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Title: Nonlinear Dynamic Analysis of a Mission-Critical Reinforced Concrete Building Including the SSI Effects for Seismic Risk Assessment

Author(s): Terani, Payman
Talebinejad, Iman
Perez, Michael
Doulgerakis, Natalie
Bassam, Asa
Tilow, Kaniel
Kosbab, Benjamin
Salmon, Michael W.

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Nonlinear Dynamic Analysis of a Mission-Critical Reinforced Concrete Building Including the SSI Effects for Seismic Risk Assessment

By: Payman Tehrani (Presenter)

Iman Talebinejad

Michael Perez

Natalie Doulgerakis

Asa Bassam

Kaniel Tilow

Benjamin Kosbab

Michael Salmon

Oct. 22, 2020



Outline

- Introduction
- Adopted Analysis Approach
- Integrated SSI Model
 - Site model
 - Structure model
 - SSI model
- Verification and Validation Analysis Results
 - Finite element testing
 - Structural component testing
 - Soil-structure system testing
- Summary

Introduction

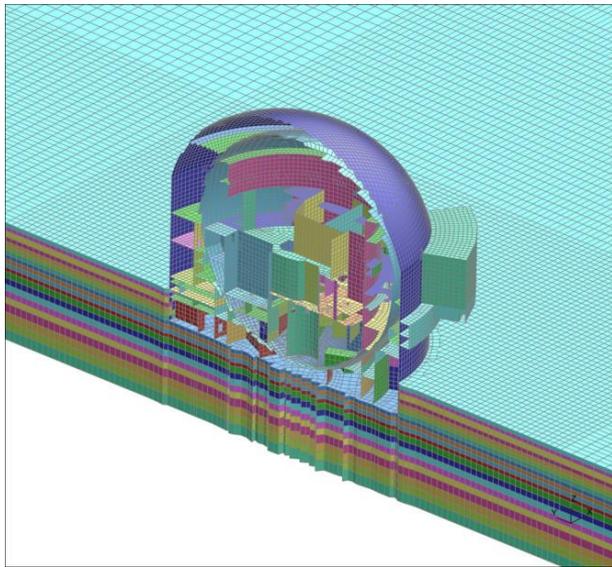
Project focus:

- Seismic performance assessment of a mission-critical reinforced concrete shear wall building
- Essential to capture the seismic response of the site, structure and their interaction over a wide range of ground motion intensities
- A single nonlinear SSI model desired for the whole hazard range of interest with potentially significant nonlinearity in the response of the site, structure, and their interface
- Desired a fully tested and verified/validated FE model through comprehensive system components and global response history testing
- Proposed an integrated nonlinear SSI analysis

Integrated Nonlinear SSI Analysis

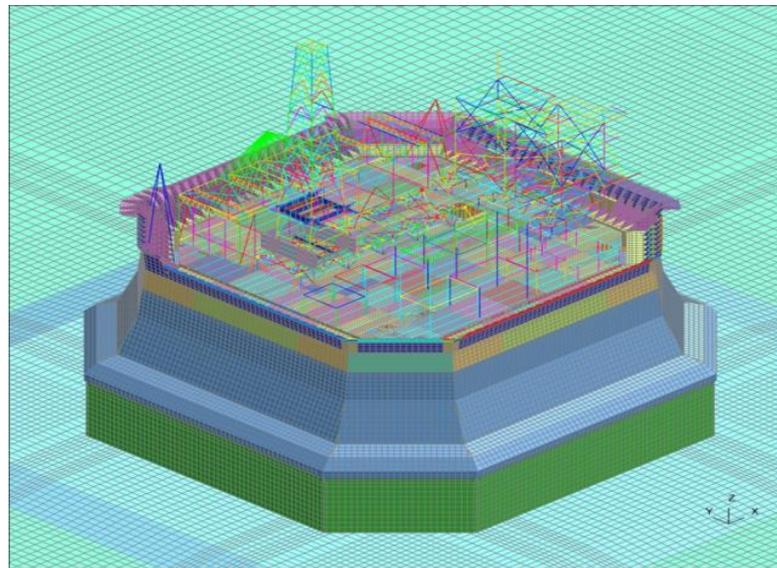
- Detailed representation of the site, structure, and their interaction in a single nonlinear model analyzed in time domain
- Precedence of the integrated nonlinear approach in the transportation, oil & gas, nuclear, water, and building industries:

European Nuclear Plant:



Ref.: Tehrani et. al., 2018

Offshore Platform:

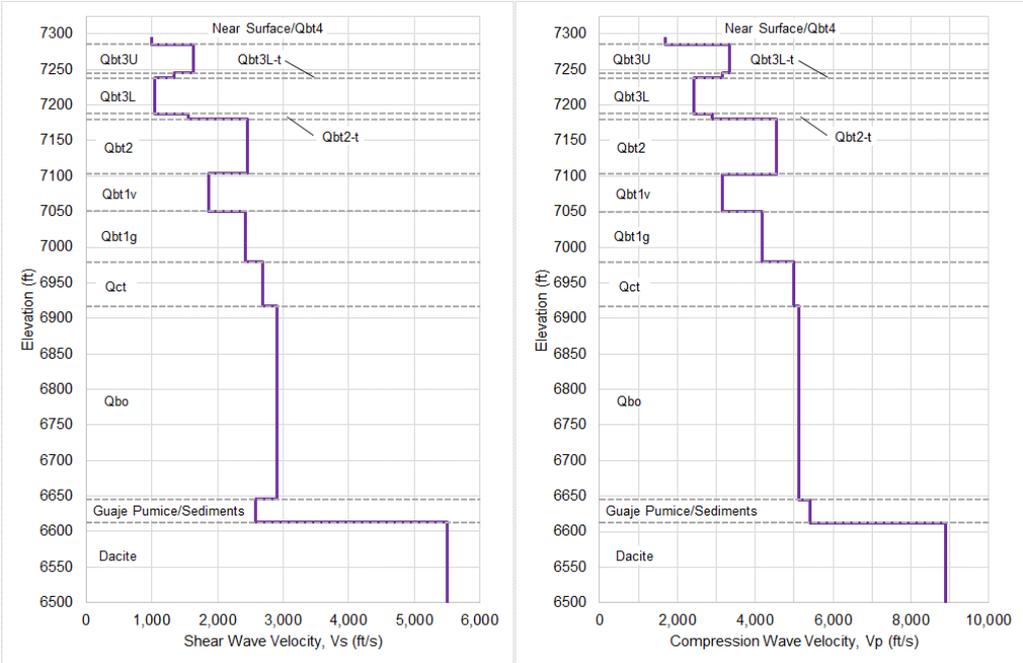


Ref.: Tehrani et. al., 2018

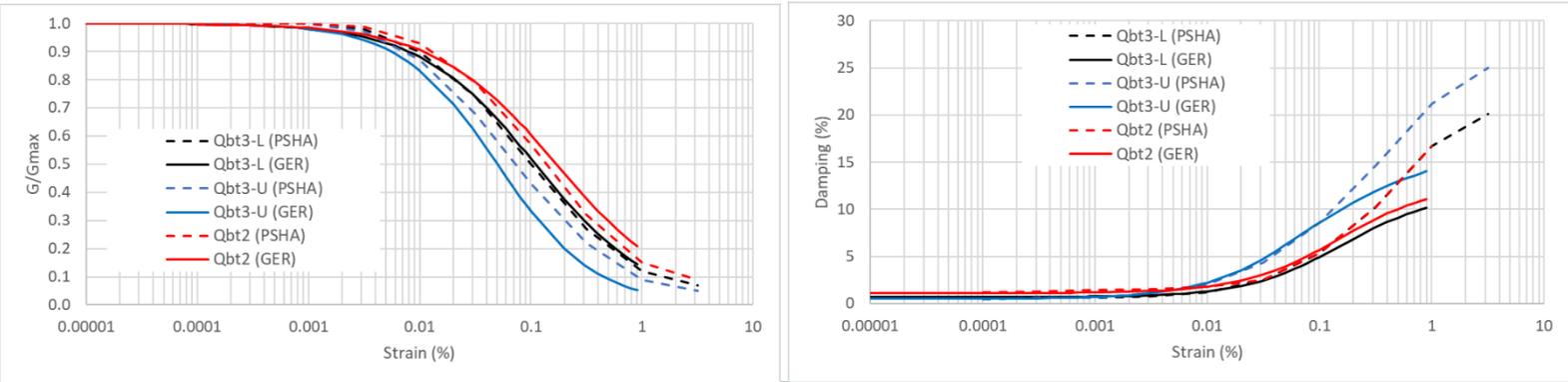
Shear Wall Building Integrated Nonlinear SSI Model

Site Model – Key Inputs

Shear and compression wave velocity profiles:

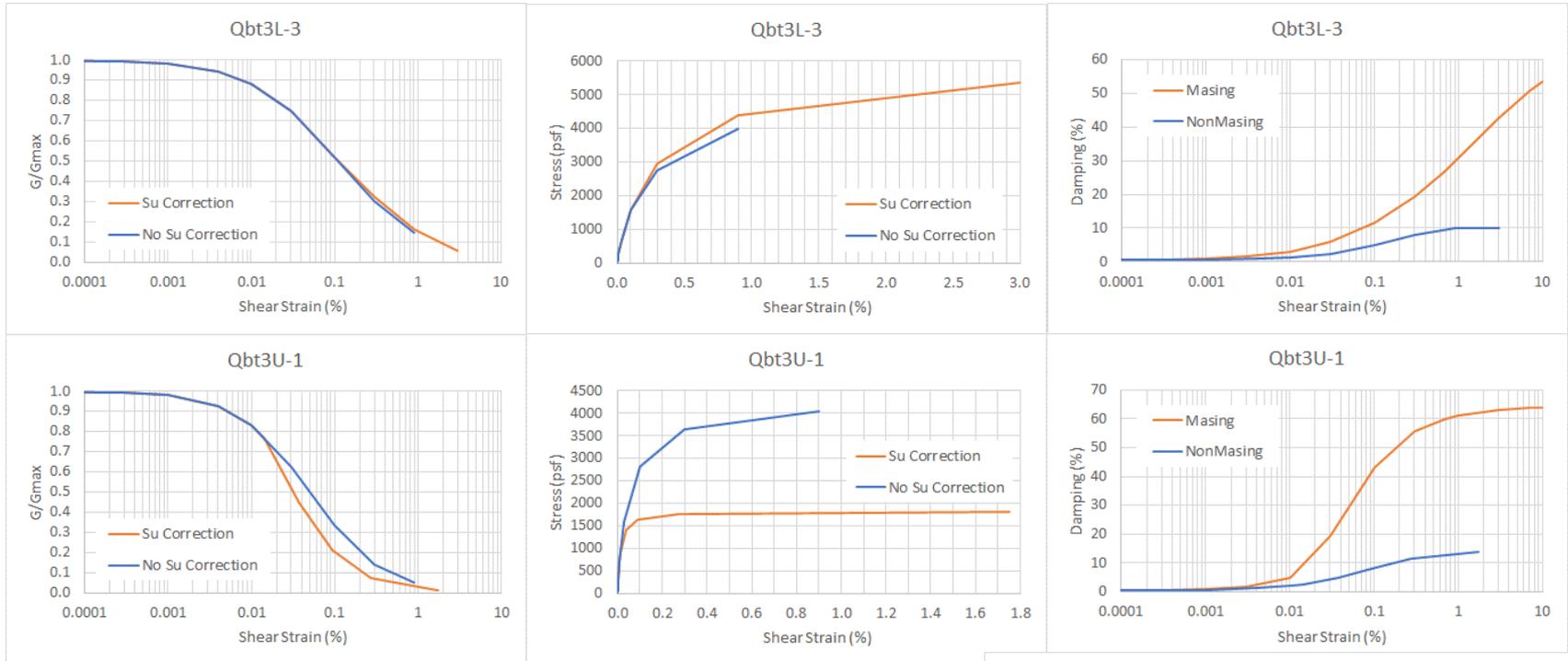


Geomaterial response – site-specific Stiffness reduction and damping curves

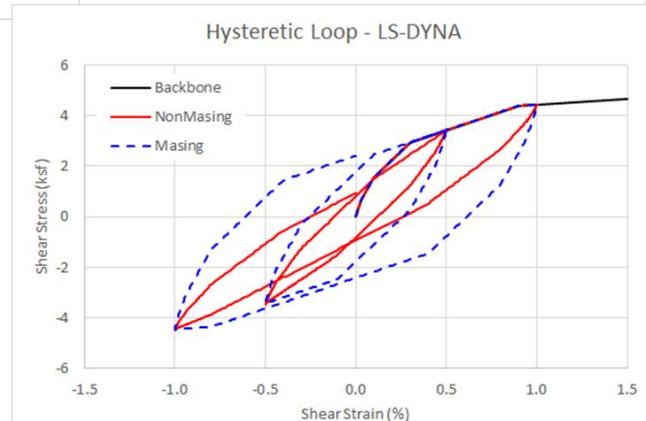


Site Material Model

Plasticity model with shear stress and hysteretic damping vs strain as main inputs:



Material law producing hysteretic damping consistent with site material damping curves:



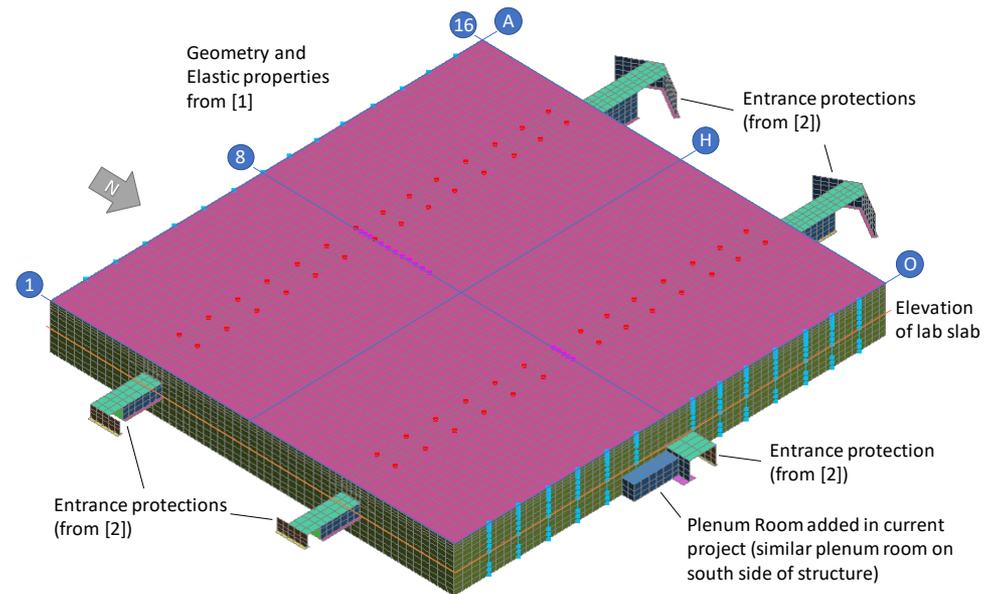
Structure FE Model

structural components :

- Primary: modeled as nonlinear
- Secondary: modeled as linear elastic with cracked or uncracked section properties

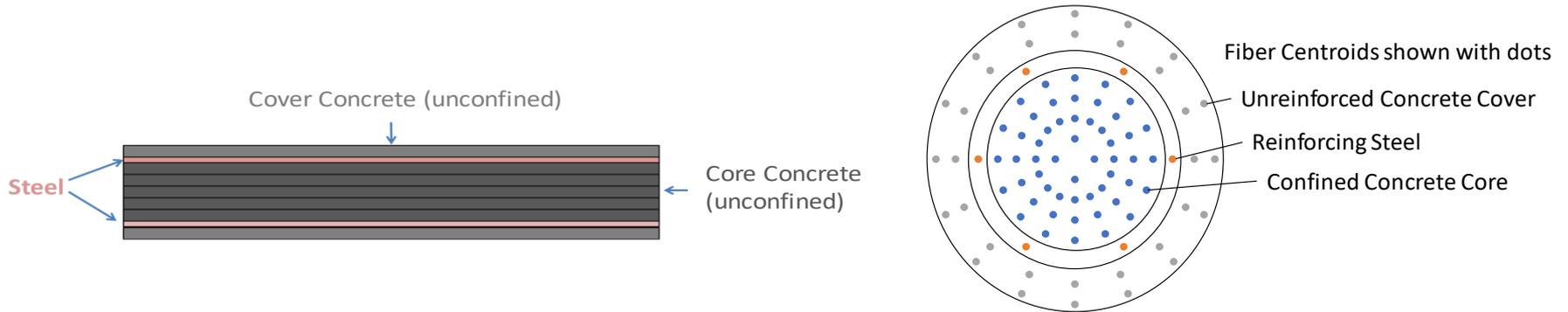
Structural components modeled as nonlinear

Component	Nonlinear Modeling Approach
Major Shear Walls	Nonlinear layered shell elements
Columns	Nonlinear fiber section beam elements
Laboratory Slab	Nonlinear composite layered shell elements
Roof Slab	Nonlinear composite layered shell elements
Entrance Connections	Nonlinear translational springs
Service Chase Roof connection	Nonlinear translational springs

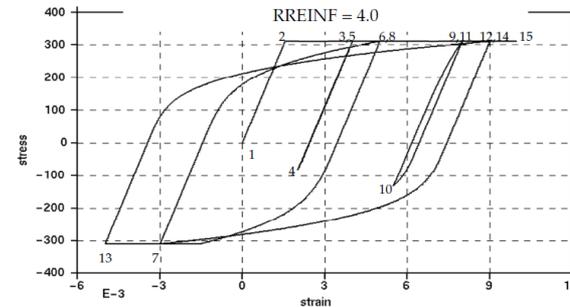
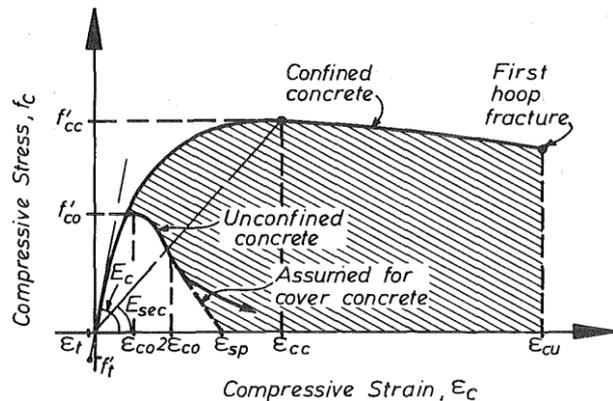


Structure FE Model

Layered shell and fiber beam elements used to model NL walls/slabs and columns



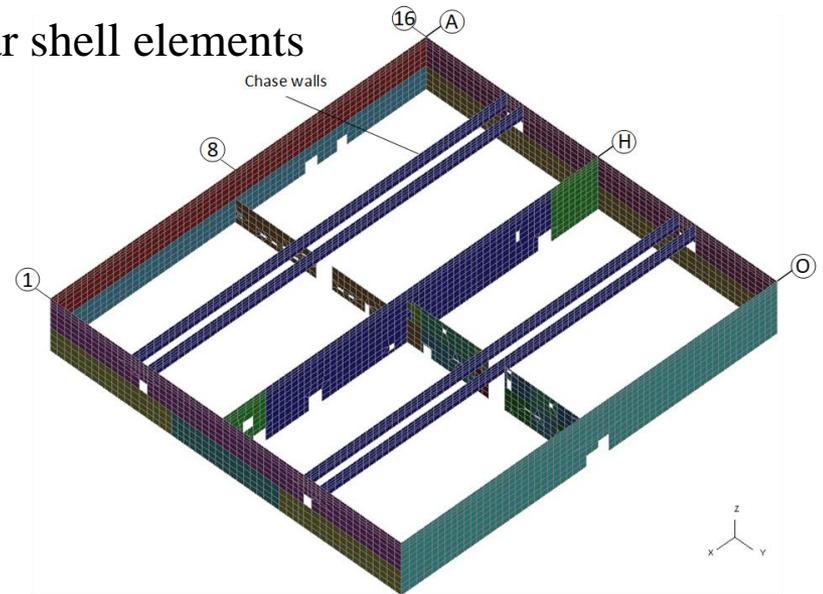
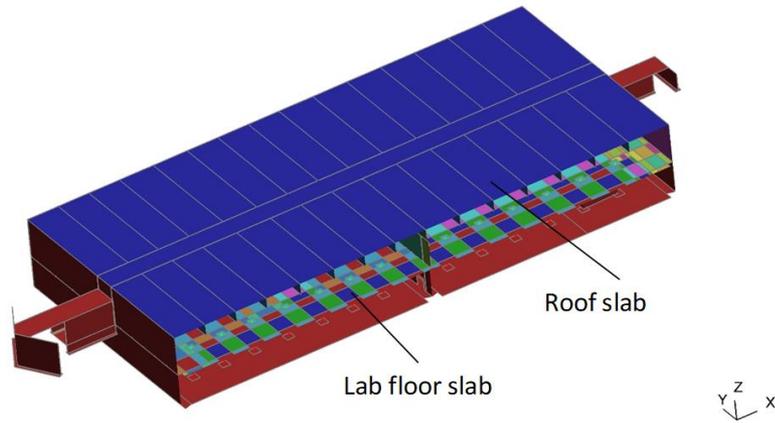
Constitutive material relations used for steel rebar and unconfined, confined concrete



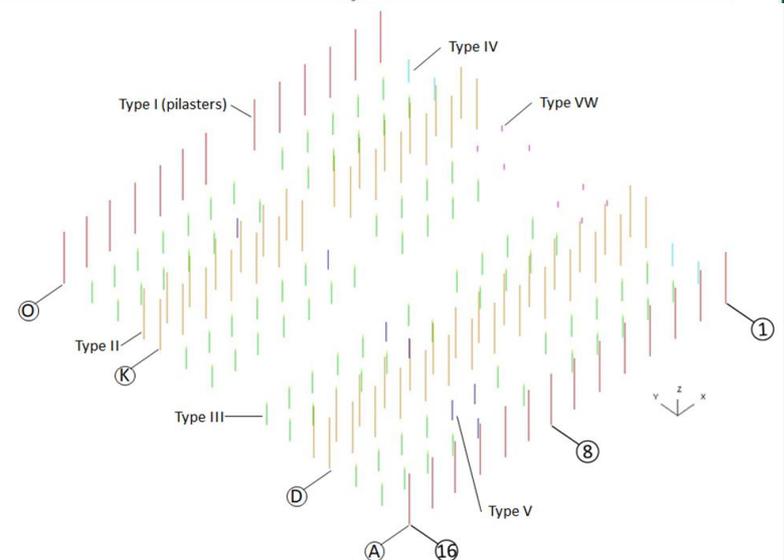
Note: Fiber beam/layered shell elements model the in-plane and bending nonlinearities. Out of plane shear response is linear.

Structure FE Model

Major shear walls and slabs modeled with nonlinear shell elements



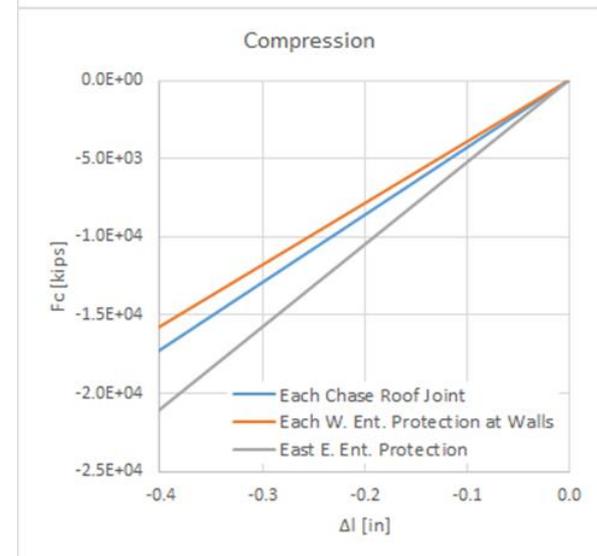
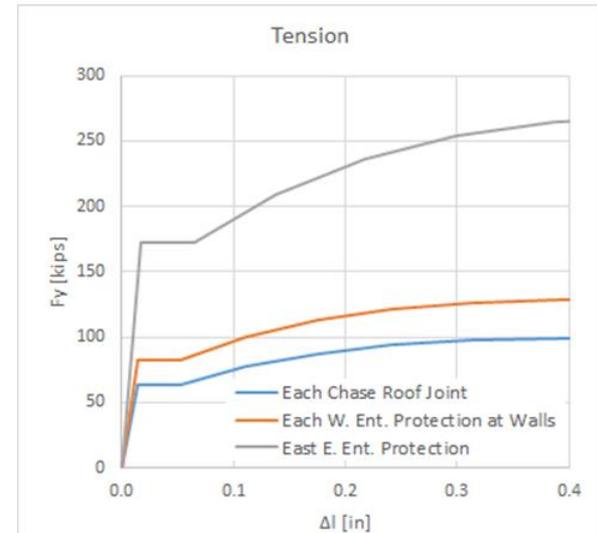
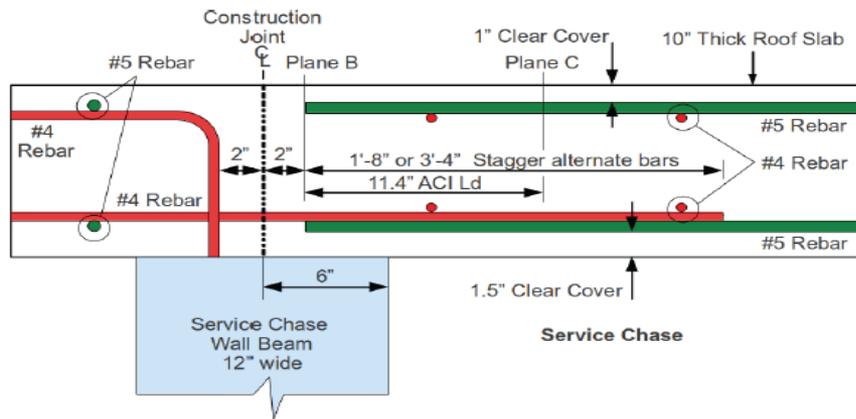
Columns modeled with nonlinear beam elements



Structure FE Model

Joints modeled with nonlinear springs

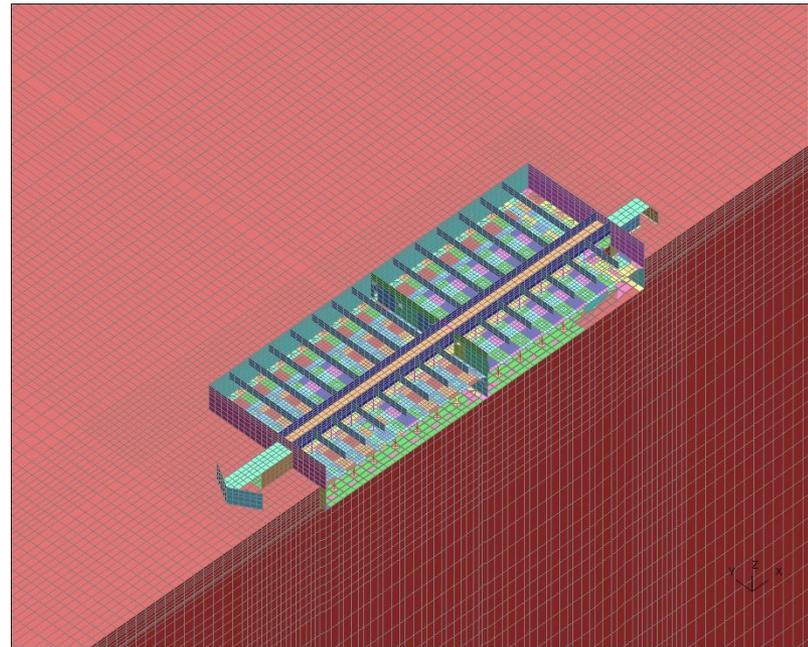
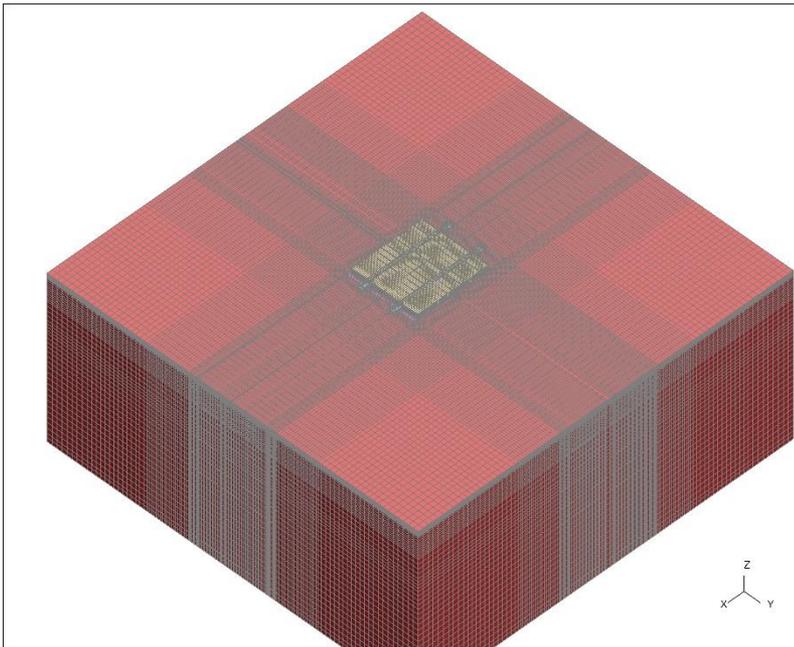
- Roof joints
- Entrance building to main building



SSI FE Model Assembly

SSI model development

- Structure is partially embedded
- The base of the structure is tied to the soil domain (to account for keyed-in base)
- Contact surfaces are defined between the exterior walls of the structure and the soil domain
- Soil domain size sufficiency confirmed by comparing the free-field response and Isolated 1D SRA results



Soil domain size: E-W: 1,500ft Square about 700ft deep comprising 1.3M solid elements

SSI Analysis Verification and Validation Results

Integrated SSI Model Testing

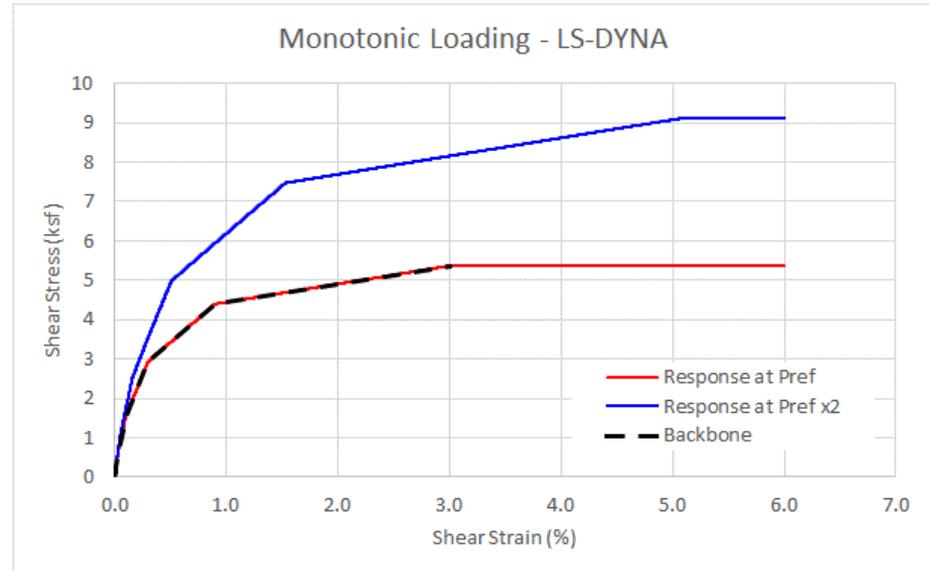
Sample Test Matrix:

Test #	Test Type	Test Description
1	Finite element testing	NL RC beam and shell element test
2		Soil continuum element
3	Component testing (local model)	NL RC column benchmark against experiment
4		NL RC shear wall benchmark against experiment
5		Site response analysis (soil column)
6	Component testing (global model)	PF4 structure columns response evaluation (shear)
7		PF4 structure walls response evaluation (in-plane shear)
8		PF4 structure walls response evaluation (out-of-plane shear)
9		PF4 structure roof response evaluation (in-plane shear)
10		PF4 structure roof response evaluation (out-of-plane shear)
11		PF4 structure roof girder response evaluation (shear)
12		PF4 structure roof joint response evaluation
13	Soil-Structure system testing	Structure frequencies
14		Site frequencies
15		Roof acceleration
16		Roof shear force

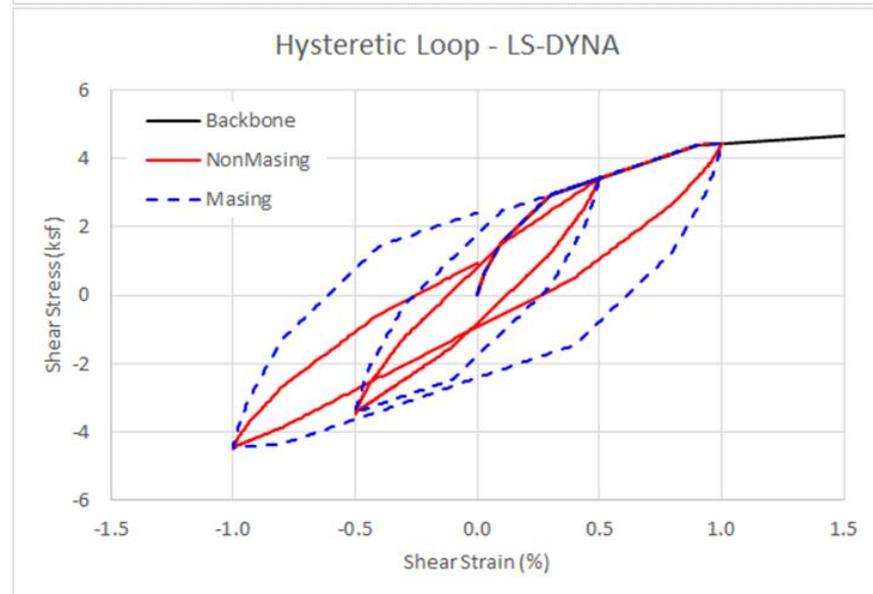
Select test results are presented herein

Geomaterial Model Testing

Monotonic - Pressure dependent:

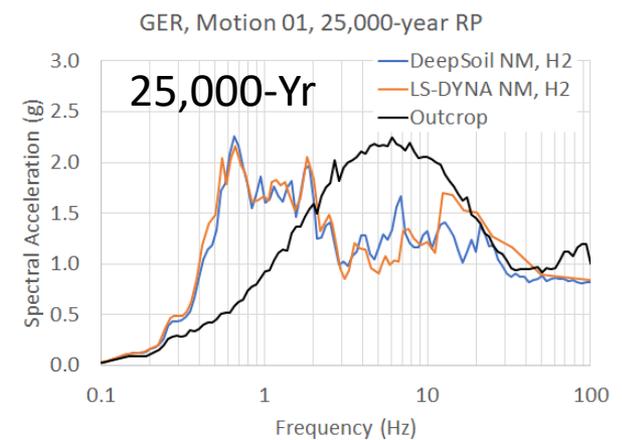
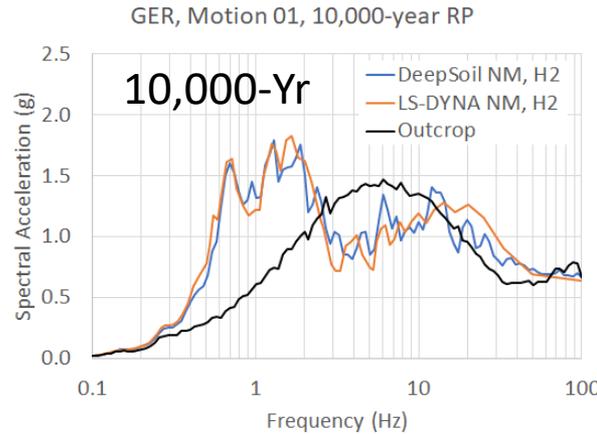
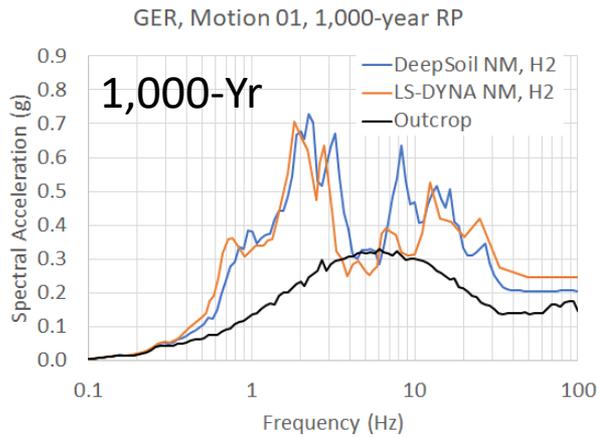


Cyclic:

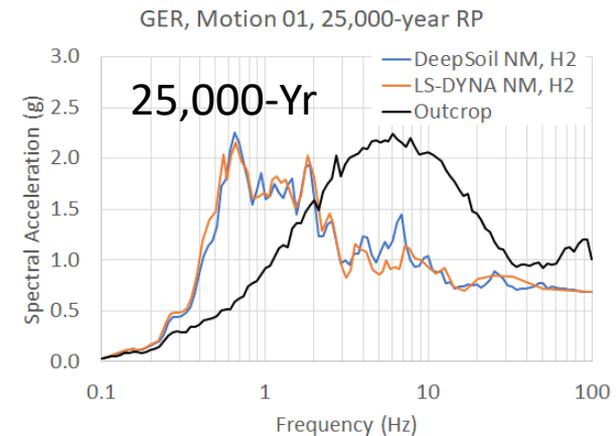
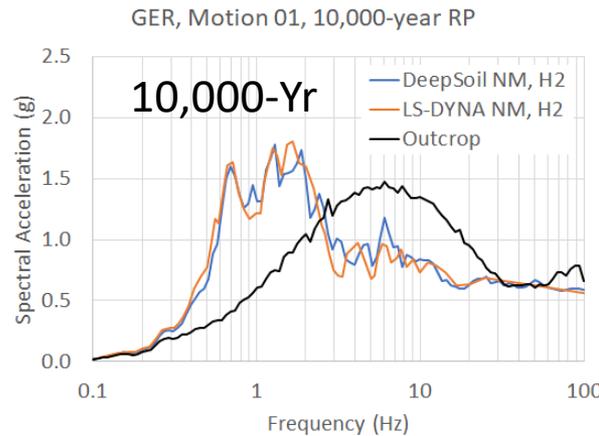
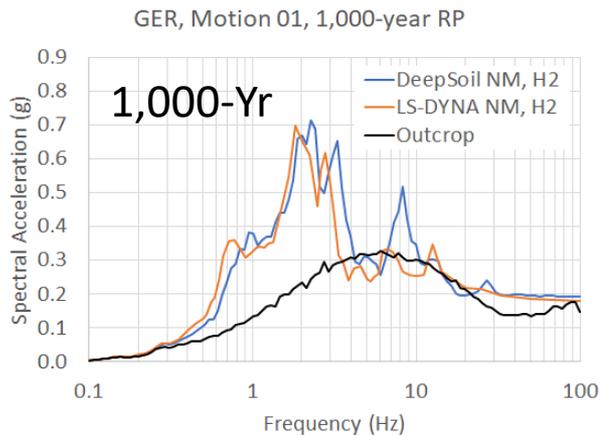


Site Soil Column Response Verification

Surface Response:



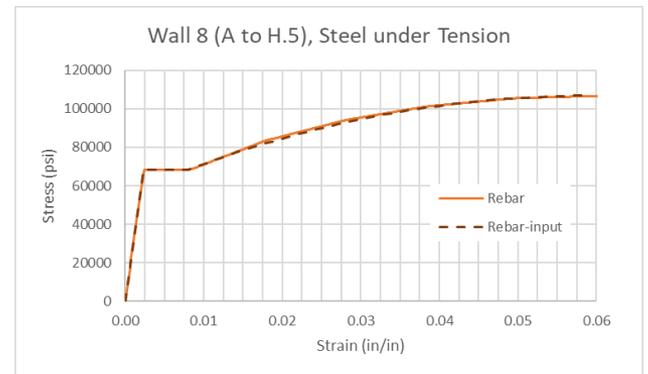
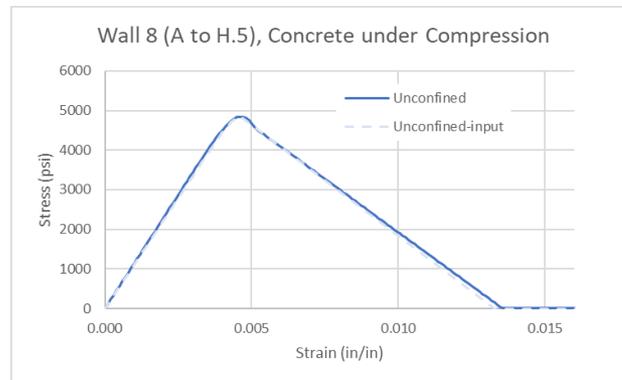
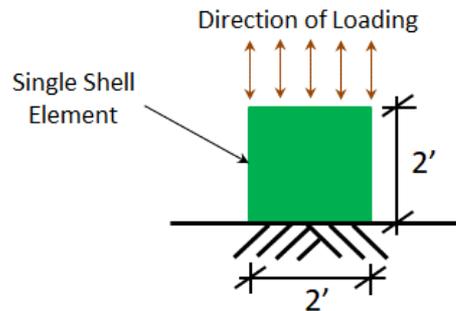
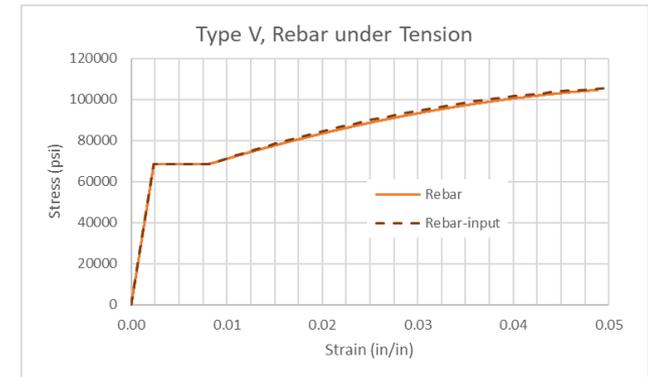
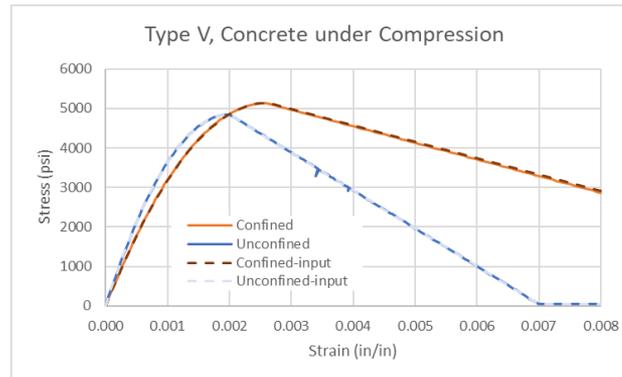
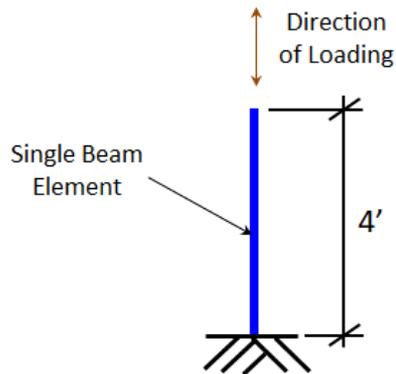
Base of Foundation Response:



NL RC Material Testing w/ Beam and Shell Finite Elements

Monotonic tension-compression test of a single beam (top) and shell (bottom) element

- Close agreement between the concrete and steel stress-strain responses with input constitutive relations



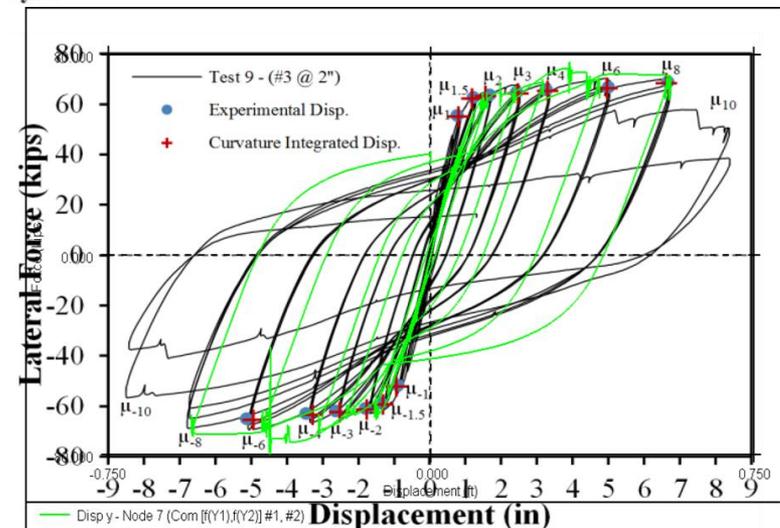
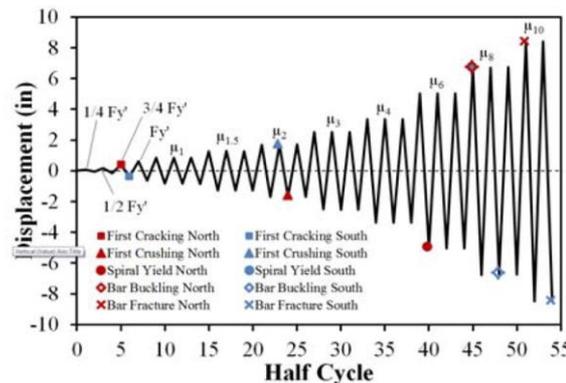
Component Testing - Local Model: NL RC Column Benchmark

Cyclic analysis of a reinforced concrete column

- Circular cantilever column subjected to symmetrical cyclic loading
- FE model of the column is developed using NL RC beam element
- Reasonable agreement between the experimental (black) and numerical (green) lateral force-drift ratio



Ref.: Goodnight et. al., 2015



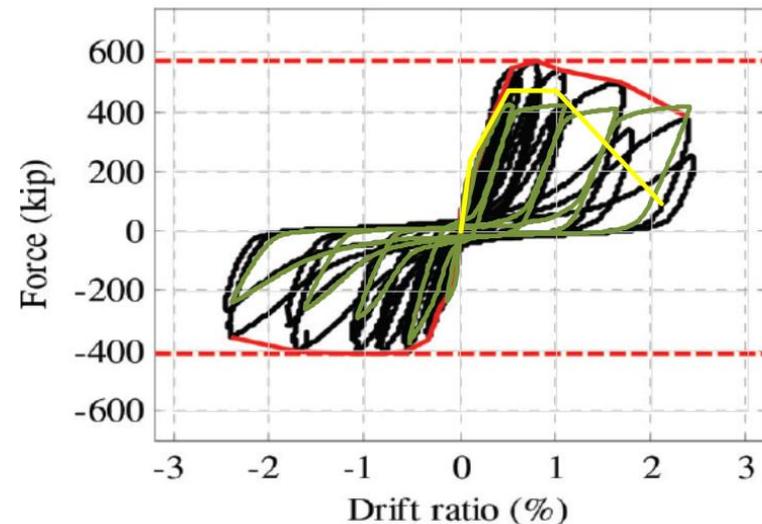
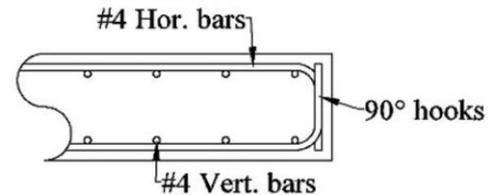
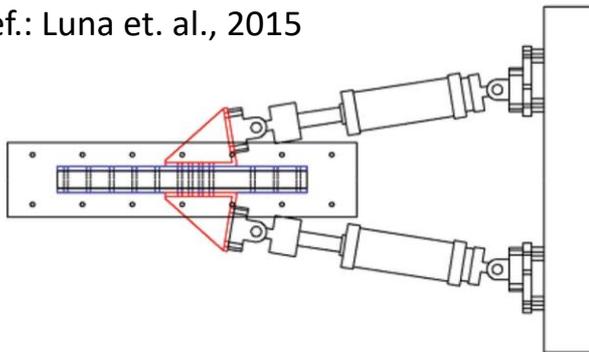
Component Testing - Local Model: NL RC Wall Benchmark

Cyclic analysis of a low aspect ratio reinforced concrete wall

- Height to length aspect ratio: 0.33, horizontal and vertical reinforcement ratio: 0.67%
- FE model of the wall is developed using NL RC shell element
- Reasonable agreement between experimental and numerical hysteresis
- Reasonable agreement between the code based (yellow, NIST backbone w/ ACI 318 capacity) and numerical (green) in-plane shear force- drift ratio (for drifts less than 1%).



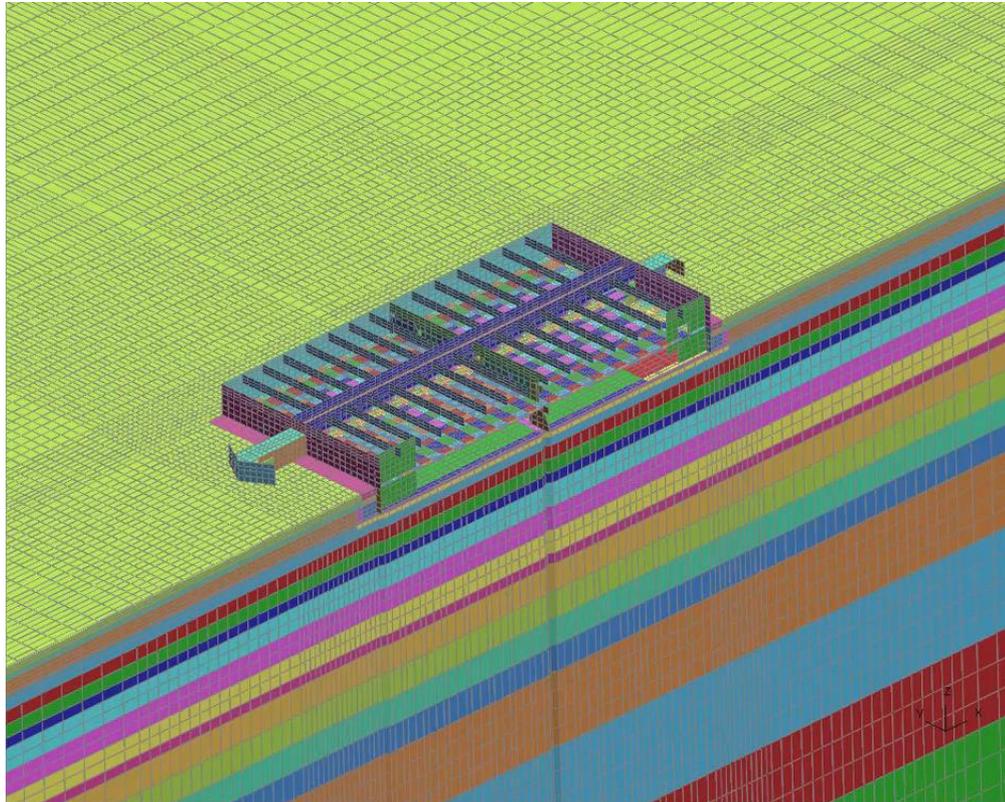
Ref.: Luna et. al., 2015



Building Component and SSI Testing - Global Model in Action

NL response history analysis of the integrated SSI model

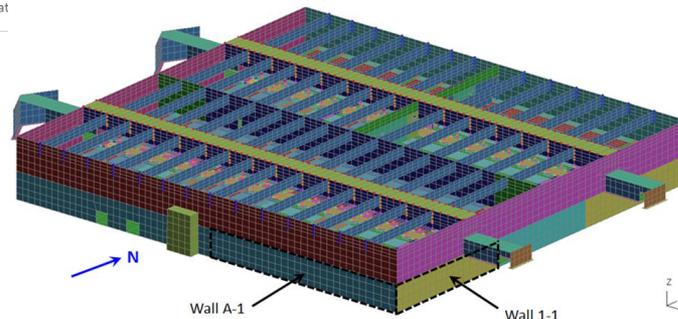
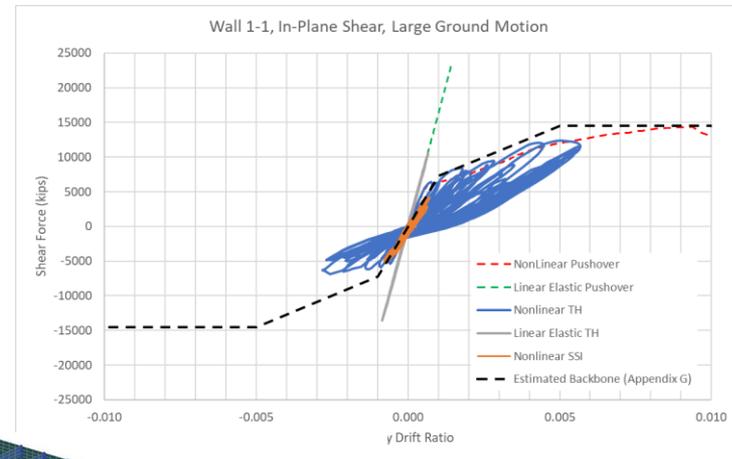
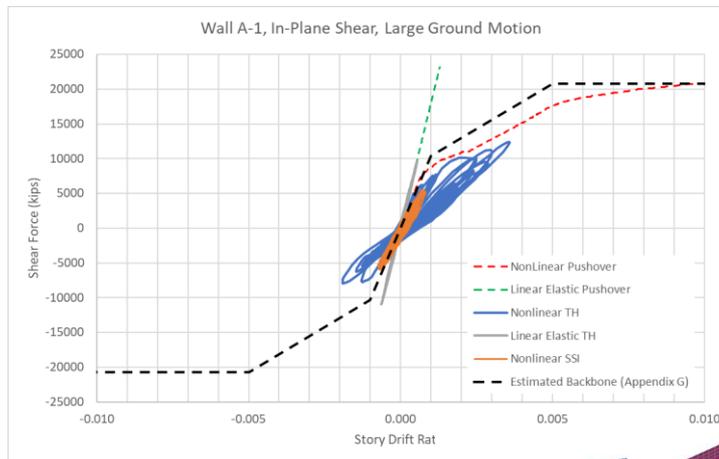
- Three components of the acceleration time histories are simultaneously applied to the base of the soil domain



Push over and response history analysis of the fixed-based structure performed to test the structure response closer to its capacity

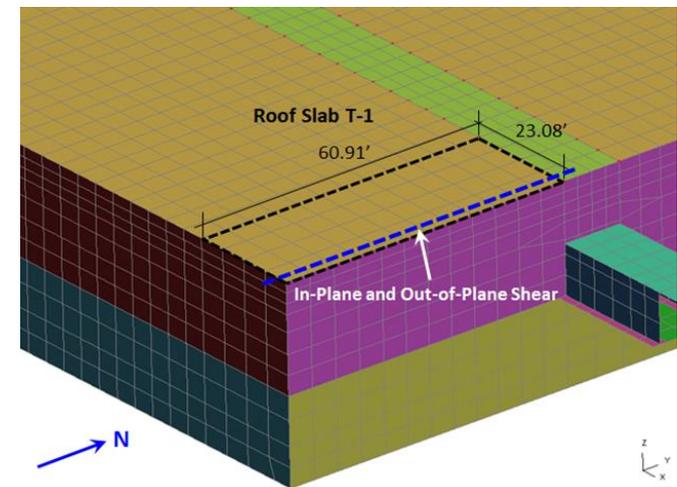
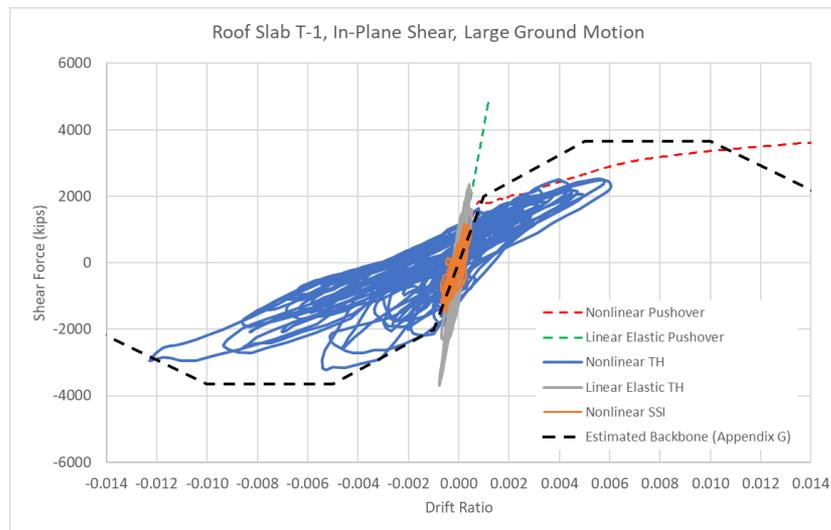
Building Shear Wall Response

- Shear walls response in SSI analysis under a relatively large GM remains elastic (orange).
- Fixed-base Structure model is exercised to demonstrate the nonlinear response of the walls (blue).
- NL pushover analysis response (red) is in good agreement with the backbone curve calculated based on EPRI NP-6041 and NIST GCR 17-917-45 (black)
- NL time history analysis responses (fixed structure: blue, SSI: orange) follow the pushover analysis response (red) and the backbone curve (black)



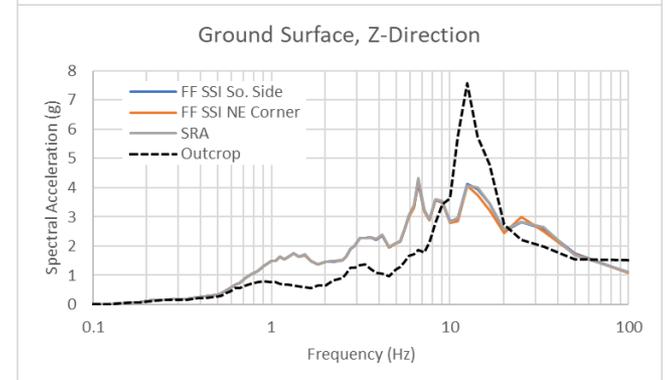
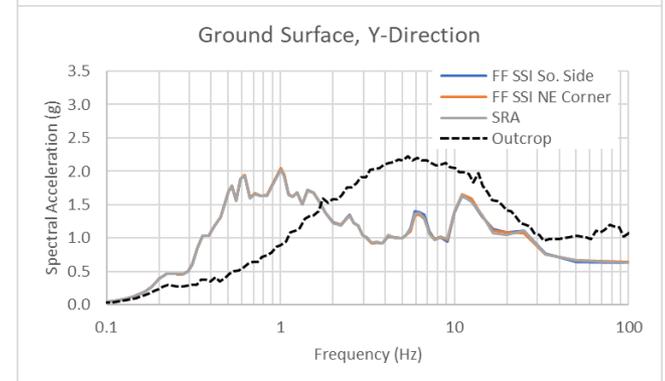
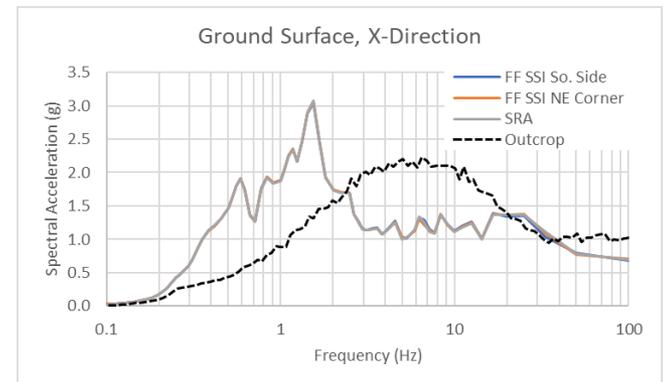
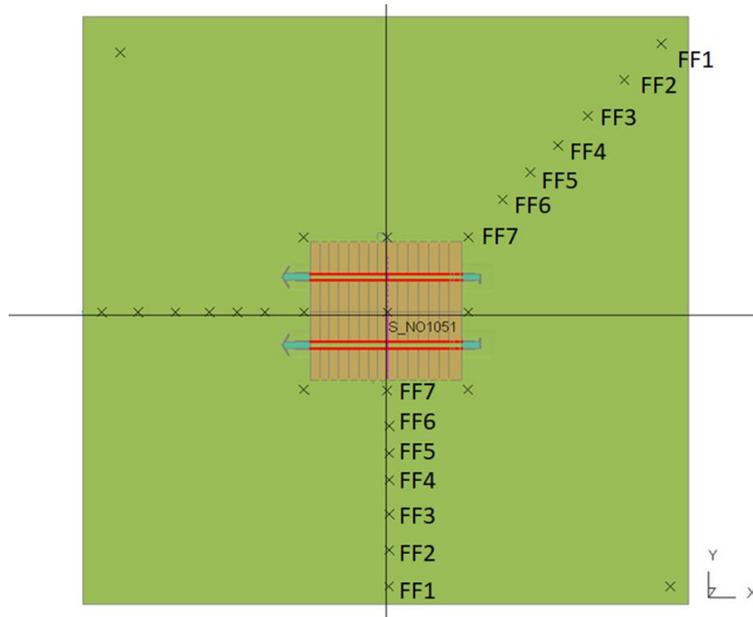
Building Roof In-Plane Shear (Diaphragm) Response

- Roof response in SSI analysis under a relatively large GM remains elastic (orange).
- Fixed-base Structure model is exercised to demonstrate the nonlinear response of the structure (blue).
- NL pushover analysis response (red) is in good agreement with the backbone curve calculated based on EPRI NP-6041 and NIST GCR 17-917-45 (black)
- NL time history analysis responses (fixed structure: blue, SSI: orange) follow the pushover analysis response (red) and the backbone curve (black)



3D Site Response Evaluation – Global SSI Model

- The input GM RS is shown in black
- FF response of the SSI model on the south side (FF1) is shown in blue
- Free-Field (FF) response of the SSI model on the NE corner (FF1) is shown in orange
- 1D soil column SRA response is shown in grey
- Good agreement between the 3D-FF and SRA responses



Structure Fixed-Base Frequencies

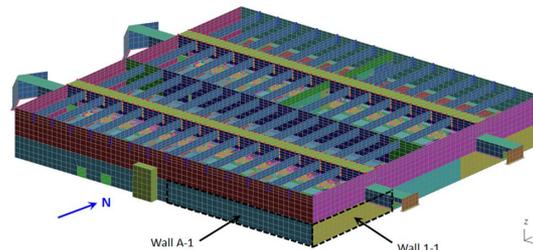
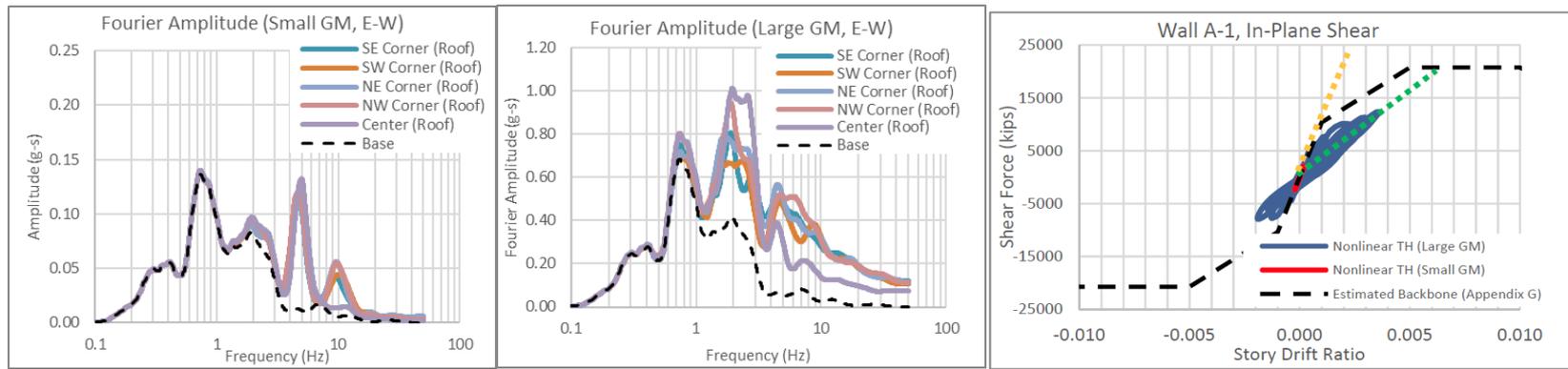
Structure frequencies estimated from roof response

Direction	Nonlinear Structure Model (small GM), Hz	Nonlinear Structure Model (large GM), Hz
E-W (X)	4.8	1.9-2.6

Small GM

Large GM

E-W Wall Response:



Based on wall responses studied, the equivalent wall stiffness is about 4-5 times smaller in the structure under large GM (compare yellow line vs. green line). Therefore, a factor of 2-2.5 reduction in frequencies is expected which is consistent with structure frequencies presented in the table.

Structure Frequencies in SSI Model

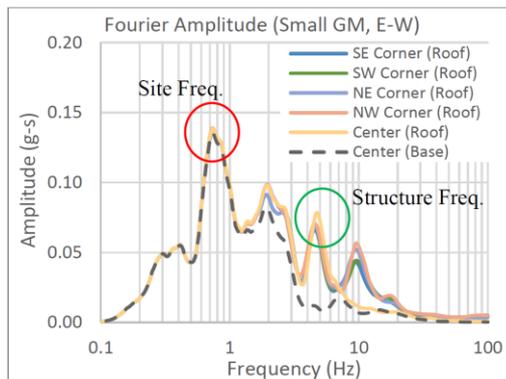
Structure frequencies estimated from roof response:

Direction	Fixed-Base Model (Small GM)	SSI Model (Small GM)		SSI Model (Large GM)	
	Structure Frequency	Structure Frequency	Site Frequency	Structure Frequency	Site Frequency
E-W (X)	4.8	4.8	0.75	4.0	0.4
N-S (Y)	4.4	4.4	0.75	3.7	0.5

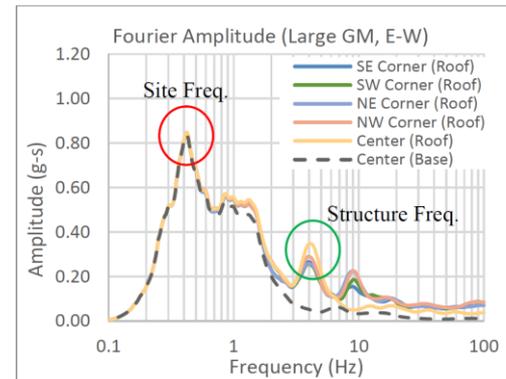
Site frequency based on Gmax:

$$f_s = \frac{V_{s-avg}}{4H_t} = 0.85$$

Small GM



Large GM



- Fundamental site frequency from the hand-calc is about 0.85 Hz consistent but slightly higher than the model with small GM (small soil degradation)
- Structure remained elastic for both small GM and large GM
- Structure frequencies with small ground motion similar to fixed base due to negligible base flexibility
- The site response is significantly softer under large ground motions evident from frequency drop
- More flexible base reduces structure frequency excited by the large ground motion

Summary

- A single integrated nonlinear model facilitates building performance evaluation over the whole hazard range of interest
- All important limit states are explicitly incorporated into the nonlinear model of the structure
 - Nonlinear response of the shear walls, slabs, columns, and important structural joints
- Relatively complex integrated SSI models are built step by step through extensive testing:
 - Soil and structure single finite element responses
 - Site response verification via 1D SRA
 - Key structural component response benchmark studies against relevant experimental data (shear walls, columns, slabs, and joints)
 - Testing the global response of the structure-only model pushed or excited well into its nonlinear response regimes
 - 3D site response verification
 - Testing of the assembled integrated soil-structure system model at various excitation levels

Acknowledgements

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- Prof. Youssef Hashash
- Prof. Andrew Whittaker
- Dr. Brian McDonald

Thank you