Fast Nonlinear Seismic SSI Analysis for Low-Rise Concrete Shearwall Buildings for Design-Basis and Beyond Design Applications

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Purpose of this Presentation

To demonstrate the application a highly efficient nonlinear SSI analysis based on a hybrid time-complex frequency approach implemented in ACS SASSI with Option NON (nonlinear structure) software.

The fast nonlinear SSI approach is applicable to *design-level* for concrete cracking and *beyond design-level* for post-cracking nonlinear RC behavior under larger earthquakes.

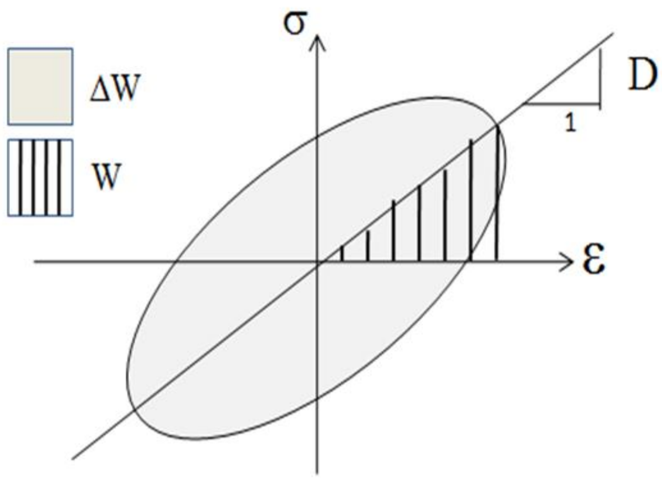
Its application is discussed in the context of the new ASCE 4/43 standard recommendations and damping value limitations.

Case studies:

- *Validation study* against nonlinear time domain integration using PERFORM3D software (trademark of CSI)
- *Review nonlinear SSI analysis results in the light of the new ASCE 4/43 recommendations* for concrete cracking for *design-level* (Response Level 2) and for nonlinear concrete behavior for *beyond design-level* (Response Level 3).

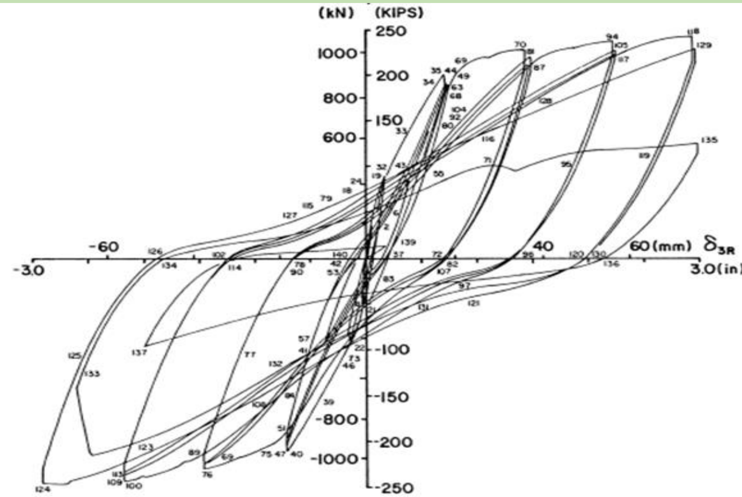
ACS SASSI NON Modeling of Hysteretic Behavior

Linearized Hysteretic Model



Frequency Domain
Linearized Hysteretic Model

Experimental Hysteretic Model



Time Domain
Hysteretic Model

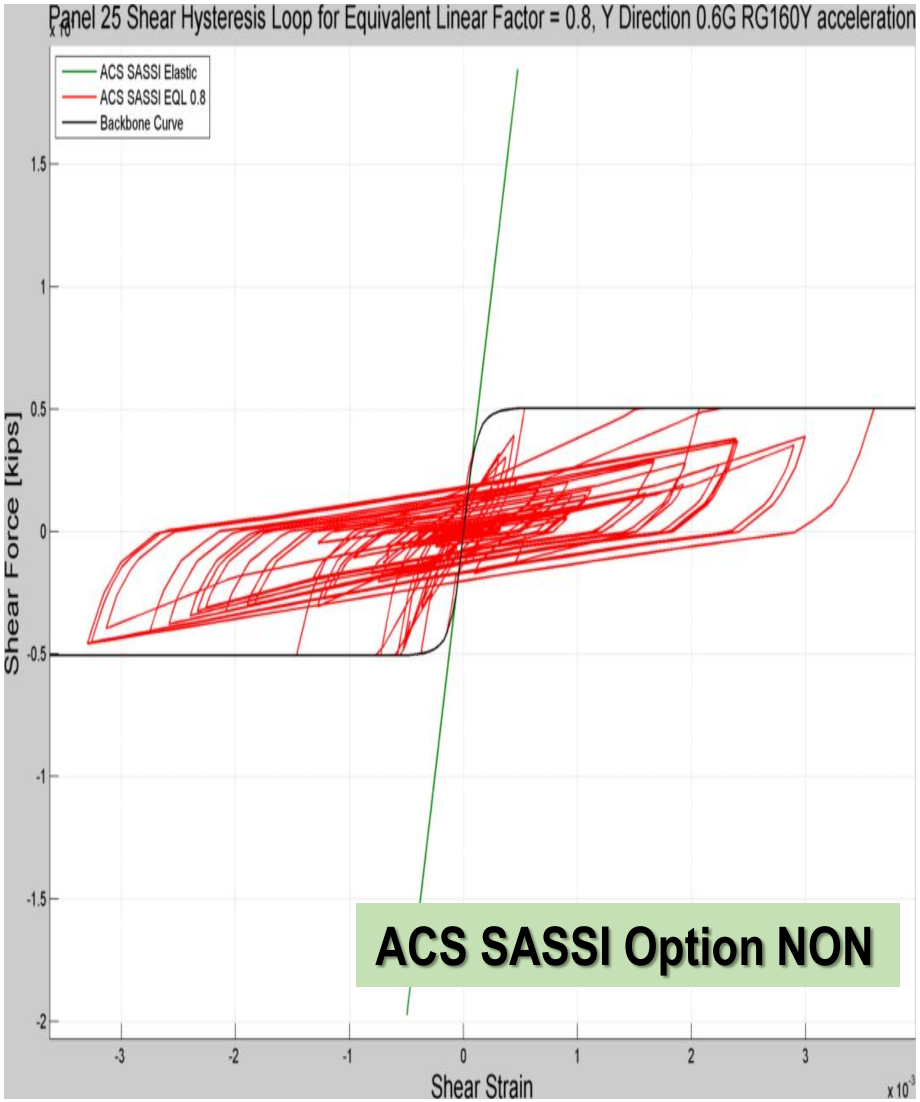
Comparative nonlinear SSI analysis results of the hybrid approach against the "*true*" nonlinear time-integration approach show a *good accuracy* (Ghiocel, SMIRT23, 2015). 3

Fast and accurate nonlinear SSI analyses at a small fraction of the runtime of a time domain nonlinear analysis, about 2-3 times linear SSI analysis runtime.

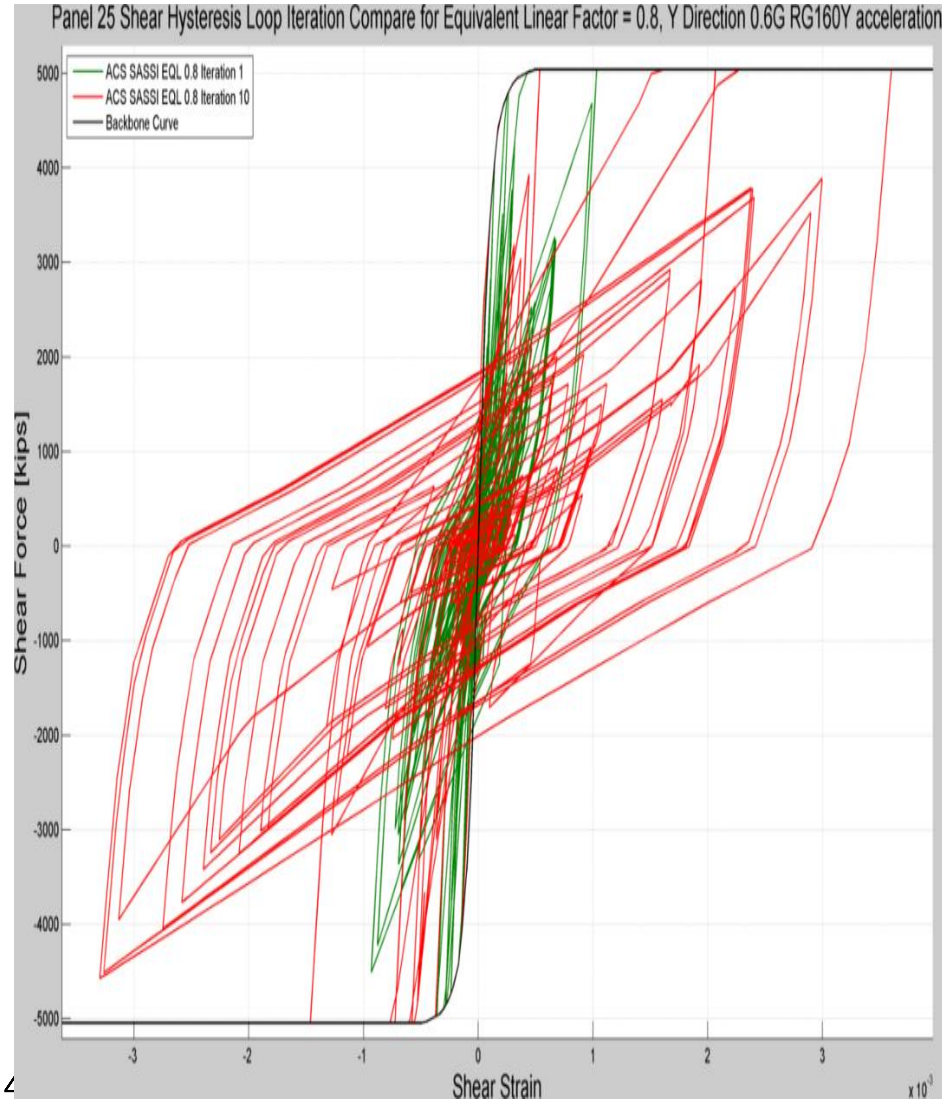
Much more robust than nonlinear time integration approaches - similar opinion has also Prof. Kausel (Kausel and Assimaki, 2002)

Reinforced Concrete Structure Nonlinear SSI Analysis

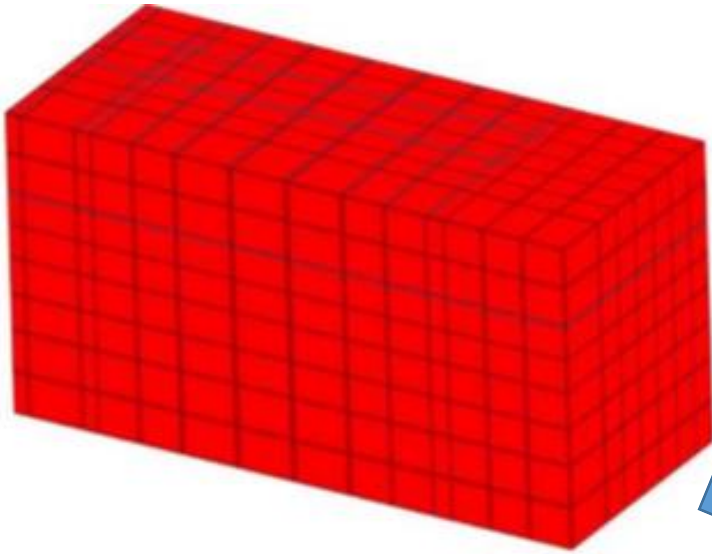
Elastic vs. Nonlinear



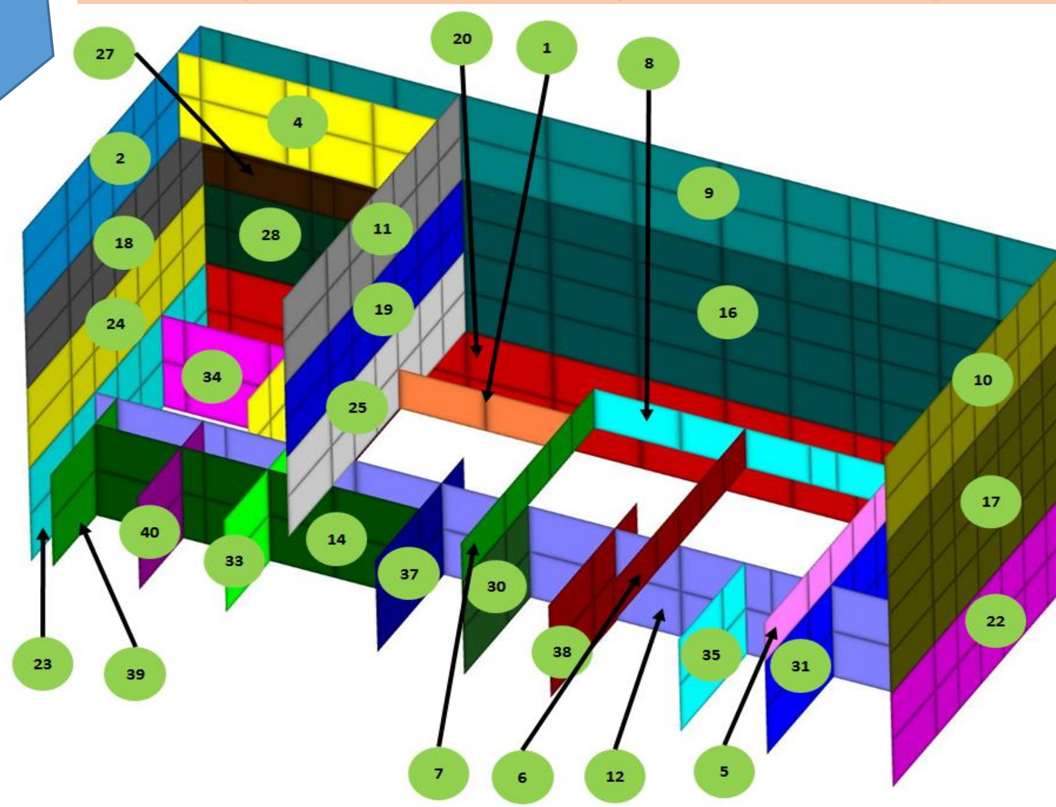
1st Iteration vs. Last Iteration



Nonlinear Concrete Building Split in Wall Panels

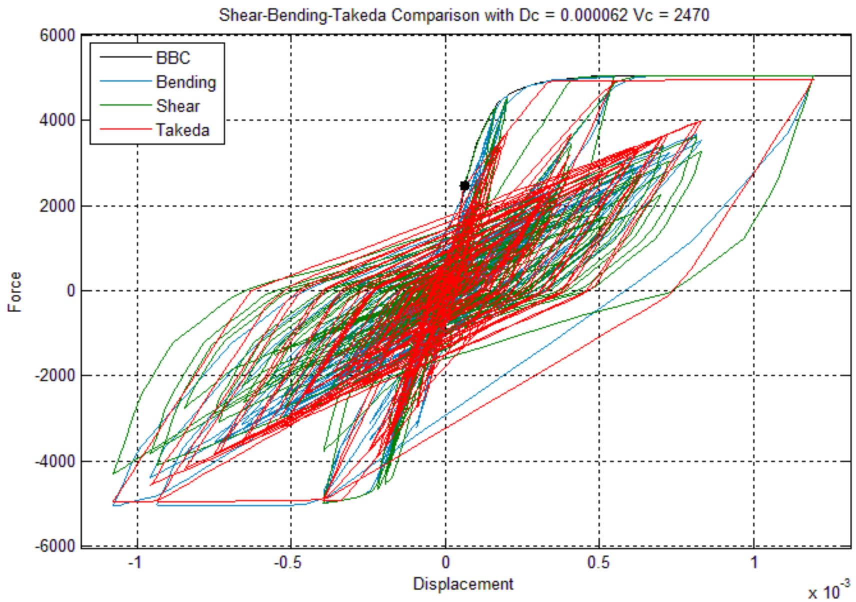


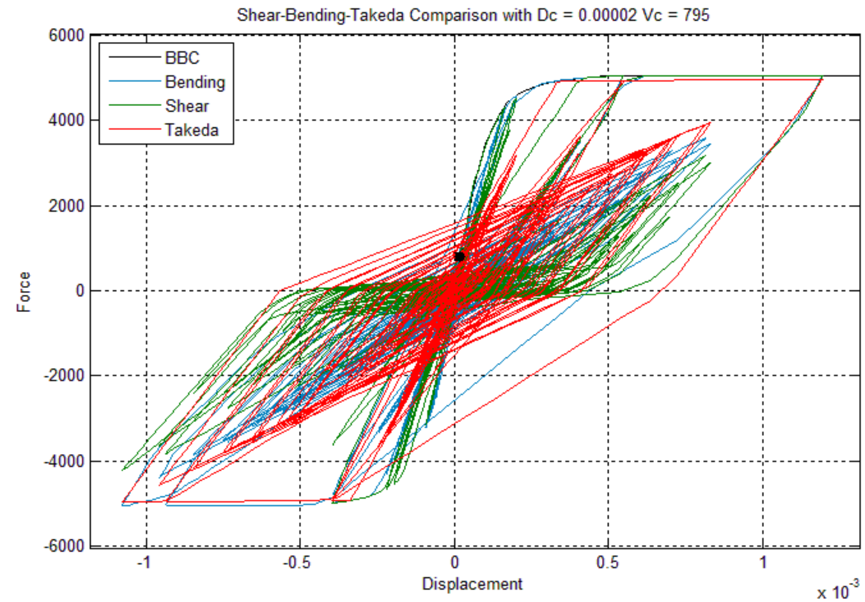
Nuclear building model split in nonlinear panels with different nonlinear properties. Many ACS SASSI User-Interface commands are available: PANELIZE, WALLFL, SPLITGROUP, MERGEPANEL, EDGE, UNIPL, MERGEGROUP, EDGEPANEL, etc.

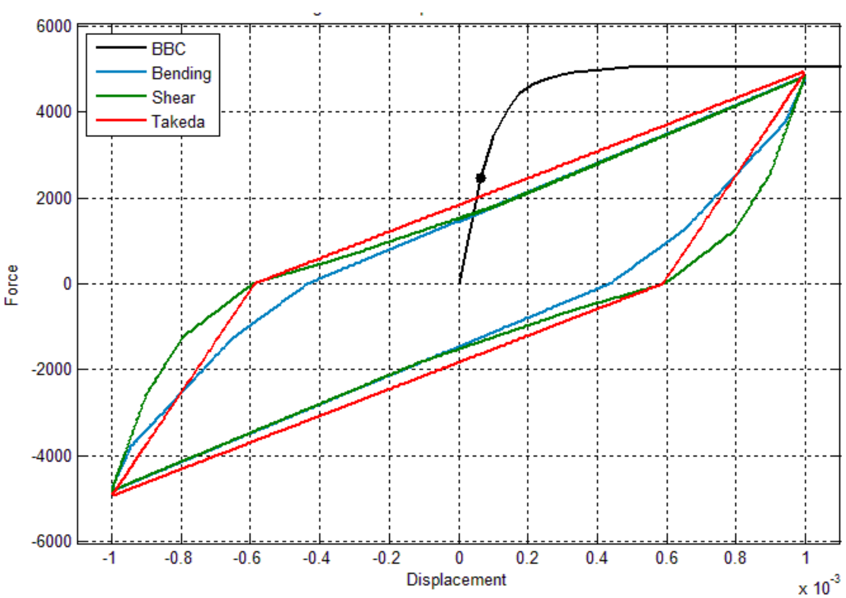


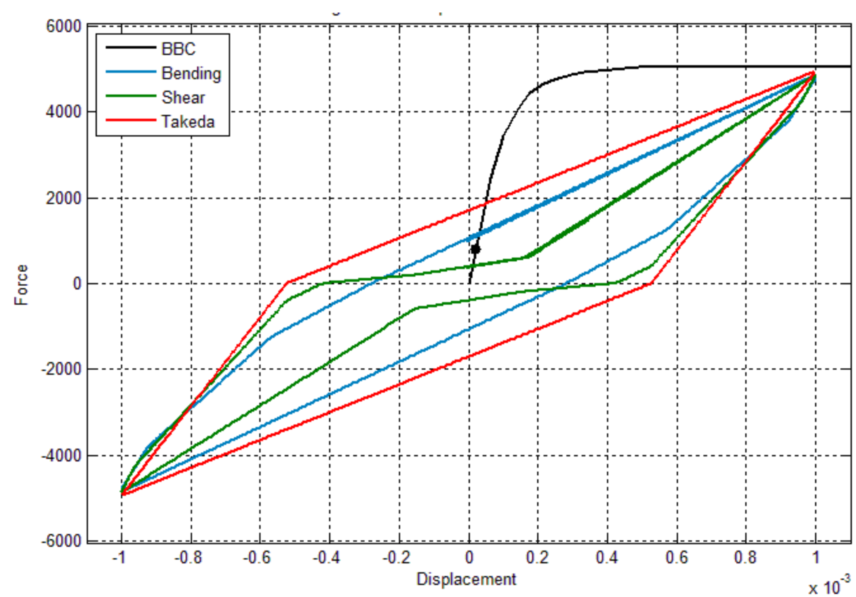
Each panel should be described by its elastic properties, BBC and hysteretic model for in-plane shear or bending deformation (Cheng-Mertz for Shear and Bending, and Takeda)

ACS SASSI Option NON Shearwall Hysteretic Models: Cheng-Mertz (CMB, CMS) and Takeda (TAK)

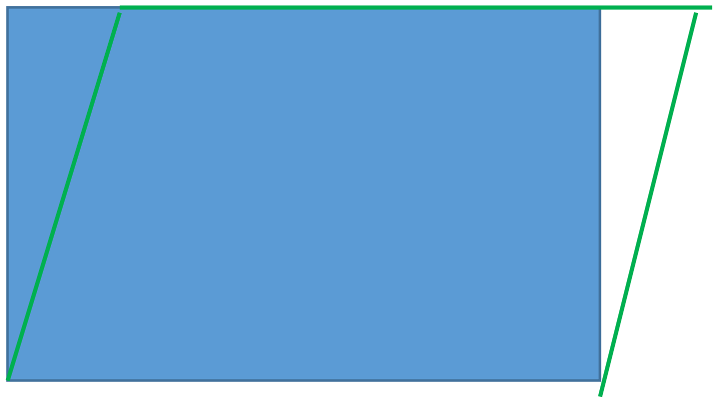








Experiment-Based Shear Capacities for Squats



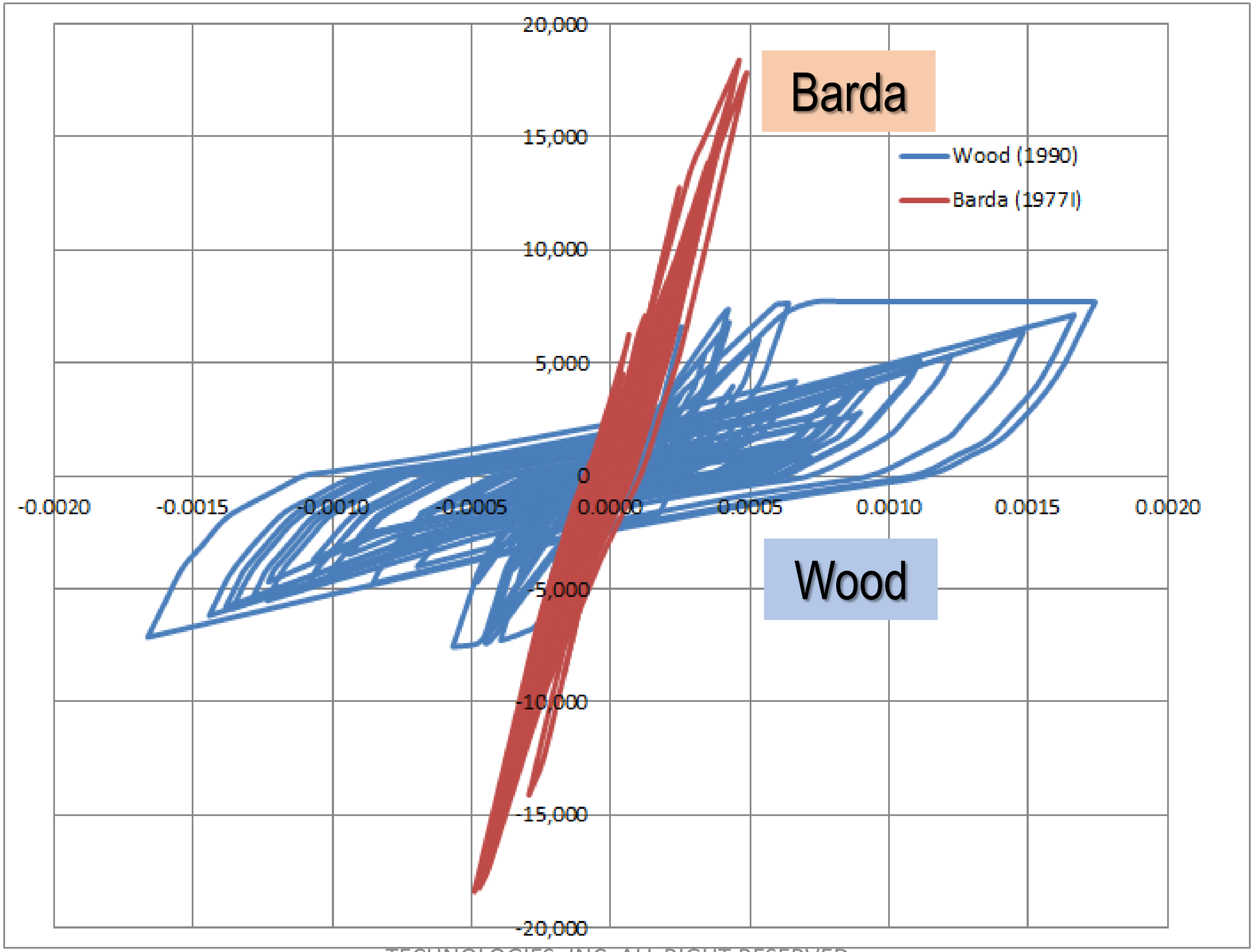
Walls have no openings!

Useful References for Peak Capacity Equations:

- Barda et al.,1977 in the 1994 EPRI Reports – could overly estimate
- ASCE 43-05, 2005 Eqs. 4-3/4 based on Barda, ASCE 43-16 took out it
- ACI 349-06, 2006, Section 11.10, 21.4, based on Barda
- Wood, 1990 – small bias, typically less 10% lower, for median capacity
- Gulec and Whittaker, 2009, Eqs. 6.9-6.10, small bias for median capacity

NOTE: ATC 72-1 Option 3, 2010 for reduce yielding and peak capacities to account cyclic degradation effects for many cycles.

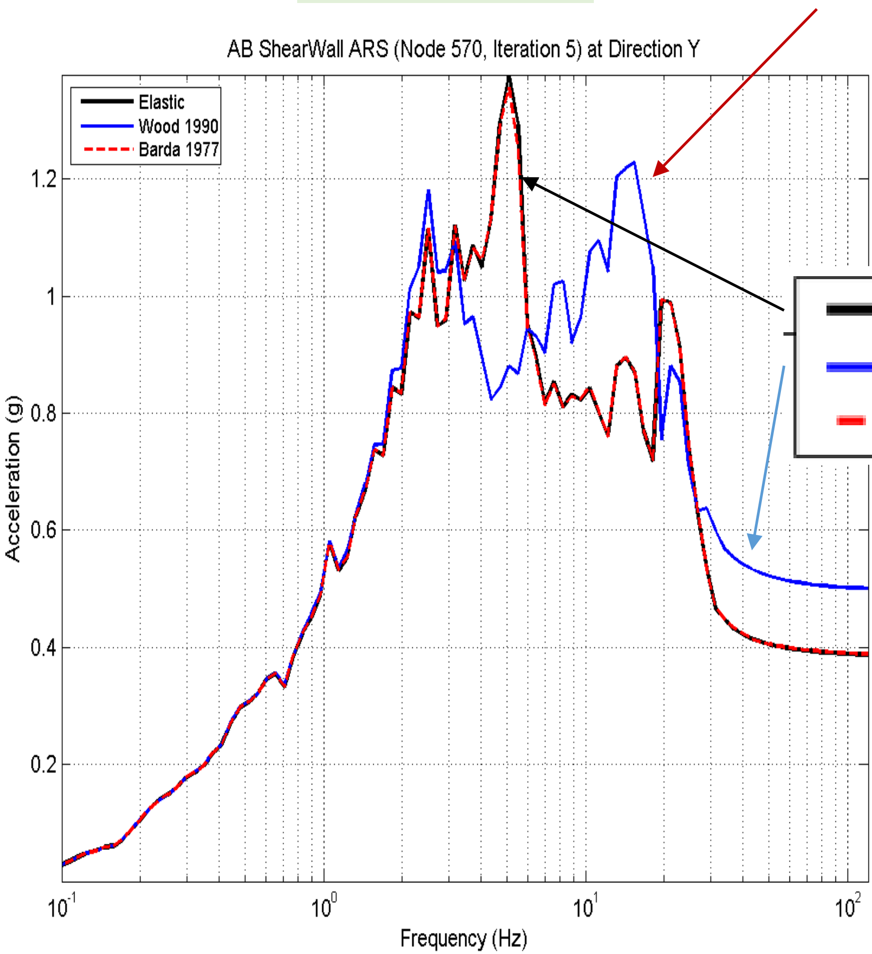
Shearwall Panel 17 Hysteretic Behavior Barda (1977) vs. Wood (1990) for 0.60g Input

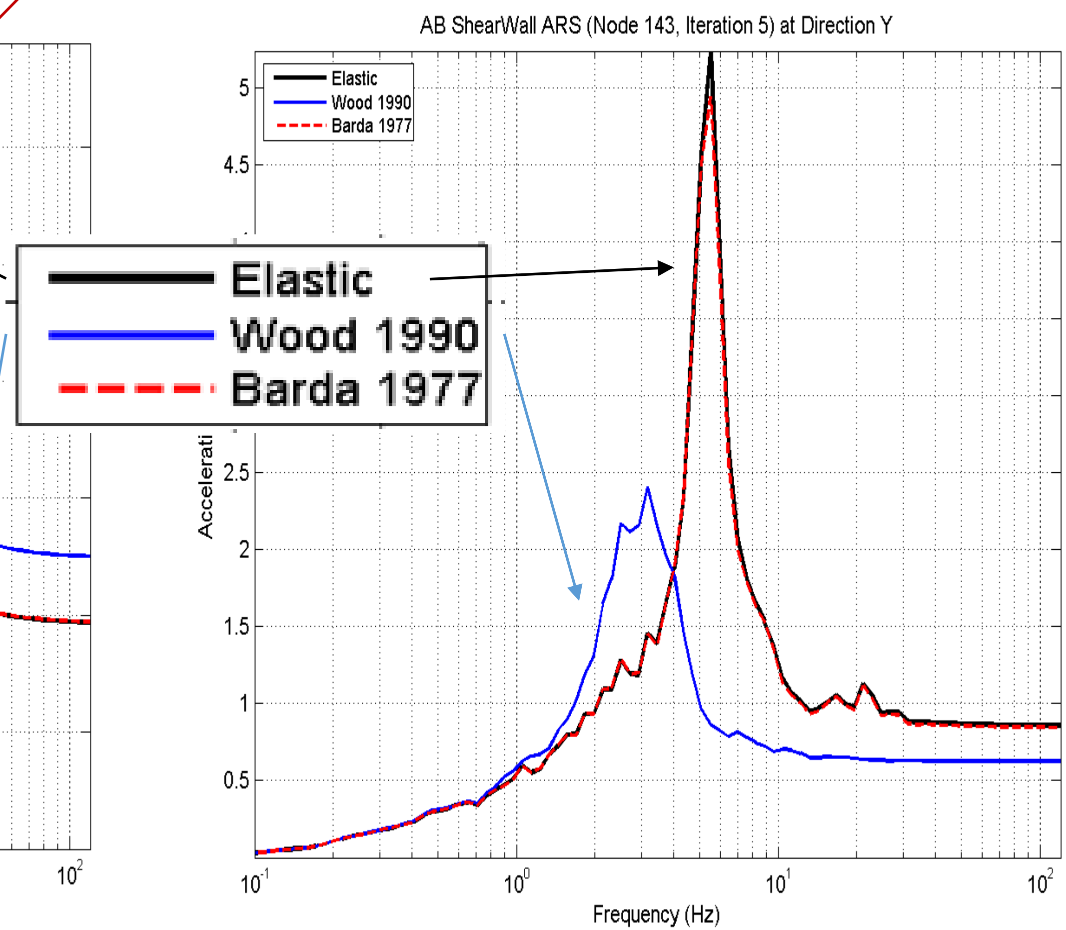


ARS at Different Elevations for Trans-Direction. Barda (1977) vs. Wood (1990) for 0.60g Input

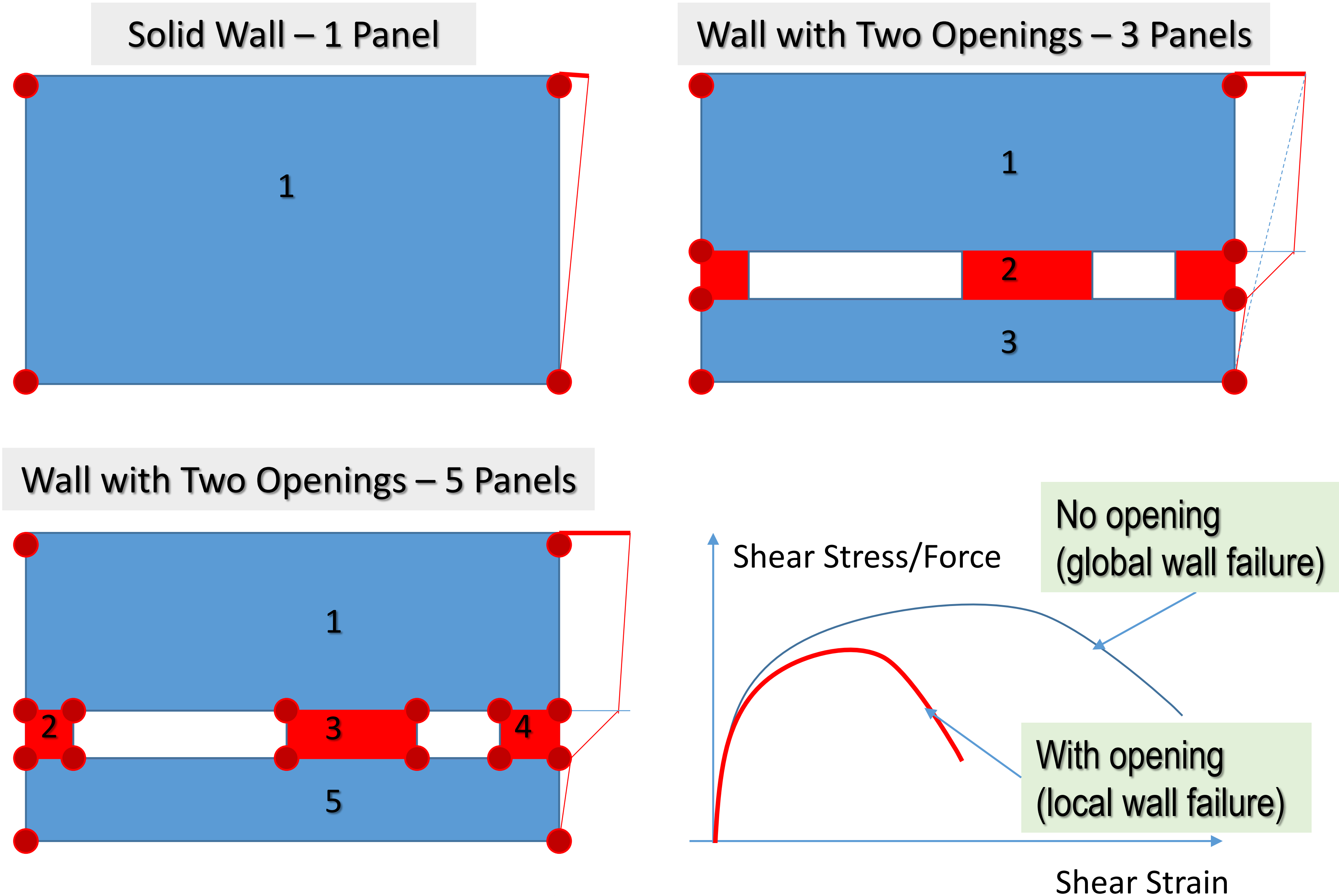
Basemat

High-Elevation



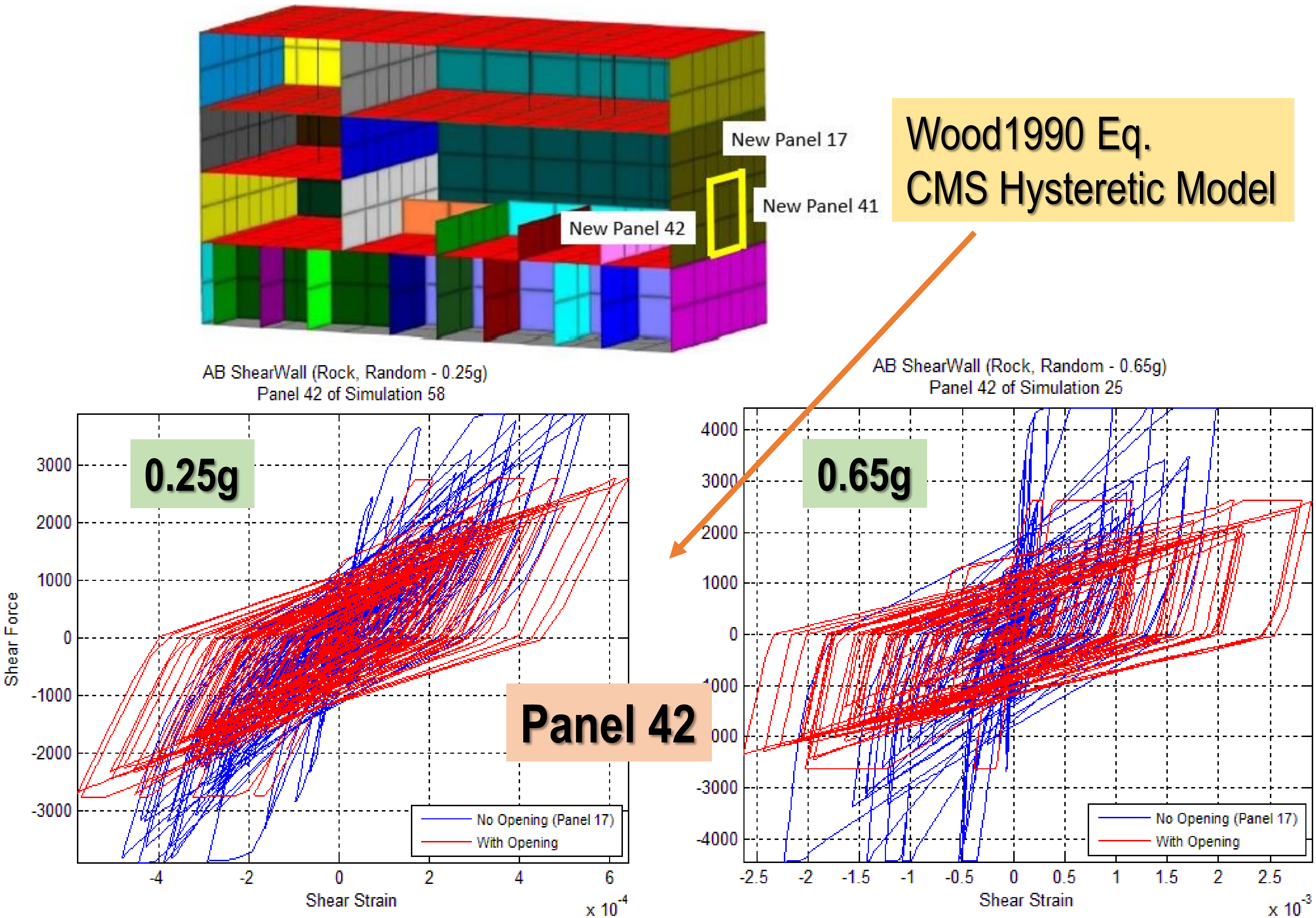


Including Wall Openings Semi Automatically

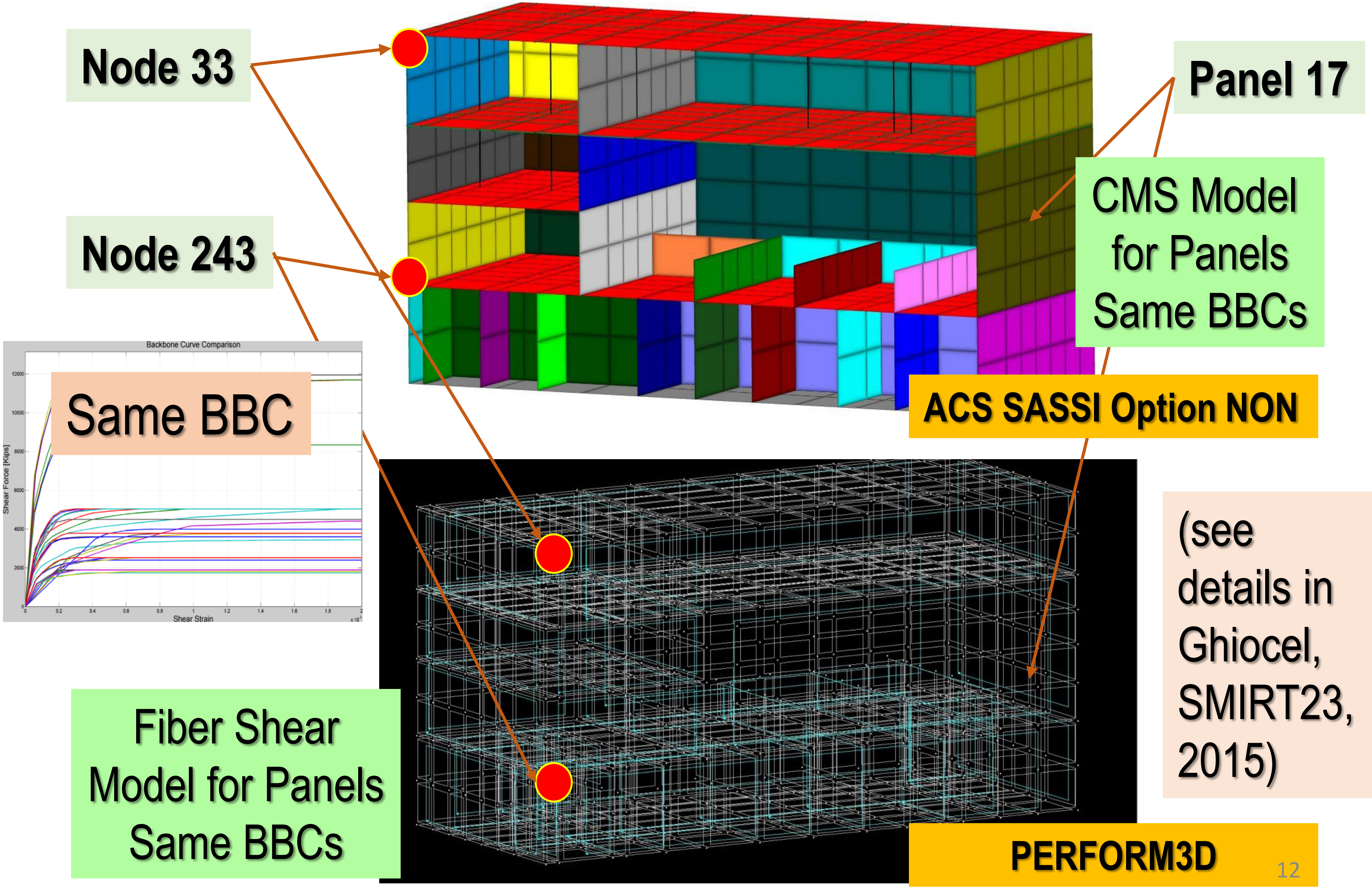


UI Commands: **EDGE, 1,0,0,1**, and then **EDGE,2**

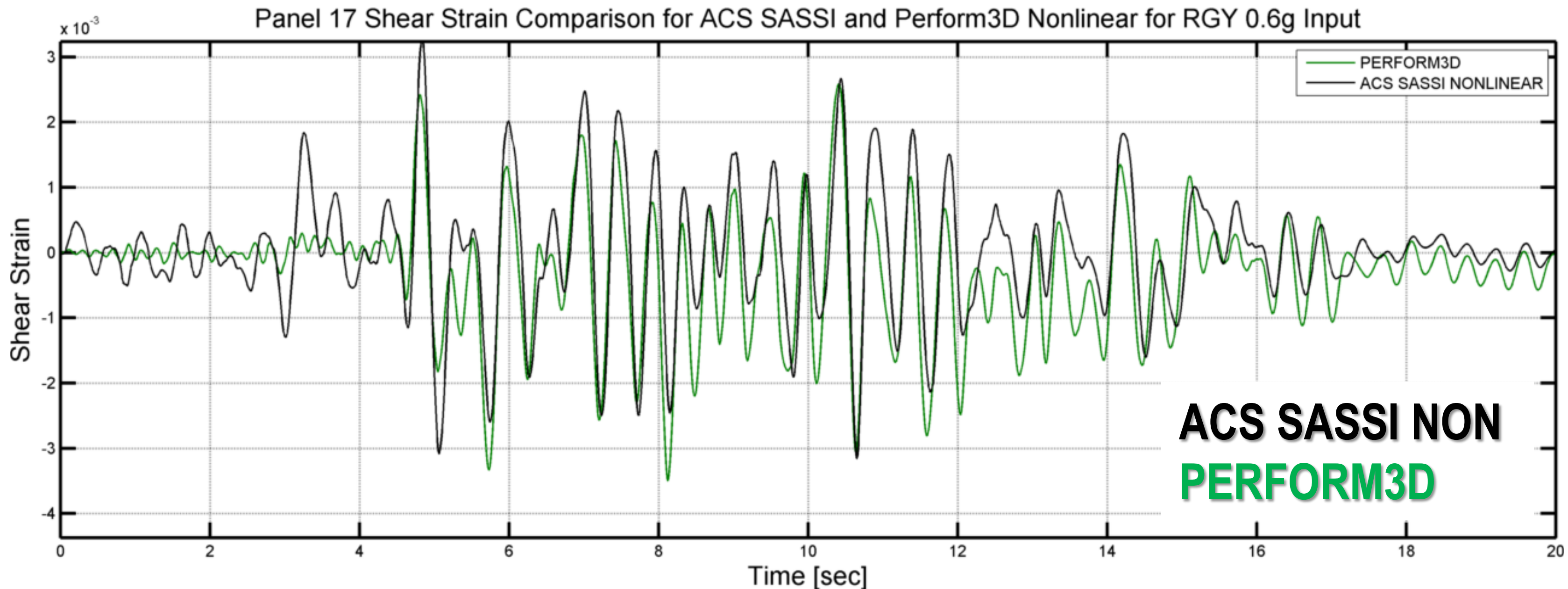
Nonlinear SSI Effects Due Openings in Walls

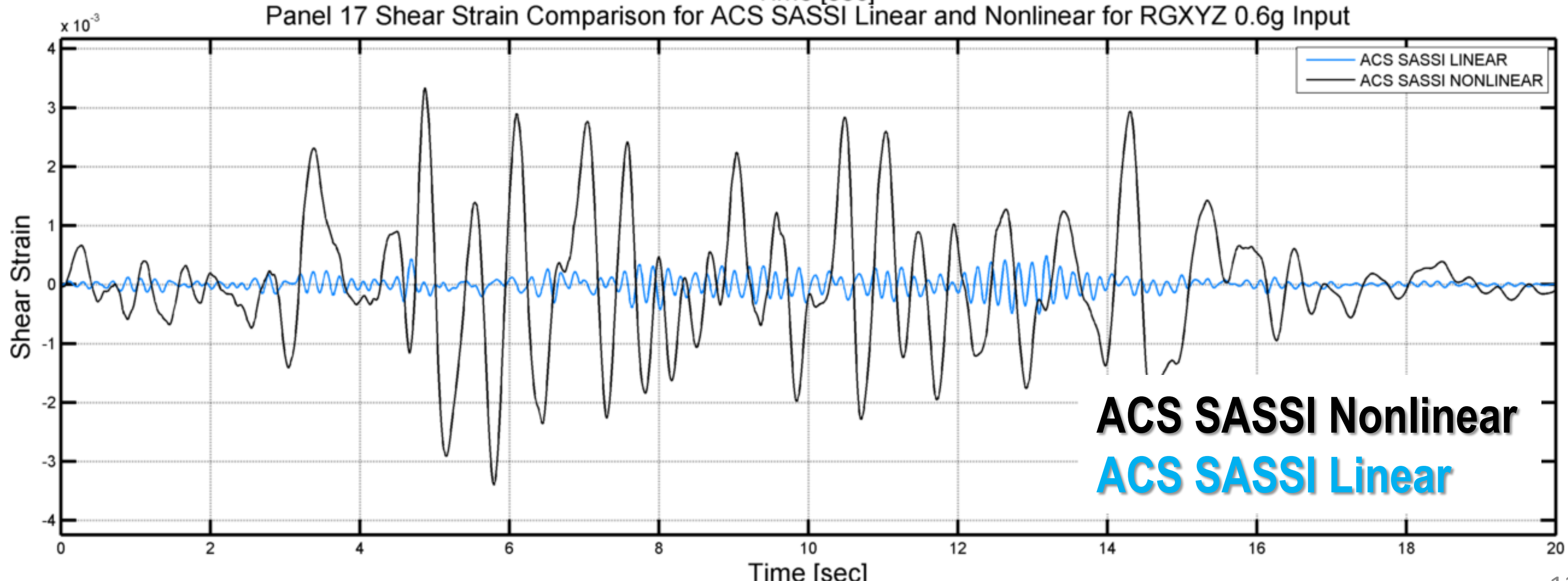


Fixed-Base Validation Study: ACS SASSI Option NON vs. PERFORM3D Nonlinear Time-History Analysis

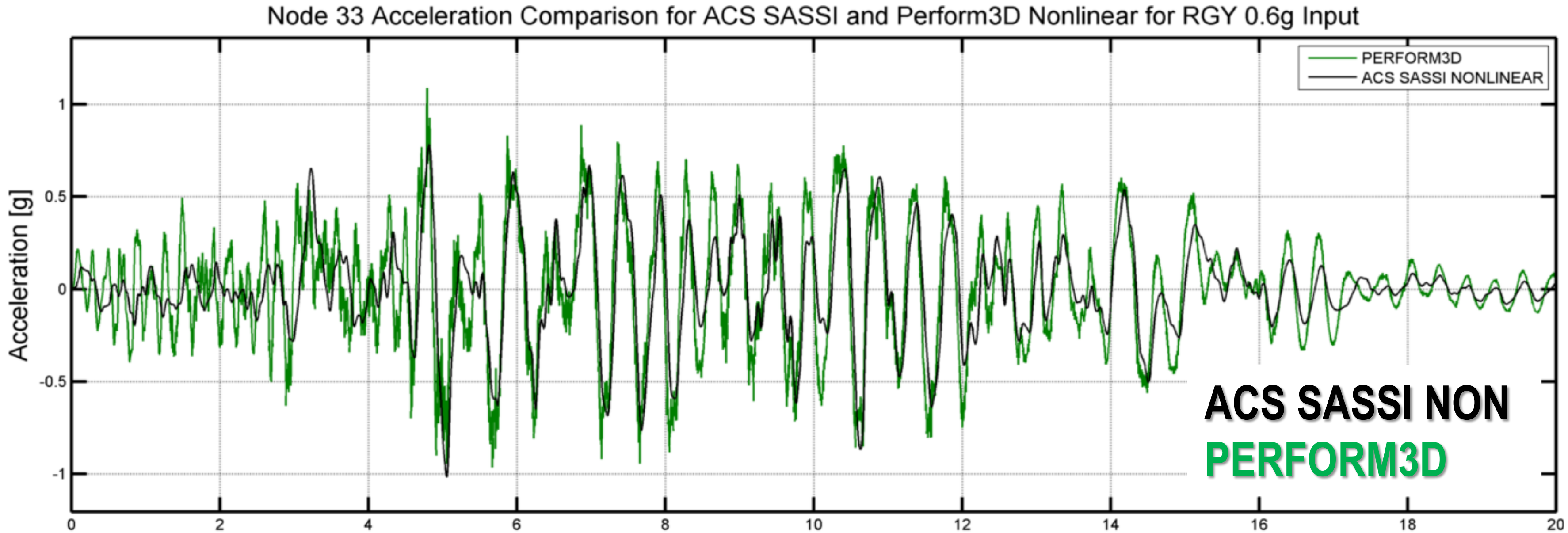


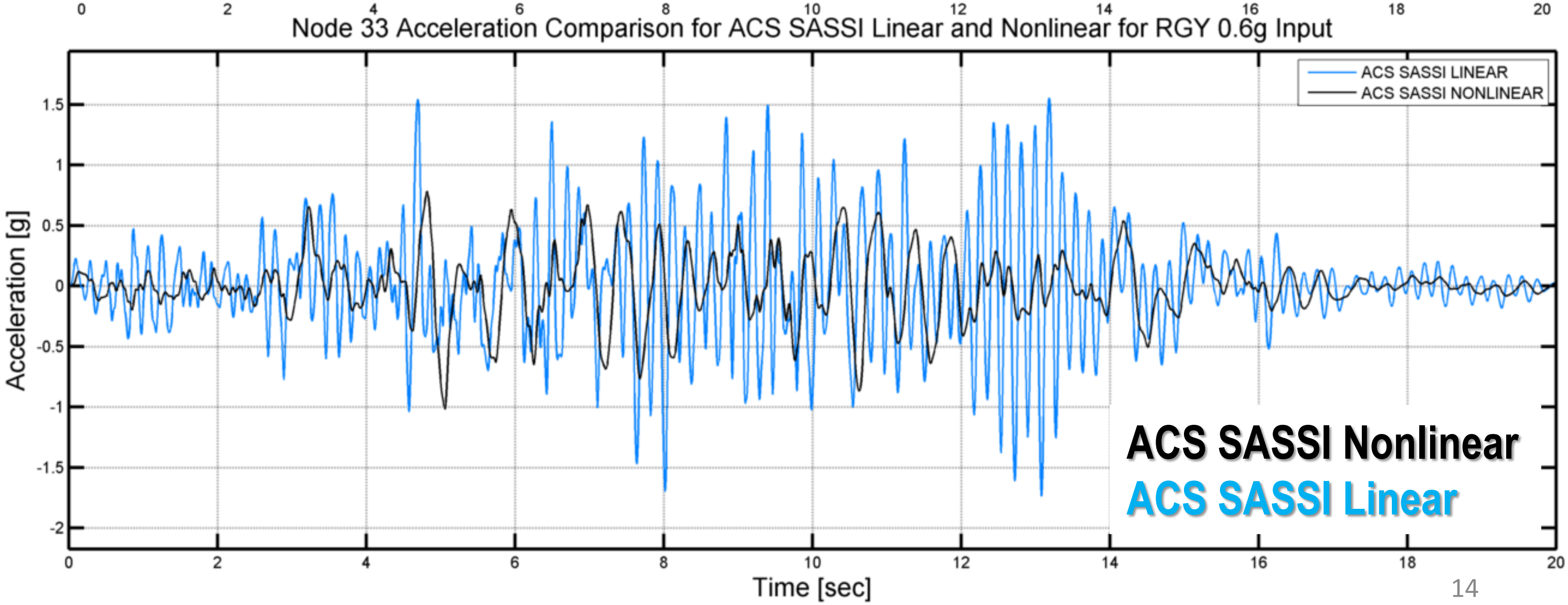
Panel 17 Shear Strains for 0.60g Input



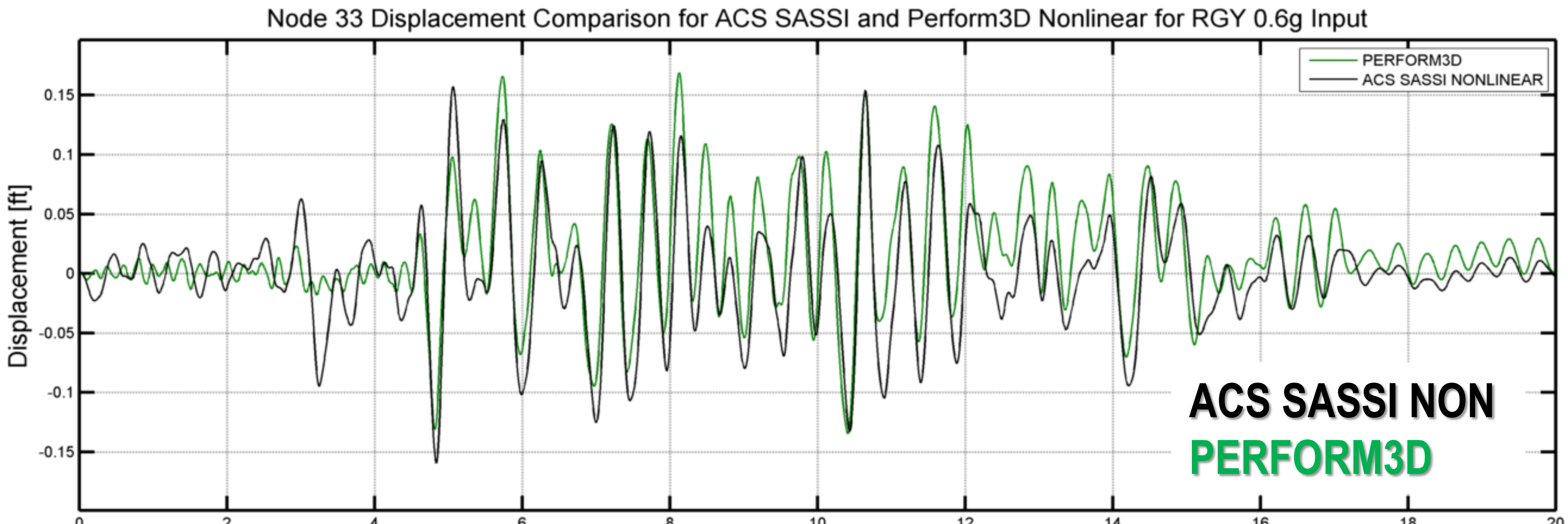


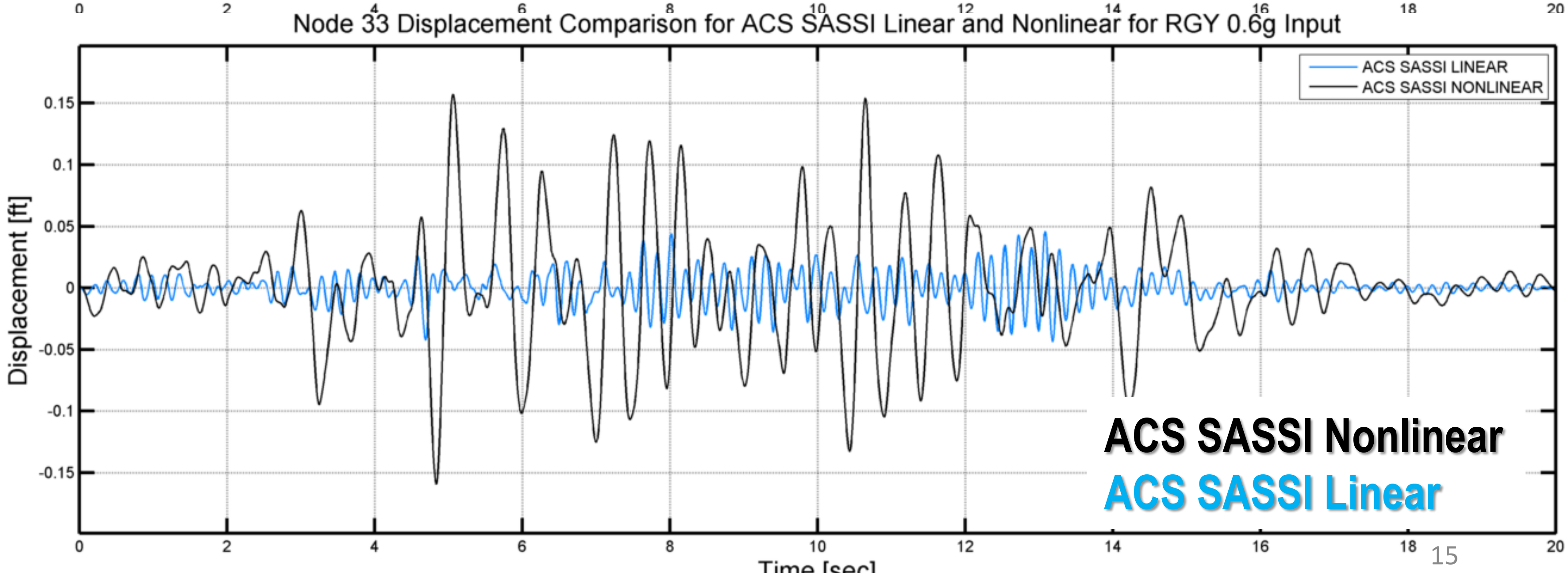
Node 33 (Top) Acceleration for 0.60g Input



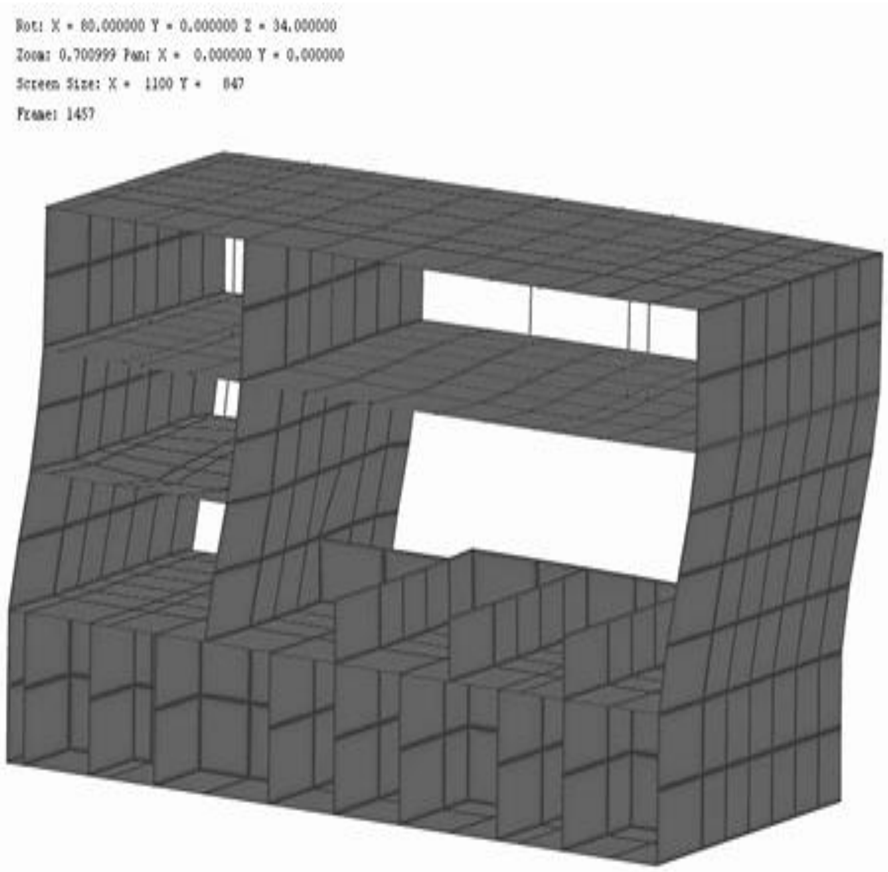


Node 33 (Top) Displacement for 0.60g Input

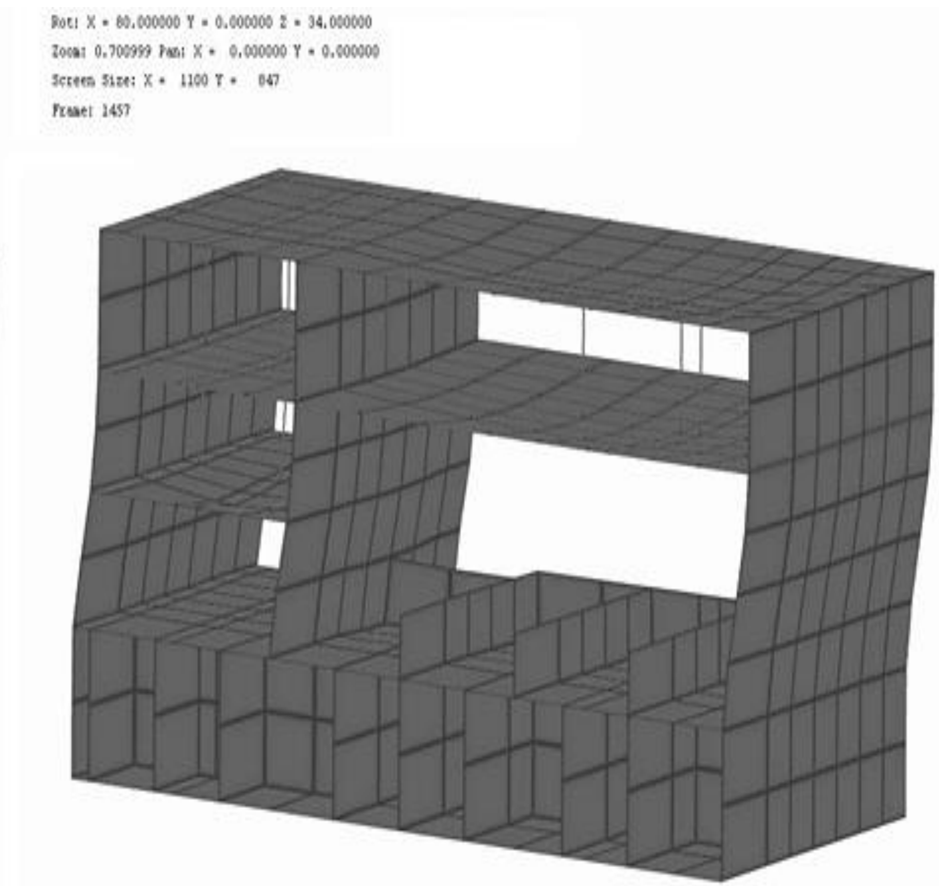




ACS SASSI NON vs. PERFORM3D Fixed-Base Structural Displacements for 0.60g Input



ACS SASSI Option NON

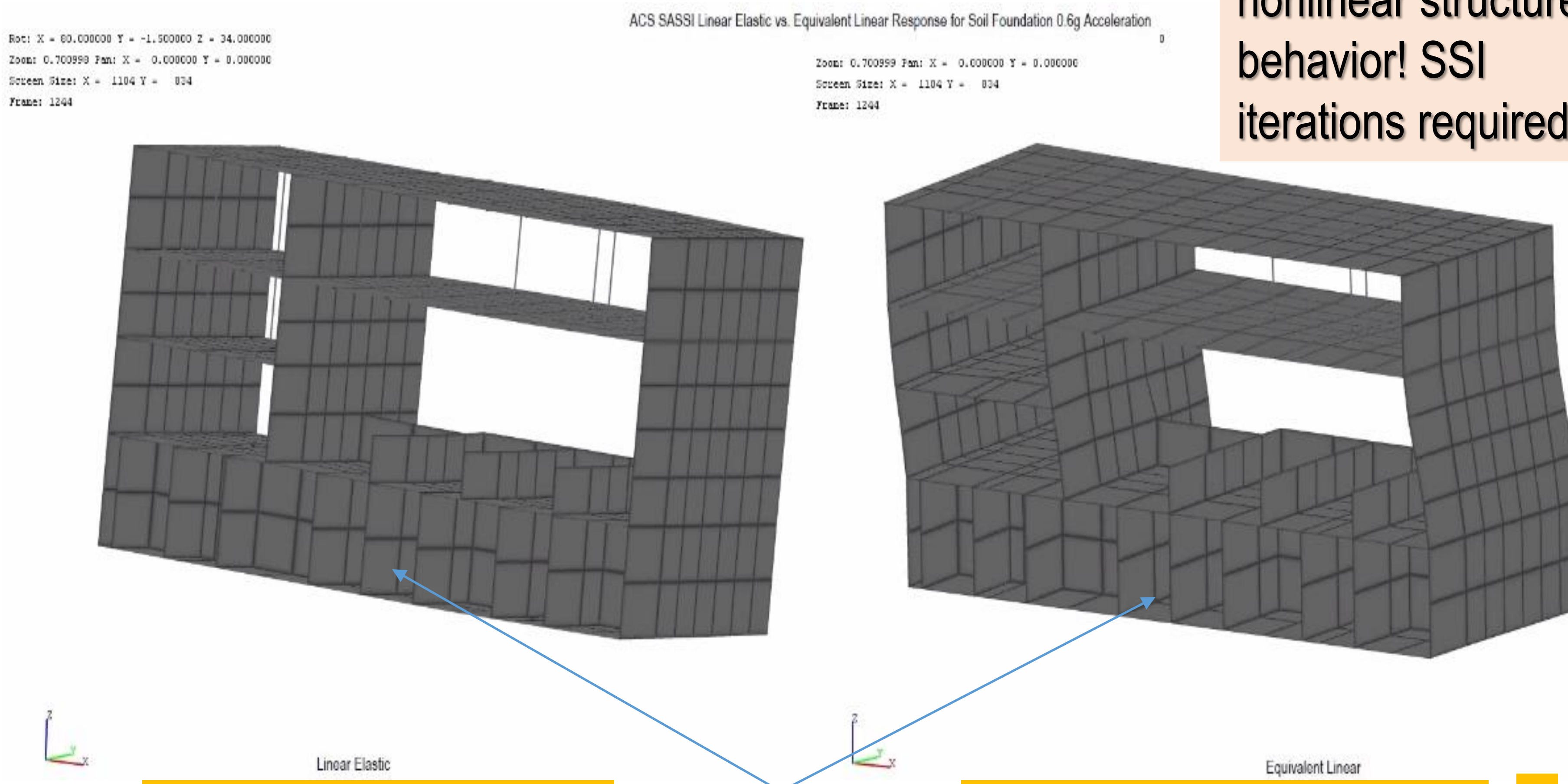


PERFORM3D

1

ACS SASSI Linear vs. Nonlinear SSI for Soil Site. Structural Displacements

Foundation motion is sensitive to nonlinear structure behavior! SSI iterations required!



ACS SASSI Linear SSI

ACS SASSI Nonlinear SSI

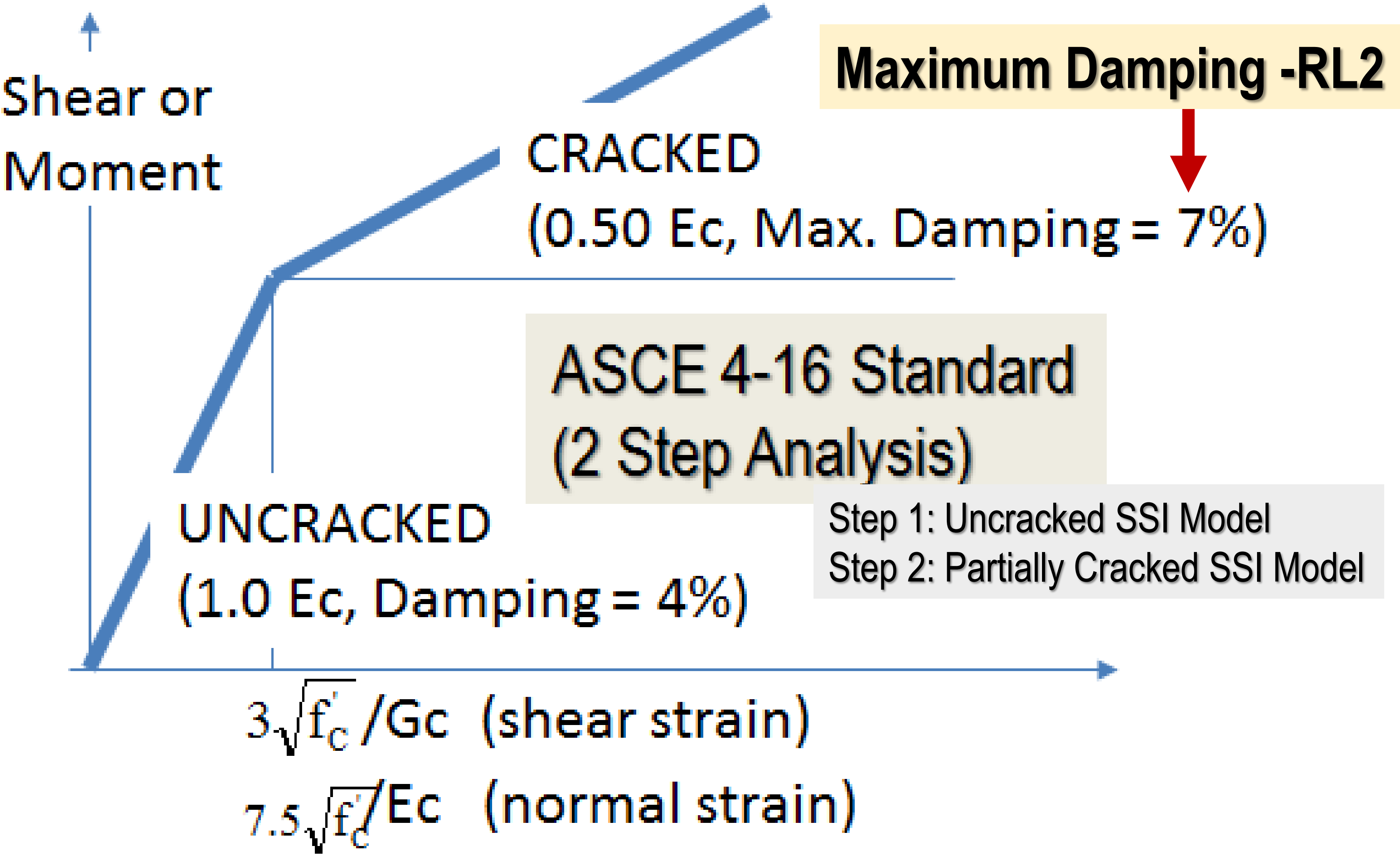
3

Inelastic Factors for Fixed-Base and SSI (Soil)

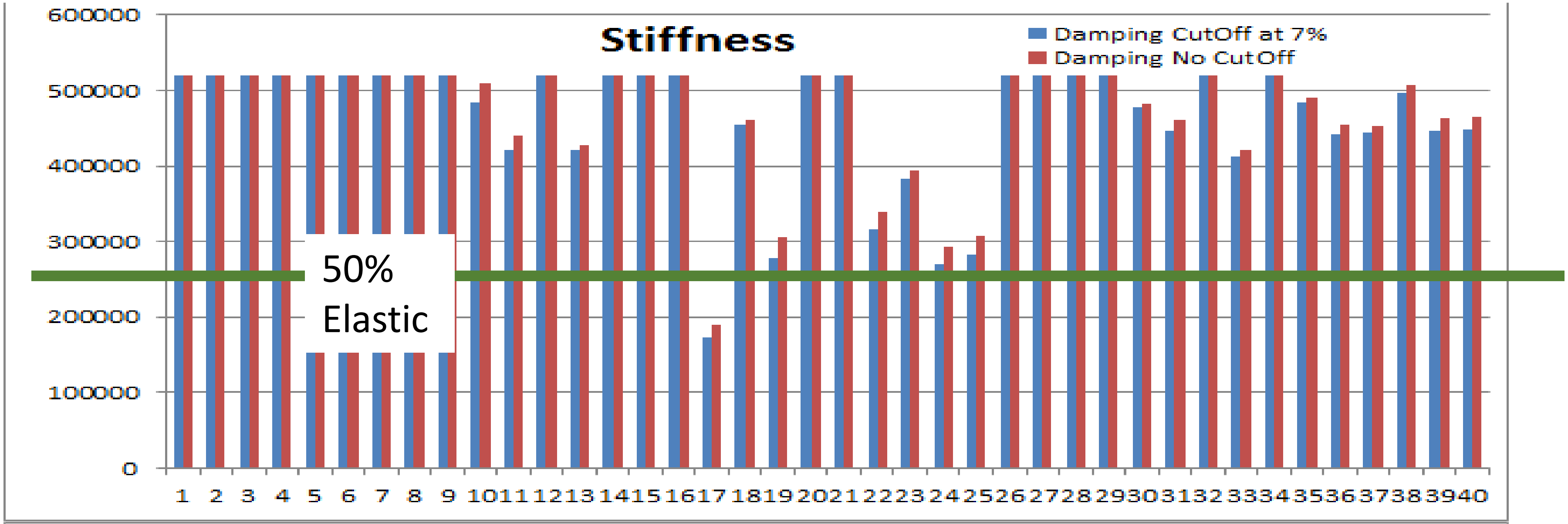
	Rock Site				Soil Site			
	0.3g		0.6g		0.3g		0.6g	
Panel	μ*	Fμ	μ*	Fμ	μ*	Fμ	μ*	Fμ
2	1.25	1.40	3.70	1.66	1.01	0.94	2.13	1.34
3	1.27	1.31	2.24	2.07	1.27	0.95	2.16	1.50
9	1.28	1.21	2.24	1.92	1.30	0.93	2.31	1.44
10	1.97	1.63	5.58	2.35	2.40	1.07	10.80	1.50
11	6.20	2.03	15.91	3.43	6.29	1.47	16.27	2.47
13	3.14	1.81	6.91	3.27	2.85	1.60	8.18	2.75
17	12.71	2.51	61.80	5.03	10.97	1.66	65.76	3.33
18	2.66	1.38	37.62	2.43	1.89	1.01	24.83	1.50
19	7.40	1.95	50.01	3.88	6.22	1.38	41.31	2.68
22	3.22	2.17	6.61	4.07	3.00	1.36	10.46	2.52
23	4.27	1.88	9.34	3.39	2.86	1.43	7.65	2.32
24	9.85	1.92	64.26	3.84	3.71	1.24	52.54	2.40
25	9.55	1.92	56.04	3.84	5.64	1.42	50.37	2.79
30	1.92	1.27	4.90	2.02	0.97	1.02	2.84	1.31
31	2.25	1.39	5.63	2.26	2.37	1.33	8.74	2.22
33	2.73	1.69	6.02	3.09	1.61	1.41	3.52	2.19
35	1.60	1.14	4.35	1.70	0.99	1.00	3.80	1.24
36	2.94	1.57	6.72	2.67	2.28	1.35	7.14	2.09
37	2.49	1.54	5.69	2.67	1.95	1.41	4.64	2.20
38	1.82	1.13	4.93	1.67	1.67	1.28	4.77	1.83
39	2.36	1.45	5.28	2.53	0.95	0.96	2.23	1.37
40	2.44	1.45	5.61	2.45	1.11	1.13	2.68	1.65
Average	3.88	1.63	16.88	2.83	2.88	1.24	15.23	2.03
Max	12.71	2.51	64.26	5.03	10.97	1.66	65.76	3.33

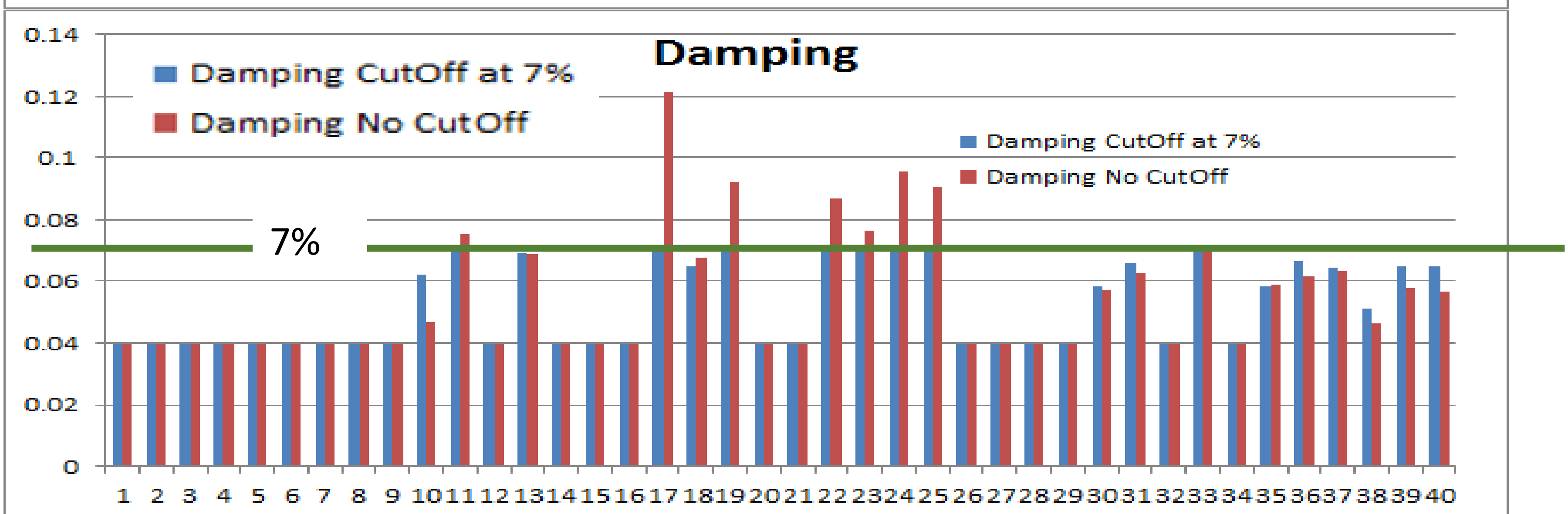
Note * : The ductility ratio are computed with respect to cracking strain

Design Level: Concrete Cracking Pattern for Site-Specific Applications Per ASCE 4-16 C3.3.2

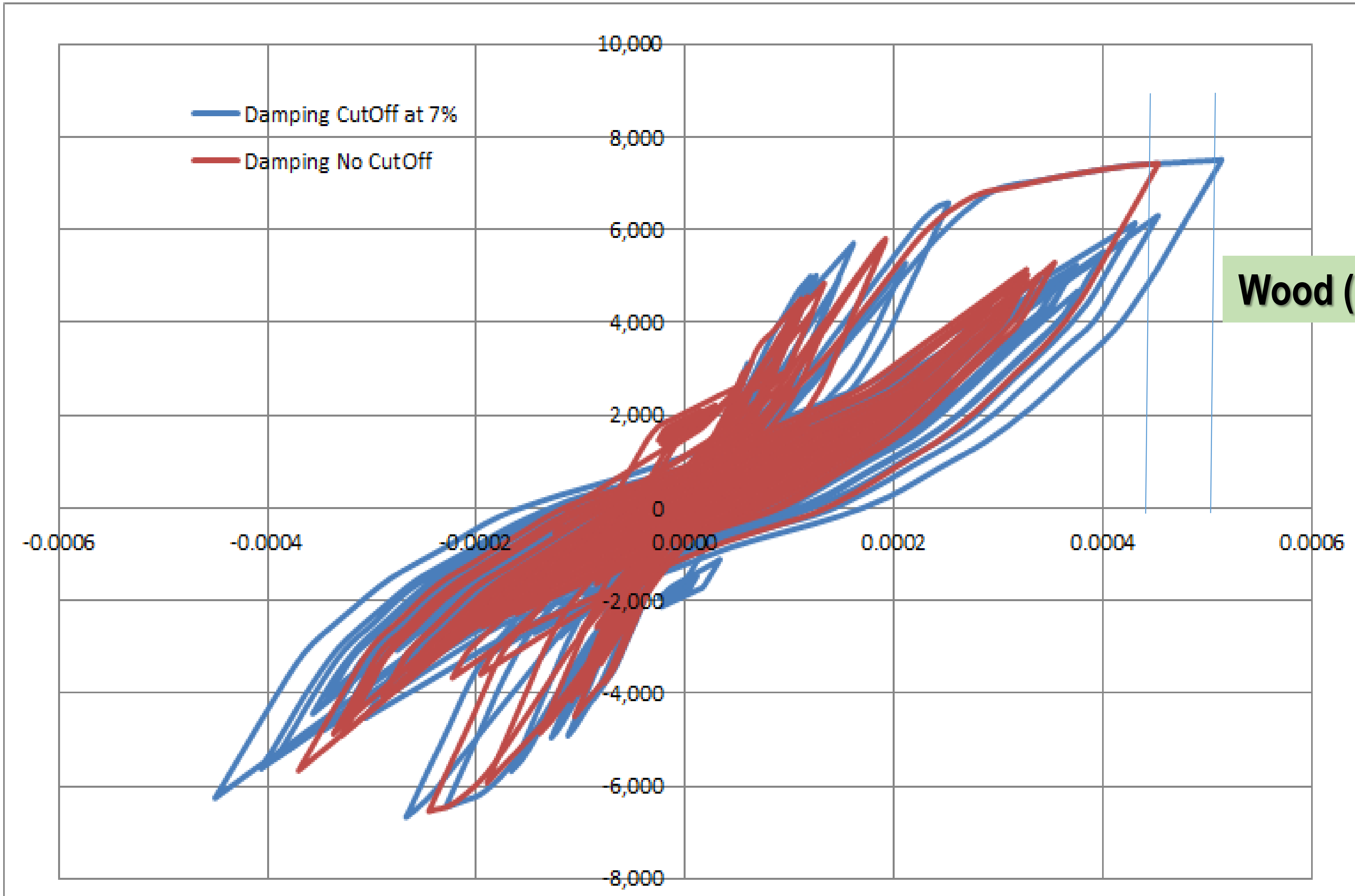


Effects of 7% Damping Cut-Off For *Design-Level* 0.30g Input on Effective Panel Stiffness



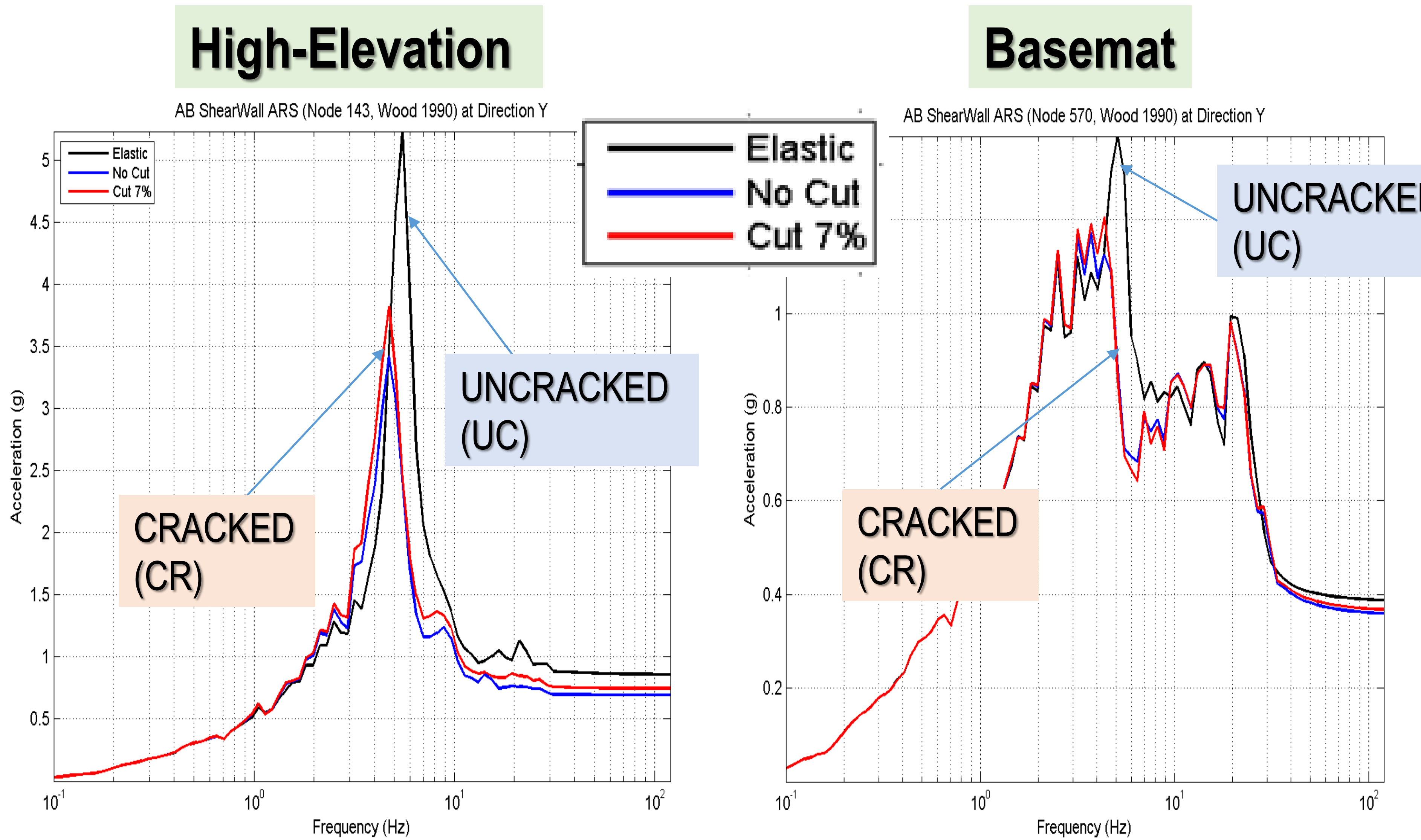


Panel 17 Hysteretic Behavior w/ and w/o 7% Damping Cut-Off for 0.30g Input

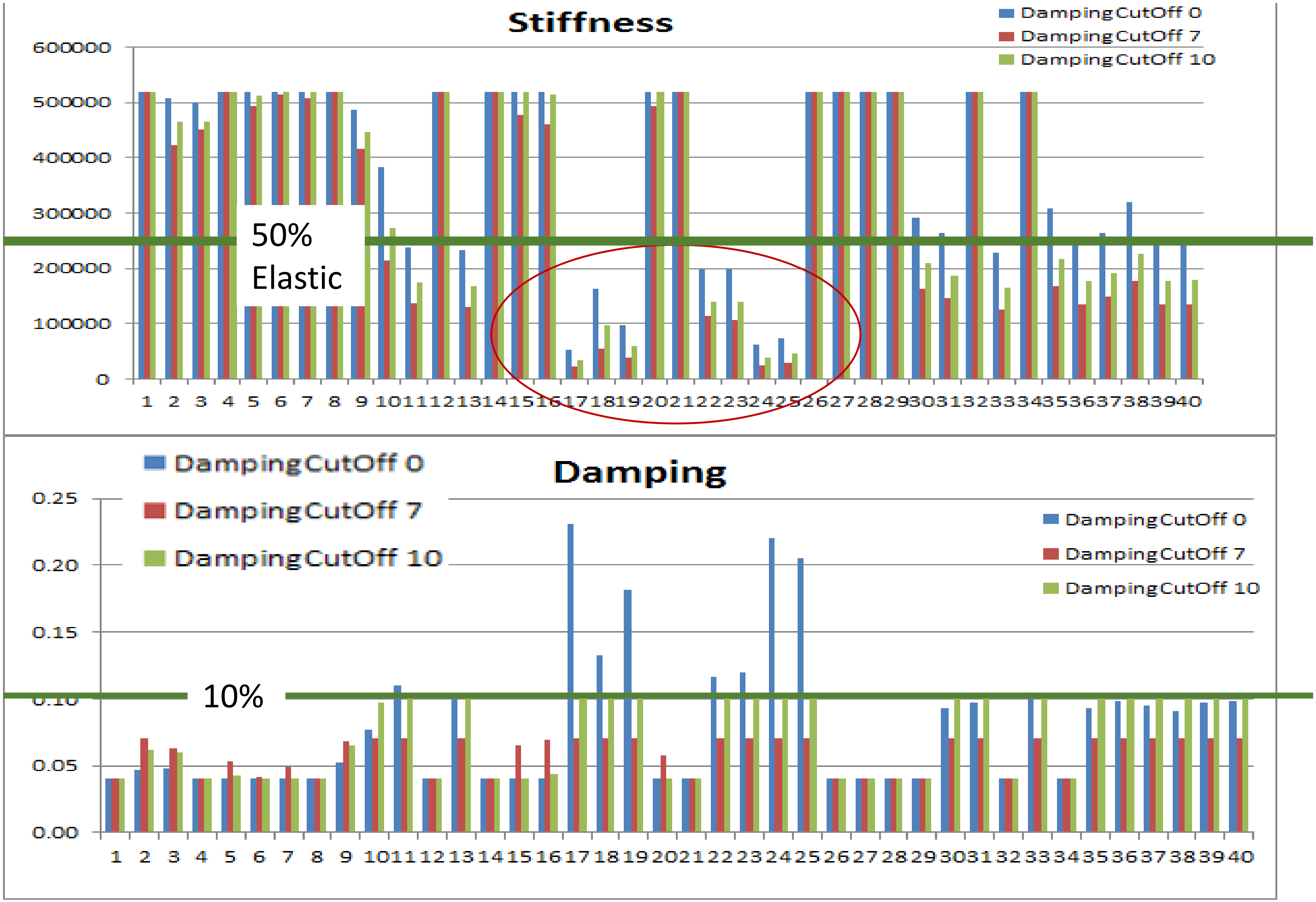


Wood (1990)

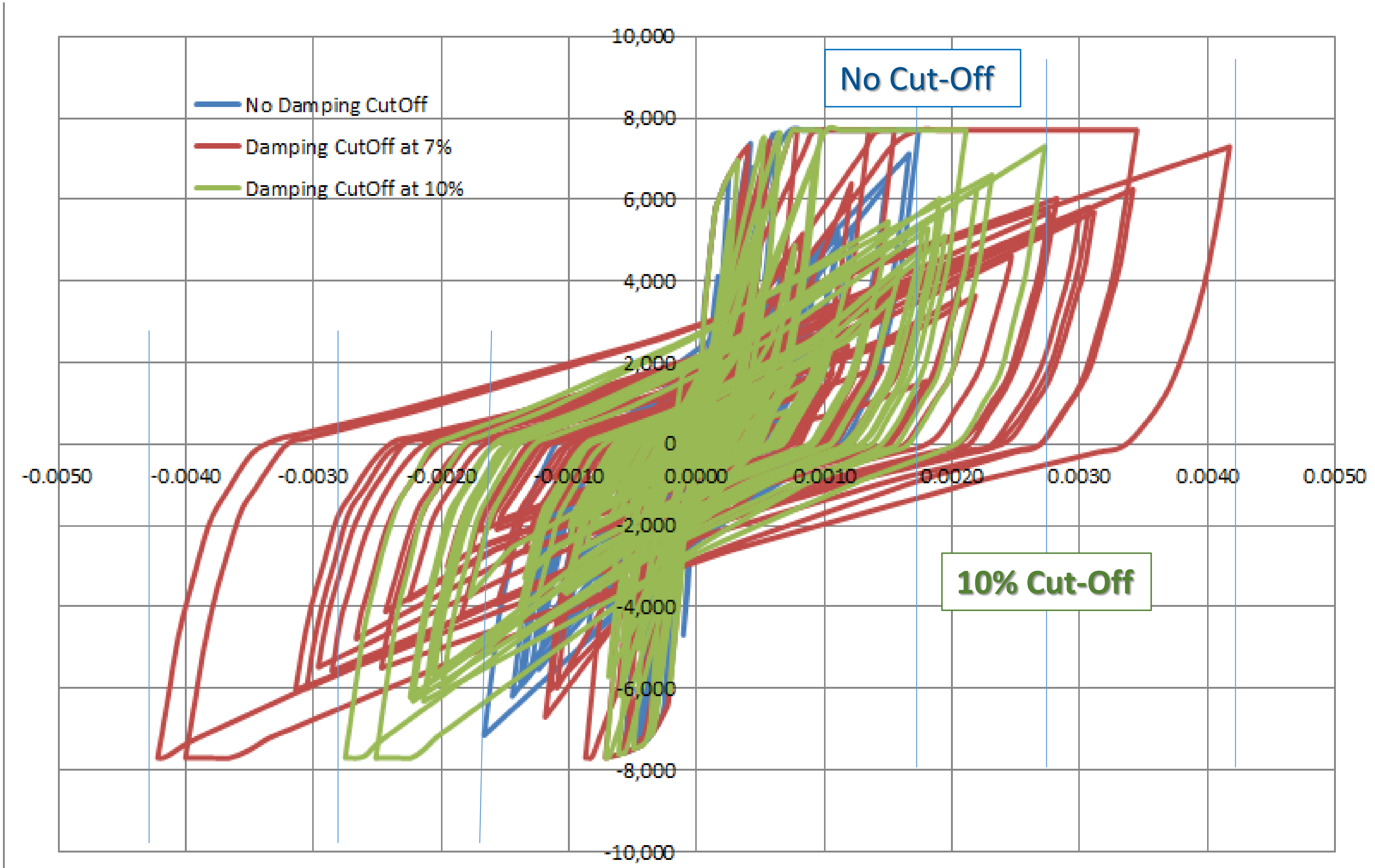
Computed ARS for *Design-Level* 0.30g Input. UC 4% and CR 7% for No Damping Cut for 0.30g



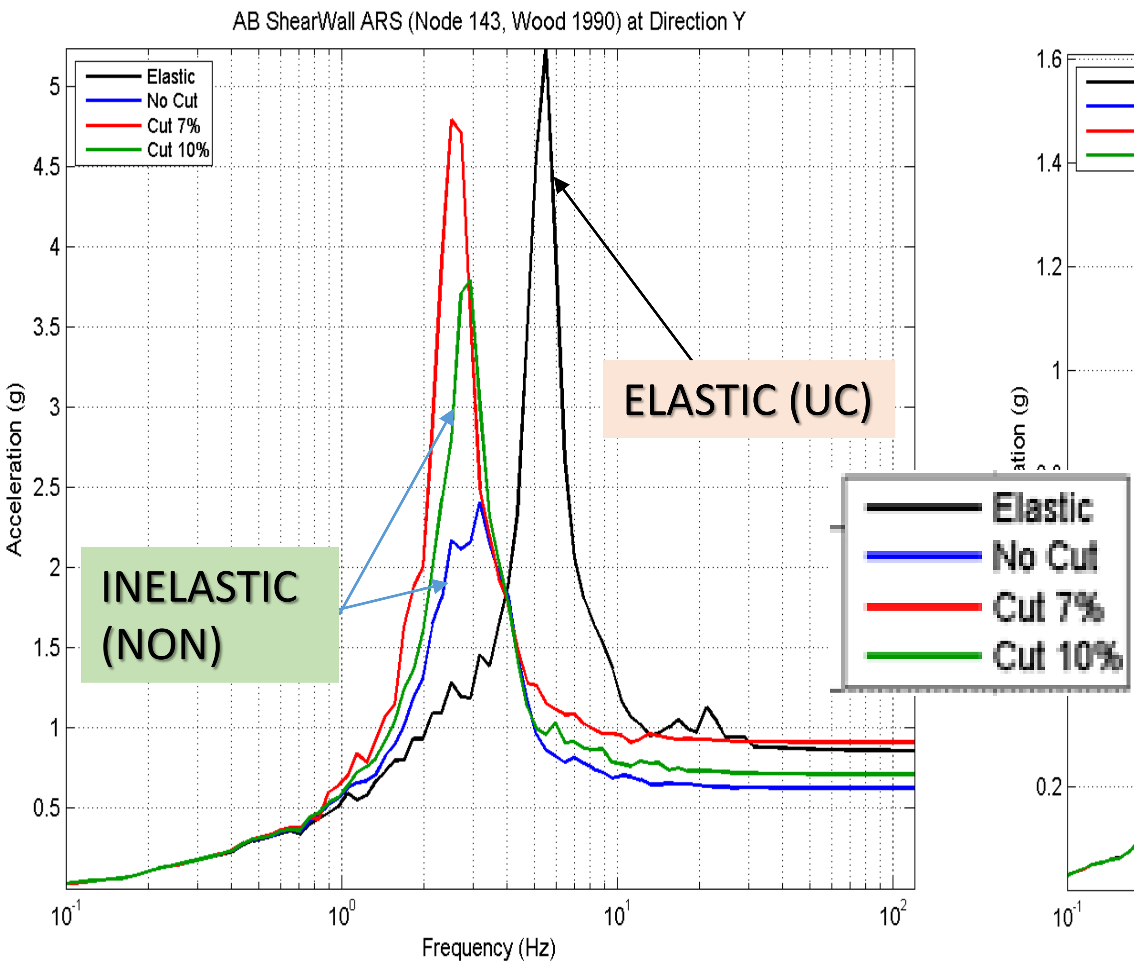
Effects of 7% and 10% Damping Cut For Beyond-Design Level 0.60g Input on Effective Stiffness

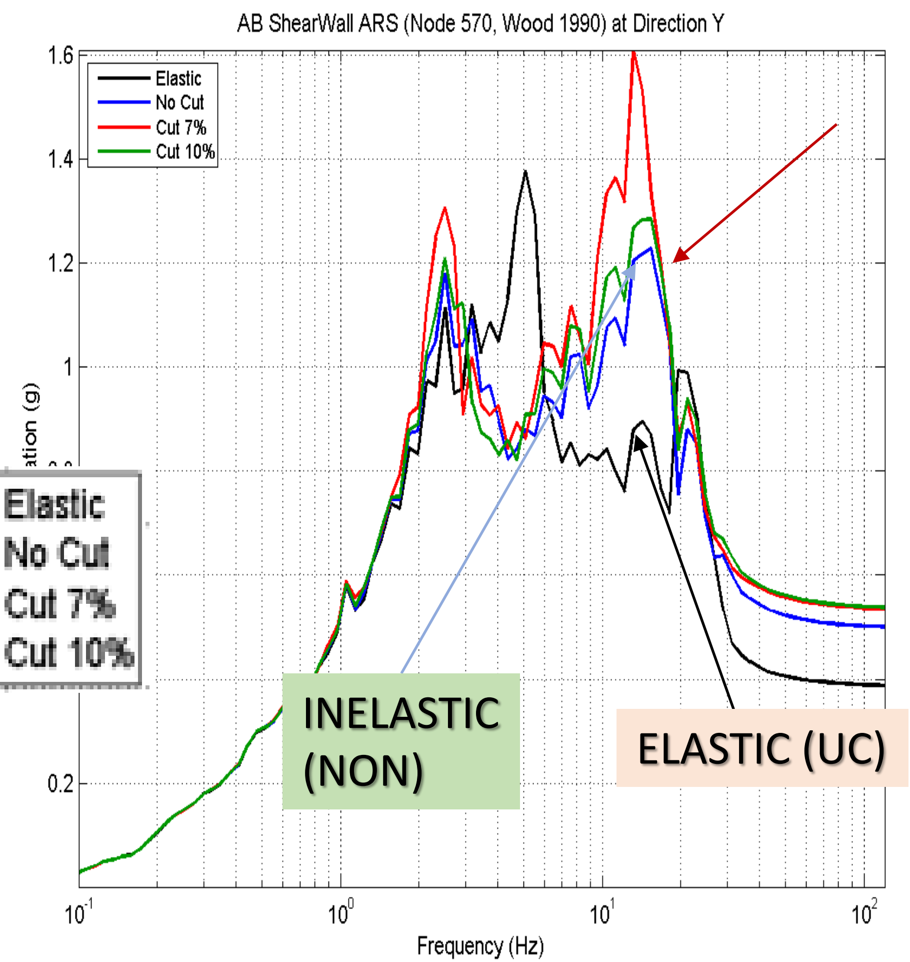


Effects of 10% Damping Cut For *Beyond-Design Level* 0.60g Input on Panel 17 Hysteretic Behavior

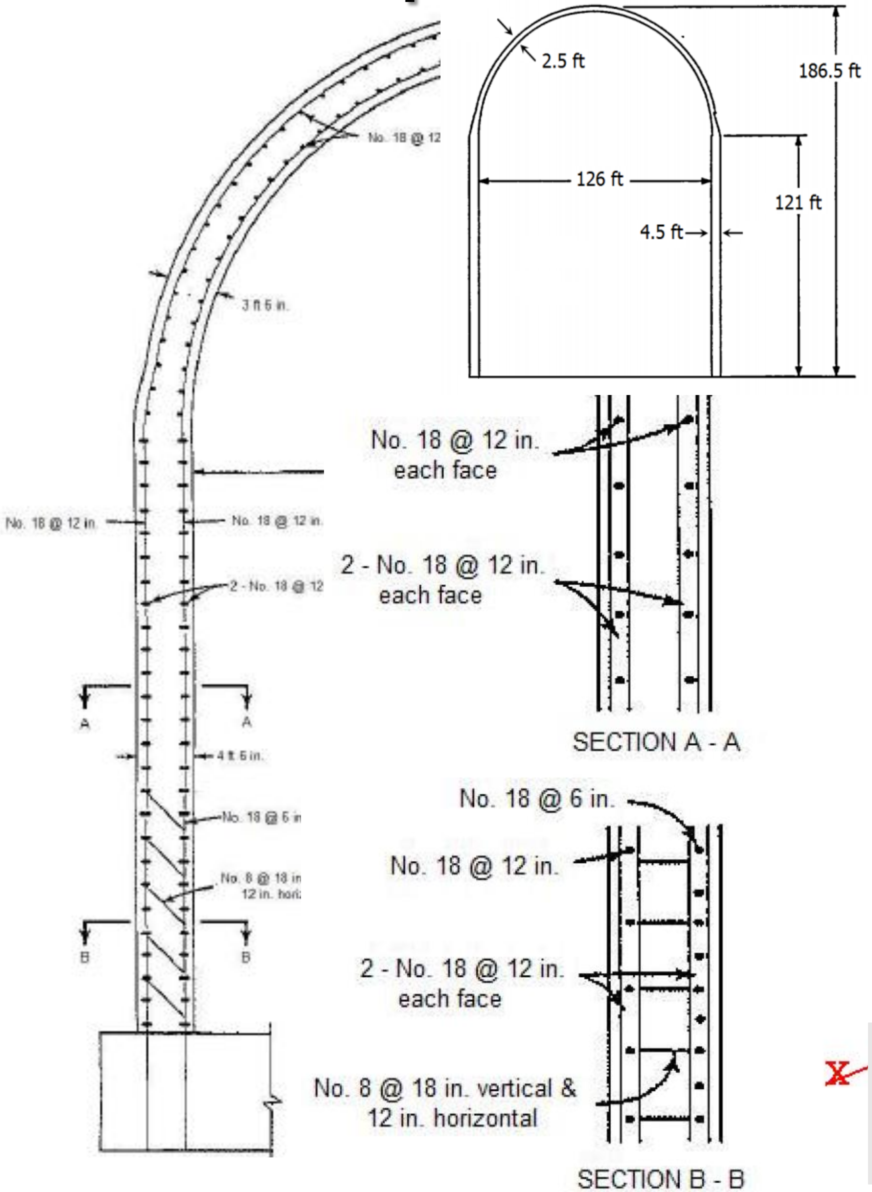


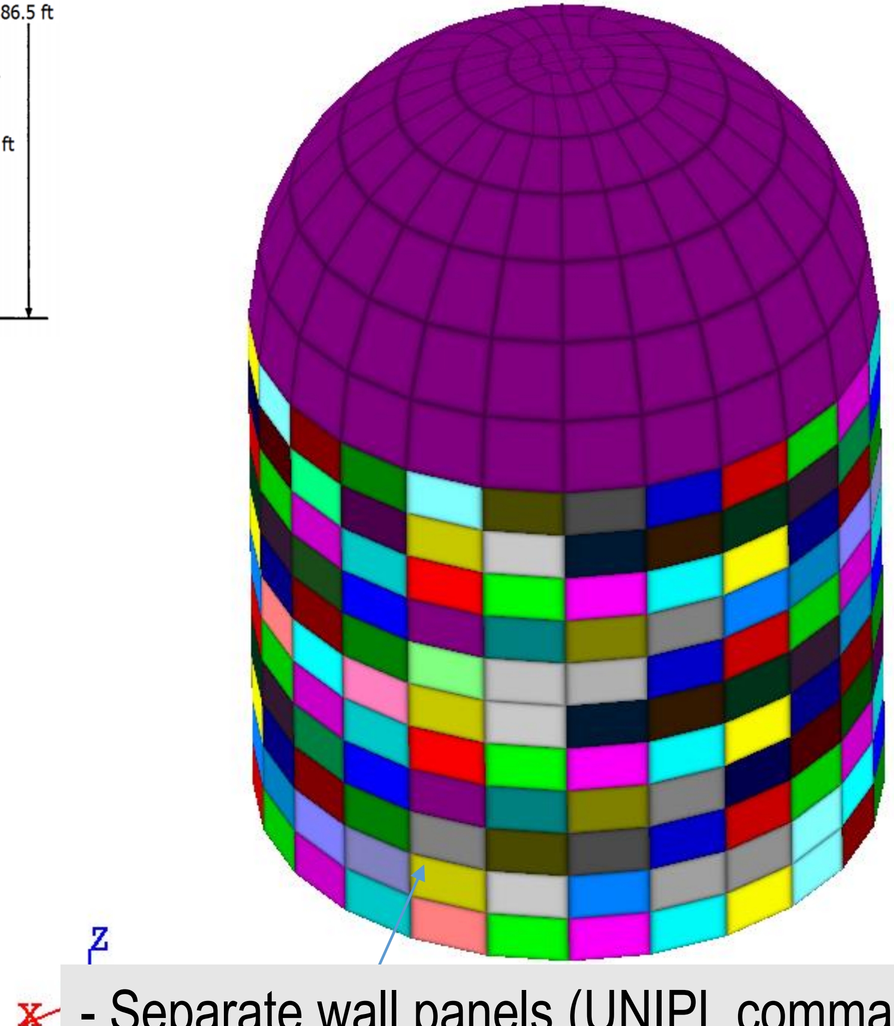
ARS at Different Elevations for Y-Dir for 0.60g Input. UC 4% and NON 7%, 10% or No Damping Cut





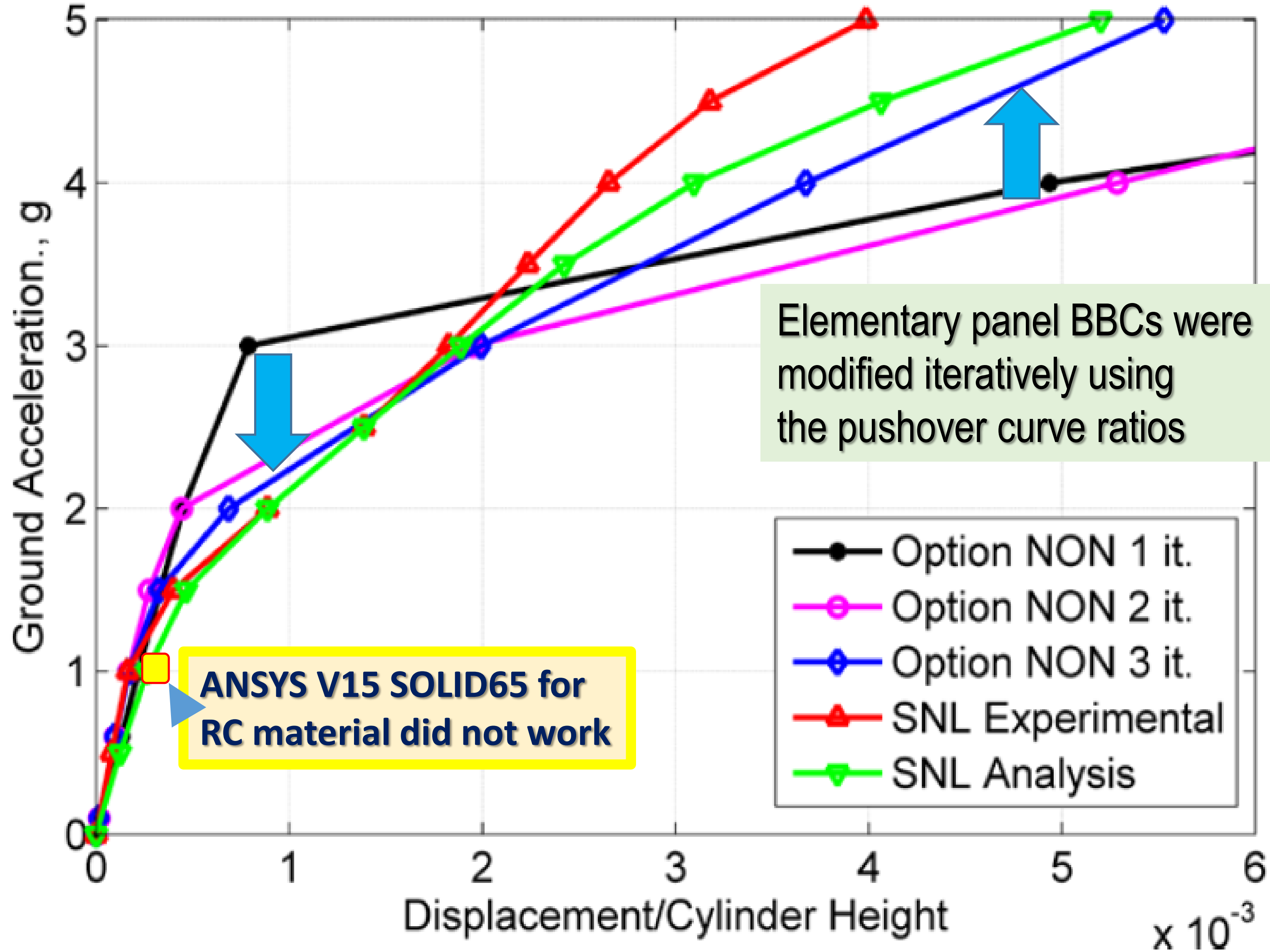
RC Containment Pushover Study (NUREG/CR-6783). ACS SASSI Option NON Used for Nonlinear Static Analysis





- Separate wall panels (UNIPL command).
- Build panel BBCs using Barda's equation

Option NON RC Containment Pushover Results Improved Iteratively Against Experimental Results



Conclusions

- The nonlinear SSI analysis based on the hybrid approach is highly efficient when compared with time domain. Only 2-3 times slower than linear SSI analysis.
- The current implementation of nonlinear SSI approach is applicable to low-rise concrete shearwall buildings. It can consider the in-plane shear and bending wall deformation, separately, or both in the same model, based on experimental hysteretic models (Cheng-Mertz, Takeda). Option NON tested for large nonlinear wall behaviors with shear strains up to 1-2%.
- It can be easily applied in compliance with the ASCE 4/43 standard recommendations for the *design-level or beyond design-level applications* to satisfy the maximum allowed damping values and stiffness reductions for Response Levels 2 and 3, respectively.
- Applicable also to containment structures based on the calibration of the panel BBC inputs against experimental/analysis pushover results. Iterative modifications of BBCs improve accuracy of the pushover results. ACS SASSI NON pushover results much better than the ANSYS SOLID65 RC element results.