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# FAST NONLINEAR SEISMIC SOIL-STRUCTURE INTERACTION (SSI) ANALYSIS OF NUCLEAR SHEARWALL CONCRETE STRUCTURES SUBJECTED TO REVIEW LEVEL EARTHQUAKE

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## ABSTRACT

The paper introduces a novel approach for modeling of nonlinear hysteretic behaviors of reinforced concrete structures in the complex frequency domain. The new approach can be used to perform fast and accurate nonlinear SSI analyses, including sophisticated nonlinear hysteretic models, at a small fraction of the runtime of a time domain nonlinear SSI analysis. The paper presents some key ideas that are behind the proposed approach. A case study of a typical low-rise shearwall nuclear plant structure is shown to demonstrate the proposed nonlinear SSI analysis approach. The in-structure acceleration response spectra (ARS) computed using both linear elastic and nonlinear SSI analyses are compared for a severe review level earthquake input with a 0.50g maximum ground acceleration. The new nonlinear SSI approach eliminates the need to use simplified cascaded multistep approaches that loose physics by neglecting the effects of the structural degradation on the SSI system dynamic behavior.

## INTRODUCTION

Based on the up-to-date technical literature, the nonlinear behavior of dynamic structural systems can be captured only by using nonlinear time domain analyses. Most of the sophisticated FEA codes use time domain algorithms for nonlinear seismic structural analysis. It has been believed so far that the nonlinear hysteretic models can be handled only in the time domain using step-by-step approaches, so that at each time step the dynamic system stiffness can be updated based on the material constitutive model and the load and response histories. So far, the nonlinear hysteretic system behavior could not be fully considered in the complex frequency domain. Only simple equivalent linear approaches were applied in frequency domain. Figure 1 shows the typical approximate equivalent linear model used in the complex frequency domain to idealize the real, nonlinear hysteretic system behavior. It should be noted that equivalent linear model considers the system stiffness and damping properties as being invariant in time and frequency. This imposes a serious limitation of the complex frequency approaches for dealing with nonlinear dynamic models. As a result of this time invariant behavior of the equivalent linear model, its dynamic system response could be either over or under estimated at different time moments during the earthquake duration.

Adequate nonlinear hysteretic models should have the stiffness and damping properties that change with the time due to the accumulation of damage in the material subjected to the random seismic loading history. Real systems have time-variant dynamic properties that also translate in frequency-variant dynamic properties. The nonlinear hysteretic systems can be defined by their dual representations in time and frequency domains, not only in time domain. Therefore, nonlinear hysteretic models can be defined as piece-wise linear models in both the time and the frequency domains. The proposed approach introduces a new way of dealing with the nonlinear hysteretic systems in frequency domain. The proposed nonlinear SSI approach in complex frequency domain is much faster and more robust than the nonlinear approaches in the time domain. The runtime of the nonlinear SSI analysis is only up to several times the runtime of a linear SSI analysis.

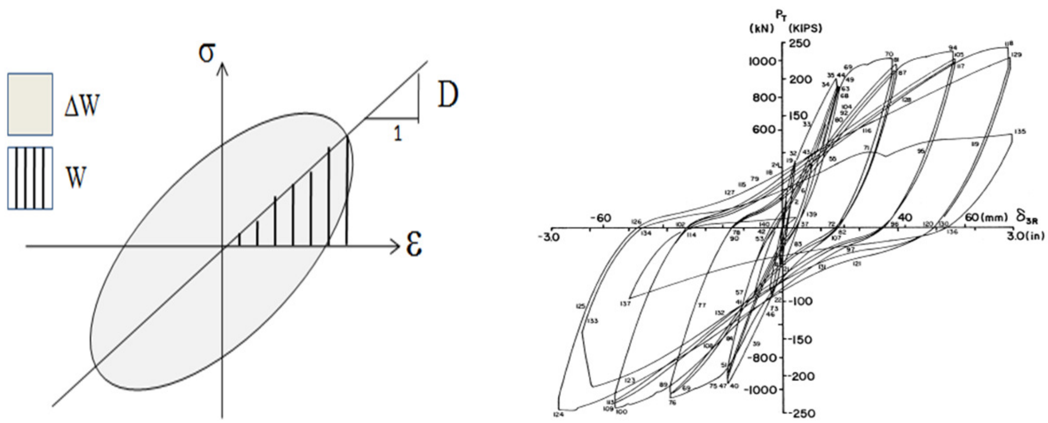



Figure 1 Traditional Equivalent Linear Model vs. Real Nonlinear Shearwall Behavior

The new nonlinear SSI approach eliminates the need to use simplified cascaded multistep approaches that loose physics by neglecting the effects of the structural material degradation on the SSI system dynamic behavior (Hashemi et. al., 2012).

## NONLINEAR HYSTERETIC MODELS IN TIME DOMAIN

The engineering literature includes many complex nonlinear hysteretic models for idealization of the reinforced concrete and steel structural element behaviors. Herein we are interested to idealize the hysteretic behavior of the low-rise shearwall structures that are of interest for nuclear buildings. From different hysteretic models proposed in the past for modeling of the low-rise shearwall behavior, we selected the Cheng-Mertz nonlinear hysteretic model (Cheng and Mertz, 1989). The Cheng-Mertz model is one of the most documented and tested models for low-rise shearwalls under shear coupled with bending deformation.

Figure 2 shows the Cheng-Mertz hysteretic models for shear and bending behavior of low-rise shearwall panels. A typical comparison between experimental testing and numerical simulation using Cheng-Mertz hysteretic of a shearwall panel is shown in Figure 3.

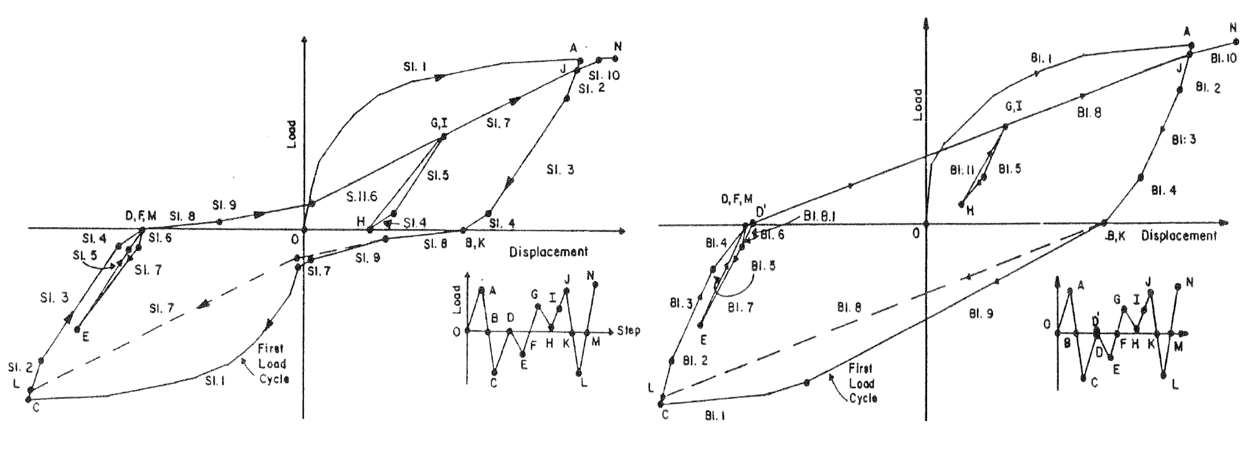



Figure 2 Cheng-Mertz Hysteretic Models for Shear Behavior (left plot) and Bending Behavior (right plot) of Low-Rise Shearwall Panels (after Cheng and Mertz, 1989)

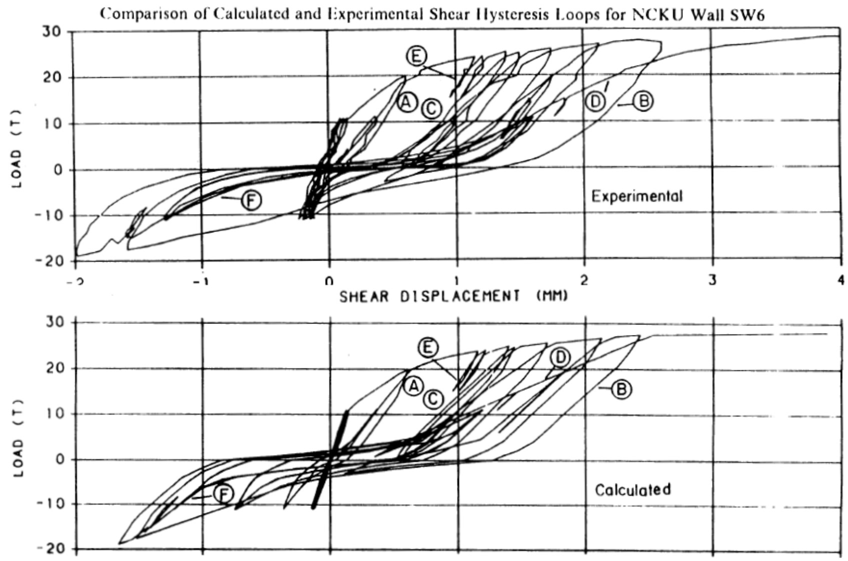



Figure 3 Experimental vs. Numerical Simulations Using Cheng-Mertz Hysteretic Model for Low-Rise Shearwall Panel (after Cheng and Mertz, 1989)

## NONLINEAR HYSTERETIC MODELS IN COMPLEX FREQUENCY DOMAIN

The frequency-dependent nonlinear hysteretic models are dual representations of the time-dependent nonlinear hysteretic models. These frequency-dependent models are obtained based on the superposition of a set of piece-wise linear hysteretic models.

.The complex frequency nonlinear hysteretic model can be expressed using frequency-dependent complex moduli:

$$G^*(\omega) = G_R(\omega) + iG_I(\omega) \tag{1}$$

The complex moduli real and imaginary parts depend on the energy dissipation mechanism. Then, the generalized Hooke's law for a shear deformation model (complex shear stress is proportional with the complex shear strain) can be written in complex frequency domain:

$$S^*(\omega) = G^*(\omega)\gamma^*(\omega) \tag{2}$$

where the superscript * denotes the complex variables. In contrast with the time domain formulation, the generalized Hooke's law in the complex frequency incorporates both the elastic force and the dissipation force contributions.

For a shearwall panel under shear deformation, the shear force in time domain can be obtained by the superposition of two components, namely, the elastic force and the dissipative force, as follows:

$$S(t) = S_{elast}(t) + S_{diss}(t) \tag{3}$$

These two force components in the time-domain can be directly computed from the frequency-domain hysteretic system behavior or vice-versa. Thus, the two force components in time domain can be computed based on their frequency domain dual representations using the generalized Hooke's law in complex frequency:

$$S_{elast}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} G_R(\omega)\gamma^*(\omega)\exp(-i\omega t)d\omega \quad (4)$$

$$S_{diss}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} G_I(\omega)\gamma^*(\omega)\exp(-i\omega t)d\omega \quad (5)$$

It should be noted that tentative attempts to use frequency-dependent piece-wise linear hysteretic models for nonlinear material behavior are not totally new. Kausel and Assimaki (2002) and Yoshida et al. (2002) proposed two different frequency dependent hysteretic models for modeling the soil material nonlinear behavior under seismic motion.

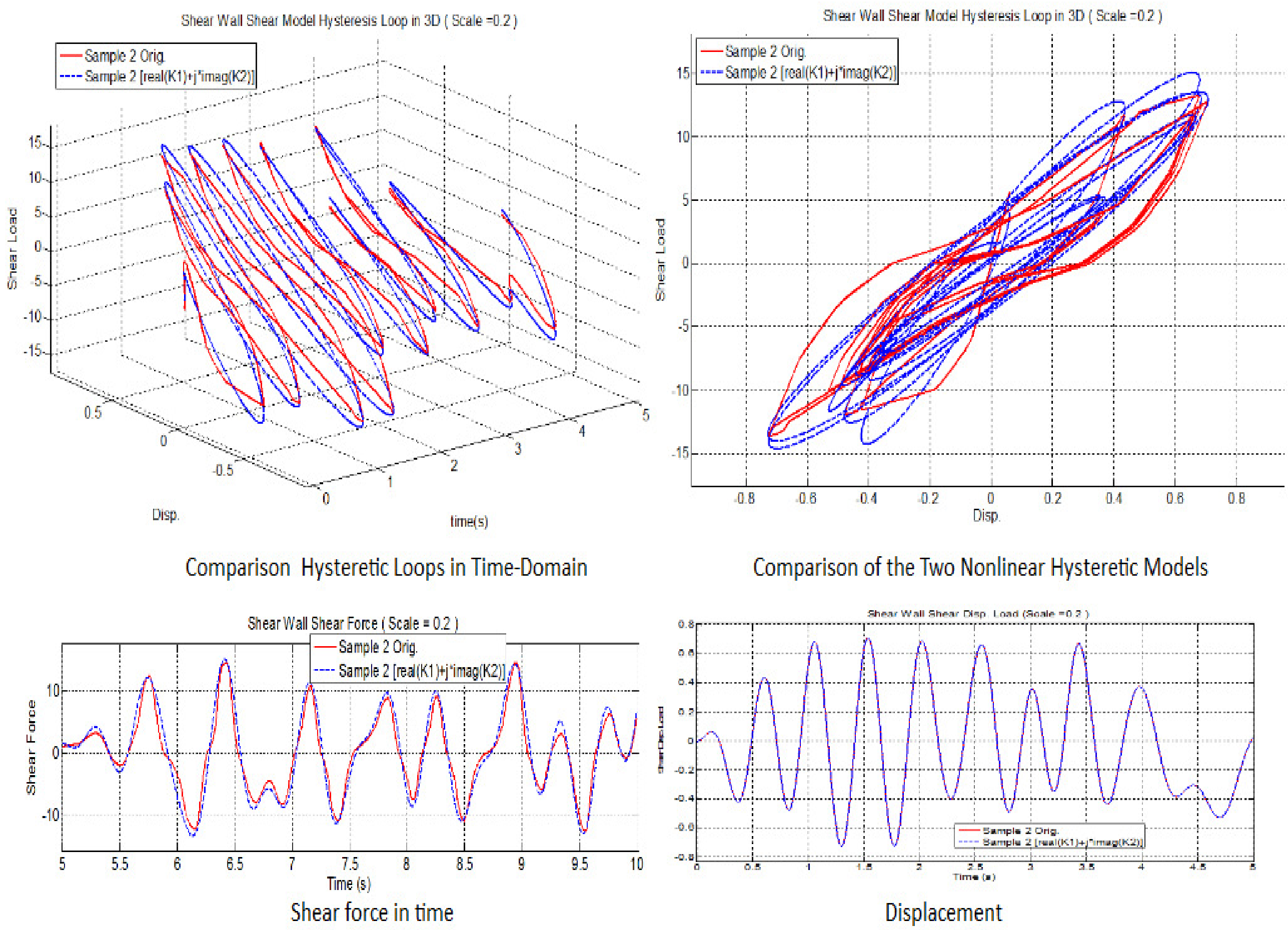



Figure 4 Comparisons Between Shear Force–Displacement Nonlinear Relationship In Time Domain (red line) and Complex Frequency Domain (blue line)

However, Kausel and Assimaki (2002) and Yoshida et al. (2002) implementations lacked in the compatibility between the frequency and the time domain representations as shown by Kwak et al. (2008). The frequency-dependent hysteretic model behaviors deviated largely from the real, nonlinear behavior of the soil material. It was remarked by Kwak et al. (2008) that the use of the frequency-dependent linearized hysteretic models “result in an unrealistic amplification of the low period (or high-frequency) components for ground motion rich in high-frequency”. Thus, it was concluded that the frequency-dependent hysteretic models did not improve the prediction accuracy of the soil nonlinear behavior under typical seismic motion inputs.

Figure 4 shows a typical comparison between the shear force-displacement loops in time-domain of a low-rise shearwall panel using the Cheng-Mertz hysteretic model defined in time domain and frequency domain. The comparison of the hysteretic loops computed based on the time and frequency domain models indicate very good matching, cycle by cycle, as shown in the top plots of Figure 4. Only minor differences can be noted between the shapes of the hysteretic loops of the two domain models. The frequency-dependent nonlinear hysteretic model results match extremely close the time-dependent nonlinear hysteretic results in terms of the response displacement and shear force histories, as shown in the bottom plots of Figure 4.

## PRACTICAL IMPLEMENTATION ASPECTS AND CASE STUDY RESULTS

To perform the nonlinear SSI analysis in complex frequency, firstly, the elementary shearwall panels within the building that might have a nonlinear behavior should be identified. These shearwall panels should be selected in such a way, so that the panel boundary conditions are similar to the boundary conditions used for the panel testing when the hysteretic models were developed. For the selected shear wall panels, the nonlinear hysteretic behavior is determined based on the computed panel drifts and shear forces assuming a Cheng-Mertz shear deformation model.

In this paper, a typical shearwall structure is investigated. The site-specific review level earthquake was assumed with a 0.50g maximum acceleration and a duration of 25 seconds.

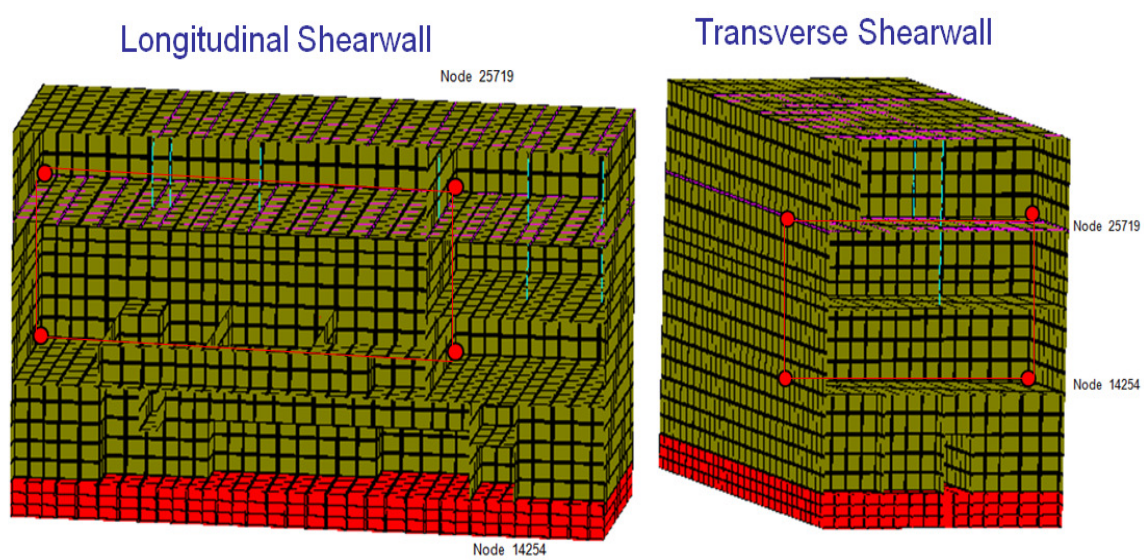
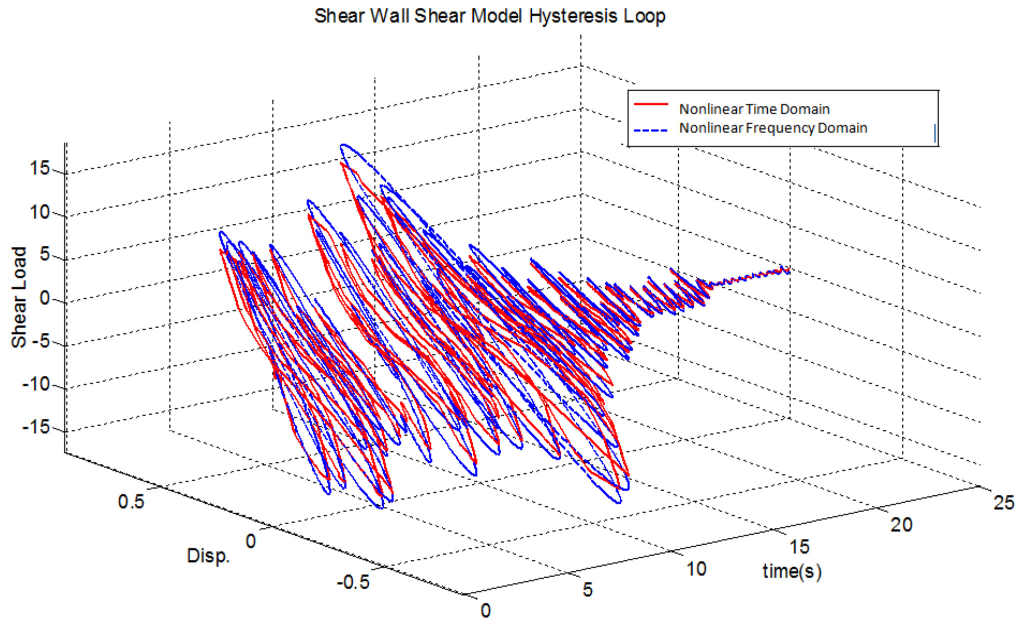
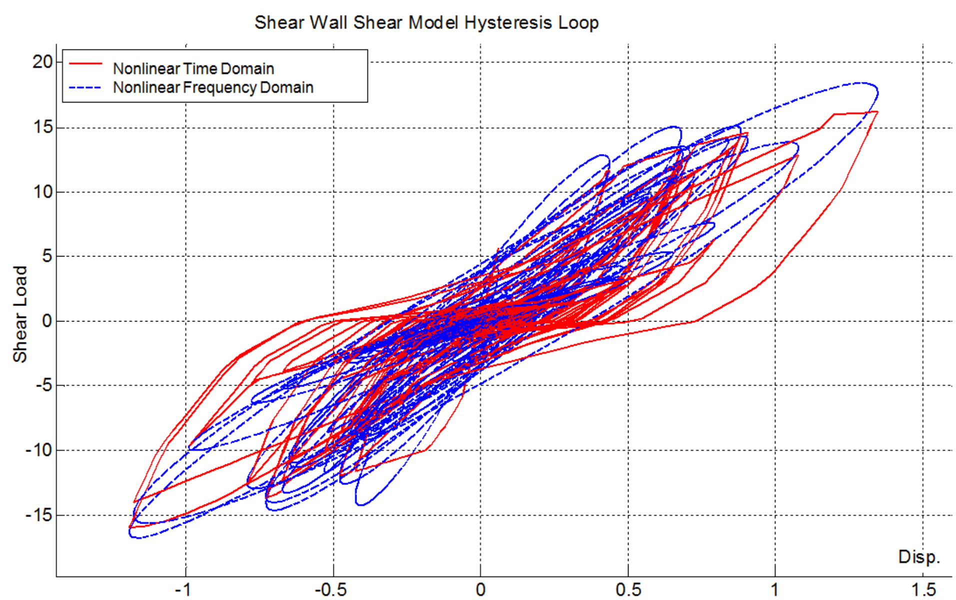



Figure 5 Examples of Selection of Shearwall Panels Assumed with Nonlinear Hysteretic Behavior

Figure 5 shows two selected shearwall panels. The four red dots delimit the selected shearwall panel that is assumed to behave nonlinearly during the seismic motion duration.




a) Evolutionary Shear Load Hysteretic Loops for the Time Domain Nonlinear Hysteretic Model (red line) and the Complex Frequency Domain Nonlinear Hysteretic Model (blue line)




b) Comparions between the Chen-Mertz Time Domain Nonlinear Hysteretic Model (red line) and Complex Frequency Domain Nonlinear Hysteretic Model (blue line)

Figure 6 Comparisons Between Time and Complex Frequency Nonlinear Hysteretic Models

To use nonlinear hysteretic models to idealize the low-rise shearwall panel behaviors, the basic model parameters that define the system backbone curve need to be defined for each panel. For the shearwall panel backbone curve parameters the recommendations of the ASCE 41-06, Supplement 1, Chapter 6 (2007) and the ASCE 43-05 (2005) were considered. The shearwall panel cracking, ultimate shear capacities and the ultimate strain are defined for each panel based on the panel geometry and concrete reinforcement.

Figures 6 and 7 describe the shear force–drift displacement relationship for the selected shearwall panel between the 2nd and 3rd floor shown in the Figure 5 left plot. The frequency-dependent nonlinear hysteretic model results are compared with the time-dependent nonlinear hysteretic model results. Figure 7 shows that the frequency-domain hysteretic models provide as accurate nonlinear analysis results as the time-domain hysteretic models. Both the shear displacement and the shear force time histories match extremely well for the two domain models. The minor differences between the shapes of the hysteretic loops as shown in Figure 6 have a negligible impact of the nonlinear analysis results.

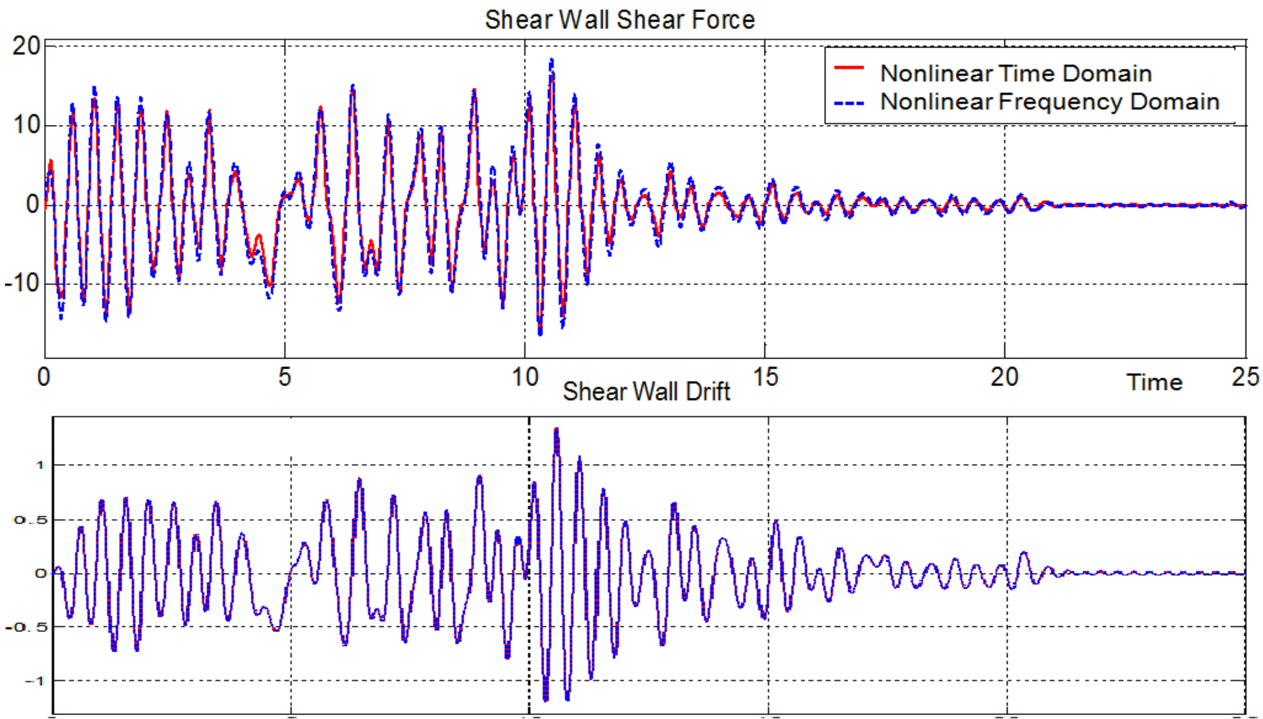


Figure 7 Shear Force and Drift Nonlinear SSI Response Time Histories for Investigated Shearwall

The new SSI approach was implemented in an in-house version of the ACS SASSI code (2012).

To perform the seismic nonlinear SSI analysis the following steps were applied:

1) For the initial iteration, perform a linear SSI analysis using the elastic properties for the selected shearwall panels
2) Compute the reinforced concrete shearwall panel behavior in time domain and frequency domain using the Cheng-Mertz hysteretic model adapted to each selected panel
3) Perform a new SSI analysis iteration using a fast reanalysis (restart analysis) in the complex frequency domain using the hysteretic models computed in Step 2 for all selected panels
4) Check convergence of the nonlinear SSI response after new SSI iteration, and go back to Step 2 if the convergence was not achieved.

Figure 8 shows a comparison between the linear and nonlinear SSI analysis results for the 0.50g review level earthquake in terms of the 5% damping in-structure ARS computed at the 2nd and

3rd floor levels. It should be noted from these results that the reinforced concrete shearwall nonlinear behavior could impact significantly on the in-structure ARS.

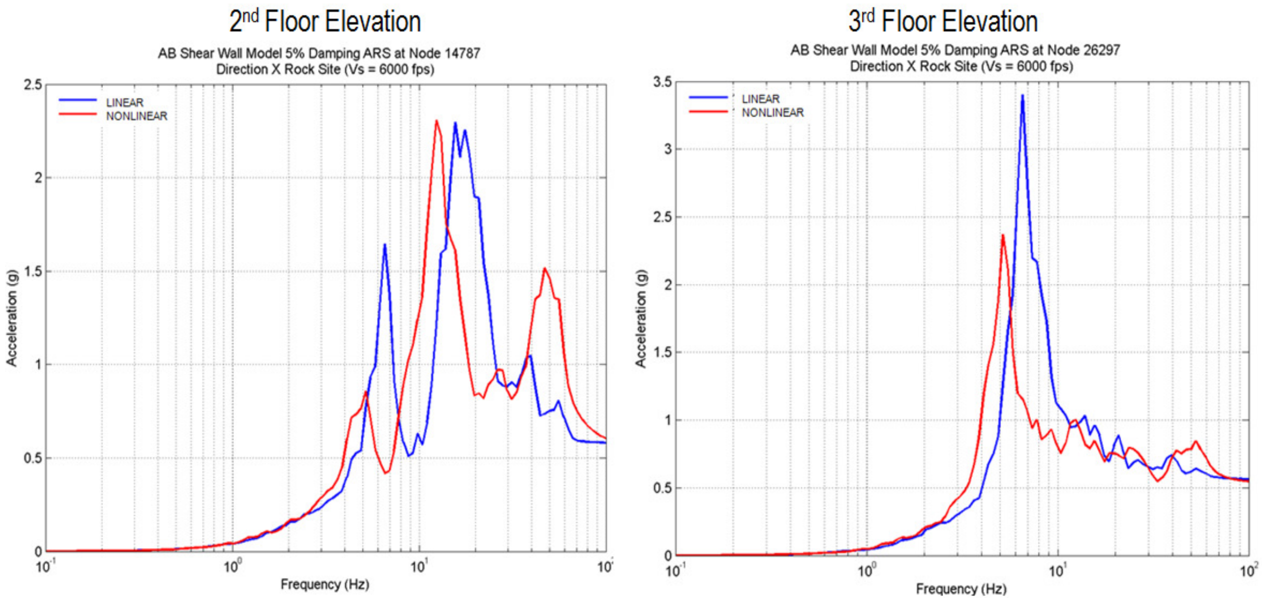



Figure 8 Linear vs. Nonlinear 5% Damping ARS at the Elevations of Shearwall Bottom and Top Floors

## CONCLUSIONS

The paper presents a novel approach for performing efficient and accurate nonlinear SSI analysis in complex frequency domain. The results of the investigated case study of the shearwall building subjected to a severe 0.50 g review level earthquake indicated that the nonlinear structural effects influences significantly the ARS within the building. The new nonlinear SSI approach eliminates the need to use simplified cascaded multistep approaches that loose physics by neglecting the effects of the structural degradation on the SSI system dynamic behavior.

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