Fast Nonlinear Seismic SSI Analysis of Nuclear Structures in Complex Frequency Domain - A Breakthrough Development -

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Purpose of This Presentation:

The presentation shows a novel nonlinear SSI 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.

A case study of a nuclear shearwall building is presented in relative detail. ACS SASSI Option N was used for nonlinear SSI analysis.
Equivalent-Linear System in Complex Frequency

Based on the up-to-date literature, the nonlinear behavior of dynamic structural systems can be captured only by nonlinear time history analyses.

Only simple equivalent linear (EQL) approaches were applied in frequency domain. As a result of the EQL model time invariant behavior, the SSI response could be either over or under estimated at different time moments.

Linear Hysteretic Model

Non-Linear Hysteretic Model

Frequency Domain
(Time-Invariant System)
(Frequency-Invariant)

Time Domain
(Time-Dependent System)
(Frequency-Dependent)
Linear Hysteretic (Voigt) Model in Complex Frequency

In complex frequency, Hooke Law is:
\[ \sigma^* (\omega) = D^* (\omega) \varepsilon^* (\omega) \]
\[ D^* (\omega) = D_R + iD_I \quad \text{(for elastic solid } D_I = 0 \text{)} \]

Linear Hysteretic Model Parameters:
\[ \beta = \frac{1}{4\pi} \frac{\Delta W}{W} \]
\[ D^* = D_R \left(1 - 2\beta^2 + 2i\beta \sqrt{1 - \beta^2} \right) \]

In time domain, using Fourier duality:
\[ \sigma(t) = \sigma_{\text{elast}}(t) + \sigma_{\text{diss}}(t) \]
\[ \sigma_{\text{elast}}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} D_R(\omega)\varepsilon^*(\omega) \exp(-i\omega t) d\omega \]
\[ \sigma_{\text{diss}}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} D_I(\omega)\varepsilon^*(\omega) \exp(-i\omega t) d\omega \]

Using Fourier duality linear (nonlinear) time response can be mapped in a complex frequency response and vice-versa.
Nonlinear Hysteretic Models in Time and Frequency

To map a linear system response time history we need a linear (frequency-independent) hysteretic model.

To map a nonlinear system response time history we need a nonlinear (frequency-dependent) hysteretic model.
Nonlinear Hysteretic Model in Complex Frequency

Comparison of the Two Nonlinear Hysteretic Models

Shear Wall Shear Model Hysteresis Loop in 3D (Scale = 0.2)

Comparison Hysteretic Loops in Time-Domain

Shear Wall Shear Force (Scale = 0.2)

Shear force in time

Displacement

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Frequency-Dependent Linearized Hysteretic Models in Complex Frequency: Kausel-Assimaki Model

Time Response

Hysteretic Loops

Kausel, E. and Assimaki, D., 2002

**Remark:** Kausel and Assimaki (2002) and Yoshida et al. (2002) implementations lacked in the compatibility between the frequency and the time domain representations.
Nonlinear Plasticity FEA Models: ANACAP Model

Figure 5-86 Comparison of X-Direction Hysteresis from ANACAP Analysis Considering Prior Damages but with X-Input Motion only and Test Result for Run-6

NUREG/CR-6925, BNL-NUREG-77370, 2006

Nonlinear FEA results not fully in agreement with the experimental data from shearwall tests.....
Nonlinear SSI Analysis of Low-Rise Shearwall Buildings

- Define shearwall panels between floors that will behave nonlinear.
- Define shearwall panel back-bone curves and hysteretic models based on experimental evidence, in accordance with recommendations of ASCE 43-2005 and ASCE 41-06.
Nonlinear SSI Analysis in Complex Frequency:

Computational Steps:

• For the initial iteration, perform a linear SSI analysis using the elastic properties for the selected shearwall panels.
• Compute the reinforced concrete shearwall panel behavior in time domain and frequency domain using the hysteretic model associated to each selected panel.
• Perform a new SSI analysis iteration using a fast SSI reanalysis (restart analysis) in the complex frequency domain using the hysteretic models computed in Step 2 for all selected panels.
• Check convergence of the nonlinear SSI response after new SSI iteration, and go back to Step 2 if the convergence was not achieved.
Nuclear Shearwall Building on A Rock Site

External Walls

Internal Walls

Transverse External Walls

Transverse Internal Walls

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Shearwall Back Bone Curves (BBC) for All Shearwalls

A number of 36 wall panels were modeled for nonlinear SSI analysis. For each BBC were determined based on ASCE 04-2013 and ASCE 43-05.

Focus of the weak story (results shown for the panels #19 and 23)
Chen-Mertz Hysteretic Model for Low-Rise Shearwalls

Cheng and Mertz, 1989
Nonlinear SSI Analysis Convergence (Per Panel and Global)

0.30g ZPGA

0.70g ZPGA
Nonlinear SSI Analysis Iteration History for Panel # 19

0.3g Y- 0.30g ZPGA

Nonlinear SSI Analysis Iteration History for Panel # 19

0.7g Y-Excitation 0.70g ZPGA

Story drift

Stiffness

Damping

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Panel #23 Comparative Linear and Nonlinear Story Drifts

0.30g ZPGA

Y 0.3g Rock Base, Displacement Time History for Panel 23, for Initial and Final Iterations

Displacement [ft]

Time [sec]

0.70g ZPGA

Y 0.7g Rock Base, Displacement Time History for Panel 23, for Initial and Final Iterations

Displacement [ft]

Time [sec]
Panel #23 Hysteretic Loops for 1st and Final Iterations

0.30g ZPGA

0.70g ZPGA
Panel #23: Frequency-Dependent Stiffness and Damping

0.30g ZPGA

Stiffness

Damping

0.70g ZPGA
Panel #23: Amplitude Fourier of Story Drifts and Shear Forces

0.30g ZPGA

0.70g ZPGA

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## ASCE 43-05 Inelastic Reduction Factors for Different Damage States

### C5-4 Typical Load-Deformation Curve and Limit States

<table>
<thead>
<tr>
<th>Limit State</th>
<th>LS-A</th>
<th>LS-B</th>
<th>LS-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMRF reinforced concrete moment frames</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beams (15 ≤ ℓ/h)</td>
<td>5.25</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Beams (ℓ/h ≤ 10)</td>
<td>3.25</td>
<td>3.0</td>
<td>2.5</td>
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<tr>
<td>Columns**</td>
<td>2.0</td>
<td>1.75</td>
<td>1.5</td>
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<tr>
<td>Reinforced concrete shear wall, in plane:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending controlled walls, ( h_w / \ell_w ≥ 2.0 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( 6 \sqrt{f'_{c_e}} \leq f_e )</td>
<td>2.25</td>
<td>2.0</td>
<td>1.75</td>
</tr>
<tr>
<td>( f_v &lt; 3 \sqrt{f'_{c_e}} )</td>
<td>2.5</td>
<td>2.25</td>
<td>1.75</td>
</tr>
<tr>
<td>Shear controlled walls, ( h_w / \ell_w &lt; 2.0 )</td>
<td>2.0</td>
<td>1.75</td>
<td>1.5</td>
</tr>
</tbody>
</table>

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**Nonlinear SSI and ASCE 43-05 Inelastic Reduction Factors**

<table>
<thead>
<tr>
<th>Panel Number</th>
<th>( \mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Shear} )</th>
<th>( \mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Shear} )</th>
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<tbody>
<tr>
<td>1</td>
<td>0.716</td>
<td>0.657</td>
<td>1.042</td>
<td>1.811</td>
<td>1.619</td>
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<td>2</td>
<td>0.662</td>
<td>0.568</td>
<td>1.004</td>
<td>1.673</td>
<td>1.532</td>
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<td>3</td>
<td>0.664</td>
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<td>1.615</td>
<td>1.493</td>
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<td>4</td>
<td>0.734</td>
<td>0.684</td>
<td>1.097</td>
<td>1.716</td>
<td>1.559</td>
<td>1.846</td>
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<tr>
<td>5</td>
<td>0.776</td>
<td>0.743</td>
<td>1.153</td>
<td>1.720</td>
<td>1.562</td>
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<tr>
<td>6</td>
<td>0.756</td>
<td>0.715</td>
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<tr>
<td>18</td>
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<tr>
<td>22</td>
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<td>1.095</td>
<td>1.144</td>
<td>3.745</td>
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<tr>
<td>23</td>
<td>1.721</td>
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<td>6.764</td>
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<td>24</td>
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<td>1.068</td>
<td>1.241</td>
<td>3.143</td>
<td>2.299</td>
<td>1.982</td>
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</tbody>
</table>

Average Building

<table>
<thead>
<tr>
<th>( \mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Shear} )</th>
<th>( \mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Final Analysis} )</th>
<th>( F_\mu, \text{Shear} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.993</td>
<td>0.939</td>
<td>1.178</td>
<td>2.993</td>
<td>2.119</td>
<td>1.900</td>
</tr>
</tbody>
</table>

Building

Large ductility demands
Nonlinear SSI and ASCE 43-05 Inelastic Reduction Factors

Y 0.3g Rock Base Response Spectrum Comparison, 3 Floor Side

Y 0.7g Rock Base Response Spectrum Comparison, 3 Floor Side

Y 0.3g Rock Base Response Spectrum Comparison, 2nd Floor

Y 0.7g Rock Base Response Spectrum Comparison, 2nd Floor

ASCE 43-05 (Full and Reduce Stiffness)
Nonlinear SSI
0.30g ZPGA

ASCE 43-05 (Full and Reduce Stiffness)
Nonlinear SSI
0.70g ZPGA
Conclusions

- Nonlinear SSI analysis in complex frequency domain is a very promising engineering approach. It is at least 500 -1000 times faster than nonlinear SSI analysis in time domain.

- It provides results consistent with the ASCE 43-05 recommendations.

- Nonlinear SSI analysis in complex frequency is much more robust than nonlinear SSI analysis in time domain that is much more sensitive, especially for higher frequencies. Nonlinear time domain analyses are more prone to analysis errors than nonlinear complex frequency domain analyses.

The nonlinear SSI approach in complex frequency is currently implemented in the ACS SASSI Option N capability. The commercial version will be available in 2014.

The nonlinear approach is currently extended to soil material hysteretic behavior (providing more realistic results than the equivalent-linear SHAKE methodology), and to other types of structural concrete components.