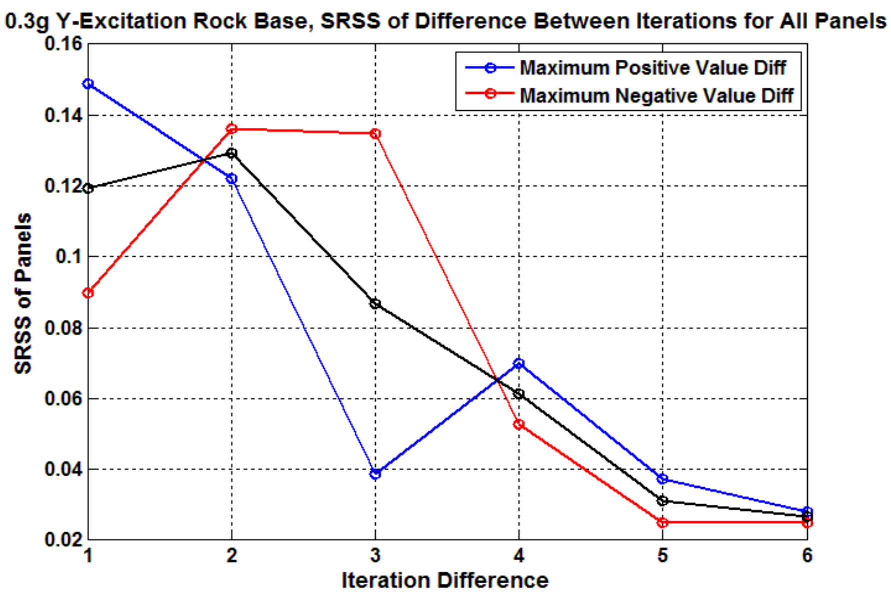
Nonlinear SSI Analysis Convergence (Per Panel and Global)

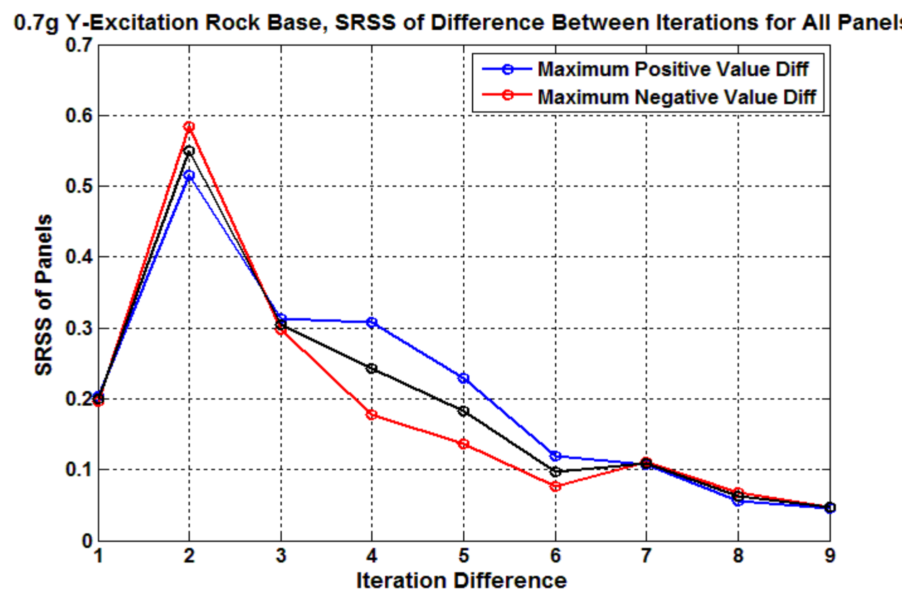
0.30g ZPGA



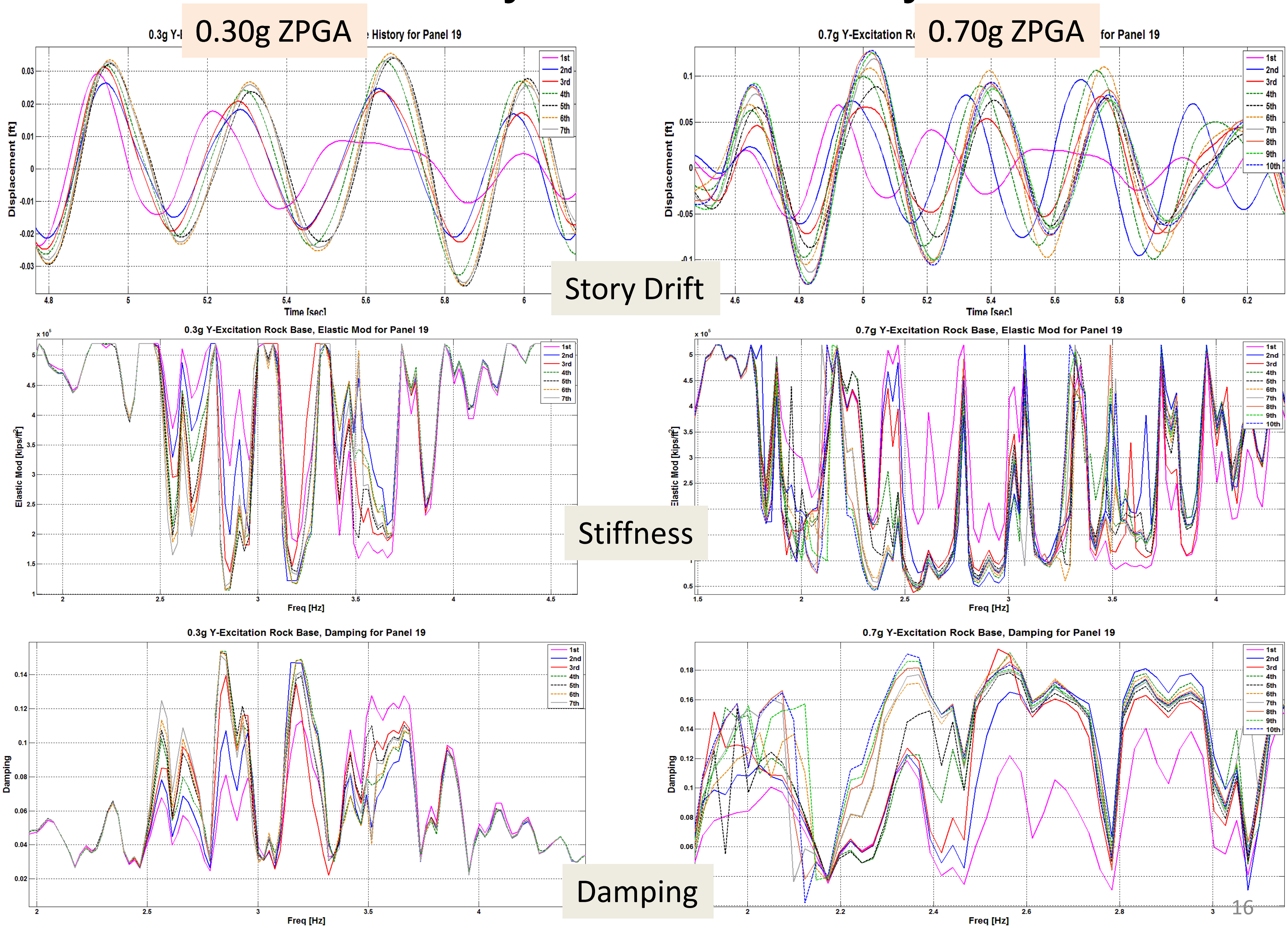
0.70g ZPGA





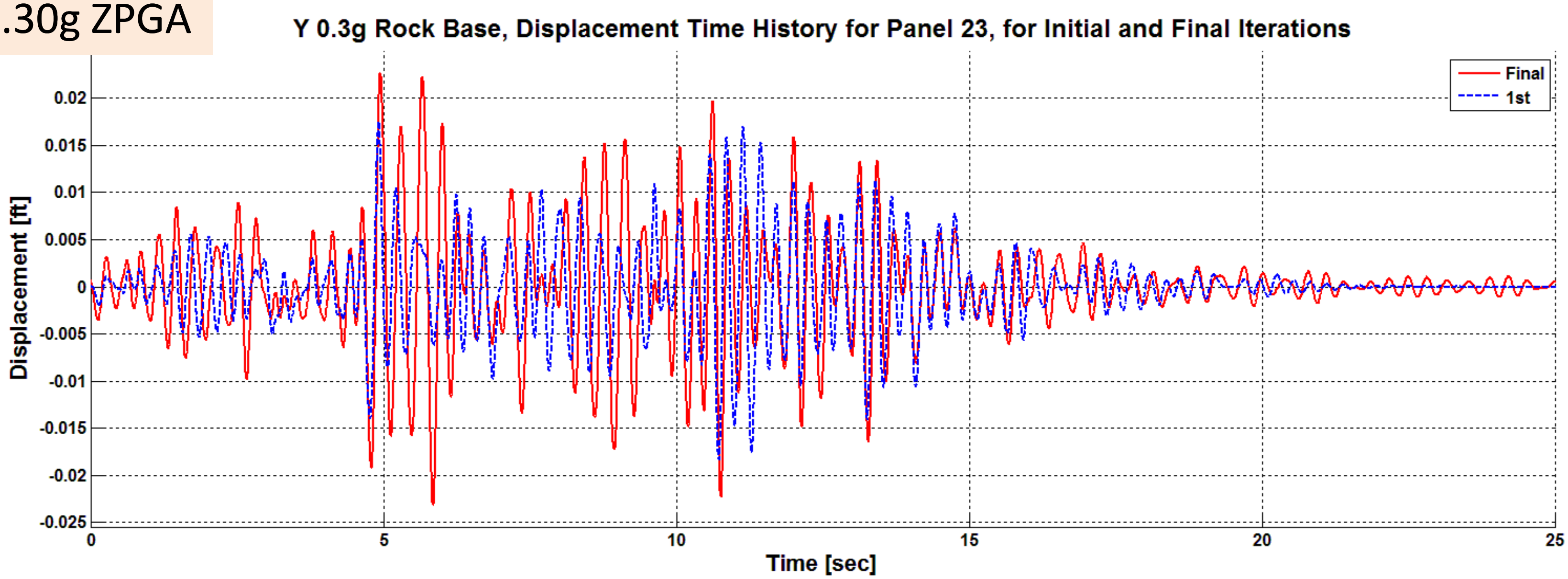


Nonlinear SSI Analysis Iteration History for Panel # 19

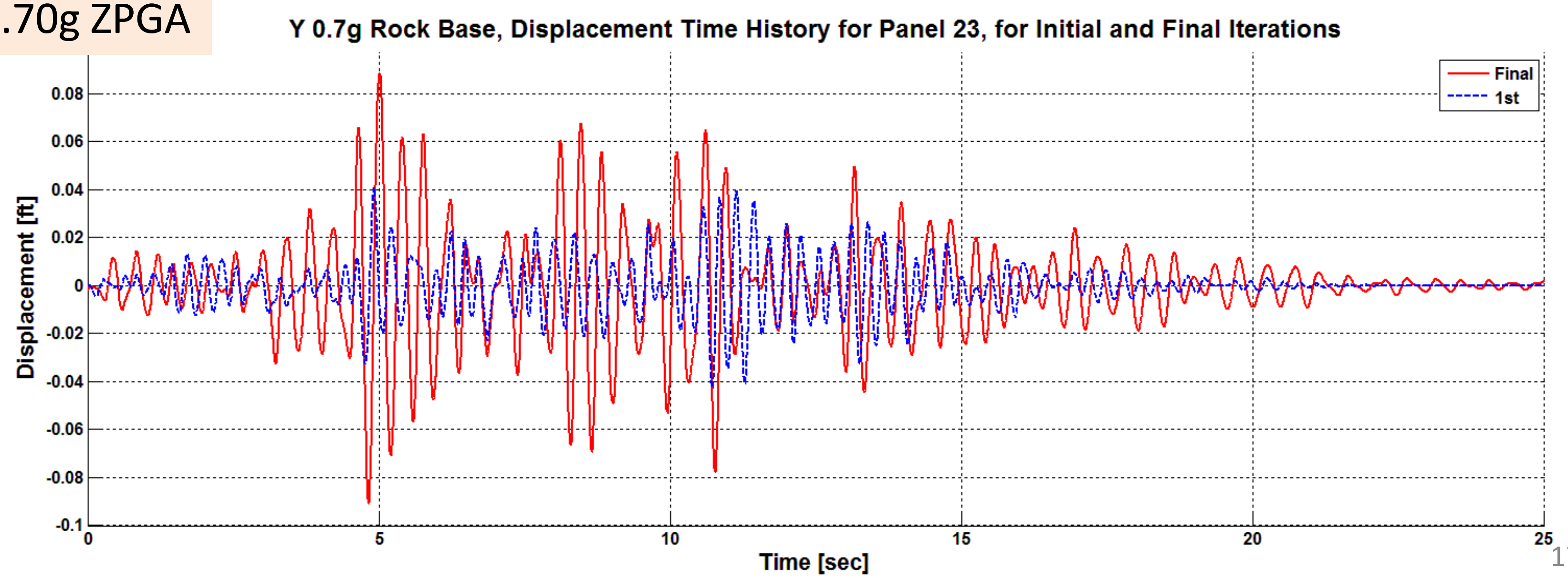


Panel #23 Comparative Linear and Nonlinear Story Drifts

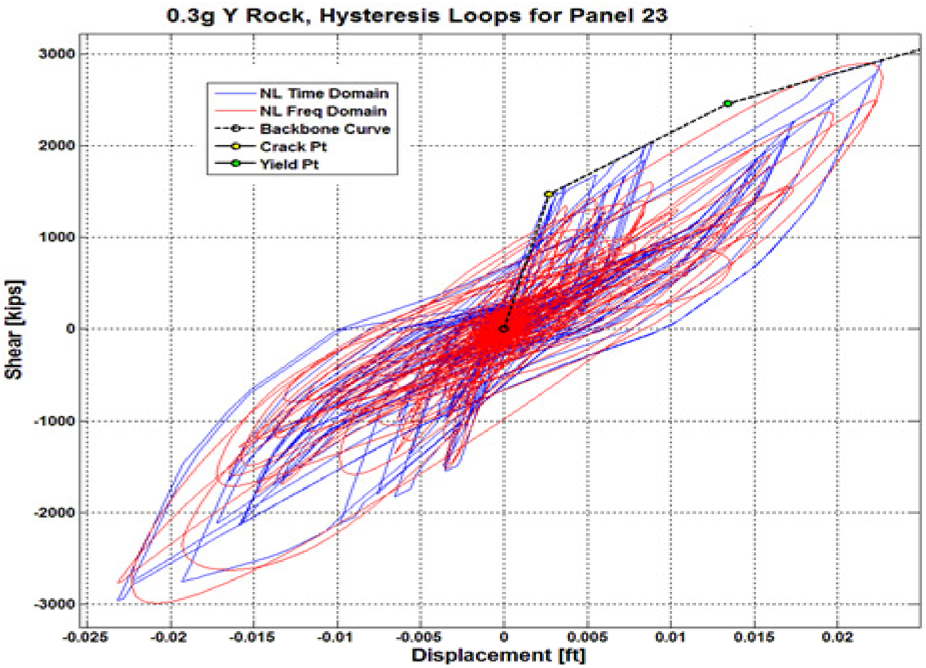
0.30g ZPGA



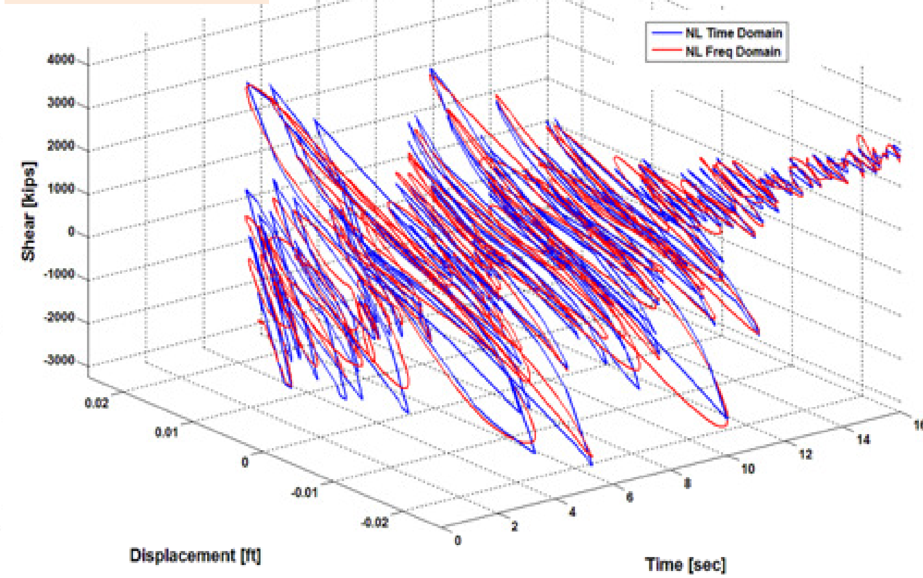
0.70g ZPGA

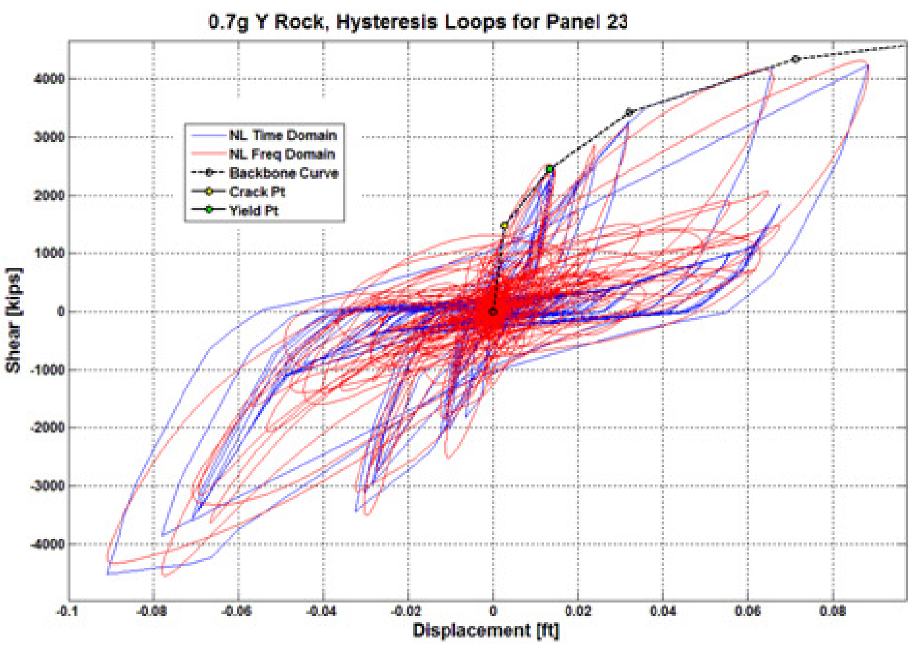


Panel #23 Hysteretic Loops for 1st and Final Iterations

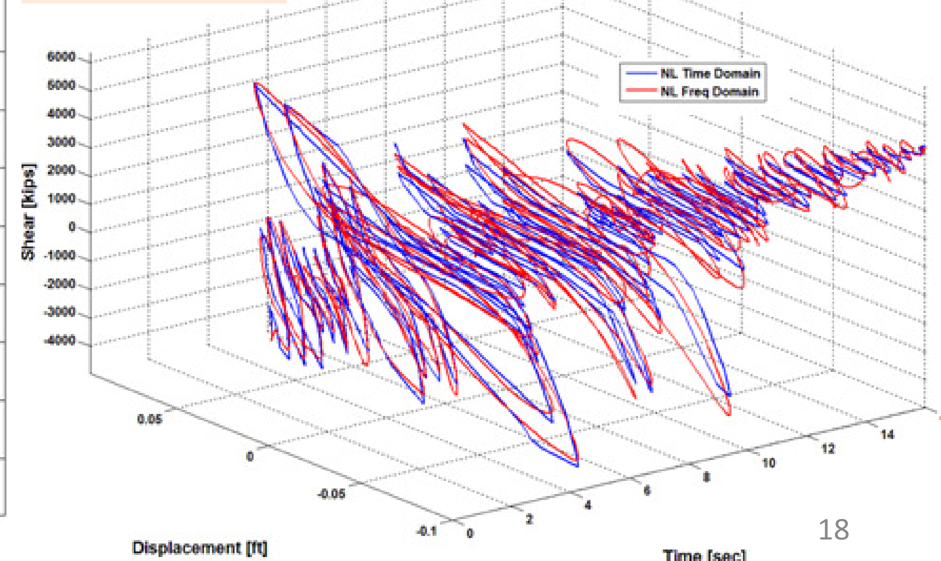


0.30g ZPGA

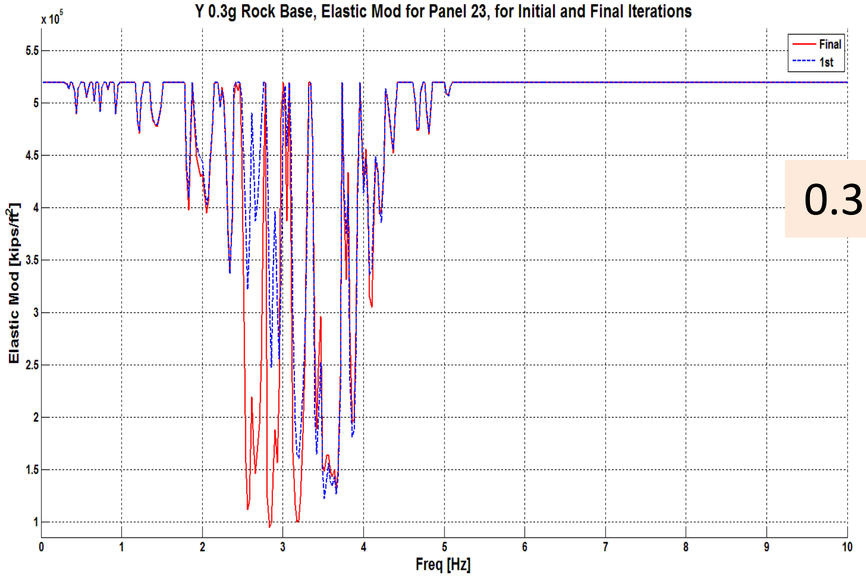




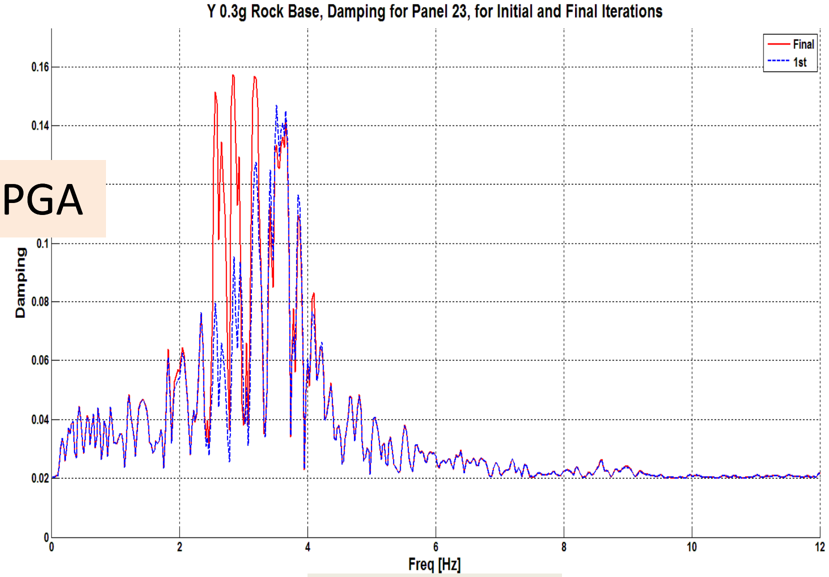
0.70g ZPGA



Panel #23: Frequency-Dependent Stiffness and Damping

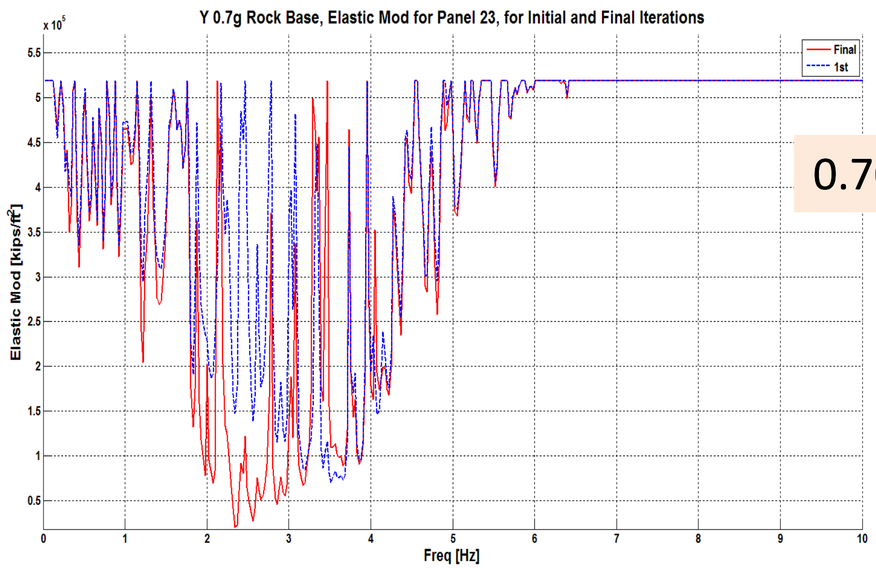


0.30g ZPGA

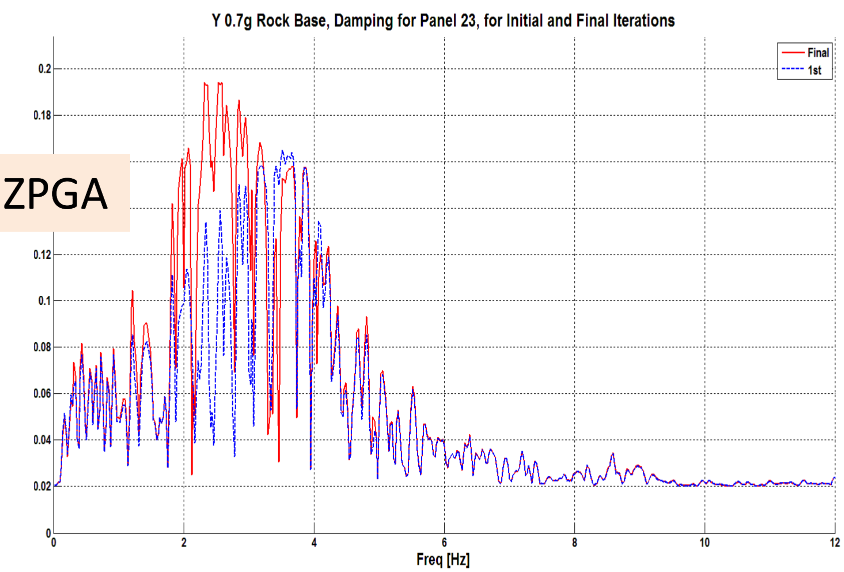


Stiffness

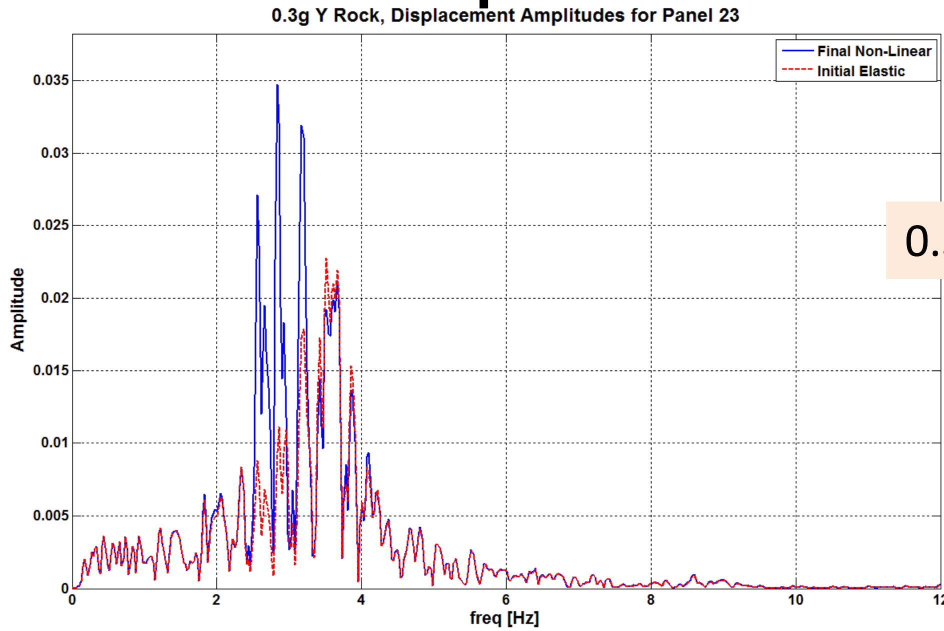
Damping



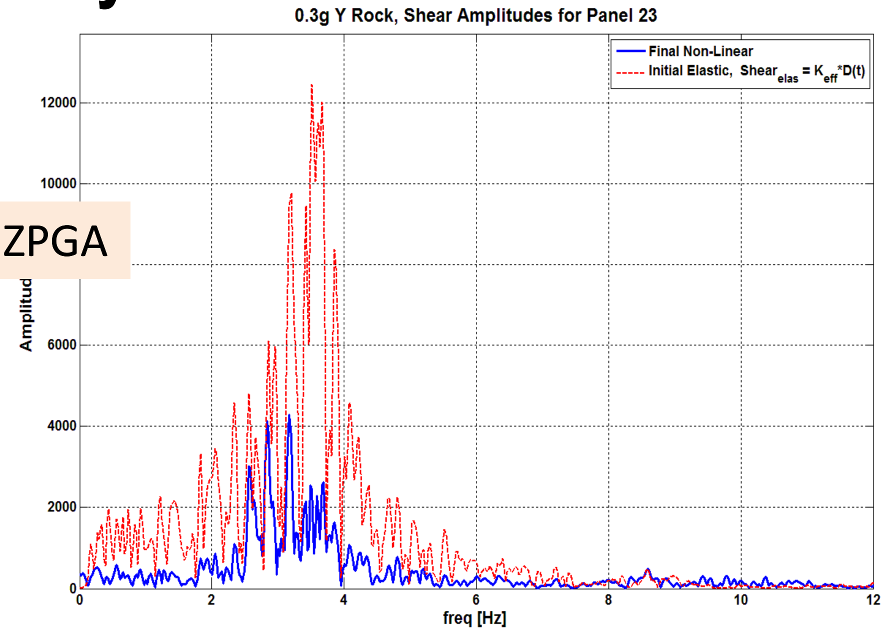
0.70g ZPGA



Panel #23: Amplitude Fourier of Story Drifts and Shear Forces

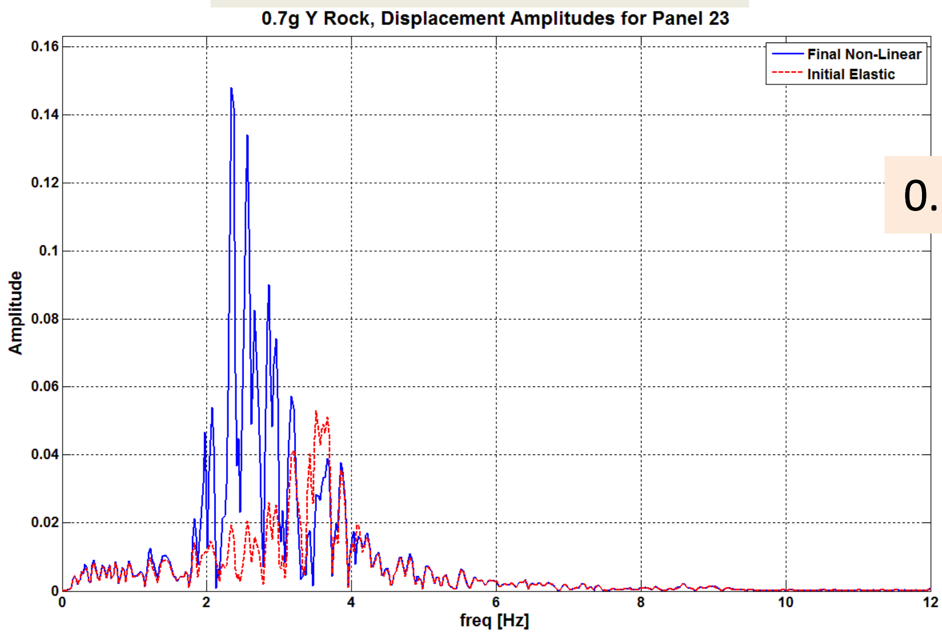


0.30g ZPGA

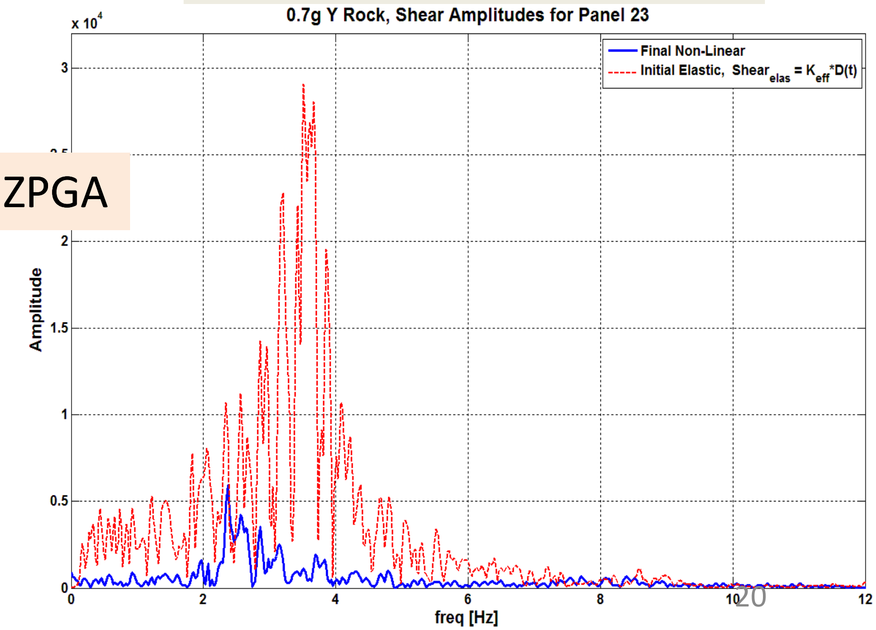


Story Drift Fourier Amplitude

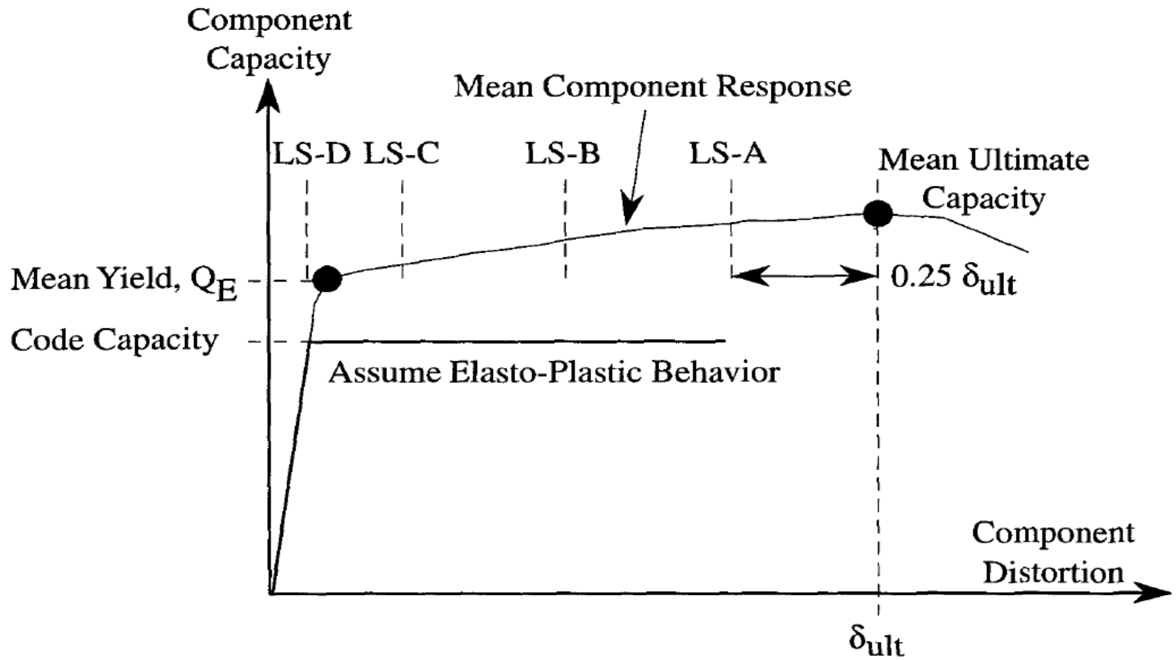
Shear Force Fourier Amplitude



0.70g ZPGA



ASCE 43-05 Inelastic Reduction Factors for Different Damage States



C5-4 Typical Load-Deformation Curve and Limit States

Limit State		LS-A	LS-B	LS-C
SMRF reinforced concrete moment frames				
Beams	$(15 \leq \ell/h)$	5.25	4.0	2.5
	$(\ell/h \leq 10)$	3.25	3.0	2.5
Columns**		2.0	1.75	1.5
Reinforced concrete shear wall, in plane:				
Bending controlled walls, $\frac{h_w}{\ell_w} \geq 2.0$				
	$6\sqrt{f_c'} < f_v$	2.25	2.0	1.75
	$f_v < 3\sqrt{f_c'}$	2.5	2.25	1.75
Shear controlled walls, $\frac{h_w}{\ell_w} < 2.0$		2.0	1.75	1.5

Nonlinear SSI and ASCE 43-05 Inelastic Reduction Factors

0.30g ZPGA Design Level (LS-D)

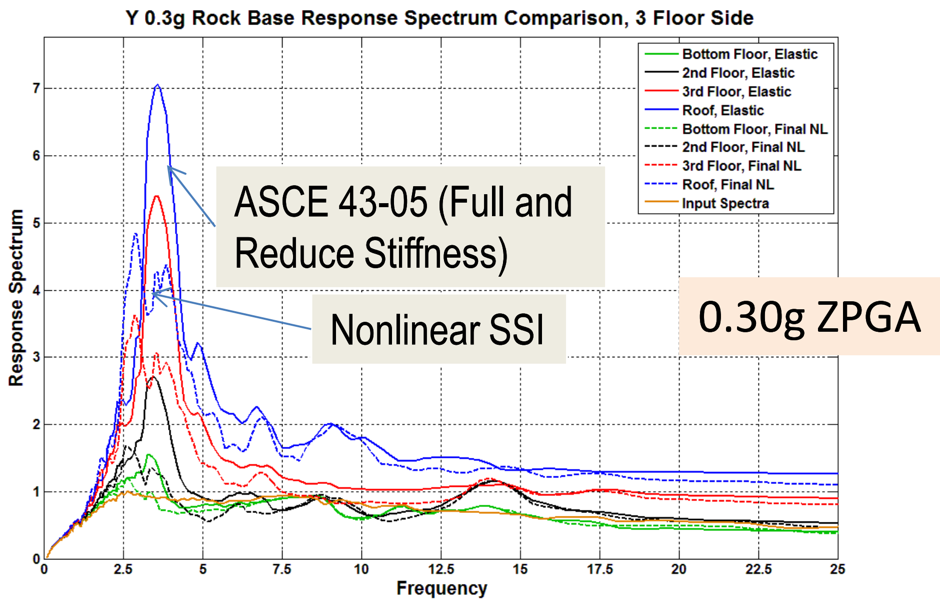
Panel Number	μ, Final Analysis	ASCE 43 Fμ, Final Analysis	Calcs Fμ, Shear
1	0.716	0.657	1.042
2	0.662	0.568	1.004
3	0.664	0.573	1.029
4	0.734	0.684	1.097
5	0.776	0.743	1.153
6	0.756	0.715	1.153
7	0.708	0.645	1.093
8	0.735	0.686	1.122
14	1.373	1.321	1.315
15	$\boxed{1.662}$	$\boxed{1.524}$	1.348
16	1.230	1.208	1.358
18	0.800	0.775	1.104
19	1.238	1.215	1.222
20	1.198	1.182	1.328
21	0.732	0.681	1.112
22	1.100	1.095	1.144
23	$\boxed{1.721}$	$\boxed{1.562}$	1.339
24	1.070	1.068	1.241
Average	**0.993**	**0.939**	**1.178**
Building	**1.177**	**1.163**	**-----**

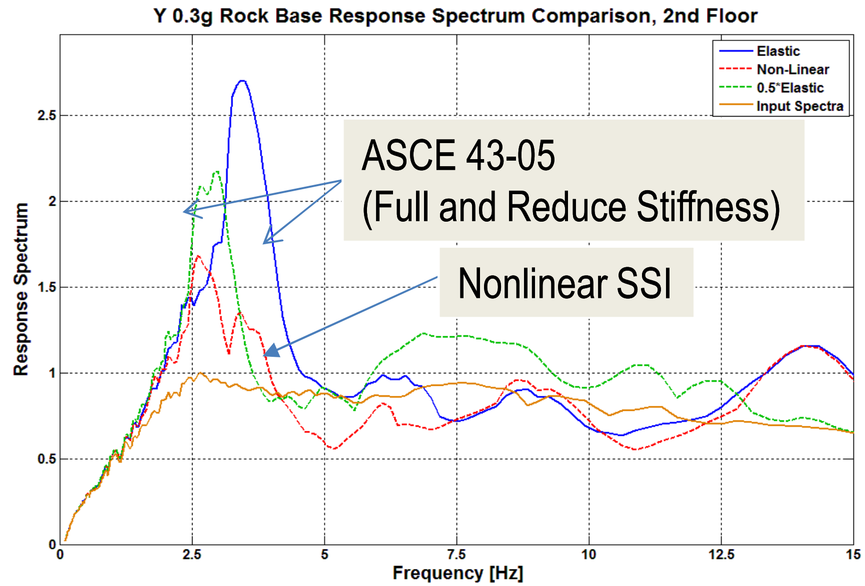
0.70g ZPGA Review Level (LS-A)

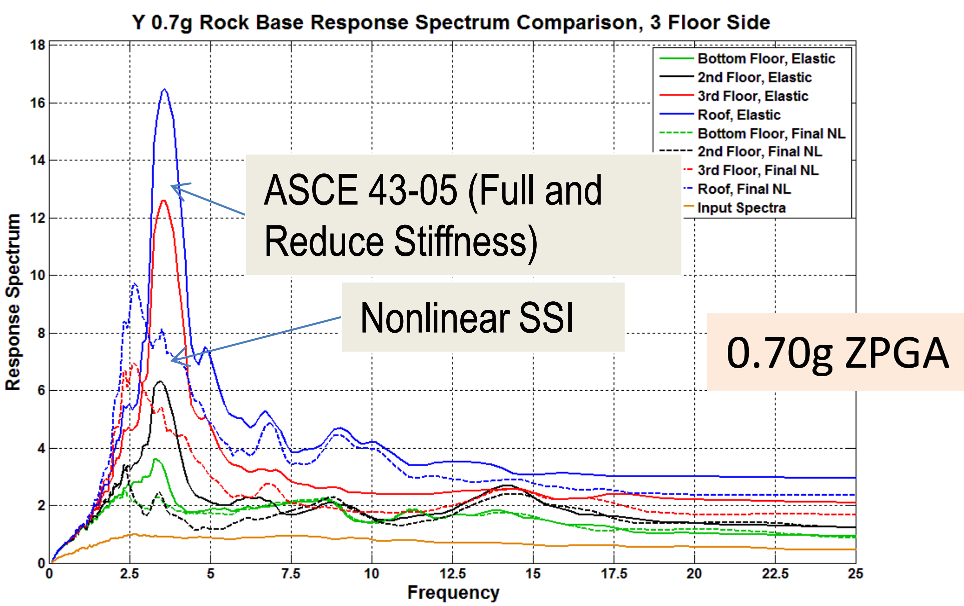
Panel Number	μ, Final Analysis	ASCE 43 Fμ, Final Analysis	Calcs Fμ, Shear
1	1.811	1.619	1.697
2	1.673	1.532	1.636
3	1.615	1.493	1.703
4	1.716	1.559	1.846
5	1.720	1.562	1.985
6	1.596	1.480	2.022
7	1.515	1.425	1.901
8	1.621	1.497	1.887
14	4.500	2.828	2.040
15	$\boxed{6.390}$	$\boxed{3.432}$	2.052
16	3.810	2.573	2.143
18	2.020	1.743	1.801
19	4.523	2.836	1.819
20	4.058	2.668	2.031
21	1.648	1.515	1.855
22	3.745	2.548	1.752
23	$\boxed{6.764}$	$\boxed{3.539}$	2.046
24	3.143	2.299	1.982
Average	**2.993**	**2.119**	**1.900**
Building	**3.801**	**2.569**	**----**

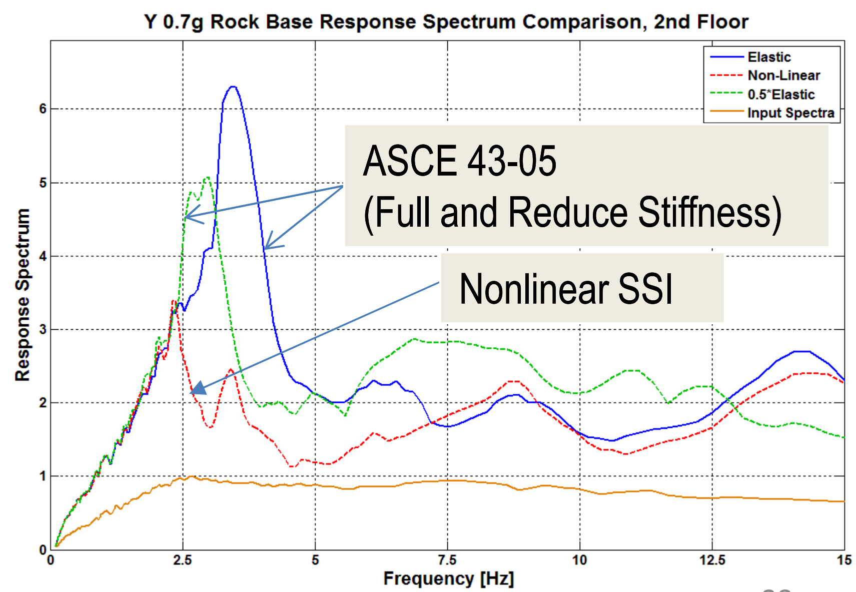
Large ductility demands

Nonlinear SSI and ASCE 43-05 Inelastic Reduction Factors









Conclusions

- Nonlinear SSI analysis in complex frequency domain is a very promising engineering approach. It is at least 500 -1000 times faster than nonlinear SSI analysis in time domain.
- It provides results consistent with the ASCE 43-05 recommendations.
- Nonlinear SSI analysis in complex frequency is much more robust that nonlinear SSI analysis in time domain that is much more sensitive, especially for higher frequencies. Nonlinear time domain analyses are more prone to analysis errors than nonlinear complex frequency domain analyses.

The nonlinear SSI approach in complex frequency is currently implemented in the ACS SASSI Option N capability. The commercial version will be available in 2014.

The nonlinear approach is currently extended to soil material hysteretic behavior (providing more realistic results than the equivalent-linear SHAKE methodology), and to other types of structural concrete components.