AN EFFICIENT SEISMIC NONLINEAR SSI APROACH BASED ON BEST PRACTICES IN US AND JAPAN. PART 2: APPLICATION

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ABSTRACT

The paper introduces an efficient nonlinear seismic SSI approach for evaluating the reinforced concrete (RC) shearwall structures behavior under severe earthquakes in accordance with the engineering practices and regulatory requirements in US and Japan. The nonlinear SSI approach is based on a hybrid approach that uses an iterative scheme which couples the equivalent-linear complex frequency SSI analysis with the nonlinear time-domain structure analysis. The iterative approach is fast converging in only few SSI restart iterations. The SSI approach implementation follows the Japanese seismic nonlinear analysis engineering practice extended to detailed 3DFEM SSI models. The implementation is compliant with the RC structure modeling standard recommendations in US and Japan. Independent verifications and validation studies confirmed that the iterative SSI approach is reasonably accurate and extremely efficient. There are two companion papers, Part 1 and Part 2, related to the iterative SSI approach: The Part 1 paper focuses on the key modeling aspects for capturing nonlinear hysteretic behavior of RC structure walls, while the Part 2 paper focuses on its application using the ACS SASSI Option NON software for a typical Reinforced Concrete (RC) shearwall building.

INTRODUCTION

This Part 2 paper describes the application of the iterative hybrid SSI approach using the ACS SASSI Option NON software (GP Technologies, 2022). As described in the Part 1 paper, the main steps of the iterative SSI approach for a 3DFEM are as follows:

1. Prepare structure 3DFEM model
2. For selected nonlinear RC walls create 3DFEM submodels
3. Perform linear SSI analysis for gravity and seismic loads to compute structural stresses
4. Perform RC wall cross-section geometry identification for all floor levels at defined sections
5. Perform automatic section-cuts for each wall for gravity and three direction seismic loads
6. Compute shear and bending back-bone curves (BBC) for each wall and floor level *per applicable best-practice recommendations in US or Japan*
7. Select appropriate shear and bending hysteretic models from the software library *per applicable best-practice recommendations in US or Japan*
8. Perform SSI and nonlinear analysis iterations using shear and bending hysteretic wall models
9. Combine the computed interacting shear and flexure responses after each iteration
10. Optionally, include the floor concrete cracking due to the bending effects under vertical motion
11. Post-process the final SSI results of 3DFEM for the converged nonlinear response

The nonlinear SSI analysis based on the iterative hybrid approach is applicable to i) Design Basis Earthquake (DBE) projects for evaluating the RC cracking pattern in structures, and ii) Beyond Design Basis Earthquake (BDBE) projects for evaluating the RC wall post-cracking and yielding behaviour until ultimate limit state is reached. Herein, due to paper size limitation, only an example including a BDBE application for a surface RC shearwall structure is presented. Additional application examples including deeply embedded structures, and validation studies of the iterative SSI approach are described elsewhere (Ghiocel, 2016, 2022, Nitta et al., 2022, Ichihara et al. 2022).

APPLICATION PROCEDURE

An overview of the general nonlinear SSI analysis procedure for a typical RC shearwall is shown in Figure 1. The nonlinear SSI analysis procedure includes eleven steps. The entire procedure is highly automatic in running all computational analysis steps. The software documentation provides demo examples and batch run script templates for performing the nonlinear seismic SSI analysis for different analysis options. *To use the script templates for new SSI models others than provided in demos, users only need to correctly define the model names and the file paths. This makes the nonlinear SSI analysis application simple and safe.*

The analyst has the responsibility to create the 3DFEM SSI model in Step 1, and then, to carefully select the nonlinear RC wall submodels from the structure model in Step 2. Analyst has also the responsibility to check the SSI analysis inputs for the initial linear SSI analysis for the uncracked structure in Steps 3-4, and for the nonlinear structure analysis in Step 6.

It should be noted that the overall procedure includes some preparatory stages for building the nonlinear structure SSI model, Steps 1-9, then, an execution stage of the iterative nonlinear analysis, Steps 10, and finally, a post-processing stage, Step 11.

During the preparation stages, users have several options for nonlinear RC wall modeling as explained in this section. For each step included in the flowchart, the notations **B** and **UI** indicate if the step is executed by running a specific software module, or by using the UI commands to create required inputs for next steps. A special notation, **EIF**, is used for Step 6 that is the analyst's review step. This **EIF** indicates that analyst is required to do editing to create the input file for Step 7 based on the output file in Step 5. Basically, in this Step 6, based on the analyst's engineering judgements, the section geometries can be adjusted, and the concrete and reinforcement material strength parameters and the reinforcement percentages should be also input.

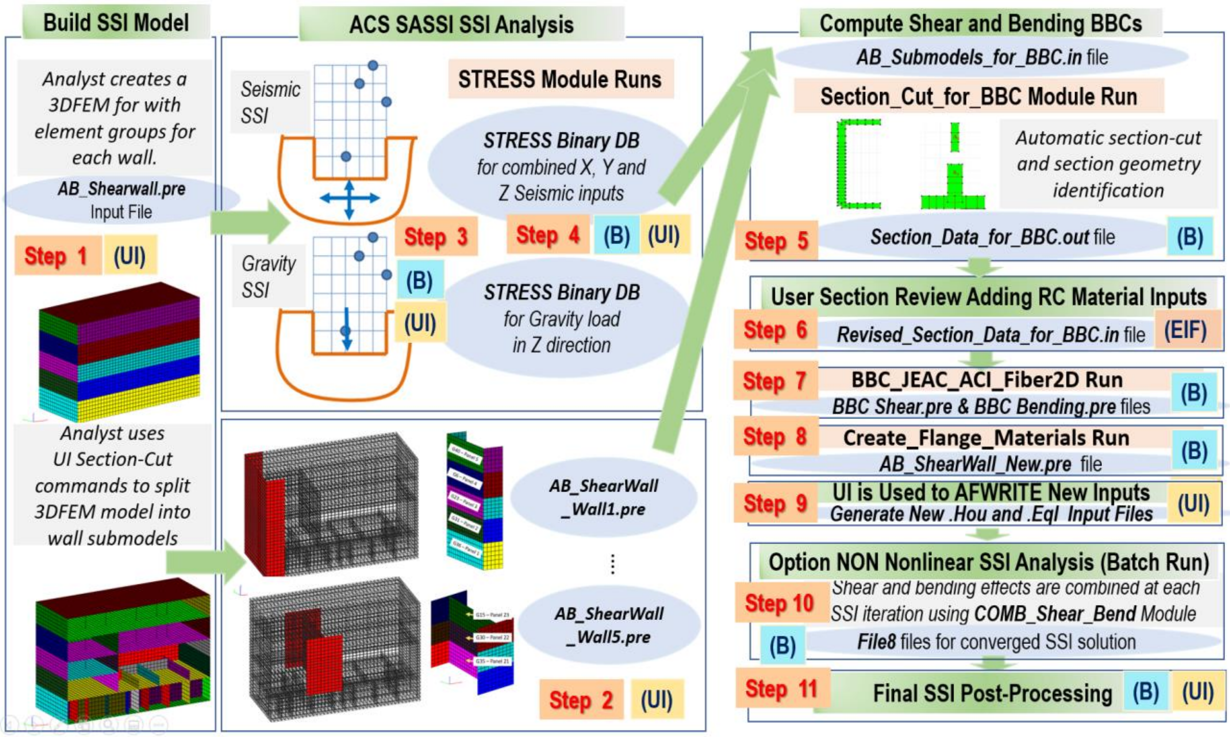


Figure 1 ACS SASSI Option NON Iterative SSI Analysis Flowchart

For deeply embedded structures as SMRs, the iterative hybrid SSI approach runtime can be further drastically reduced if applied in conjunction with the FVROM-INT approach implemented in ACS SASSI software (Ghiocel, 2022).

In addition to the main ***NONLINEAR*** module of ACS SASSI Option NON for performing the iterative nonlinear structure SSI analysis, the flowchart in Figure 1 includes other specialized software modules:

- ***The Section_Cuts_for_BBC module*** – This performs automatic wall section geometry identification and computes the wall section-cut forces for user-defined panels

- ***The BBC_JEAC_ACI_Fiber2D module*** – This computes shear and bending back-bone curves (BBC) for all the user-defined panels based on either the US standards or Japan standard recommendations or using a wall fiber model.

- ***The Create_Flange_Materials module*** – This creates wall flange nonlinear materials for each RC wall panel which are used to create a new structure model input file for performing nonlinear structure analysis

- ***The COMB_Shear_Bend module*** – This combines the nonlinear shear and bending interactive effects in RC wall panels at each SSI iteration.

There is also another module named **Floor_Cracking module which** is used only if the RC floor-cracking option is considered. It computes for the top and bottom floor faces for each thick shell element, the maximum principal stresses and compare them with the given concrete tension strength (per ACI 318 or ASCE 4-16 for US and JEAC 4601 for Japan) to identify the cracked elements.

The eleven steps for performing nonlinear SSI analysis briefly described below:

Step 1. Build the structure SSI model and write its input file. The RC walls should be spilt in separate wall panels that are defined at each floor level by an element shell group associated to each panel.

Step 2: Create the wall submodels for the major RC walls considered with nonlinear behavior

Step 3: Prepare input scripts for creating the initial SSI analysis input for performing the linear SSI analysis for the uncracked structure for seismic inputs (X, Y, Z) and gravity load.

Step 4: Run the initial linear SSI analysis including the STRESS module runs for the seismic and gravity load inputs. This step also combines the seismic X, Y and Z input direction STRESS binary response databases.

Step 5: Prepare the input files for the ***Section_Cuts_for_BBC*** module run. In this step, user also creates input files required in Step 8 and Step 10, respectively. Then, run the ***Section_Cuts_for_BBC*** module *which* creates the *Revised_Section_Data_for_BBC_wall#.in* text files including wall section-cut information at each floor level which need to be reviewed and modified by the analyst in next step.

Step 6: The analyst revises the *Revised_Section_Data_for_BBC_wall#.in* files including wall section-cut geometries and inputs new input data for nonlinear material parameters and reinforcement percentages, and eventually information on the section meshing if the 2D-section Fiber Model is used. The revised file is required as input for computing shear and bending BBCs

Step 7: After modifying the *Revised_Section_Data_for_BBC_wall#.in* files in Step 6, the ***BBC_JEAC_ACI_Fiber2D*** module is run to create the computed BBC files

Step 8: Run the ***Create_Flange_Materials*** module to create a new structure model that includes new materials which correspond to the wall flange materials.

Step 9: Use the ACS SASSI UI to create the inputs for the nonlinear SSI analysis in Step 10. This input file includes information on the BBC data produced in Step 7 and creates a complete input set for shear and bending for performing nonlinear SSI analysis using the ***NONLINEAR*** module.

Step 10: Run the nonlinear structure analysis using the ***NONLINEAR*** module at each iteration. After each nonlinear analysis iterative run, the shear and bending effects in the RC walls are combined using the ***COMB_Shear_Bend*** module.

Step 11: Finally, post-process the nonlinear SSI analysis results after the convergence is reached. The post-processing depends on the analyst' goals.

The above steps are run quasi-automatically with the exception of the preparatory input steps in Steps 1-2 for the FE models, Step 6 for the analyst'review of the wall section geometries and define input data for nonlinear materials, and Step 9 for integrating computed BBC data with new FE models created in Step 8.

ILLUSTRATIVE APPLICATION EXAMPLE

Seismic SSI Analysis Inputs

In this example an Auxiliary Building (AB) is considered. The RC shearwall building structure 3DFEM model is described in Figures 2 and 3.

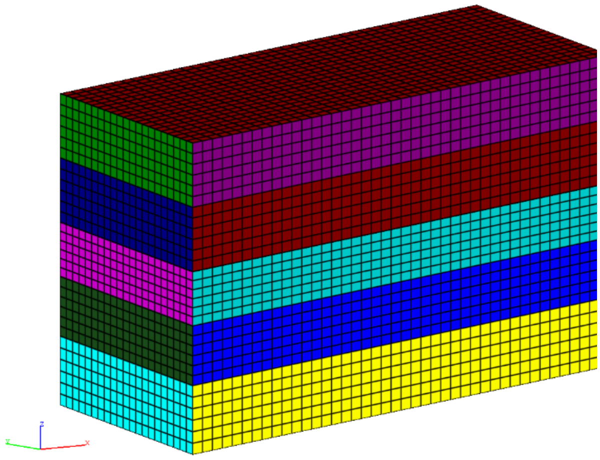


Figure 2: AB Shearwall Building Exterior View

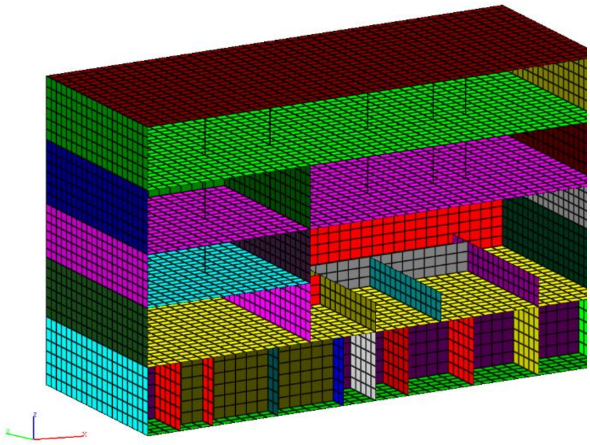


Figure 3: AB Shearwall Building Interior View

The AB shearwall SSI model is a surface model sitting on a uniform deep soil formation with V_s = 5,000 ft/s. The seismic input is defined by three RG1.60 spectrum compatible acceleration time histories defined at the ground surface for a BDBE level with the maximum ground acceleration scaled to 0.7g. The AB structure SSI model input file is AB_Model.pre shown in Figure 3 (for Step 1).

The static gravity input is simulated by a slow-varying sine curve with a 1.0g amplitude and a Fourier period of 40.96 seconds (8192 data points and a 0.005 sec. time step). The sine input should start from zero and end to zero in exactly all Fourier period points to avoid creating any dynamic effects. Due to the slow variation, this gravity input produces no dynamic response, providing only a static result.

Iterative Equivalent-Linear SSI Analysis Procedure

As part of the nonlinear SSI analysis process, the 3DFEM structure model (created in Step 1) must be split (in Step 2) into a set of selected nonlinear wall submodels as shown in Figure 4. The selected nonlinear wall submodels should include the main resistance walls of the structure. The RC wall submodel input files are AB_Model_Wall1.pre...AB_Model_Wall9.pre shown in Figure 4 (for Step 2).

For the 3DFEM structure model, there are nine major RC walls which are considered to behave inelastically, as illustrated in Figure 4. For each nonlinear wall, a submodel is created along the wall web, also including the perpendicular flanges at the ends of the wall. These submodels can be created in the ACS SASSI UI by first adding elements to a cut volume or adding selected elements, and then saving resulting cut to a wall submodel, as shown in red colored shell elements in Figure 3 for Step2.

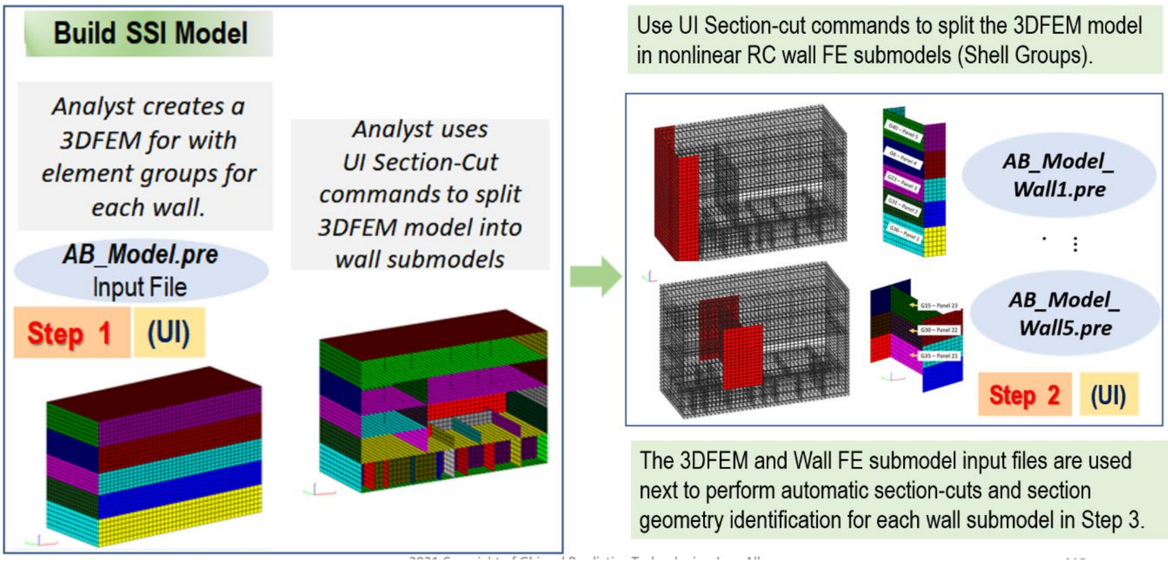


Figure 4 Creating AB SSI Model (Step 1) and RC Wall Submodels (Step 2)

It should be noted that for each floor level, different shell element groups should be defined as illustrated by the different colors in Figure 5. These shell element groups are associated with a corresponding wall panel at each floor level, using specialized commands in the ACS SASSI UI.

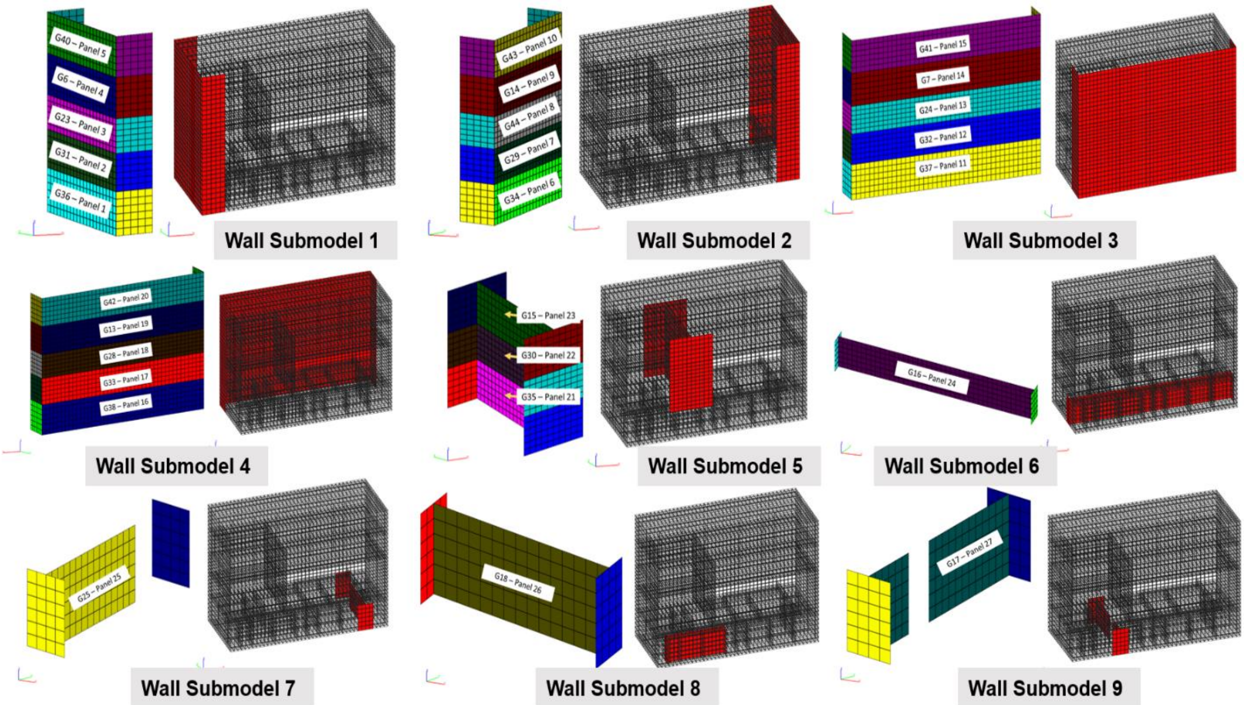


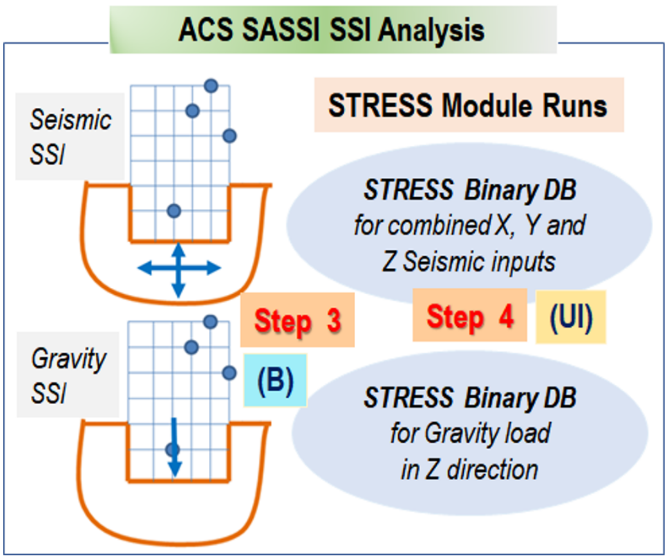
Figure 5 AB Structure Nonlinear RC Wall Submodels (Step 2)

The numbering of the panels shall be continuous from the first wall submodel to the last wall submodel and numbered from the bottom floors up to the top floors for each submodel (Figure 5).

In general, the RC walls start from the basemat level, as wall submodels 1-4, and 6-9, but in some cases, the RC walls may start from a higher elevation floor slab, between different floor levels, as wall submodel 5. These wall submodels are used to compute the seismic demands on the RC walls by performing automatic wall section-cuts at all floor levels. The structural wall flange sizes in submodels defined when creating the submodels should be larger than the effective flange sizes required by the applicable standard.

It should be noted that for the wall capacity and the BBC calculations, the effective flange sizes are automatically computed per the US or Japan RC standard requirements. However, the computed flange sizes can be adjusted based on engineering judgement as needed (in Step 6).

After the RC wall submodels are created, the initial linear SSI analysis for the uncracked structure is run for seismic inputs and gravity load (in Step 3), and the shell element stresses in the entire structures are computed and saved in two binary databases (in Step 4), as shown in Figure 6.

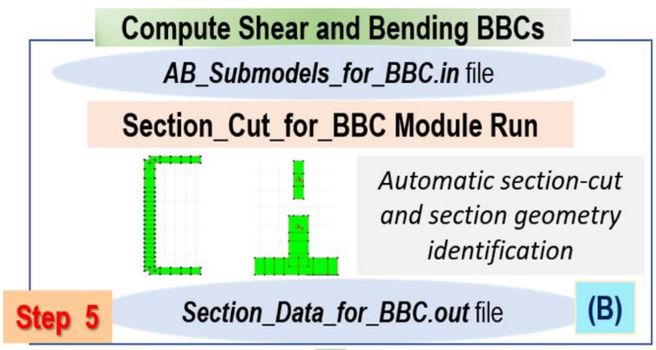


Step 3:
Perform SSI analysis (Batch)
1) Perform seismic ACS SASSI SSI analysis for the 3DFEM model using "Simultaneous Cases" ANALYS option to get FILE8s for post-processing
Step 4:
STRESS post-processing runs (Batch):
2) Run STRESS for the seismic inputs in X, Y and Z directions and create three binary DB for each input direction.
3) Run STRESS for the gravity (static) load for Z direction and create gravity binary DB
Combine X,Y,Z STRESS binary BD (B or 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.

Figure 6 Run SSI Analyses (Step 3) and Compute Structural Stresses (Step 4); Details are on right

After the structure stress databases for seismic inputs and gravity load are available (in Step 4), the wall sectional forces are computed for all nonlinear RC walls for all floor levels, and their section geometries are automatically identified, as shown in Figure 7 (Step 5). The ***Section_Cuts_for_BBC*** module is run in this step.



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

Figure 7 Compute Sectional Forces and Identify Sectional Geometries (Step 5); Details are on right

The ***Section_Cuts_for_BBC*** module run generates the *Section_Data_for_BBC.in* text files for each wall that needs to be edited and reviewed by the analyst in Step 6, as shown in Figure 8. This file should be edited and revised by the analyst as described in the figure. The generated *Section_Data_for_BBC.in* file has many output parameters with zero value (see green highlighted lines). The zero parameters correspond to the concrete and steel material properties and must be input by analyst (see rose highlighted lines). The analyst can change the section geometry parameters based on engineering judgement, if applicable. The analyst input for these material parameters is described in Figure 9. After the analyst edited these text files for each wall, the wall panel BBCs can be computed in Step 7.

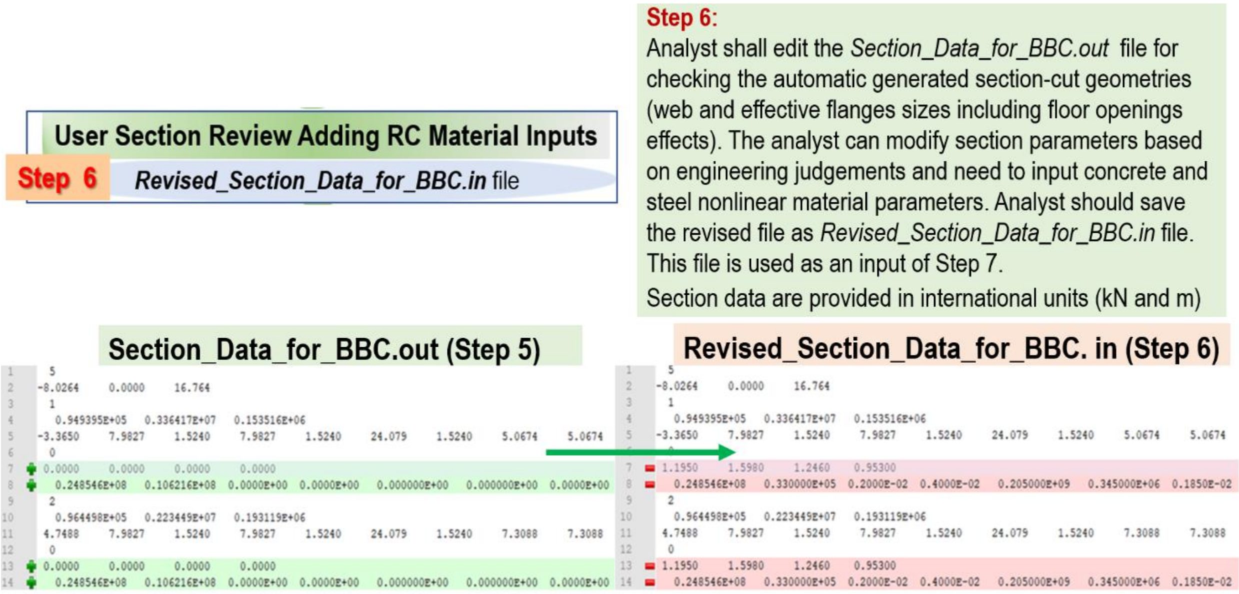


Figure 8 Analyst Reviews Wall Section Forces and Geometry Information (Step 6)

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 and each floor level

Figure 9 Analyst Needs to Input Data for Concrete and Reinforcement Materials (Step 6)

The shear and bending wall BBCs are computed by running the ***BBC_JEAC_ACI_Fiber2D*** module in Step 7. The wall section geometries can be regular wall planar shapes, as C, T, I cross-sections, or can be any non-planar wall shapes, as described in Figure 10. Computed BBC outputs are in Figure 11.

Computed shear and bending BBCs for the RC walls 1, 2 and 5 are shown in Figure 12. Two sets of BBCs are plotted, one set based on ACI 318-19/ASCE 4-16 standard in US and one set based on JEAC 4601-2015/AIJ RC 2018 in Japan. It should be noted that shear BBC based on Japan standards are higher for ultimate point computed with US standards. Explanation could be related to the lab test results, which for Japan standards include massive walls with closed sections or strong flanges (Taitokui, 1987). Also, ACI 318-19 wall shear capacity equations do not consider the bending moment and axial force interaction effects with the shear force. The wall bending BBC capacities using ACI 318 are lower at upper floors due to the reduced effective flanges computed for top floors.

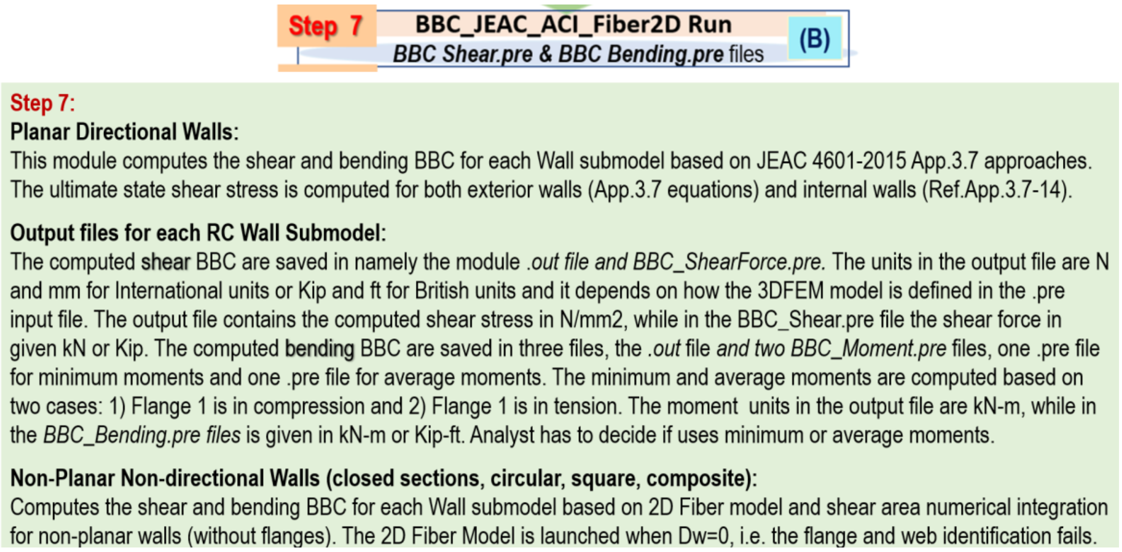
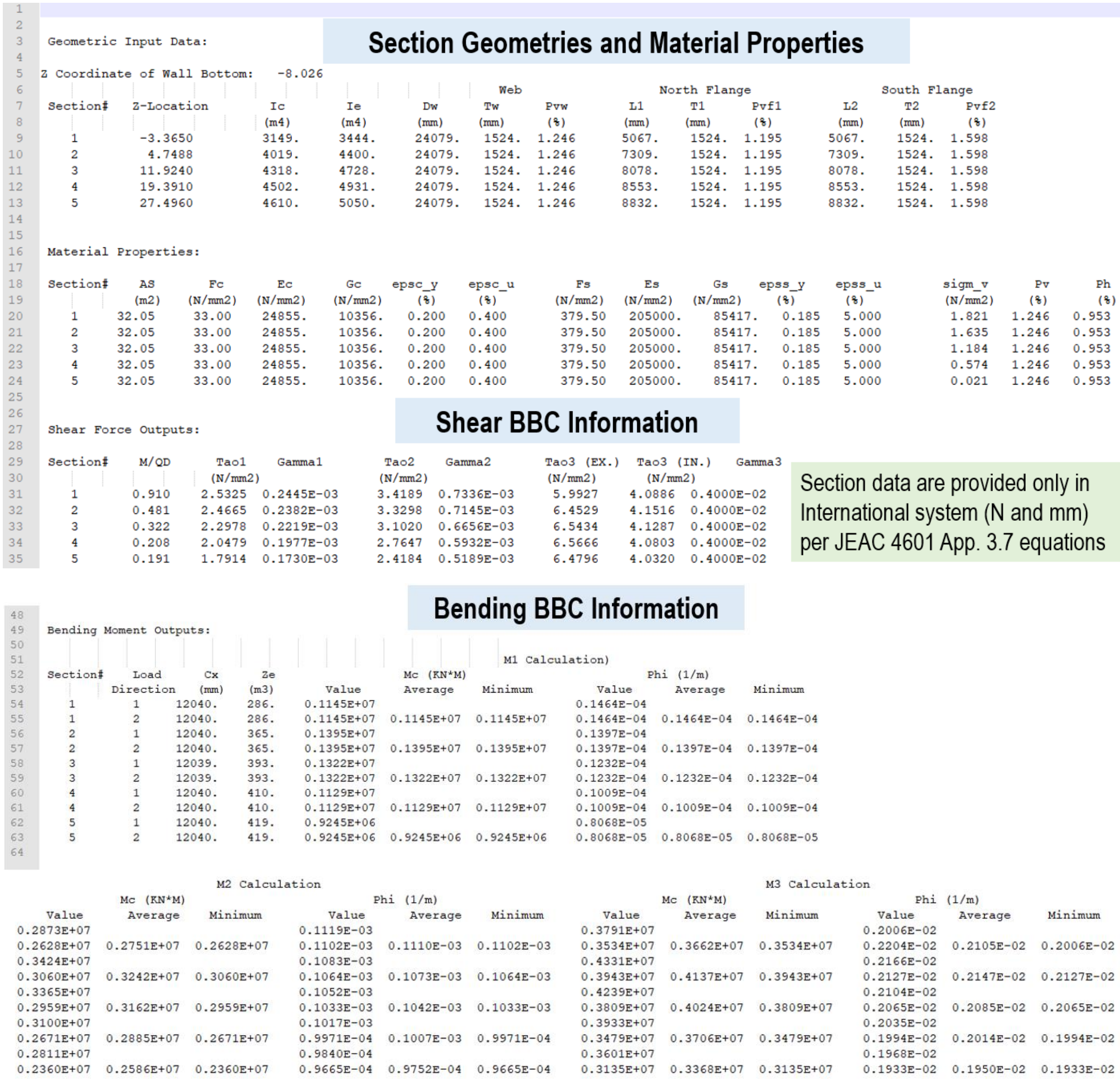


Figure 10 Compute Shear and Bending Wall Section BBCs for All Floor Levels (Step 7)



Section Geometries and Material Properties

Geometric Input Data:

Z Coordinate of Wall Bottom: -8.026

Section#	Z-Location	Ic (m4)	Ie (m4)	Dw (mm)	Web Tw (mm)	Web Pvw (%)	North Flange L1 (mm)	North Flange T1 (mm)	North Flange Pvf1 (%)	South Flange L2 (mm)	South Flange T2 (mm)	South Flange Pvf2 (%)
1	-3.3650	3149.	3444.	24079.	1524.	1.246	5067.	1524.	1.195	5067.	1524.	1.598
2	4.7488	4019.	4400.	24079.	1524.	1.246	7309.	1524.	1.195	7309.	1524.	1.598
3	11.9240	4318.	4728.	24079.	1524.	1.246	8078.	1524.	1.195	8078.	1524.	1.598
4	19.3910	4502.	4931.	24079.	1524.	1.246	8553.	1524.	1.195	8553.	1524.	1.598
5	27.4960	4610.	5050.	24079.	1524.	1.246	8832.	1524.	1.195	8832.	1524.	1.598

Material Properties:

Section#	AS (m2)	Fc (N/mm2)	Ec (N/mm2)	Gc (N/mm2)	epsc_y (%)	epsc_u (%)	Fs (N/mm2)	Es (N/mm2)	Gs (N/mm2)	epss_y (%)	epss_u (%)	sigm_v (N/mm2)	Pv (%)	Ph (%)
1	32.05	33.00	24855.	10356.	0.200	0.400	379.50	205000.	85417.	0.185	5.000	1.821	1.246	0.953
2	32.05	33.00	24855.	10356.	0.200	0.400	379.50	205000.	85417.	0.185	5.000	1.635	1.246	0.953
3	32.05	33.00	24855.	10356.	0.200	0.400	379.50	205000.	85417.	0.185	5.000	1.184	1.246	0.953
4	32.05	33.00	24855.	10356.	0.200	0.400	379.50	205000.	85417.	0.185	5.000	0.574	1.246	0.953
5	32.05	33.00	24855.	10356.	0.200	0.400	379.50	205000.	85417.	0.185	5.000	0.021	1.246	0.953

Shear BBC Information

Shear Force Outputs:

Section#	M/QD	Tao1 (N/mm2)	Gamma1	Tao2 (N/mm2)	Gamma2	Tao3 (EX.) (N/mm2)	Tao3 (IN.) (N/mm2)	Gamma3
1	0.910	2.5325	0.2445E-03	3.4189	0.7336E-03	5.9927	4.0886	0.4000E-02
2	0.481	2.4665	0.2382E-03	3.3298	0.7145E-03	6.4529	4.1516	0.4000E-02
3	0.322	2.2978	0.2219E-03	3.1020	0.6656E-03	6.5434	4.1287	0.4000E-02
4	0.208	2.0479	0.1977E-03	2.7647	0.5932E-03	6.5666	4.0803	0.4000E-02
5	0.191	1.7914	0.1730E-03	2.4184	0.5189E-03	6.4796	4.0320	0.4000E-02

Section data are provided only in International system (N and mm) per JEAC 4601 App. 3.7 equations

Bending BBC Information

Bending Moment Outputs:

M1 Calculation)

Section#	Load Direction	Cx (mm)	Ze (m3)	Mc (KN*M) Value	Mc (KN*M) Average	Mc (KN*M) Minimum	Phi (1/m) Value	Phi (1/m) Average	Phi (1/m) Minimum
1	1	12040.	286.	0.1145E+07			0.1464E-04		
1	2	12040.	286.	0.1145E+07	0.1145E+07	0.1145E+07	0.1464E-04	0.1464E-04	0.1464E-04
2	1	12040.	365.	0.1395E+07			0.1397E-04		
2	2	12040.	365.	0.1395E+07	0.1395E+07	0.1395E+07	0.1397E-04	0.1397E-04	0.1397E-04
3	1	12039.	393.	0.1322E+07			0.1232E-04		
3	2	12039.	393.	0.1322E+07	0.1322E+07	0.1322E+07	0.1232E-04	0.1232E-04	0.1232E-04
4	1	12040.	410.	0.1129E+07			0.1009E-04		
4	2	12040.	410.	0.1129E+07	0.1129E+07	0.1129E+07	0.1009E-04	0.1009E-04	0.1009E-04
5	1	12040.	419.	0.9245E+06			0.8068E-05		
5	2	12040.	419.	0.9245E+06	0.9245E+06	0.9245E+06	0.8068E-05	0.8068E-05	0.8068E-05

M2 Calculation

Section#	Load Direction	Mc (KN*M) Value	Mc (KN*M) Average	Mc (KN*M) Minimum	Phi (1/m) Value	Phi (1/m) Average	Phi (1/m) Minimum
1	1	0.2873E+07			0.1119E-03		
1	2	0.2628E+07	0.2751E+07	0.2628E+07	0.1102E-03	0.1110E-03	0.1102E-03
2	1	0.3424E+07			0.1083E-03		
2	2	0.3060E+07	0.3242E+07	0.3060E+07	0.1064E-03	0.1073E-03	0.1064E-03
3	1	0.3365E+07			0.1052E-03		
3	2	0.2959E+07	0.3162E+07	0.2959E+07	0.1033E-03	0.1042E-03	0.1033E-03
4	1	0.3100E+07			0.1017E-03		
4	2	0.2671E+07	0.2885E+07	0.2671E+07	0.9971E-04	0.1007E-03	0.9971E-04
5	1	0.2811E+07			0.9840E-04		
5	2	0.2360E+07	0.2586E+07	0.2360E+07	0.9665E-04	0.9752E-04	0.9665E-04

M3 Calculation

Section#	Load Direction	Mc (KN*M) Value	Mc (KN*M) Average	Mc (KN*M) Minimum	Phi (1/m) Value	Phi (1/m) Average	Phi (1/m) Minimum
1	1	0.3791E+07			0.2006E-02		
1	2	0.3534E+07	0.3662E+07	0.3534E+07	0.2204E-02	0.2105E-02	0.2006E-02
2	1	0.4331E+07			0.2166E-02		
2	2	0.3943E+07	0.4137E+07	0.3943E+07	0.2127E-02	0.2147E-02	0.2127E-02
3	1	0.4239E+07			0.2104E-02		
3	2	0.3809E+07	0.4024E+07	0.3809E+07	0.2065E-02	0.2085E-02	0.2065E-02
4	1	0.3933E+07			0.2035E-02		
4	2	0.3479E+07	0.3706E+07	0.3479E+07	0.1994E-02	0.2014E-02	0.1994E-02
5	1	0.3601E+07			0.1968E-02		
5	2	0.3135E+07	0.3368E+07	0.3135E+07	0.1933E-02	0.1950E-02	0.1933E-02

Figure 11 Computed Shear and Bending BBC Output Files for User Review (Step 7)

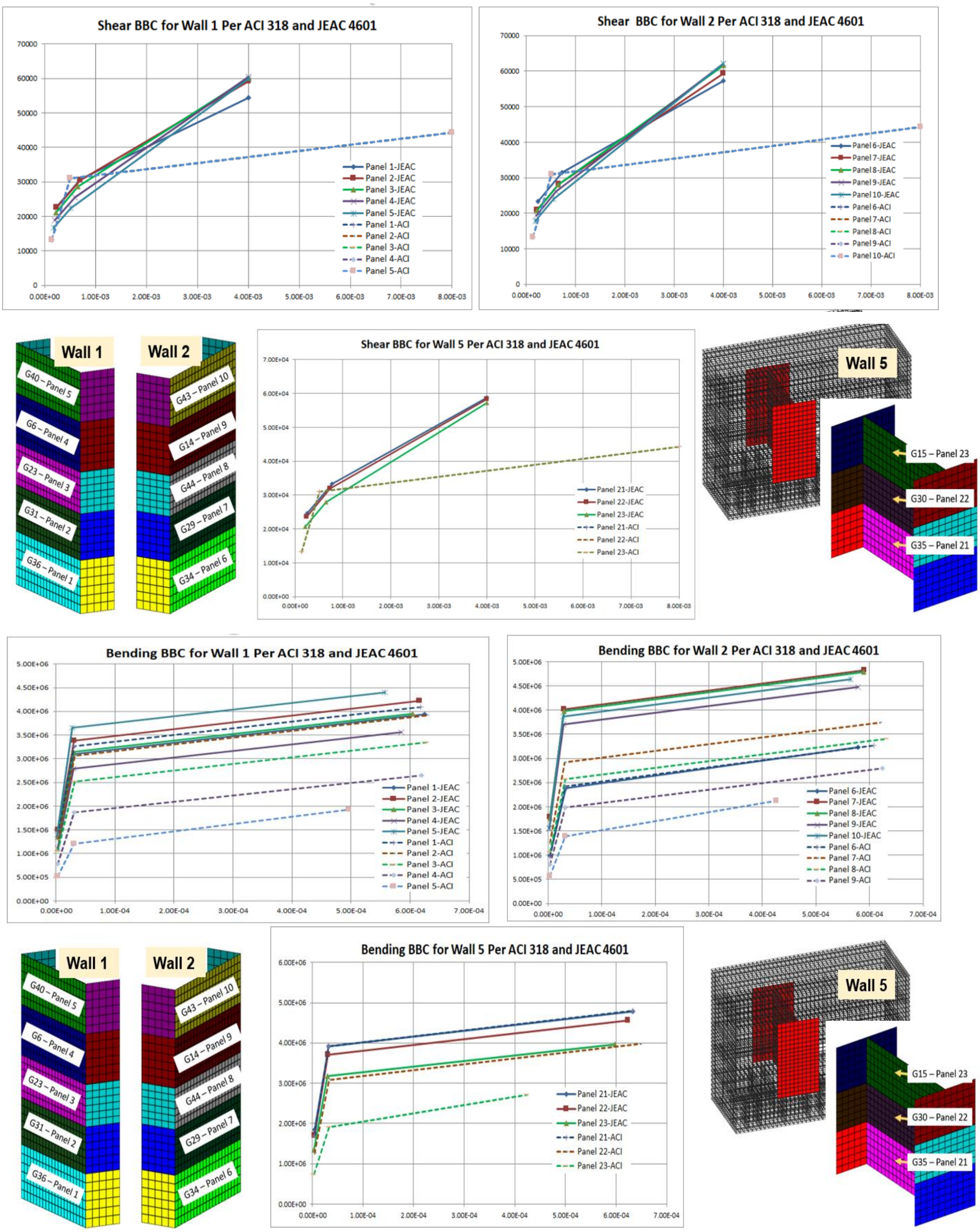


Figure 12 Computed Shear and Bending BBCs for Walls 1, 2 and 5 Based on US and Japan Standards

In next step, Step 7, the the ***Create_Flange_Materials*** module is run to create a new structure model including new nonlinear materials for the wall flanges extended to cover the effective flange widths. This module is run only for the first iteration. Figure 13 shows the new FE models including separate flange materials for ACI 318-19 standards and JEAC 4601-2015 and AIJ RC-2018 standards.

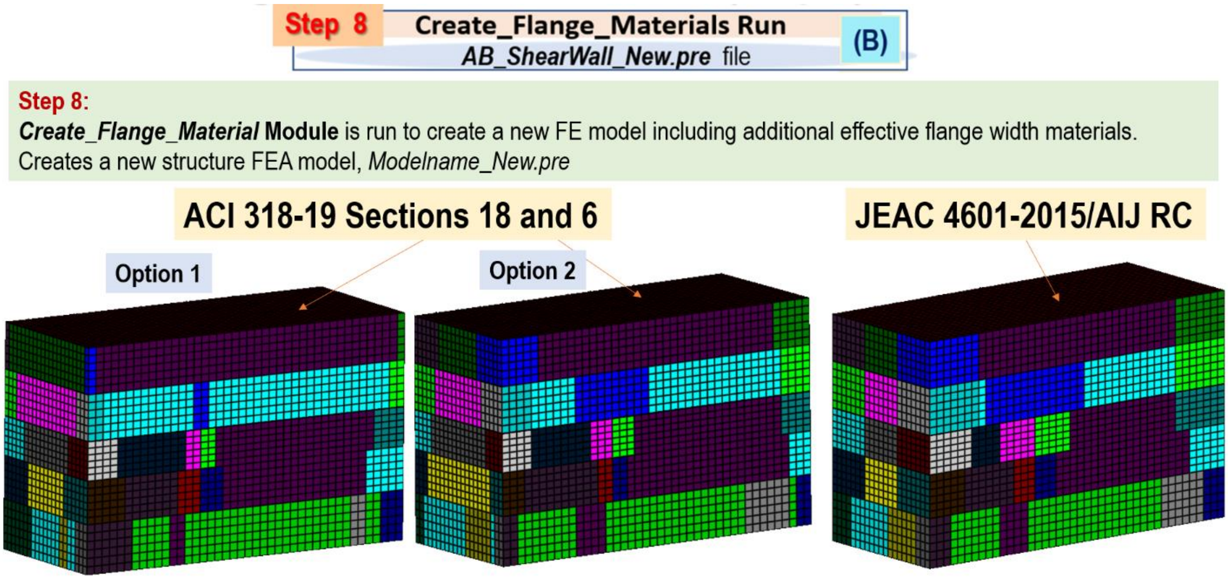


Figure 13 New FE Models Including Nonlinear Flange Materials Using US and Japan Standards

The generated new FE model for nonlinear analysis is identical with the initial elastic FE model, except that the shell element groups included in the wall panels include new materials for flanges.

It should be noted that the new variable size flange wall FE model per height shown in Figure 13 is used for computing the wall panel BBCs and the iterated effective stiffness and damping values computed during nonlinear analysis (later in Step 10). The initial constant flange size wall FE model with uncracked concrete materials shown in Figure 5 is used only in Step 5 for computing the initial panel sectional forces and moments. After the new FE models are automatically created in Step 8, the final input file for the nonlinear structure analysis can be generated using the ACS SASSI UI in Step 9. Then, the NONLINEAR module is iteratively run for nonlinear structure analysis in Step 10. Figure 14 summarizes the Steps 9, 10 and 11. The Step 11 is basically outside the iteration loop after the nonlinear responses are converged in about 5-6 iterations.

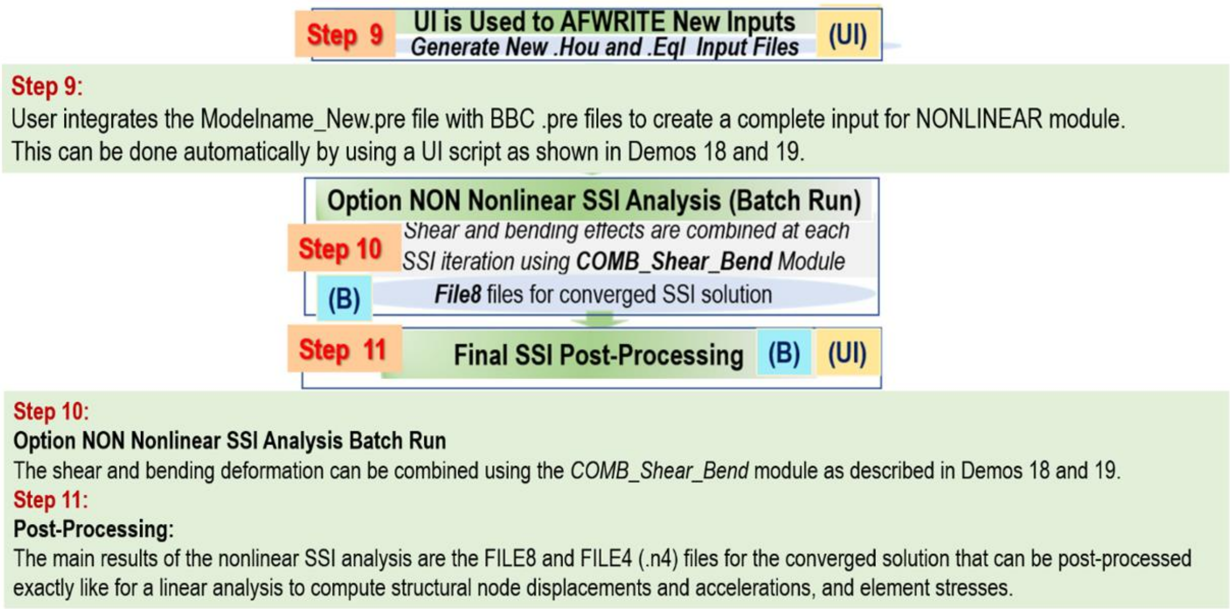


Figure 14 Preparing Inputs (Step 9) and Running Iterative Nonlinear Structure Analysis (Step 10), Plus Post-Processing SSI Nonlinear Responses After Convergence is Reached (Step 11)

In this application example, four RC wall hysteretic models were considered based on the US (CMS and CMB models) or Japan (PO and PODT models) practices:

- Cheng-Mertz Shear model (model 1) - US
- Cheng-Mertz Bending model (model 2) - US
- JEAC 4601 Point-Oriented shear model (model 5) - Japan
- JEAC 4601 Point-Oriented Degraded-Trilinear bending model (model 6) – Japan

Nonlinear SSI Analysis Results (Iterated Responses) Using US and Japan Standards

Damping Limitation Effects

Per ASCE 4-16 Section 3 recommendation, the RC wall equivalent damping ratios were limited to 10% for the 0.70g BDBE input level, defined in standard as Response Level 3. Figure 15 shows the effects of 10% damping limitation on the nonlinear ISRS using ACI 318-based BBC and Cheng-Mertz models.

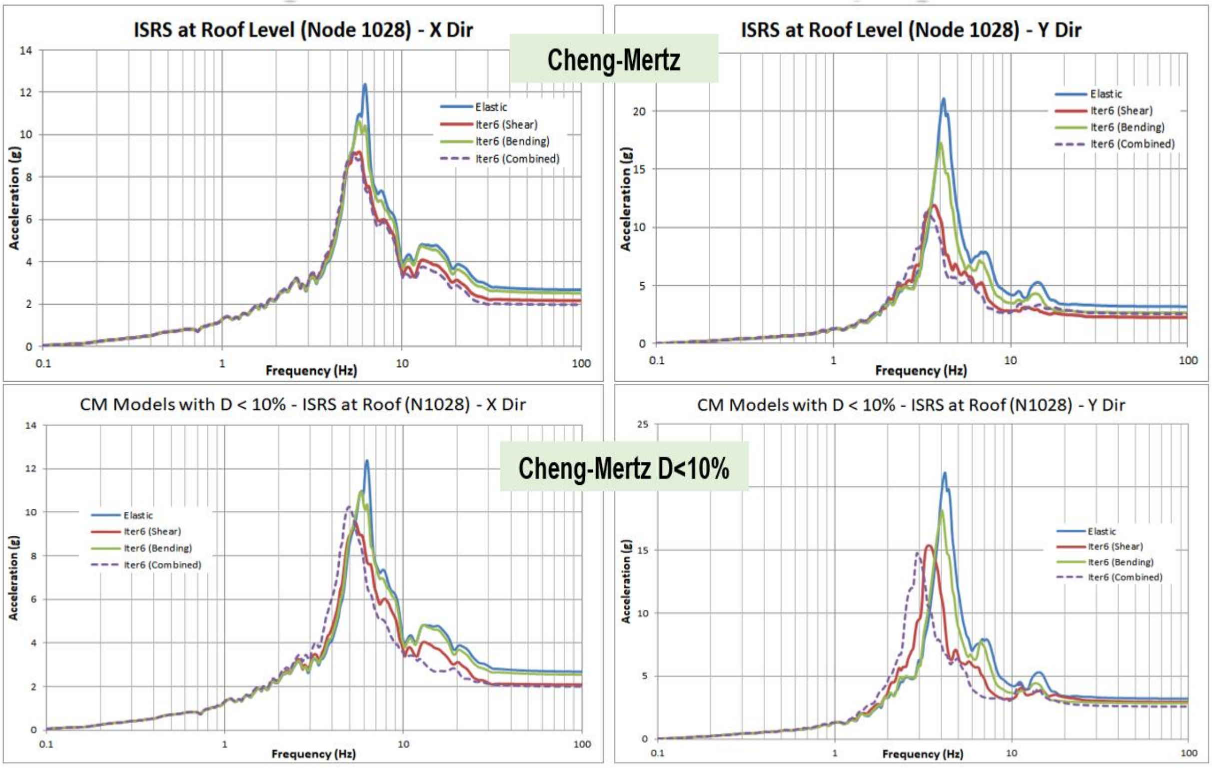


Figure 15 Effects of Equivalent Damping Limitation to 10% Per ASCE 4-16 for Response Level 3

It should be noted that for the case of 10% damping limit, the nonlinear ISRS amplitude at the top of the AB structure in transverse (Y) direction increases from 11g to 15g for 0.70g seismic input.

Comparative Nonlinear SSI Responses Using US and Japan Standards

In Figures 16 through 21 show comparative nonlinear SSI responses based on US standards, ACI in legend, and Japan standards, JEAC Option 2 in legend. The JEAC Option 1 in legend implies the zero hysteretic damping assumption based on the JEAC 4601 standard zero hysteretic damping requirement for close or stable loop, which implies that there is no energy dissipation for a hysteresis closed cycle (Ghiocel et al., 2022).

The JEAC Option 1 that is overly conservative, usually is being disregarded in Japan practice and replaced with the JEAC Option 2 that compute the hysteretic damping based on the energy loss during the entire earthquake duration (Nitta et al., 2022).

Figures 16 and 17 show the iterated equivalent elastic modulus and equivalent viscous damping for shear and bending effects. The differences between the computed results using US (red) and Japan (green) standards are relatively minor. The shear deformation is more significant on the stiffness degradation for most of RC walls, but for the base floor sections which are most damaged walls, both shear and bending damaging effects are quite similar. The small arrow marks the wall panels 1, 7 and 21 (see Figure 12 for their floor locations and BBCs) which are the most damaged.

Figures 18 and 19 show the nonlinear hysteretic responses of the same wall panels, 1, 7 and 21, for the in-plane shear deformation and bending using US practice, ACI 318-based BBCs and Cheng-Mertz models (CMS and CMB) and Japan practice, JEAC 4601 BBCs and PO models (PO and PODT). The JEAC 4601-based hysteretic responses show slightly larger deformation and larger sectional forces and moments for selected wall panels.

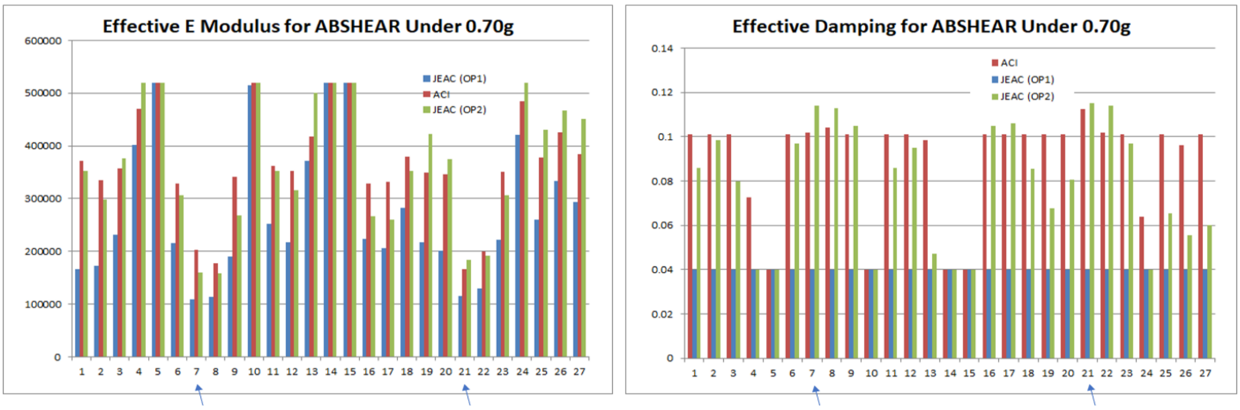
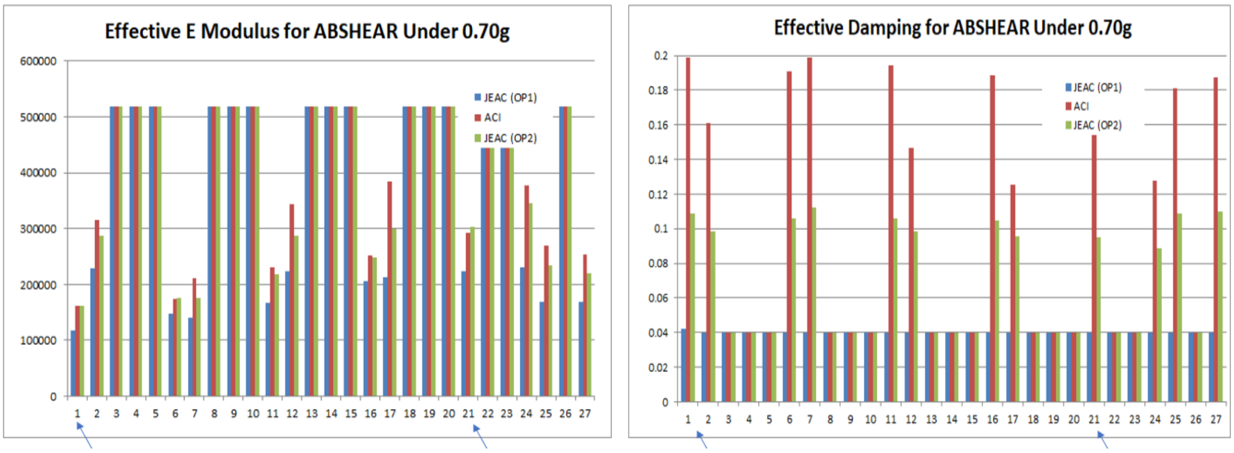


Figure 16 Equivalent Elastic Modulus and Equivalent Damping Due to Shear Effects



Figures 17 Equivalent Elastic Modulus and Equivalent Damping Due to Bending Effects

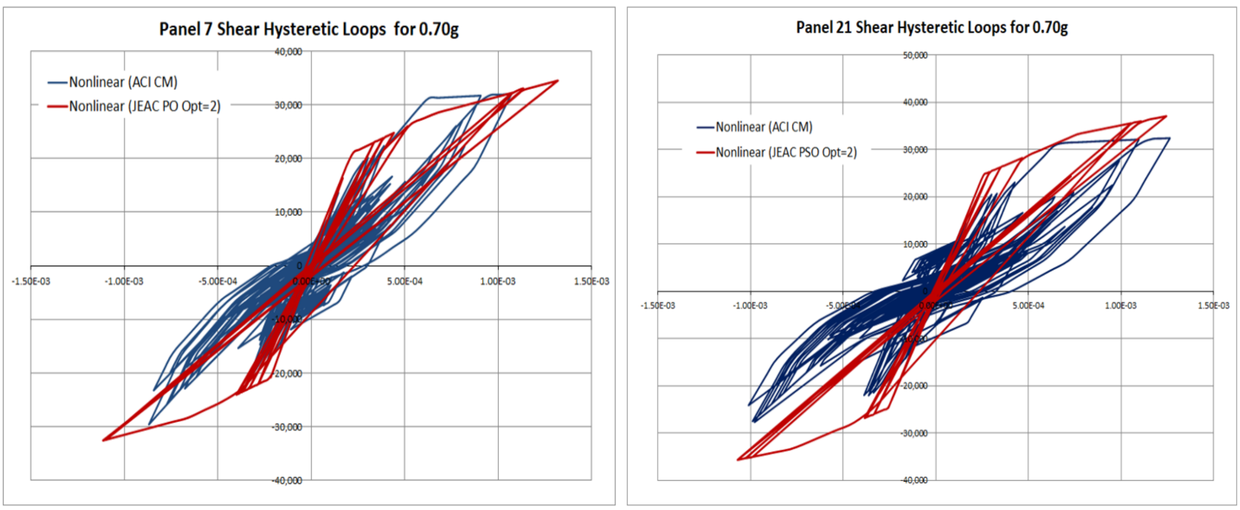


Figure 18 Shear Hysteretic Responses for Wall Panels 7 and 21 (see Figure 12 for locations and BBC)

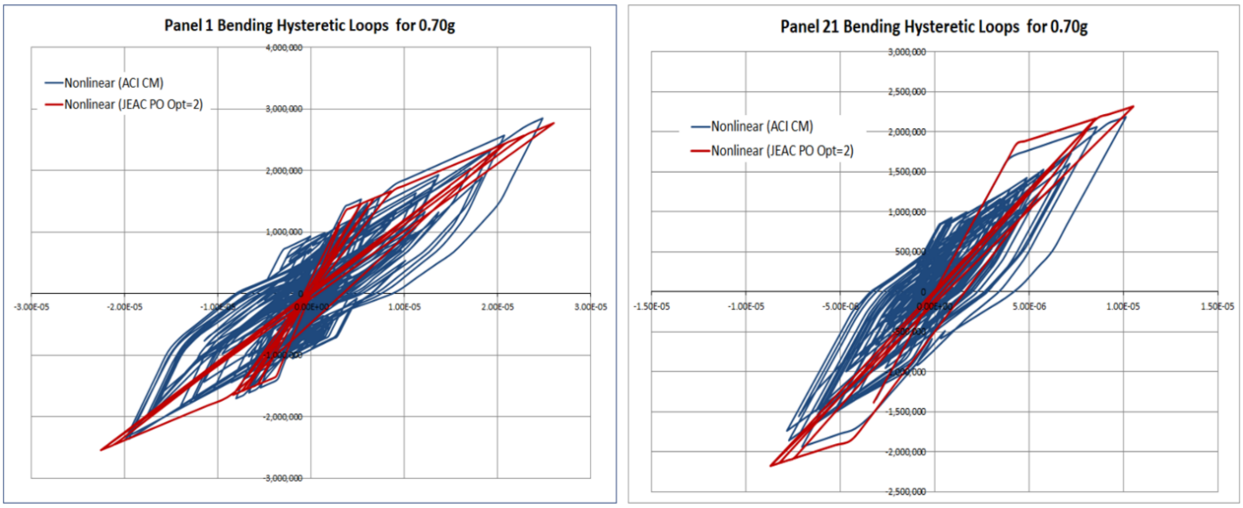


Figure 19 Bending Hysteretic Responses for Panels 7 and 21 (see Figure 12 for locations and BBC)

Figures 20 and 21 show the computed ISRS and the SSI displacements at the top of the AB structure.

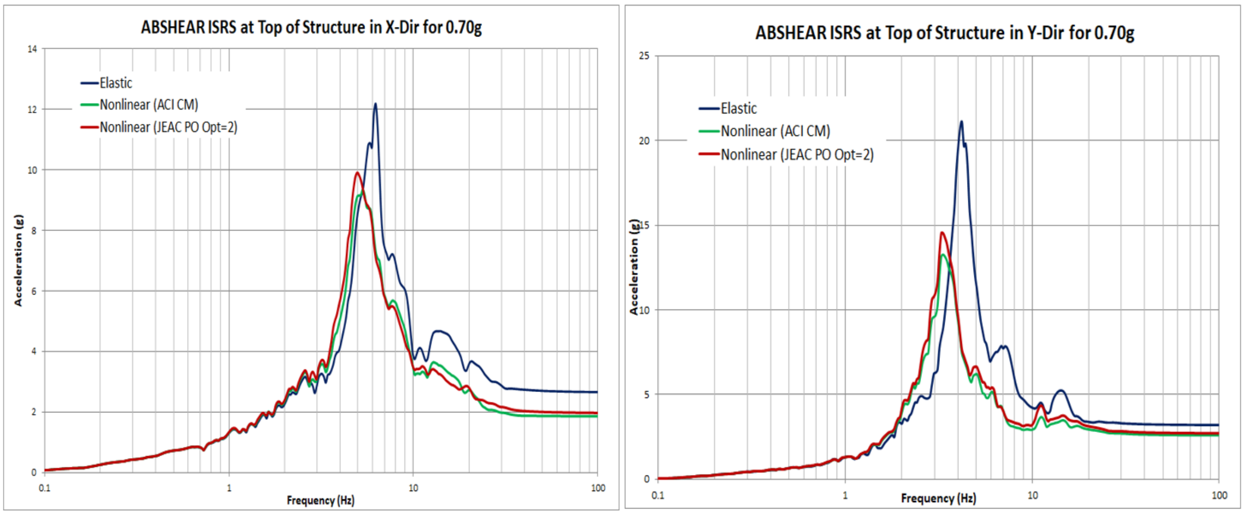


Figure 20 Comparative Nonlinear ISRS at Top of AB Structure in X (Long) and Y (Trans) Directions

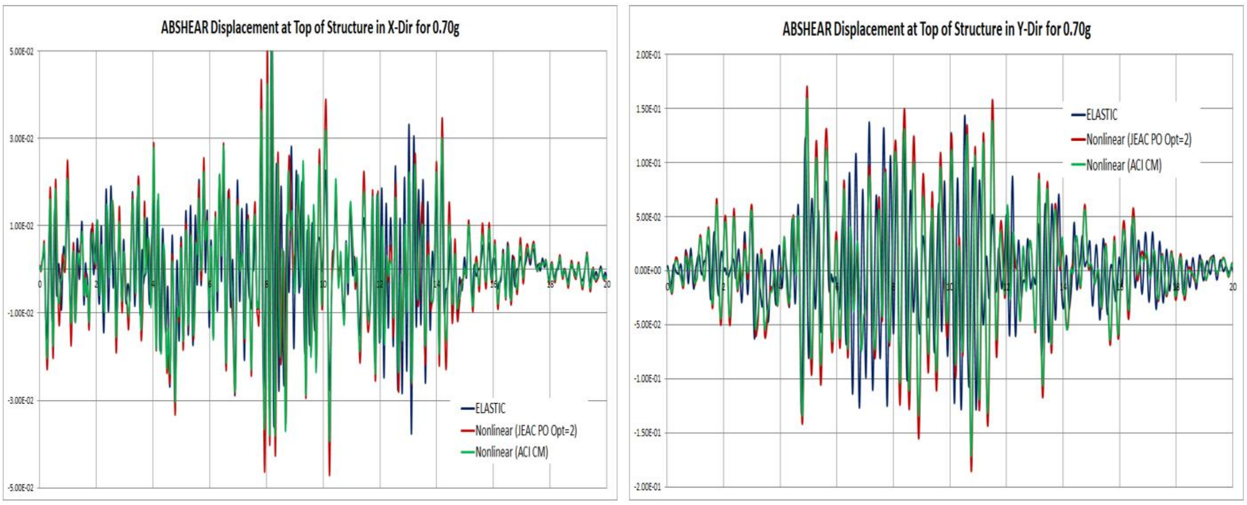


Figure 21 Nonlinear SSI Displacements at Top of AB Structure in X (Long) and Y (Trans) Directions

Floor Cracking Effects on Floor Vertical ISRS and Displacements

Figures 22 through 24 show the effect of floor cracking on the vertical ISRS and displacement of the floors. Figure 22 visually shows the effect of cracking based on ACI 318/ASCE 4-16 Section 3 and JEAC 4601 criteria. It should be noted that concrete tension strength is lower for JEAC 4601.

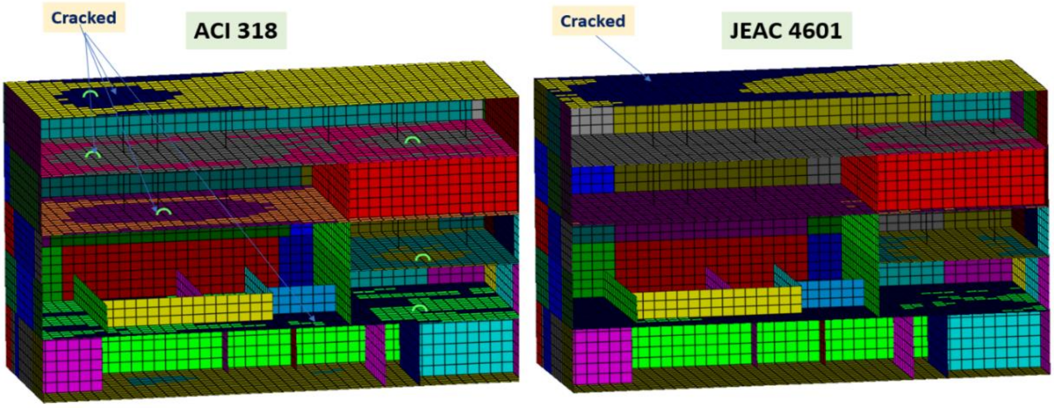


Figure 22 Computed Floor Cracking Patterns Based on US and Japan Standards

Figures 23 and 24 show the computed ISRS and displacements for the 3rd Floor level (Elevation 26.9ft) and the 6th Floor level (Elevation 79.6ft) based on the ASCE 4-16 Section 3 cracking criterion. It should be noted that in some cases the floor cracking effects can increase the floor vertical ISRS and maximum displacements up to 20-30%, as shown in Figures 23 and 24. For the other floor locations the cracking effects were less significant. Not shown herein are the horizontal ISRS that are only minorly, basically negligibly, affected.

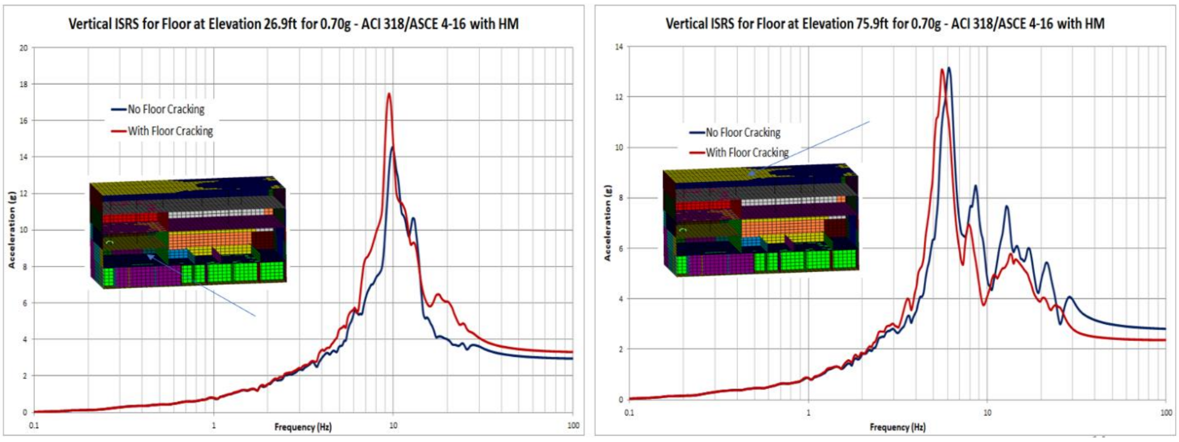


Figure 23 Effects of Floor Cracking on Vertical ISRS for 3rd Floor and 6th Floor (Roof) Slabs

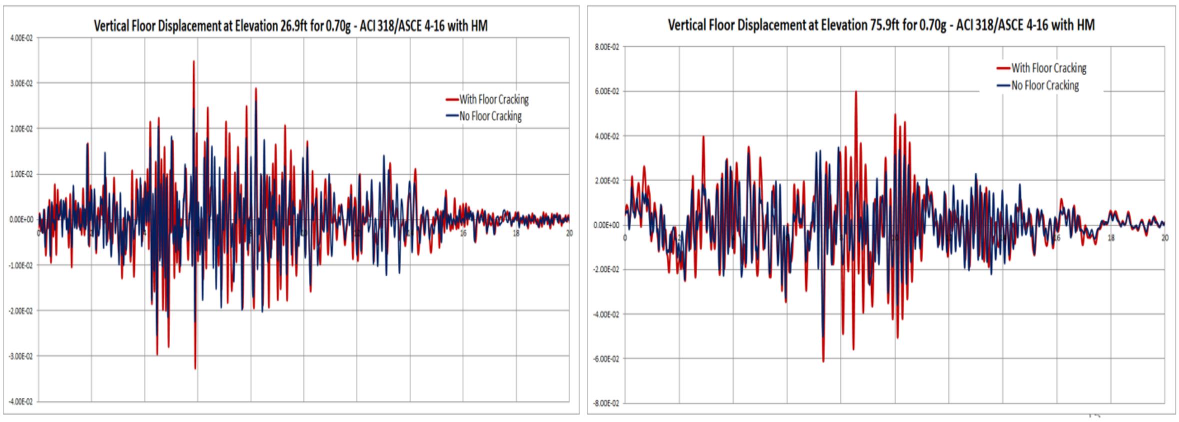


Figure 24 Effects of Floor Cracking on Vertical Displacement for 3rd Floor and 6th Floor (Roof) Slabs

CONCLUDING REMARKS

The Part 1 paper introduces a practical nonlinear SSI analysis approach based on an iterative procedure that efficiently couples the equivalent-linear complex frequency SSI analysis with the nonlinear time-domain structure analysis. The iterative hybrid SSI approach is applicable to both the DBE and BDBE project applications.

The Part 2 paper explains in relative detail the application of the iterative SSI hybrid approach and exemplifies it for an Auxiliary Building RC shearwall structure. Comparative SSI results based on US and Japan standard requirements are shown. The effects of floor cracking are also investigated.

The iterative SSI hybrid approach implemented in the ACS SASSI Option NON permits an affordable, fast and accurate, nonlinear seismic SSI analysis in compliance with current regulatory requirements in US and Japan. Several independent multiyear studies as mentioned herein, validated the practicality of the iterative SSI hybrid approach for potential application in future to the new advanced reactor projects.

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