NONLINEAR SEISMIC SSI FOR REINFORCED CONCRETE BUILDINGS IN ACCORDANCE WITH ENGINEERING BEST PRACTICES IN US AND JAPAN

PART 1: Modeling of RC Structural Wall Nonlinear Behavior

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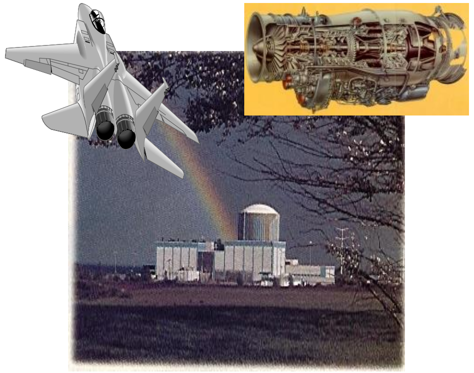


DOE/NRC Natural Phenomena Hazards Meeting

October 20-22, 2020

Purpose of This Presentation

To describe the implementation of an efficient and practical nonlinear seismic SSI approach for the reinforced concrete shearwall NPP structures based on the best engineering design practices in US and Japan.

The idea behind the developed nonlinear SSI analysis tool (ACS SASSI Option NON) is to provide the needed practical support to engineering designers by providing a analysis tool which *in compliance with the current structural design standards and nuclear regulatory requirements*.

Acknowledgements:
We thank very much to the SHIMIZU structural designers who have closely cooperated with us over the last couple of years during the development of this nonlinear SSI tool, so that the newly produced Option NON software is compliant with the nuclear seismic design regulations in Japan.

Part 1 Presentation Content

1. Brief Description of the Nonlinear SSI Methodology

2. Modeling RC Wall Nonlinear Behavior; Back-Bone Curves and Hysteretic Models

3. Modeling of Interaction Between Shear and Bending Effects

4. Comparative Nonlinear Results vs. PERFORM3D for A *Low-Rise* Shearwall Building

5. Comparative Nonlinear Results Vs. OpenSees Codes for A *Mid-Rise* Shearwall Building

Continue in Part 2…

1. Brief Description of the Nonlinear SSI Methodology

The nonlinear SSI analysis is based on an iterative scheme that includes two separate computational steps at each iteration, as follows:

- Step 1: Perform an *equivalent-linear SSI analysis* in complex frequency via SASSI approach to compute the structural displacements for each nonlinear RC wall, and then,
- Step 2: Perform a *nonlinear time-integration analysis* for each RC wall submodel loaded with the SSI displacements from Step 1, to compute the in-plane shear and bending nonlinear wall responses using *standard-based BBCs and selected hysteretic models*. Then, determine *the equivalent-linear stiffness and damping for each wall* using DRF to be used for next SSI iteration, until converged.

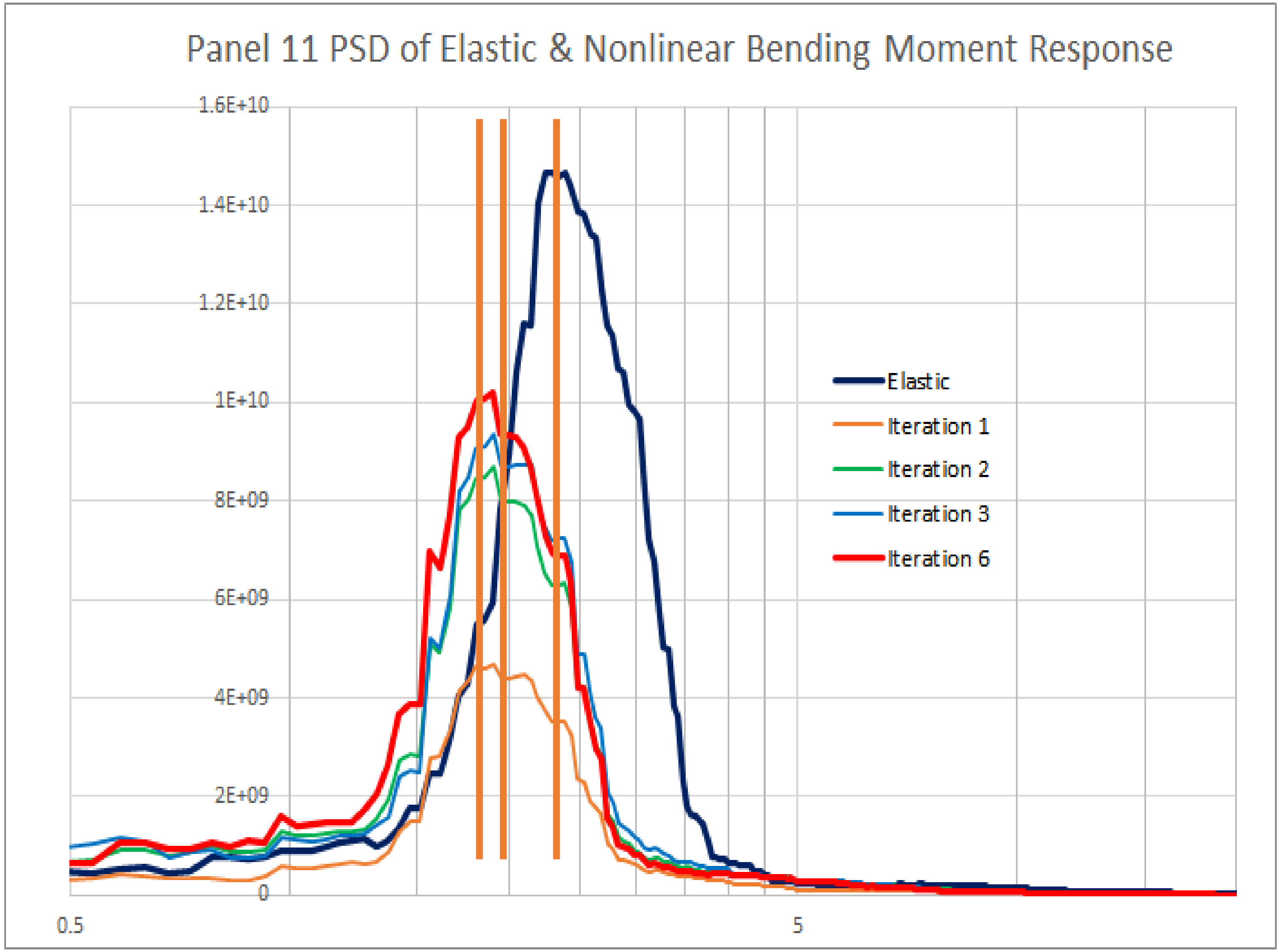
REMARKS:

1) Step 1 uses the *original, refined FE SSI model*, while Step 2 uses a *reduced-order structural model* composed by nonlinear RC walls. Therefore, the nonlinear time-domain Step 2 analysis is extremely fast. For DES, *condensed soil impedance matrix* should be used for SSI iterations (ANALYS option).
2) This methodology was validated for several shearwall building models against CSI PERFORM3D code and the OpenSees 3D FIBER model and 2D MVLEM software.

Iterative Equivalent Linearization Using Variable or Constant DRF

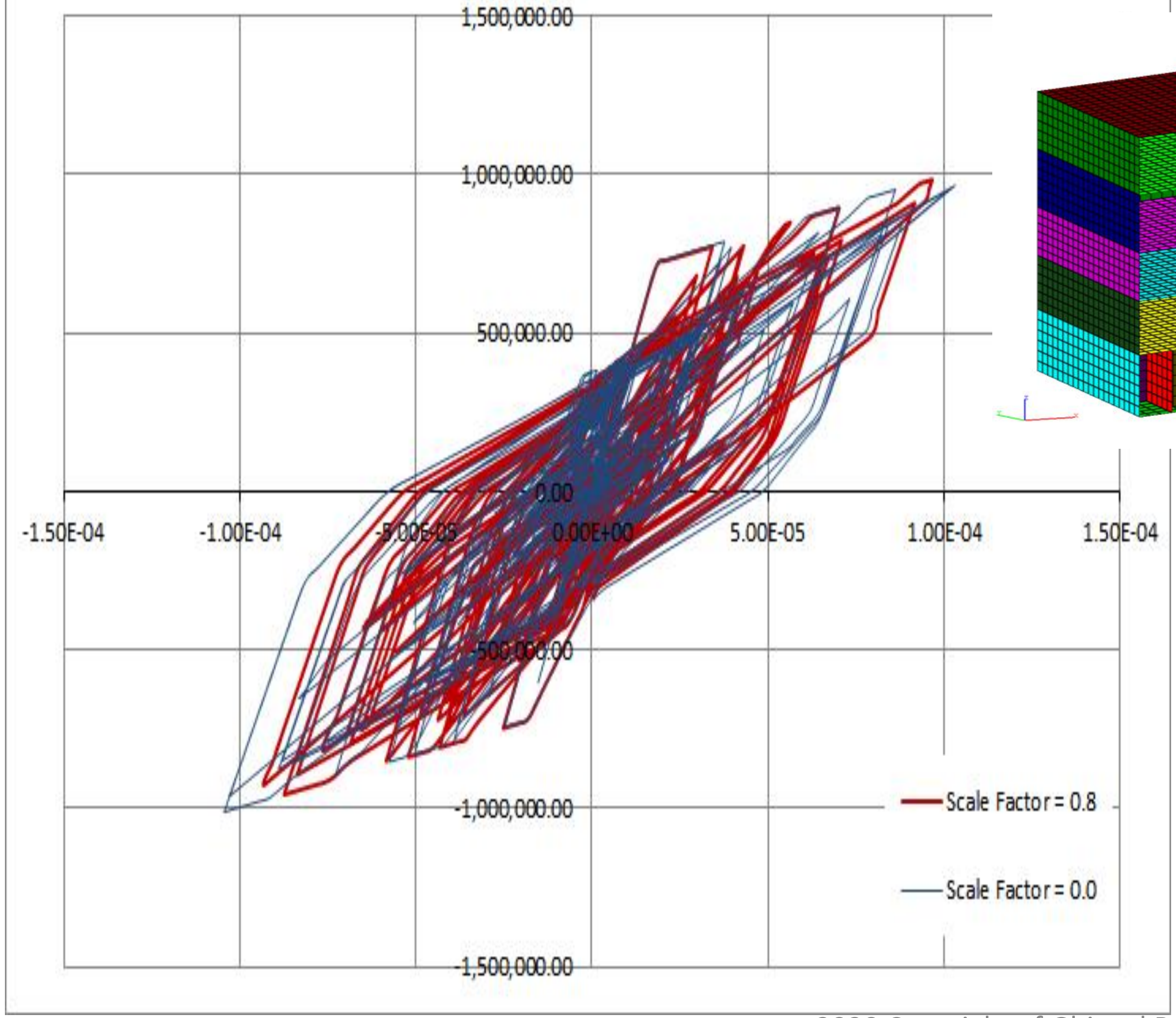
The *PSD-based DRF* is computed based on the frequency content of the PSD frequency computed for the nonlinear shear force or bending moment for each wall at each floor level and each iteration.

The DRF is computed based the PSD dominant frequency shifts at each iteration, as shown in the right-side figure.

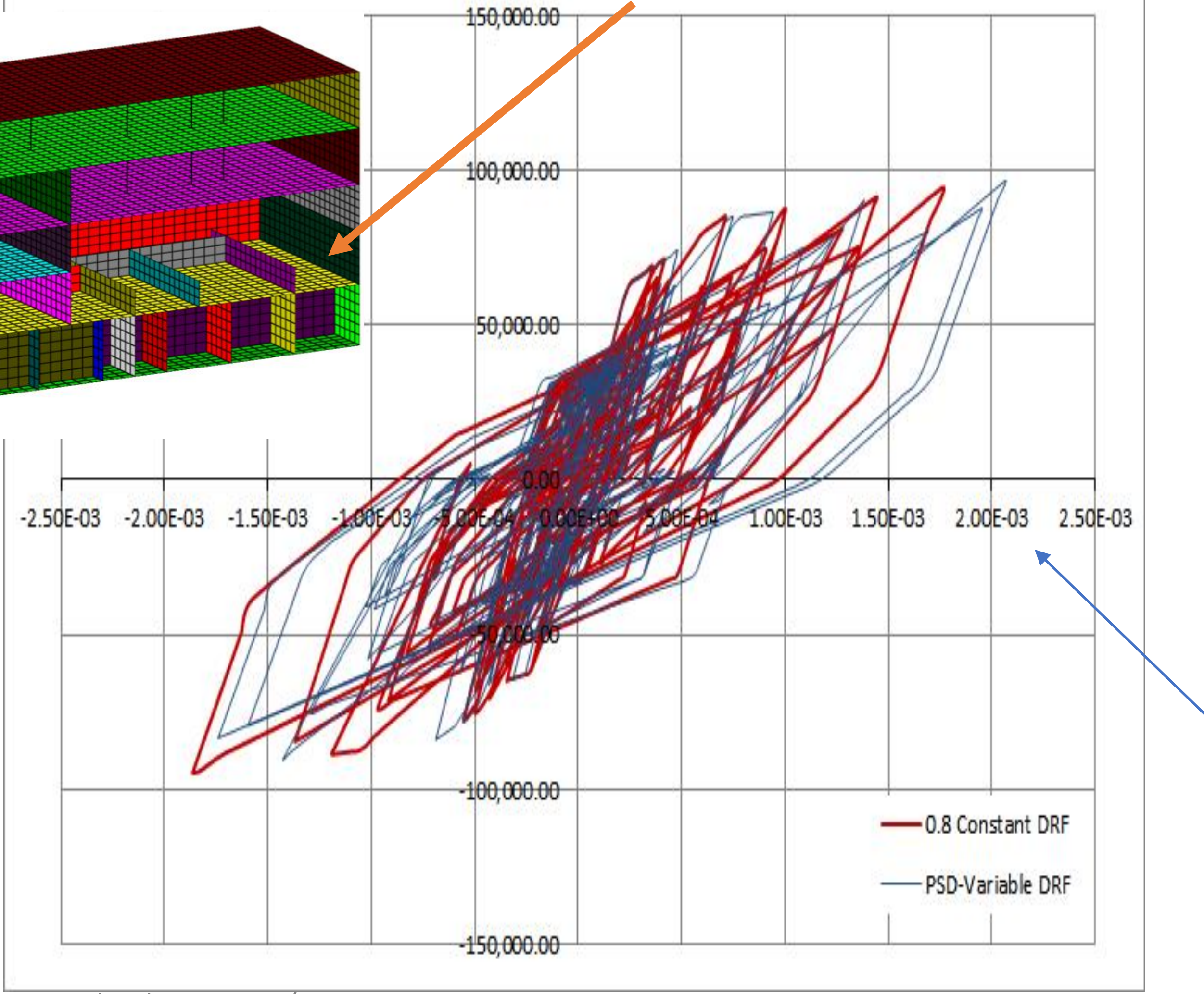


Hysteretic Responses for PSD-based Variable DRF vs. 0.80 DRF

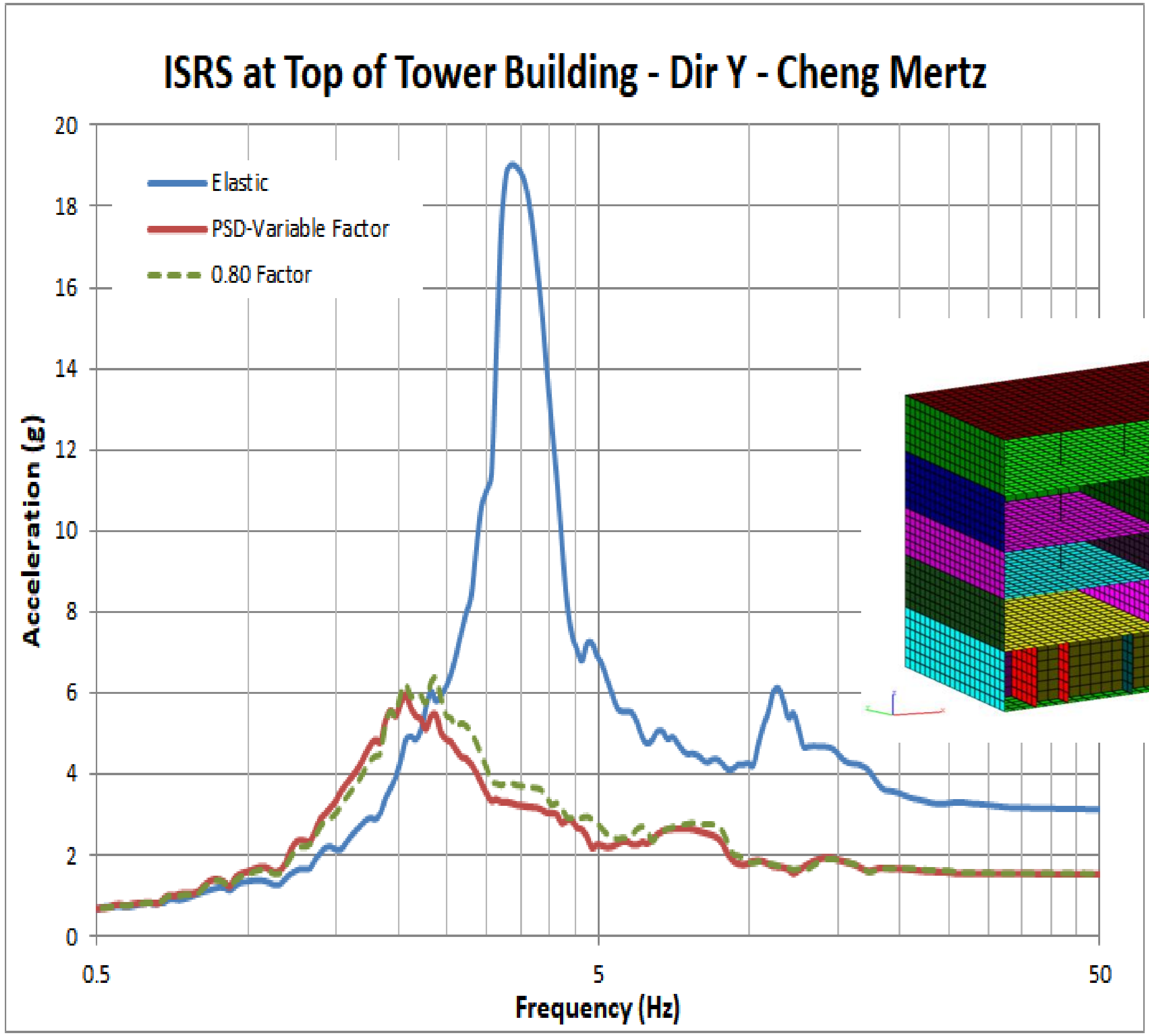
Panel 11 Bending CM Loops

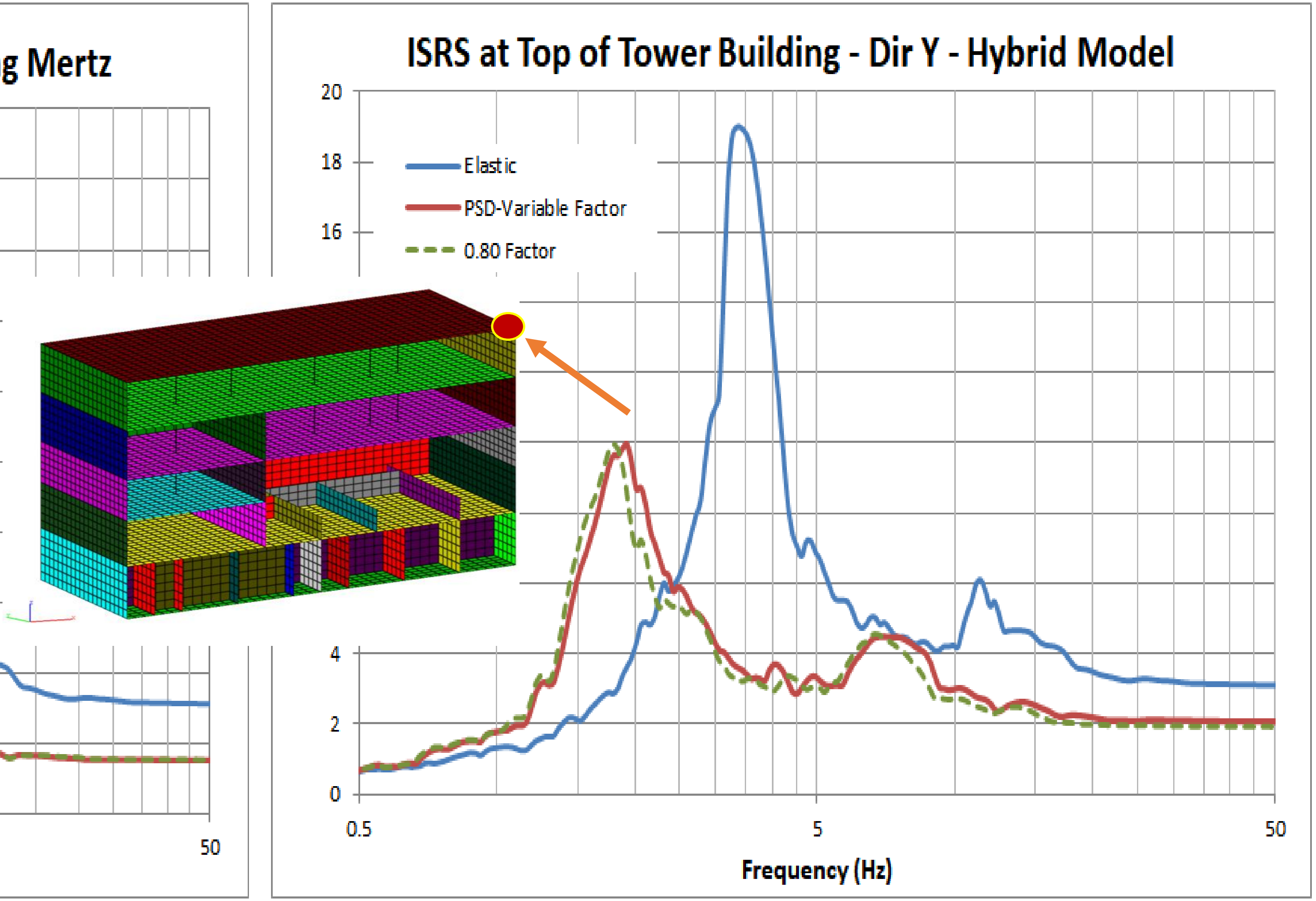


Panel 11 Shear CM Loops



Nonlinear ISRS Computed Using PSD-based DRF vs. 0.80 DRF





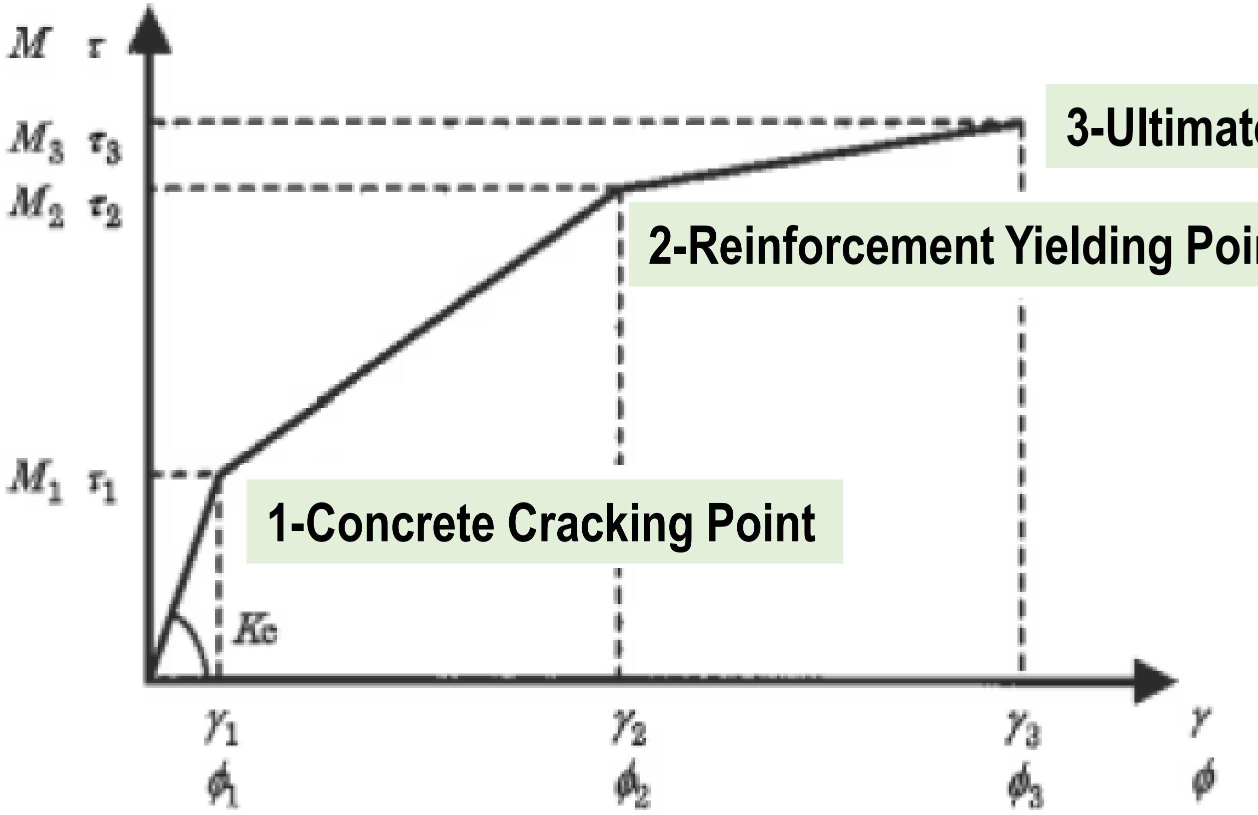
Main Steps of Nonlinear SSI Analysis Procedure Based on Engineering Best Practice Recommendations

Here are the main steps of the procedure:

1. Prepare structure FE model.
2. Select from structure FE model the nonlinear wall FE submodels
3. Perform initial SSI analysis for the gravity and seismic loads
4. Perform automatic wall cross-section geometry identification and automatic section cuts for each wall at each floor level for the gravity and seismic loads.
5. Compute shear and bending BBCs for each wall *per applicable best-practice recommendations*
6. Select shear and bending hysteretic wall models *per applicable best-practice recommendations*
7. Perform iterative nonlinear SSI analysis using the shear and bending hysteretic wall models and combine their responses at each iteration.
8. Post-process the final SSI results for the converged nonlinear response

2. Modeling RC Wall Nonlinear Behavior; Back-Bone Curves (BBC) and Hysteretic Models

BBC Curves: Are trilinear BBCs for both the shear and bending deformation following typical engineering practice, also recommended by the JEAC 4601-2015 Sect.3.5.6 (See figure below)



Exp. Figure 3.5.6-1 Trilinear skeleton curve.

Shear BBCs Computed per JEAC 4016-2015 Standard App.3.6

a. Shear deformation ($\tau\gamma$ relationship)

First turning point

$$\left[\begin{array}{l} \tau_1 = \sqrt{0.31\sqrt{F_c}\,(0.31\sqrt{F_c} + \sigma_v} \quad (\mathrm{N/mm^2}) \\ \gamma_1 = \tau_1 / G \end{array}\right.$$

Second turning point

$$\left[\begin{array}{l} \tau_2 = 1.35\tau_1 \quad (\mathrm{N/mm^2}) \\ \gamma_2 = 3\gamma_1 \end{array}\right.$$

Shear BBC at each floor level depends on the axial compression stress from gravity and the seismic bending moment by M/Q ratio (shear span ratio)

Ultimate point

$$\left[\begin{array}{lll} \tau_3 = \left(1 - \dfrac{\tau_s}{1.4\sqrt{F_C}}\right)\tau_0 + \tau_s & (\mathrm{N/mm^2}) & \tau_s \le 1.4\sqrt{F_c} \\ \quad = 1.4\sqrt{F_c} & (\mathrm{N/mm^2}) & \tau_s > 1.4\sqrt{F_t} \\ \gamma_3 = 4.0 \times 10^{-3} & & \end{array}\right.$$

where $\tau_0 = \left(0.94 - \dfrac{0.56M}{QD}\right)\sqrt{F_t}$ when $\dfrac{M}{QD} > 1,\quad \dfrac{M}{QD} = 1$

$$\tau_s = \frac{(P_V + P_H)_s \sigma_y}{2} + \frac{(\sigma_v + \sigma_H)}{2}$$

Shear BBCs Computed Based on ASCE 4 & ACI 318 Standards

ACI 318-14 Section 18 for Shear Strength

$$V_n = A_{cv}(\alpha_c \lambda \sqrt{f'_c} + \rho_t f_y)$$

where the coefficient α_c is 3.0 for $h_w/\ell_w \le 1.5$, is 2.0 for $h_w/\ell_w \ge 2.0$, and varies linearly between 3.0 and 2.0 for h_w/ℓ_w between 1.5 and 2.0.

any one of the individual wall piers, V_n shall not be taken larger than $10A_{cw}\sqrt{f'_c}$, where A_{cw} is the area of concrete section of the individual pier considered.

Option NON BBC_GENERATION Module Implementation

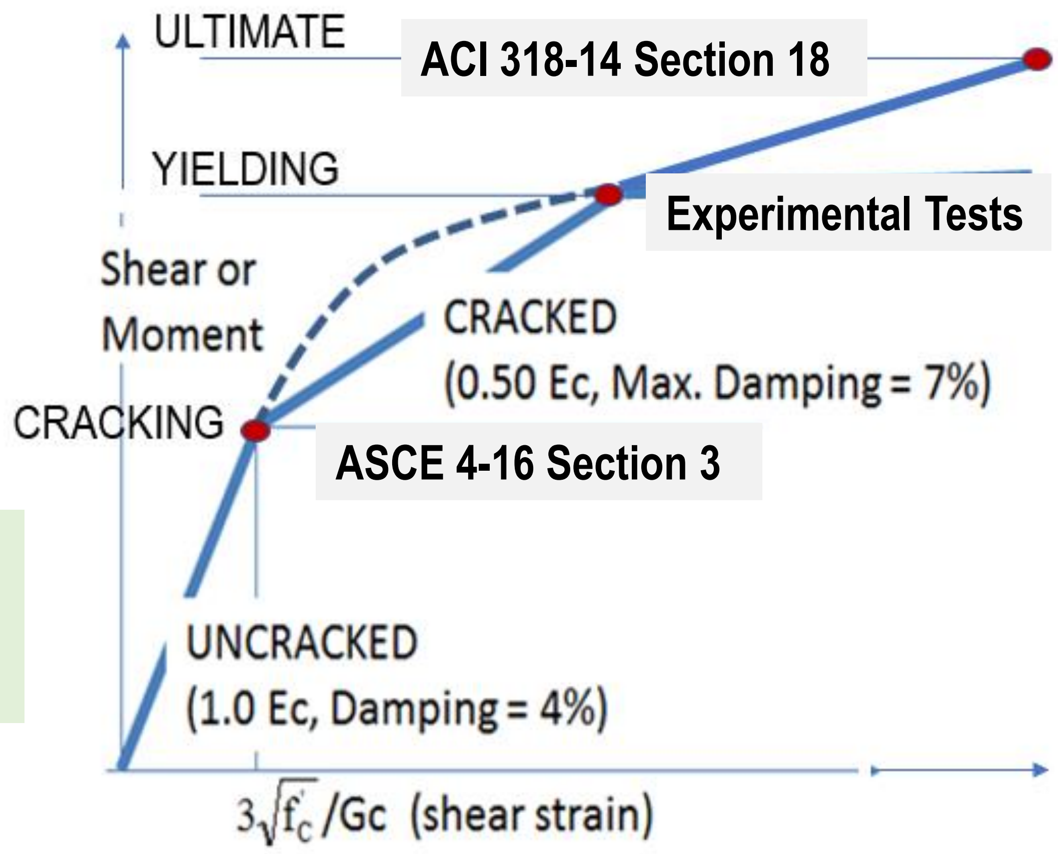
$$\boxed{V = \left(\alpha_c \sqrt{f'_c} + \rho_H f_y\right) A_W \le 10\sqrt{f'_c} A_W}$$

Does no depend on axial force or bending effects!

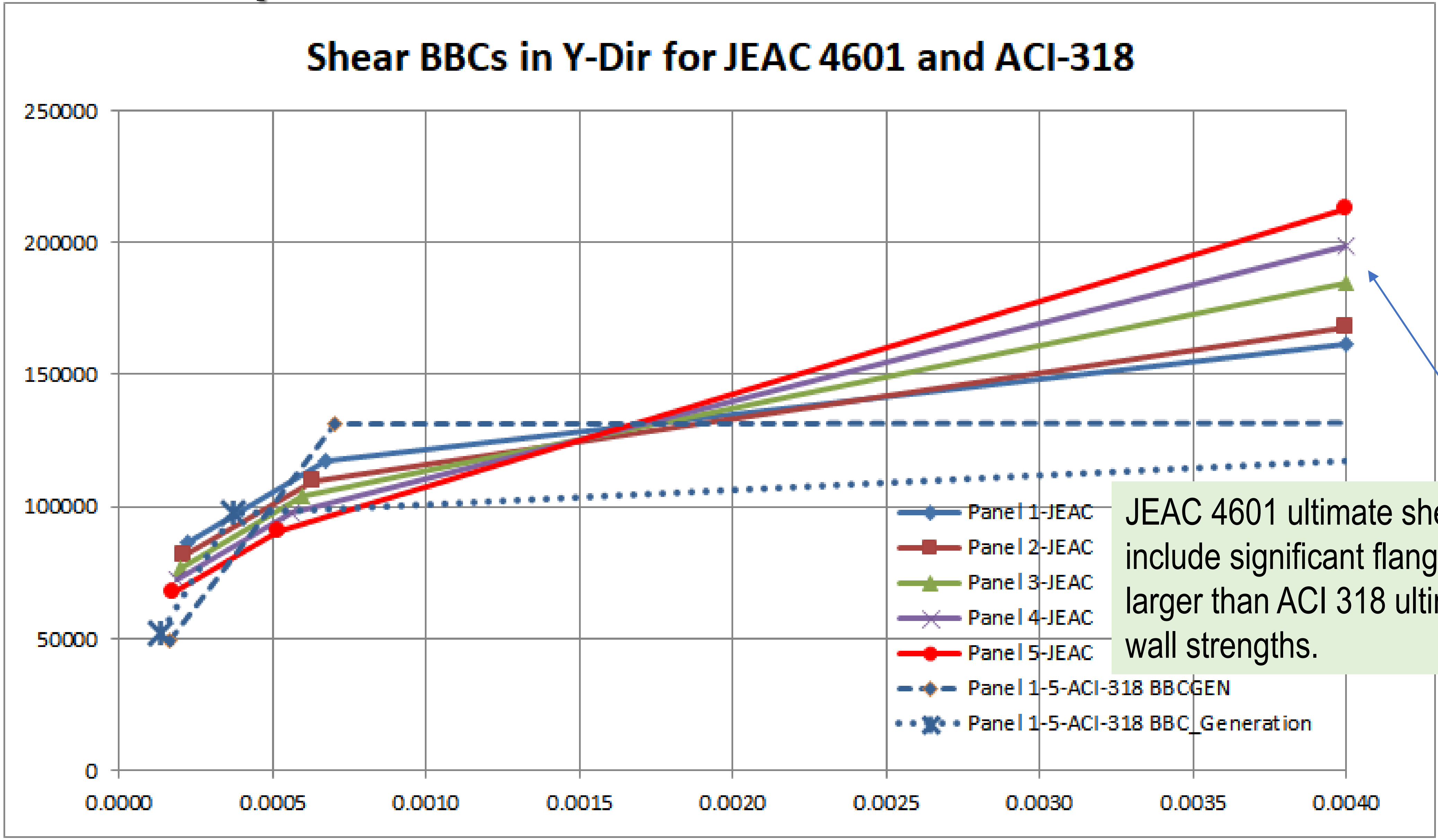
ASCE 4-16 Section 3

RC wall shear cracking occurs when the shear stress is larger than $3.\sqrt{f'_c}$

Trilinear Shear BBC Curve

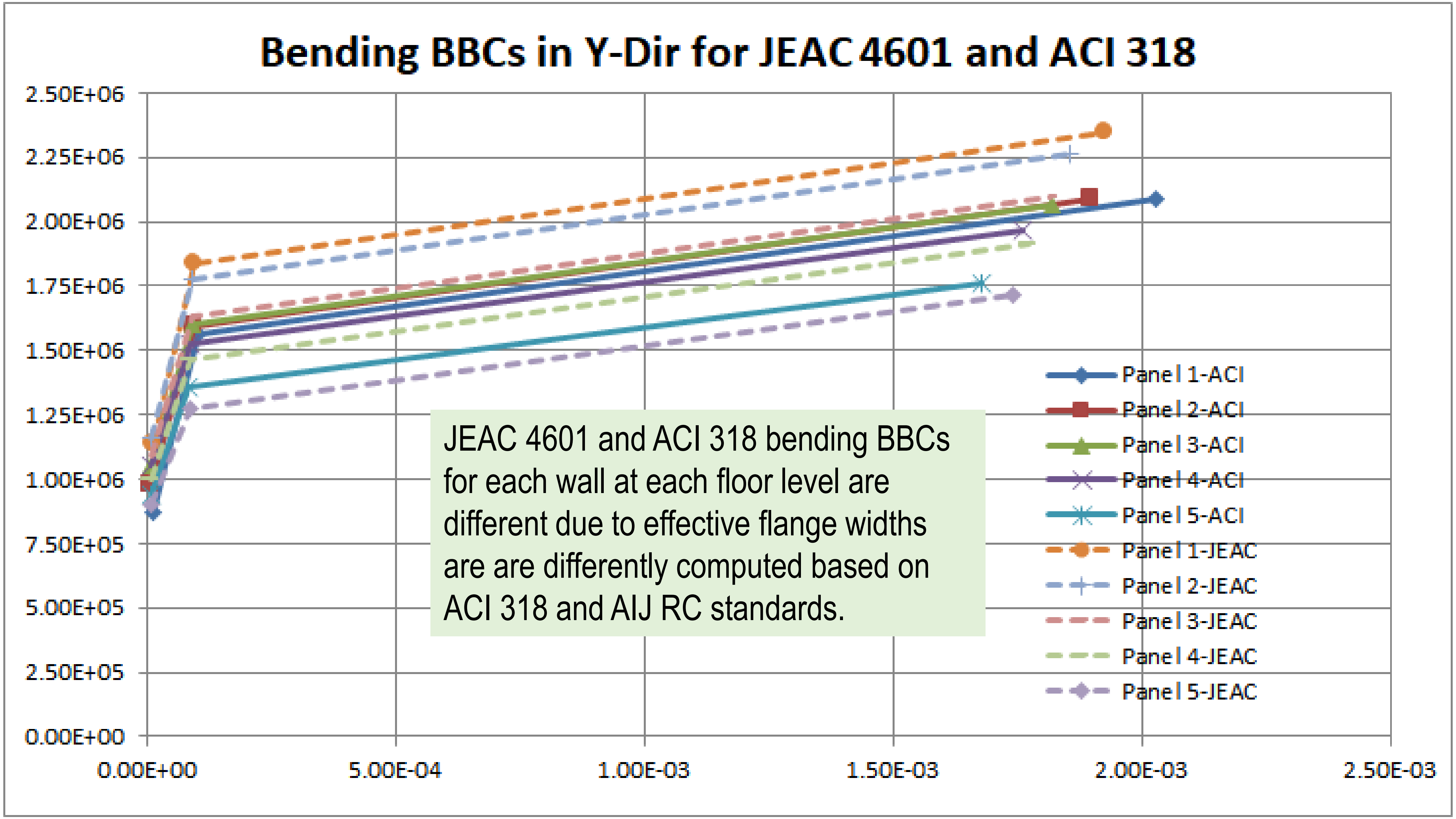


Computed Shear BBCs for TB RC Walls in Y-Dir



JEAC 4601 ultimate shear forces include significant flange effects; larger than ACI 318 ultimate shear wall strengths.

Computed Bending BBCs for TB RC Walls in Y-Dir



Hysteretic Models Library Available for Nonlinear RC Walls

The hysteretic model library includes 8 types of models applicable to the structure RC walls:

1-Cheng-Mertz Shear (CMS)

2-Cheng-Mertz Bending (CMB)

3-Takeda (TAK)

4-General Massing Rule (GMR)

5-Maximum Point-Oriented (PO) for Shear - per JEAC 4601 App. 3.6

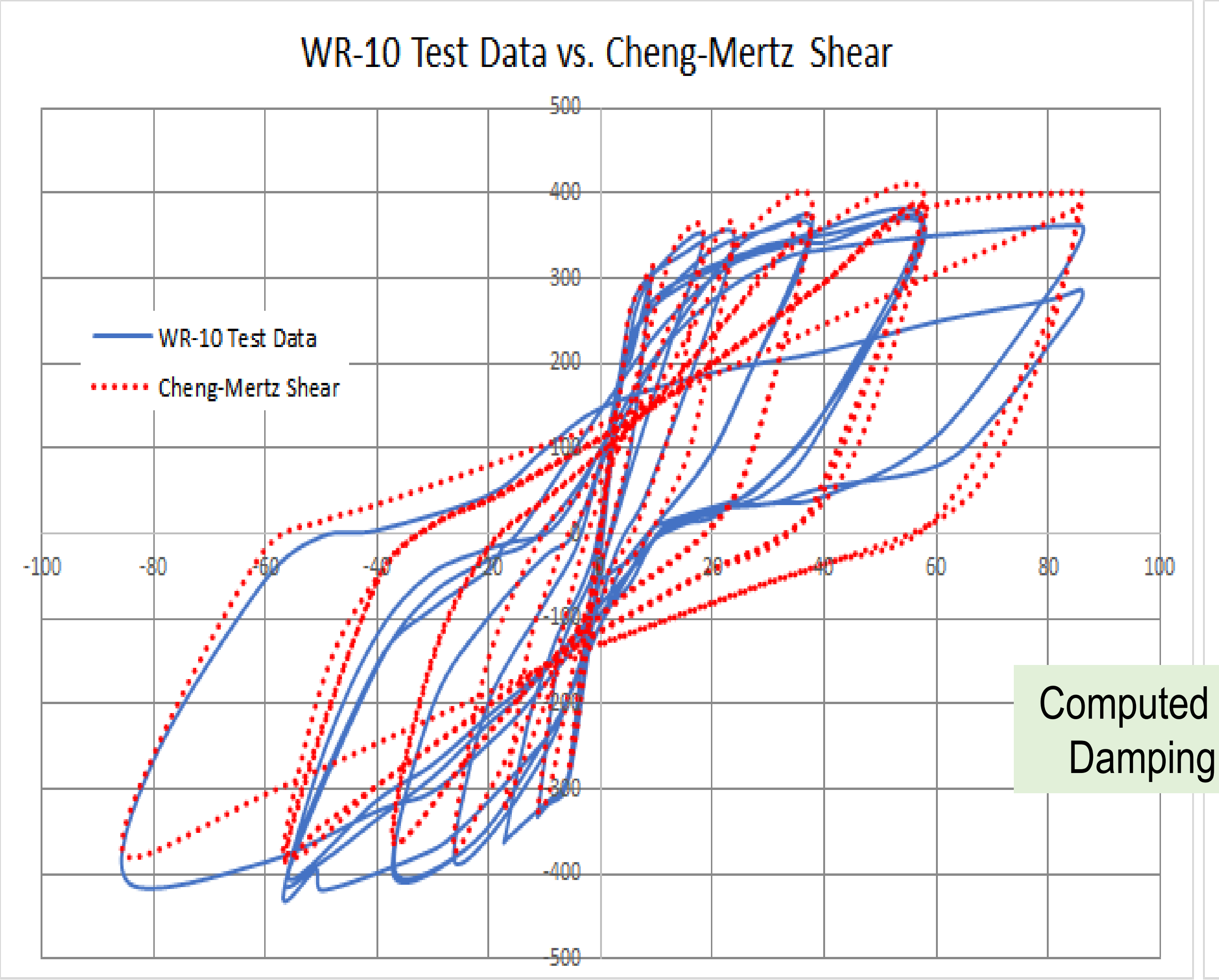
6-Maximum Point-Oriented Degrading Trilinear (PODT) for Bending - per JEAC 4601 App. 3.6

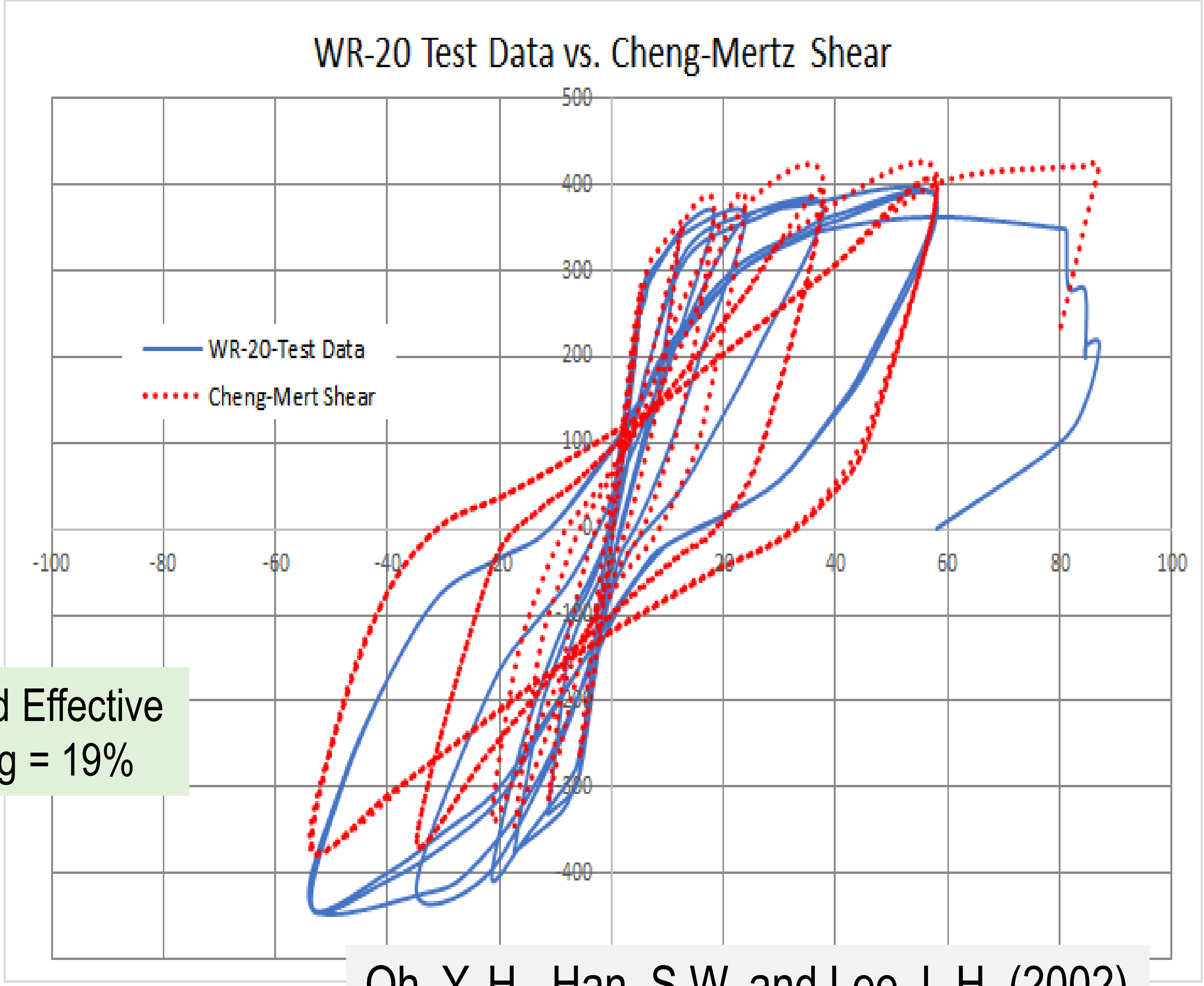
7-Hybrid Shear (HYS) – obtained by combining PO Shear and CMS models

8-Hybrid Bending (HYB) - obtained by combining PODT Bending and CMB models

Cheng-Mertz Shear Hysteretic Model Against HU Wall Test Data

Cheng-Mertz Shear Model (Model 1)



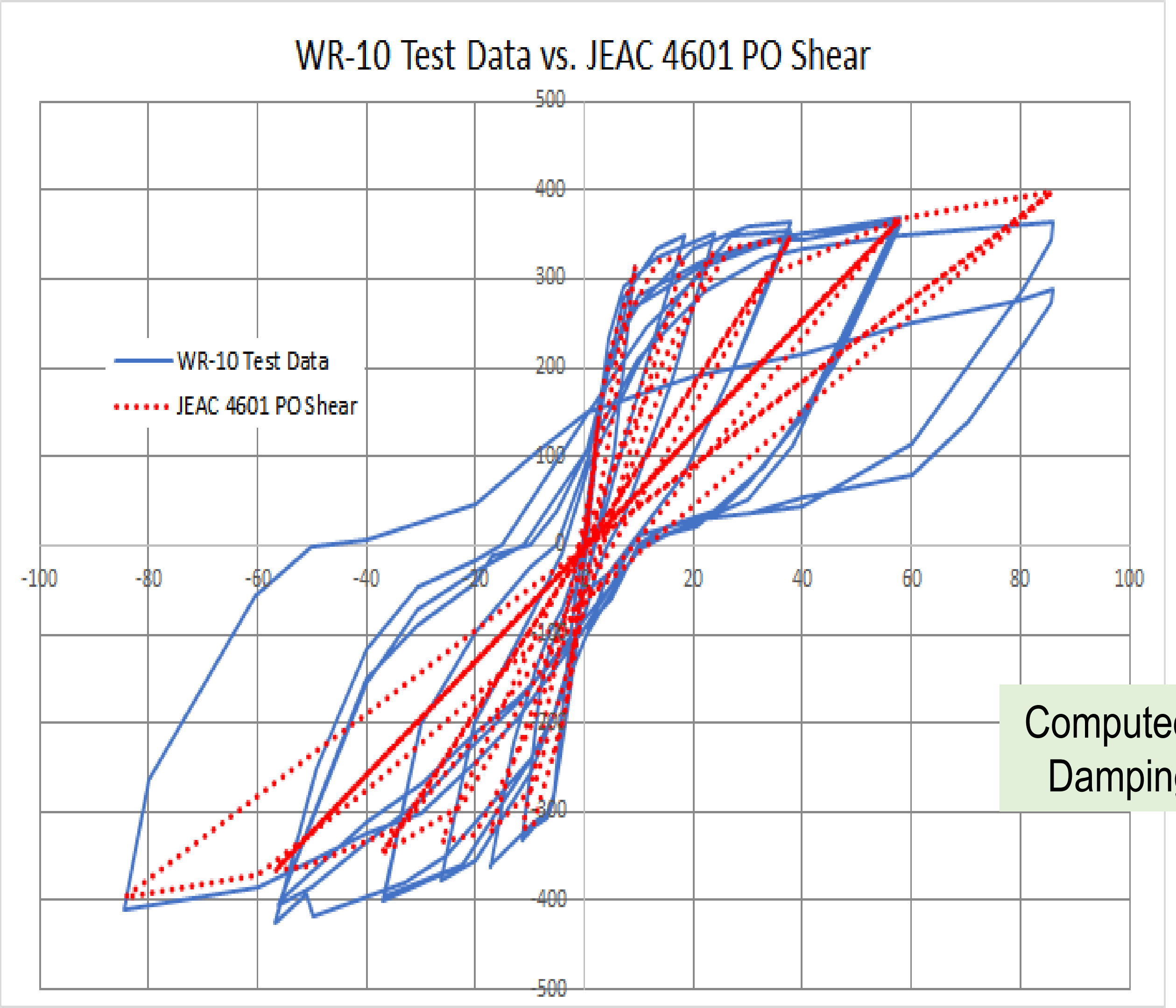


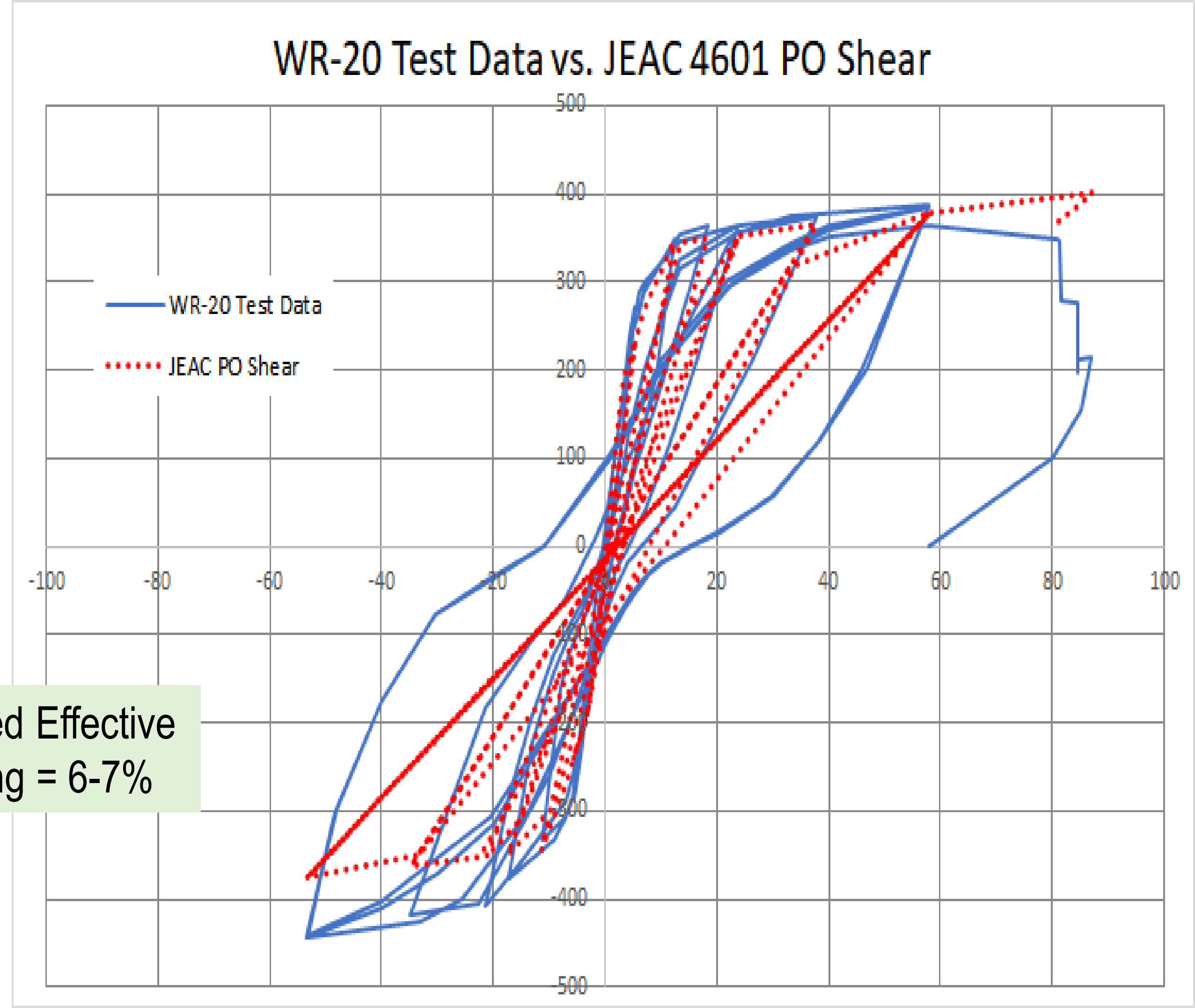
Computed Effective Damping = 19%

Oh, Y. H., Han, S.W. and Lee, L.H. (2002)

JEAC PO Shear Hysteretic Model Against HU Wall Test Data

JEAC 4601 Point-Oriented (PO) Shear Model (Model 5)

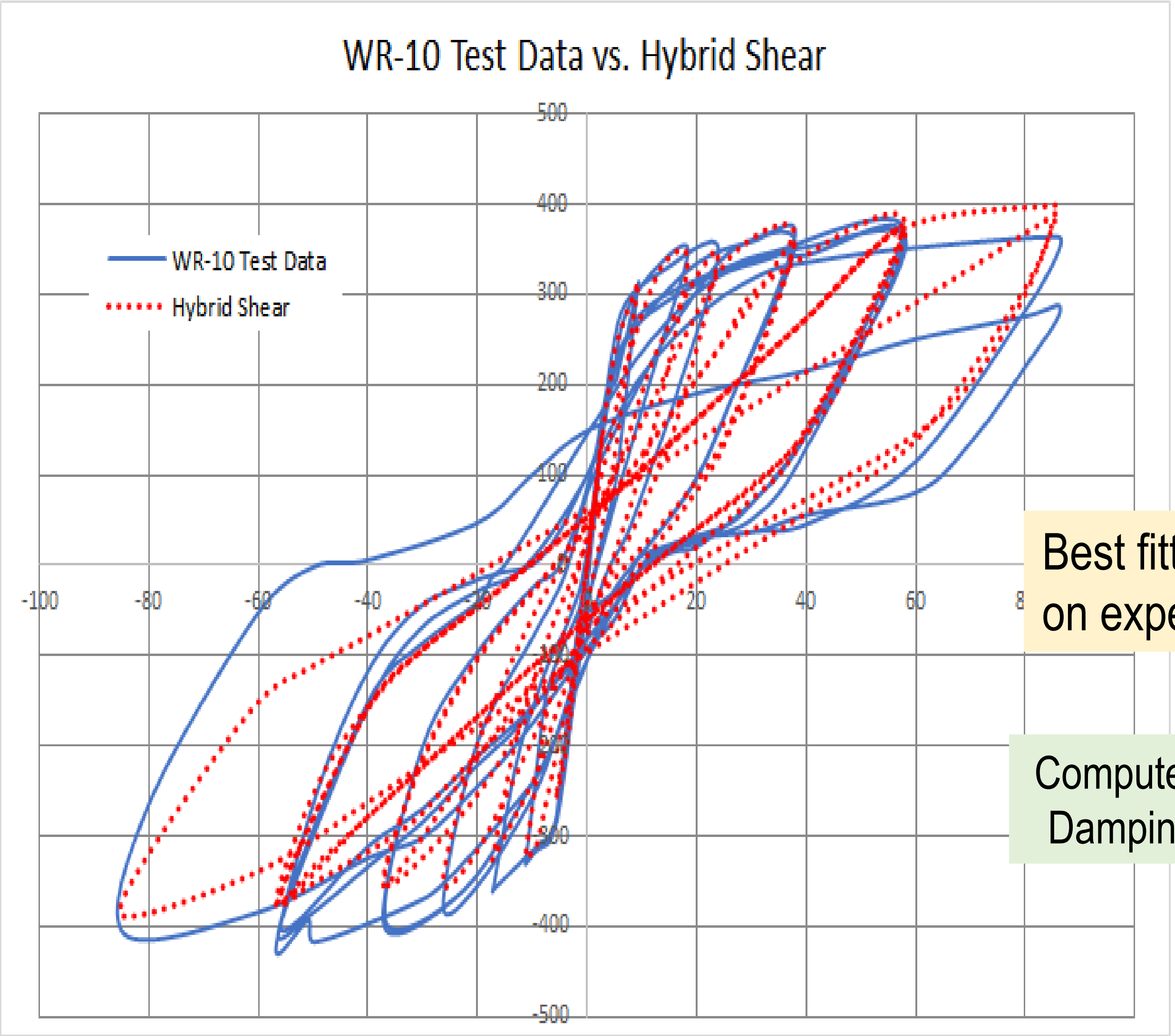




Computed Effective Damping = 6-7%

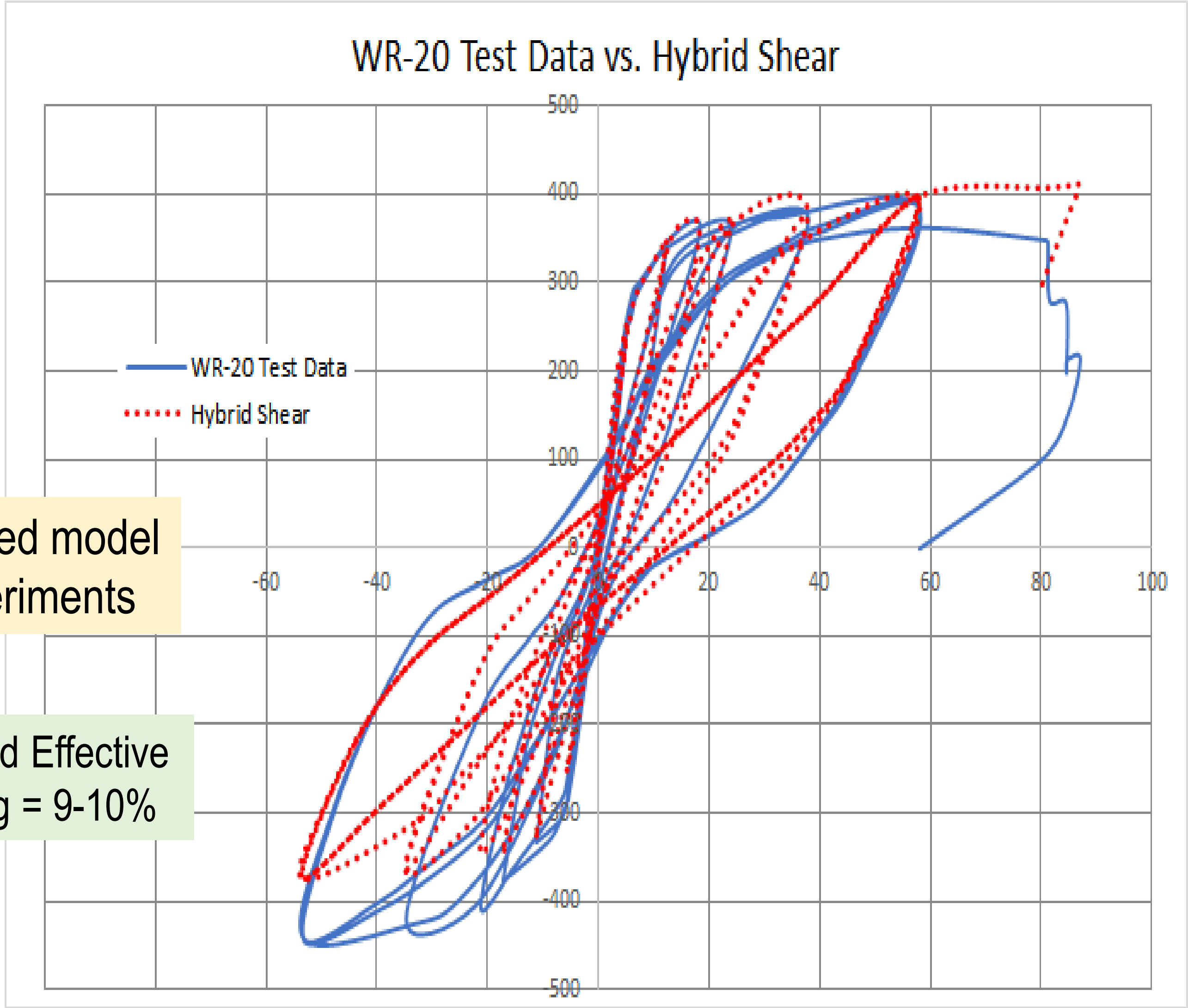
Hybrid Shear Hysteretic Model Against HU Wall Test Data

Hybrid Shear Model (Model 7)

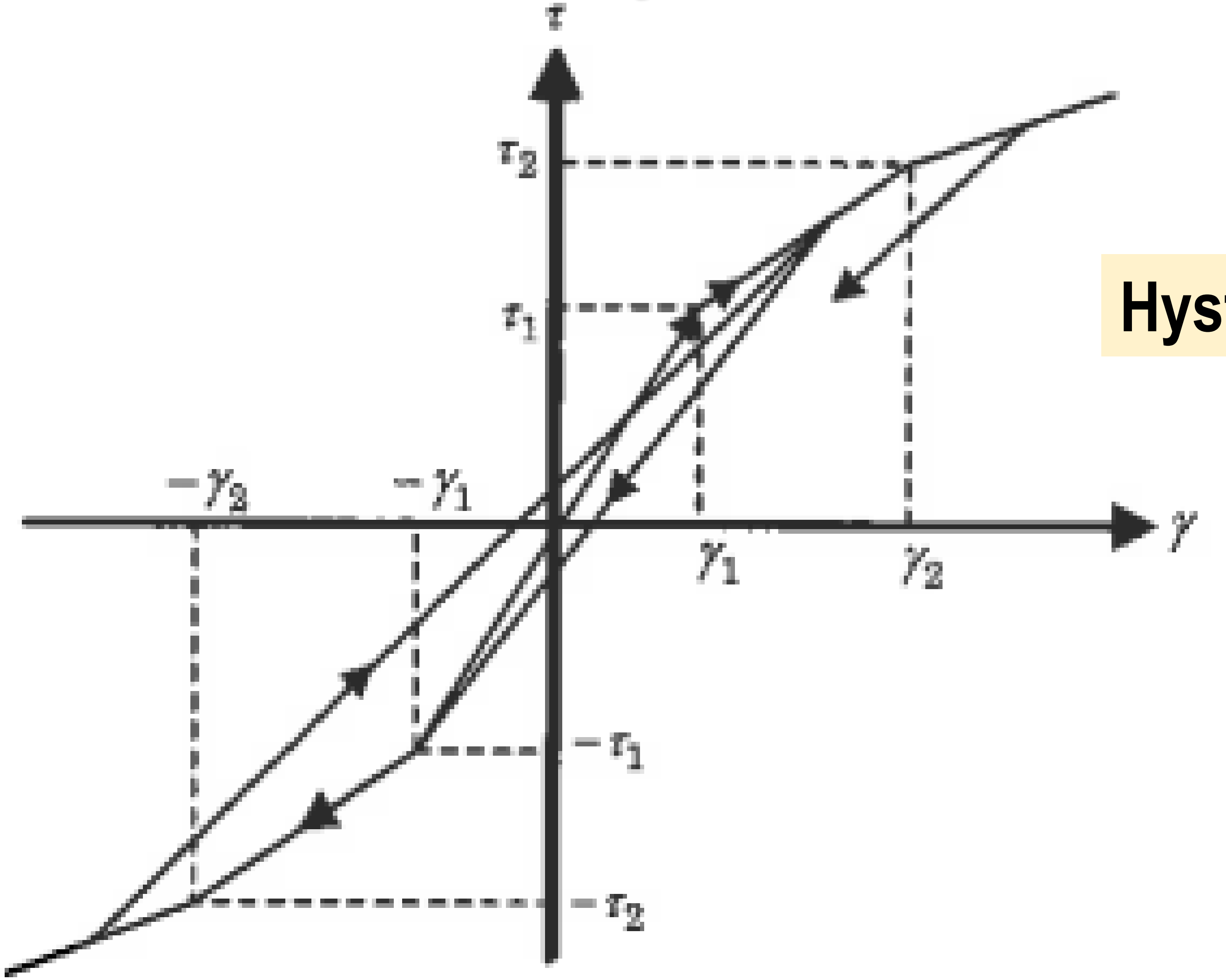


Best fitted model on experiments

Computed Effective Damping = 9-10%

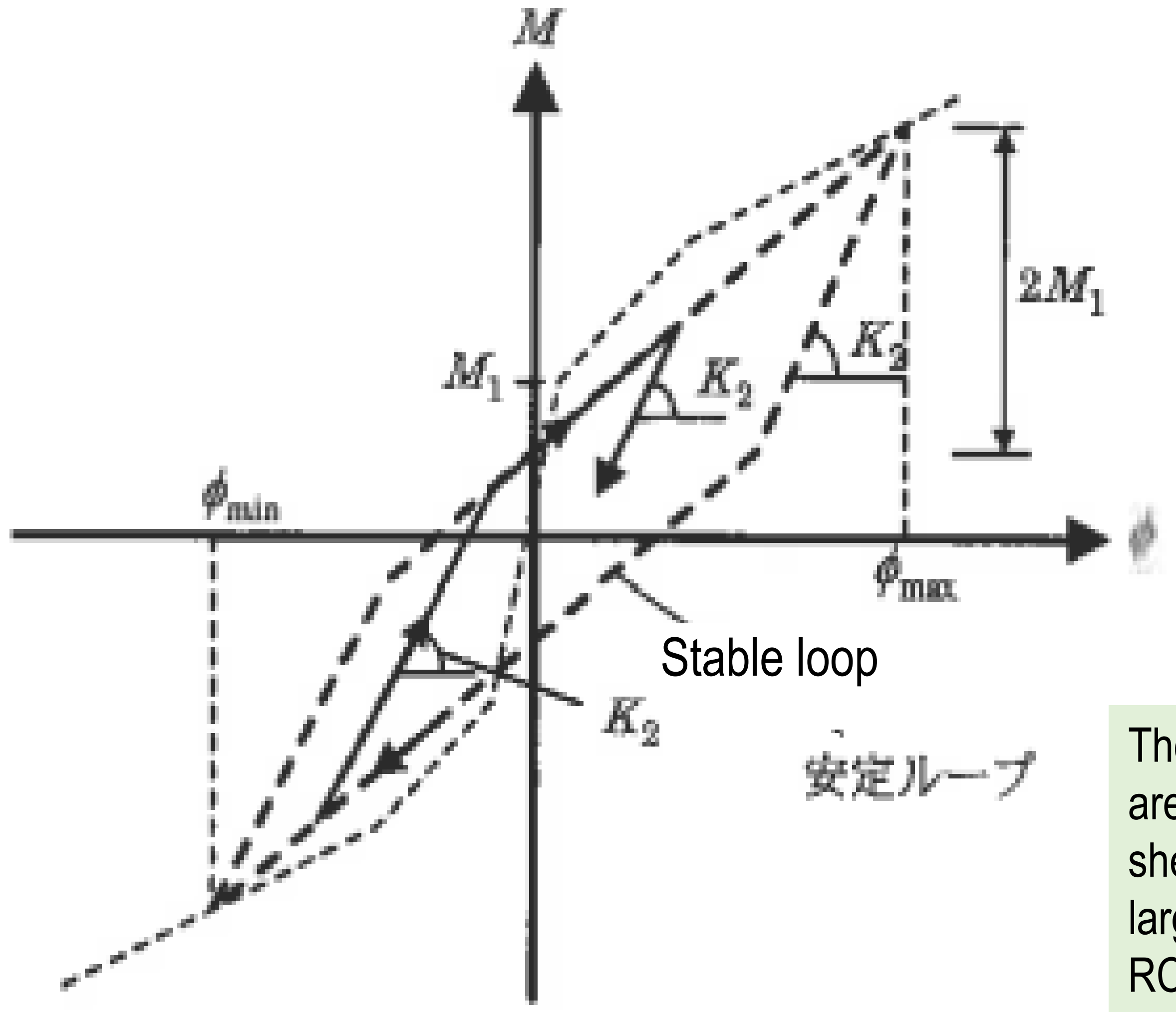


Remarks for JEAC 4601 Point-Oriented (PO) Shear Hysteretic Model

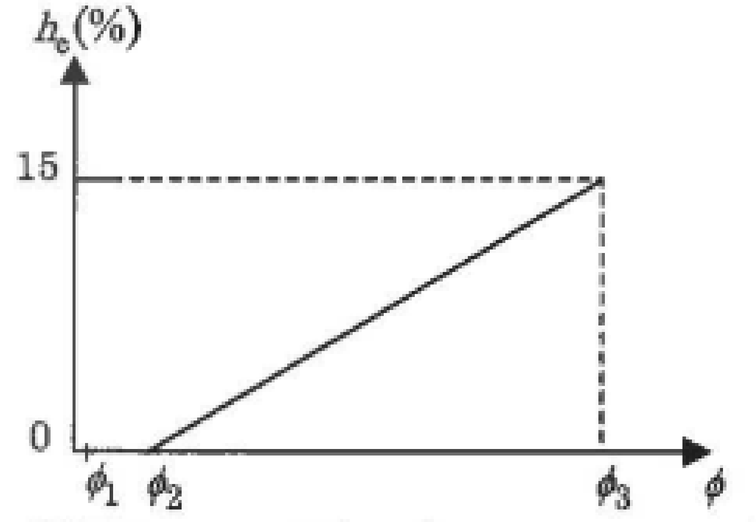


Hysteretic Damping is zero!

Remarks for JEAC 4601 Point-Oriented-Degraded-Trilinear (PODT) Bending Hysteretic Model



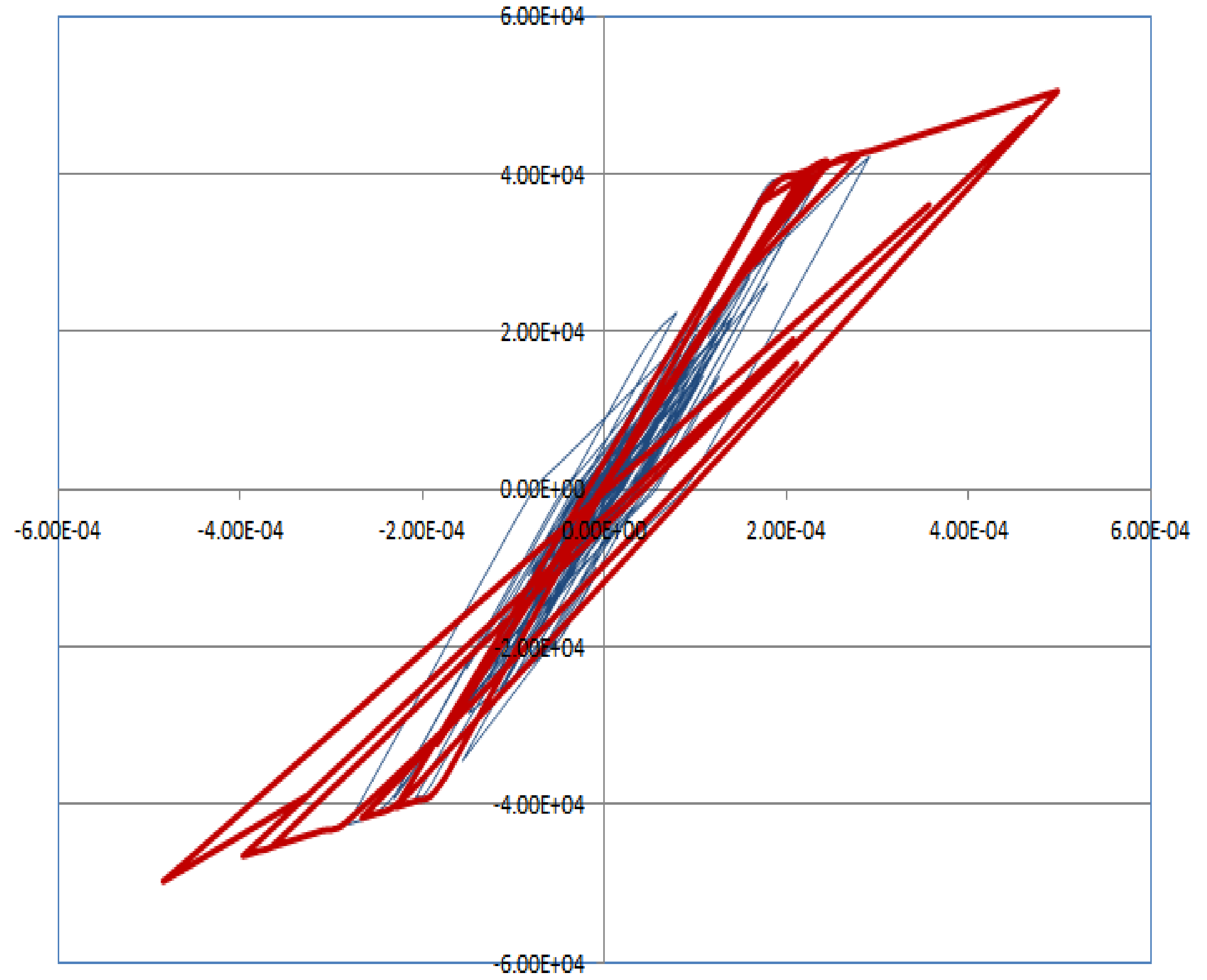
Hysteretic Damping varies from 0% to 15%; 0% at yielding and 15% at failure (ultimate).



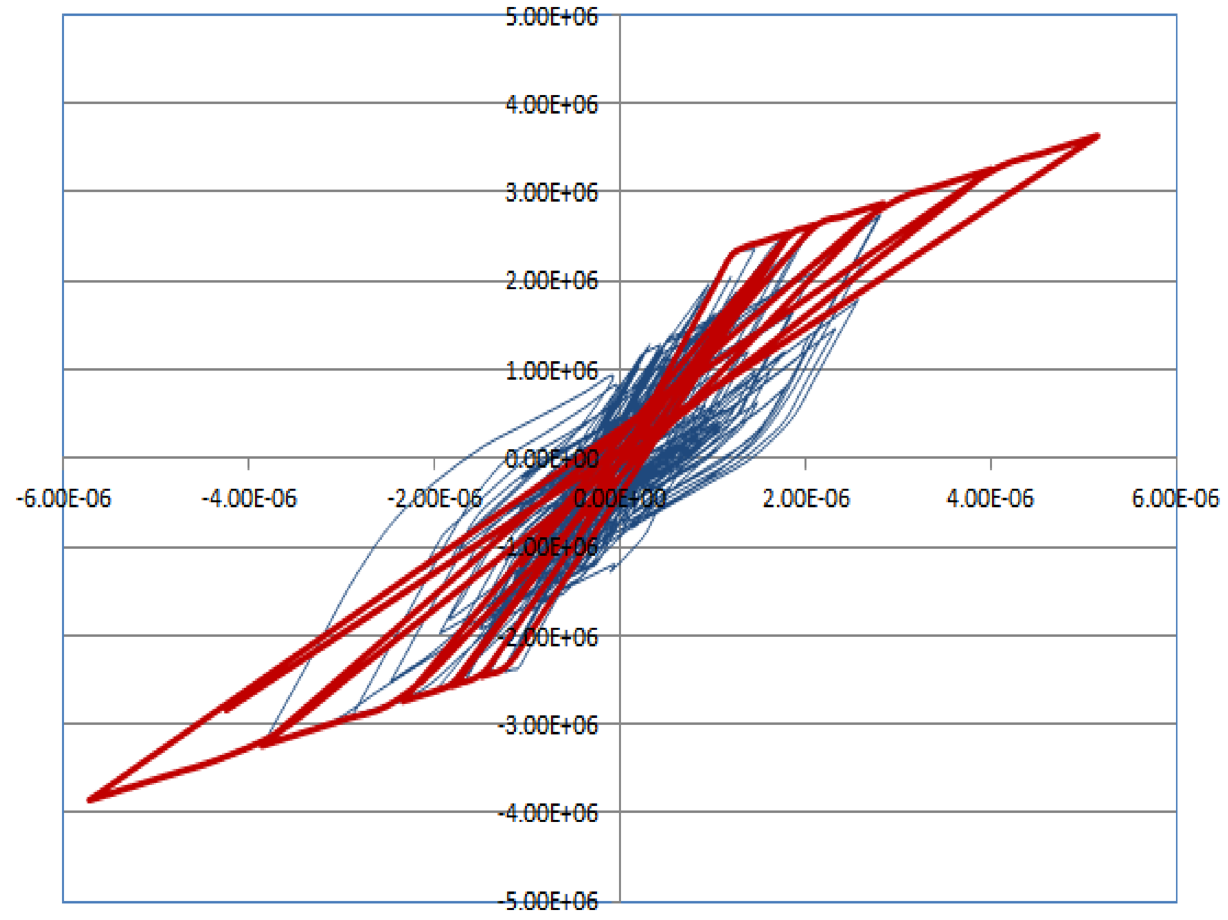
The low hysteretic damping values recommended in the JEAC 4601 are based on a series of experimental tests done for various shearwall configurations and typical NPP structure RC walls with larger thicknesses and reinforcement percentages than those of the RC walls in conventional structures (Taitokui report, 1987). These damping values are lower than those computed using FEA codes.

Comparisons of JEAC and Cheng-Mertz Model Loops Based on Separate Nonlinear SSI Analyses (with Dynamic Effects)

Panel 11 Shear for CMS vs. JEAC PO



Panel 11 Bending for CMB vs. JEAC PODT



3. Modeling of Interaction Between Shear and Bending Effects

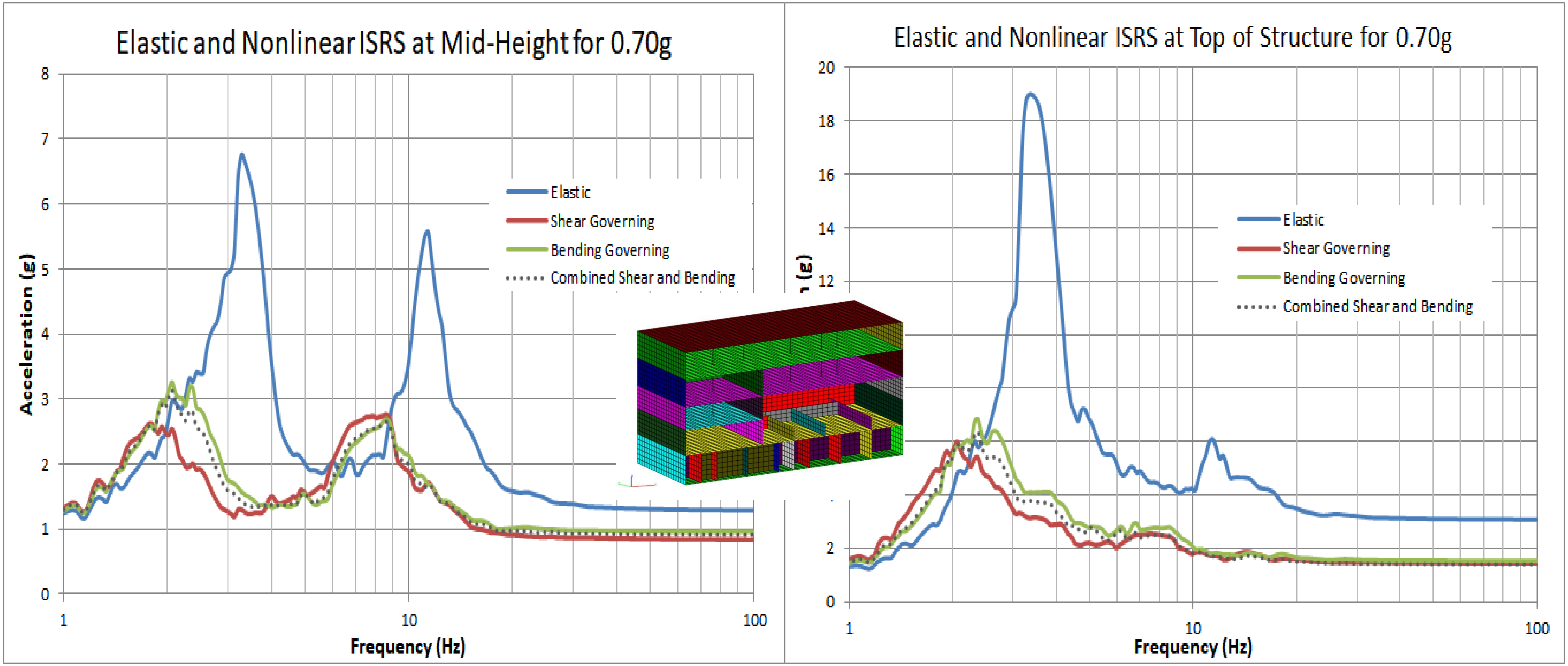
These interaction effects are included at each SSI iteration by the following Option NON options:

1) *Shear Governing:* Assuming that the shear stiffness variations are governing the wall stiffness degradation at each SSI iteration *(RC wall material stiffness degradation based on the Shear hysteretic models only, i.e. material Esb=Es, fully coupled)*

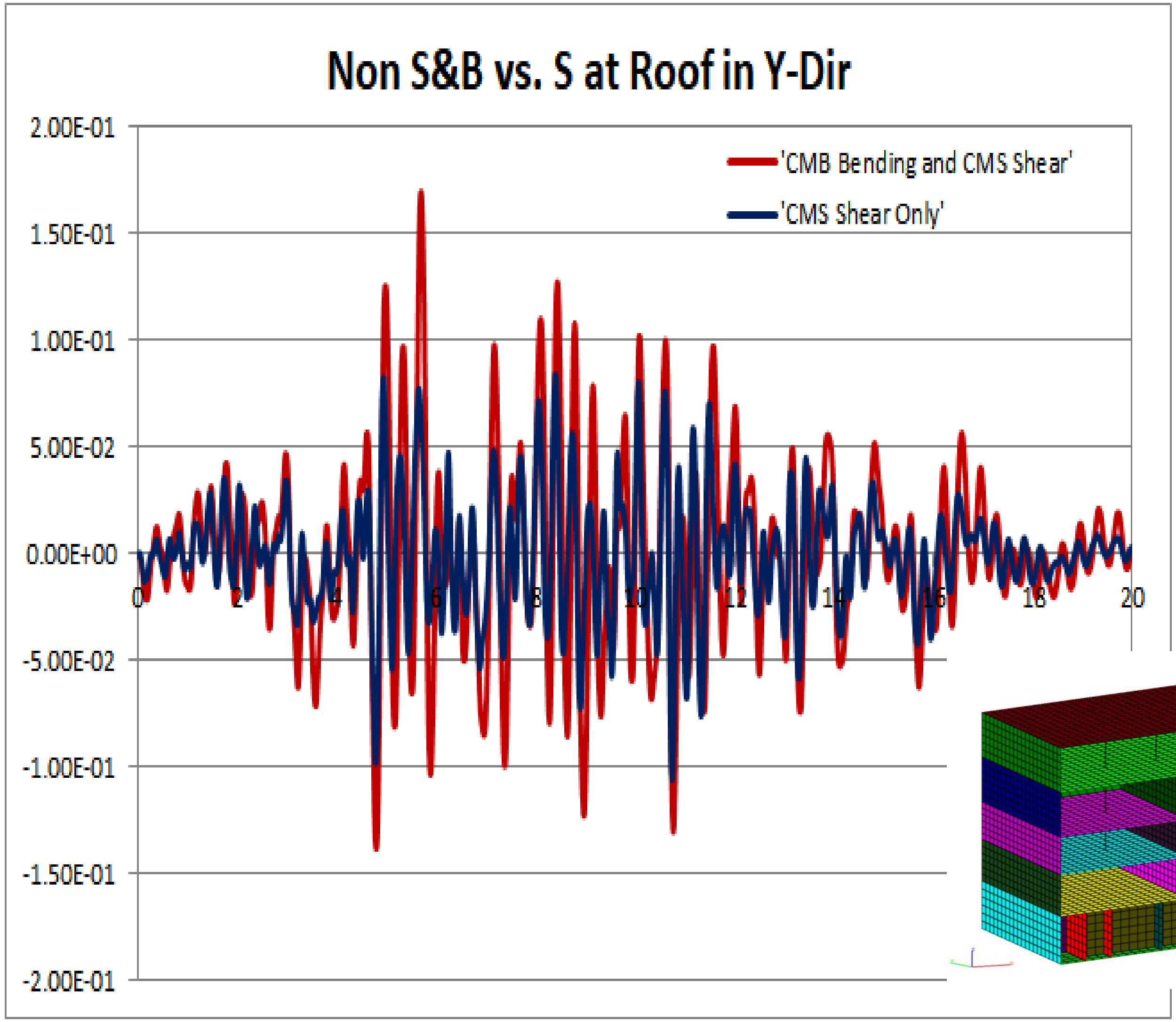
2) *Bending Governing:* Assuming that the bending stiffness variations are governing the wall stiffness at each SSI iteration *(RC wall material stiffness degradation based on the Bending hysteretic models only, i.e. material Esb=Eb, fully coupled)*

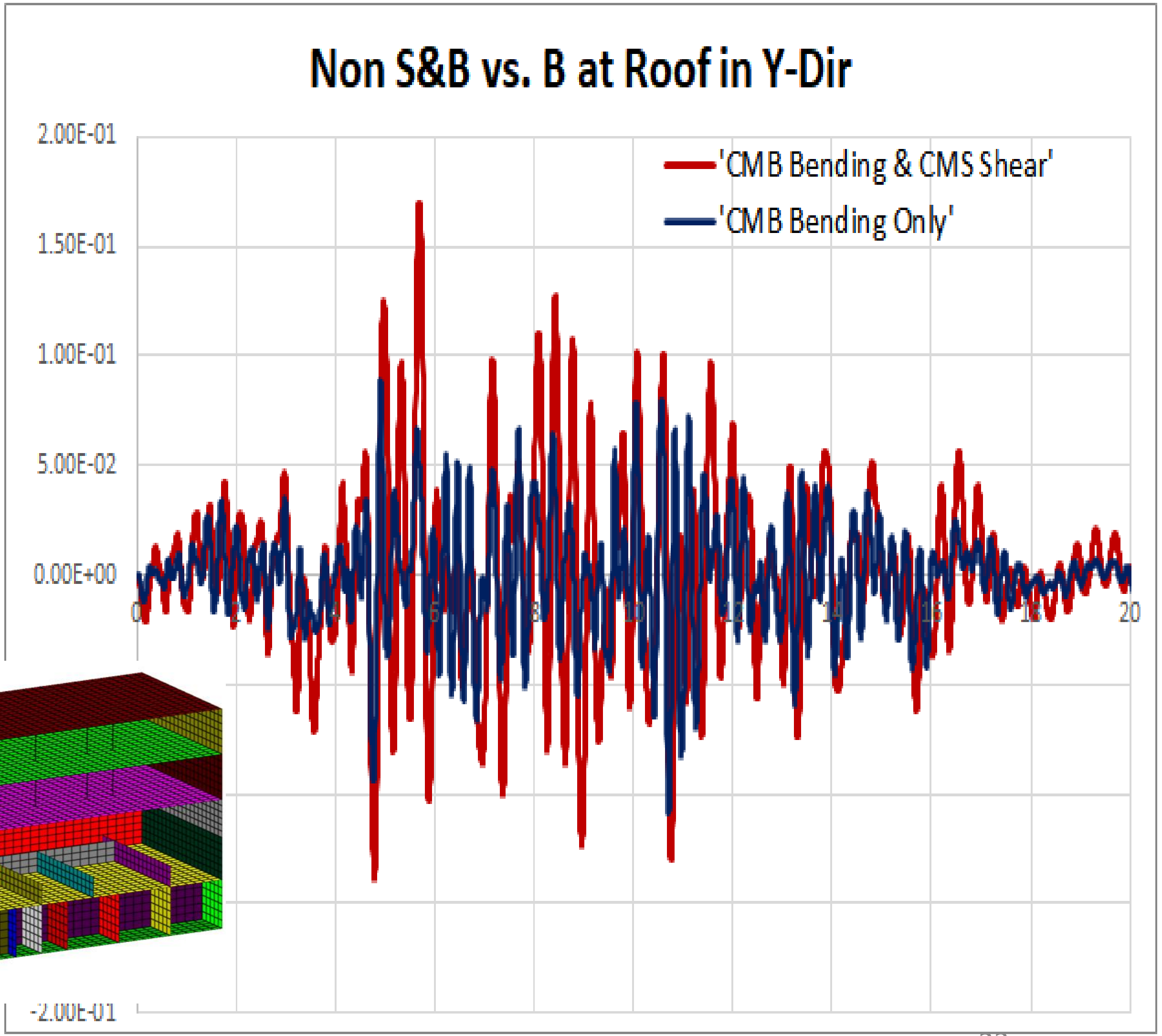
3) *Shear and Bending:* The equivalent bending and shear stiffnesses are computed independently at each SSI iteration *(RC wall material stiffness degradation based on both Shear and Bending hysteretic models, i.e. material Esb is different from Es and Eb). An elliptical interaction curve for combining the shear and bending stiffnesses is applied at each SSI iteration.*

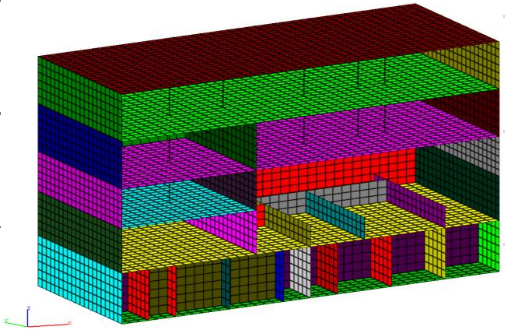
Computed AB ISRS for 0.70g: 1) Shear Governing, 2) Bending Governing and 3) Combined Shear and Bending



Nonlinear AB Structure Displacements for 1) Shear Governing, 2) Bending Governing and 3) Combined Shear and Bending



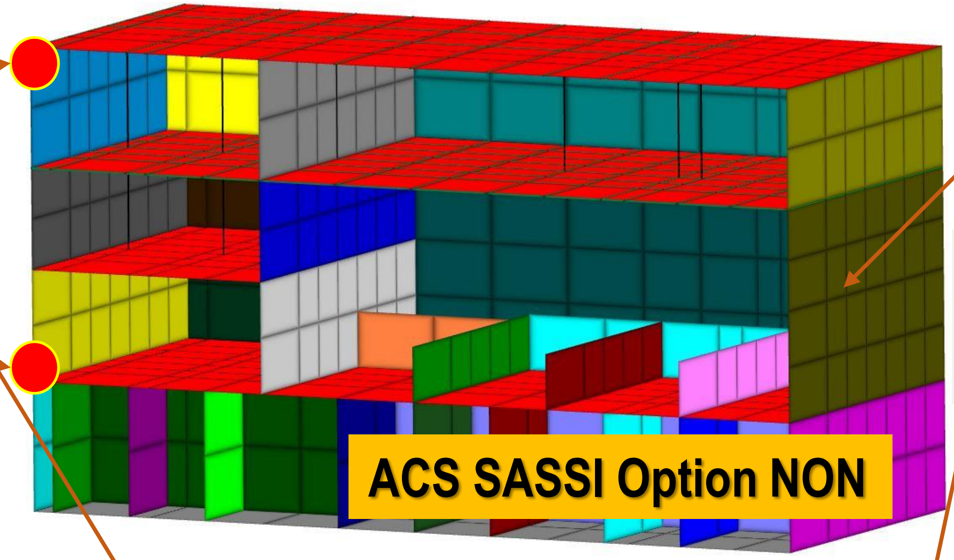




4. Comparative Nonlinear Results Vs. CSI PERFORM3D Code for Low-Rise Shearwall Auxiliary Building (AB)

Node 33

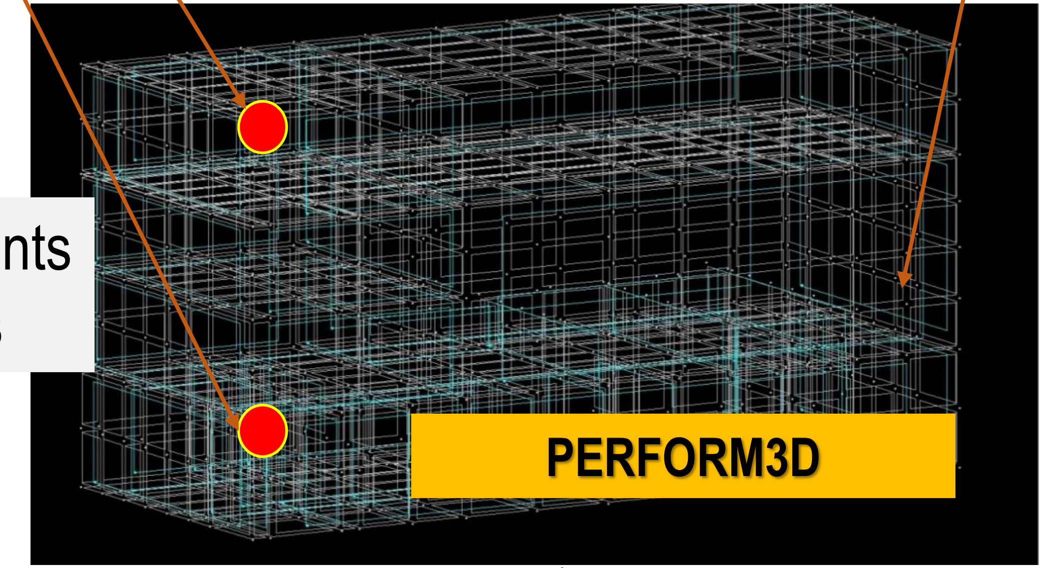
Node 243



Panel 17-Most Damaged

CM Shear Model for Wall Panels

AB is a low-rise building governed by nonlinear shear deformation effects.



Shear Wall Elements for Wall Panels

0.60g RG1.60 Input (2xDBE)

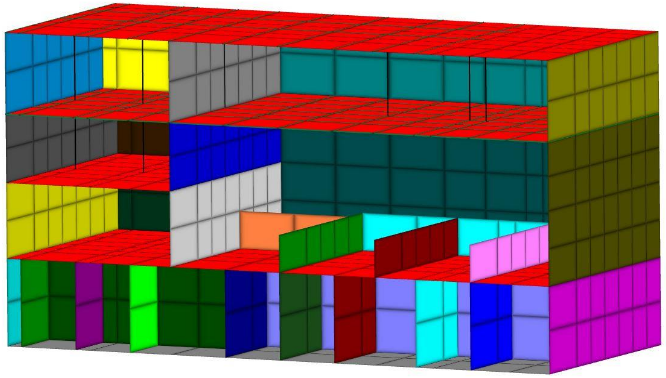
Rigid soil, fixed-base.

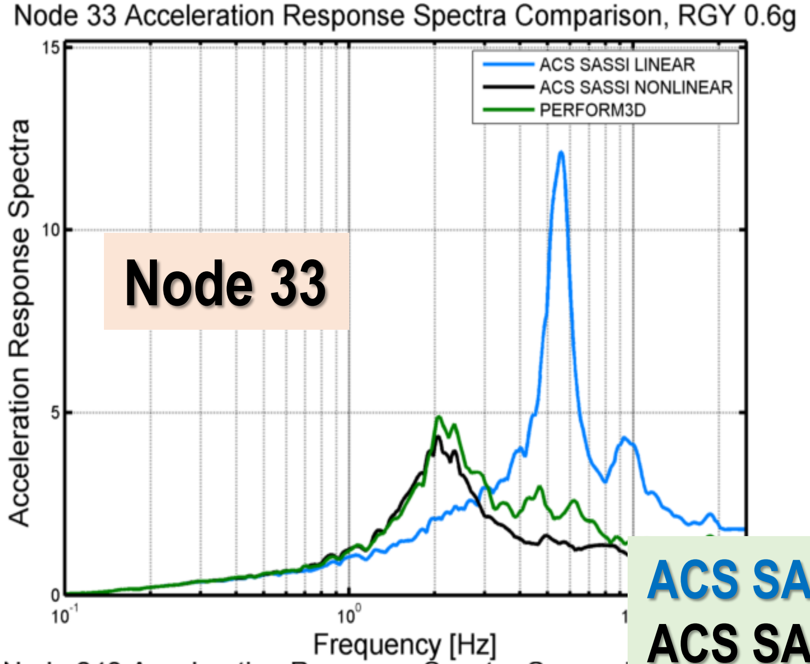
Same BBC for both models.

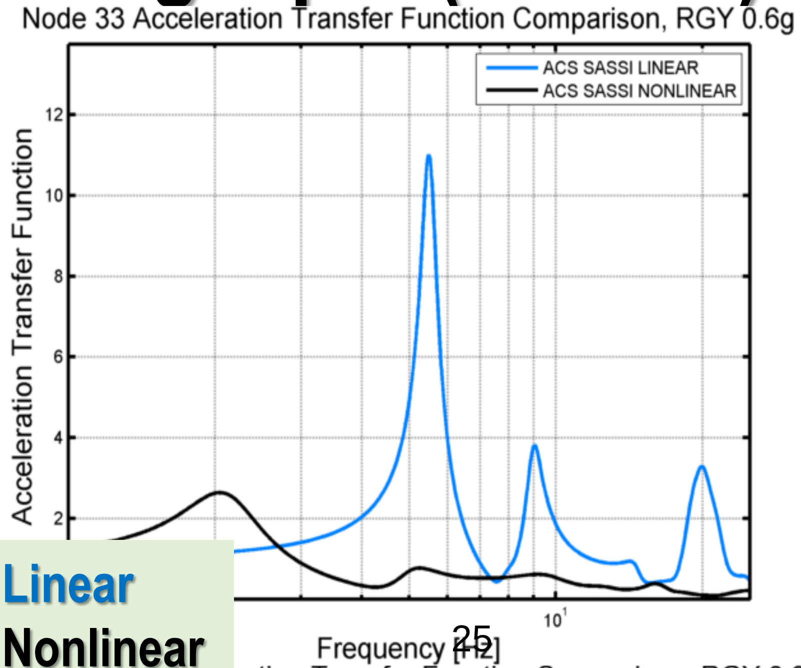
1% reinforcement for all walls

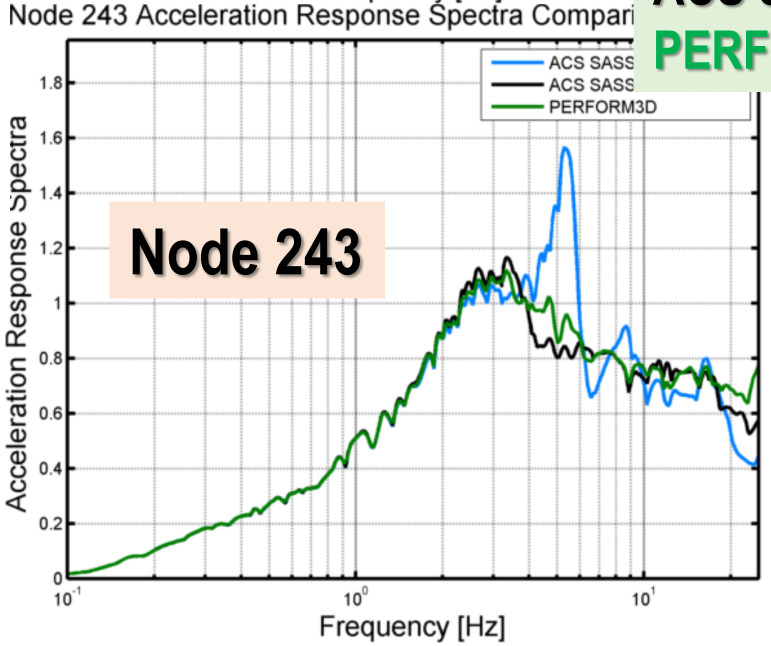
Comparative ISRS and ATF Results for 0.60g Input (2x DBE)

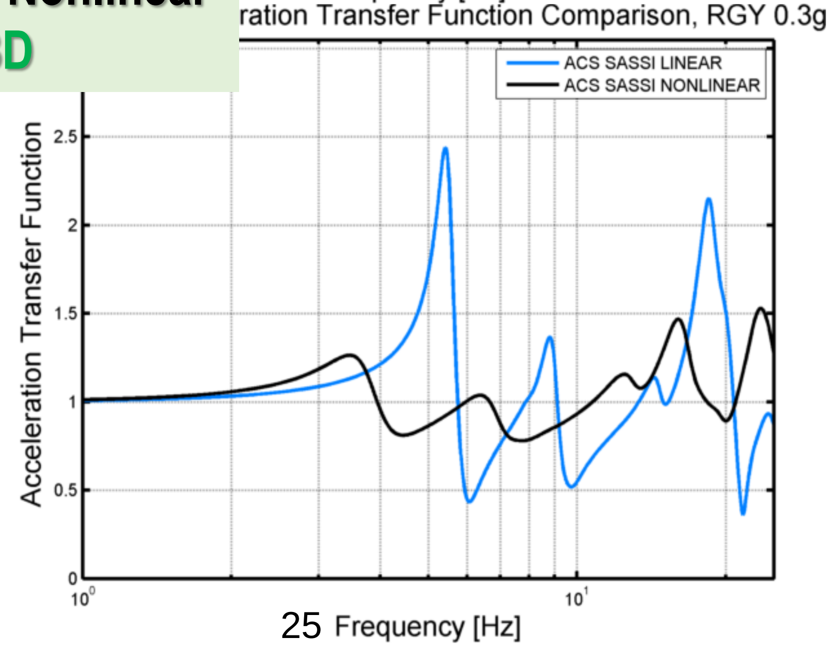
Low-Rise Aux Building (AB)
Include Shear Effects Only







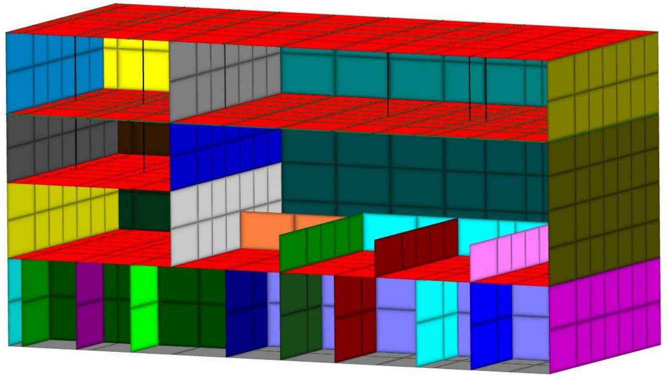


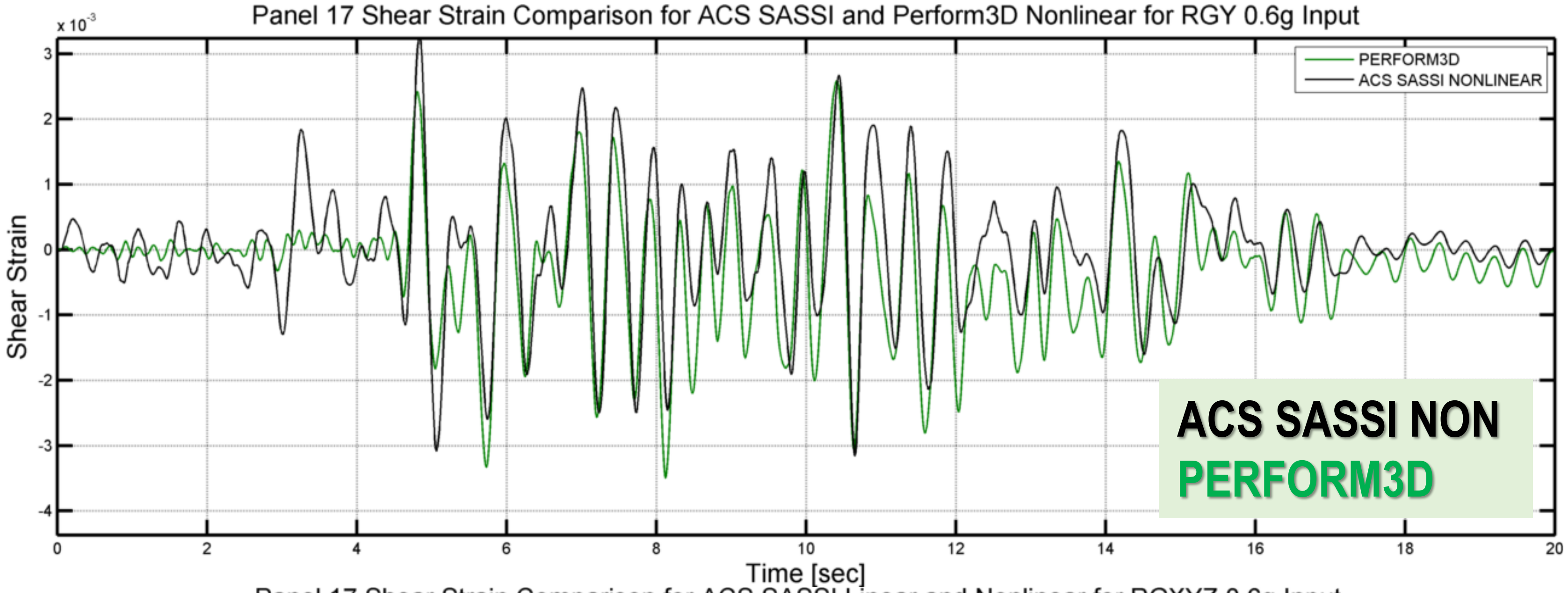


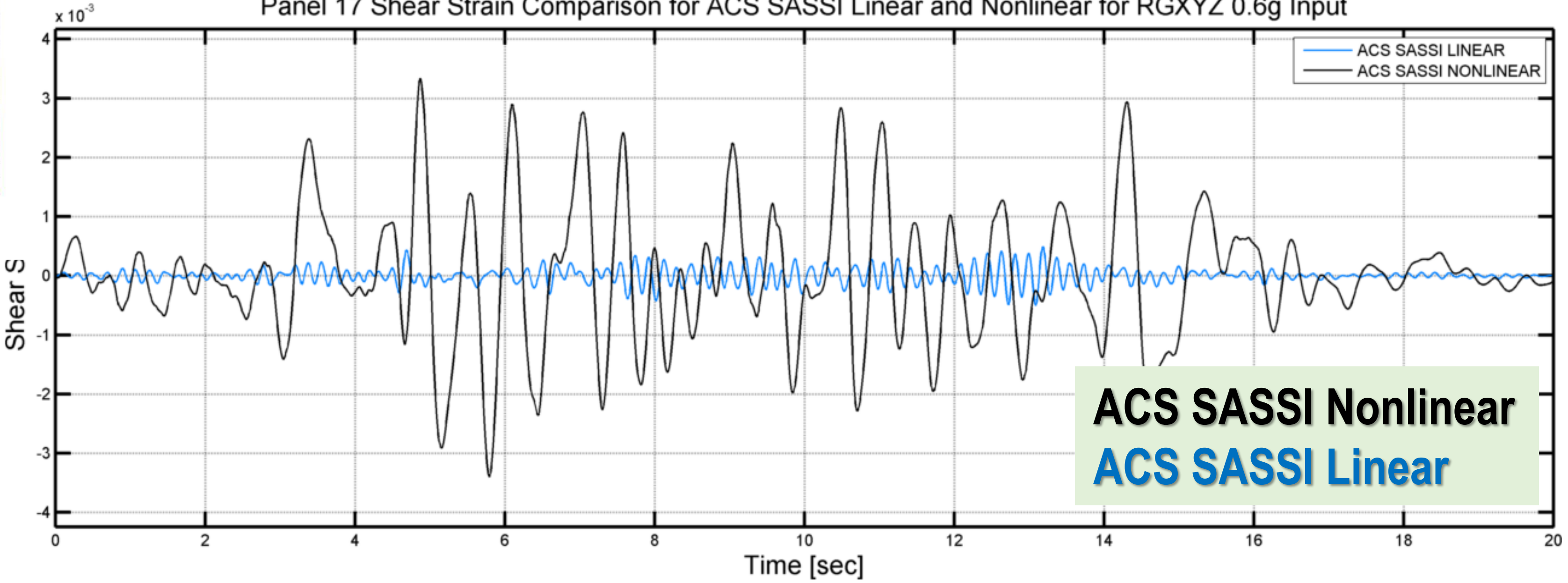
ACS SASSI Linear
ACS SASSI Nonlinear
PERFORM3D

Comparative Nonlinear Shear Strain in Panel 17 for 0.60g (2xDBE)

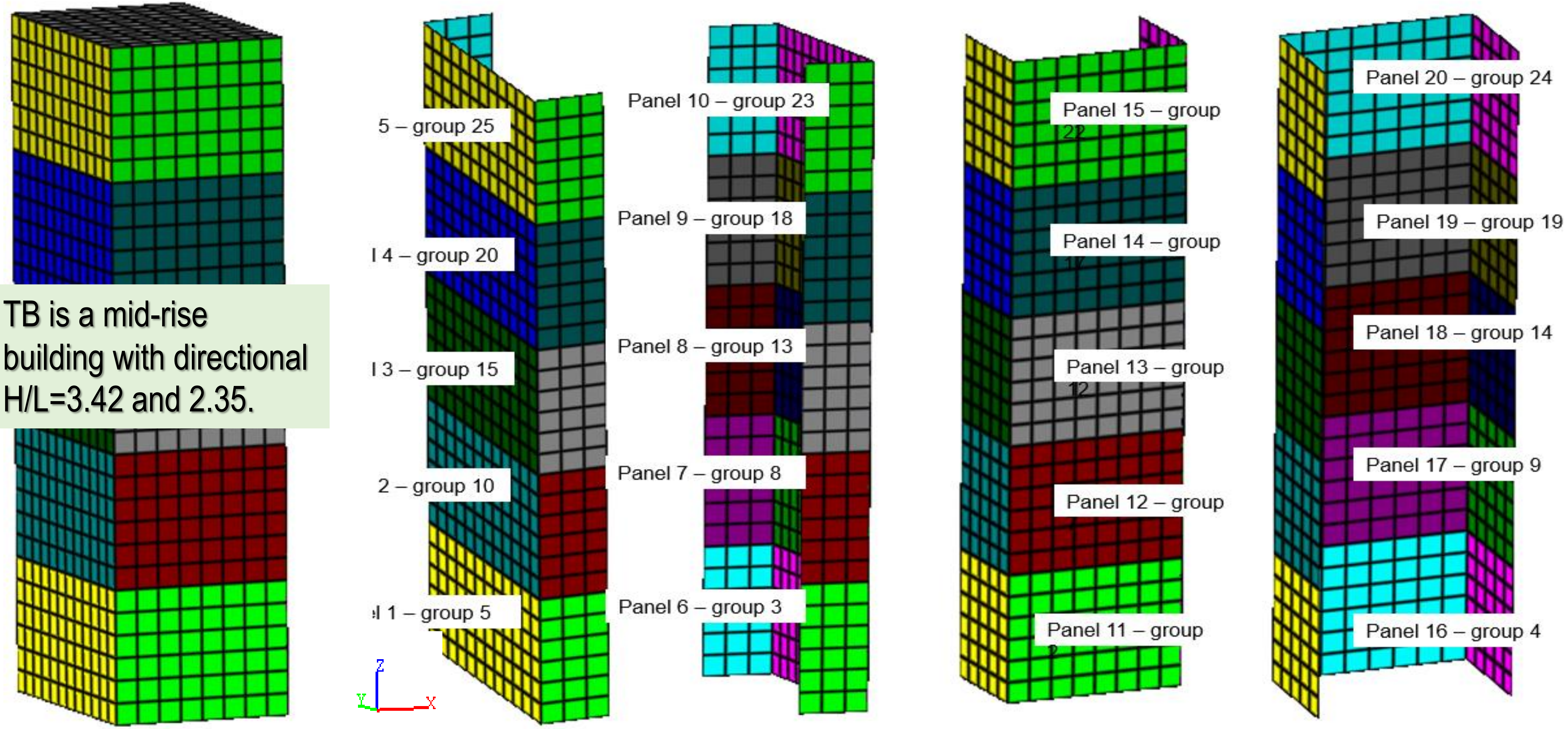
Low-Rise Aux Building (AB)
Include Shear Effects Only







5. Comparative Nonlinear Results Vs. OpenSees Codes for Mid-Rise Shearwall Tower Building (TB)



TB is a mid-rise building with directional H/L=3.42 and 2.35.

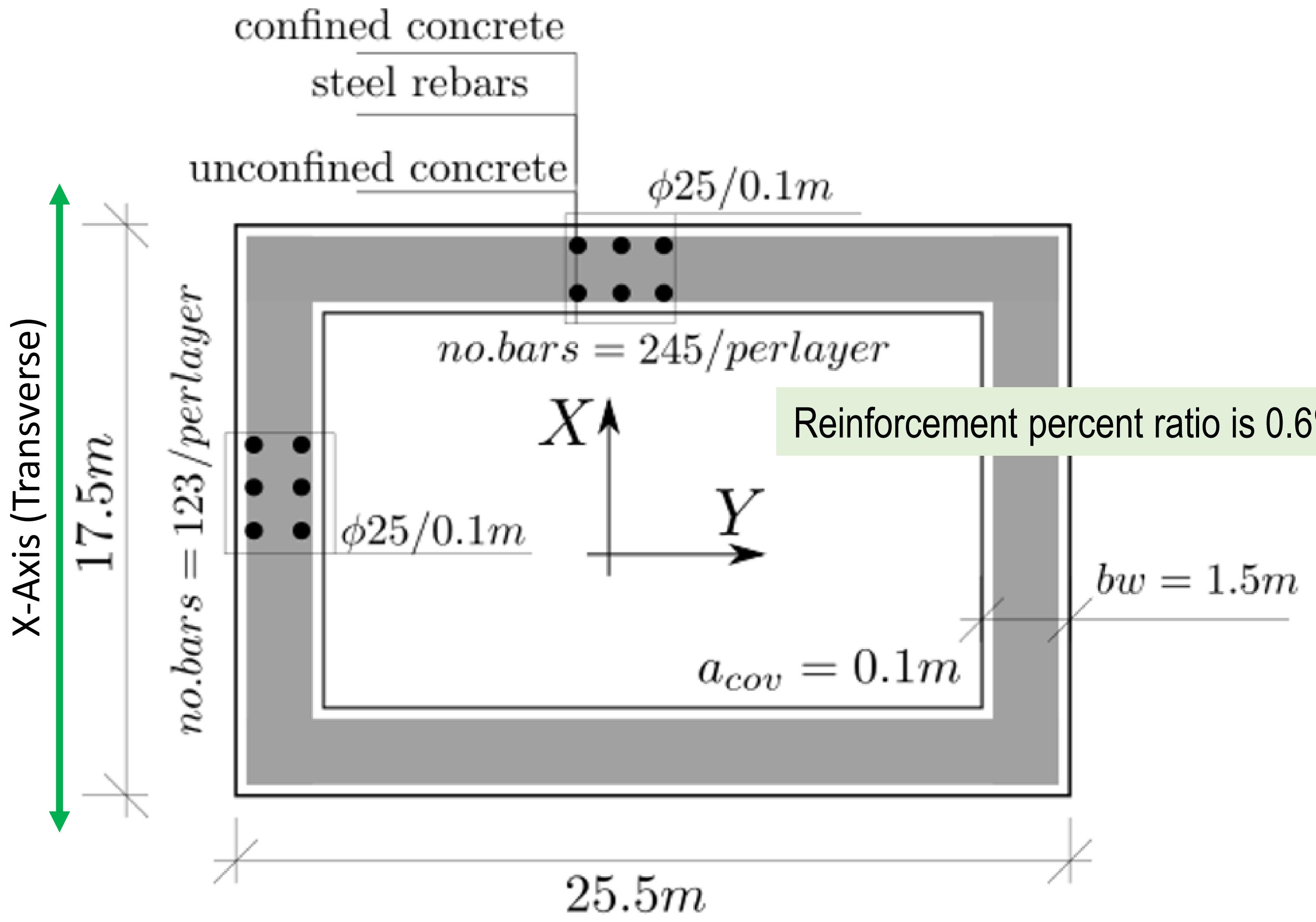
SSI Inputs and RC Wall Section Geometry and Reinforcement

Seismic Input

RG1.60 Spectrum with 0.70g

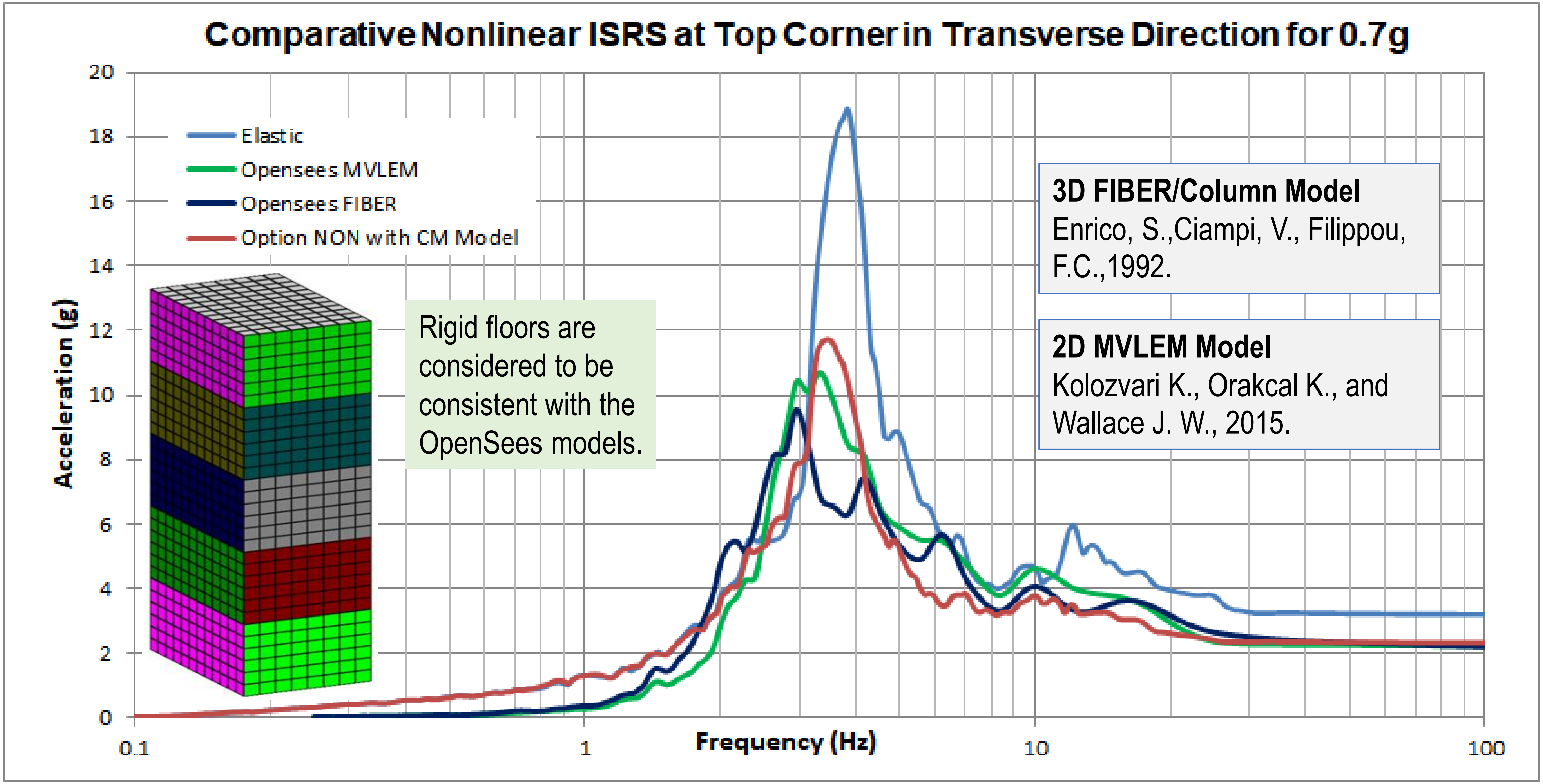
Soil Layering

Uniform hard rock (rigid)



Reinforcement percent ratio is 0.6%

ISRS for Option NON w/ CM vs. OpenSees RC Structure Codes



Rigid floors are considered to be consistent with the OpenSees models.

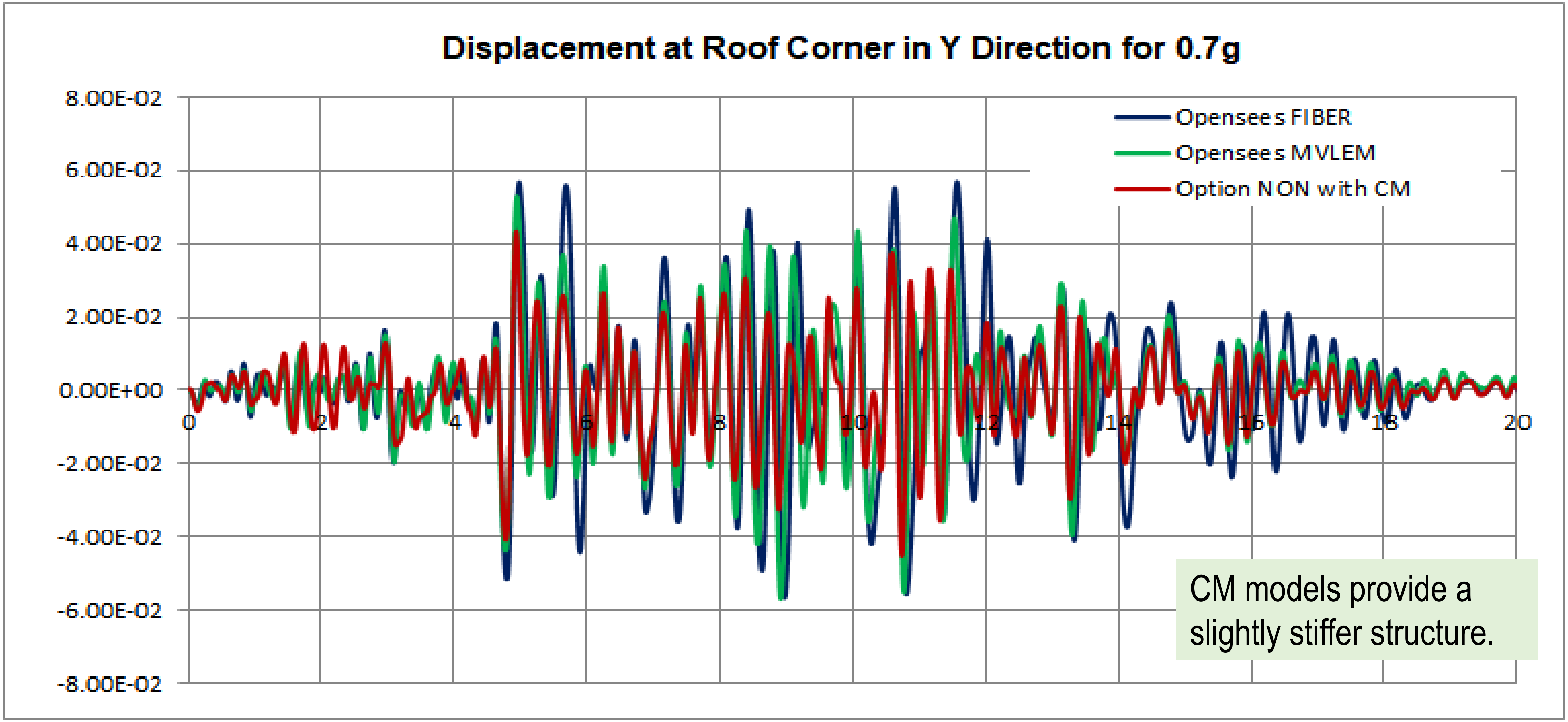
3D FIBER/Column Model
Enrico, S.,Ciampi, V., Filippou, F.C.,1992.

2D MVLEM Model
Kolozvari K., Orakcal K., and Wallace J. W., 2015.

Nonlinear Displacements for Option NON w/ CM vs. OpenSees

X-Dir

Y-Dir



CM models provide a slightly stiffer structure.

End of Part 1

Thank you!

NONLINEAR SEISMIC SSI FOR REINFORCED CONCRETE BUILDINGS IN ACCORDANCE WITH ENGINEERING BEST PRACTICES IN US AND JAPAN

PART 2: Implementation & Application Based on US and Japan Practices

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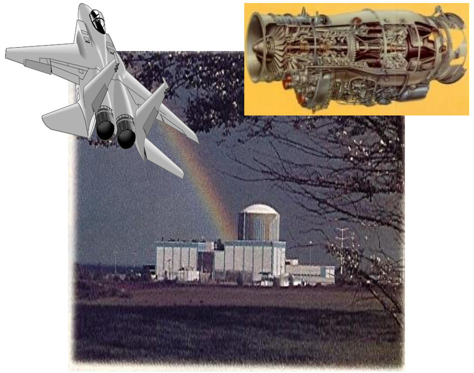


DOE/NRC Natural Phenomena Hazards Meeting

October 20-22, 2020

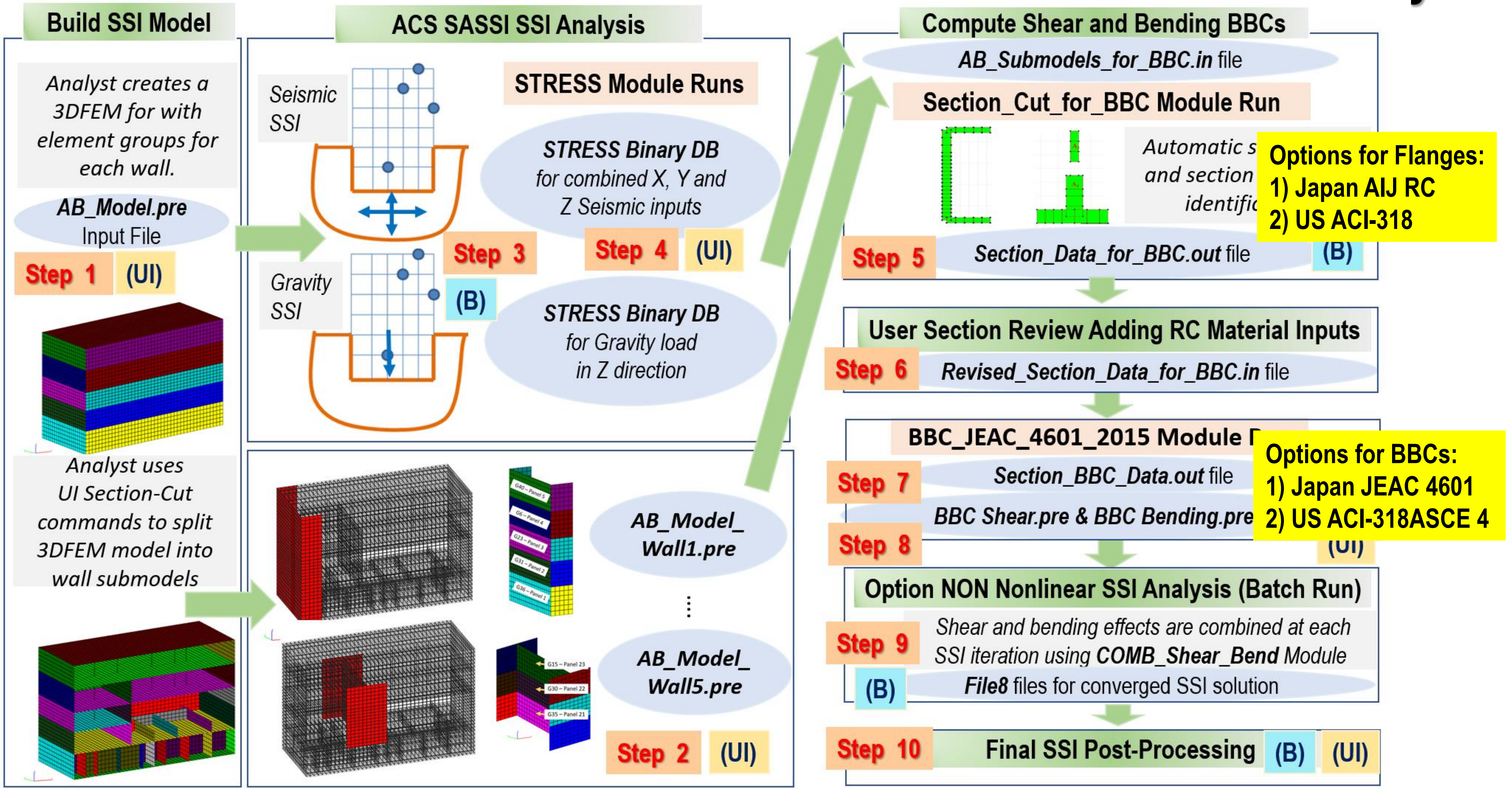
Part 2 Presentation Content

6. ACS SASSI Option NON Implementation for Nonlinear SSI Analysis

7. Comparative TB Nonlinear Results for US and Japan Practices

8. Concluding Remarks

6. ACS SASSI Opt NON Implementation for Nonlinear SSI Analysis



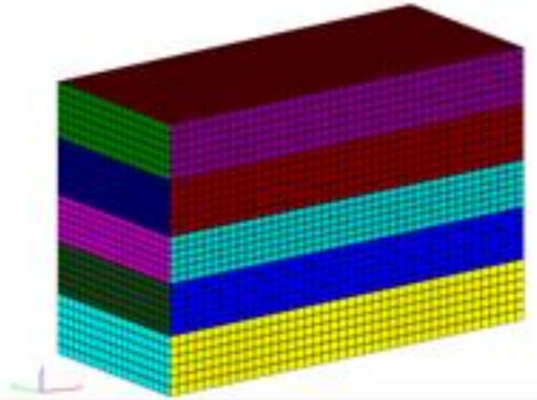
Steps 1-2: Prepare the 3DFEM with Separate Shell Groups for Walls

Build SSI Model

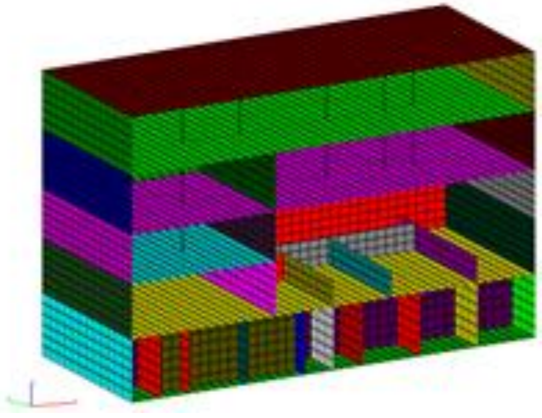
Analyst creates a 3DFEM for with element groups for each wall.

AB_Model.pre
Input File

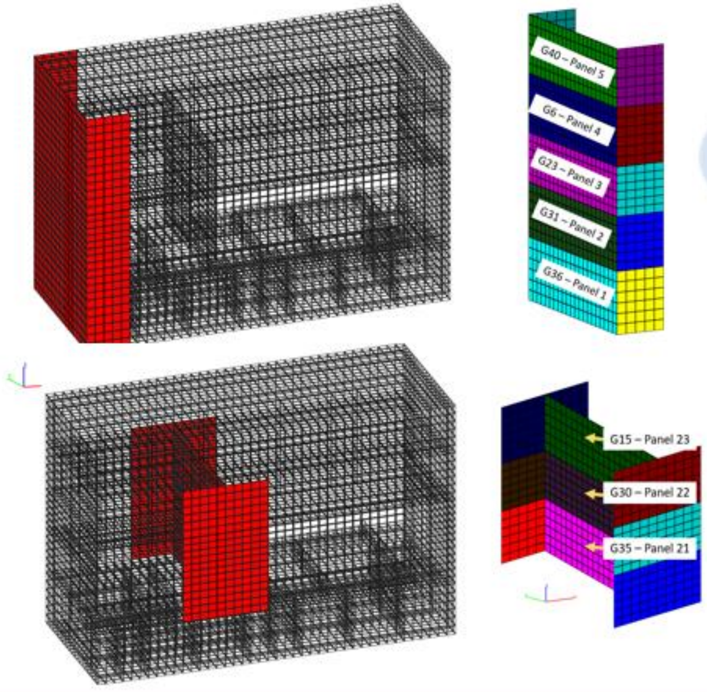
Step 1 (UI)



Analyst uses UI Section-Cut commands to split 3DFEM model into wall submodels



Use ACS SASSI UI Section-cut commands to split the 3DFEM model in Wall submodels (Shell Groups).



AB_Model_ Wall1.pre

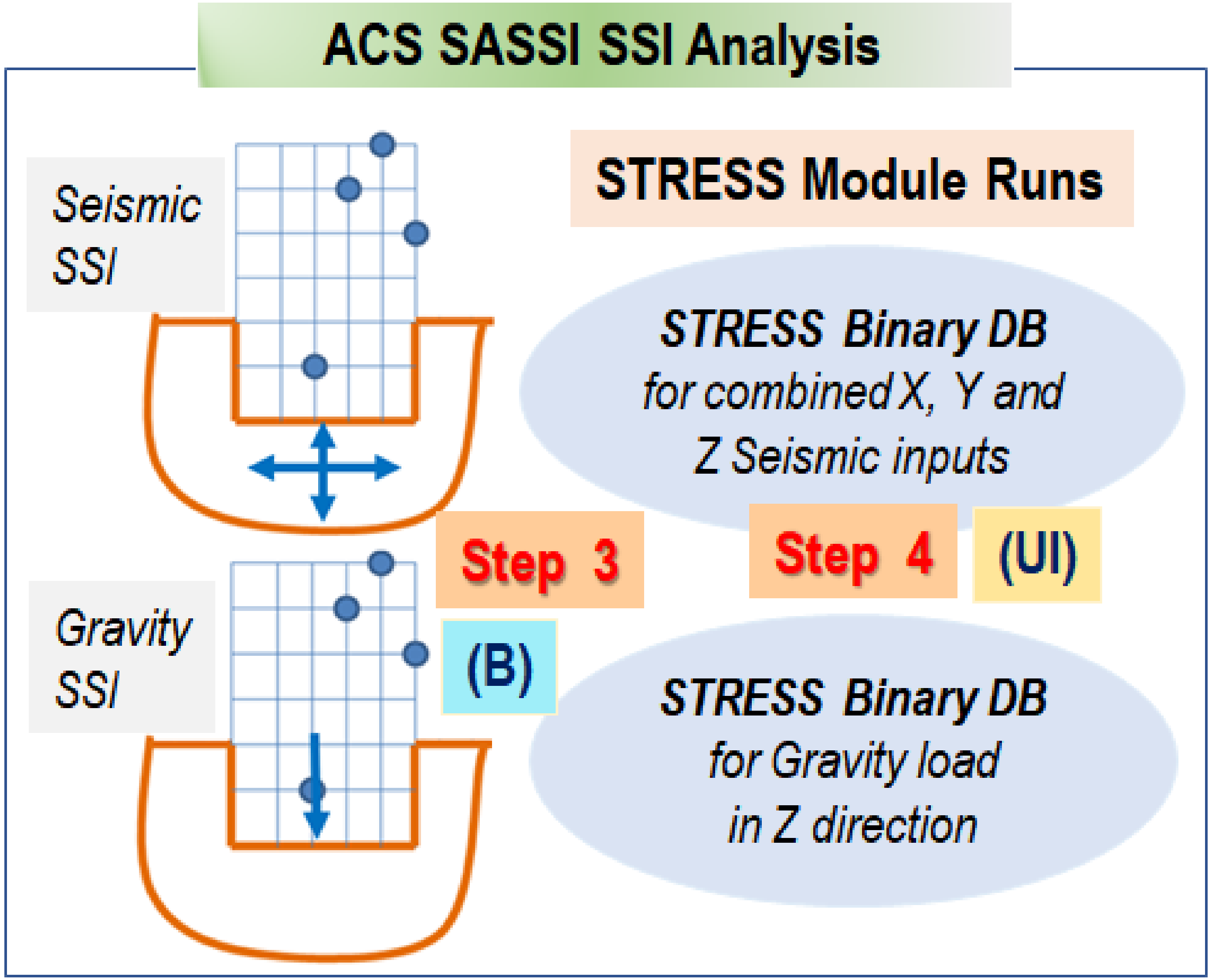
⋮

AB_Model_ Wall5.pre

Step 2 (UI)

The 3DFEM and Wall submodel .pre file are used next to perform automatic section-cuts, section geometry identification for each wall submodel.

Steps 3-4: Perform SSI Analysis for Gravity and Seismic Loads



Step 3:
Perform SSI analysis (Batch)
1) Perform seismic ACS SASSI SSI analysis for the 3DFEM model using "Simultaneous Cases" ANALYS option to get FILE8s for post-processing

Step 4:
STRESS post-processing runs (Batch):
2) Run STRESS for the seismic inputs in X, Y and Z directions and create three binary DB for each input direction.
3) Run STRESS for the gravity (static) load for Z direction and create gravity binary DB

Combine Three Seismic STRESS binary BD (UI):
4) Use COMBTHSDB to combine the seismic binary DBs for X, Y and Z in a single binary DB.

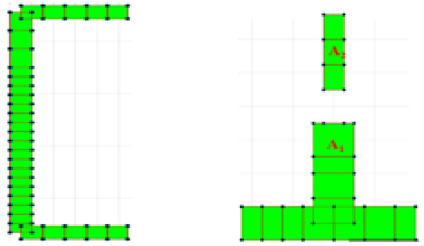
The Gravity and Seismic binary DBs are used in Step 5 for automatic section-cut calculations.

Step 5: Automatic Section Geometry Identification and Section-Cuts at Each Floor Level

Compute Shear and Bending BBCs

AB_Submodels_for_BBC.in file

Section_Cut_for_BBC Module Run



Automatic section-cut and section geometry identification

Step 5

Section_Data_for_BBC.out file

(B)

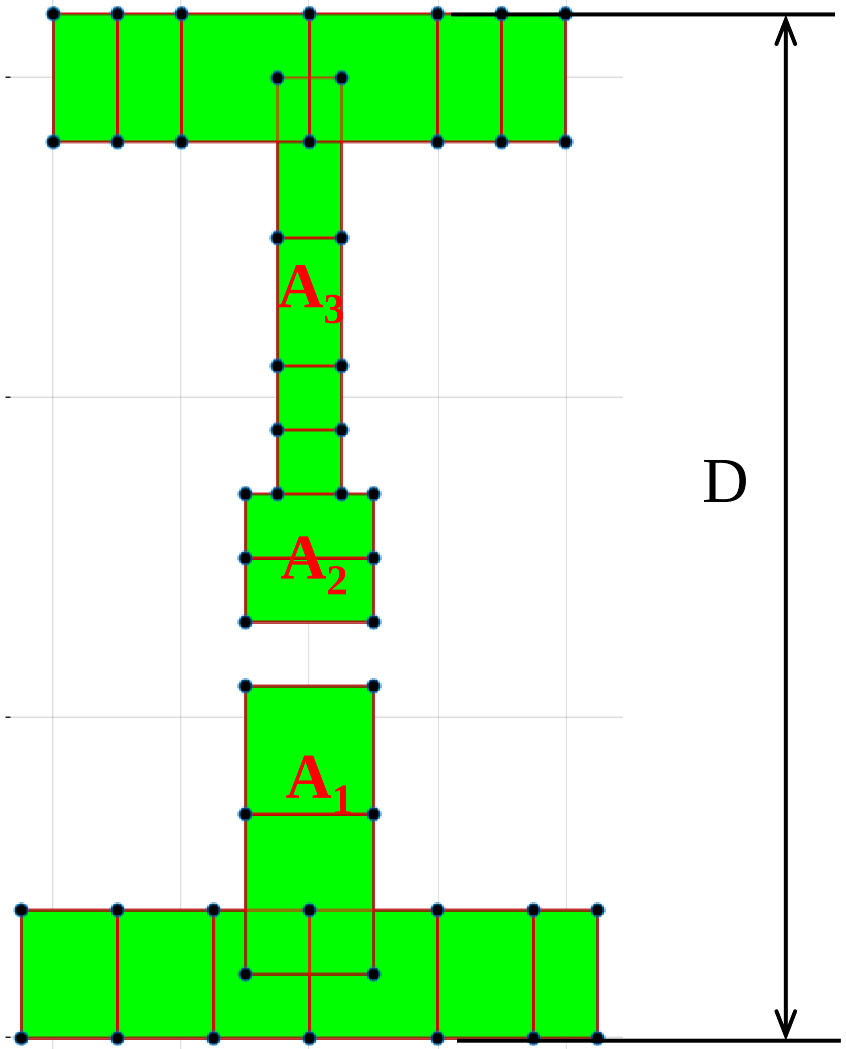
Step 5:

Section_Cut_for_BBC **Module_runs (Batch):**
This module performs automatic section-cuts and identify the section geometries for all floor levels.

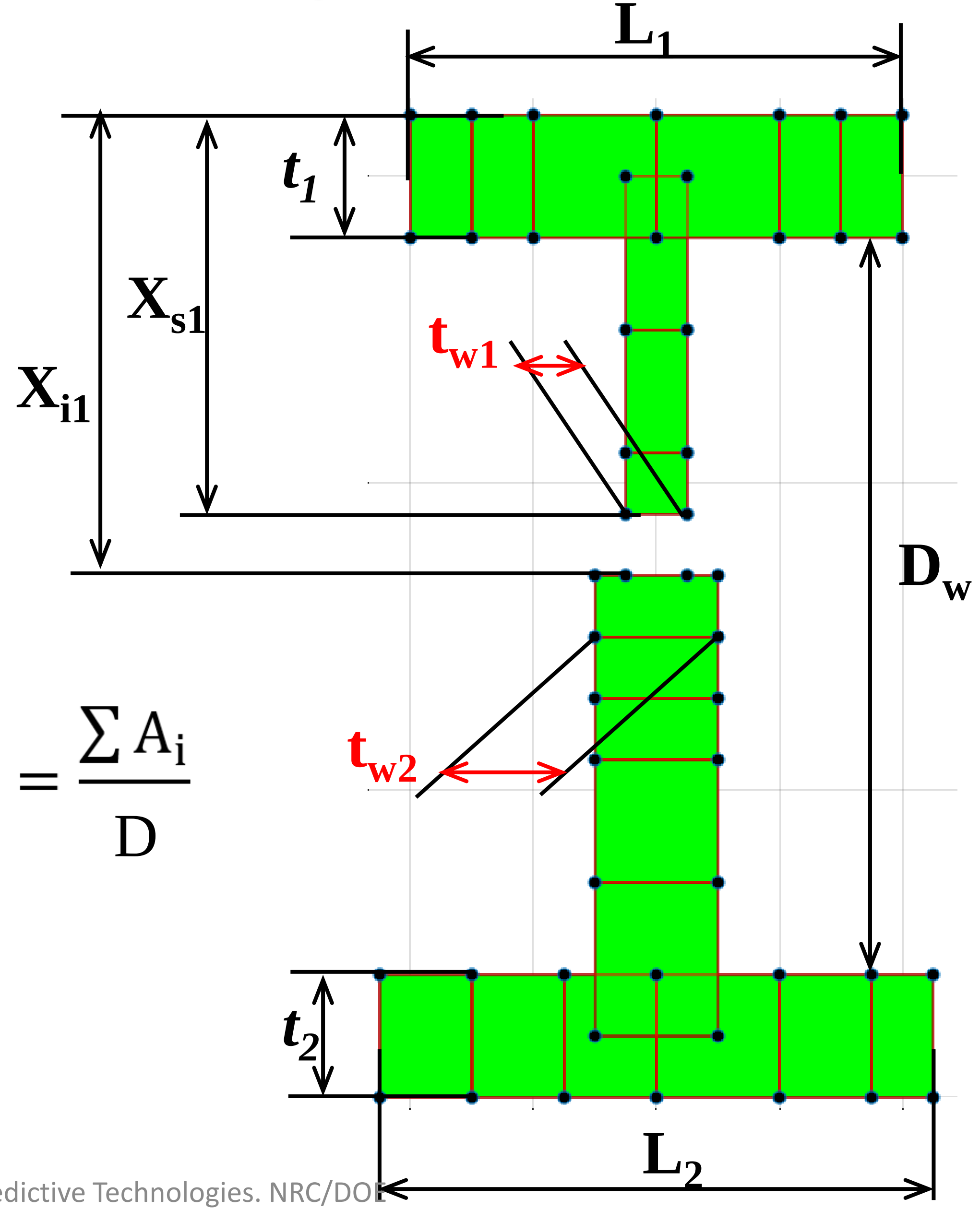
Output files:
The *Section_Data_for_BBC.out* output file produced by the run includes section-cut forces and geometry to be reviewed by the user in Step 6.

The *Modelname_Section_Data.out* as the general output file with input data and section geometry results.
The *Modelname_Section_Data.txt* , *output* file with the section data and other input data for next step

Examples of Section Geometry Identification



$$t_{eq} = \frac{\sum A_i}{D}$$



Step 6: Analyst Review of *Section_Data* Files To Prepare Nonlinear Input

User Section Review Adding RC Material Inputs

Step 6 *Revised_Section_Data_for_BBC.in* file

Step 6:

Analyst shall edit the *Section_Data_for_BBC.out* file for checking the automatic generated section-cut geometries (web and effective flanges sizes including floor openings effects). The analyst can modify section parameters based on engineering judgements and need to input concrete and steel nonlinear material parameters. Analyst should save the revised file as *Revised_Section_Data_for_BBC.in* file. This file is used as an input of Step 7.

Section data are provided in international units (kN and m)

Section_Data_for_BBC.out (Step 5)

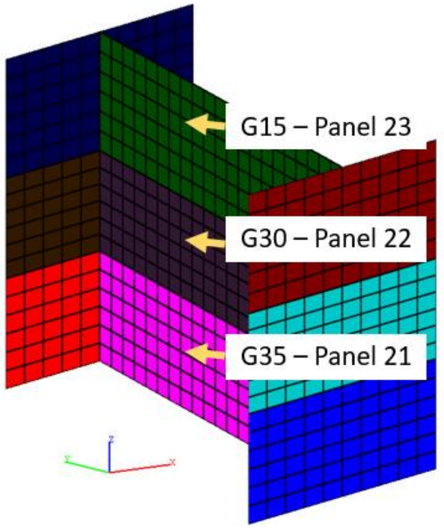
```
5
-8.0264      0.0000      16.764
 1
 0.949395E+05  0.336417E+07  0.153516E+06
-3.3650   7.9827   1.5240   7.9827   1.5240   24.079   1.5240   5.0674   5.0674
 0
0.0000     0.0000     0.0000     0.0000
 0.248546E+08  0.106216E+08  0.0000E+00  0.0000E+00  0.000000E+00  0.000000E+00  0.0000E+00
 2
 0.964498E+05  0.223449E+07  0.193119E+06
4.7488   7.9827   1.5240   7.9827   1.5240   24.079   1.5240   7.3088   7.3088
 0
0.0000     0.0000     0.0000     0.0000
 0.248546E+08  0.106216E+08  0.0000E+00  0.0000E+00  0.000000E+00  0.000000E+00  0.0000E+00
```

Revised_Section_Data_for_BBC. in (Step 6)

```
5
-8.0264      0.0000      16.764
 1
 0.949395E+05  0.336417E+07  0.153516E+06
-3.3650   7.9827   1.5240   7.9827   1.5240   24.079   1.5240   5.0674   5.0674
 0
1.1950     1.5980     1.2460     0.95300
 0.248546E+08  0.330000E+05  0.2000E-02  0.4000E-02  0.205000E+09  0.345000E+06  0.1850E-02
 2
 0.964498E+05  0.223449E+07  0.193119E+06
4.7488   7.9827   1.5240   7.9827   1.5240   24.079   1.5240   7.3088   7.3088
 0
1.1950     1.5980     1.2460     0.95300
 0.248546E+08  0.330000E+05  0.2000E-02  0.4000E-02  0.205000E+09  0.345000E+06  0.1850E-02
```

Section_Data_for_BBC.out File from *Section_Cuts_for_BBC Module* (Step5)

Example for Wall 5 Submodel with 3 Floors (and Sections)




```
3
-8.0264     16.764     40.843
1
  0.264106E+05   0.409823E+06   0.404182E+05
  4.7488     14.441     1.5240     14.441     1.5240     24.079     1.5240     13.801     13.801
  0
  0.0000     0.0000     0.0000     0.0000
  0.248546E+08   0.106216E+08   0.00E+00   0.00E+00   0.000E+00   0.000E+00   0.00E+00  0.00E+00
2
  0.228232E+05   0.188437E+06   0.358970E+05
 11.924     14.441     1.5240     14.441     1.5240     24.079     1.5240     17.650     17.650
  0
  0.0000     0.0000     0.0000     0.0000
  0.248546E+08   0.106216E+08   0.00E+00   0.00E+00   0.000E+00   0.000E+00   0.00E+00  0.00E+00
3
  0.124042E+05   0.371685E+05   0.215392E+05
 19.391     14.441     1.5240     14.441     1.5240     24.079     1.5240     20.946     20.946
  0
  0.0000     0.0000     0.0000     0.0000
  0.248546E+08   0.106216E+08   0.00E+00   0.00E+00   0.000E+00   0.000E+00   0.00E+00  0.00E+00
```

Automatic Section Cut results for N, M and V

Automatic Section Data

Concrete and steel material parameters, reinforcement ratios. To be completed by analyst after reviewing section geometries.

Revised_Section_Data_for_BBC.in File Data Description

Line 6: NOPN, X0S, X0I, Z0S, Z0I, X1S, X1I, Z1S, Z1I (Openings explicitly defined) where
NOPEN = Total number of openings of the wall
X0S, X1S, … = Superior X coordinates at the top of each wall panel opening
X0I, X1I, … = Inferior X coordinates at the bottom of each wall panel opening
Z0S, Z1S, … = Superior Z coordinates at the top of each wall panel opening
Z0I, Z1I , … = Inferior Z coordinates at the bottom of each wall panel opening

Line 7: PVf1, PVf2, PVw, PHw (Wall Reinforcement Percentage)
PVf1 = Reinforcement percentage for Flange 1 (top)
PVf2 = Reinforcement percentage for Flange 2 (bottom)
PVw = Reinforcement percentage for Web (vertical)
PHw = Reinforcement percentage for Web (horizontal)

Line 8: Ec, Fc, Epsc_y, Epsc_u, Es, Fs, Epss_y, Epss_u
Ec = Concrete E modulus
Fc = Concrete Fc strength
Epsc_y = Concrete Yielding strain
Epsc_u = Concrete Ultimate strain
Es – Steel E modulus
Fs – Steel Fy yielding
Epss_y – Steel Yielding strain
Epss_u – Steel Ultimate strain

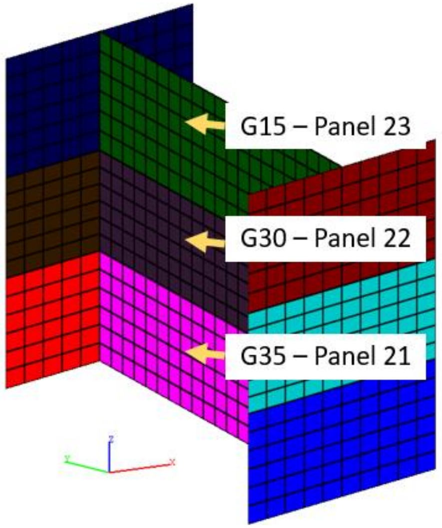
These are parameters shall be input by analyst for each wall submodel for each floor level cross-section

Repeat line 3 to line 8 for all the sections of the wall.

Revised_Section_Data_for_BBC.in Input for *BBC_JEAC_4601_2015 Module*

Example for Wall 5 with 3 Floors (and Sections)

```
 3
-8.0264    16.764    40.843
 1
  0.264106E+05   0.409823E+06   0.404182E+05
4.7488    14.441    1.5240    14.441    1.5240    24.079    1.5240    13.801    13.801
 0
1.1950    1.5980    1.2460   0.95300
0.248546E+08   0.3300E+05  0.200E-02  0.400E-02   0.205000E+09   0.3450E+06  0.185E-02  0.500E-01
 2
  0.228232E+05   0.188437E+06   0.358970E+05
11.924    14.441    1.5240    14.441    1.5240    24.079    1.5240    17.650    17.650
 0
1.1950    1.5980    1.2460   0.95300
0.248546E+08   0.3300E+05  0.200E-02  0.400E-02   0.205000E+09   0.3450E+06  0.185E-02  0.500E-01
  3
  0.124042E+05   0.371685E+05   0.215392E+05
19.391    14.441    1.5240    14.441    1.5240    24.079    1.5240    20.946    20.946
 0
1.1950    1.5980    1.2460   0.95300
0.248546E+08   0.3300E+05  0.200E-02  0.400E-02   0.205000E+09   0.3450E+06  0.185E-02  0.500E-01
```



Section data are provided only in International system (kN and m)

Steps 7-8: Computes Shear and Bending BBCs

BBC_JEAC_4601_2015 Module Run

Step 7 — *Section_BBC_Data.out* file — (B)

Step 8 — *BBC Shear.pre & BBC Bending.pre* files — (UI)

Steps 9-10: Nonlinear SSI Analysis and Post-Processing

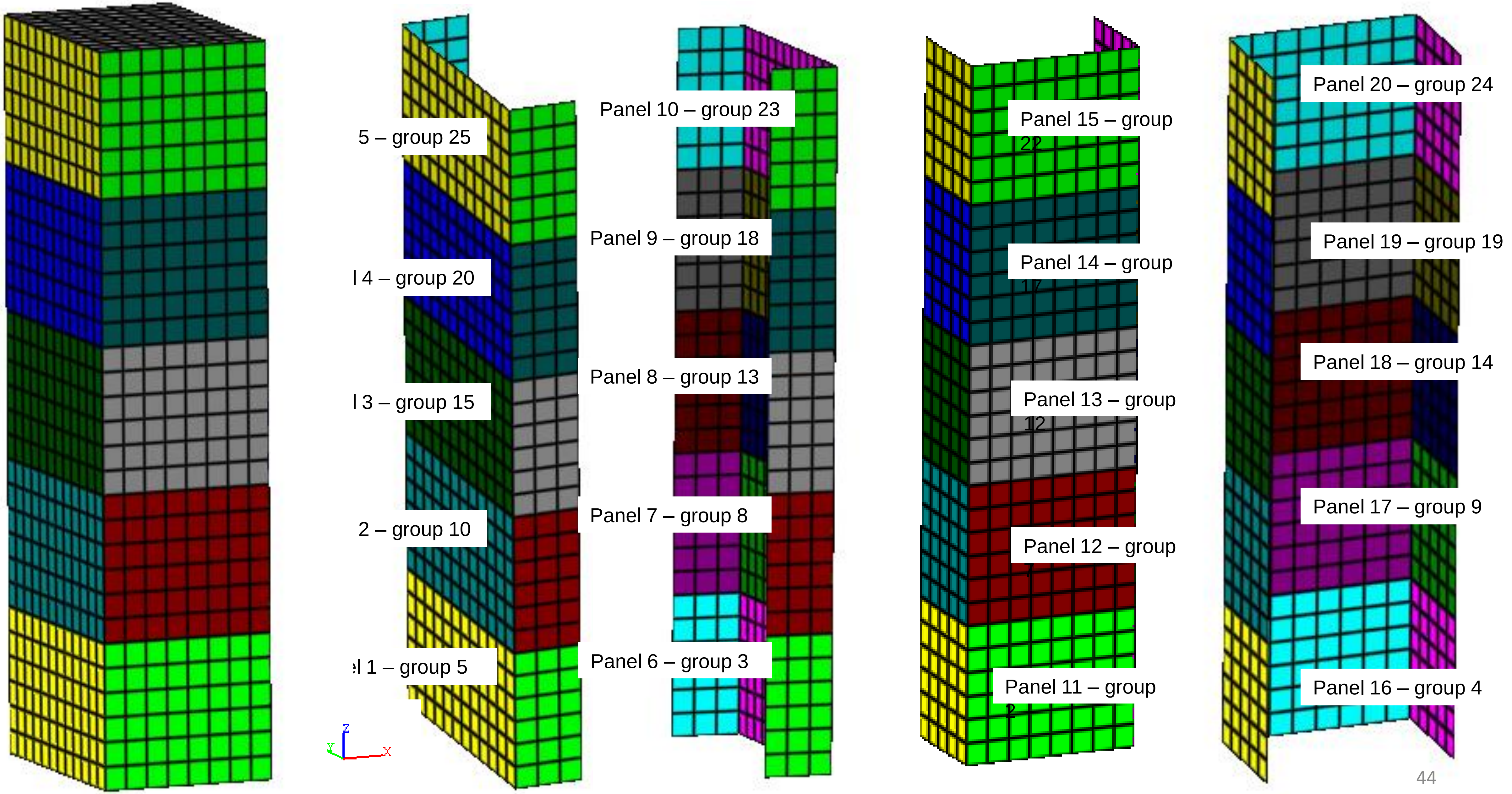
Option NON Nonlinear SSI Analysis (Batch Run)

Step 9 — *Shear and bending effects are combined at each SSI iteration using **COMB_Shear_Bend** Module*

(B) — ***File8*** files for converged SSI solution

Step 10 — **Final SSI Post-Processing** — (B) (UI)

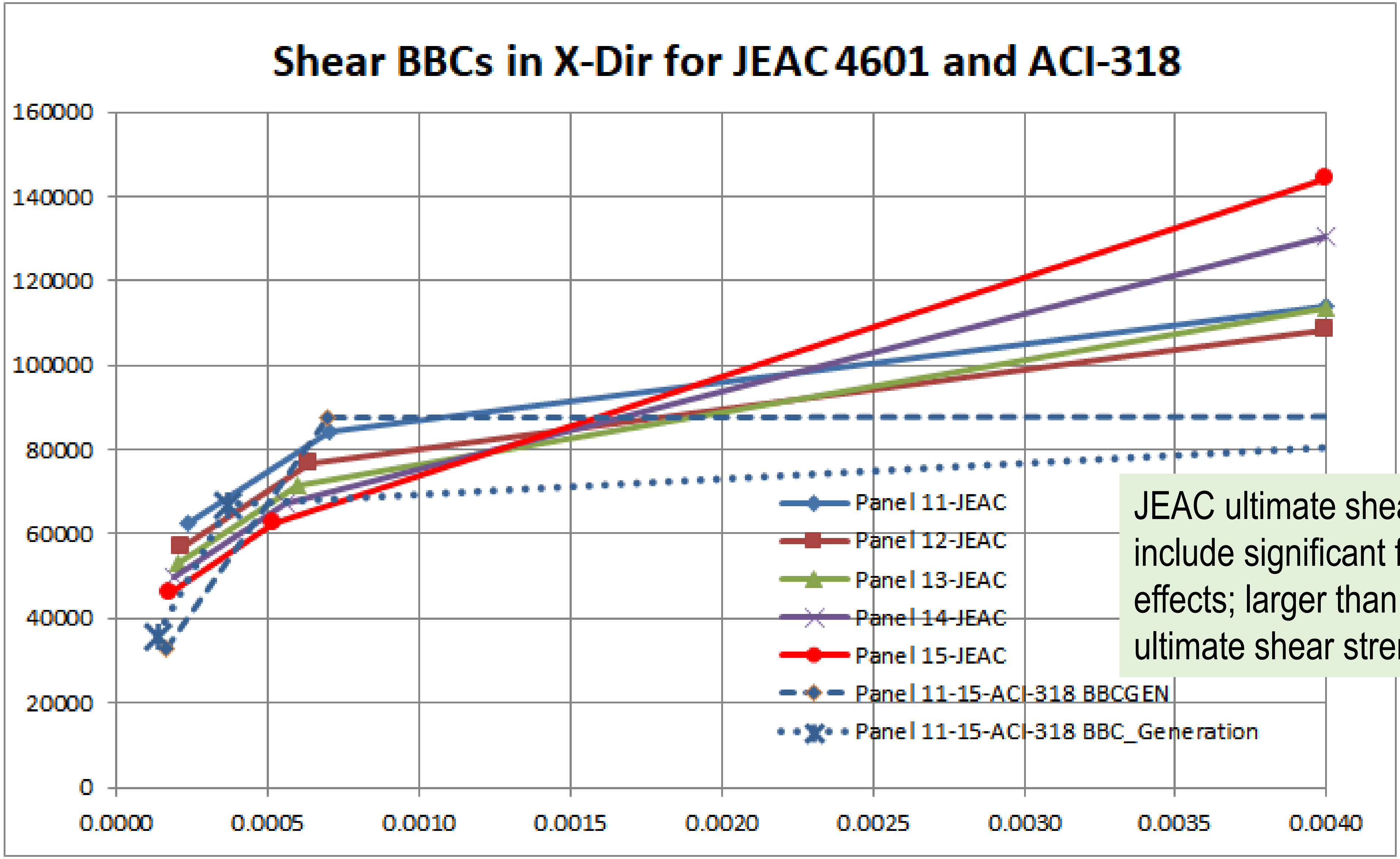
7. Comparative TB Nonlinear Results for US and Japan Practices



Computed Effective Flange Width for ACI-318 and JEAC 4601

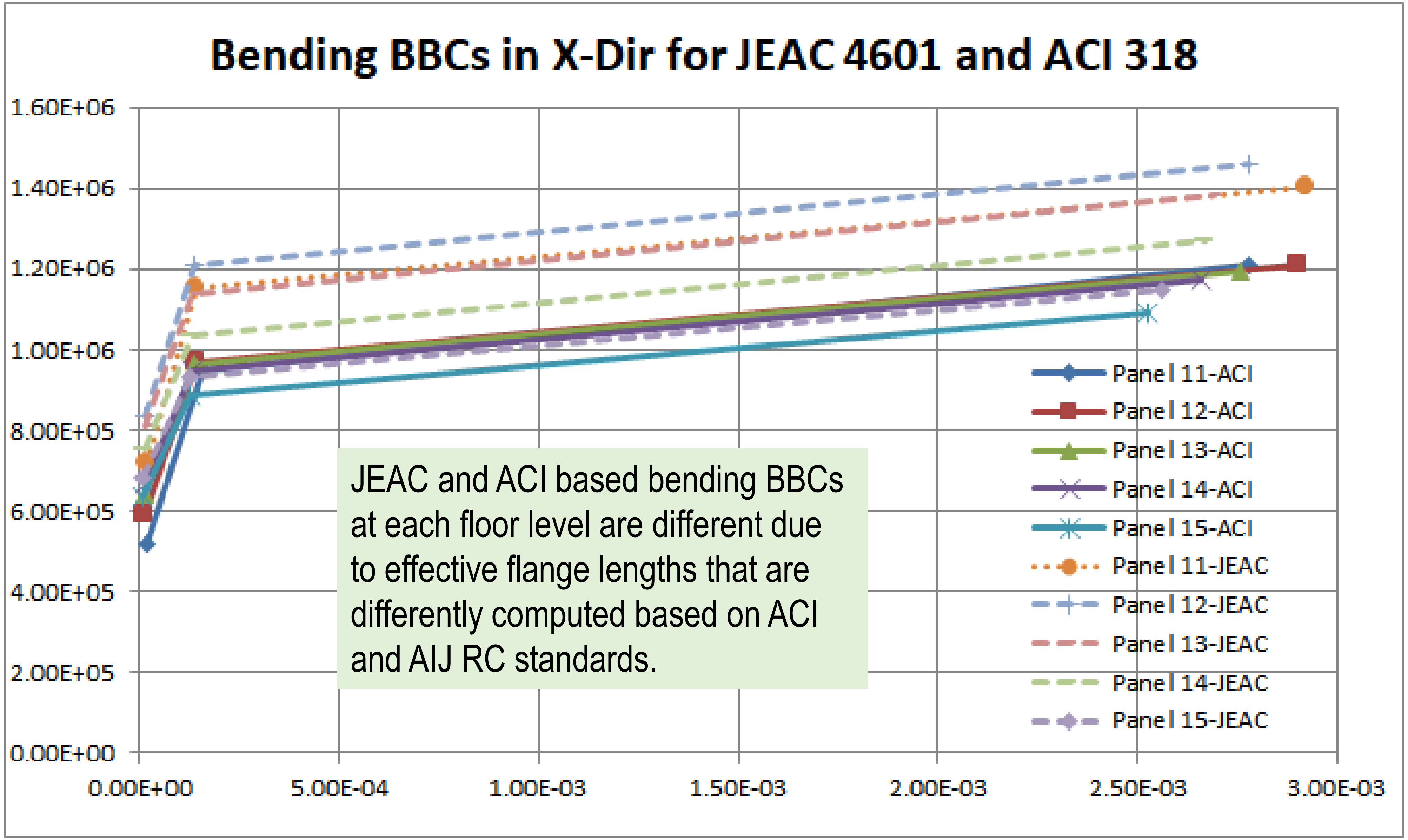
Panel #	Flange 1 L1C (m)		Flange 2 L2C (m)	
	JEAC 4601 2015	ACI 318-14	JEAC 4601 2015	ACI 318-14
1, 6	6.12	3.5	6.12	3.5
2, 7	7.43	5.5	7.43	5.5
3, 8	7.87	7.5	7.87	7.5
4, 9	8.09	8.75	8.09	8.75
5, 10	8.22	8.75	8.22	8.75
11, 16	6.42	3.5	6.42	3.5
12, 17	9.58	5.5	9.58	5.5
13, 18	10.64	7.5	10.64	7.5
14, 19	11.16	9.5	11.16	9.5
15, 20	11.48	10.5	11.48	10.5

Computed Shear BBCs for TB Transverse Walls in X-Dir

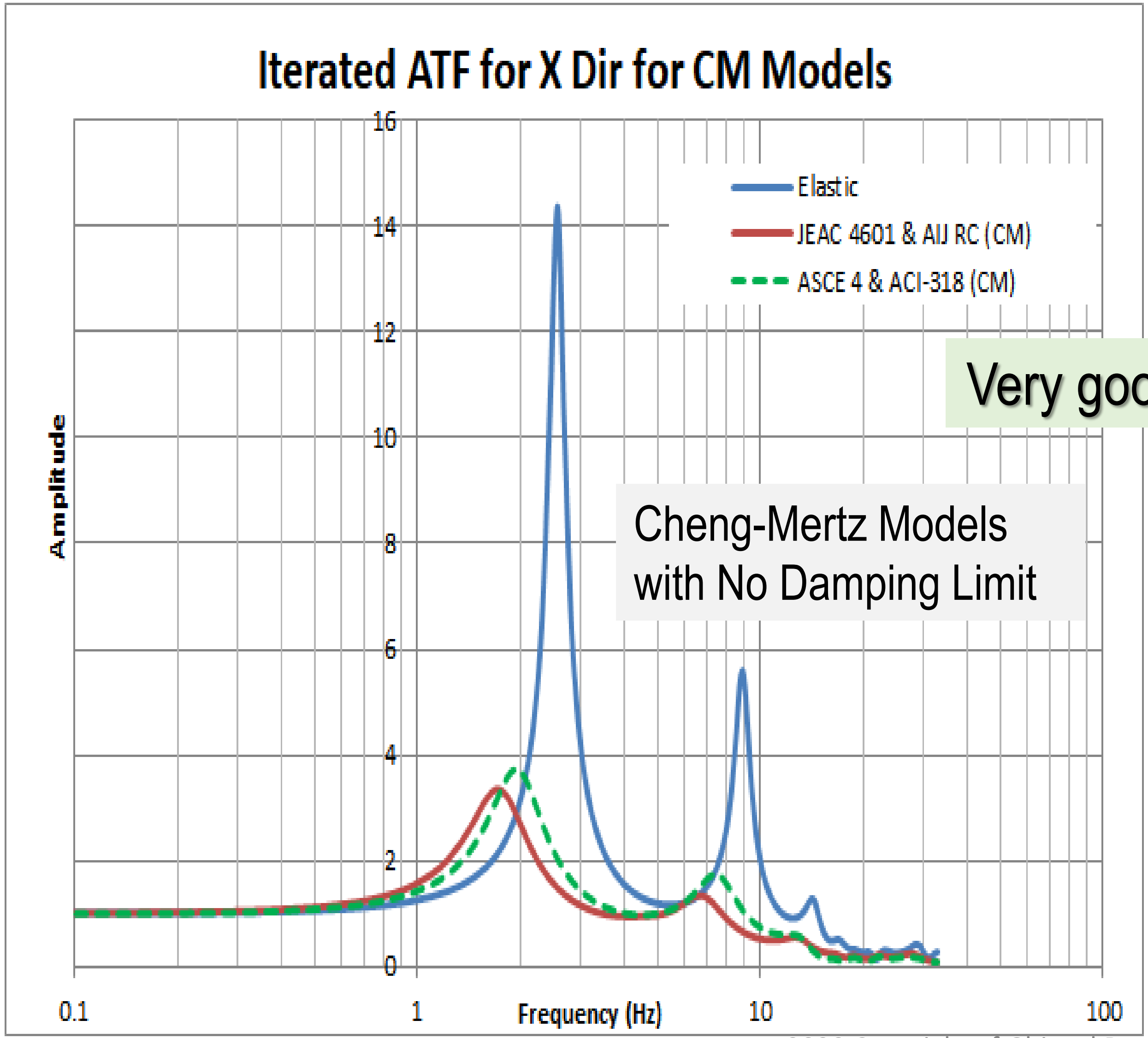


JEAC ultimate shear forces include significant flange effects; larger than ACI-318 ultimate shear strengths.

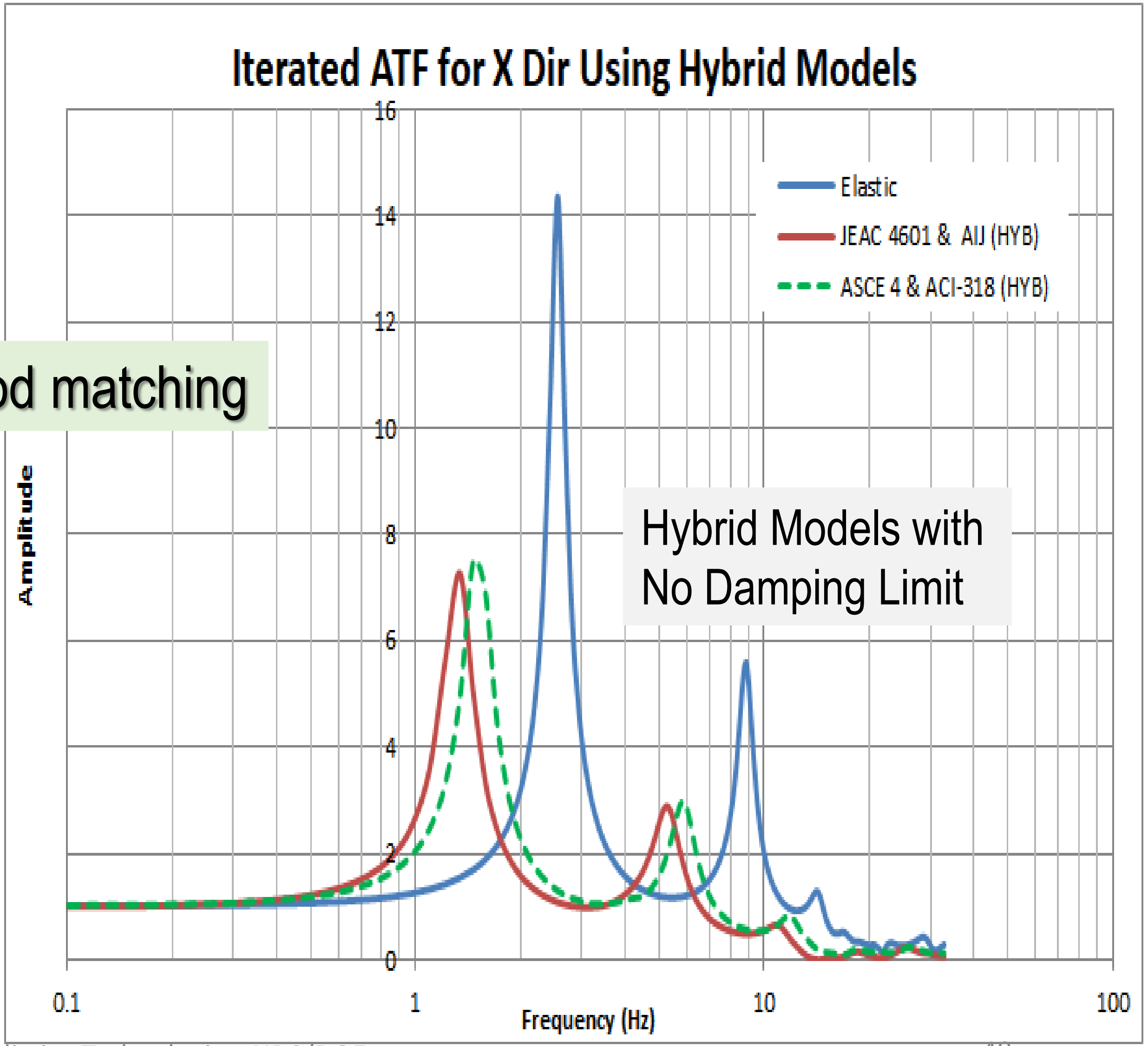
Computed Bending BBCs for TB Transverse Walls in X-Dir



Iterated ATF Response Using Same Hysteretic Models for US and Japan Design Practices

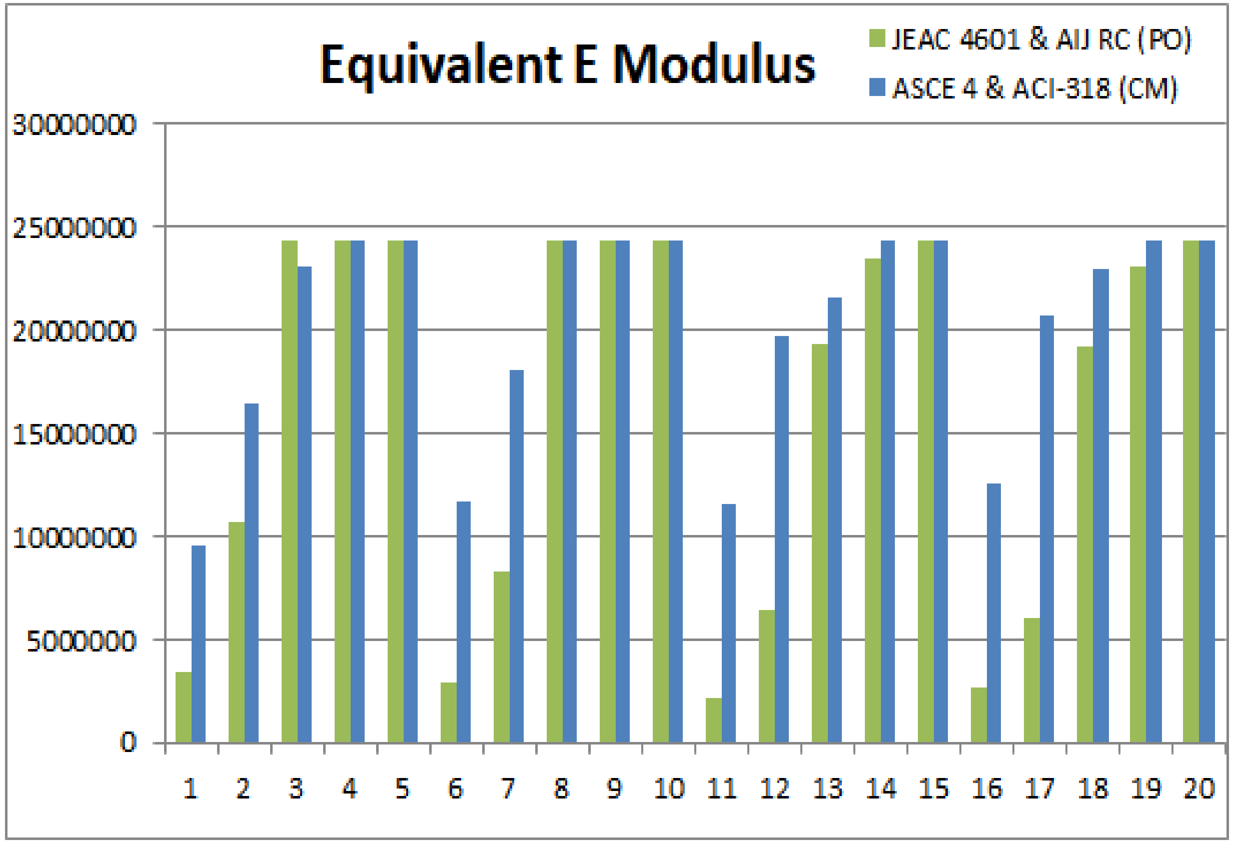


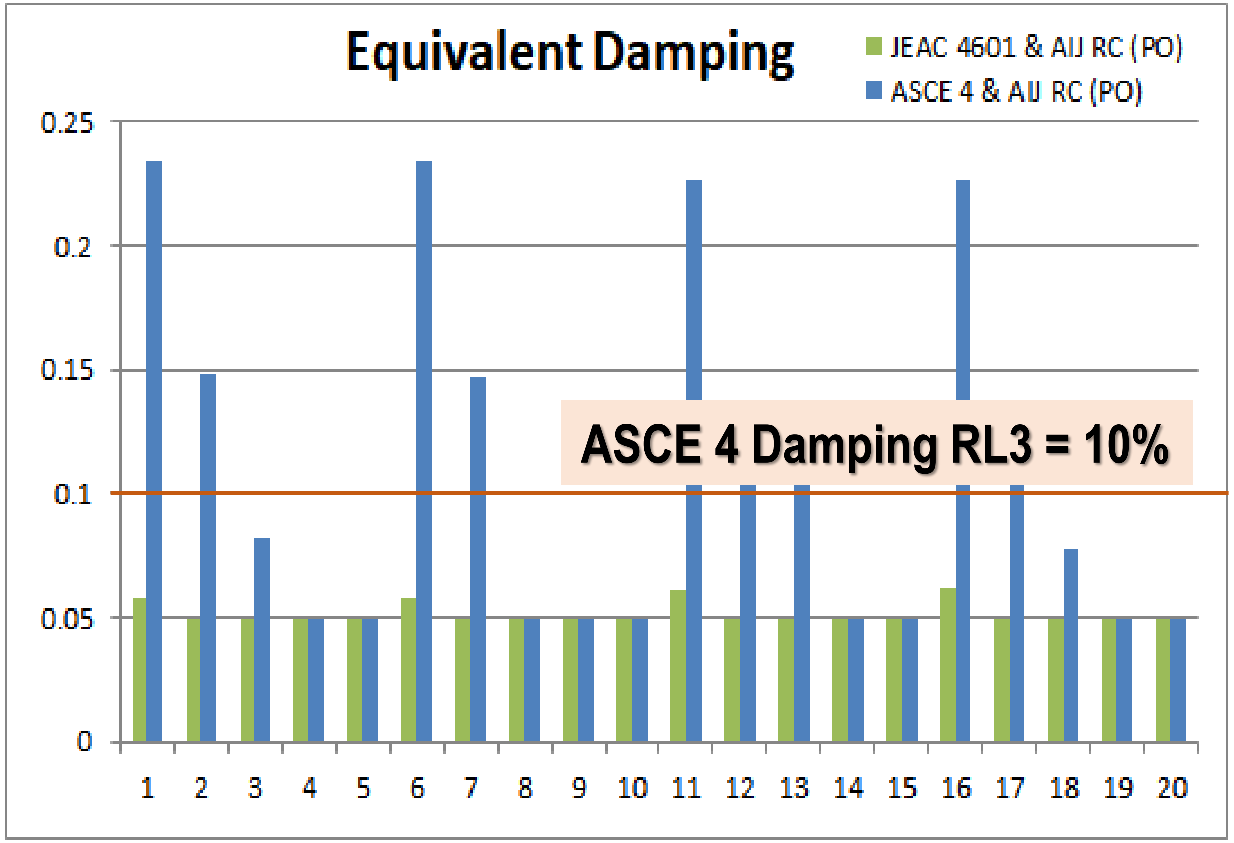
Very good matching



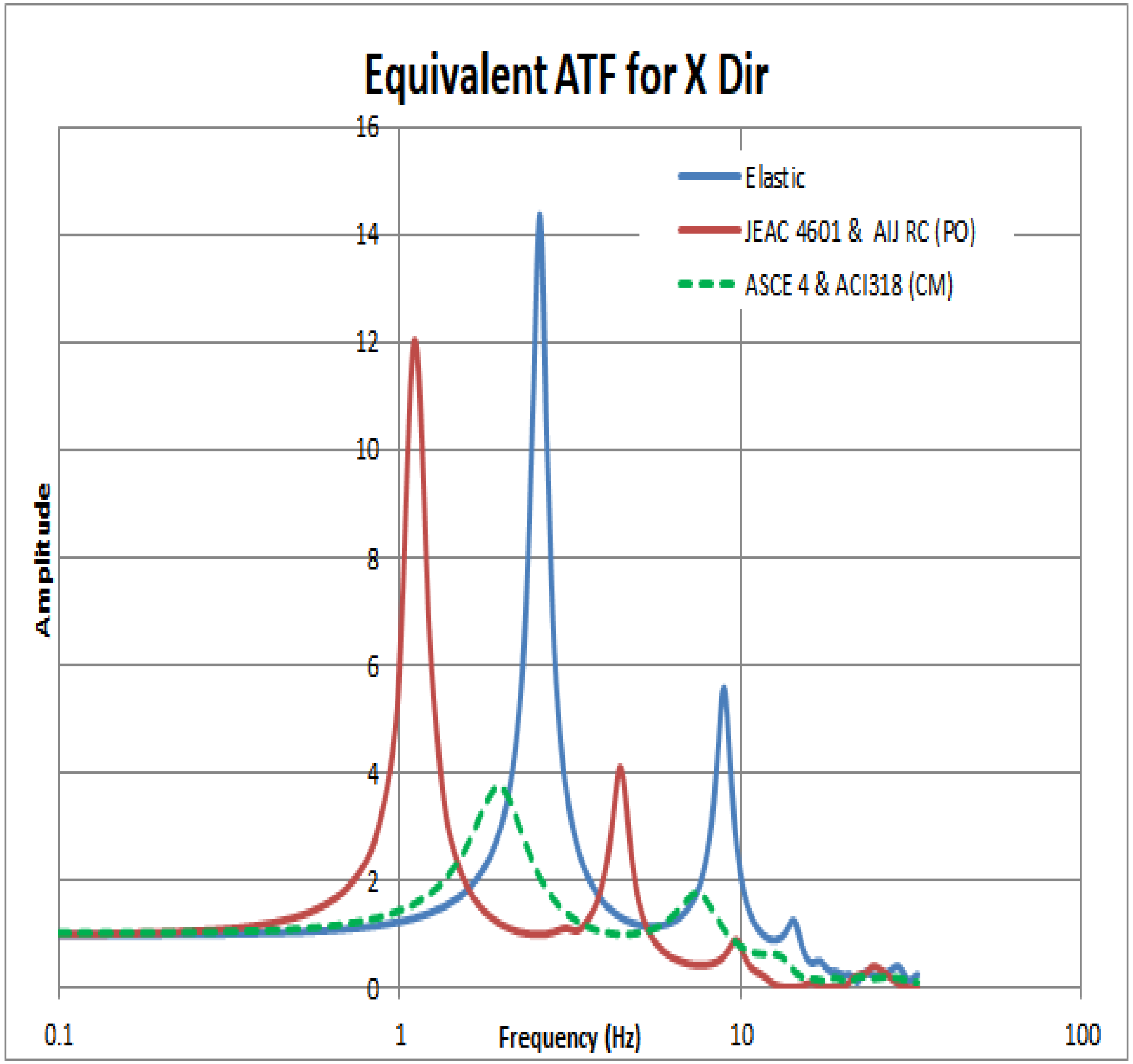
Iterated Walls Stiffness and Damping for 0.70g RG1.60 Input

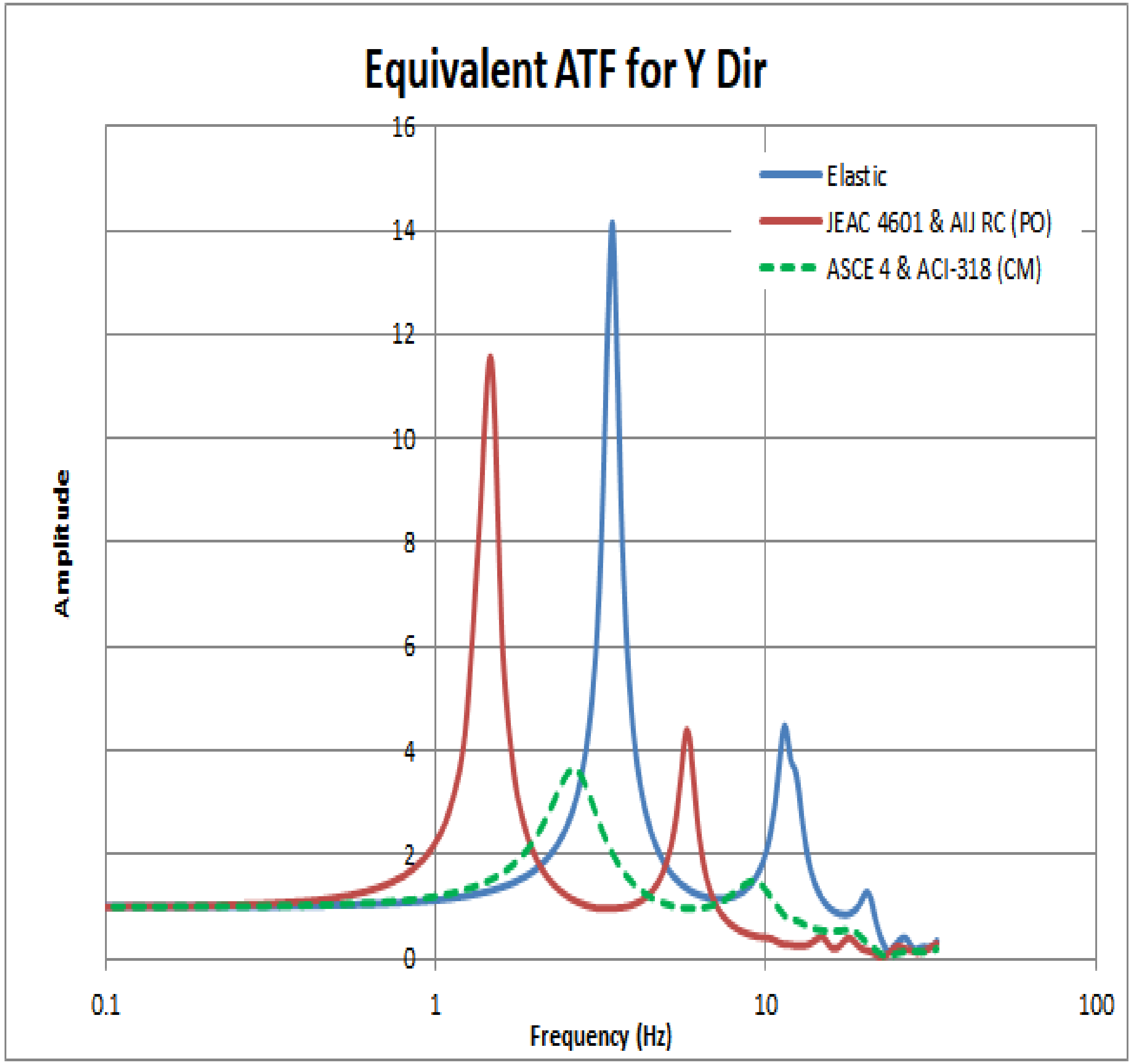
Using JEAC PO Models and CM Models with **No Damping Limit** (directly FEA nonlinear results)



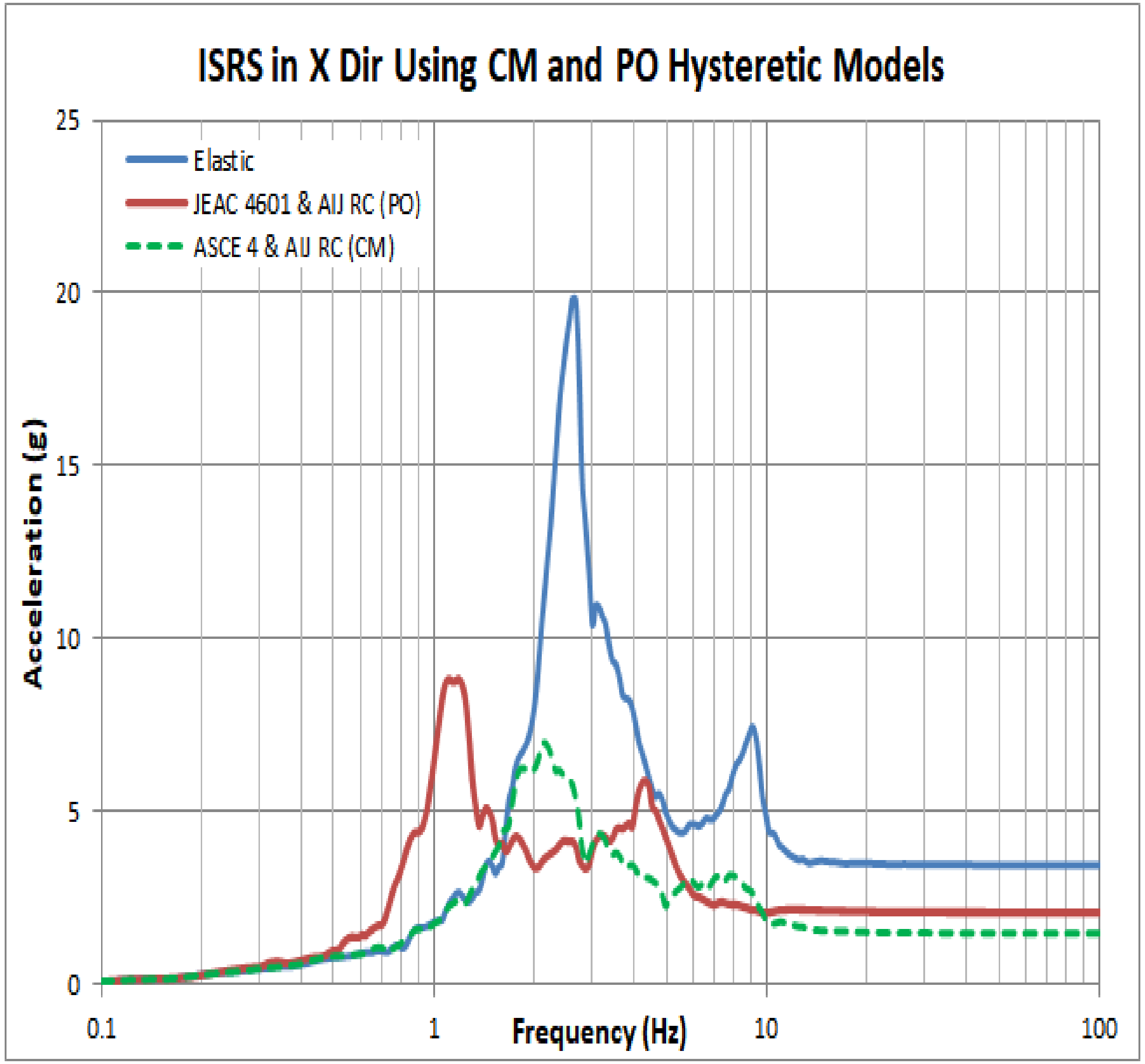


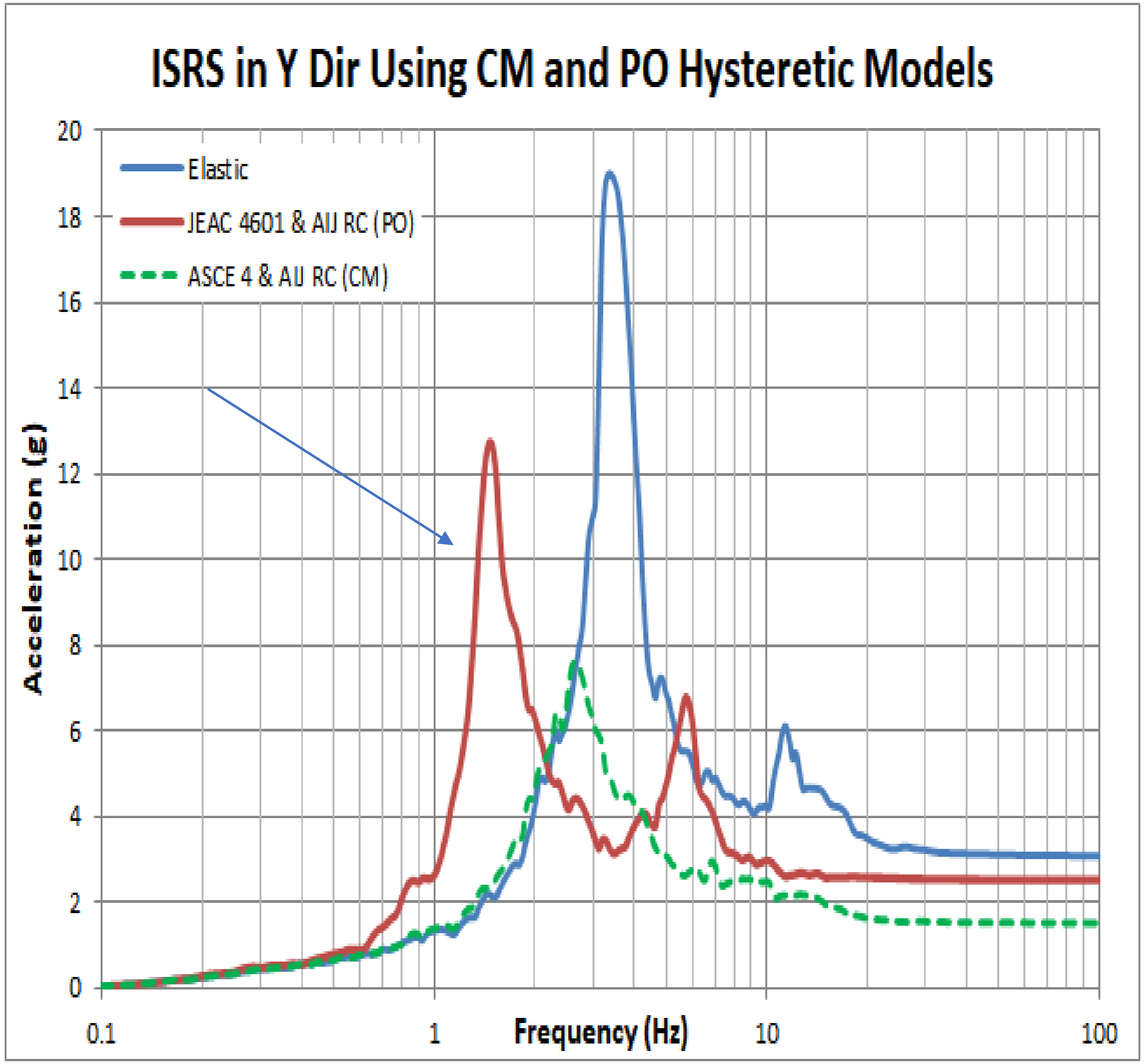
Iterated ATF for JEAC PO Models and CM Models w/ No Damping Limit





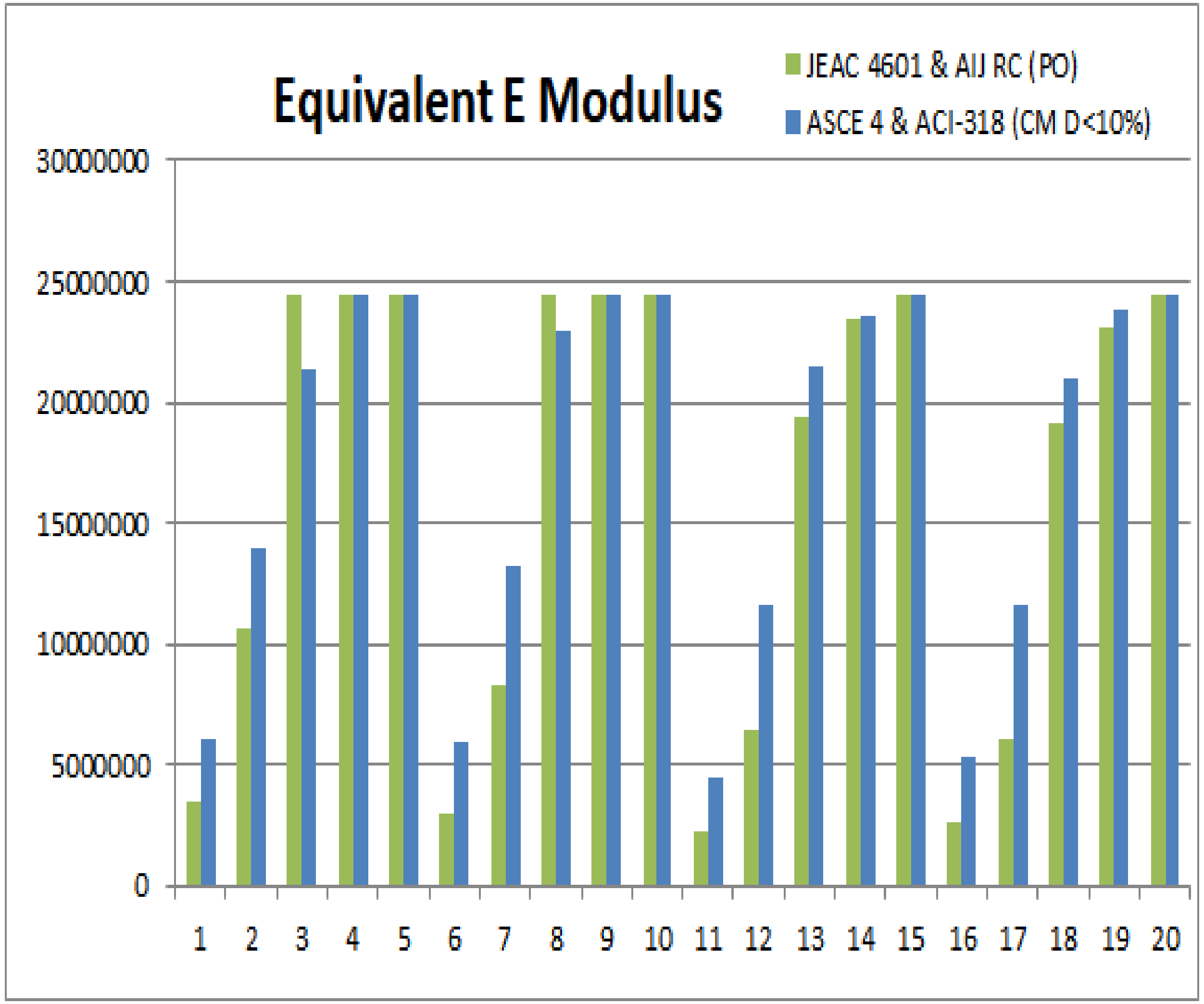
Iterated ISRS for JEAC PO Models and CM Models w/ No Damping Limit)

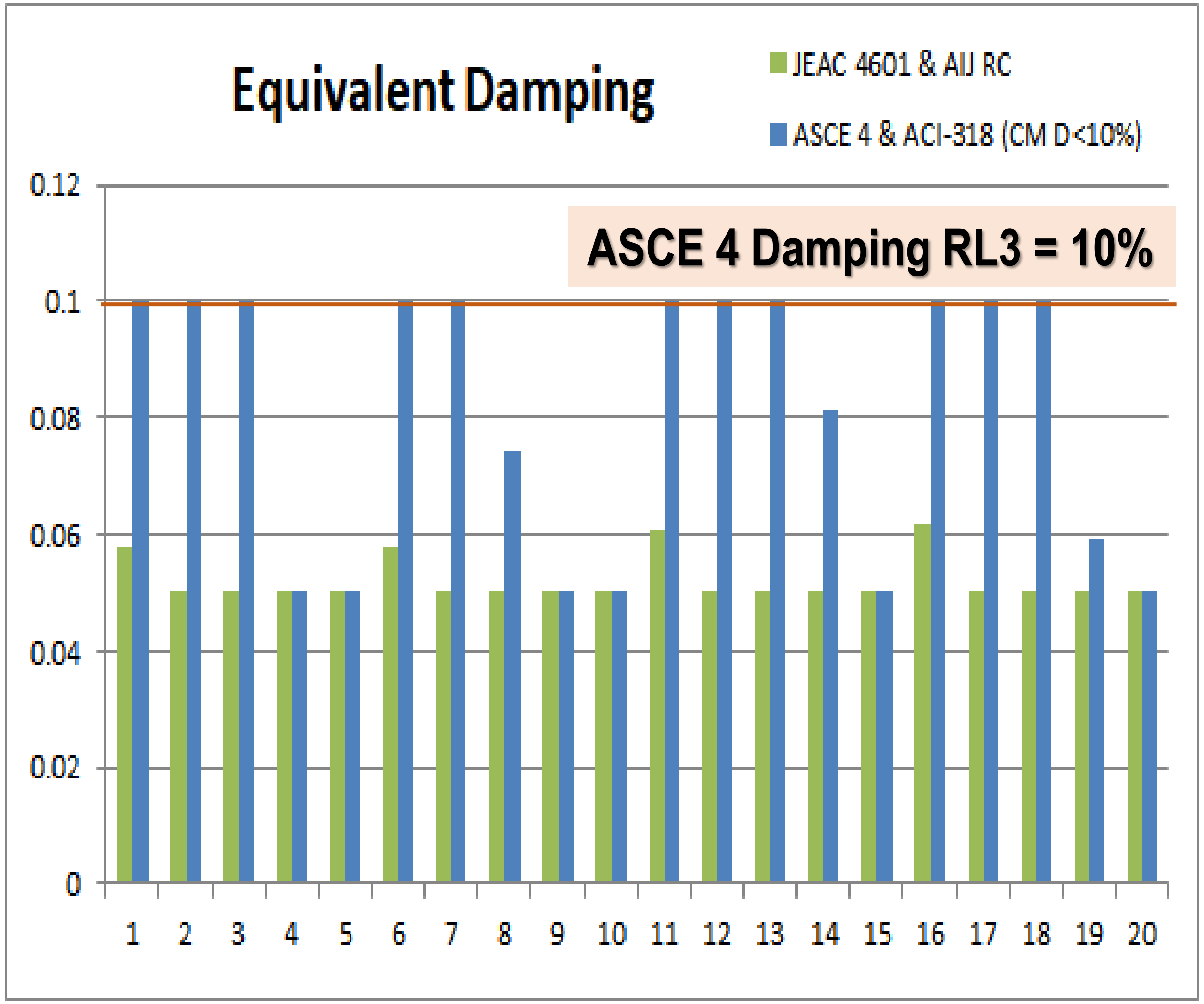




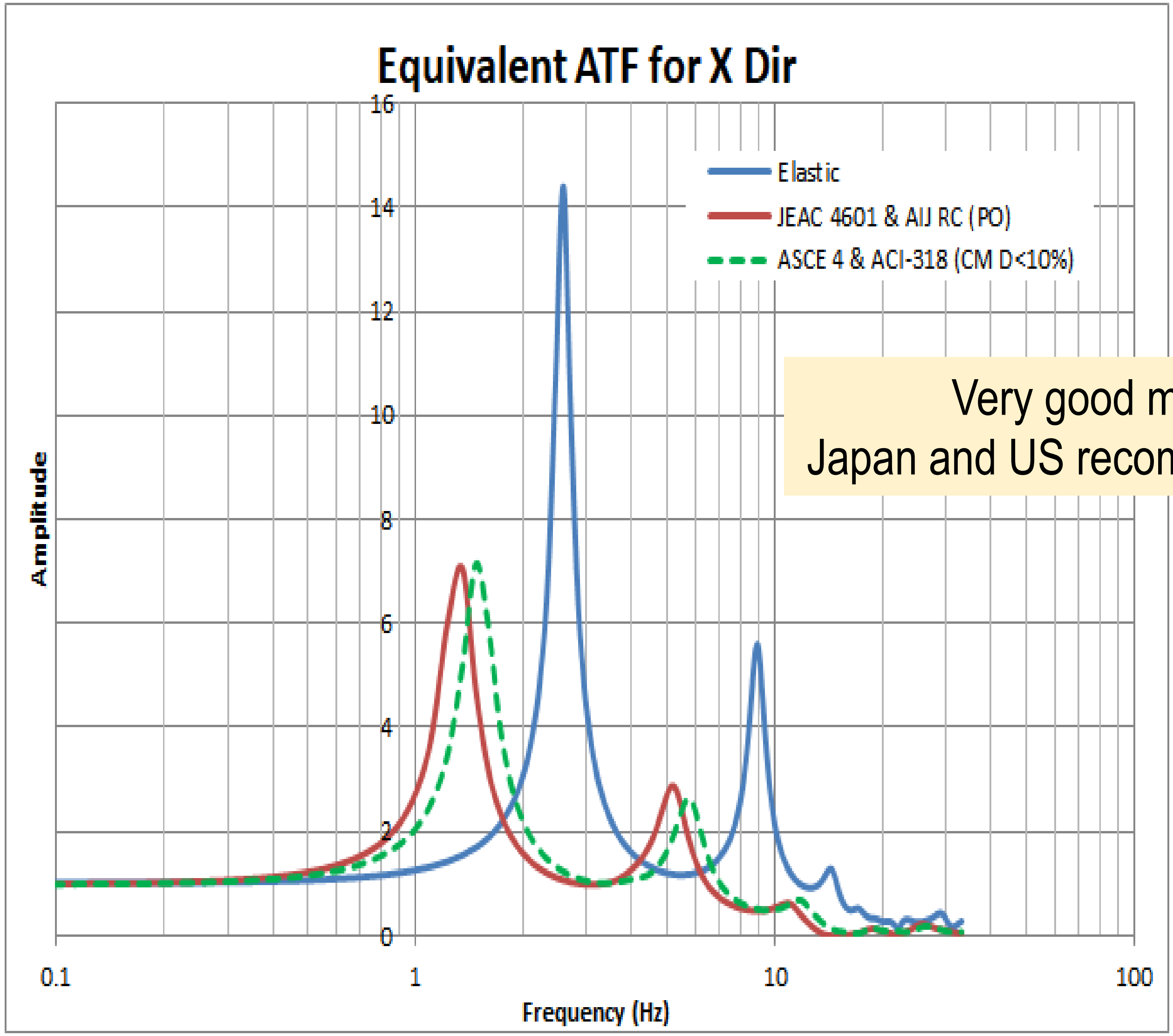
Iterated Walls Stiffness and Damping for 0.70g RG1.60 Input

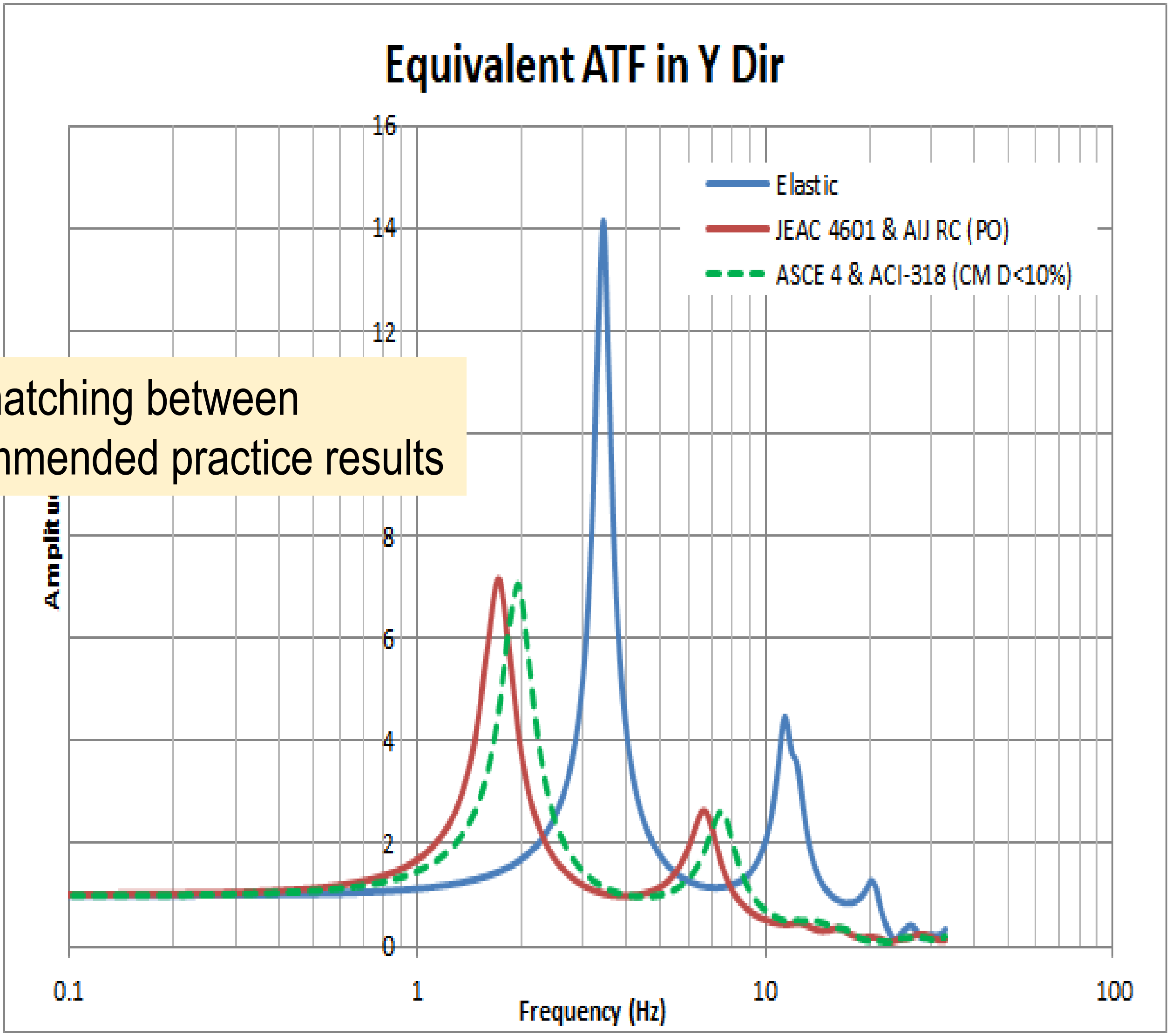
Using JEAC PO and CM Models with **Damping < 10%** per ASCE 4 Section 3 Recommendation





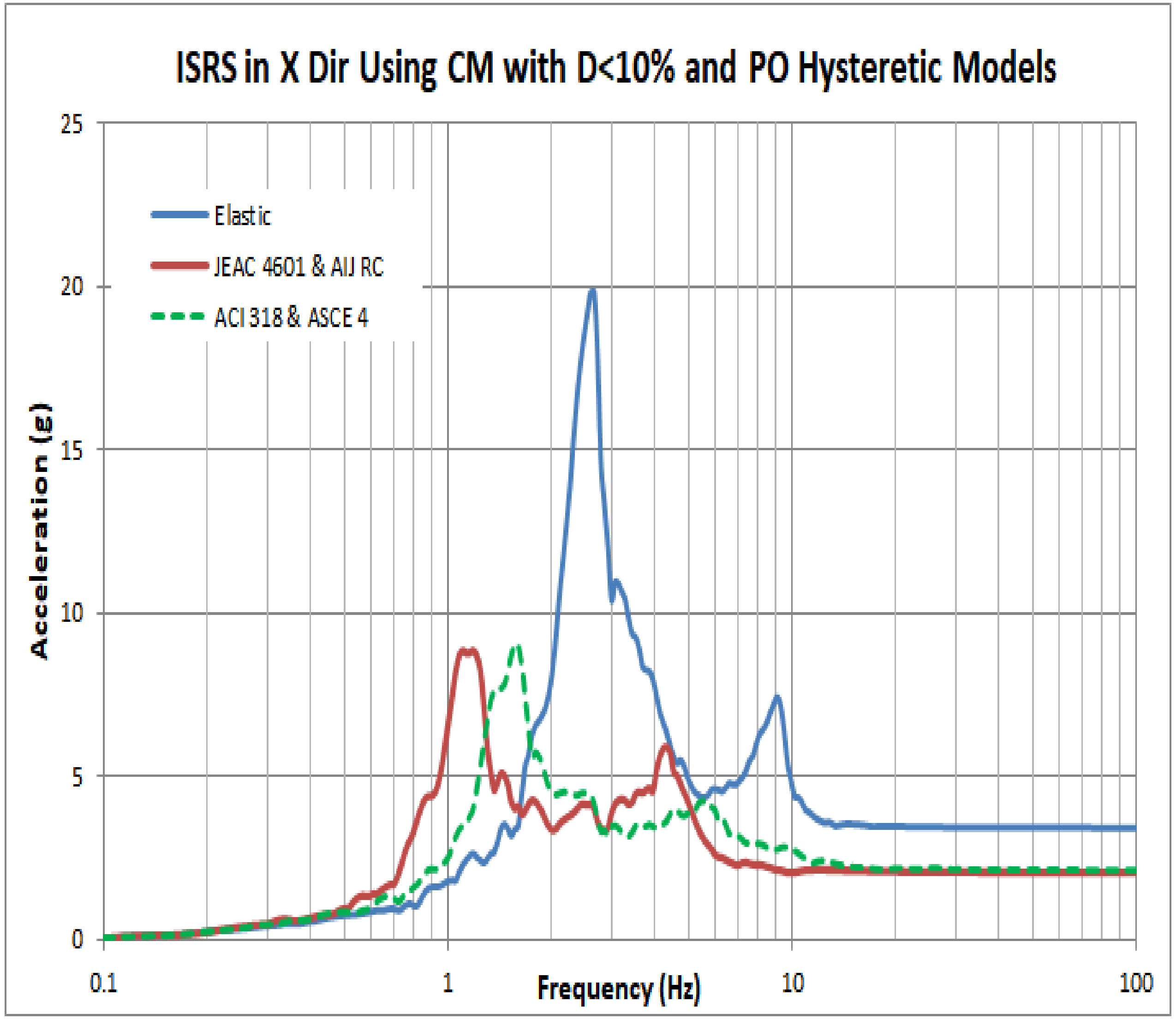
Iterated ATF for JEAC PO Models and CM Models with D<10%

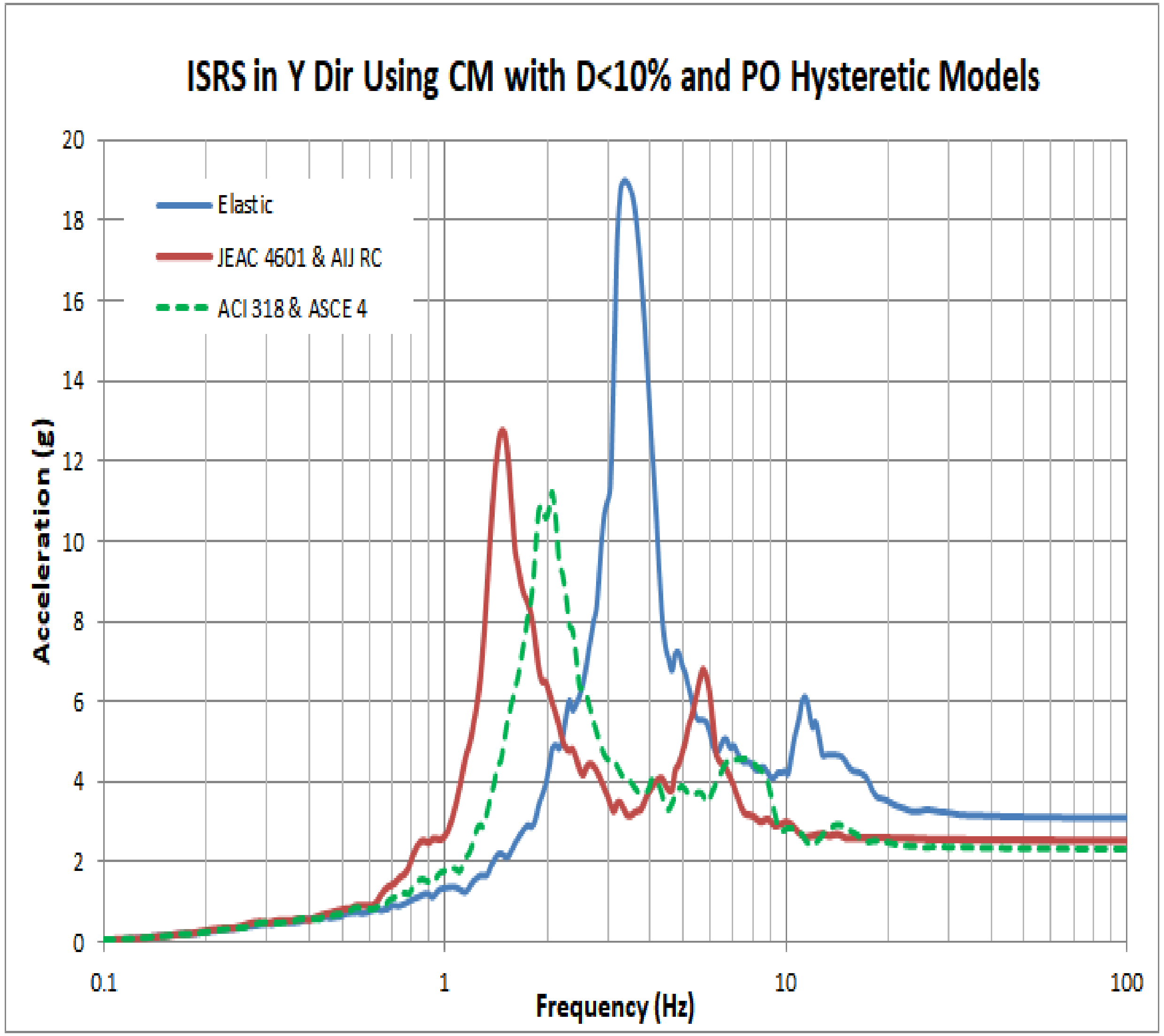




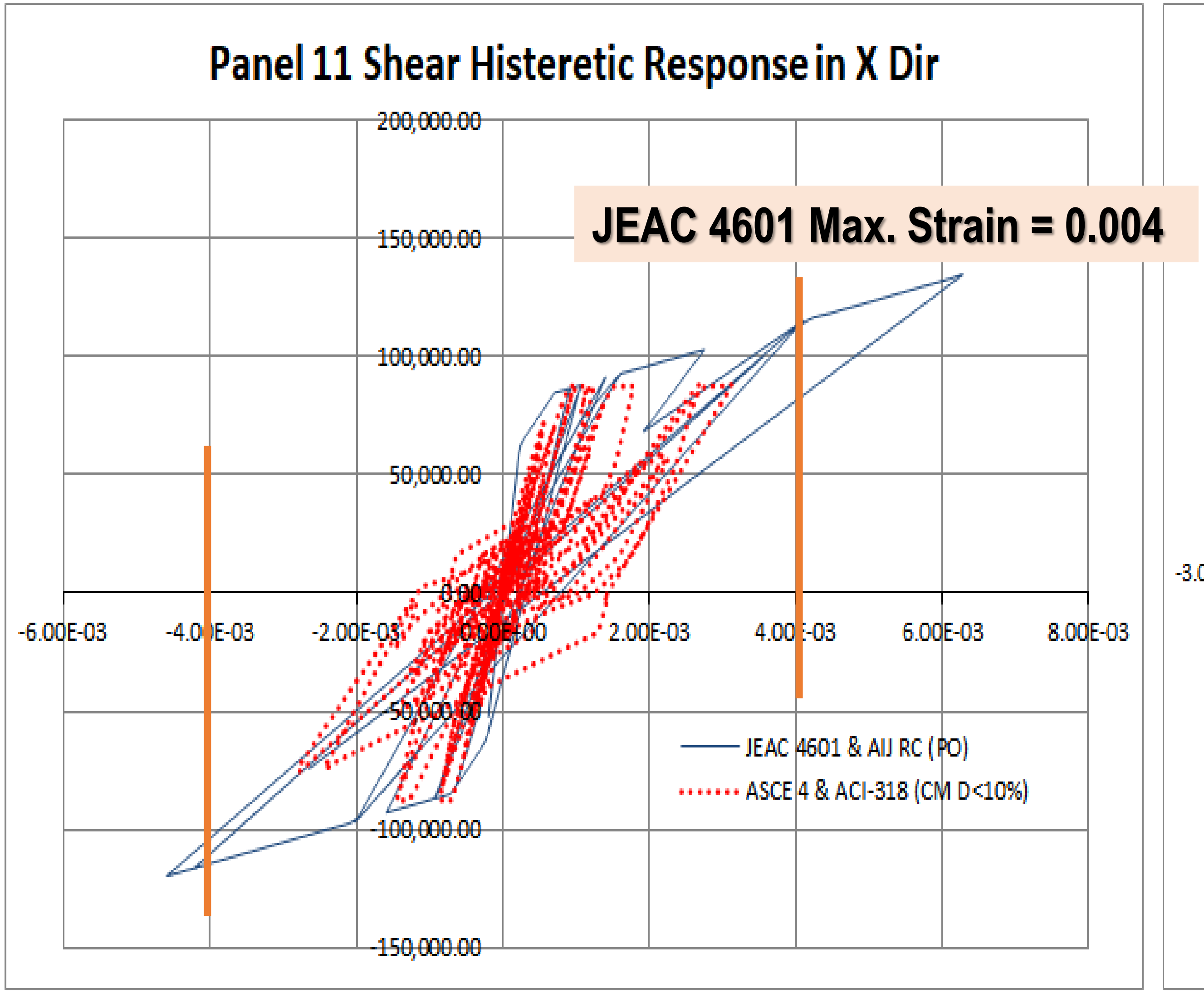
Very good matching between
Japan and US recommended practice results

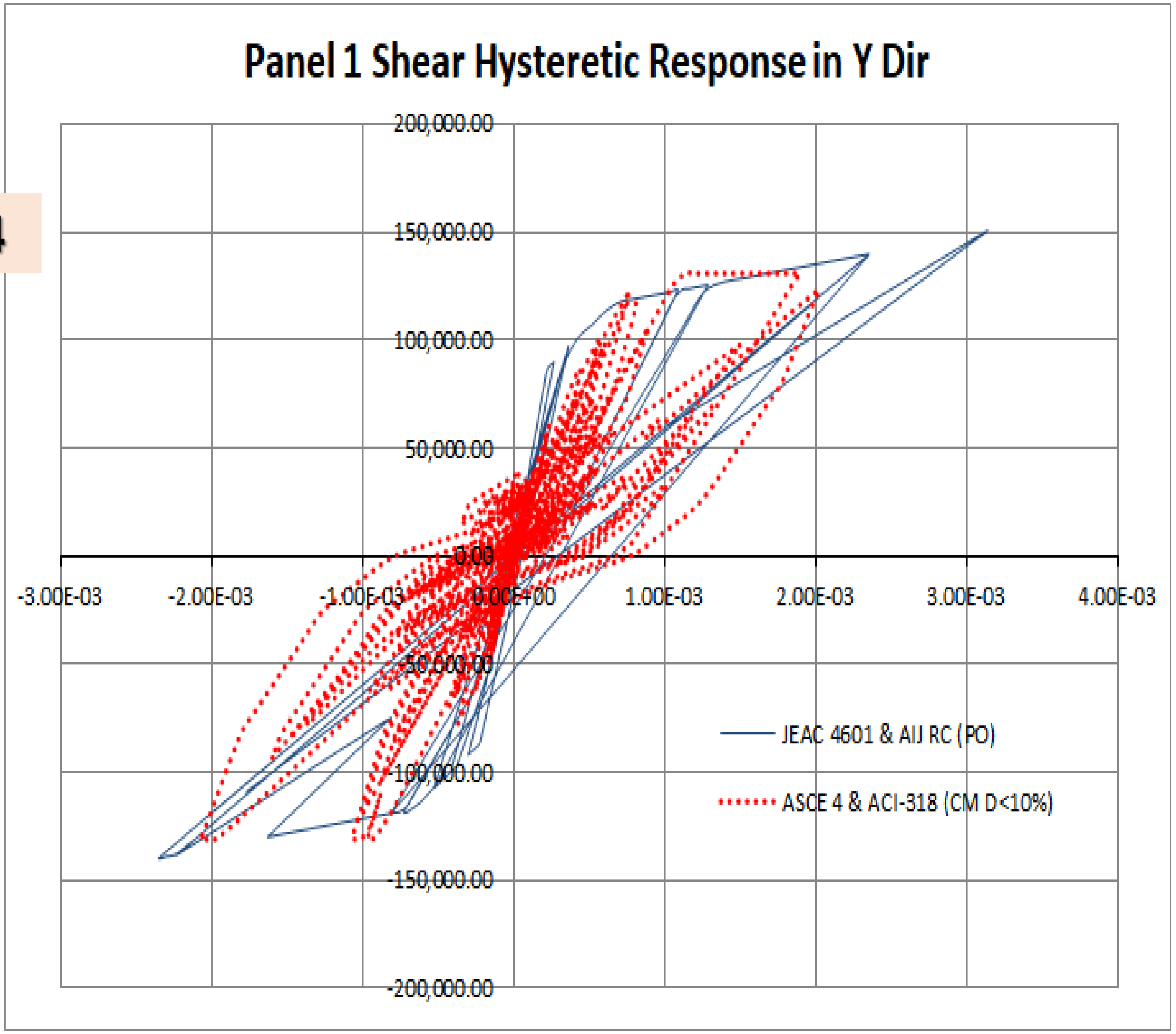
Iterated ISRS for JEAC PO Models and CM Models with D<10%



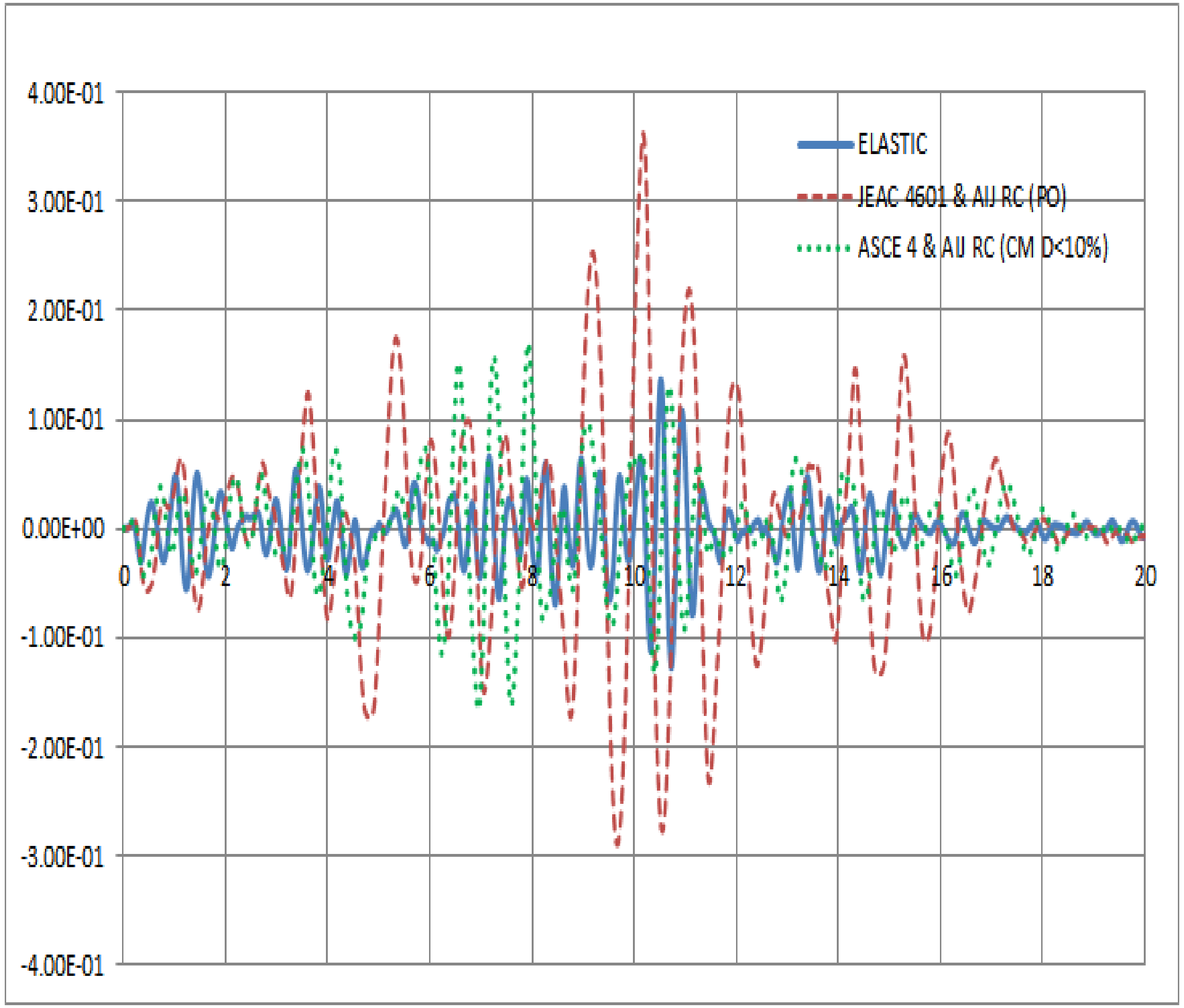


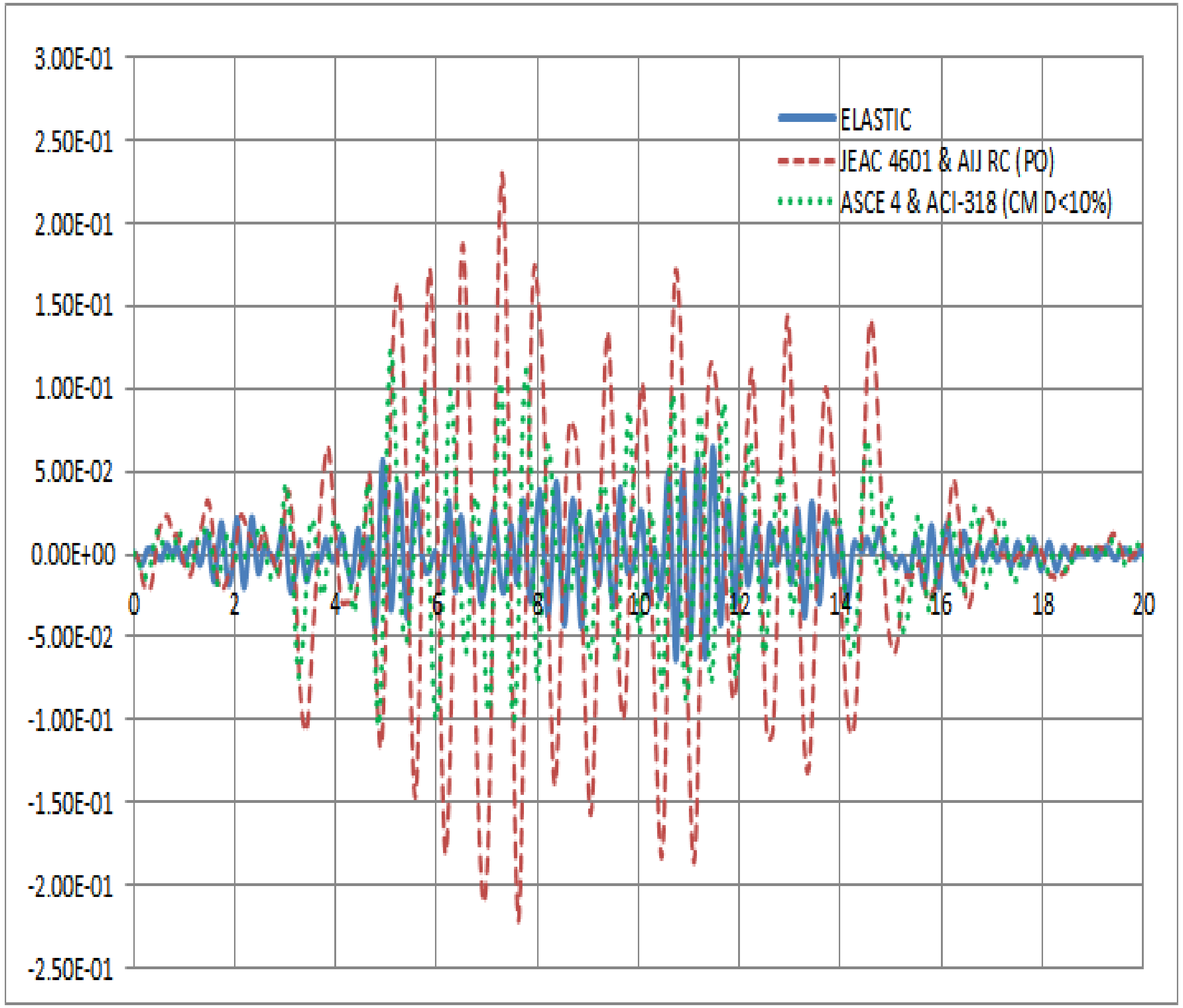
Shear Hysteretic Response for JEAC PO and CM with D<10%





Nonlinear Displacements for X and Y Dir at Top of TB for JEAC PO Models and ASCE 4 CM with D<10%





Concluding Remarks

A. Remarks on Nonlinear SSI Analysis Procedure Based on Best Practices

Very importantly, the developed nonlinear SSI analysis tool (ACS SASSI Option NON) *maintains the safety margins as accepted by the current standards and regulations*, at the same time providing a large reduction of the nonlinear SSI analysis costs in comparison with the existing, more sophisticated nonlinear FEA codes in the time domain.

We believe that such a *practical engineering analysis tool* is highly needed for nuclear industry.

B. Remarks on Nonlinear Results Based on US and Japan Design Practices

1. The comparative study results show that if the Japanese and US standard recommendations for hysteretic damping limitation are respected, then, the computed nonlinear ISRS amplitudes are close.
2. The JEAC PO hysteretic models have much lower hysteretic damping (PO shear model has no damping and PODT bending has between 0 and 15%) which amplifies seismic responses and produces a shift of the structural dominant frequencies to lower frequencies. As a result of the lower damping, the structural displacements are significantly larger for the JEAC PO models.
3. Using directly the nonlinear FEA code results (similar with using the CM models with no damping limit) could produce much lower nonlinear SSI responses than those computed by respecting the Japanese or US standard recommendations, especially due to the lack of hysteretic damping limitation.

WARNING: Using directly the nonlinear FEA code results without checking the compliance with regulatory requirements could significantly lower the nonlinear responses. By this may produce much lower seismic safety margins that those corresponding to the existing design regulation requirements. Nuclear industry analysts should understand and pay attention to these serious methodology risks.

References

1) Oh, Y. H., Han, S.W. and Lee, L.H. (2002). “Effect of boundary element details on the seismic deformation capacity of structural walls”, J. of Earthquake Engng Struct. Dyn. 2002; 31:1583–1602

2) Cheng, Y. F. (1993).”Coupling Bending and Shear Hysteretic Models of Low-Rise R.C. Walls”.

3) Cheng, Y. F. and Mertz, G. (1989).”Inelastic Seismic Response of R.C. Low-Rise Shear Walls and Building Structures”, Dept. of Civil Engineering, Report 89-30, University of Missouri-Rolla, Rolla, MO

4) Enrico, S.,Ciampi, V., Filippou, F.C. (1992). “A Beam Element for Seismic Damage Analysis”, University of California at Berkeley, Report No. UCB/EERC-92/07

5) Kolozvari K., Orakcal K., and Wallace J. W. (2015). "Shear-Flexure Interaction Modeling of Reinforced Concrete Structural Walls and Columns under Reversed Cyclic Loading", PEER Center, University of California at Berkeley.

6) Park, Y. J., Hoffmayer, C.H. and Costello, J.F. (1994). “Understanding Seismic Design Criteria for Japanese Nuclear Power Plants”, Brookhaven Labs, Report, BNL-NUREG-60885, Upton, NY

7) Taitokui (1987). Report in Japanese. Communication from SHIMIZU.

End of Part 2

Thank you!