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COMPARATIVE STUDY USING 3DFEM AND STICK NONLINEAR SSI MODELS FOR RC SHEARWALL STRUCTURE

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ABSTRACT

Due to the high seismic site conditions, the nonlinear seismic SSI analysis is required in Japan for the design basis analyses of the NPP structures. The nonlinear SSI analysis methodology under a severe earthquake motion is provided in the Japan JEAC 4601-2015 code recommendations. The code provides the evaluation method of restoring force characteristics of RC walls based on the experimental data of the RC wall. The JEAC 4601 approaches were implemented in the ACS SASSI Option NON software which is based on an iterative hybrid complex frequency-time domain approach for modelling the hysteretic behaviour of RC walls (Ghiocel et al. 2022a, 2022b). In the previous study, the nonlinear analysis methodology of the Option NON was validated by the comparison of analysis results obtained by DYNA2E (CTC ITOCHU, 2019), which is a conventional FEA software using the time-domain direct integration method (Nitta et al. 2022a). The comparative nonlinear SSI analysis results showed good agreement. However, the used building model was very simple tower structure with fixed base condition. Therefore, in this paper a realistic, typical nuclear RC shearwall building with a complex structural configuration founded on firm soil was considered. The paper provides further analysis comparison results using both 3DFEM and Stick nonlinear SSI models for the RC structure surface mounted on the uniform site condition.

INTRODUCTION

Application of JEAC 4601-2015 Code for Seismic Analysis and Design

The JEAC 4601-2015 code provides recommendations for seismic design of the nuclear facilities in Japan. It requires designers to ensure that there is sufficient deformation capability and ultimate capacity of RC structures against the design basis earthquake (Ss). The code also provides recommendations for the nonlinear SSI analysis methodology under a severe earthquake motion. The nonlinearity to be considered includes material nonlinearity in concrete structure and soil, geometric nonlinearity due to foundation uplift (Nitta et. al, 2022b), and restoring force characteristics of structure. This paper focuses on the force characteristics of structure according to Section 3.5.6 of the JEAC 4601-2015. ACS SASSI Option NON has been developed as an alternative to replace the lumped mass stick model modelled based on JEAC 4601-2015 with a 3DFEM model. While it can consider foundation uplift based on JEAC 4601-2015, the contact and separation between the embedment and the surrounding soil are not considered.

According to JEAC 4601-2015, when the structure is modelled as a lumped mass stick model and a horizontal seismic response analysis is performed, the restoring force characteristics of the RC shear wall must be evaluated in two ways: in a shear stress-shear strain relationship (hereinafter referred to as "τ-ɤ relationship") and the bending moment-curvature relationship (hereinafter referred to as “M-φ relationship”). The code provides the evaluation method of restoring force characteristics based on the experimental data of the RC building shear wall of the reactor building.

Both the shear τ-ɤ relationship and bending M-φ relationship are indicated by a trilinear Back-bone Curve s (BBCs) as shown in Figure 1. Details of the evaluation method are shown in Appendix 3.7 of JEAC 4601-2015 and summarized in Nitta et al. (2022a). The hysteresis characteristic of τ-ɤ relation is the maximum point-oriented type (PO), and the stable loop has no hysteresis damping. The hysteresis characteristics of M-φ relation is the maximum point-oriented degrading trilinear type (PODT). The ratio of bending deformation to the total deformation is considered be quite small before bending yielding. Therefore, a stable loop without having an area is considered before bending yielding (in the first and second stiffness regions). However, hysteresis damping was considered in the third stiffness range.

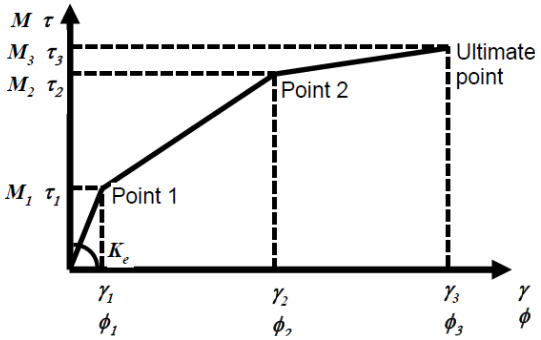


Figure 1 Back-bone Curve (BBC)

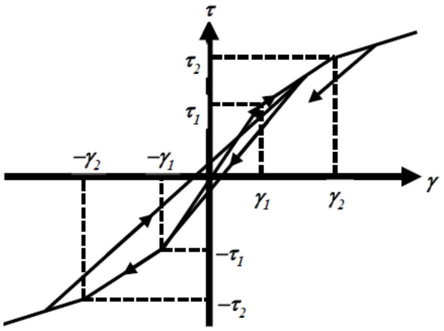


Figure 2 Maximum Point-Oriented (PO) Shear Model

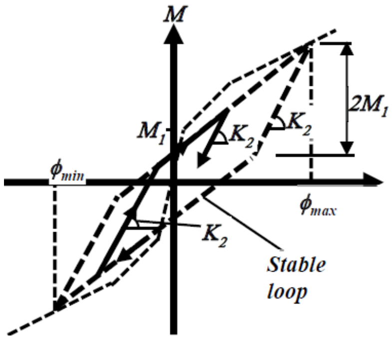


Figure 3 Maximum Point-Oriented Degraded-Trilinear (PODT) Bending Model

Application of Iterative Equivalent-Linearization for Nonlinear Seismic SSI Analysis

The JEAC 4601 code approaches were implemented in the ACS SASSI Option NON software, which is based on a hybrid complex frequency-time domain approach that uses an iterative equivalent-linearization procedure for modelling the hysteretic behaviour of the RC walls (Ghiocel, 2022a and 2022b). The software includes the automatic computation of the RC wall back-borne curves (BBC) for shear and bending deformation including both the effects of gravity and 3D seismic loads in walls, based on JEAC 4601-2015.

The applied hybrid approach based on iterative equivalent-linearization procedure for modelling the hysteretic behaviour of RC walls provides a highly efficient and reasonably accurate approach to nonlinear seismic analysis as mentioned by several engineering studies in US, France and more recent in Japan (Ghiocel, 2015, Herve-Secourgeon et al., 2018, Ichihara et al., 2022).

Herve-Secourgeon (Secourgeon et al., 2018) based on a series of seismic analysis research studies (not including SSI effects) mentioned that the iterative equivalent-linearization "*gains are impressive, and the results are very consistent*" when benchmarked against full nonlinear time-domain analysis and validated against experimental RC structure tests at the CEA Saclay laboratories.

Ichihara (Ichihara et al., 2022) based on multiyear validation studies sponsored by JAEA concluded that the iterative *"equivalent-linear analysis is suitable for practical SSI analysis*". Ichihara mentioned that it provides simpler analytical conditions than nonlinear analysis, includes frequency-independent damping, and the computation time is much shorter comparing with "*nonlinear 3DFEM analysis based on the conventional material constitutive law requires detailed FEM modeling, including the surrounding soil, which requires several weeks for a single analysis even with current high-performance computers"*

In addition to the mentioned studies, in a previous study, Nitta (Nitta et al., 2022a) validated the nonlinear seismic analysis methodology implemented in the ACS SASSI Option NON software using a simple two-story tower building with fixed base condition. The seismic analysis results obtained using ACS SASSI Option NON were compared with the results obtained using the DYNA2E software (CTC ITOCHU, 2019). DYNA2E is a seismic SSI analysis software with time-domain direct integration method applied to nonlinear stick models. The comparison results showed good agreement for ISRS and structural forces.

However, it was also found that there are some differences in in-structure response spectra (ISRS), although the peak frequency and acceleration of two methods are close. The DYNA2E spectra has the second peak at the higher frequencies associated to elastic frequency, but the ACS SASSI spectra have only one peak. This is due to the time-domain transient analysis of DYNA2E with a degrading structure from initial elastic state to the final nonlinear state. Since ACS SASSI is based on iterative equivalent linear analysis, the peak is based on the final equivalent stiffness frequency, and the transient peak shift in the time-domain can't be captured precisely. This transient peak shifting effect is highly dependent of the input motion time-history (Fourier) phasing which is different from input motion to input motion. To compensate for this shortcoming of ISRS by equivalent-linear analysis, the method applying multiple displacement reduction factors (DRF) is studied in the next section. A practical solution to avoid input motion phasing effects is to use multiple seismic input motions and compute mean responses as required by ASCE 4-16 code.

The previous study was limited to a simple tower building model and fixed base condition. Therefore, in this paper a realistic, typical nuclear RC shearwall building with a complex structural configuration founded on firm soil was considered. This paper provides further analysis comparison results using both 3DFEM and Stick nonlinear SSI models for the RC structure surface mounted on the uniform and constant soil condition.

For this study, multiple time-history input motions were considered. Seven seismic input motion were used. The result comparisons were done for the mean ISRS and mean of maximum structural forces as recommended by ASCE 4-16 code. The averaging of the sample responses reduces the eventual biases existing for each sample due to the input motion phasing effects.

STUDY OF DISPLACEMENT REDUCTION FACTOR (DRF)

The ACS SASSI Option NON is based on a hybrid complex frequency-time domain approach that uses a local iterative equivalent-linearization procedure for modelling the hysteretic behaviour of the RC walls. Figure 4 shows the local iterative equivalent-linearization procedure. At each iteration step, if convergence does not satisfy the specific criteria, (3) nonlinear force time history is calculated from the deformation time history and nonlinear BBC of each wall. Then, (4) equivalent stiffness used for next step are calculated by multiplying the displacement reduction factor (DRF) to the maximum displacement of the previous step as shown in Figure 4 right. For (5) equivalent damping ratio, there are two options available. The first one is calculating equivalent damping ratio as the viscous damping ratio that can absorb the same energy loss by hysteresis loop area per a loop cycle with the maximum deformation. The second one is calculating equivalent damping ratio as the viscous damping ratio that can absorb the same energy loss by hysteresis loop area per the total accumulated energy in time history. The first one is applied for the M-φ relation of PODT model. The second one is applied for the of τ-ɤ relation of PO model, because the PO model has no hysteresis damping in a stable loop as shown in Figure 2.

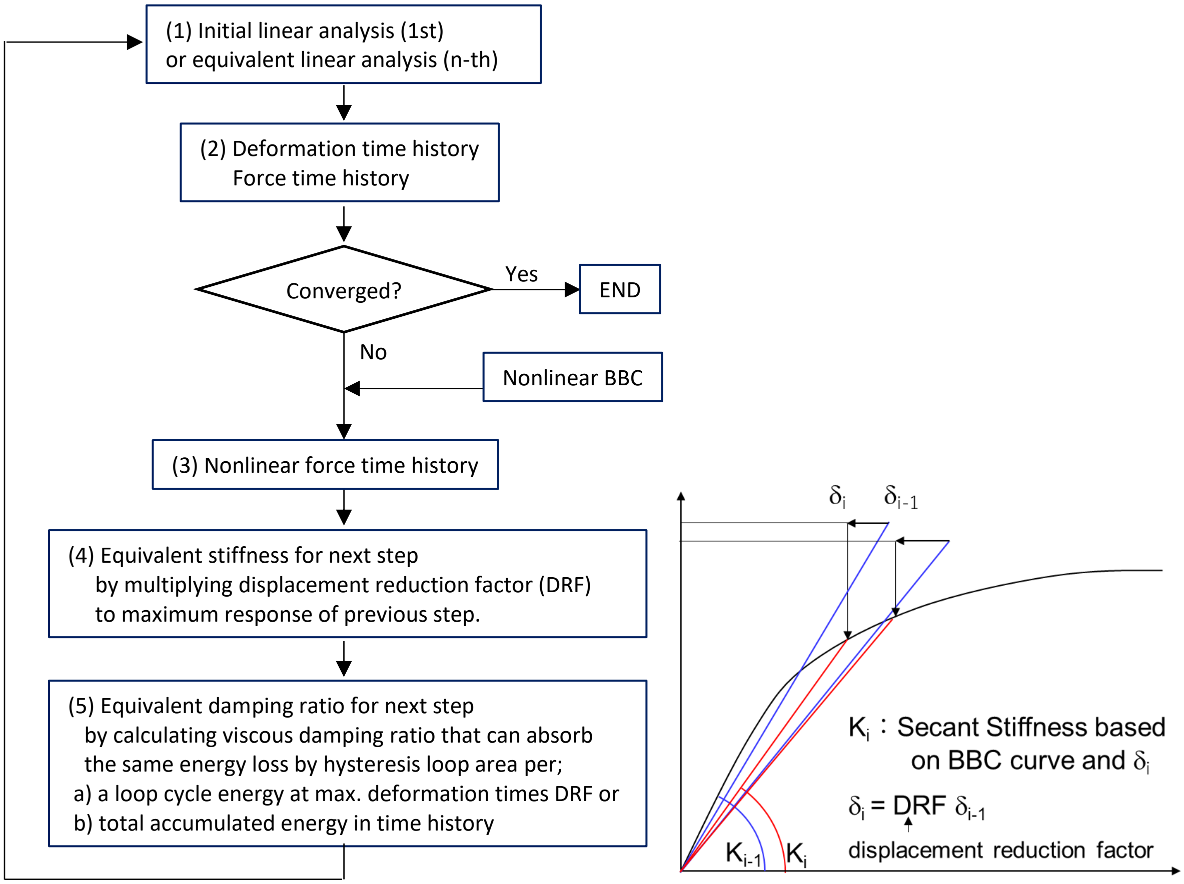
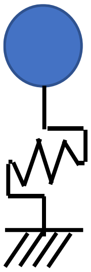


Figure 4 Iterative Equivalent-Linearization Procedure and Displacement Reduction Factor

For the DRF value, ACS SASSI User Manual (Ghiocel Predictive Technologies, 2022) recommends the best-estimate value of 0.8, with a wider applicable range between 0.75-0.85. To confirm this DRF value, a parametric study is performed using the single degree of freedom (SDOF) mass model and its BBC curve shown in Figure 5.



Mass	M	100 ton
Initial frequency	f_0	5 Hz
Initial stiffness	K_0	98696 kN/m
Damping ratio	h	5 %

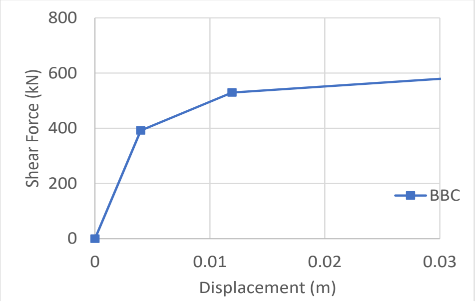


Figure 5 Single Degree Mass Model and BBC Curve

The initial structure damping is set to 5%. For the hysteresis characteristic, the PO shear model is used. Figure 6 shows input motion spectra used for this study. They are generated based on NRC RG 1.60 spectrum with seven different phases. Input level is scaled as the maximum acceleration 0.3g. ISRS is evaluated by averaging the analysis results of seven input motions, according to ASCE 4-16. The time step was 0.005 sec and duration time was 20 sec. For the ACS SASSI FFT calculation, a Fourier number of 8192 was considered including with a zero-padding interval.

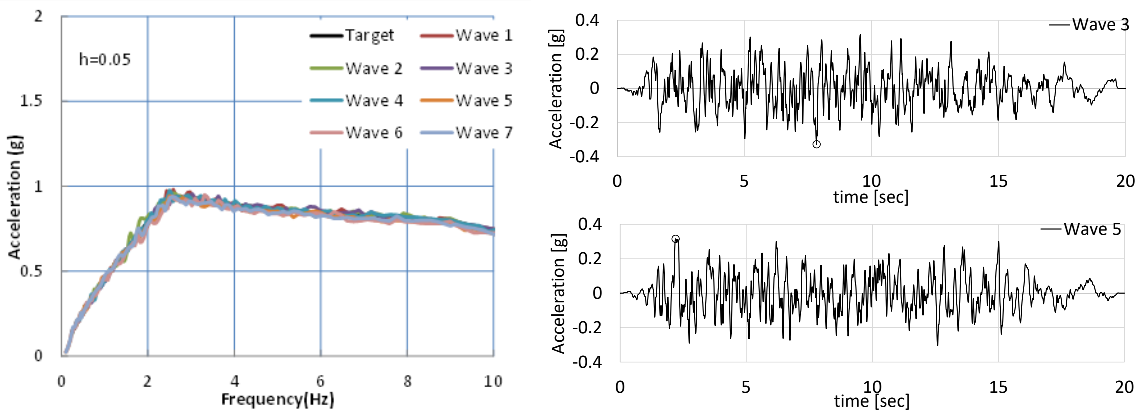


Figure 6 Response Spectra and Time Histories of Seven Input Motions

At each iteration, convergence is checked if the residual value, *di*, computed on the following equation is less than an accepted small tolerance.

$$d_i = \left|\frac{E_i - E_{i-1}}{(E_i + E_{i-1})/2}\right|, \quad \text{where } Ei \text{ ; equivalent stiffness at iteration step } i \qquad (1)$$

An example of change of equivalent stiffness and damping ratio at each step is shown in Figure 7 from the analysis results for input motion, Wave 4. For the DRF values, four cases, 0.6, 0.7, 0.8, 0.9 are calculated. Convergence is reached at less than 12 iteration steps. When the response displacement exceeds the elastic or concrete cracking limit, the equivalent stiffness decreases, and equivalent damping increases up to around 12%. The ASCE 4-16 standard Section 3 recommends that for the Response Level 3 applicable to the BDBE levels, the total damping of up to 10% is acceptable. Otherwise, the analyst needs to justify larger damping values. Ichihara et.al. (2021) selected 9% for the upper limit of equivalent damping, based on the sensitivity study for experiment results of seismic wall ultimate behaviour. For this study, three cases of equivalent damping, without any limitation and with upper limitation of 10% and 9%, are calculated.

Figure 8 shows the ISRS (h=5%) of the mass for three cases of equivalent damping limitation and various DRS values compared with the DYNA2E results, which were obtained by the direct integration method with Newmark-β method (β =1/4, γ=1/2). The integration time step for the nonlinear analysis was 0.0005 sec. It is found from this comparison that the case of 9% cut-off equivalent damping covers the DYNA2E ISRS.

Figure 9 shows the ISRS averaged envelope of DRF=0.6 and 0.8 for 9% cut-off equivalent damping against seven input motions. It has very good agreement with the average ISRS of DYNA2E results. Figure 10 shows the comparison of the acceleration time histories between ACS SASSI and DYNA2E. In the initial time frame up to 6 sec, DRF=0.6 equivalent-linear response has a good agreement with DYNA2E response, however, after peak acceleration occurred around 10 sec, the vibration period becomes longer, then DRF=0.8 response has a good agreement with DYNA2E response. The hysteresis loops in Figure 11 shows similarity between ACS SASSI Option NON with DRF=0.8 and DYNA2E.

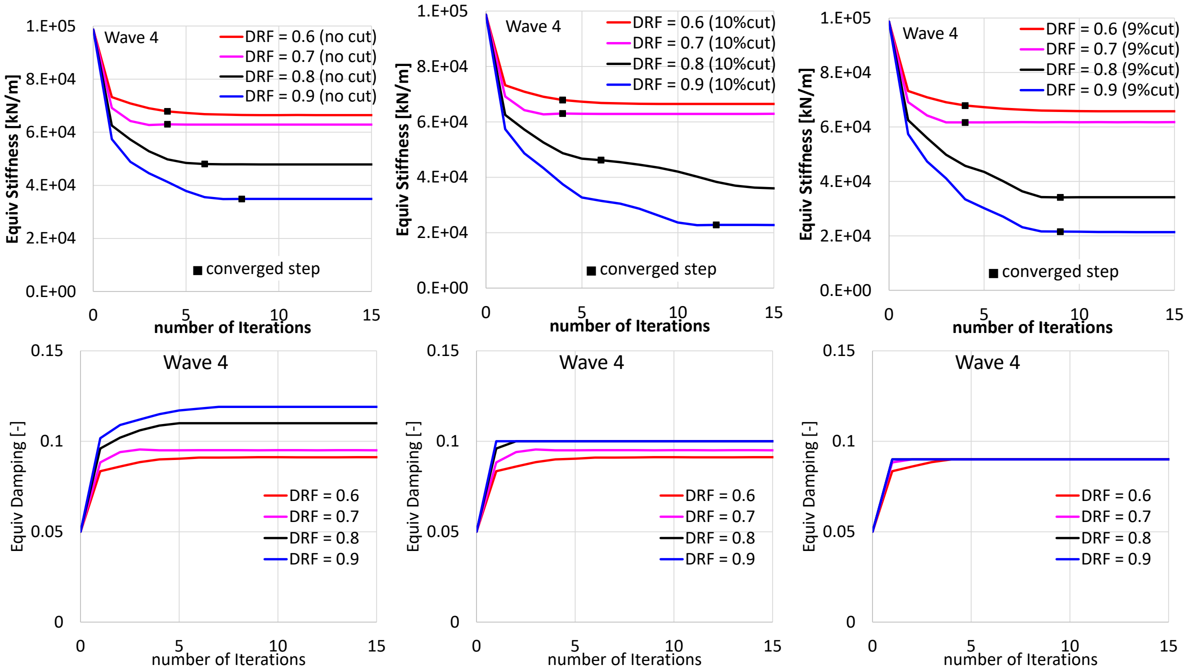


Figure 7 Equivalent Stiffness and Damping Ratio at Iteration Steps (Wave 4)

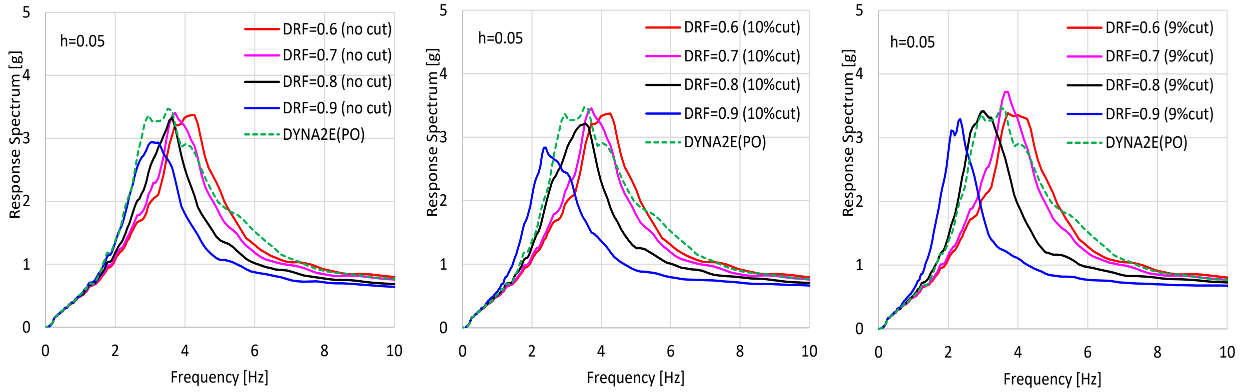


Figure 8 Comparison of ISRS for Equivalent Damping Limitation and DRF Values (Averaged)

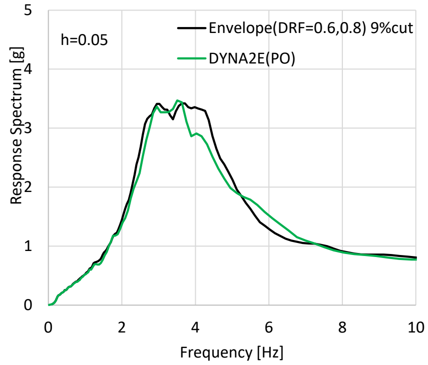


Figure 9 ISRS (DRF=0.6,0.8) 9%cut (Mean)

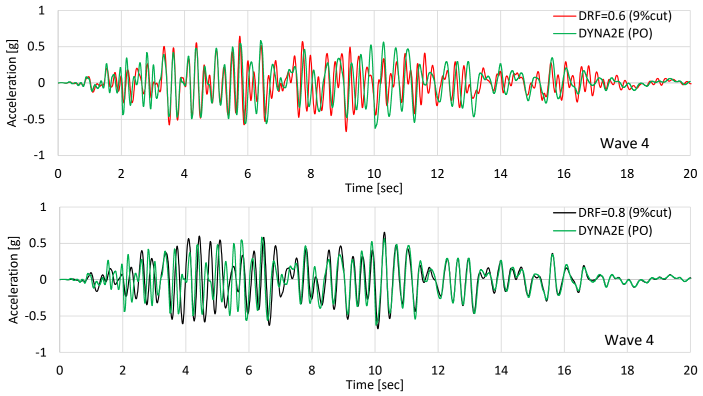


Figure 10 Acceleration Time Histories (Wave 4)

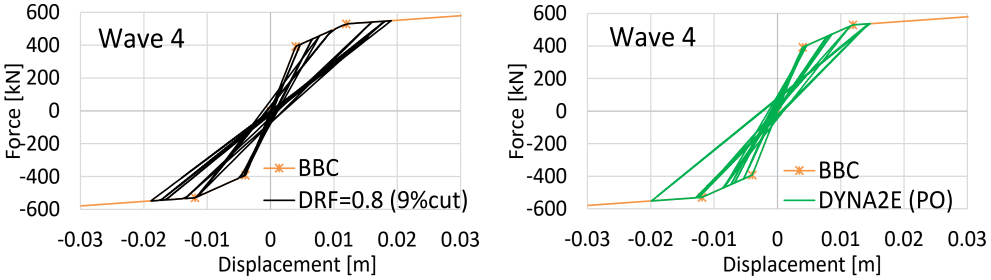


Figure 11 Hysteresis Loop (Wave 4)

SEISMIC SSI ANALYIS OF RC SHEARWALL STRUCTURE

3DFEM and Stick Models Used for AB Structure Comparative SSI Analyses

To validate the nonlinear analysis methodology implemented in the ACS SASSI Option NON software, a typical AB shearwall structure surface mounted on the uniform site condition was analysed. The Option NON, results were compared with those obtained by DYNA2E.

The AB structure 3DFEM model is shown in Figure 12. The AB is a five stories RC structure, which horizontal size is 60.66 x 25.6 m, and height is 39.27 m. It is surface mounted on the uniform and constant soil condition (unit weight of 23.56 kN/m^3, Vs of 1,524 m/s, Vp of 3048 m/s, damping ratio of 0.01). Figure 13 shows the ACS SASSI 3DFEM-Stick and DYNA2E Stick models for the longitudinal X-direction seismic input. Figure 14 shows the models for the transversal Y-direction seismic input. It should be noted that the 3DFEM-Stick models are 3DFEM shell element submodels including only RC walls parallel to the input direction, so that their structure configurations are similar with the Stick models with beam elements.

For this comparative study, four types of structure models were considered as shown Table 1. Both ACS SASSI 3DFEM-Stick and Beam-Stick models were analysed for DRF=0.8 based on the recommendation in ACS SASSI User Manual (Ghiocel Predictive Technologies, 2022) and validation results in the previous studies such as Ichihara (Ichihara et al.,2022). By comparing the SSI analysis results of these models, modelling difference between 3DFEM and the Lumped Mass Stick (LMS) models can be evaluated. The ACS SASSI Stick models and the DYNA2E Stick model have an identical stick structure configuration. By comparing the SSI analysis results of these models, nonlinear analysis difference between the iterative equivalent-linear SSI analysis and the direct integration SSI analysis in time domain can be evaluated.

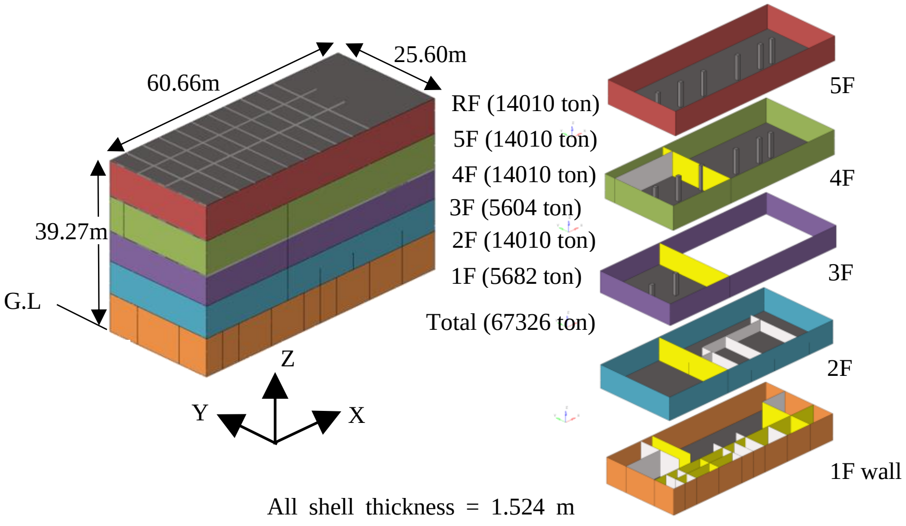


Figure 12 Overview of AB Structure Full 3DFEM

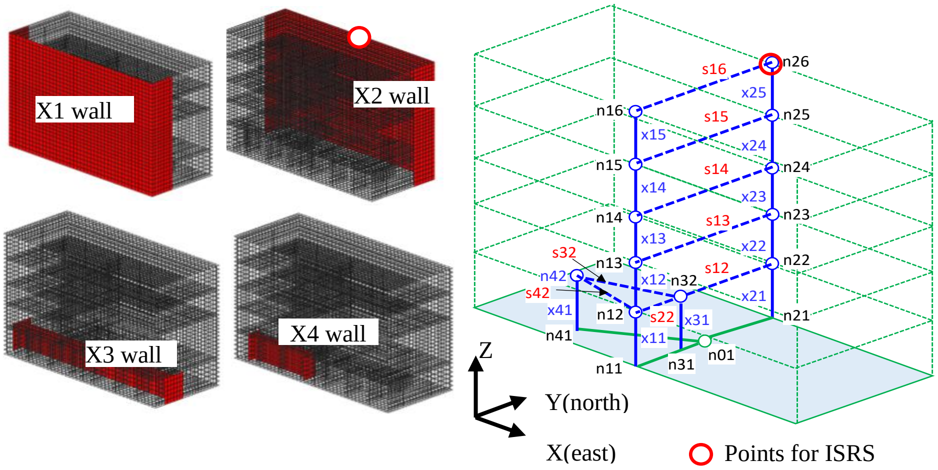


Figure 13 3DFEM-Stick (red walls) and Beam-Stick Models for X-dir. Input

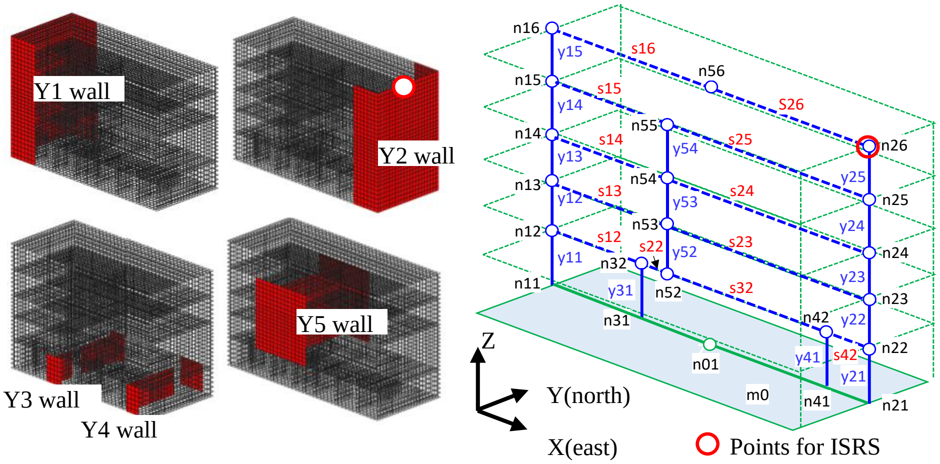


Figure 14 3DFEM-Stick (red walls) and Beam-Stick Model for Y-dir. Input

The three ACS SASSI models shown in Table 1 include a “3DFEM-Stick” model, a “Spring-Stick” and a “Beam-Stick”. The “Spring-Stick” model that uses translational shear and rotational bending springs, and the “Beam-Stick” model uses special beam elements for the RC wall modelling having a theoretical formulation similar with the DYNA2E nonlinear beam elements.

Seven RG1.60 spectrum compatible acceleration input motions were utilised for the seismic response analysis (shown in Figure 6). Input level is scaled as the maximum acceleration 0.6g for X-direction and the maximum acceleration 0.4g for Y-direction which were determined based the nonlinearity levels of walls for each direction. The largest nonlinearity is achieved in transverse direction for 0.40g at the 2nd floor which correspond to the weak story of the AB structure.

Figure 15 shows the 3DFEM-Stick models for the X and Y directions. This 3DFEEM-Stick model is a 3DFEM shell model with the same structure configuration as the beam stick models (Figures 13, 14 and 15). In comparison with the full 3DFEM model, 3DFEM-Stick model retains only the RC walls which are parallel to the input motion direction including their web and two end flanges. The comparison of responses between the full 3DFEM and 3DFEM-Stick models is shown in Section ‘3DFEM-Stick Model vs. Full

3DFEM for AB Structure.' To be compatible with the stick models, the 3DFEM-Stick model floors are assumed to rigid massless floors.

Table 1 Three Types of Analysis Model for Comparative Study

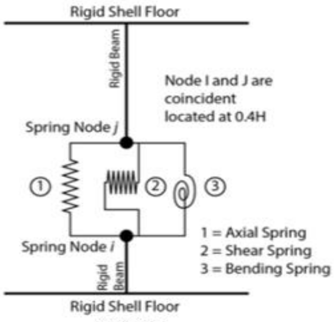
Model type	**ACS SASSI 3DFEM-Stick**	**ACS SASSI Spring-Stick**	**ACS SASSI Beam-Stick**	**DYNA2E Beam-Stick**
Structure model	3DFEM (1)	Lumped mass stick model	Lumped mass stick model	Lumped mass stick model
SSI Analysis Type	Iterative Equivalent Linearization (DRF=0.80)	Iterative Equivalent Linearization (DRF=0.80)	Iterative Equivalent Linearization (DRF=0.80)	Nonlinear Time-Integration
RC Wall Hysteretic Model	Shell with shear and bending BBC and hysteresis characterises	Multiple-vertical-line-element-model (MVLEM) (2)	Beam with shear and bending BBC and hysteresis characterises	Beam with shear and bending BBC and hysteresis characterises
Floor Slab Model	Rigid shell	Multi-point constraint	Multi-point constraint	Multi-point constraint
Basemat	Rigid shell	Rigid shell	Rigid springs	Rigid springs
Soil Media	Thin layer method (Half-space uniform soil)	Thin layer method (Half-space uniform soil)	Thin layer method (Half-space uniform soil)	Sway rocking spring and dashpot (3)
RC Wall Damping	Initial 4% Equivalent hysteretic damping	Initial 4% Equivalent hysteretic damping	Initial 4% Equivalent hysteretic damping	Initial 4% Hysteretic Damping

Notes:

(1): Mass are distributed only on the floor slab nodes of 3DFEM.

(2): Wall BBC and hysteresis characteristics are considered using multiple vertical-line-element-model (MVLEM) is based on Kolozvari et. al, 2015.

(3): Sway rocking spring values are determined by real part of soil impedance (ω=0) obtained by ACS SASSI rigid basemat model. The dashpot values are determined by imaginary part of soil impedance (ω=f_1). f_1 is the first mode angular frequency of soil-structure interaction system.



MVLEM

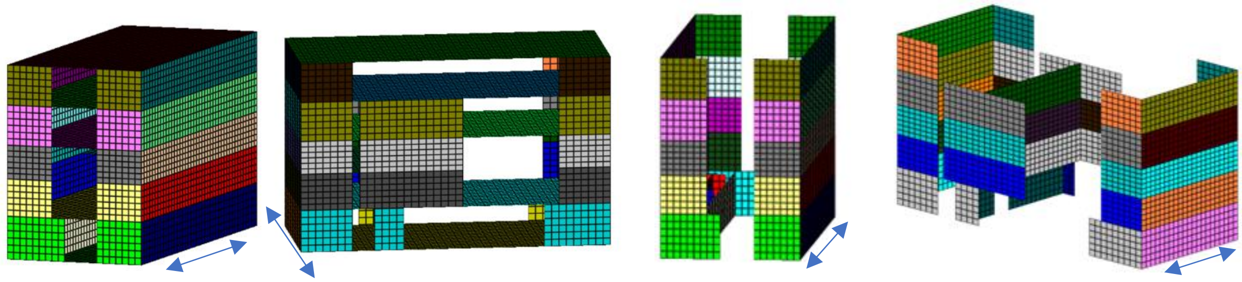


Figure 15 3DFEM-Stick Models for X and Y Directions With (left) and Without (right) Floors

Maximum AB Structure Maximum Shear Force Diagrams

DYNA2E Stick model results indicate that Wave 5 is the severest for X direction, while Wave 3 is the severest for Y direction. For these two wave inputs we compare all SSI stick model results. Figure 16 shows the maximum shear force diagrams in the X2 wall (nodes 21-26) for X input direction (for Wave 5, 0.6g) and in the Y2 wall (nodes 21-26) for Y input direction (for Wave 3, 0.4g). The plots include the comparative results for the four SSI models in Table 1.

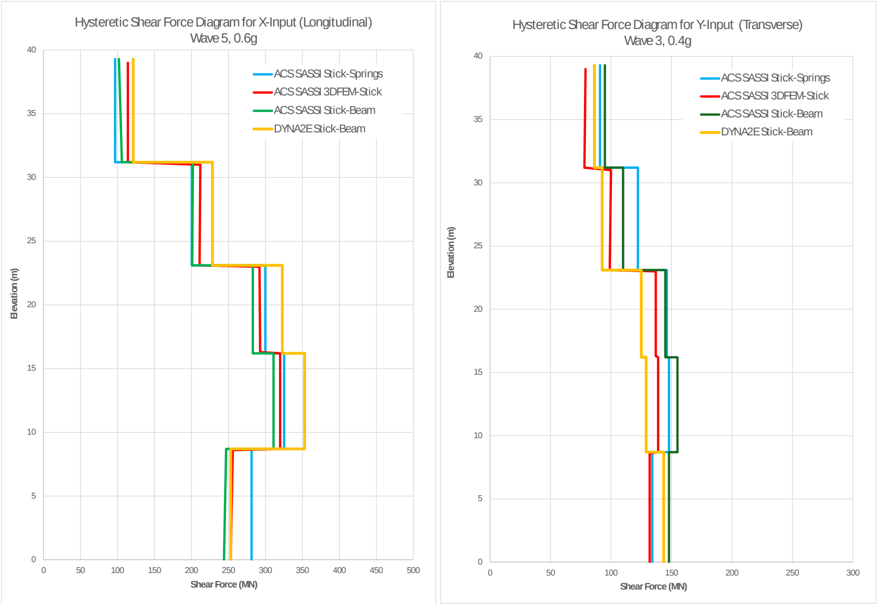


Figure 16 Comparative Maximum Shear Force Diagrams in AB Structure

The differences between the ACS SASSI Option NON and DYNA2E maximum nonlinear shear forces along the AB structure height are below 20% for X direction and up to 12% for Y direction considering the DYNA2E results as the reference.

RC Wall Shear and Bending Hysteretic Responses in Transverse Walls

Figures 17 and 18 show the shear force and bending moment hysteretic loops for the Y2_2F transverse wall panel (Y2 wall at 2nd floor) for transverse Y-input direction. The transverse Y2 wall has the highest seismic demands at the 2nd floor which is the weak story of the AB structure, and therefore, exhibits the largest nonlinear behaviour (for Wave 3, 0.4g).

The four SSI models in Table 1, ACS SASSI 3DFEM-Stick, Beam-Stick, Stick-Springs and DYNA2E Beam-Stick models show quite similar hysteretic responses as illustrated in Figures 17 and 18 left plots. As expected, the comparison of the hysteretic responses between the ACS SASSI Beam-Stick and DYNA2E Beam-Stick models using similar beam element formulation provide the closest results for both shear and bending effects as illustrated in Figures 17 and 18 right plots. Differences are minimal for these two nonlinear Stick models using beam elements.

It should be noted that there are some minor differences between the maximum shear forces shown in Figure 16 and 17 due to the fact the computations were done on different models; Figure 16 used section-cuts in the equivalent-linear model while Figure 17 used directly the nonlinear wall panel hysteretic time-domain analysis results.

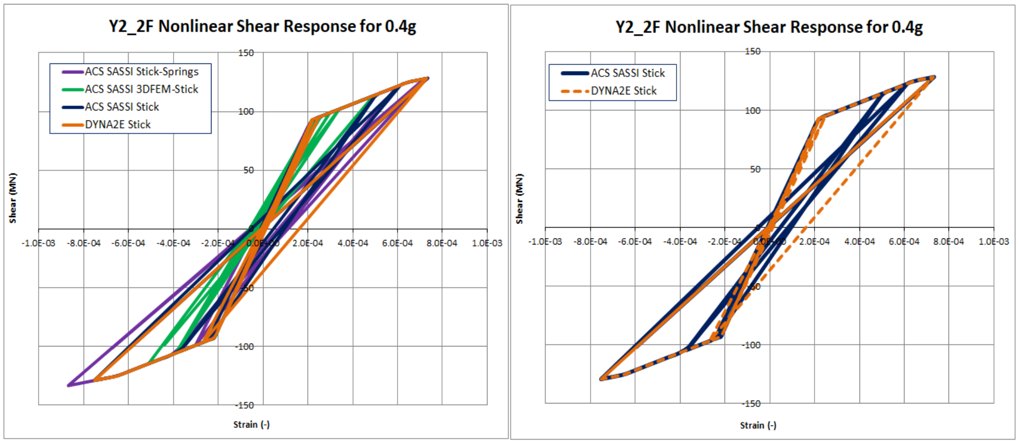


Figure 17 Shear Force Hysteretic Loop of Y2 wall 2F floor (Y-dir. Wave 3, 0.4g input)

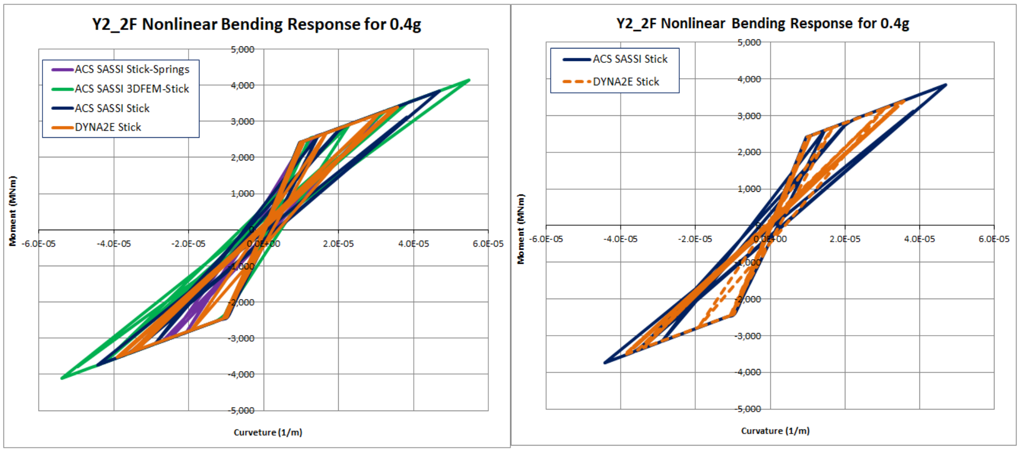


Figure 18 Bending Moment Hysteretic Loop of Y2 wall 2F floor (Y-dir. Wave 3, 0.4g input)

In-Structure Response Spectra (ISRS)

It should be noted that nonlinear ISRS at AB roof level are sensitive to seismic input motion phases varying randomly from wave to wave. Figure 19 shows the mean ISRS and the 7 sample ISRS for the 7 input motions considered in the study. The computed nonlinear ISRS in transverse Y-direction are computed for DYNA2E and ACS SASSI Stick models using beam elements and ACS SASSI 3DFEM-Stick model using shell elements.

Figure 19 shows that for nonlinear ISRS there is a slightly larger statistical scatter for the DYNA2E nonlinear time-domain solution than for the ACS SASSI iterative equivalent-linearization solution. As expected, the motion random phasing effects which affect structure nonlinear transient behaviour manifests more pronounced for time-integration approach. As a result of input motion phasing effects, the mean ISRS peak frequency bandwidth is a bit larger for the time-integration approach than the iterative equivalent-linearization approach. For a general case, depending of motion phasing, if the average envelope ISRS computed for DRF=0.6 and 0.8 is used, then, the deviations between the ACS SASSI Stick ISRS and the DYNA2E Stick ISRS may become smaller as shown in Figure 9.

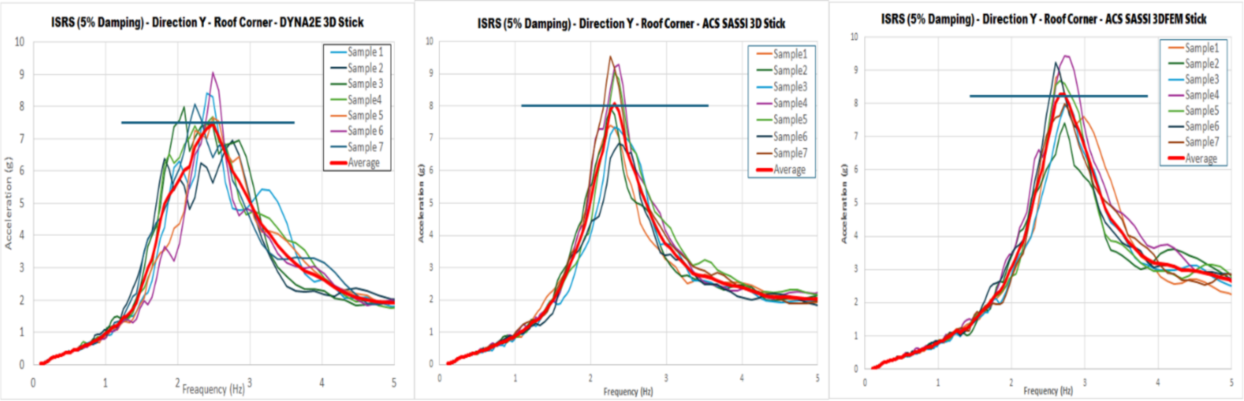
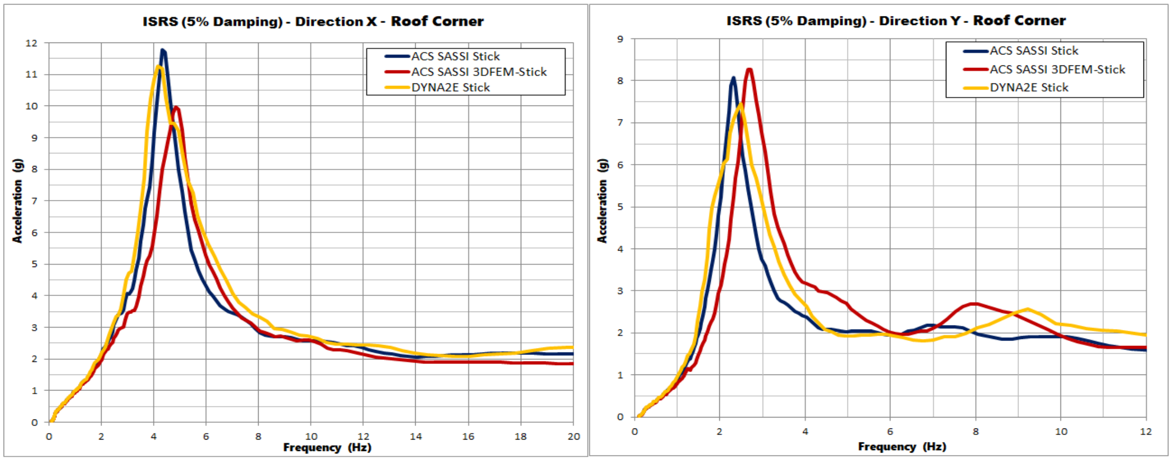


Figure 19 Nonlinear Mean ISRS and 7 Sample ISRS for DYNA2E Beam-Stick and ACS SASSI Beam-Stick and 3DFEM-Stick Models in Transverse Y-Direction

Figure 20 shows the nonlinear mean ISRS at AB roof corner in both X and Y input directions for ACS SASSI Beam-Stick and 3DFEM-Stick models, and DYNA2E Beam-Stick model. The longitudinal X-input has a 0.6g maximum input acceleration, while the transverse Y-input has a 0.4g maximum input acceleration. The mean ISRS results are reasonably close for the three stick-configuration SSI models, indicating that the two SSI approaches implemented in DYNA2E and ACS SASSI Option NON produce basically same results. However, the ISRS computed for 3DFEM-Stick model with shell elements slightly deviates from ISRS computed for Beam-Stick models with beam elements for RC wall modelling.



(a) X2 wall top (X-dir., 0.6g input) (b) Y2 wall top (Y-dir., 0.4g input)

Figure 20 Nonlinear ISRS at AB Roof Corner

The comparative SSI results shown in Figures 16 through 20 indicate that the ACS SASSI Option NON hybrid approach based on iterative equivalent-linearization procedure provides reasonably accurate results in comparison with the DYNA2E “true” nonlinear analysis based on time-integration approach. All comparison models including ACS SASSI Beam-Stick, DYNA2E Beam-Stick and ACS SASSI 3DFEM-Stick, are based on the stick type structure configurations using either beam or shell elements for the RC wall modeling.

3DFEM-Stick Model vs. Full 3DFEM for AB Structure

A key aspect of structural modeling related to the JEAC 4601 code application is the split of the 3D structure model into two separated stick structure models for each horizontal input direction. Therefore, it is accepted to simplify the 3D modeling by splitting two 2D stick models, one for X direction and one for Y direction.

The ACS SASSI 3DFEM-Stick models in X and Y directions are 3DFEM shell models that have the same structure configurations with the stick beam models in X and Y directions. The 3DFEM-Stick models use explicit FE shell modeling of the RC walls including the wall webs and end flanges instead of using line beam elements. To be compatible with the Stick beam models, the 3DFEM-Stick model floors were assumed rigid and massless.

Figure 21 shows the 3DFEM-Stick model for transverse Y-direction without including the connecting rigid floors. It should be noted that the perpendicular longitudinal walls are not fully included. Only the wall flanges associated with the transverse walls are included. Therefore, the stiffness contribution of these perpendicular walls (see line in Figure 21) to the overall structure transverse stiffness is reduced for the 3DFEM-Stick model in comparison with the full 3DFEM model.

For the AB structure, for the full 3DFEM having a closed cross-section wall profile, the transverse stiffness is larger than for the 3DFEM-Stick having an open cross-section wall profile. Figure 22 shows the computed elastic ISRS at the AB roof for the full 3DFEM and 3DFEM-Stick model in transverse direction. It should be noted that the 3DFEM-Stick model has a lower structure frequency than the full 3DFEM frequency. For the particular wall layout of the AB structure, it should be noted that the connections between the internal wall between the 2nd and 4th floor only (Y5 wall in Figure 14), and the two external walls (Y1 and Y2) are more flexible for the 3DFEM-Stick modeling due to very reduced flange size at the bottom floor level (which corresponds to Y3 wall flange). The wall flange sizes were computed based on the AIJ RC 2018 code requirements and depend strongly on the clearances between walls and the wall conventional heights.

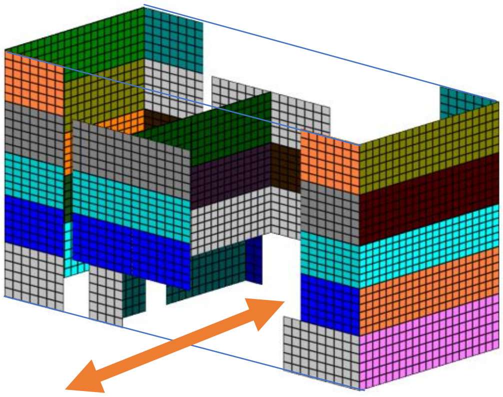


Figure 21 3DFEM-Stick for Y-Dir RC Walls

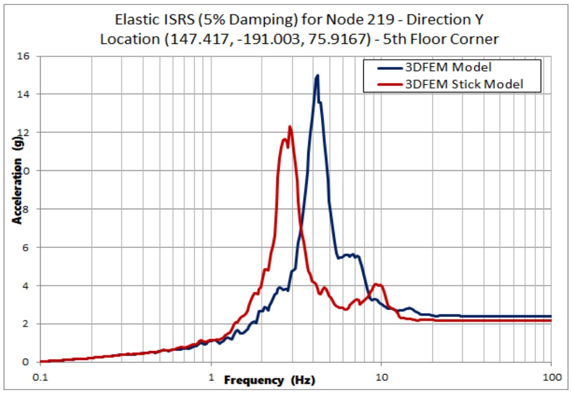


Figure 22 ISRS for 3DFEM and 3DFEM-Stick

For the AB structure with an unique, complex wall 3D configuration, the applied transverse stick-type models developed per code requirements and best design practices still provide simplified structural models with a slightly modified dynamic behavior than the complete 3DFEM.

CONCLUSIONS

The paper compares nonlinear seismic SSI analysis results based on two different approaches implemented in two specialized seismic SSI analysis software, ACS SASSI Option NON and DYNA2E. ACS SASSI Option NON uses a fast, iterative equivalent-linear procedure implemented within a hybrid complex frequency-time approach, while DYNA2E uses a rigorous "true" nonlinear time-integration approach. ACS SASSI Option NON can consider both 3DFEM and Stick models, while DYNA2E can consider only Stick models. Herein, the DYNA2E Stick model results are considered the reference results.

The comparison study is performed for a typical Auxiliary Building (AB) RC shearwall structure. Results are summarized as follow.

1) According to the parametric pre-test analyses using the single degree of freedom (SDOF) mass model, it was confirmed that the DRF value 0.8, can be used for equivalent linear analysis to estimate the

maximum response of the structures with the restoring force characteristics of the RC shearwall per JEAC 4601.

2) According to the comparative study using the typical AB shearwall structure, it was confirmed that the maximum nonlinear structural responses obtained by ACS SASSI 3DFEM-Stick (with DRF=0.8) and ACS SASSI Beam-Stick (with DRF=0.8) have good agreement with the maximum nonlinear structure responses computed by DYNA2E using direct time-integration method. The shear force and bending moment hysteretic loops computed for the critical wall panel at the 2nd floor show also good agreement. The DRF value in this study was set to 0.8 based on the recommendation in ACS SASSI User Manual (Ghiocel Predictive Technologies, 2022) and validation results in the previous studies such as Ichihara (Ichihara et al.,2022).

3) The nonlinear mean ISRS computed at AB roof level using the ACS SASSI Beam-Stick and 3DFEM-Stick models (with DRF=0.8) are close to the nonlinear mean ISRS computed using the DYNA2E Stick model. Only a slight difference is noted between the 3DFEM-Stick model and other Stick models. The 3DFEM-Stick model appears slightly stiffer.

4) In general, to develop accurate Stick models, performing an initial validation against 3DFEM is very important. For the particularity of the AB structure layout, it is shown that the transverse Stick models, including 3DFEM-Stick model, appear to be more flexible than the full 3DFEM, although stick models are developed in compliance with best practices. This increased stick flexibility is due to the missing parts of longitudinal walls (including no webs and limited flange sizes) and the complex connection floor modelling between the interior wall (discontinued at the first floor) and the external walls.

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