New ASCE 4-Based Probabilistic Nonlinear SSI Analysis for Improving Seismic Fragility Computations

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Session VIII–Uncertainty in Soil-Structure Interaction (SSI) Analysis Invited Panel

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Purpose of This Presentation:

To show the application of the new ASCE 4-16 based probabilistic simulation-based SSI analysis recommendations (Chapters 2 and 5) can be applied to improve fragility calculations by presenting a case study of for a reinforced concrete shearwall building.

To answer key questions:

- How can be the new ASCE 4 recommendations on probabilistic SSI can be integrated for *beyond design-level* analyses within seismic fragility calculations? PART 1 will respond to this.

- How the 2016 ASCE 4-based results differ from the 1994 EPRI-based results? PART 2 will respond to this.

2016 ACS SASSI V3 with Options PRO and NON was used.

Introduction to New ASCE 4 Recommendations for Probabilistic Site Response and SSI Analysis

New ASCE 4 Probabilistic Site Response Analysis (PSRA) and Probabilistic SSI Analysis (PSSIA)

Based on the new ASCE 04-2016 recommendations for probabilistic seismic SSI analyses:

- *Probabilistic SSI analyses should be performed using at least 30 LHS randomized simulations*

- *Probabilistic SSI responses should defined with the 80% non-exceedance probability* level for the design-level applications.

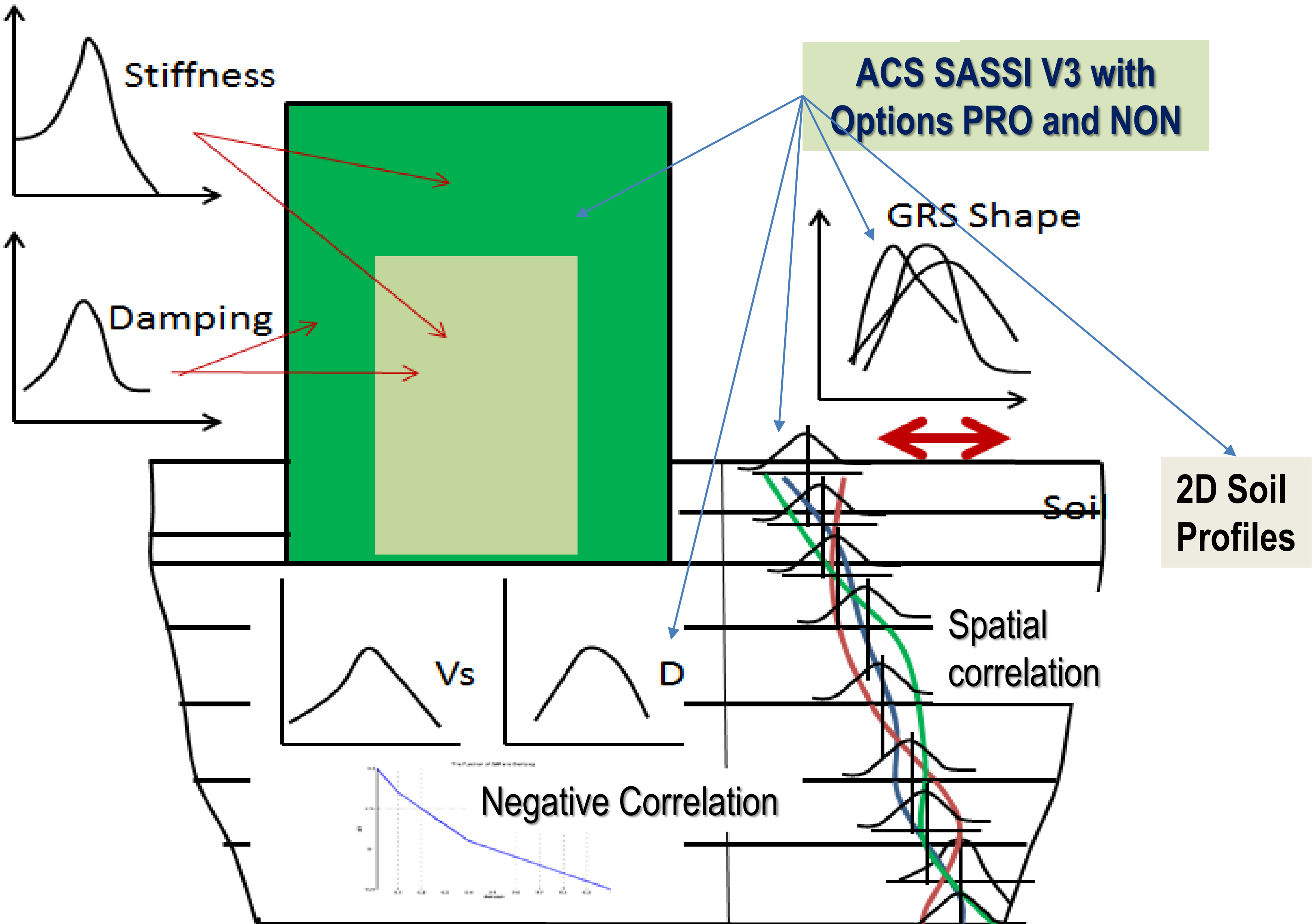
- Probabilistic modeling should minimally include:

  - SEISMIC INPUT: GMRS/UHRS amplitude assumed to randomly varying (Methods 1 and 2).

  - SOIL PROFILE: Vs and D profiles (include spatial correlation)

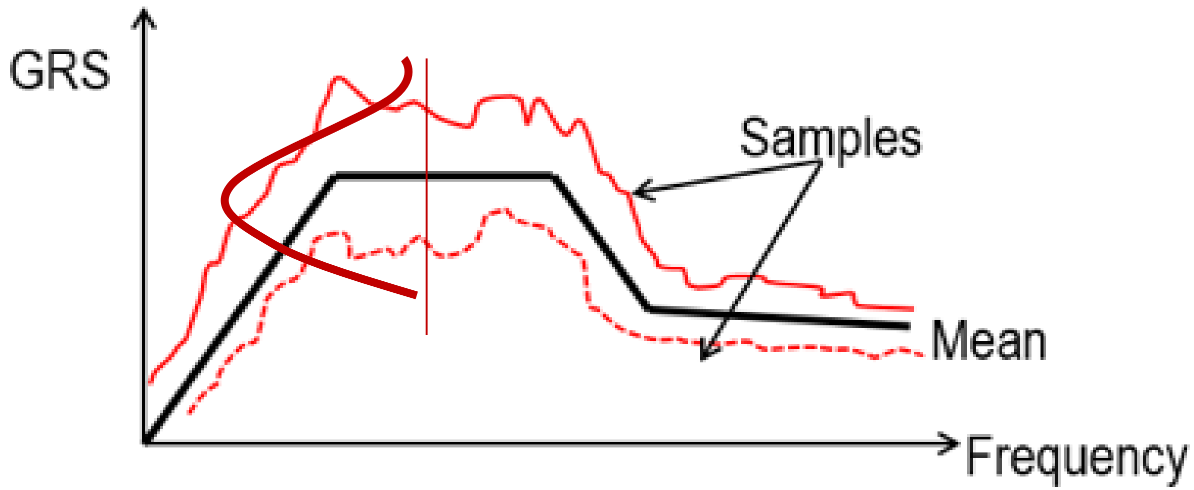
  - STRUCTURE: Effective stiffness K and damping D as functions of the stress/strain levels in different parts of structure.

ASCE 4-16 Probabilistic SSI Simulation Concept

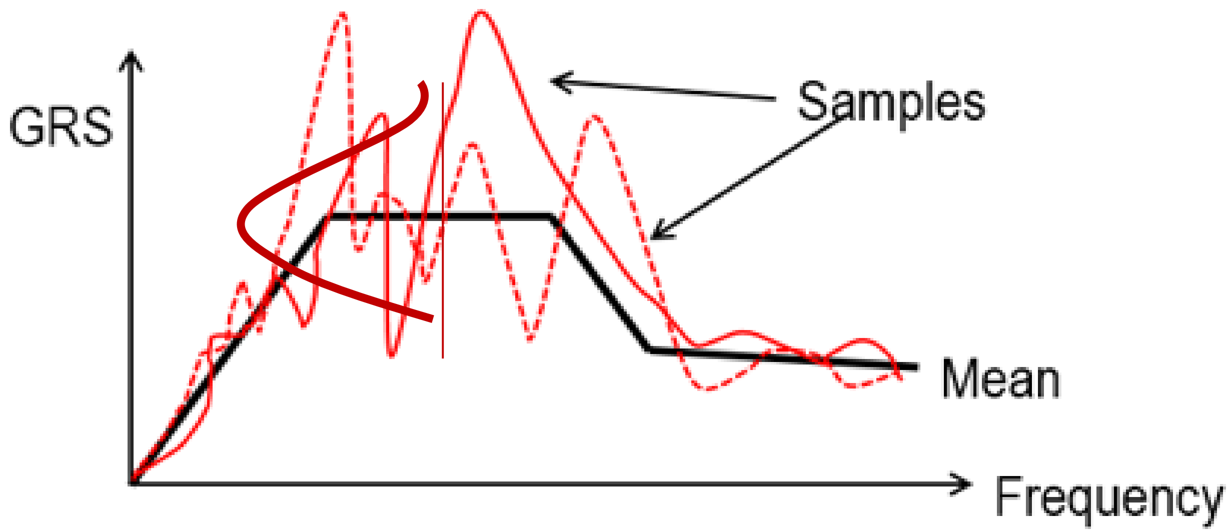


Probabilistic Seismic Input Models

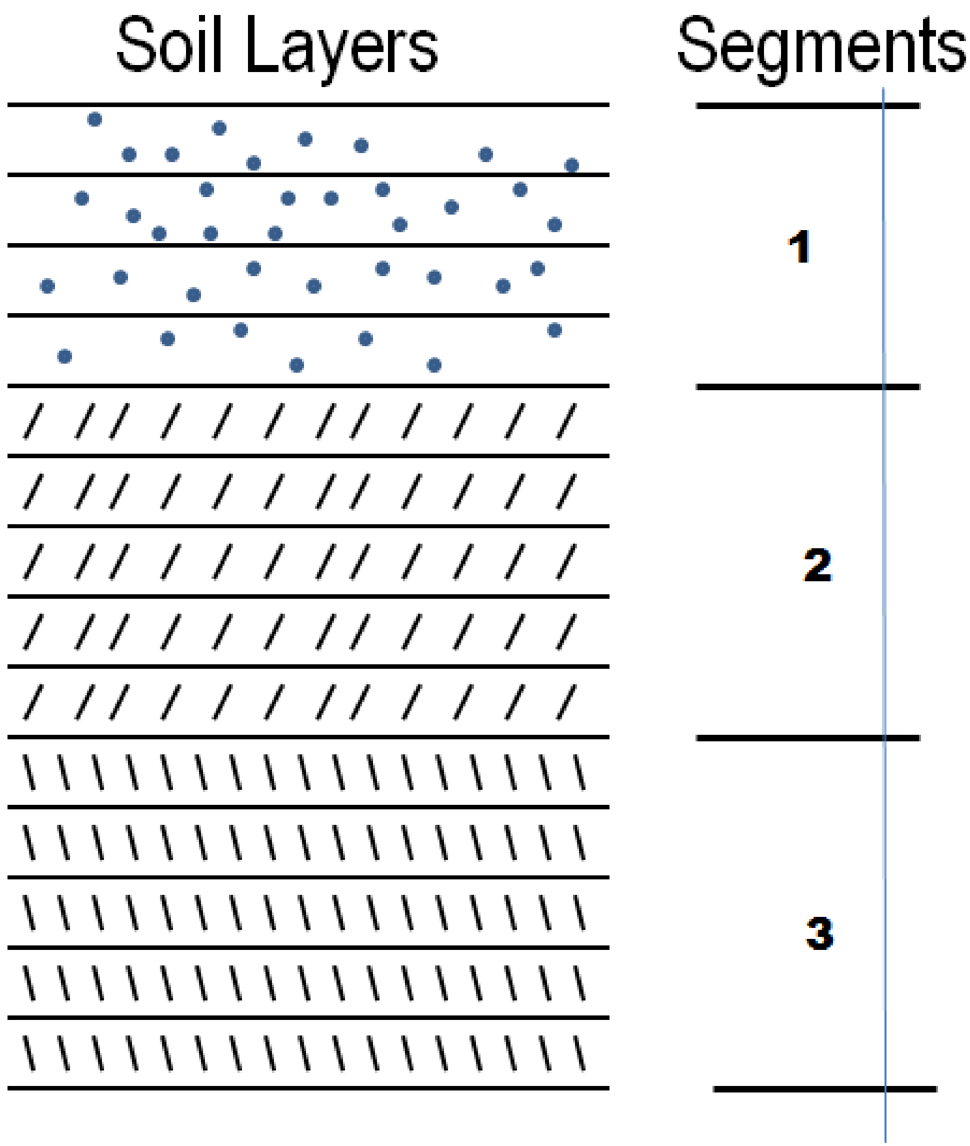
ASCE 04-2015 Method 1



ASCE 04-2015 Method 2

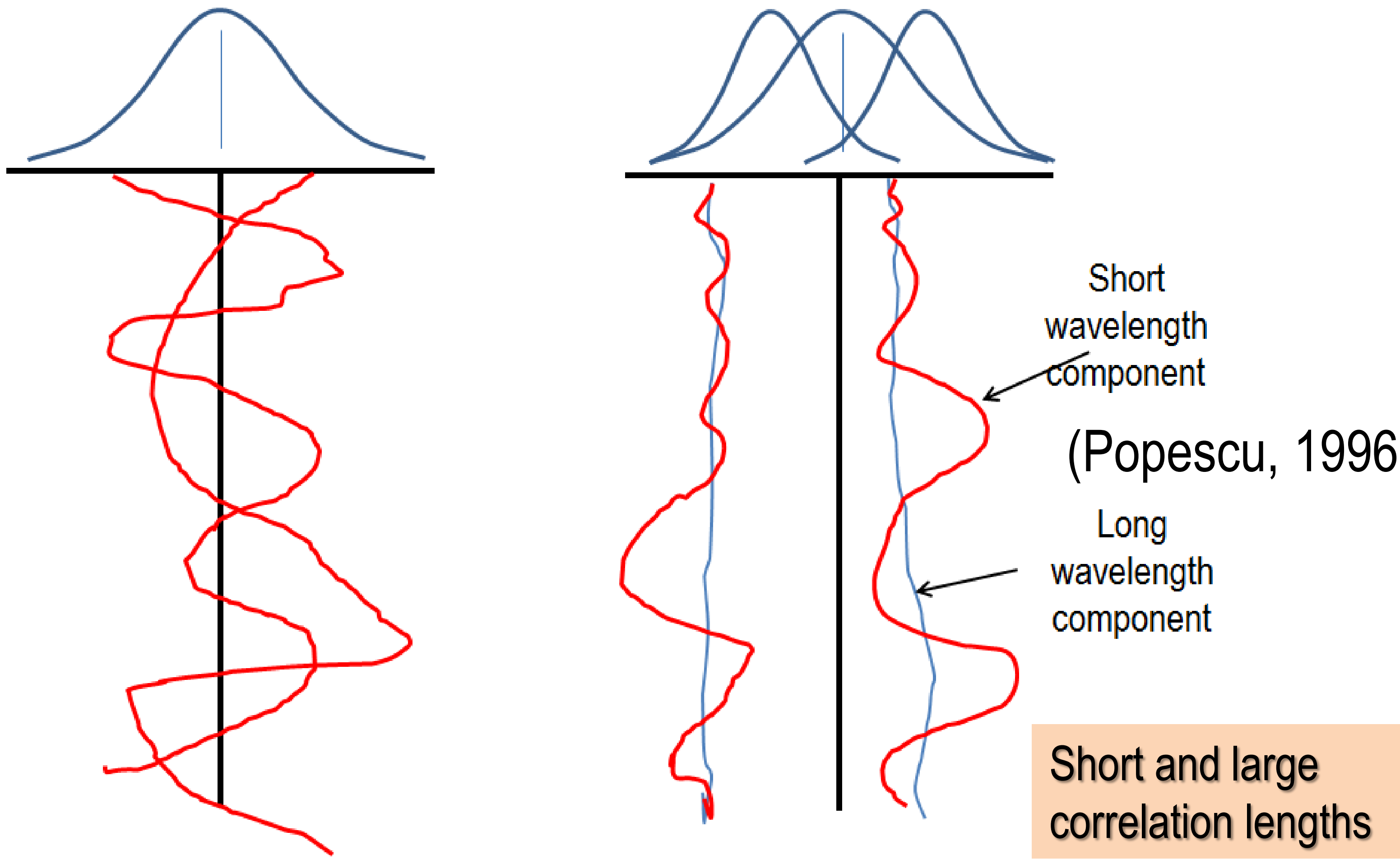


Vs and D Soil Profile Probabilistic Models Using Multiple Segments Split



Different statistical properties for different soil profile segments in depth

Vs and D Soil Profile Probabilistic Models. Two Variation Scale Models Based on Field Data

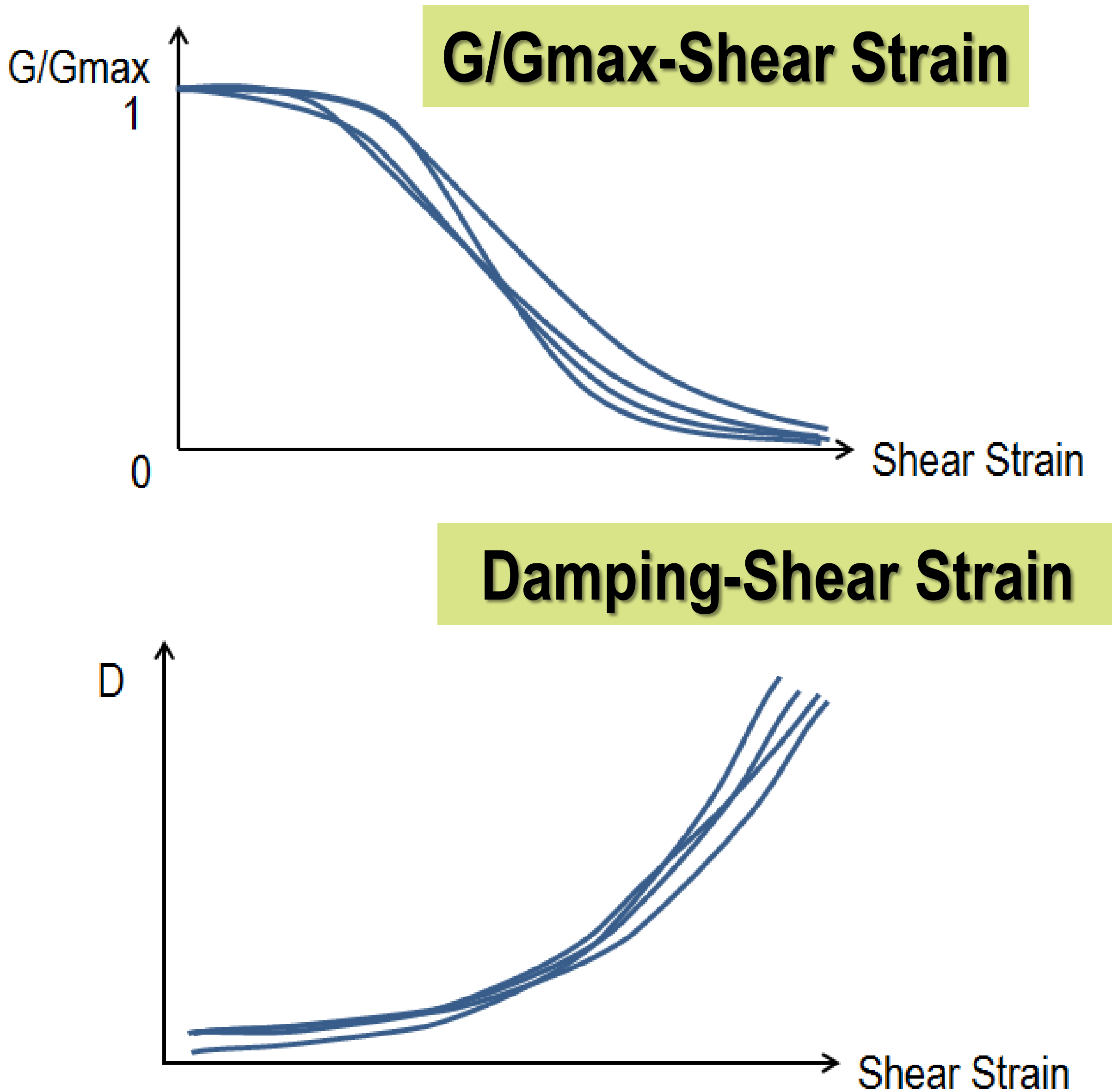


Short and large correlation lengths

Model 1 (Simple)

Model 2 (Composite)

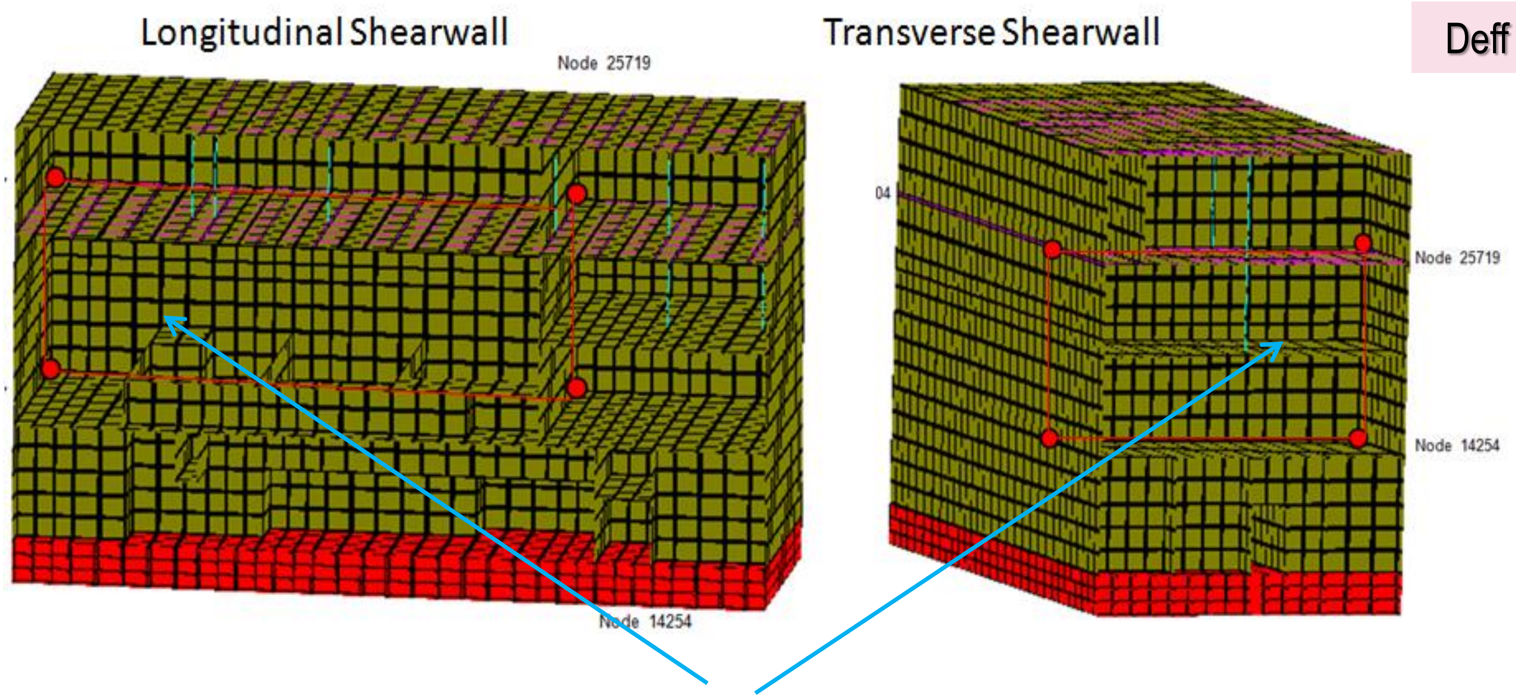
Probabilistic Soil Material Curve Models



Soil curves show large correlation lengths along the shear strain axis.

Probabilistic Structural Models. Effective Stiffness and Damping of Panels Are Dependent on Strain Level

- Keff and Deff variables should defined by user for each element group.
- Effective stiffness ratio Keff/Kelastic and damping ratio, Deff, are modeled as statistically *dependent* random variables. They can be considered *negatively correlated*, or Deff defined as a *response function* of Keff/Kelastic based on experimental tests



Deff = f (Keff/Kelastic)

Stiff	Damp
0.01	0.20
0.10	0.17
0.20	0.15
0.30	0.13
0.40	0.11
0.50	0.10
0.60	0.09
0.70	0.08
0.80	0.07
0.90	0.06
1.00	0.05

ACS SASSI PRO Probabilistic SRA and SSIA

Three major steps are applied:

1) **PREPARE SSI INPUTS:** Using *ACS SASSI PRO modules*, generate statistical ensembles for Probabilistic SRA and/or Probabilistic SSI analysis input simulations *(ProEQUAKE, ProSITE, ProSOIL and ProHOUSE, ProMOTION, ProSTRESS)*

2) **PERFORM SSI ANALYSIS:** Using *ACS SASSI modules,* run in batch the ensembles of the simulated input files to compute the SSI responses (SITE, SITE, SOIL, HOUSE, ANALYS, MOTION, RELDISP, NONLINEAR, STRESS).

3) **POST-PROCESS SSI RESPONSES:** Using *ACS SASSI PRO* module, post-process statistically the ensembles of the SSI responses *(ProSRSS, ProRESPONSE)*

PART 1:
ASCE 4 Probabilistic SSI Simulation-Based Fragility Analysis

Low-Rise Reinforced Concrete Shearwall Building Example

ASCE 4/43 Probabilistic SSI-Based Fragility Using Multiple Point Estimates (3-7 Review Levels)

- Probabilistic models for SEISMIC motion input for each review levels are necessary. The UHRS input for each review level are necessary. Currently, 3 levels, 1e-4, 1e-5 and 1e-6 are considered. Deaggregate the bedrock UHRS in governing seismic events. *Probabilistic models assume that the UHRS amplitude and frequency content have random variations.*

- Probabilistic models for SOIL layer profiles for each review level are necessary*. Includes at least the Vs, D profiles and soil constitutive curves*. It should include the nonlinear soil behavior for each seismic motion simulation input.

- Probabilistic models for STRUCTURE material properties for each review level are necessary. *Includes effective stiffness and damping variations*. It should include the nonlinear structure behavior for each seismic motion simulation input.

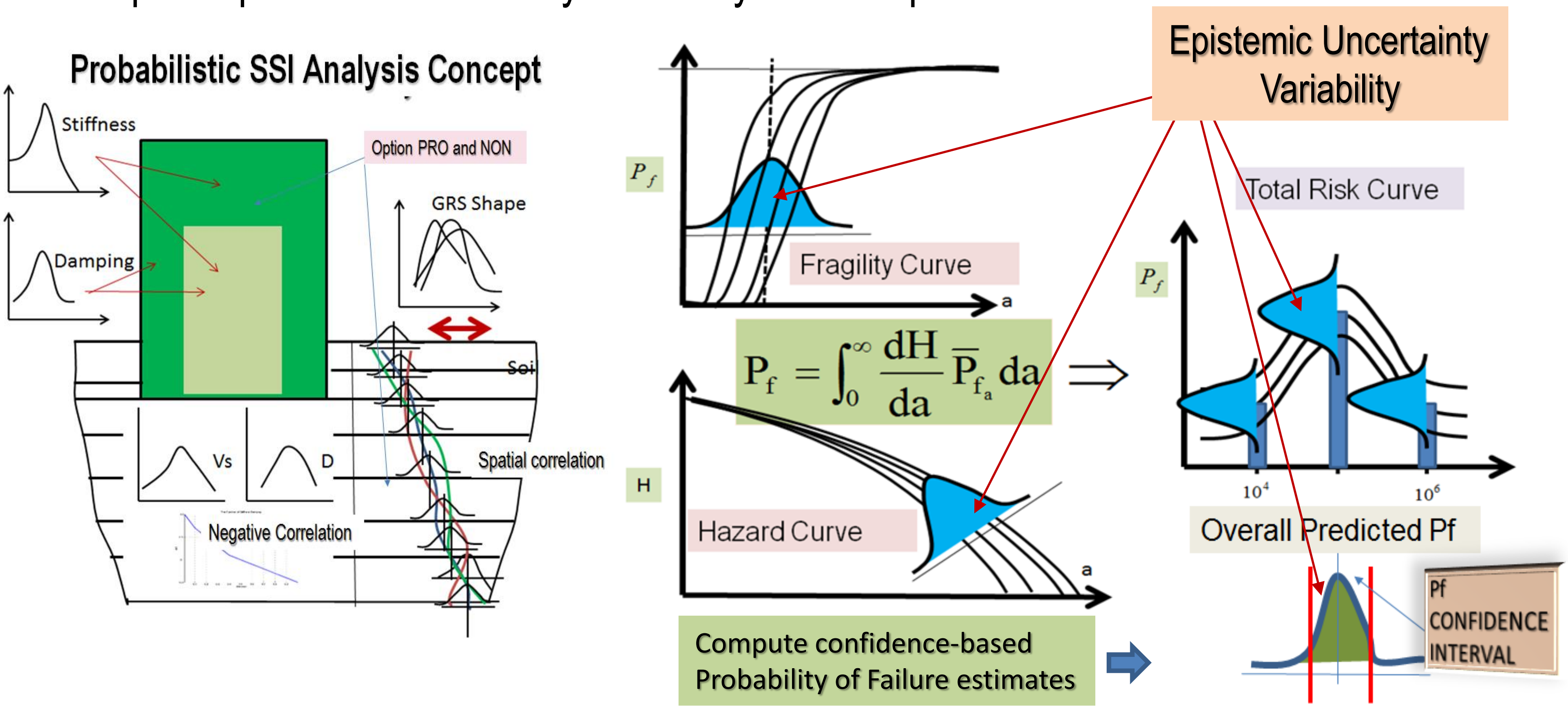
Probabilistic SSI Performed Twice for Each Review Level for Random and Composite Variations

Two probabilistic SSI analysis input sets are required for PSA investigations

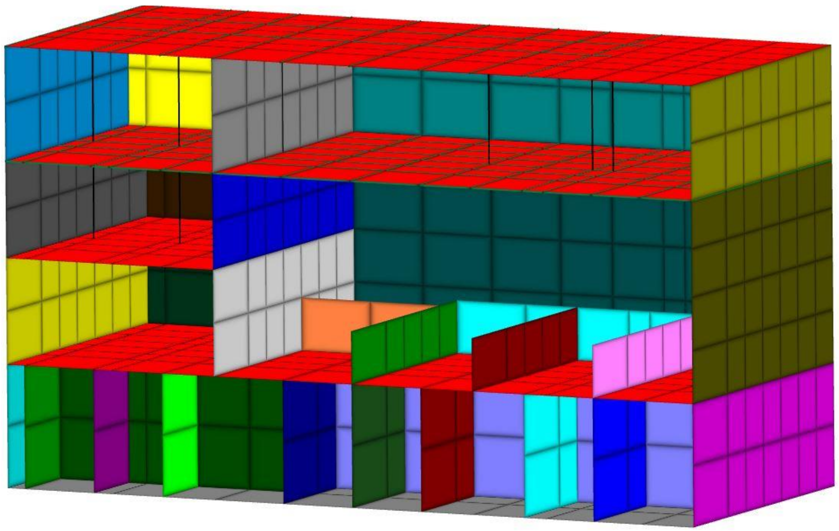
1) All the randomness and the epistemic uncertainty variations to get the total variability (β_C)

2) All the randomness variations to get the randomness variability (β_R)

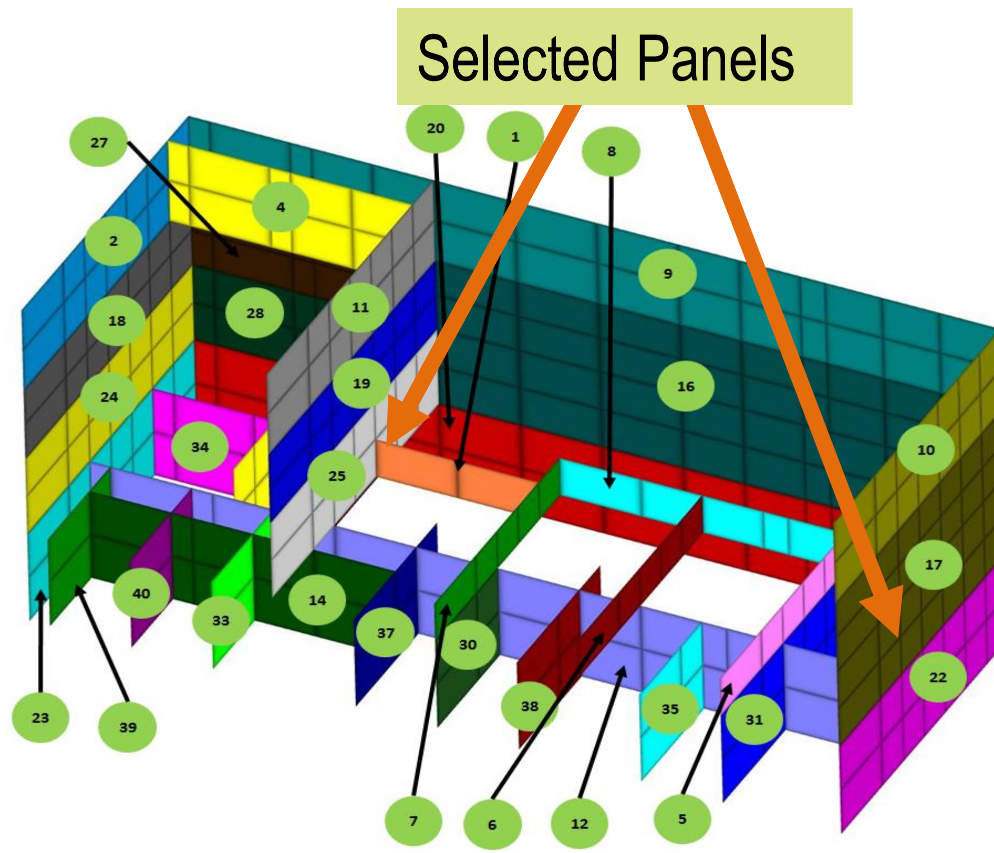
Compute epistemic uncertainty variability from Steps 1 and 2.



New ASCE 4 Probabilistic SSI Based Fragility Analysis for A Low-Rise RC Shearwall Building



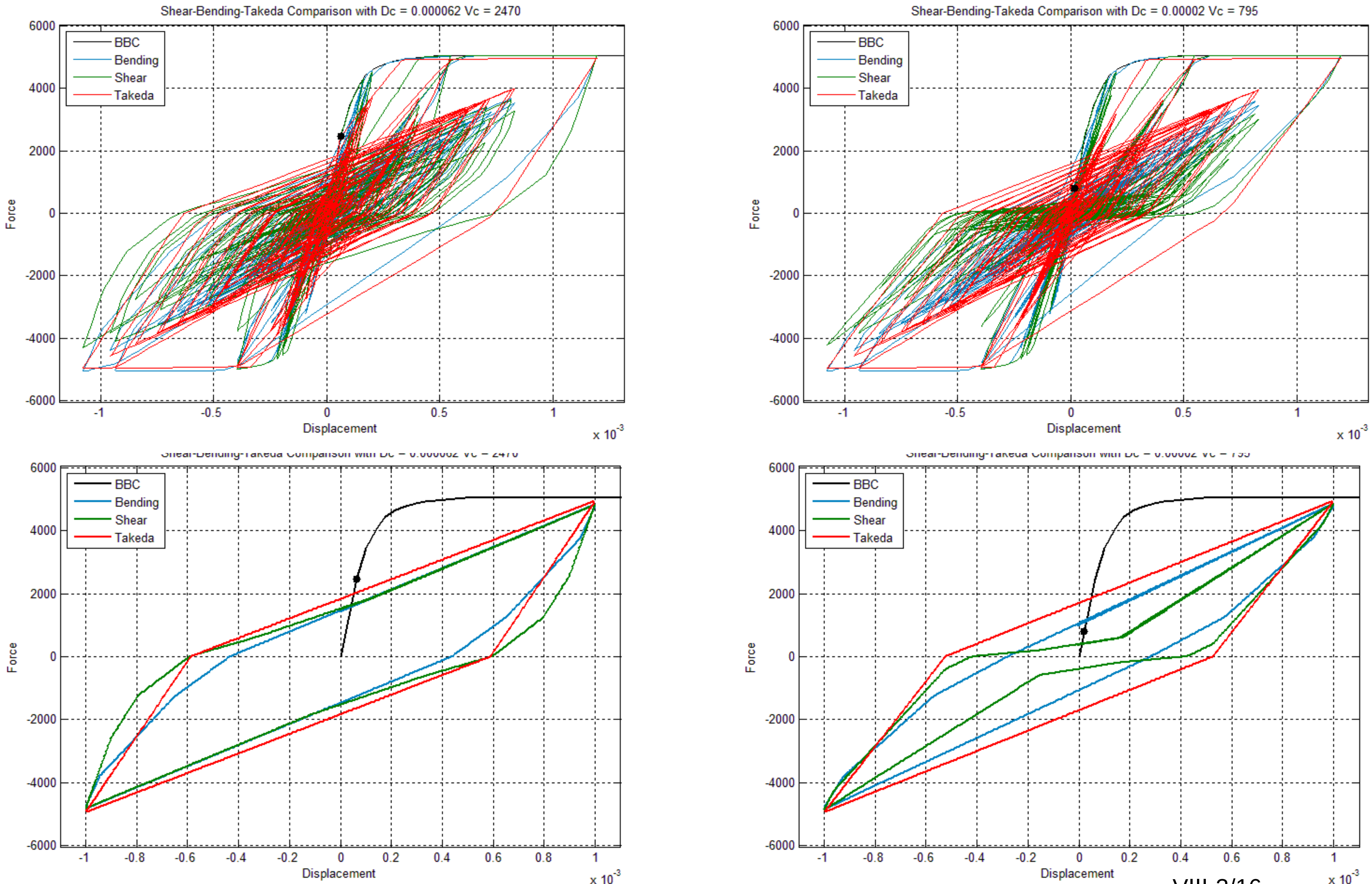
Nuclear building model split in nonlinear panels; Done semi-automatically using ACS SASSI UI



Using ACS SASSI Option NON the effective stiffness and damping is automatically computed for each simulation

Wood 1990 Panel Shear Capacity, and Cheng-Mertz Hysteretic Model

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



Experiment-Based Shear Capacities for Squats

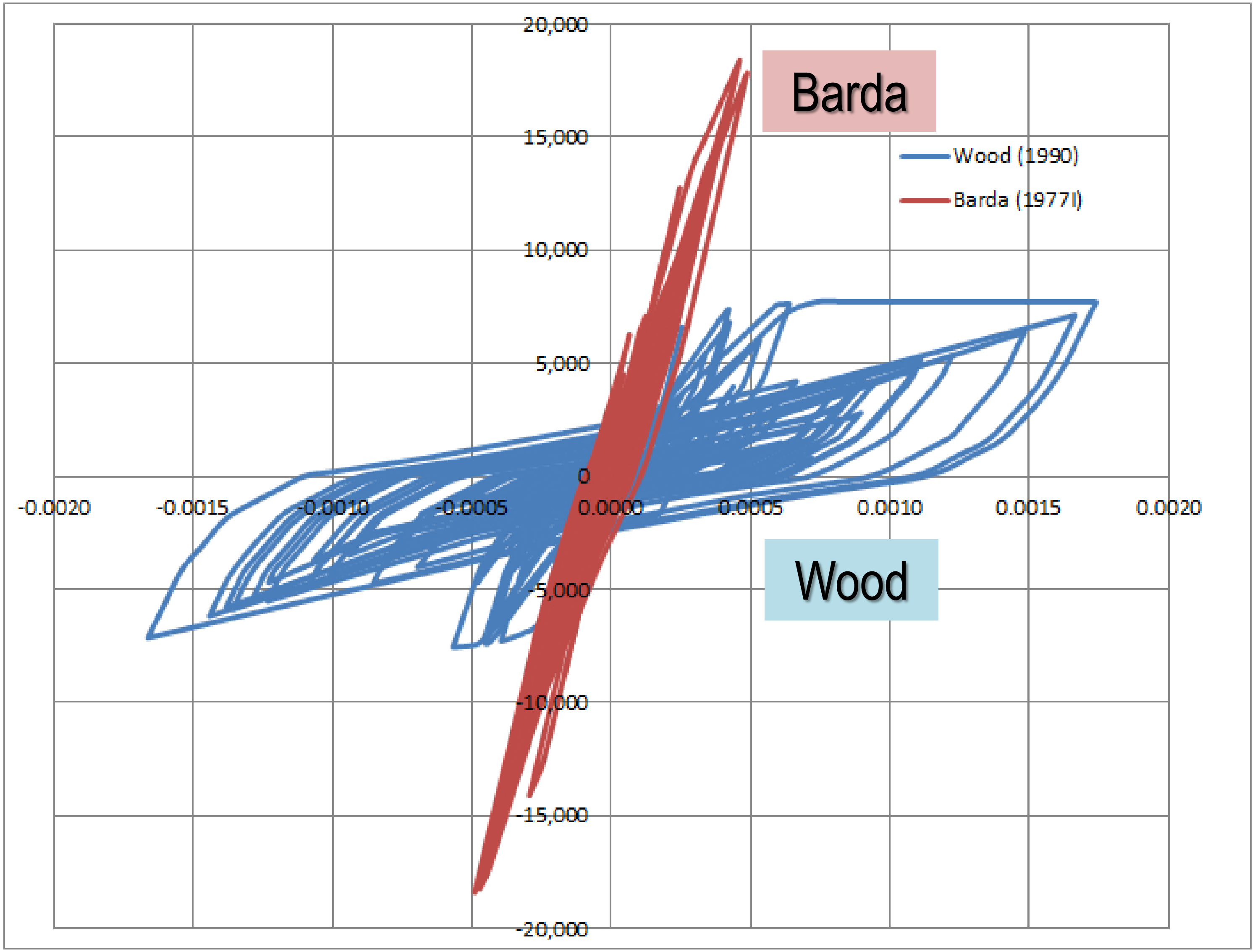
Walls have no openings!

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

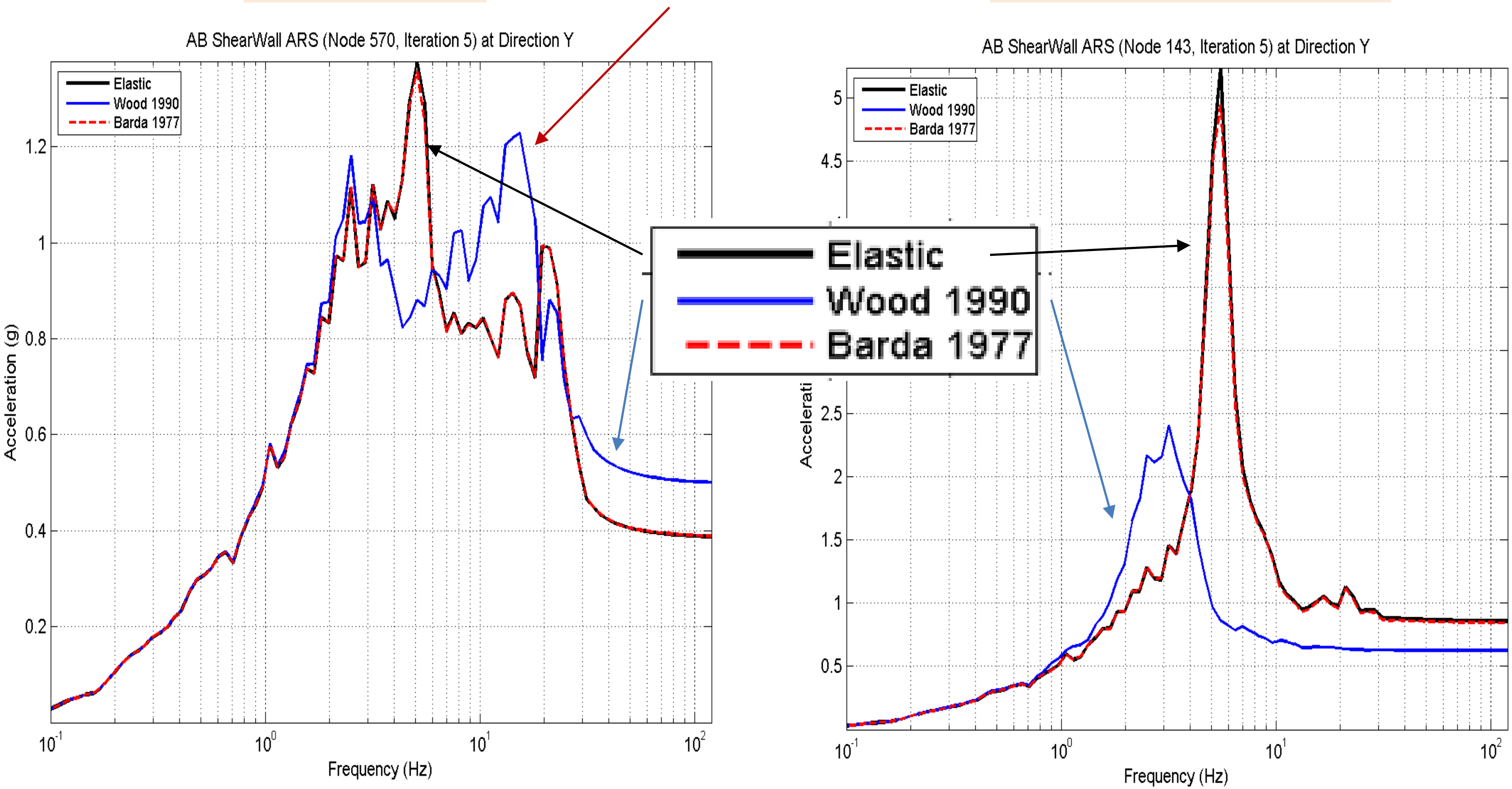
NOTE: ATC 72-1 Option 3, 2010 for reduce yielding and peak capacities to account cyclic degradation effects for many cycles.

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



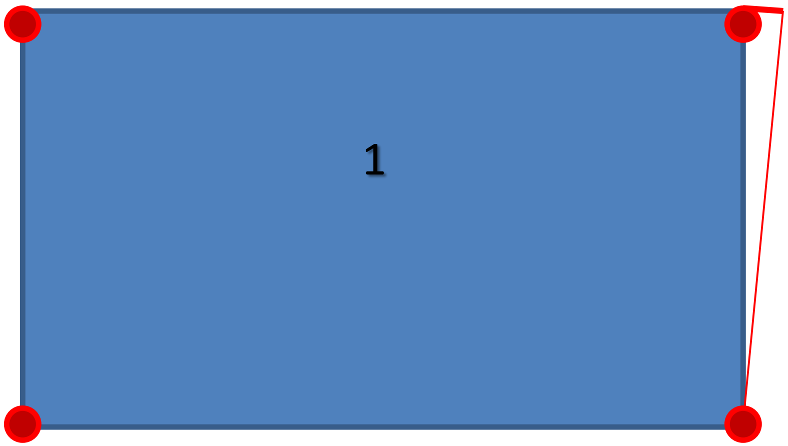
ARS at Different Elevations for Trans-Direction. Barda (1977) vs. Wood (1990) for 0.60g Input

Basemat **High-Elevation**

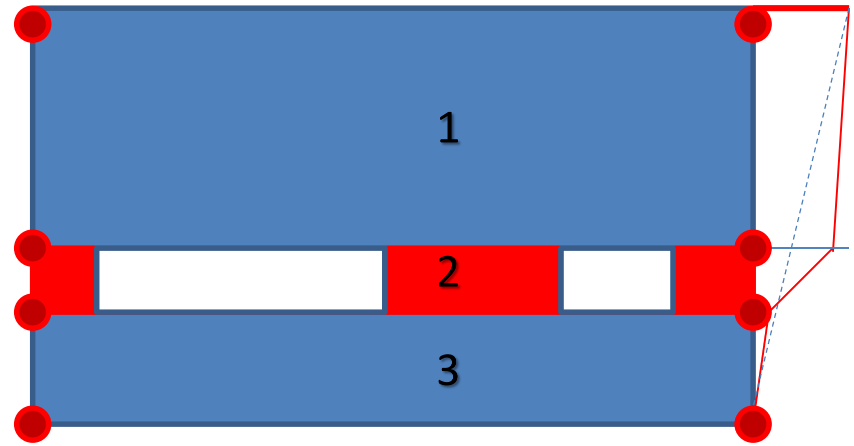


Including Wall Openings Semi Automatically

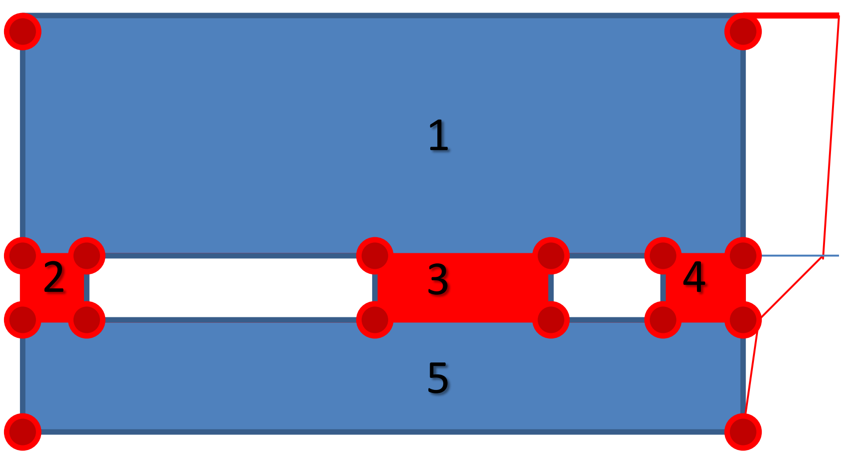
Solid Wall – 1 Panel

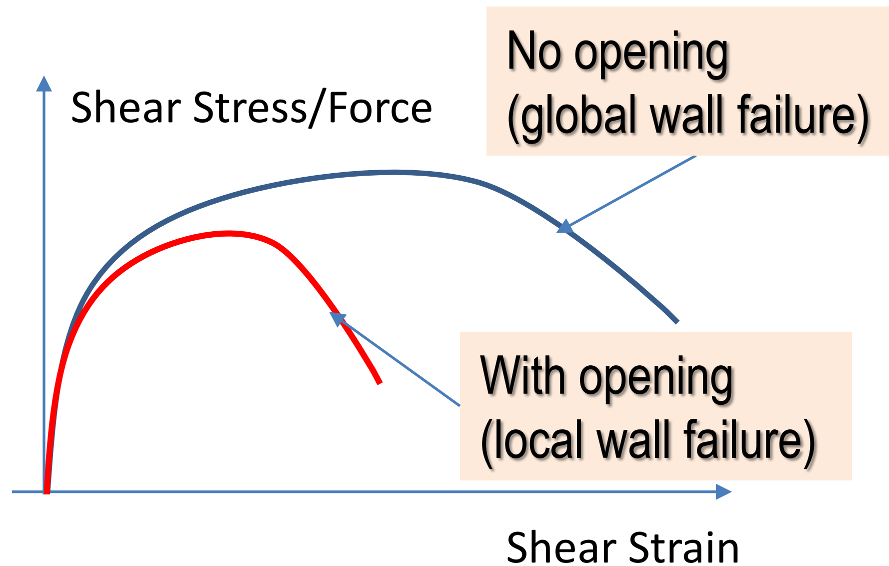


Wall with Two Openings – 3 Panels



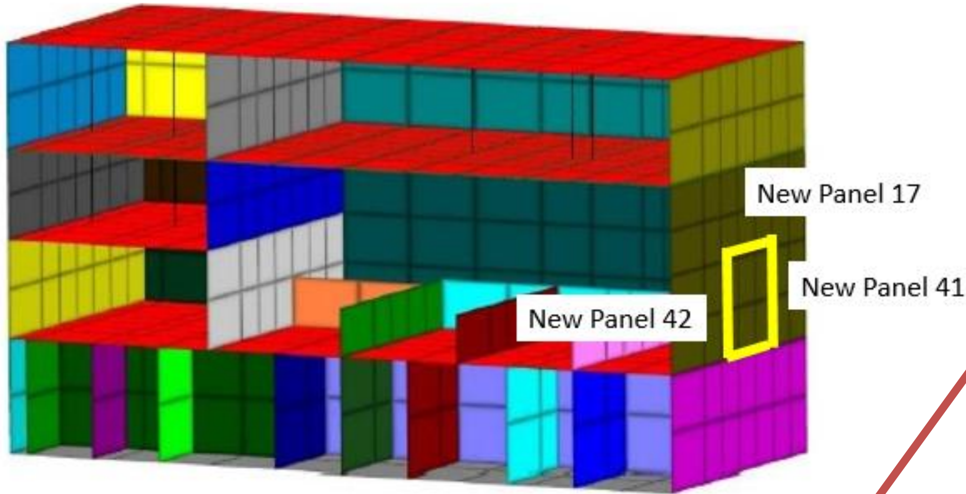
Wall with Two Openings – 5 Panels



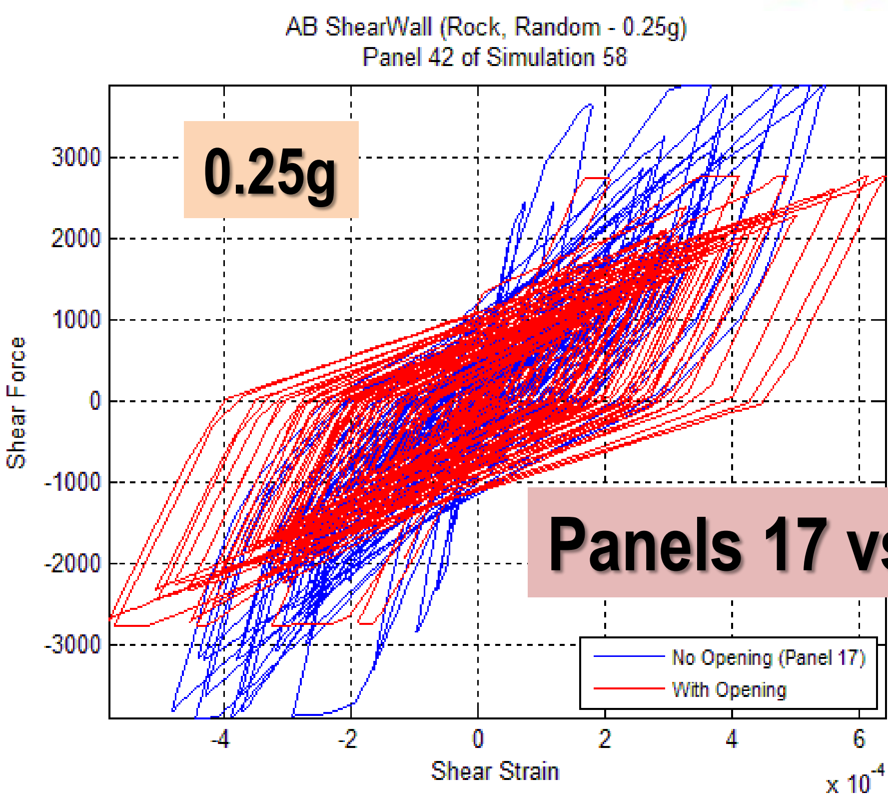


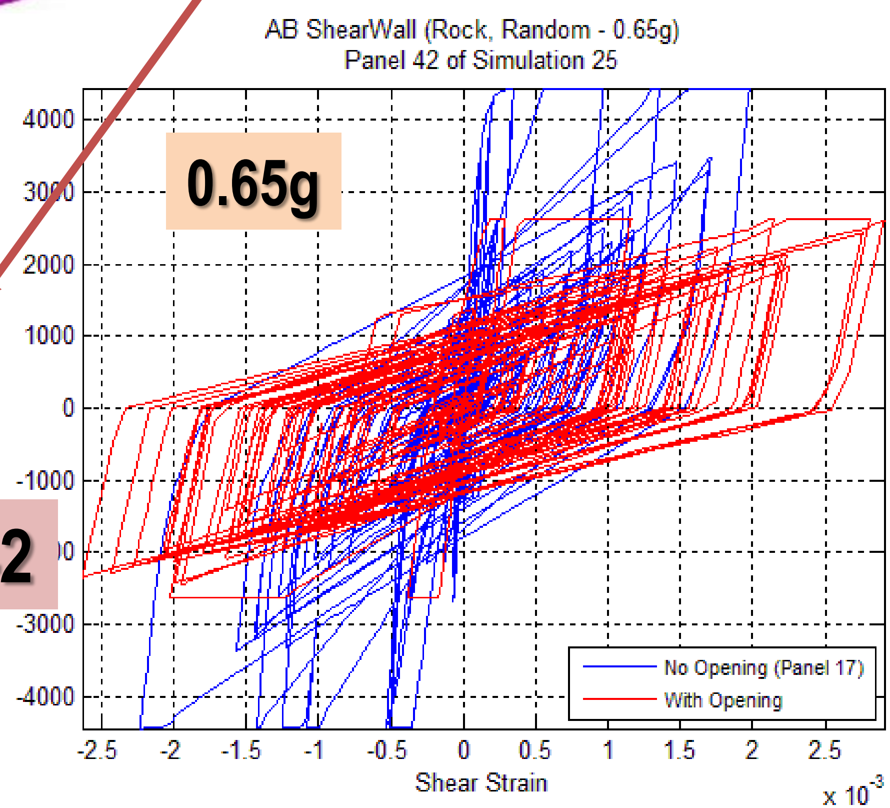
UI Commands: **EDGE, 1,0,0,1**, and then **EDGE,2**

Nonlinear SSI Effects Due Openings in Walls



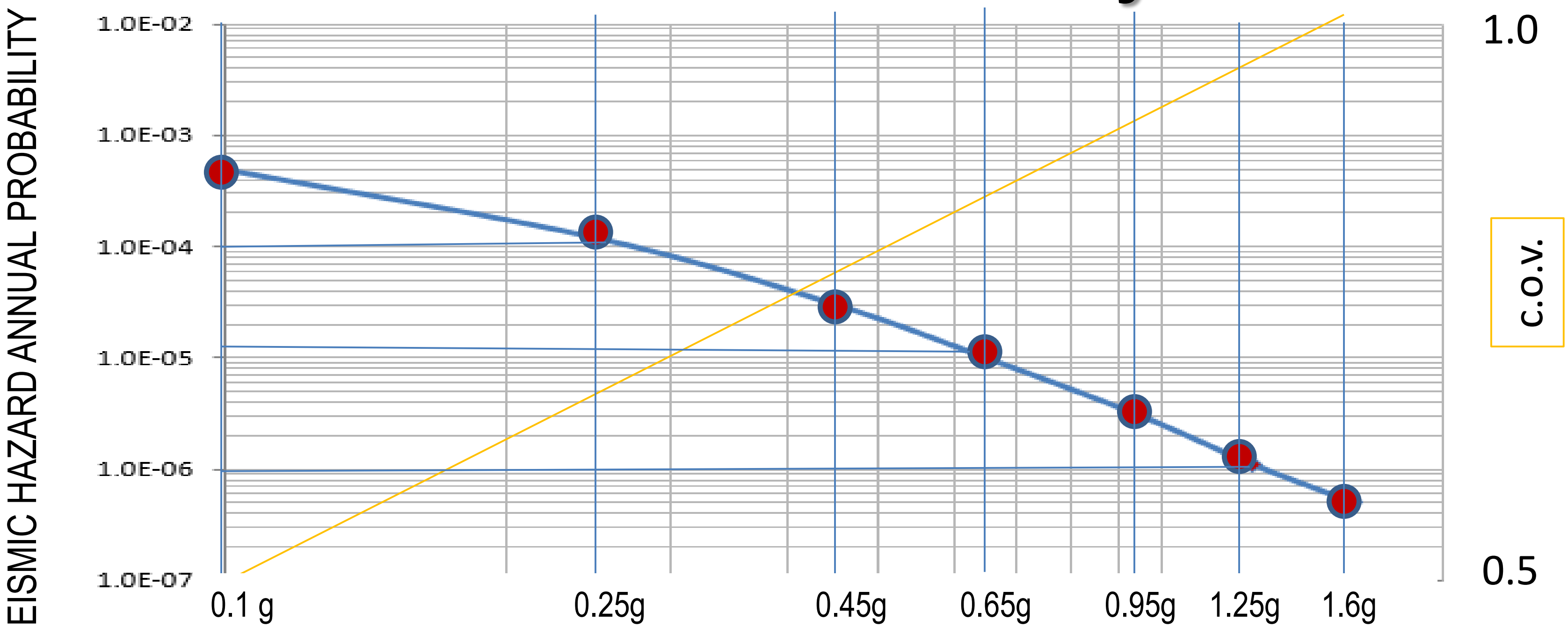
Wood1990 Eq.
CMS Hysteretic Model



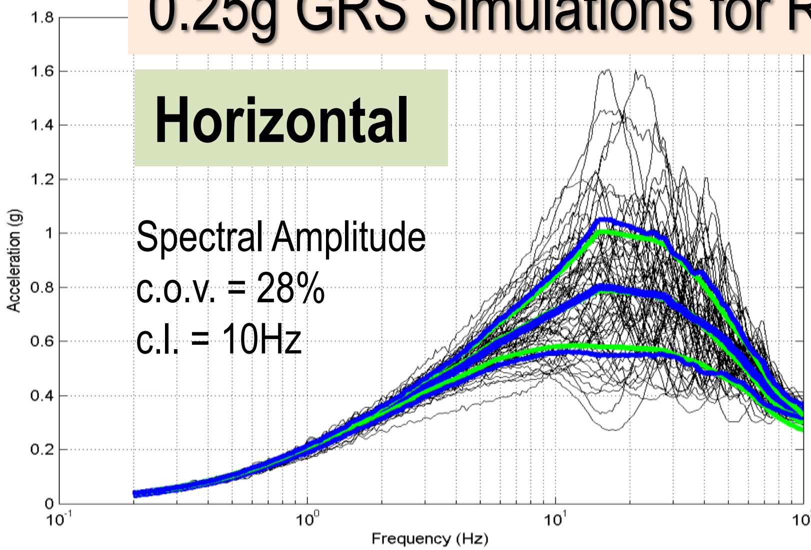


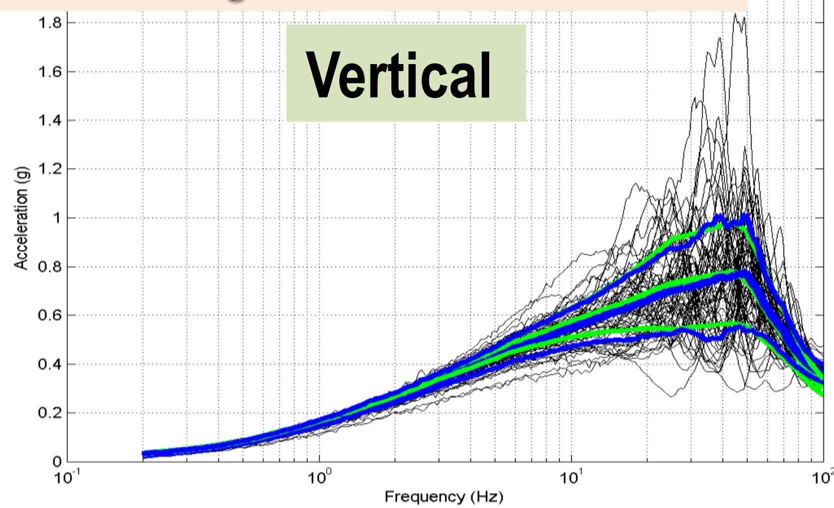
Panels 17 vs 42

Hazard Curve from PSHA Study - 7 Levels

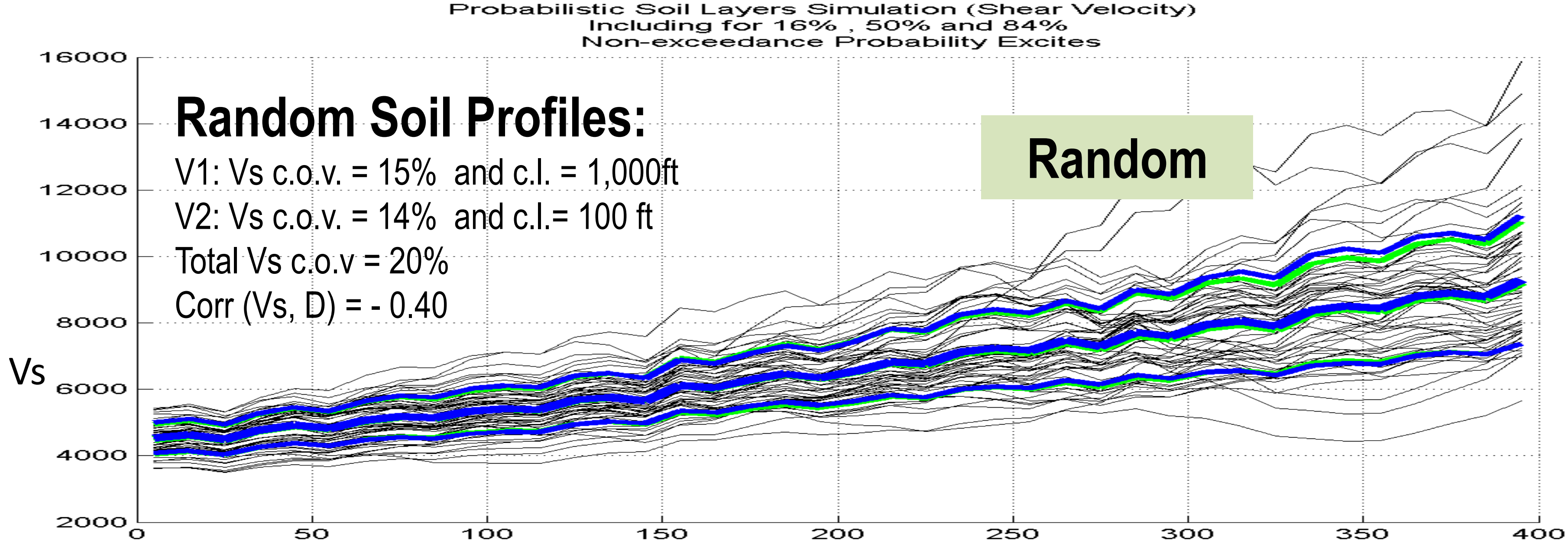


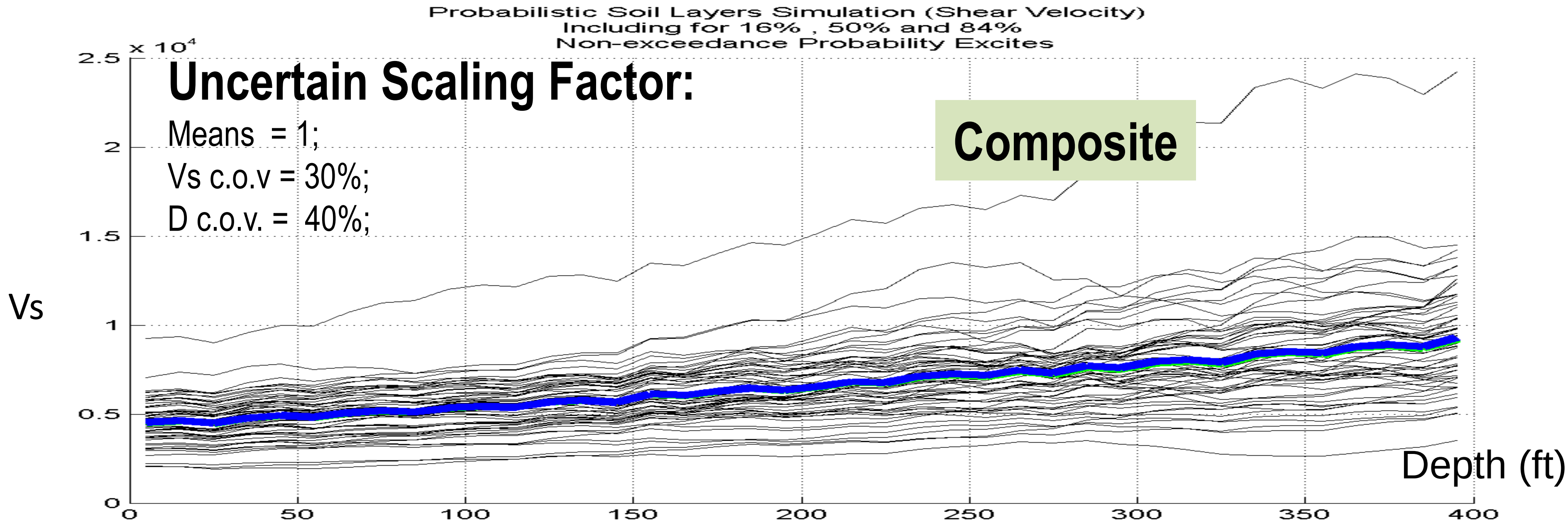
0.25g GRS Simulations for Rock Site Using ASCE 4 Method 2



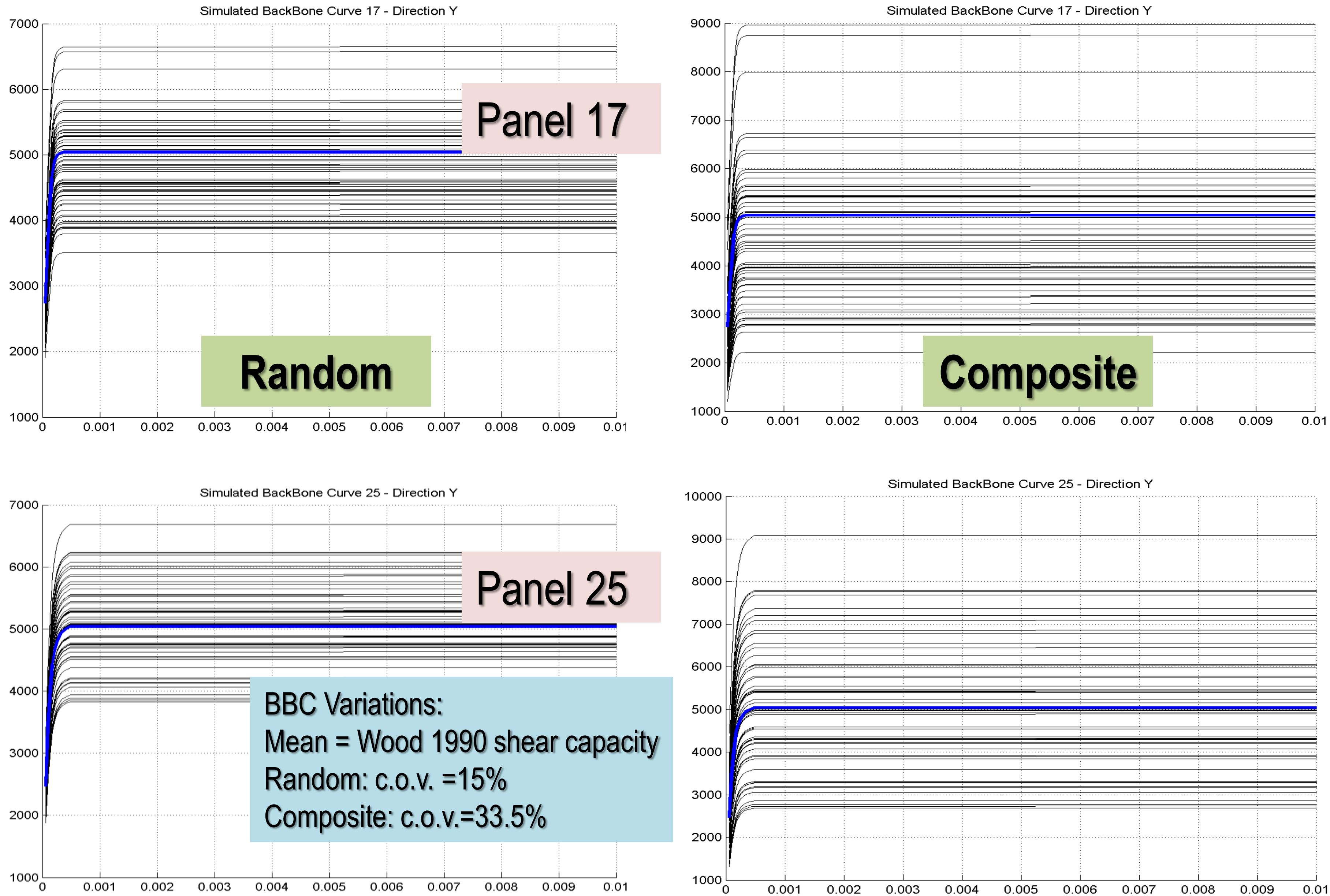


Simulated Rock Site Vs Profiles

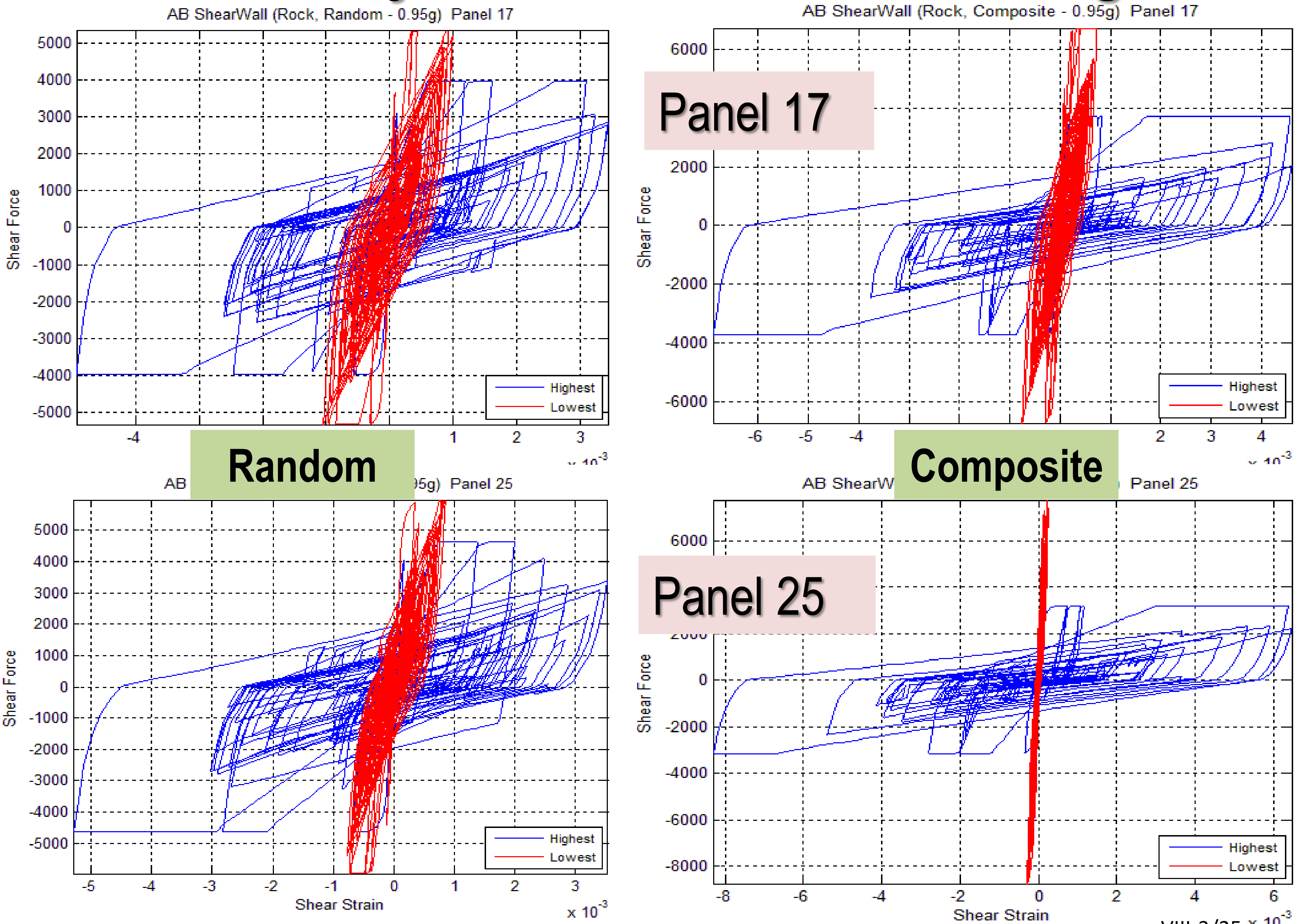




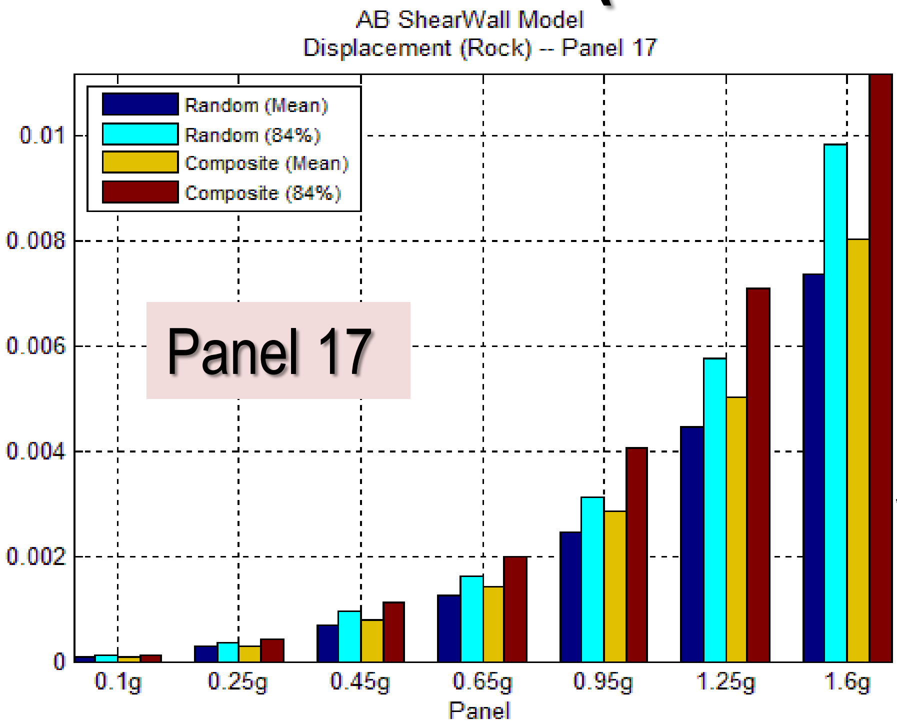
Random BBC Input Variations for Nonlinear Walls

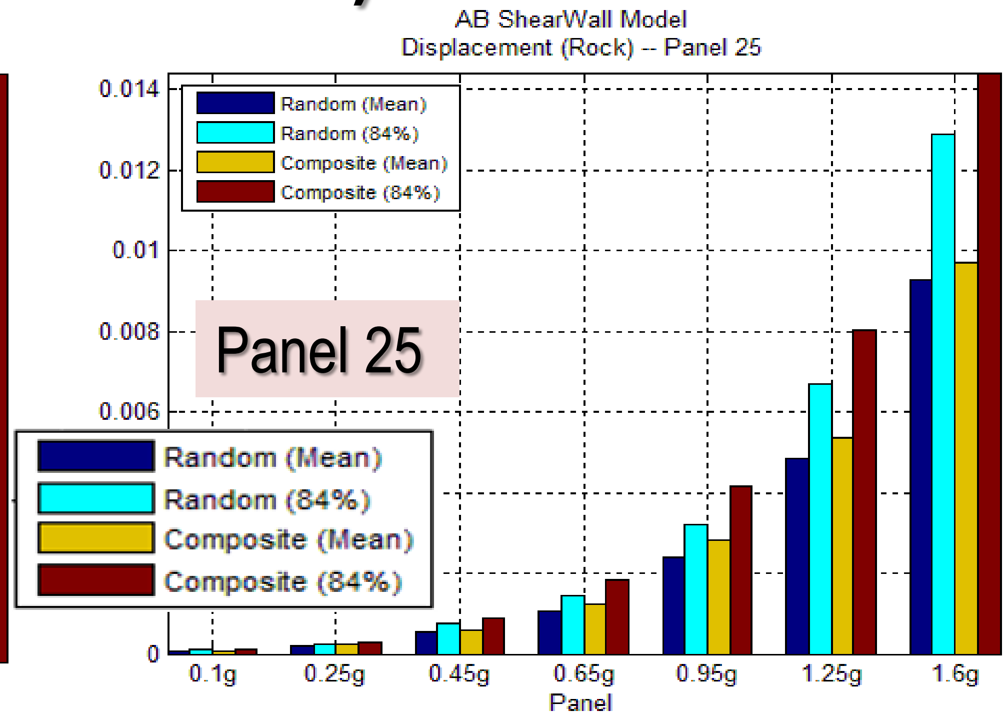


Wall Panel Hysteretic Behavior for 0.95g Level



Panel Strain (Mean & 84%NEP) and U Variable



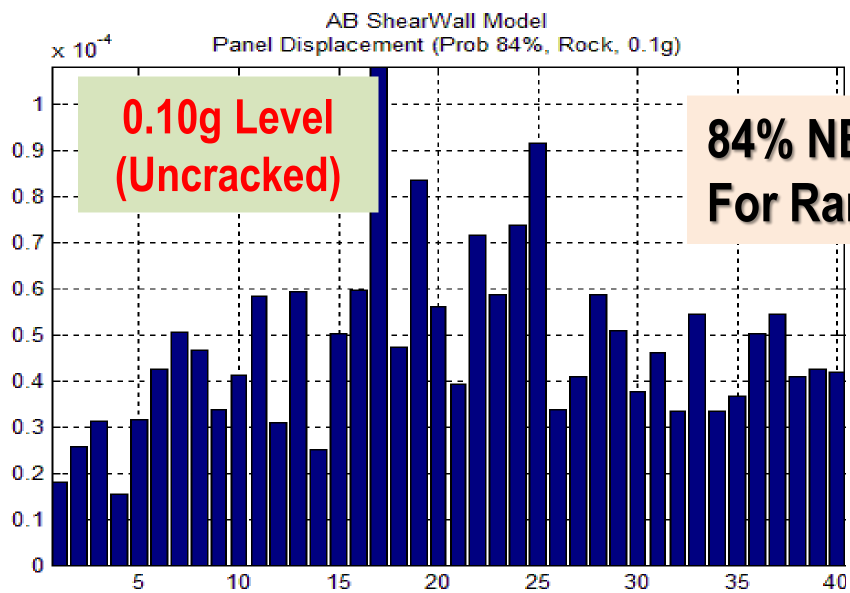


Physics-Based U Random Variable Computation

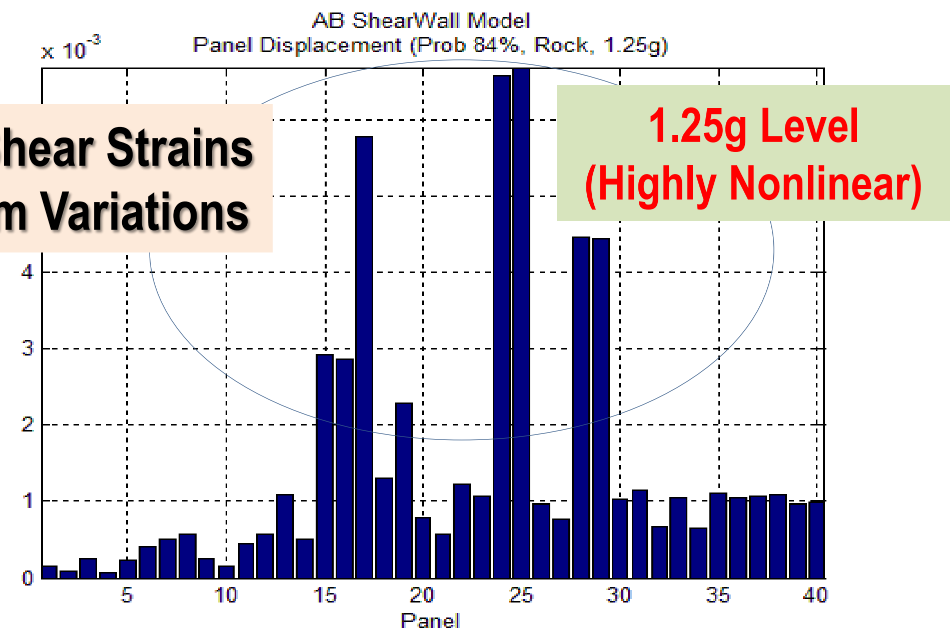
Displacement:	0.1g		0.25g		0.45g		0.65g		0.95g		1.25g		1.6g	
Node#	U mean	U C.O.V.	U mean	U C.O.V.	U mean	U C.O.V.	U mean	U C.O.V.	U mean	U C.O.V.	U mean	U C.O.V.	U mean	U C.O.V.
15	1.0164	0.2148	1.0243	0.2585	1.0193	0.2328	1.0338	0.2255	1.0450	0.2286	1.0776	0.2612	1.0665	0.2559
16	1.0003	0.1979	1.0575	0.2526	1.0605	0.2816	1.1542	0.3697	1.2183	0.3494	1.2433	0.2982	1.2301	0.2545
17	1.0085	0.1774	1.0516	0.1719	1.0792	0.1884	1.0988	0.1964	1.0876	0.2320	1.0864	0.2525	1.0734	0.2683
24	1.0289	0.2199	1.0386	0.2621	1.1108	0.2664	1.2602	0.2841	1.2946	0.3333	1.2345	0.3240	1.1885	0.3482
25	1.0156	0.1673	1.0504	0.2346	1.1293	0.2968	1.1644	0.3078	1.1546	0.2924	1.1799	0.3709	1.2225	0.4778
28	1.0197	0.1459	1.0223	0.1492	1.0555	0.1934	1.0345	0.1515	1.0470	0.1660	1.0573	0.1802	1.0329	0.1936
29	1.0271	0.1544	1.0136	0.1467	1.0240	0.1763	1.0321	0.1667	1.0300	0.1700	1.0502	0.1678	1.0218	0.1866

Compute uncertainty variable for each response simulation j, as Uj = Cj/Rj for each quantity. Using the Uj simulations compute the Umean and U c.o.v. for each response variable.

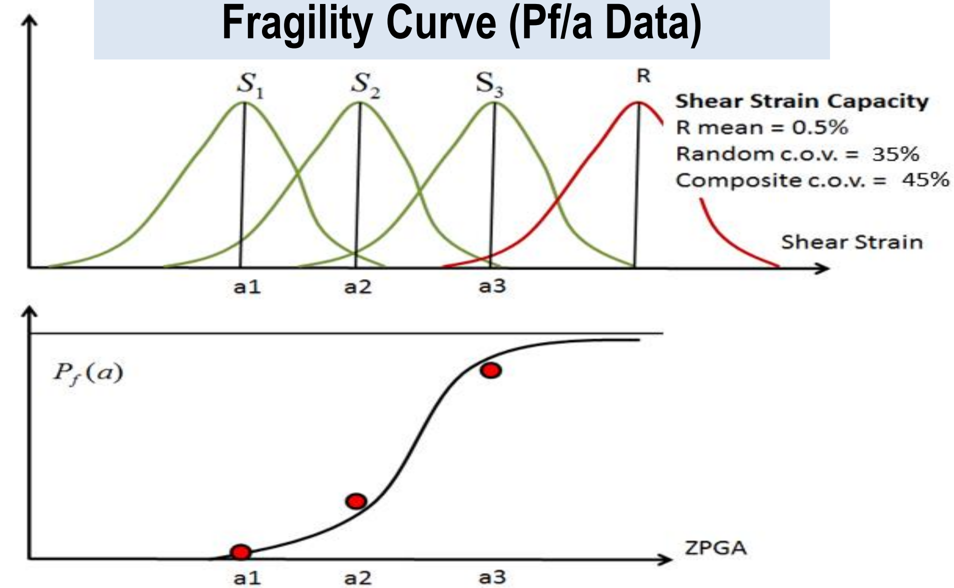
Computed 84% NEP Shear Strain and Pf/a in Walls



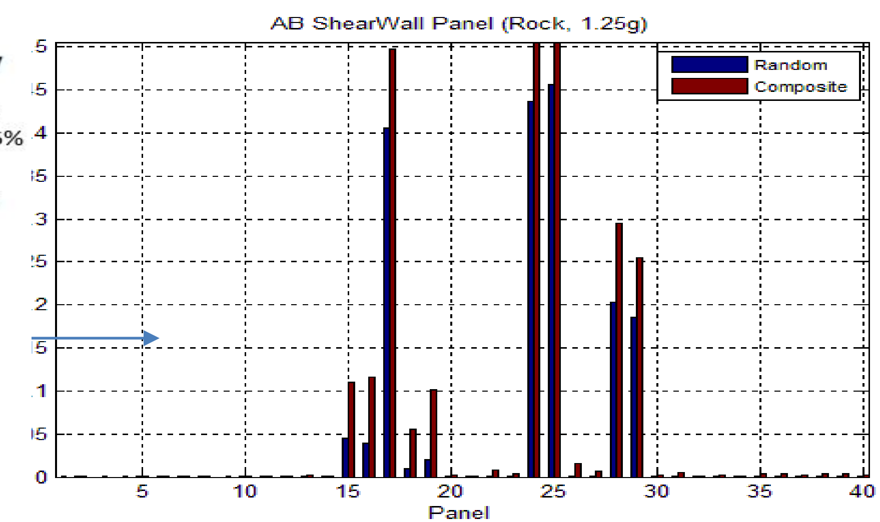
84% NEP Shear Strains
For Random Variations



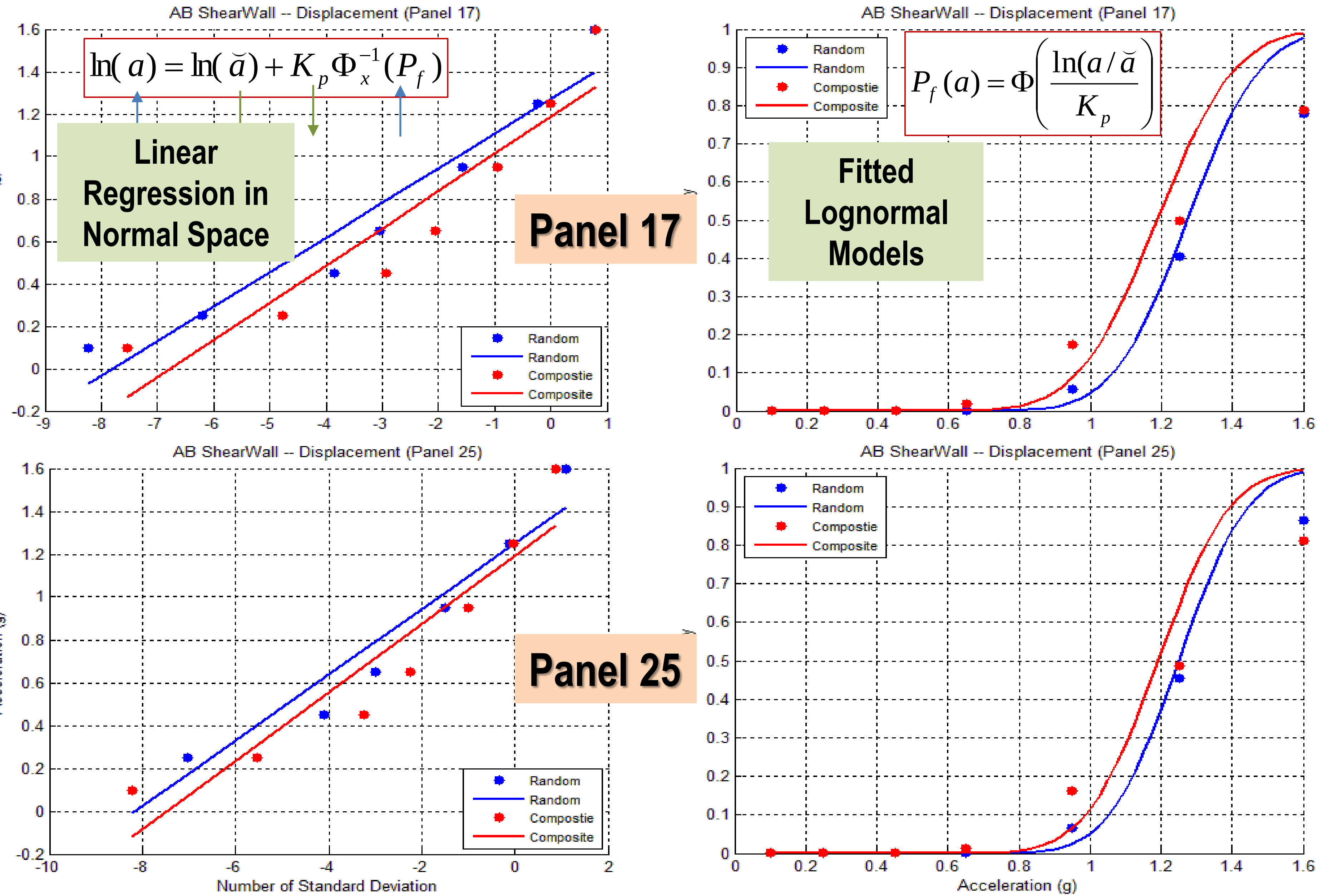
Ln R/S Reliability Model to Build Fragility Curve (Pf/a Data)



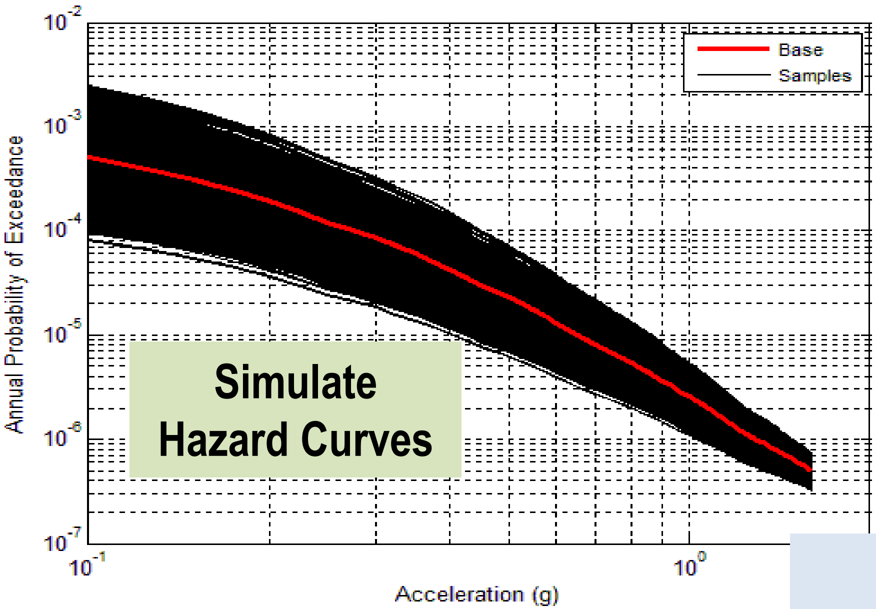
Computed Pf/a for a=0.95g Level

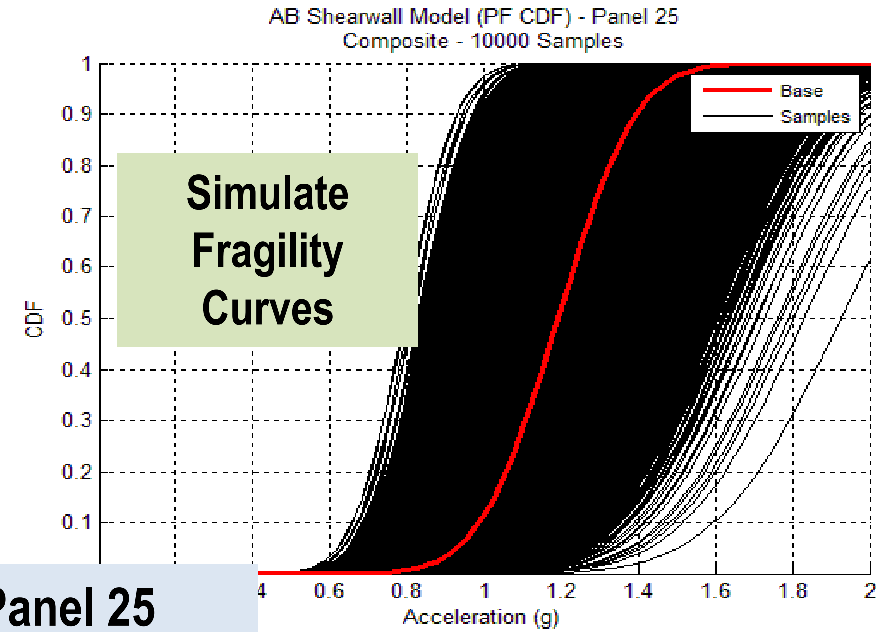


Fitting Lognormal Models for Fragility Curves

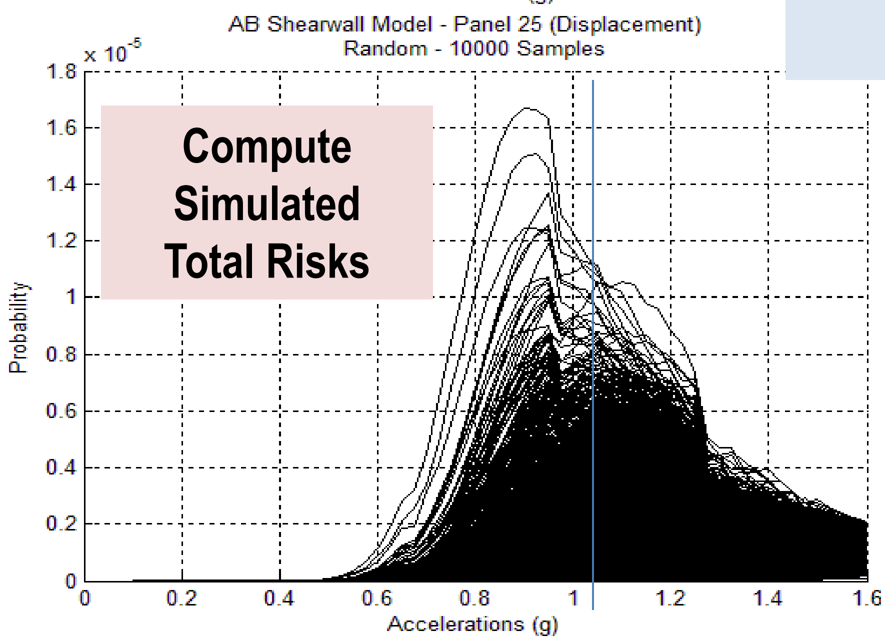


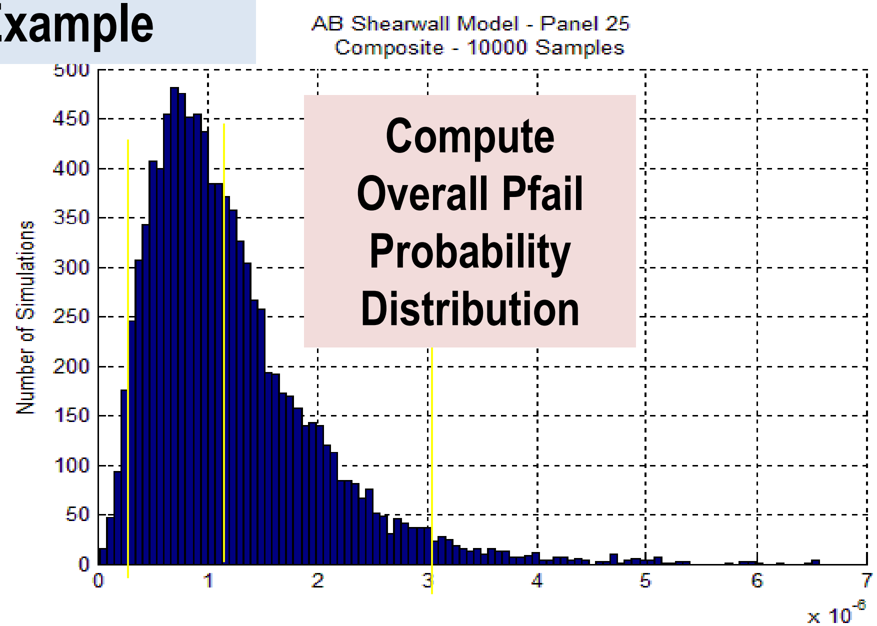
Computation Overall Risk, Unconditional Pfail





Panel 25 Example





Pf for 7, 3 and 1 Level Seismic Hazard Levels

7 ZPGA Levels

Displacement

Panel #	pf mean	pf C.O.V.	pf 90%CDF	pf 90%LOGN	pf 95%CDF	pf 95%LOGN
15	1.82E-007	0.71	3.60E-007	3.38E-007	4.27E-007	4.27E-007
16	2.40E-007	1.06	5.48E-007	5.02E-007	7.17E-007	6.88E-007
17	7.80E-007	0.49	1.26E-006	1.27E-006	1.48E-006	1.50E-006
24	8.78E-007	0.60	1.55E-006	1.53E-006	1.85E-006	1.87E-006
25	9.22E-007	0.68	1.71E-006	1.68E-006	2.11E-006	2.10E-006
28	4.59E-007	0.24	6.04E-007	6.04E-007	6.53E-007	6.58E-007
29	4.16E-007	0.46	6.65E-007	6.65E-007	7.72E-007	7.81E-007

3 ZPGA Levels

Displacement Random

Panel #	pf mean	pf C.O.V.	pf 90%CDF	pf 90%LOGN	pf 95%CDF	pf 95%LOGN
15	3.94E-008	0.54	6.85E-008	6.63E-008	7.61E-008	7.96E-008
16	4.34E-008	0.81	8.95E-008	8.39E-008	1.10E-007	1.09E-007
17	6.67E-007	1.06	1.52E-006	1.39E-006	1.97E-006	1.91E-006
24	6.56E-007	0.80	1.35E-006	1.26E-006	1.64E-006	1.63E-006
25	6.17E-007	0.70	1.18E-006	1.13E-006	1.43E-006	1.42E-006
28	2.98E-007	0.96	6.65E-007	6.06E-007	8.61E-007	8.13E-007
29	2.30E-007	0.87	4.87E-007	4.54E-007	6.09E-007	5.96E-007

1 ZPGA Level; 1e-4 or 0.25g

Displacement Random

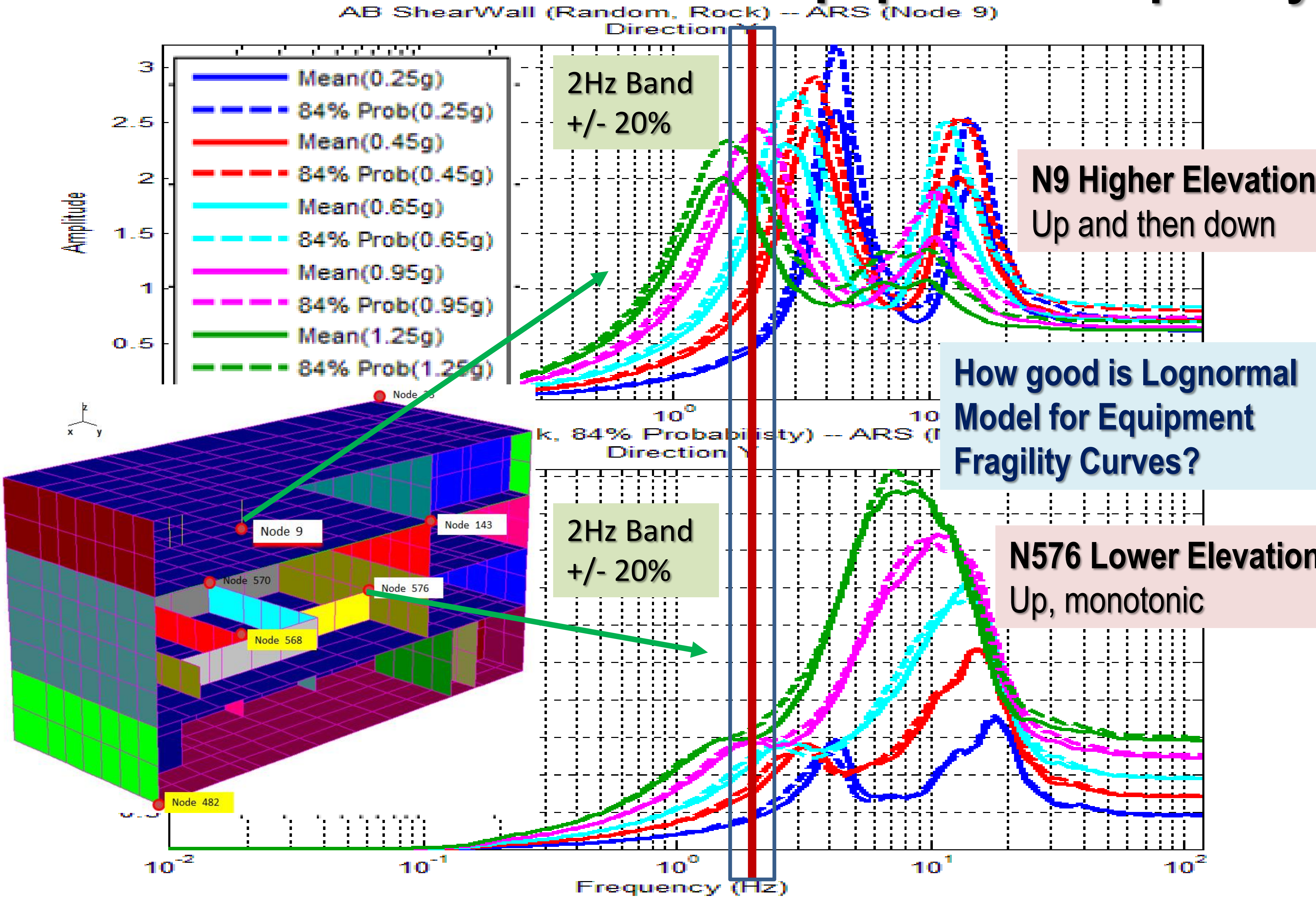
Panel #	pf mean	pf C.O.V.	pf 90%CDF	pf 90%LOGN	pf 95%CDF	pf 95%LOGN
15	5.20E-006	2.79	1.39E-005	1.16E-005	2.77E-005	1.98E-005
16	1.51E-005	4.66	2.72E-005	3.13E-005	6.61E-005	5.85E-005
17	4.39E-008	1.17	1.03E-007	9.38E-008	1.38E-007	1.32E-007
24	8.14E-008	3.34	2.14E-007	1.79E-007	3.88E-007	3.17E-007
25	3.26E-008	2.66	8.74E-008	7.34E-008	1.52E-007	1.24E-007
28	2.61E-005	3.96	4.82E-005	5.54E-005	1.25E-004	1.01E-004
29	4.49E-007	4.33	8.83E-007	9.40E-007	2.00E-006	1.74E-006

1 ZPGA Level; 1e-5 or 0.65g

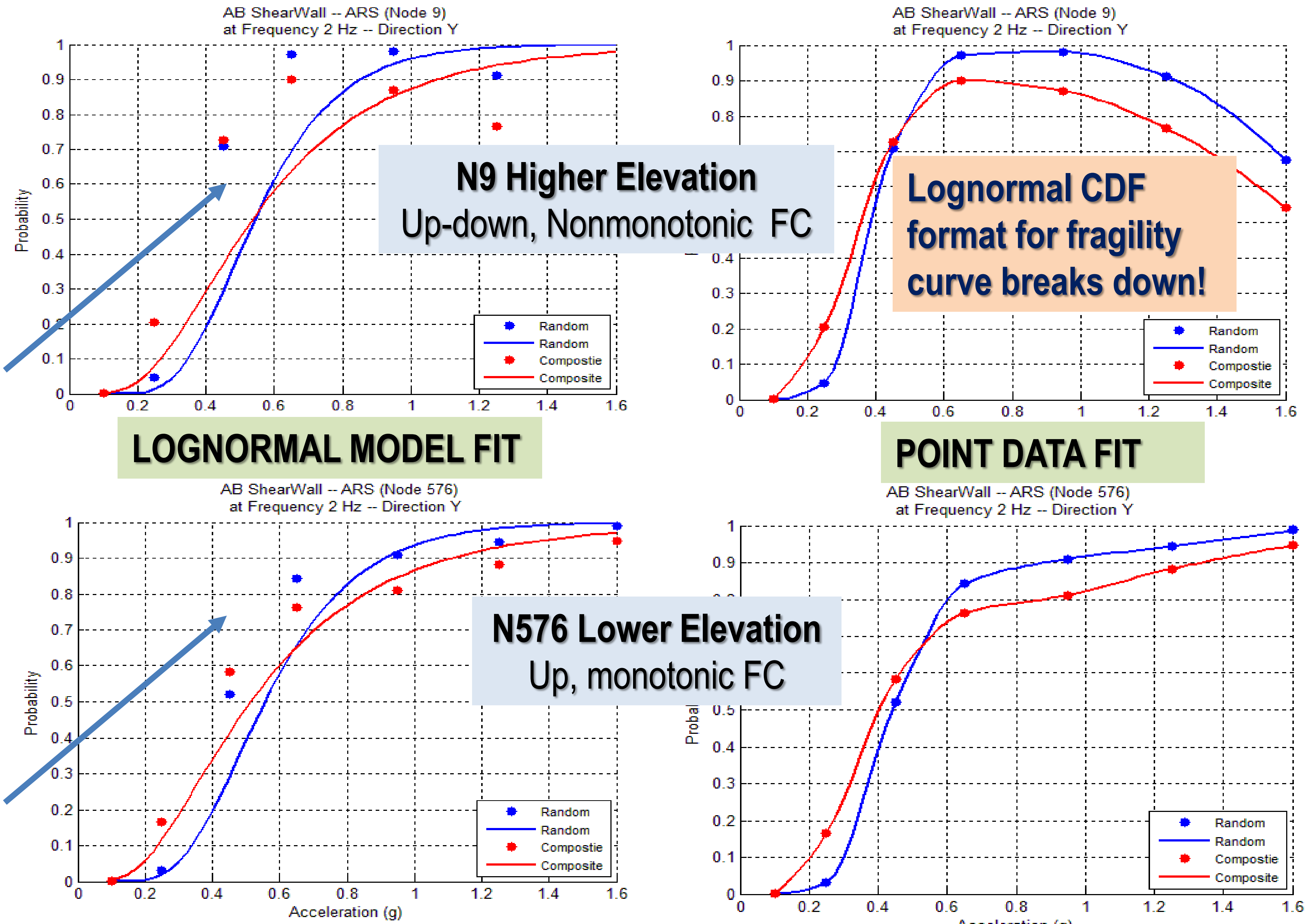
Displacement Random

Panel #	pf mean	pf C.O.V.	pf 90%CDF	pf 90%LOGN	pf 95%CDF	pf 95%LOGN
15	1.41E-008	0.95	3.21E-008	2.85E-008	4.08E-008	3.81E-008
16	2.47E-008	1.35	6.05E-008	5.43E-008	8.45E-008	7.85E-008
17	3.48E-007	1.11	7.90E-007	7.34E-007	1.06E-006	1.02E-006
24	2.46E-007	1.10	5.68E-007	5.18E-007	7.52E-007	7.17E-007
25	2.22E-007	1.02	4.87E-007	4.59E-007	6.50E-007	6.23E-007
28	7.78E-008	1.02	1.71E-007	1.61E-007	2.31E-007	2.18E-007
29	4.98E-008	0.94	1.06E-007	1.00E-007	1.38E-007	1.34E-007

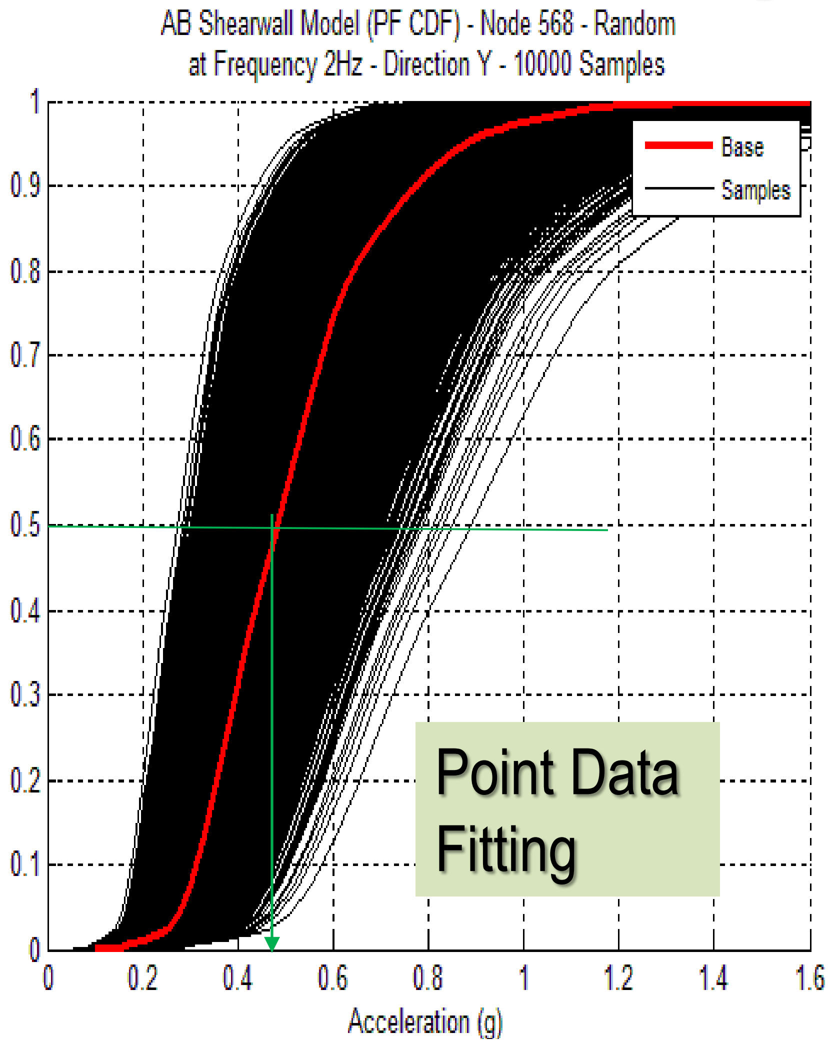
ARS for 5 Seismic Levels/2Hz Equipment Frequency



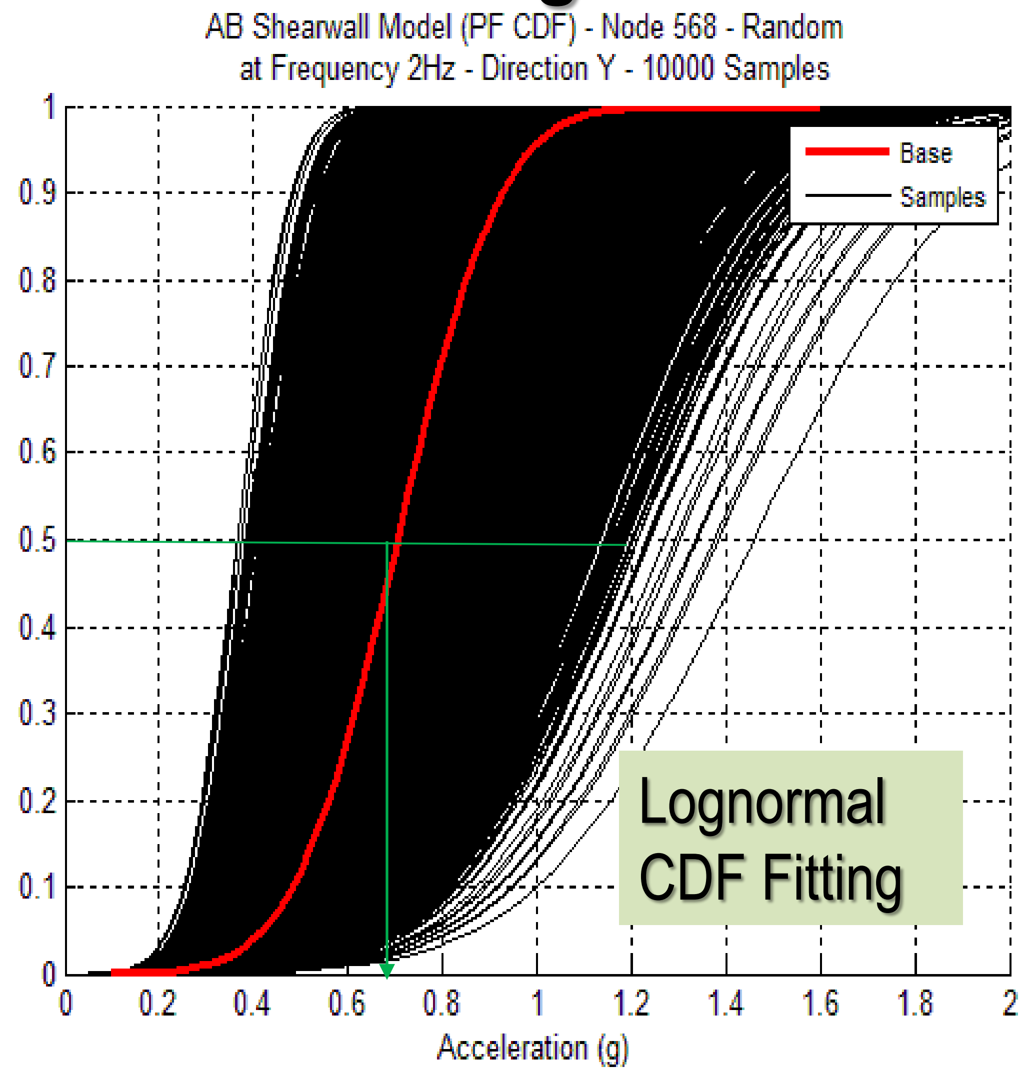
Lognormal Model for Fragility Curve Could Fail!



Pf for N568 Y Using Point Data vs. Lognormal Fit



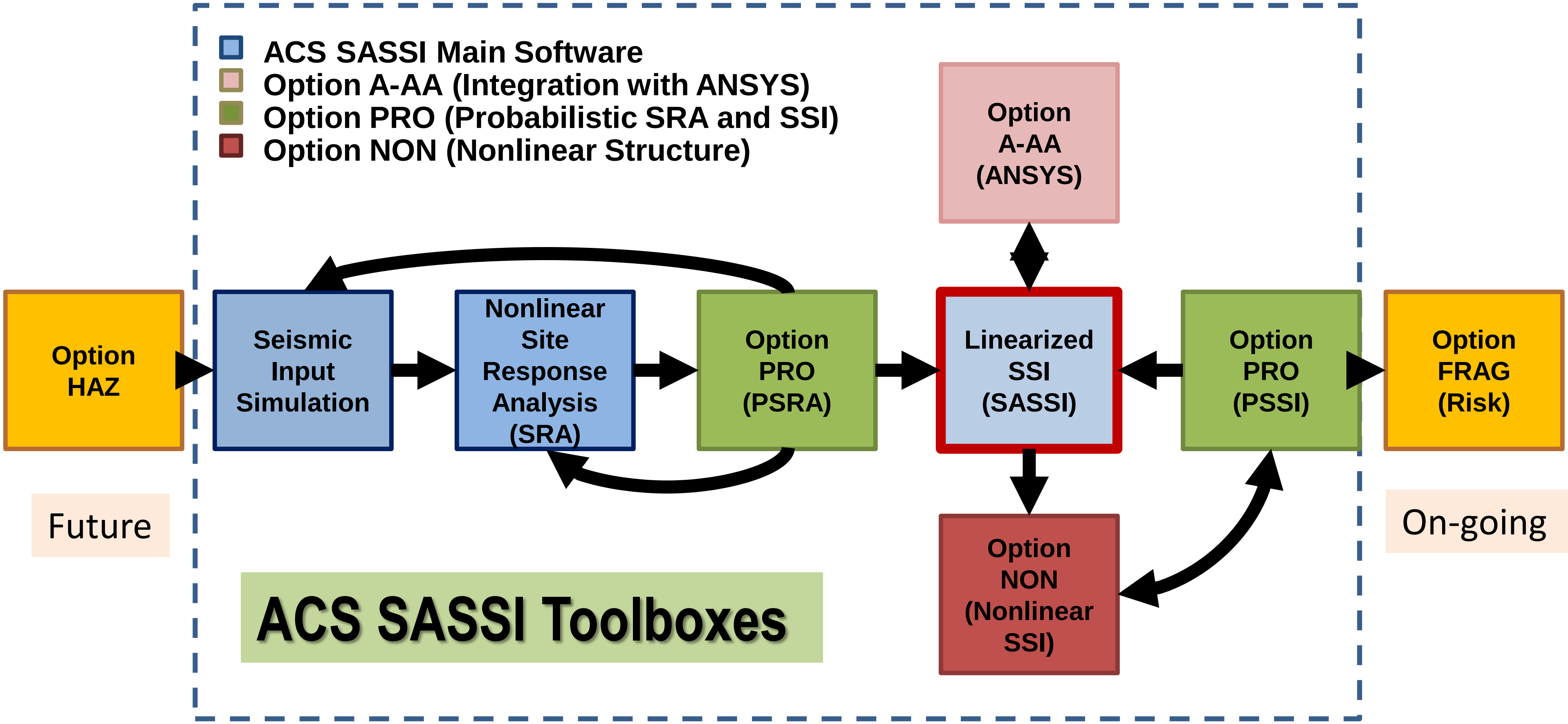
ISRS Node #	Random pf mean	2Hz pf C.O.V.
482	3.81E-005	0.53
568	3.89E-005	0.57
570	3.97E-005	0.59
576	5.17E-005	0.79



ISRS Node #	Random pf mean	2Hz pf C.O.V.
482	1.57E-005	0.67
568	1.46E-005	0.69
570	1.44E-005	0.71
576	1.24E-005	0.79

ACS SASSI Framework Development

Present/Options A-AA, NON and PRO, Future/Options HAZ and FRAG



PART 1 CONCLUSIONS

- *ASCE 4-16 provides a probabilistic physics-based modelling for computing SSI response variations and fragility data, reducing substantially the traditional fragility model "expert" subjectivity…*

- *Traditional lognormal model for fragility curves appears to be often crude or even inappropriate on a case-by-case basis.*

  This is especially true for the equipment fragility curves due to the ISRS resonant frequency shifting that is not captured by the simple lognormal probability model. *Different fragility curve models should be used in future.*

- *The multiple level/multipoint estimate approach provides significantly different risk predictions than the traditional one level/point estimate approach with SSI response scaling.*

  Using *1e-5 probability level with nonlinear SSI analysis* as review level is better than using *1-e4 probability level with linear SSI analysis*.

PART 2:
2016 ASCE 4 PSSI-Based Results vs. 1994 EPRI DSSI-Based Results

Low-Rise Reinforced Concrete Shearwall Building Example

EPRI Deterministic SSI-Based Methodology

The SSI analysis is performed for 5 SSI cases: BEstr-BEsoi, LBstr-BEsoi, UBstr-Besoi, BEstr-LBsoi and BEstr-UBsoi.

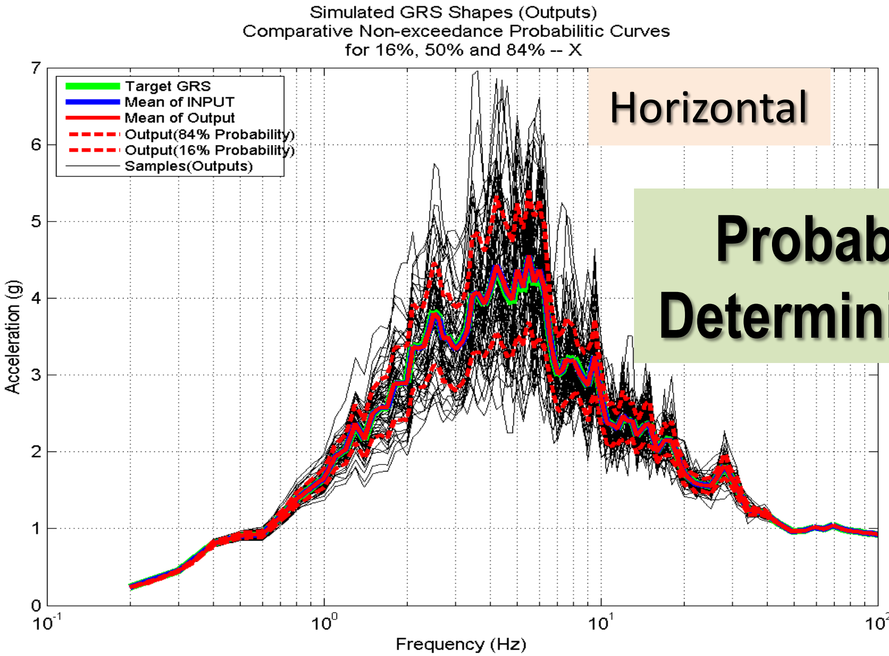
The performance-based GMRS input is considered for seismic input. The ZPGA is 1g. For each SSI case, the Seismic input variability was considered by 5 sets of spectrum compatible acceleration histories based on "seed" records.

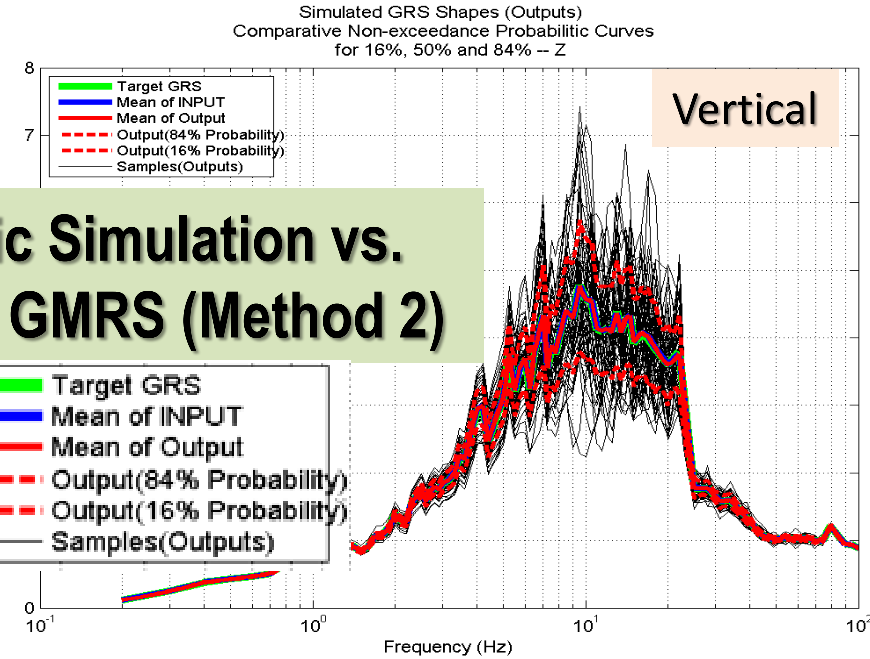
The 3 deterministic soil profiles, LB, BE and UB were obtained based on the 60 probabilistic nonlinear site response simulations assuming the UHRS inputs defined at bedrock (Vs > 9,200 fps).

The maximum SSI responses are computed for 15 Soil variability cases (5 inputs for each of the 3 cases BEstr-BEsoi, BEstr-LBsoi and BEstr-UBsoi) and 15 Structure variability cases (5 inputs for each of the 3 cases BEstr-BEsoi, LBstr-BEsoi and UBstr-BEsoi). Stifness variations is elastic x 0.50 +/- 33%.

The SSI response median and variations are computed considering all the Seismic input, Soil and Structure variability cases. The total variation is based on the variations computed separately for Seismic, Soil and Structure variabilities.

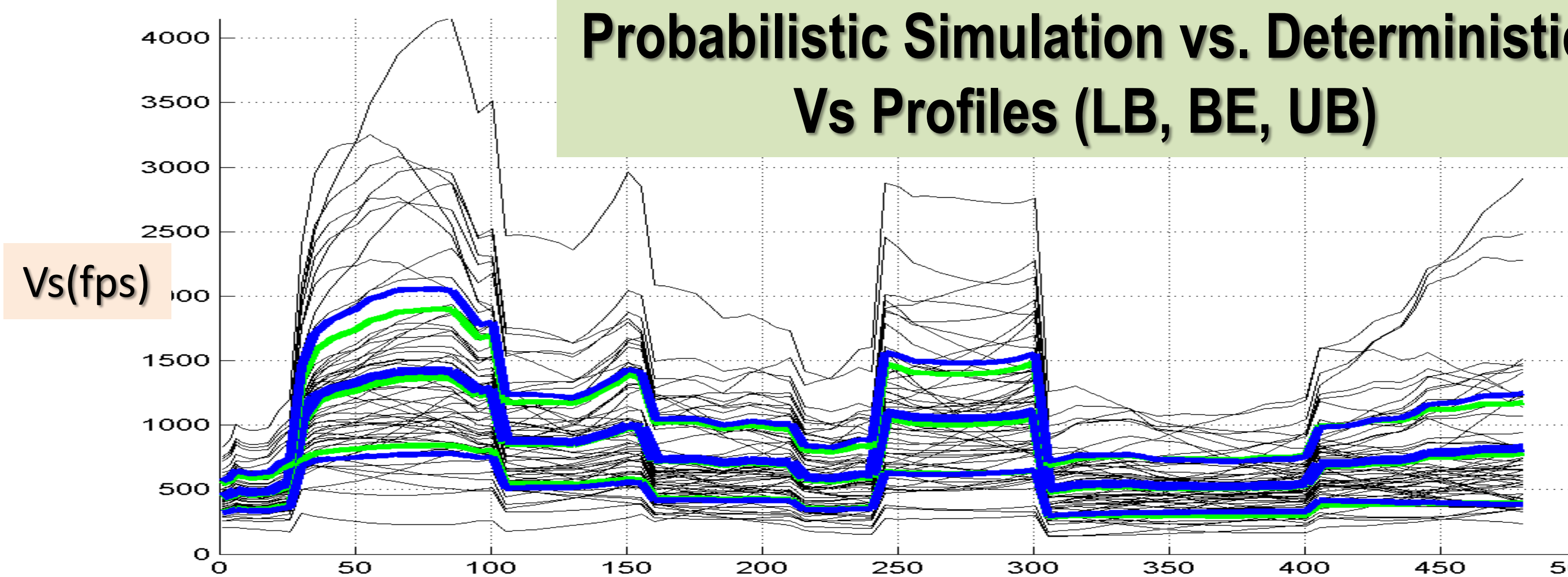
ASCE 4 Probabilistic SSI-Based Methodology



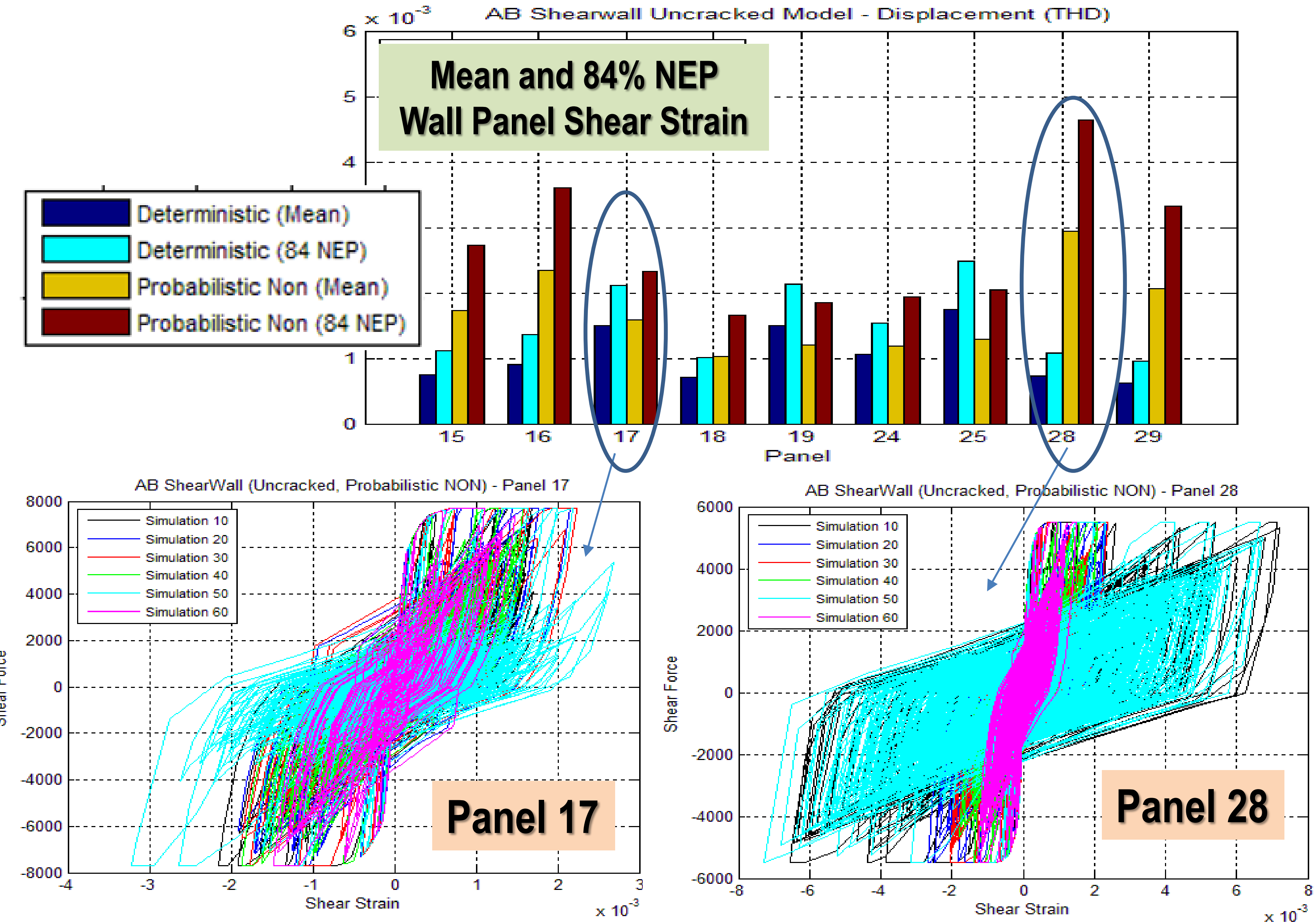


Probabilistic Simulation vs. Deterministic GMRS (Method 2)

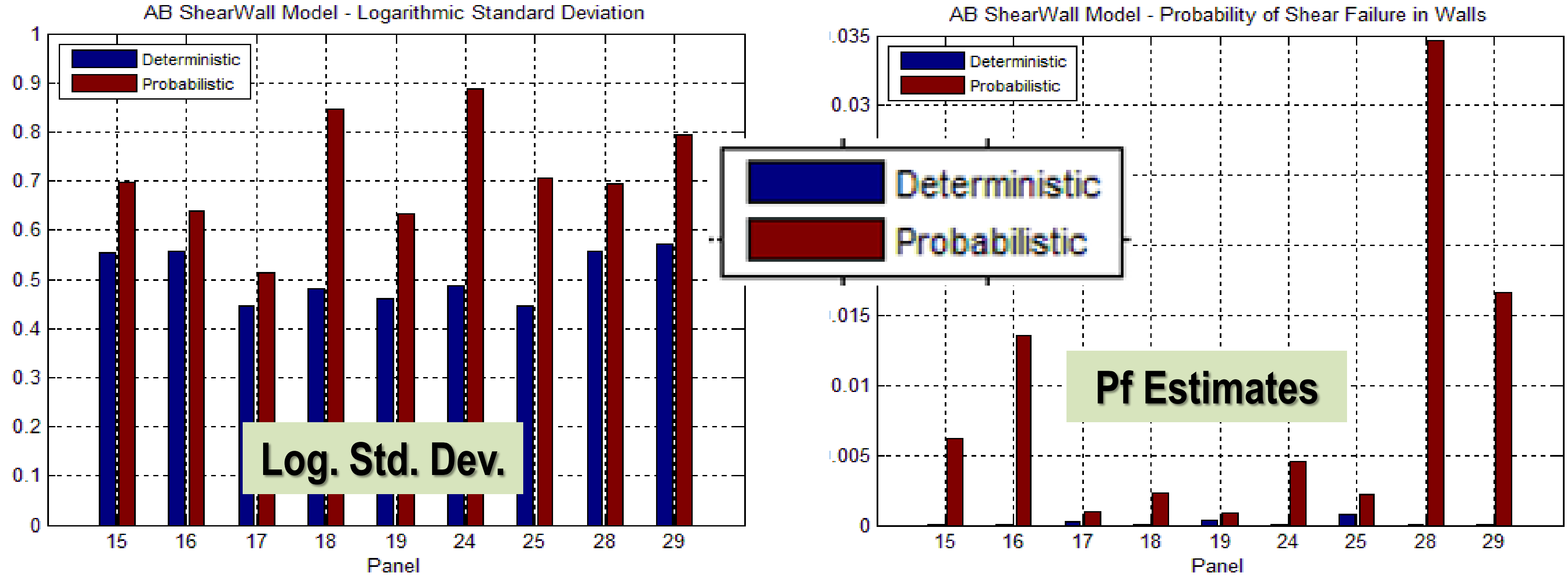
Probabilistic Simulation vs. Deterministic Vs Profiles (LB, BE, UB)



Probabilistic SSI vs. Deterministic SSI Results



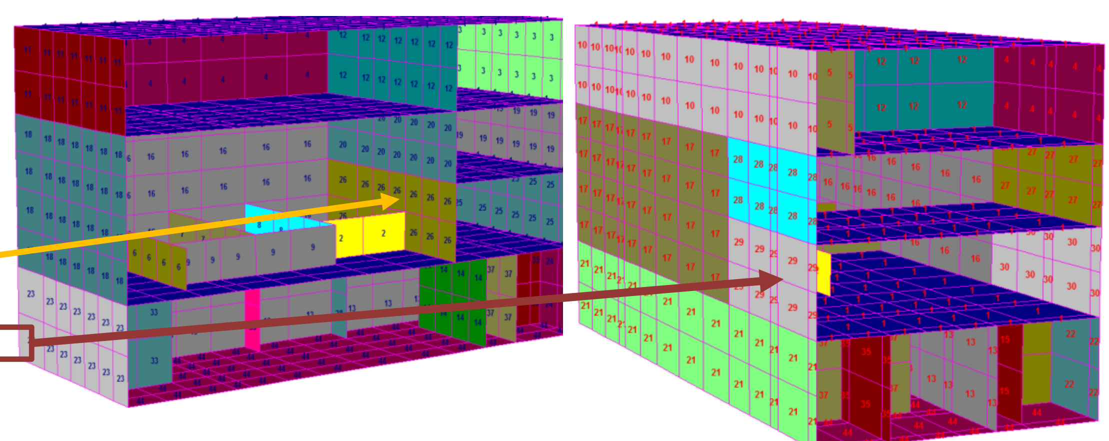
ASCE 4-Probabilistic SSI vs. EPRI-Deterministic SSI



Shear Failure; Prob Failure Vector

Panel#	EPRI	ASCE
15	1.790800e-005	6.241121e-003
16	6.724524e-005	1.353563e-002
17	2.637003e-004	9.223205e-004
18	2.142619e-006	2.344936e-003
19	3.349372e-004	8.197812e-004
24	5.165391e-005	4.604686e-003
25	7.356790e-004	2.189513e-003
28	1.504838e-005	3.465759e-002
29	8.276881e-006	1.667625e-002

EPRI vs. ASCE 4 Highest Risk Wall Panels

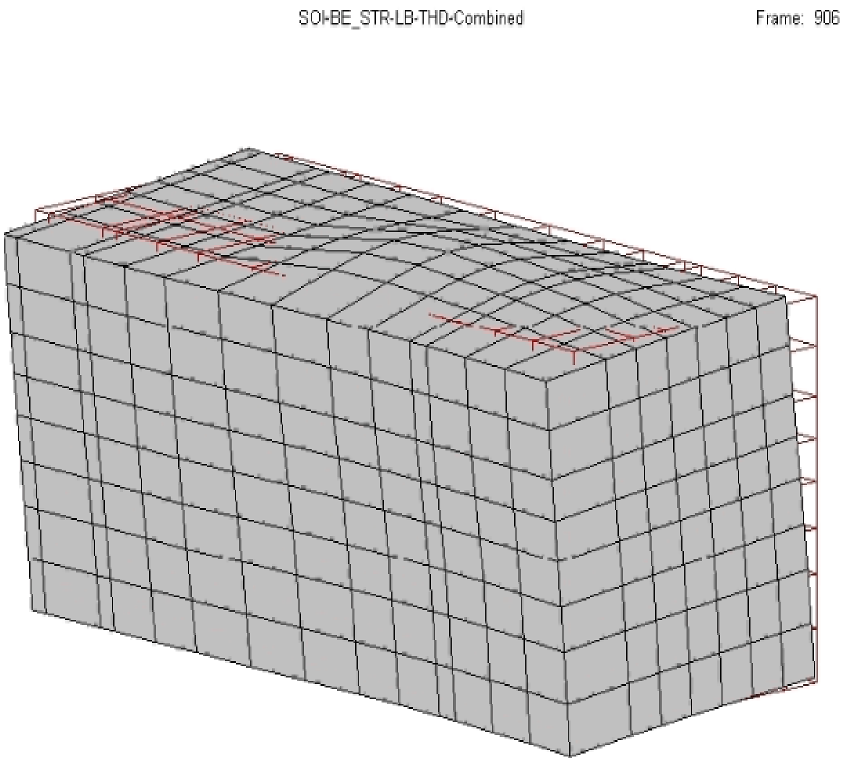


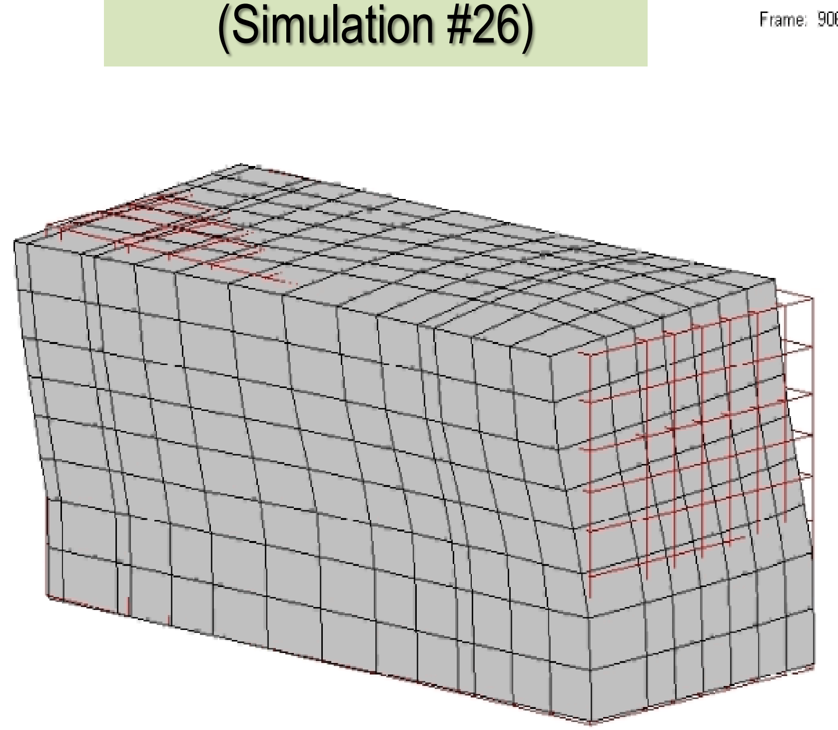
Probabilistic SSI vs. Deterministic SSI Responses

Comparative Structure Deformation at Same Time

Deterministic SSI
(BEsoi-LBstr)

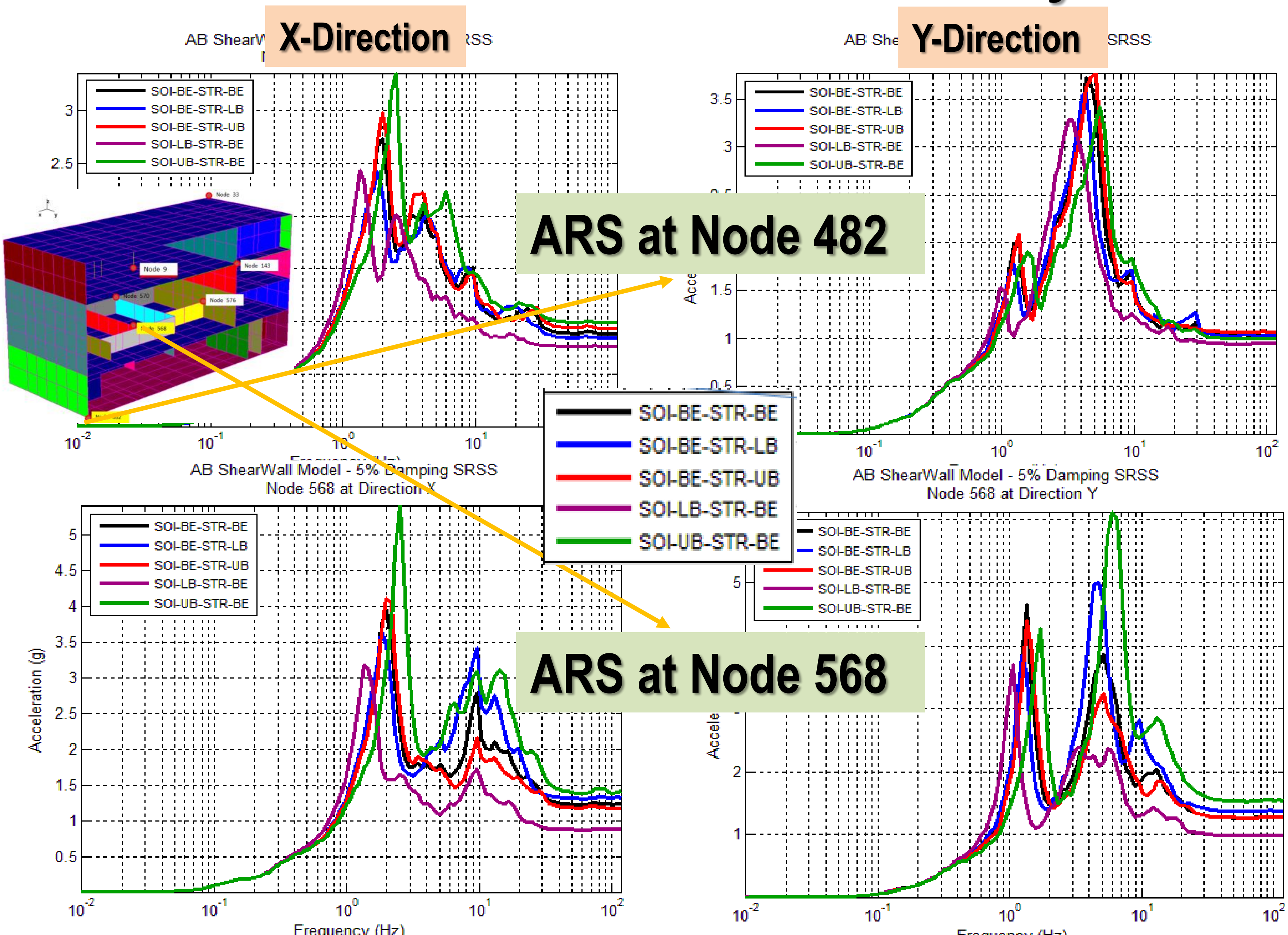
Probabilistic
Nonlinear SSI
(Simulation #26)



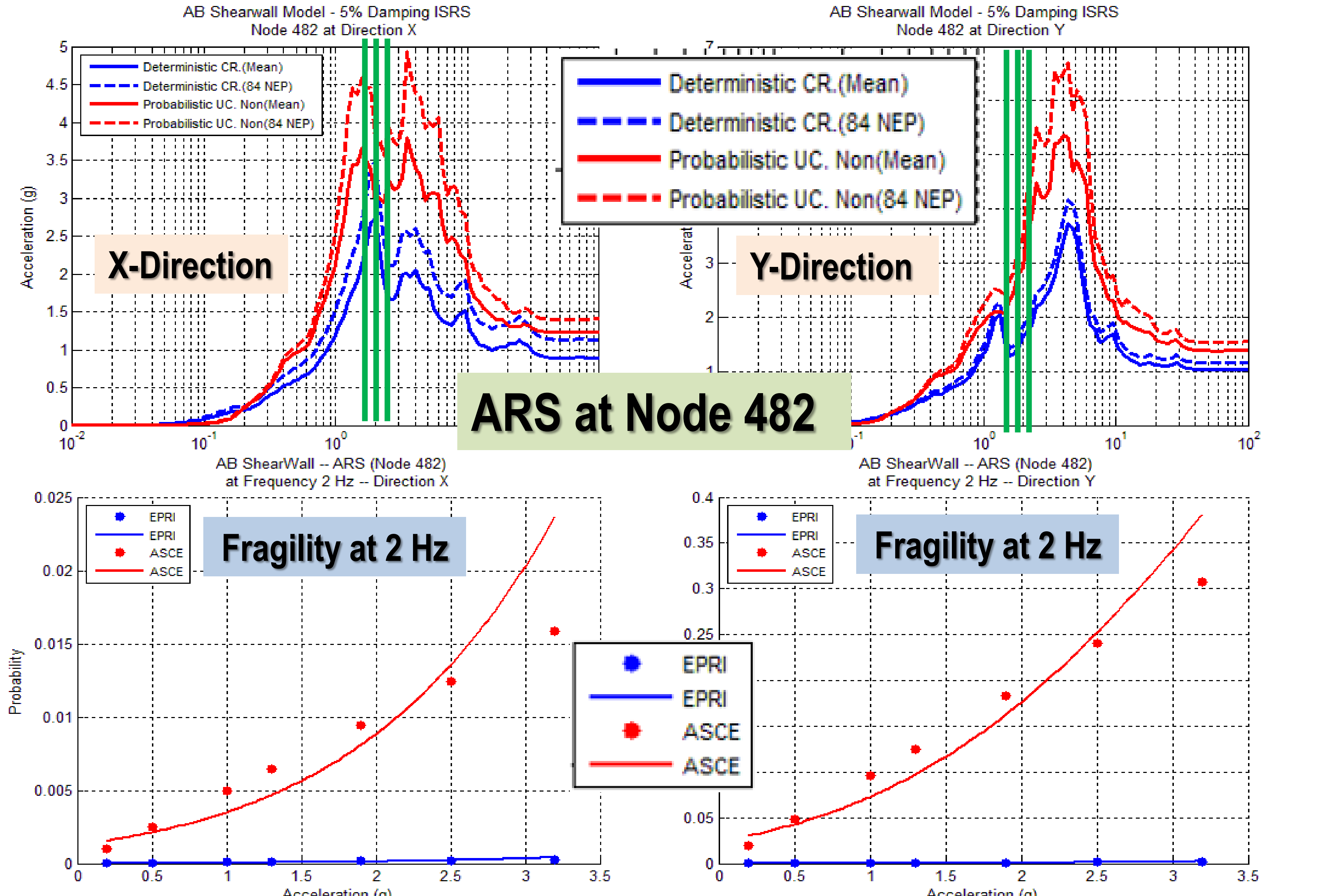


SEE ANIMATION

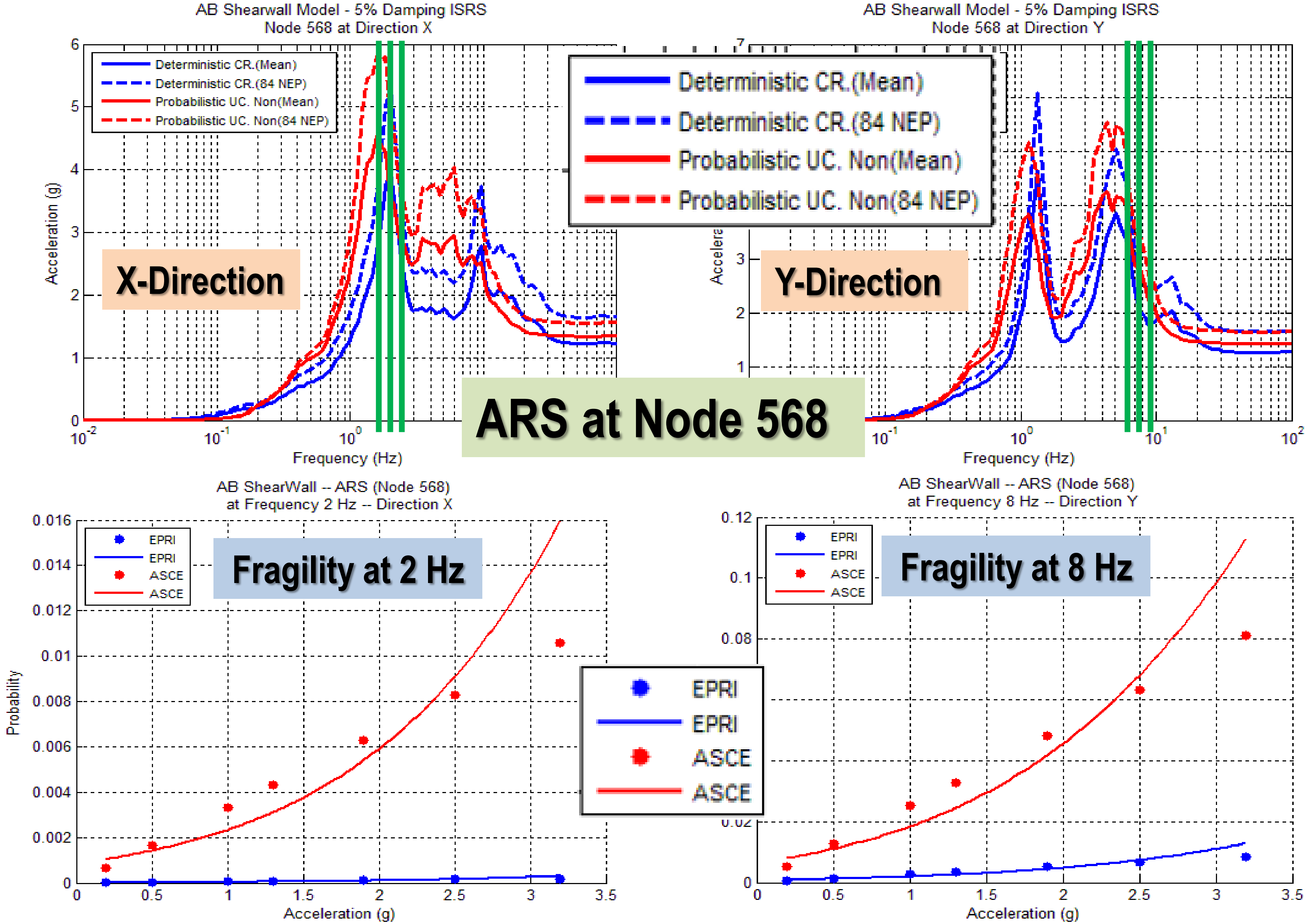
EPRI Deterministic SSI-Based 5 Analysis Cases



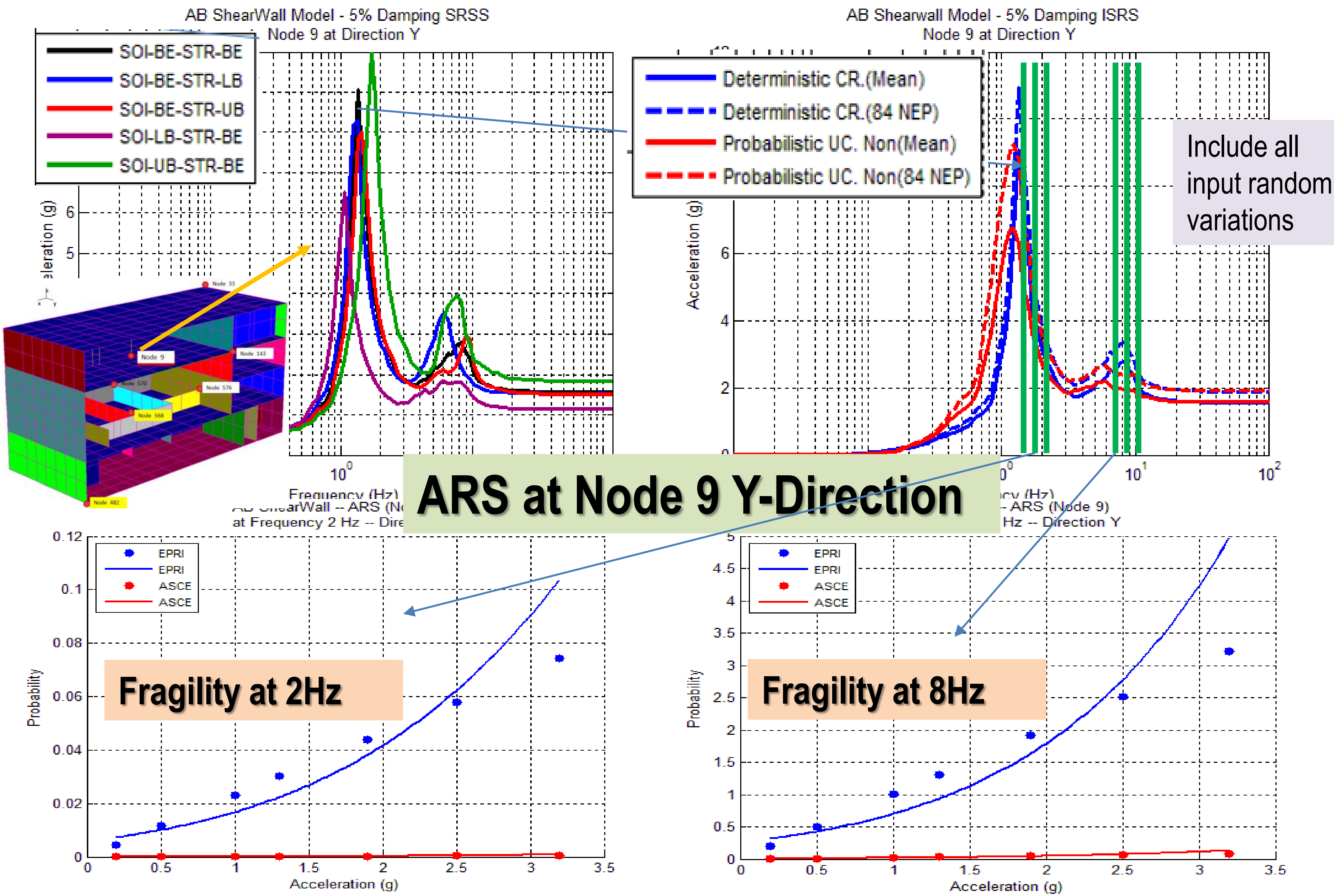
ASCE 4 PSSI-Based ARS vs. EPRI DSSI-Based ARS



ASCE 4 PSSI-Based ARS vs. EPRI DSSI-Based ARS



ASCE 4 PSSI-Based ARS vs. EPRI DSSI-Based ARS



ASCE 4 PSSI-Based ARS vs. EPRI DSSI-Based ARS

Comparative Fragility/Conditional Pf Estimates

ISRS X-Dir Prob Failure Vector

Frequency	2Hz		8Hz	
Node #	EPRI	ASCE	EPRI	ASCE
9	4.569765e-005	3.777722e-003	2.483734e-004	4.792264e-003
33	4.275362e-005	2.002747e-003	3.487098e-004	3.180917e-003
143	4.866542e-005	6.688034e-003	5.350239e-004	8.567610e-003
482	7.994426e-005	4.961024e-003	6.513999e-005	4.437899e-002
568	5.733355e-005	3.313409e-003	4.931325e-004	1.797246e-003
570	4.864856e-005	1.933949e-003	1.929920e-004	1.886620e-002
576	5.392025e-005	3.222089e-003	3.879110e-004	1.957318e-002

ISRS Y-Dir Prob Failure Vector

Frequency	2Hz		8Hz	
Node #	EPRI	ASCE	EPRI	ASCE
9	2.317968e-002	1.755416e-004	1.005848e-003	2.620980e-005
33	1.733793e-002	1.140928e-004	1.055803e-004	2.442733e-003
143	2.115206e-002	1.367721e-004	4.619638e-004	1.109834e-003
482	5.026507e-004	9.617958e-002	7.939274e-005	4.233506e-002
568	4.309107e-003	5.703761e-005	2.649222e-003	2.534387e-002
570	1.041260e-002	6.178707e-006	1.584783e-003	6.712163e-003
576	1.905288e-002	3.277204e-006	9.061175e-004	1.206431e-002

PART 2 CONCLUSIONS

- The SSI structural behaviour is very different for ASCE 4 probabilistic nonlinear SSI simulations (nonlinear structure model) and the EPRI deterministic linear SSI simulations (linear cracked structure model with 0.5 median stiffness reduction and 7% damping). ASCE 4 PSSI modelling including nonlinear structure captures well the physical-behaviour including the shear deformation within structure.
- New ASCE 4 PSSI-based fragility results are quite different than the EPRI DSSI-based fragility results. Differences in the predicted risks/fragilities could be up to 1-2 order of magnitudes.
- The new ASCE 4-based probabilistic nonlinear SSI analysis provides a significant improvement of fragility calculations