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# COMPARATIVE STUDY USING STICK AND 3DFEM NONLINEAR SSI MODELS PER JEAC 4601-2015 RECOMMENDATIONS

**Nitta Y[1], Ikeda R[2]., Horiguchi T[3], and Ghiocel D. M.[4]**

[1] Senior Engineer, SHIMIZU Corporation, Tokyo, Japan (nitta_y@shimz.co.jp)
[2] General Manager, SHIMIZU Corporation, Tokyo, Japan (ikedar@shimz.co.jp)
[3] Structural Engineer, Terrabyte Corporation, Tokyo, Japan (tomohiro.horiguchi@terrabyte.co.jp)
[4] President, Ghiocel Predictive Technologies, Inc., New York, USA (dan.ghiocel@ghiocel-tech.com)

## ABSTRACT

The paper illustrates the nonlinear SSI analysis under a severe earthquake motion, based on the Japan JEAC 4601-2015 recommendations (JEA 2015). The JEAC 4601 approaches were implemented in the ACS SASSI Option NON software (GP Technologies, 2021), which is based on a hybrid complex frequency-time domain approach that uses a local iterative equivalent-linearization procedure for modelling the hysteretic behavior of the RC walls (Ghiocel, et. al, 2022a and 2022b).

To validate this newly implemented nonlinear analysis methodology, a simple test buildings with fixed base are modelled with a 3DFEM model and a stick model by using ACS SASSI Option NON. The results were compared with those obtained by the stick model using the program DYNA2E (CTC Itochu, 2019), which is the nonlinear time-domain analysis program broadly used for the nonlinear SSI analysis of nuclear facilities in Japan.

The both results obtained by the ACS SASSI Option NON and DYNA2E software show good agreement in the nonlinear hysteresis loops, the maximum responses and the response spectra. The results also show some different characteristics between the hybrid complex frequency-time domain approach and the conventional time-domain direct integration approach and between 3DFEM model and stick model.

## INTRODUCTION

JEAC 4601-2015 (JEA 2015) describes the recommendation for the seismic design method of the nuclear facility in Japan. It requires the sufficient deformation capability and ultimate capacity of total structures against the design basis earthquake (Ss). The code also provides recommendation for the nonlinear SSI analysis methodology under a severe earthquake motion. The nonlinearity to be considered includes material nonlinearity in soil, geometric nonlinearity due to foundation uplift (Nitta et. al, 2022), 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.

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.

***Back-bone curves (BBC)***

Both the shear τ-ɤ relationship and bending M-φ relationship are indicated by a trilinear BBC as shown in Figure 1. Details of the evaluation method are shown in Appendix 3.7 of JEAC 4601-2015.

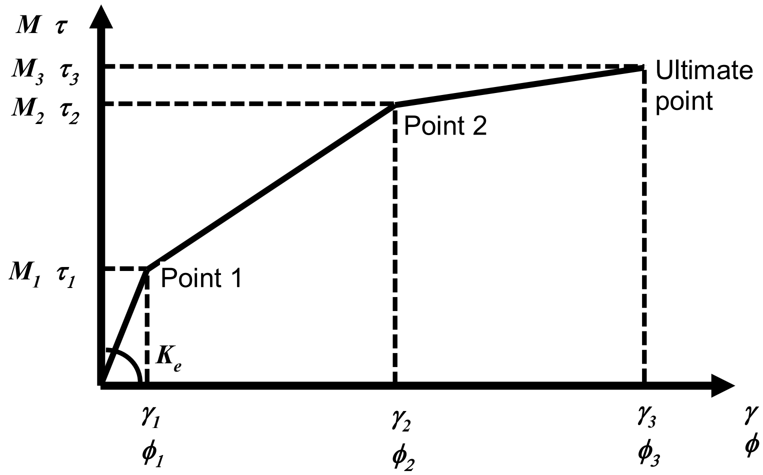



Figure 1. Back-bone Curve (BBC)

***Hysteresis characteristics***

**a. τ-ɤ relationship**

The hysteresis characteristic of τ-ɤ relation is the maximum point-oriented type, and the stable loop has no hysteresis damping. The maximum point-oriented (PO) model is shown in Figure 2.

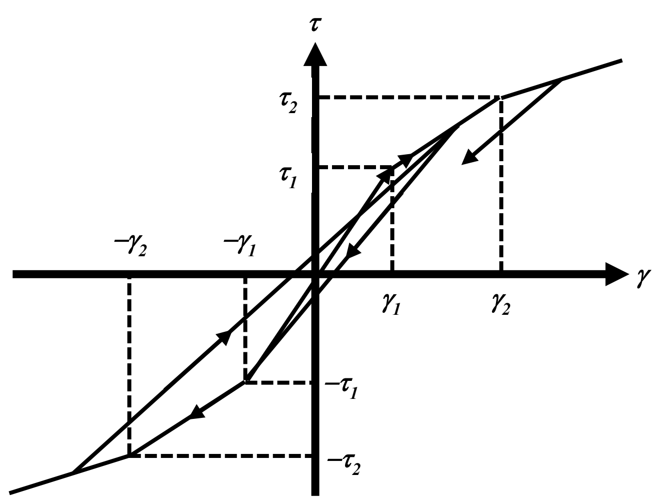



Figure 2 Maximum Point-Oriented (PO) Shear Model

**b. M-φ relationship**

The hysteresis characteristics of M-φ relation is the maximum point-oriented type. The ratio of bending deformation to the total deformation is considered to 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. The maximum point-oriented degrading trilinear (PODT) model shown in Figure 3 is adopted.

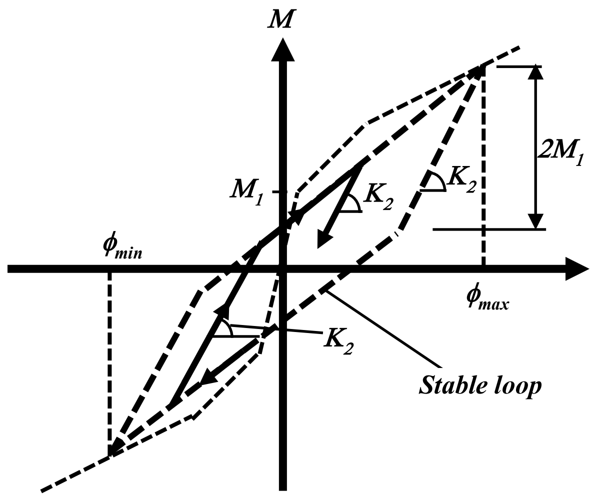



Figure 3 Maximum Point-Oriented Degraded-Trilinear (PODT) Bending Model

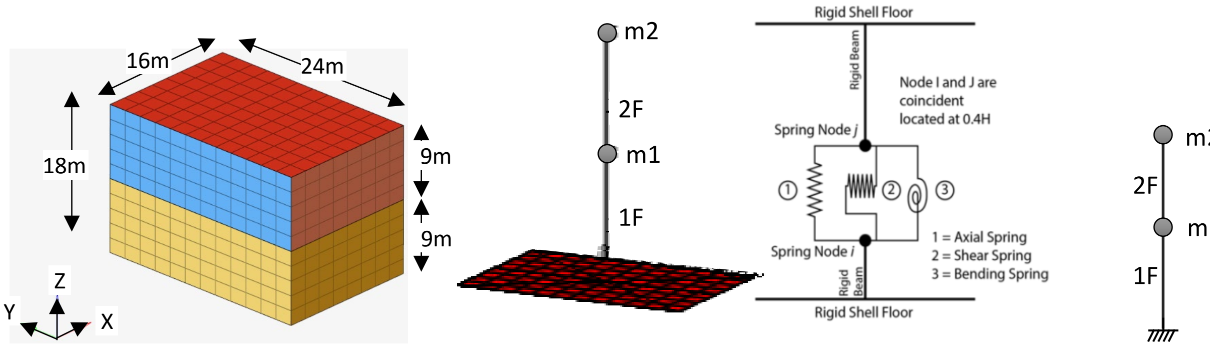
This JEAC 4601 approaches were implemented in the ACS SASSI Option NON software (GP Technologies, 2021), which is based on a hybrid complex frequency-time domain approach that uses a local iterative equivalent-linearization procedure for modelling the hysteretic behavior of the RC walls (Ghiocel, 2022a and 2022b). The software also 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.

To validate the nonlinear analysis methodology implemented in the ACS SASSI Option NON software, a simple two-stories building are analyzed by using Option NON. The results were compared with those obtained by DYNA2E, which is the conventional software with time-domain direct integration method, by using nonlinear stick model.

## ANALYSIS MODEL

Analysis models used for the comparison study are shown in Figure 4. The size of test building is 16 x 24 m, the height is 18 m. The assumed structural properties are shown in Table 1. Because this study focuses on the structural nonlinearity, the soil media was considered rigid (fixed base model). ACS SASSI is used for the two models, (a) 3D FE model which considers nonlinearity of the walls according to JEAC 4601-2015, and (b) lumped mass stick model, whose stick considers nonlinearity using multiple-vertical-line-element-model (MVLEM) (Kolozvari et. al, 2015). On the other hand, (c) DYNA2E model is the lumped mass stick model, whose stick is modeled by nonlinear bar elements.

For this study, the BBC of shear and bending deformation are calculated by ACS SASSI according to JEAC 4601-2015 and then used for the ACS SASSI stick model (MVLEM) and DYNA2E model. In order to calculate the BBC from the 3DFEM model, the RC shearwall structure nonlinear behavior is idealized by using a macro-mechanics hysteretic modeling for each wall. These macro-mechanics models are defined by the groups of the shell elements that include the wall webs. The nonlinear wall panels defined at each floor level (differently colored in Figure 5) are assumed to be subjected to uniform shear and bending deformation patterns shown in Figure 6. The forces and moments induced in panels are calculated by section cut at each wall panel. The calculated BBCs are shown in Figure 7. Since the wall in Y-direction is longer than that in X-direction, Y-direction shear and moment capacity are larger than X-direction. Shear capacity of 1F wall is slightly smaller than that of 2F wall, because the shear span ratio M/QD of 1F is larger than that of 2F. Bending capacity of 1F wall is slightly larger than that of 2F wall, because the axial dead load of 1F is larger than that of 2F.




(a) ACS SASSI 3DFEM model (b) ACS SASSI stick model (MVLEM) (c) DYNA2E model

Figure 4 Analysis Models for Comparison Study

Table 1 Structural Properties

| Structural properties | Wall | Floor slab | Basemat |
|---|---|---|---|
| Thickness (m) | 0.3 | 1.0 | 2.0 |
| Unit weight [kN/m$^3$] | 23.0 | 46.1 | 0 |
| Young's modulus [kN/m$^2$] | $2.44\times10^7$ | $4.88\text{x}10^7$ | $1\times10^{12}$ |
| Poisson ratio | 0.2 | 0.2 | 0.2 |
| Damping ratio | 0.05 | 0.05 | 0.05 |

| Strength Properties | Wall |
|---|---|
| Compressive strength [kN/m$^2$] | $3.0\times10^4$ |
| Rebar ratio (%) | 1.2 |
| Rebar Young's modulus [kN/m$^2$] | $2.05\times10^8$ |
| Rebar yield stress [kN/m$^2$] | $3.45\times10^5$ |

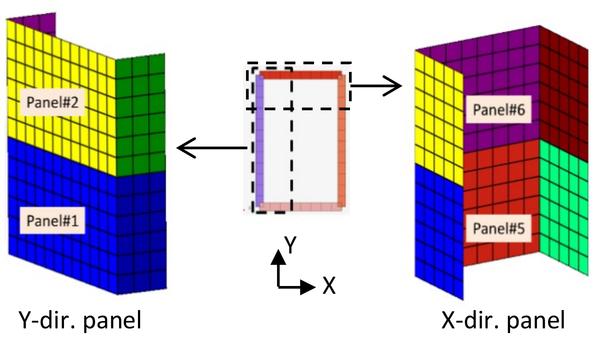



Figure 5 Nonlinear Wall Panels

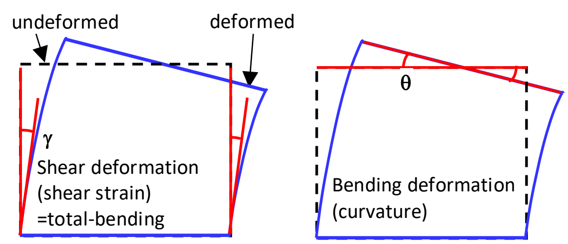



Figure 6 Panel Shear and Bending Deformation

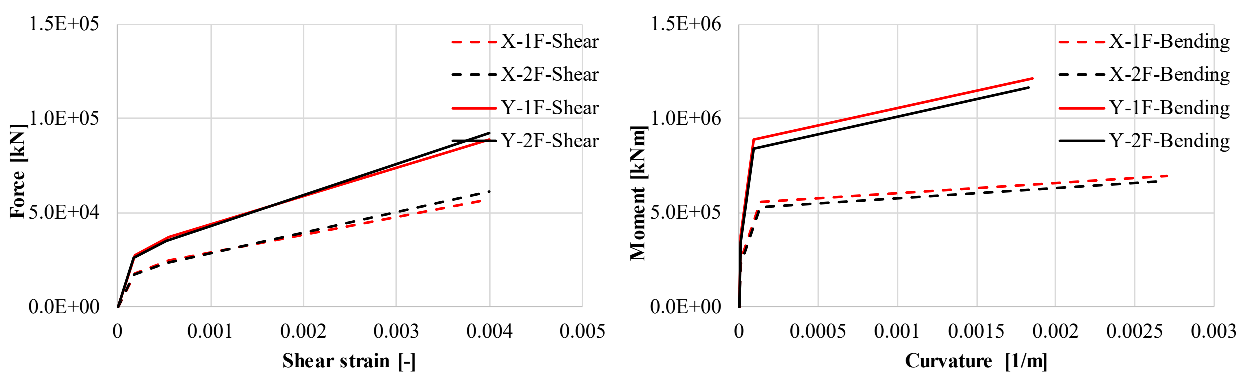



Figure 7 BBC for Shear Force and Bending Moment

## EQUIVALENT LINEAR STIFFNESS AND DAMPING

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 behavior of the RC walls. Figure 8 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, the equivalent stiffness and damping ratio used for next step are calculated. For (4) equivalent stiffness, there are two options are available. One is the constant displacement reduction factor (DRF) method and the other is the variable DRF method based on dominant frequency of power spectral density of force time history. Because the test model for this study is simple, constant DRF, 0.8, is used.

For (5) equivalent damping ratio, there are also two options are available. In the first method, the equivalent damping ratio is calculated as the viscous damping ratio that can absorb the same energy loss by hysteresis loop area per a loop cycle with the maximum deformation. This was originally introduced methods for the various nonlinear hysteresis model. As seen in Figure 9, JEAC 4601 PO model has no hysteresis loop area in a stable loop. It is considered too conservative, so the alternative method was incorporated for the PO model. In the second method, the equivalent damping ratio is calculated as the viscous damping ratio that can absorb the same energy loss by hysteresis loop area per the total accumulated energy in time history.

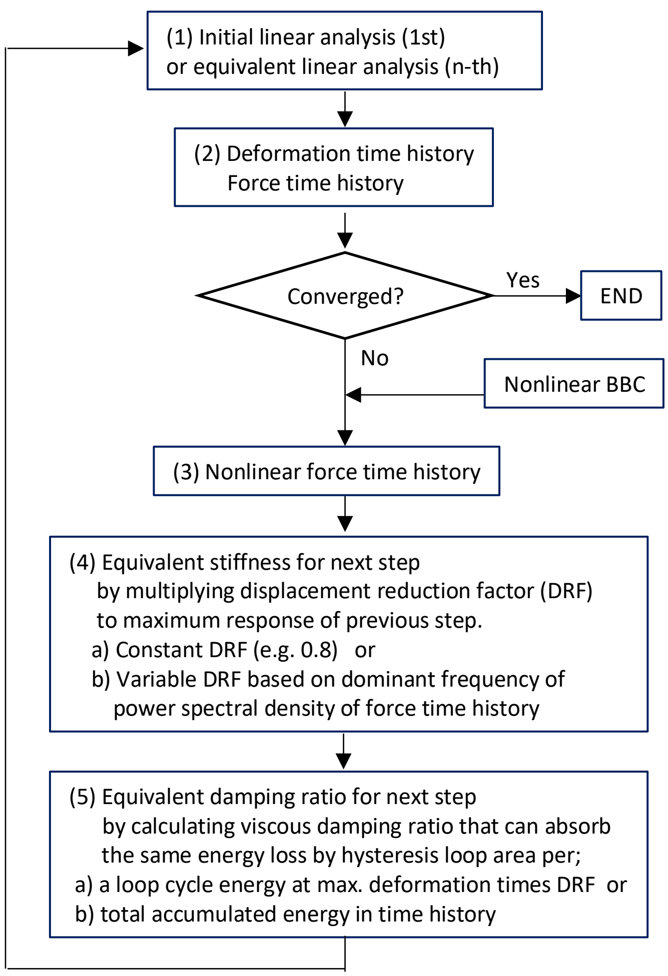



Figure 8 Iterative Equivalent-Linearization Procedure

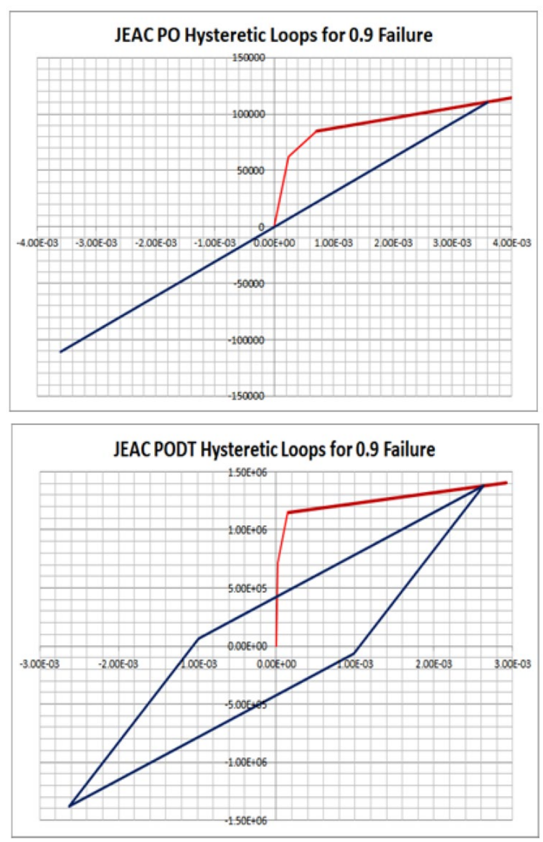



Figure 9 Stable Hysteretic Loops for JEAC PO for Shear and PODT for Bending

For an example of calculating the equivalent damping ratio based on the total accumulated energy in time history, Figure 10 shows a hysteresis loop obtained by DYNA2E PO model in time-domain analysis. The absorbed hysteresis damping energy for this loop and the equivalent viscous damping energy that can absorb the same total energy are shown in Figure 11.

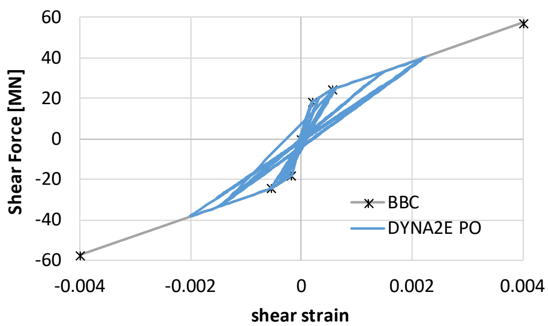



Figure 10 Example of PO Hysteresis Loop

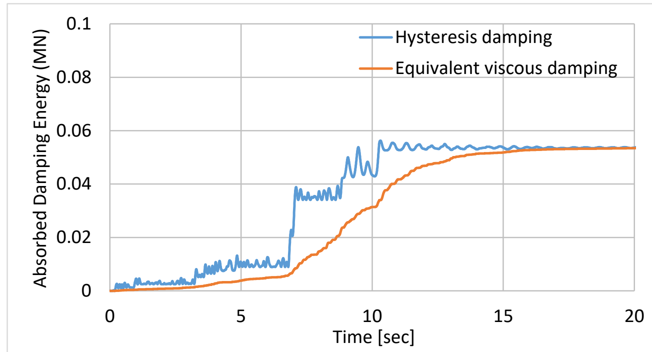
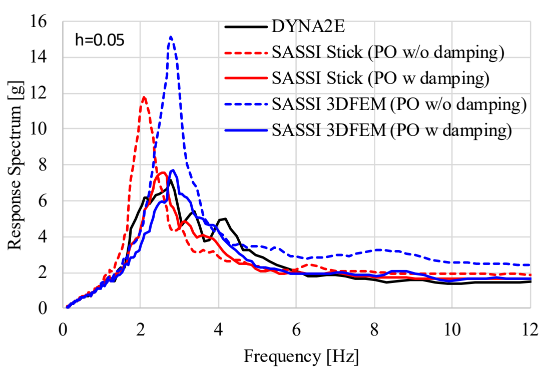
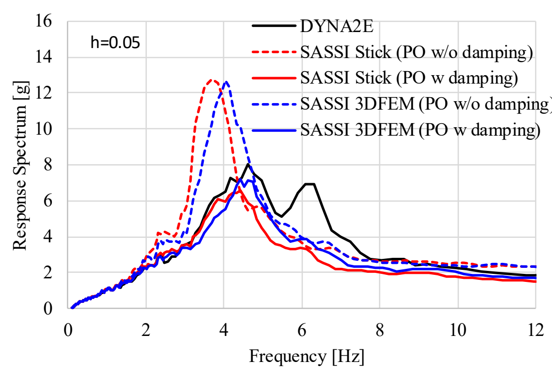



Figure 11 Equivalent Viscous Damping Energy

Figure 12 shows comparison of the response spectra at the roof floor between the both damping treatments. The ACS SASSI Stick and 3DFEM with the equivalent damping are matching with the DYNA2E results better than those without damping. In the following sections, only the ACS SASSI model with equivalent damping are used for the comparison studies.




(a) X-direction (0.6g input)




(b) Y-direction (0.6g input)

Figure 12 Comparison of Response Spectra at RF between PO model Without and With Damping

## SEISMIC INPUT MOTION

Figure 13 shows the input motion used for the comparison study. It is generated based on NRC RG 1.60 spectrum. Input level is scaled as the maximum acceleration 0.2g for linear response check, 0.4g and to 0.6g for nonlinear response against severe earthquake and very severe earthquake.

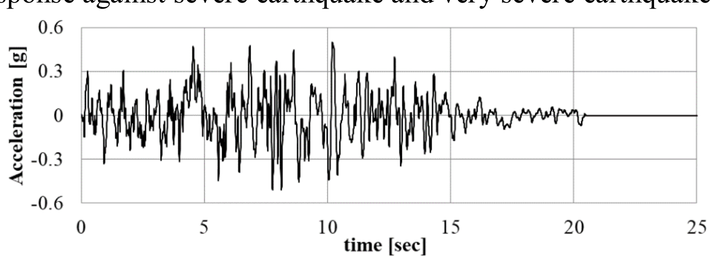
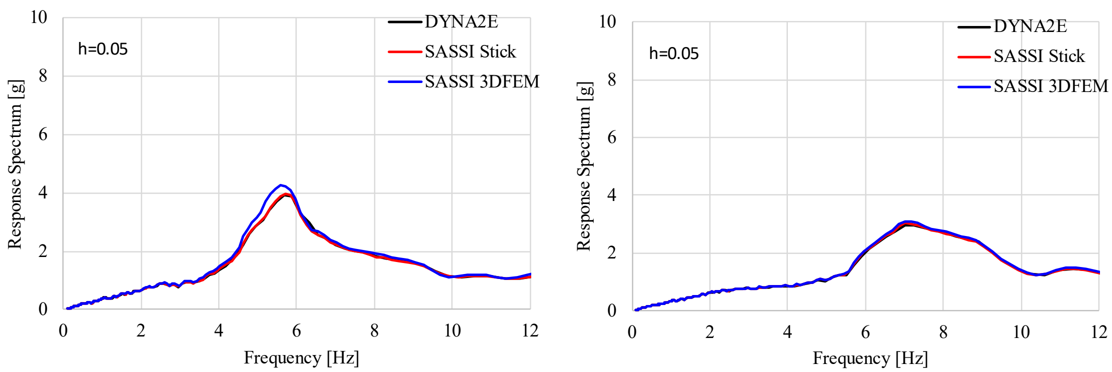



Figure 13 Seismic Input Motion

## COMPARISON OF LINEAR RESPONSE

In order to check the compatibility of the analysis models, linear response results for 0.2g input are compared. Figure 14 compares the response spectra at the roof floor. In Y-dir. (longitudinal), the three models show good agreement. In X-dir. (transversal), the spectra peak frequency of SASSI 3DFEM is slightly smaller than the other two models. The peak frequency is 5.7 Hz in X-dir. and 7.0 Hz in Y-dir. Figure 15 shows the comparison of maximum responses. The moment at the wall bottom is used for evaluating nonlinear bending behavior, where DYNA2E is most conservative among three models.




(a) X-direction (b) Y-direction

Figure 14 Comparison of Response Spectra at RF (0.2 g Input Linear)

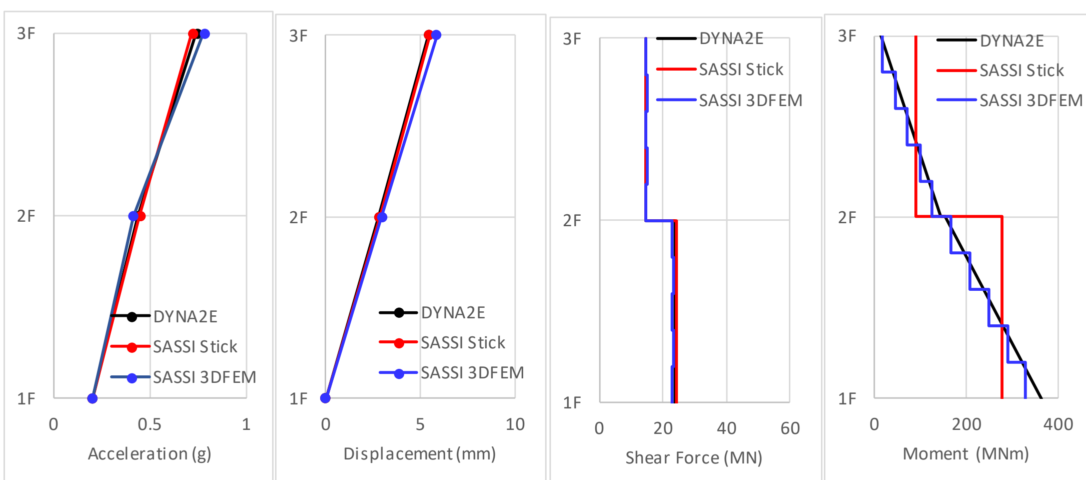
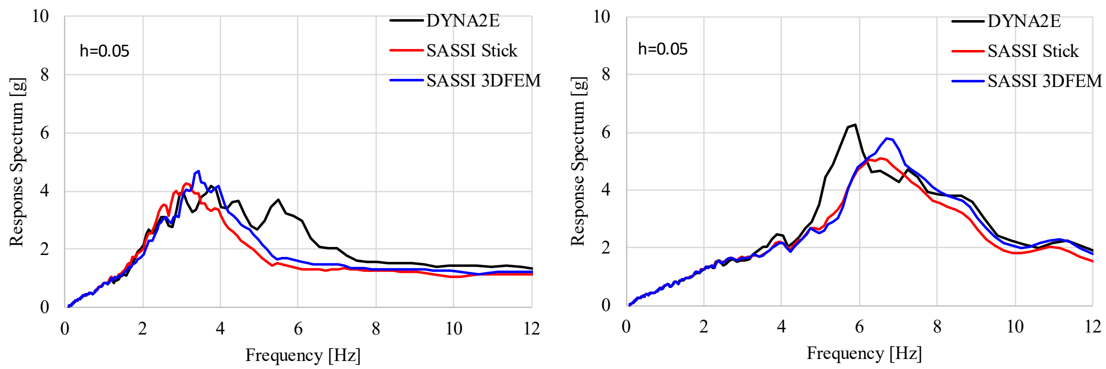



Figure 15 Comparison of Maximum Response (X-dir., 0.2 g Input, Linear)

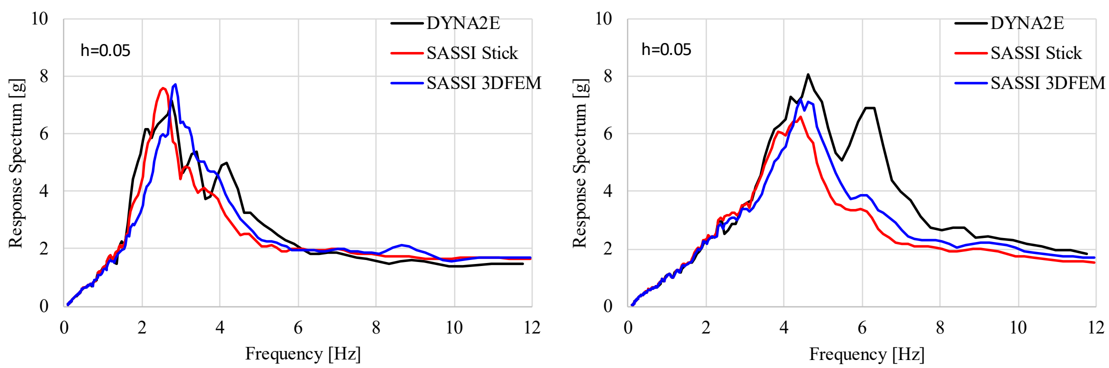
## COMPARISON OF NONLINEAR RESPONSE

Figures 16 and 17 show response spectra at roof floor obtained from the three models. The frequency peaks of three models are moved to the lower frequencies from the linear analysis in Figure 14 depending on increasing nonlinearity. The peak frequency and acceleration have good agreement between DYNA2E model and ACS SASSI stick and 3DFEM model. The DYNA2E spectra has the second peak at the higher frequencies. This is considered due to the time-domain analysis. Since ACS SASSI is equivalent linear analysis, the peak is based on the final equivalent stiffness. Figure 18 compares the acceleration time histories at the RF between the three models in the early time-frame (2-6 sec) and the maximum response time-frame (8-12 sec). Although the responses at the time-frame (8-12 sec) shows good agreement, the responses at the time-frame (2-6 sec) shows some difference between DYNA2E and ACS SASSI.



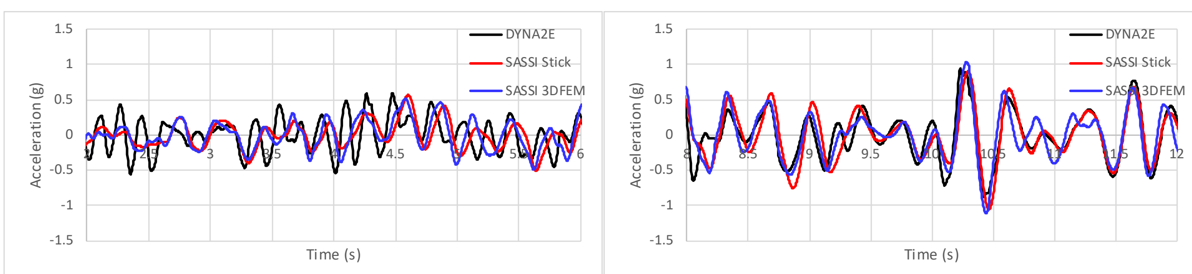

(a) X-direction (b) Y-direction

Figure 16 Comparison of Response Spectra at RF (0.4 g Input Nonlinear)




(a) X-direction (b) Y-direction

Figure 17 Comparison of Response Spectra at RF (0.6 g Input Nonlinear)




(a) Early time-frame (2-6 sec) (b) Maximum response time-frame (8-12 sec)

Figure 18 Comparison of Acceleration Time History at RF (0.4 g Input, X-dir.)

## COMPARISON OF HYSTERESIS LOOP

Figure 19 shows the comparisons of the hysteresis loops of the 1F wall between DYNA2E model and ACS SASSI stick and 3DFEM model. Each case has two hysteresis loops, one is the PO model for shear deformation and the other is the PODT model for bending deformation. The three model shows good agreement except for 0.6g input in X-direction. In this case, only DYNA2E bending deformation exceeds the rebar yielding curvature. This is considered due to the difference in moment evaluation locations as explained above.

For the other cases, the maximum shear strains of the three models in the case exceed 2.0 x $10^{-3}$, which is the allowable limitation of shear strain of RC walls required by the JEAC 4601-2015. It was confirmed that the three models provide good agreement within the allowable shear limitation 2.0 x $10^{-3}$.

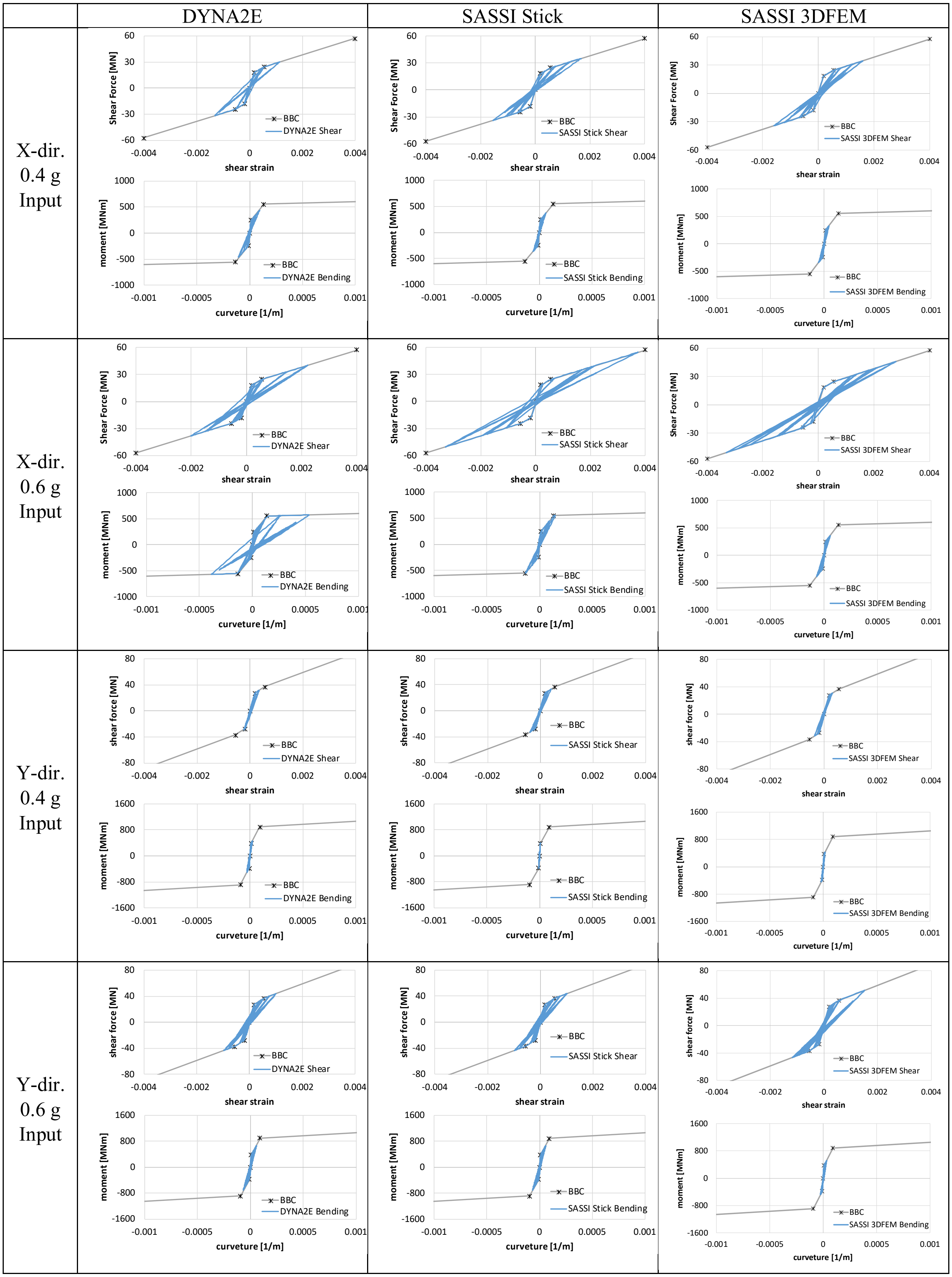



Figure 19 Comparison of Hysteresis Loop of 1F Wall

## CONCLUSION

JEAC 4601-2015 (JEA 2015) describes the recommendation for the seismic design method of the nuclear facility in Japan, and for the nonlinear SSI analysis methodology under a severe earthquake motion, including the structural nonlinearity with restoring force characteristics of structure. This JEAC 4601 approaches were implemented in the ACS SASSI Option NON software, which is based on a hybrid complex frequency-time domain approach that uses a local iterative equivalent-linearization procedure for modelling the hysteretic behavior of the RC walls

In order to validate the nonlinear analysis methodology implemented in the ACS SASSI Option NON software, a simple two-stories building are analyzed. The results were compared with those obtained by DYNA2E, which is the conventional software with time-domain direct integration method. The results obtained by the ACS SASSI stick and 3DFEM model show good agreement with DYNA2E results for the maximum responses, in-structure response spectra (ISRS) and hysteresis loop response up to the shear strain level $2x10^{-3}$, which is the allowable limitation of shear strain of RC walls required by the JEAC 4601-2015.

As a result of the comparison study, it was also found that there are some difference in the ISRS, although the peak frequency and acceleration of two methods are close well. The DYNA2E spectra has the second peak at the higher frequencies but the ACS SASSI spectra have only one peak. This is considered due to the time-domain analysis of DYNA2E. Since ACS SASSI is equivalent linear analysis, the peak is based on the final equivalent stiffness and the peak shift in the time-domain cannot be capture precisely.

JEAC 4601-2015 recommend to arrange RC shearwalls well uniformly in two orthogonal directions to make load path becomes clear during an earthquake. It recommends, as a general rule, the horizontal direction seismic analysis shall be performed in each direction independently, based on the various experiments which confirmed that a nonlinear behavior of RC shearwall subjected to two-direction input can be equally evaluated by the one-direction input. Accordingly, in this comparison study, the nonlinear response was evaluated in two directions separately. On the other hands, ACS SASSI Option NON has a function that the shear and bending nonlinear effects in the RC shearwalls are combined after each iteration and the nonlinear analysis is performed using the combined displacements based on simultaneous seismic component inputs.. Those extensive functions should be verified further separately.

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