Comparative Study of Time-Domain versus Frequency-Domain Seismic Soil-Structure Interaction Analysis of Pressurized Water Reactor Containment Building

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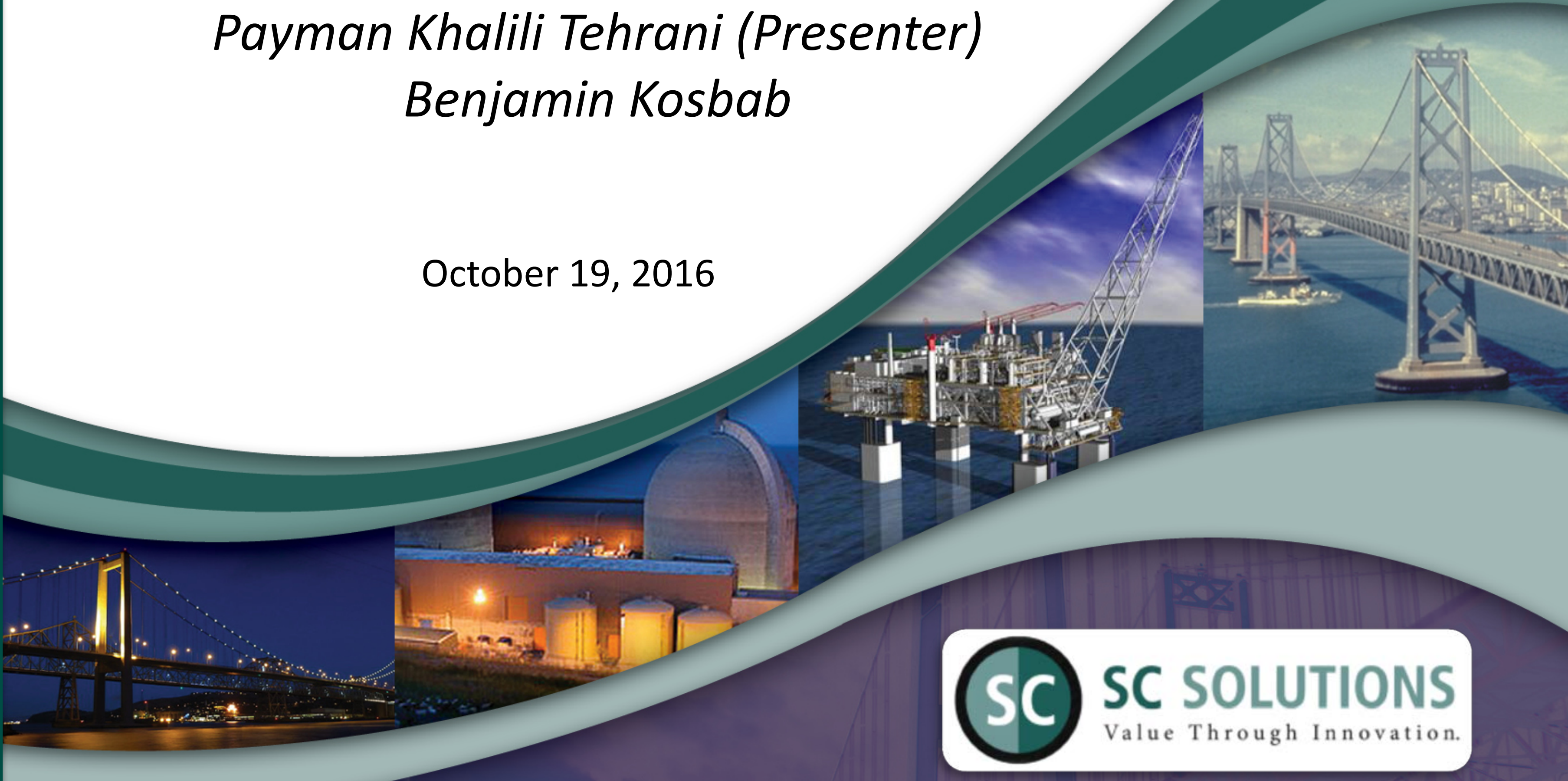
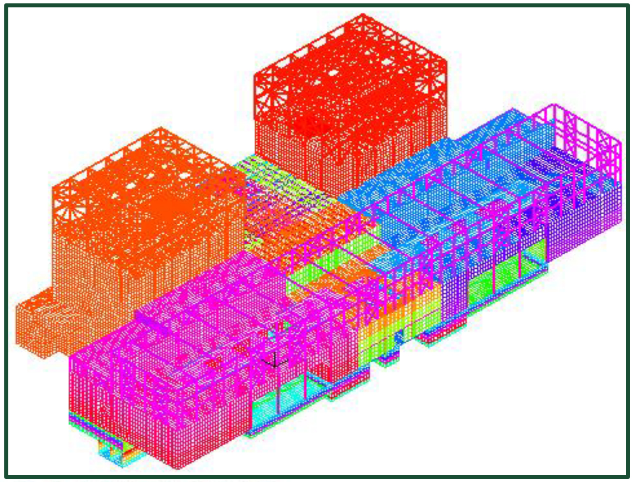
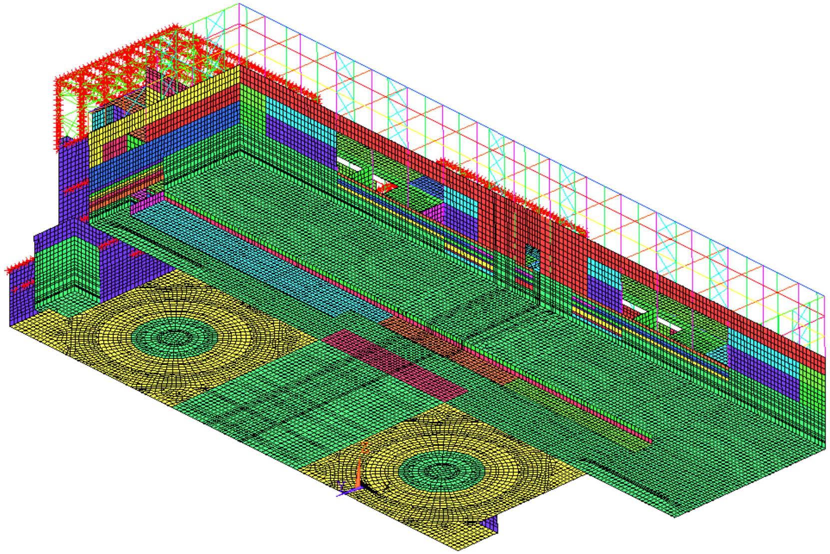
October 19, 2016



State of Practice: Nuclear Industry

- Pioneering industry in recognizing the importance of SSI
- Standard analysis approach: Equivalent Linear in Frequency Domain (ELFD) – Ground breaking in '80s, still perfectly fine for small-to-medium intensity shaking
- Historically limited to simplified (e.g. stick) models but detailed models possible today





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ELFD Approach Limitations

- **Equivalent Linear Assumption**
  - Linear material properties for soil and structure
  - Tied soil-structure interface behavior
  - Applicable to small range of seismic hazard: (i.e. unique model needed for each hazard level)
  - Cannot address seismic isolation, impact, etc.

- **Analysis Time**
  - Function of interaction nodes - Inefficient specially when dealing with deeply embedded structures

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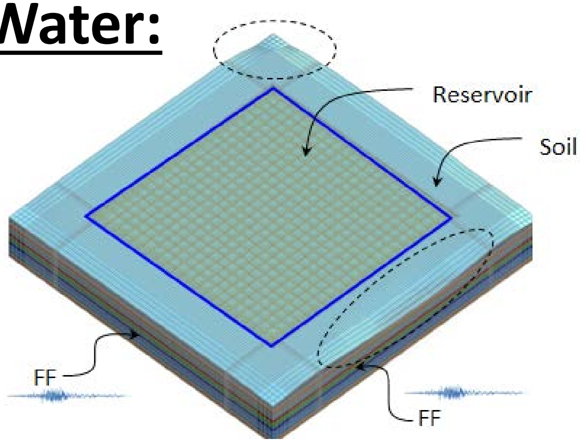
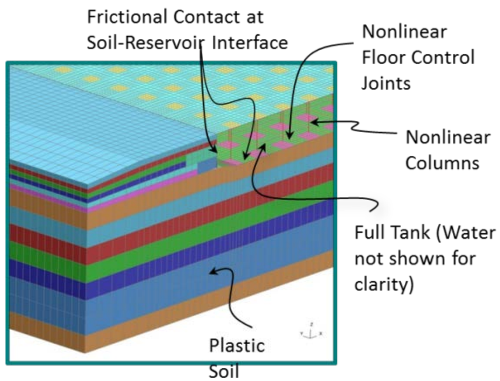
Alternative: Nonlinear Time Domain (NLTD)

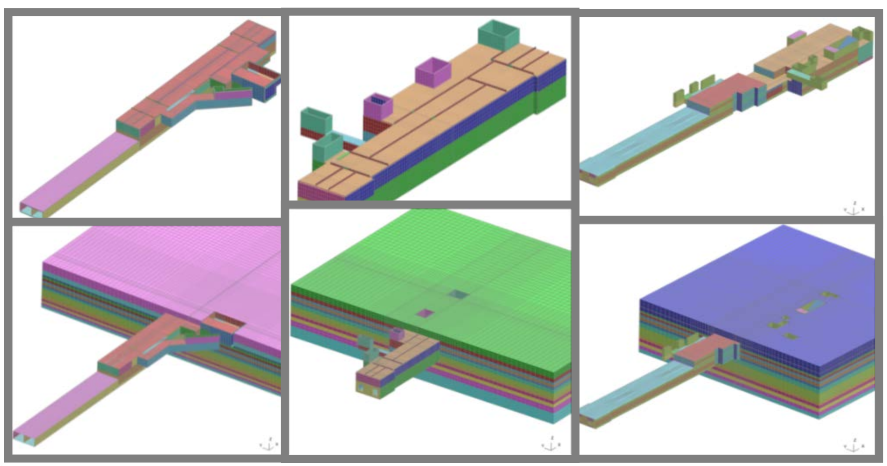
Water:





- Non-horizontal Layering
- Topography – Slope Stability
- FSI

Transportation:



- Extreme shearing of soft soil layers due to seismic wave propagation

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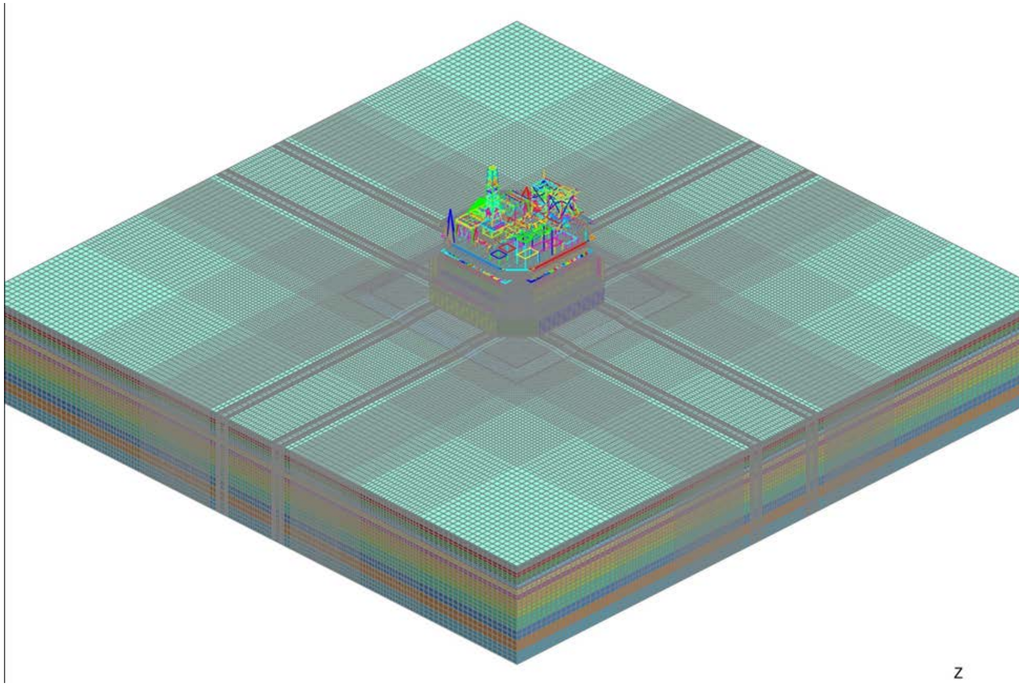
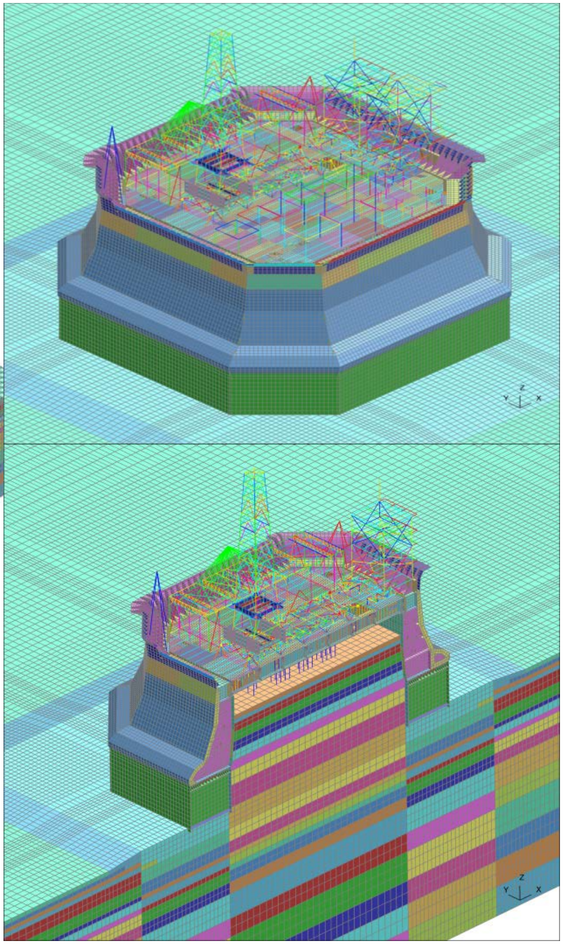
Alternative: Nonlinear Time Domain (NLTD)

<u>Oil & Gas:</u>





- **Seismically isolated deck via LRBs**
- **Unique Sandcore challenge**

Recent initiatives in nuclear industry for NLTD: ASCE4-16 and studies at National Labs

Study Plan – Contribute to Industry Advancement

Key: Step by step confidence building, evolve from ELFD to NLTD: Two different approaches and different results not convincing

- Under similar and realistic assumptions, demonstrate a good match between TD and FD: Need a successful and consistent EL analysis in Time Domain (ELTD)
- Subsequently demonstrate potential savings/benefits offered by NLTD
- Demonstration via a realistic problem: detailed 3D FEM (not stick model), excited in all 3 directions, nuclear site and GM characteristics

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Equivalent Linear Time Domain (ELTD)

Challenges in TD:

- Soil domain truncation:

  Solution:
  - Truncation via PML
  - Radiation damping in a large-enough domain

- Frequency-Independent damping:

  Solution:
  - Abandon Historically simplified treatment of damping in TD, i.e. Rayleigh and modified Rayleigh
  - Achieve nearly hysteretic damping through Viscoelasticity

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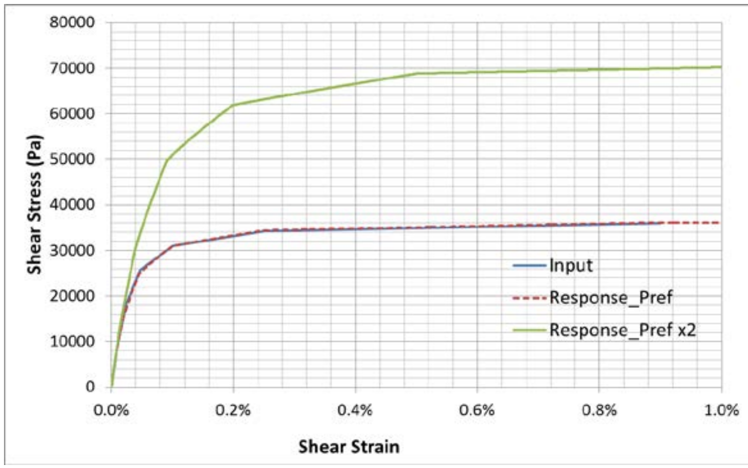
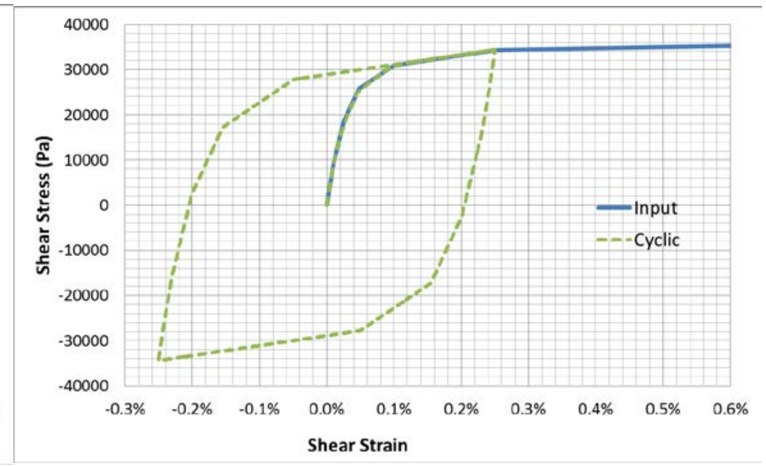
Nonlinear Time Domain (NLTD)

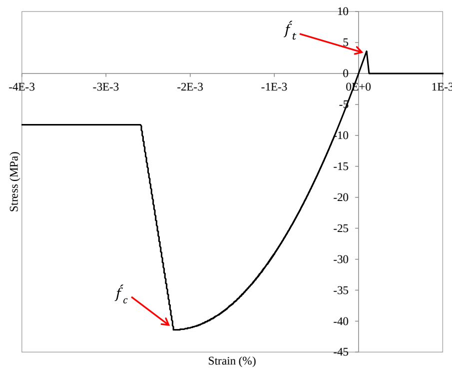
- Soil plasticity with explicit hysteretic damping



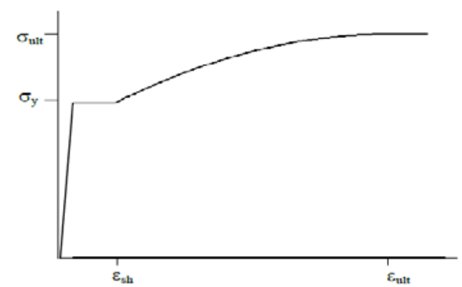


- Structural Material and geometric nonlinearities

Concrete:



Steel:

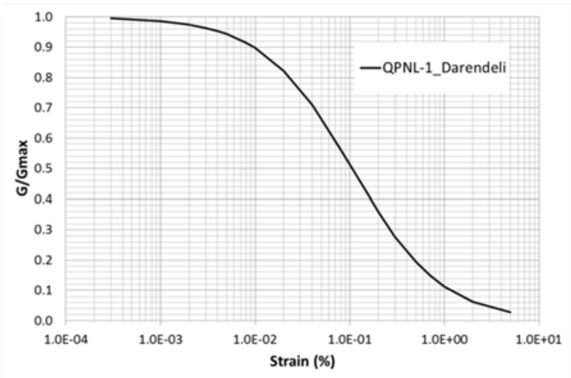


- Gapping and sliding at the soil-structure interface
- Base Isolation, FSI, etc.

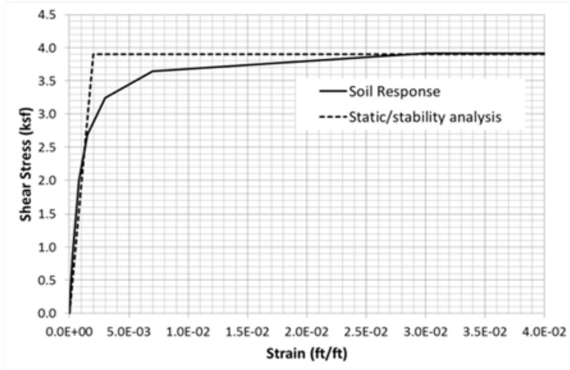
Soil Modeling: Improving the State of Practice

- Disconnect between small-strain and large strain response of the soil in geotechnical engineering practice
- Marriage between the two is necessary for large seismic events. (Stewart et al 2008)

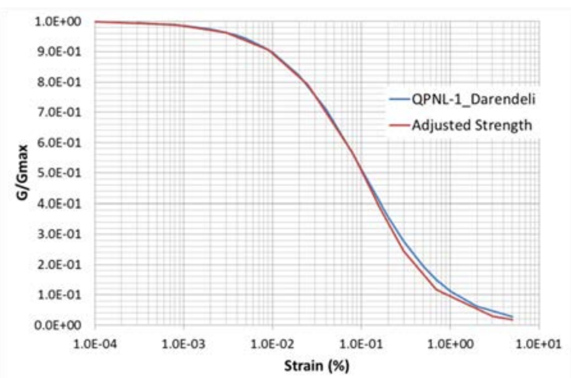
G/Gmax: small strain seismic SRA



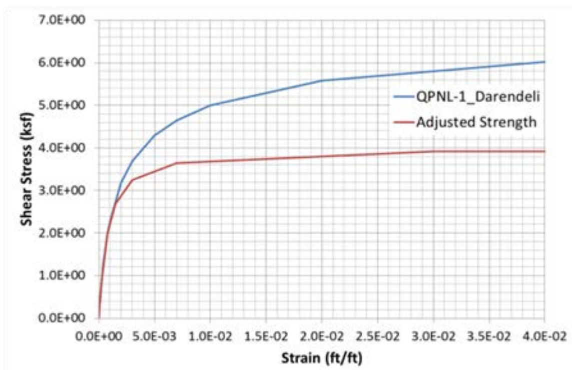
Shear stress-strain: Static limit state and stability analysis



Hybrid G/Gmax: Seismic analyses



Hybrid Stress-Strain: Seismic analyses



PWR CONTAINMENT BUILDING ANALYSIS

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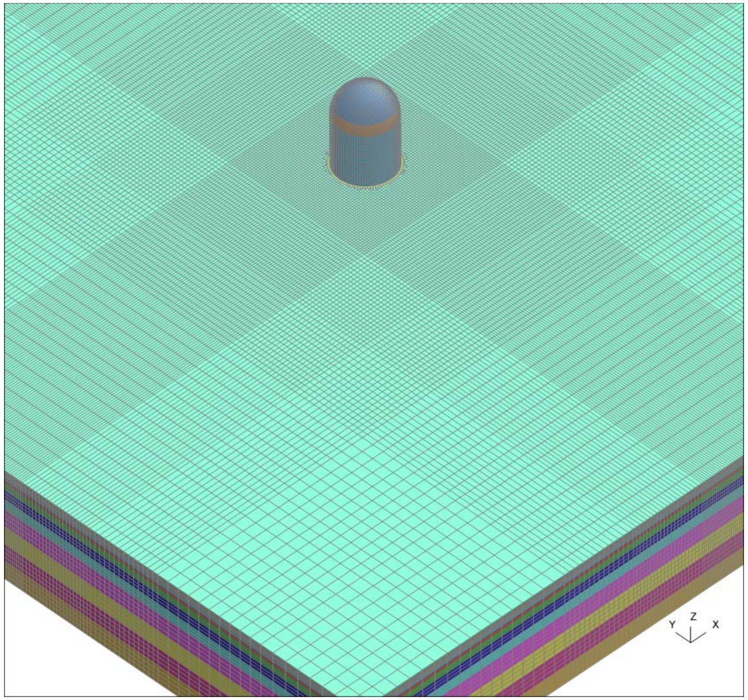
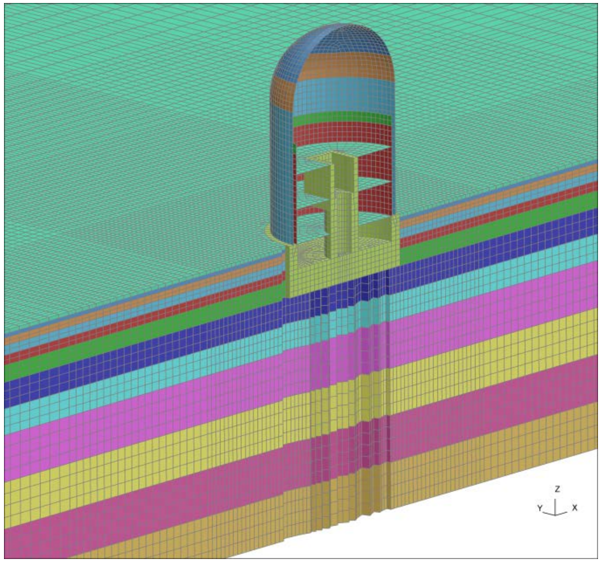
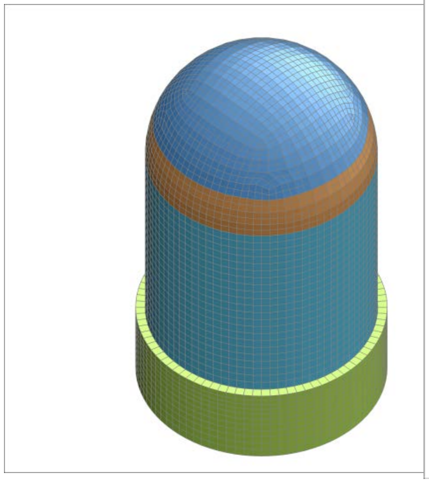
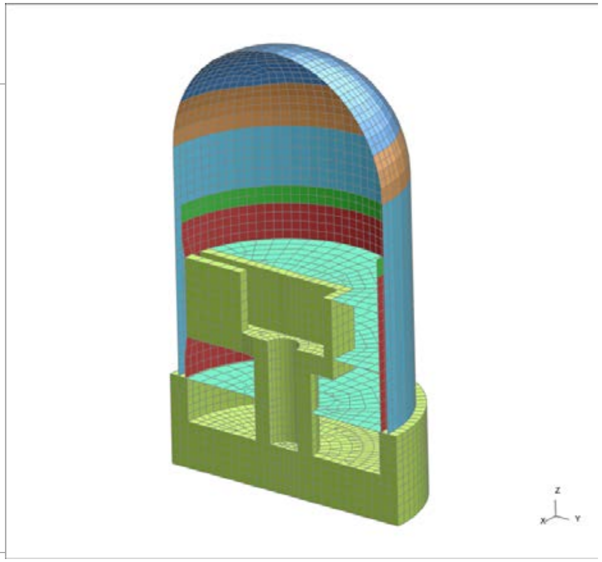
FEM – PWR Containment Bldg





Structure: Elastic in all analyses





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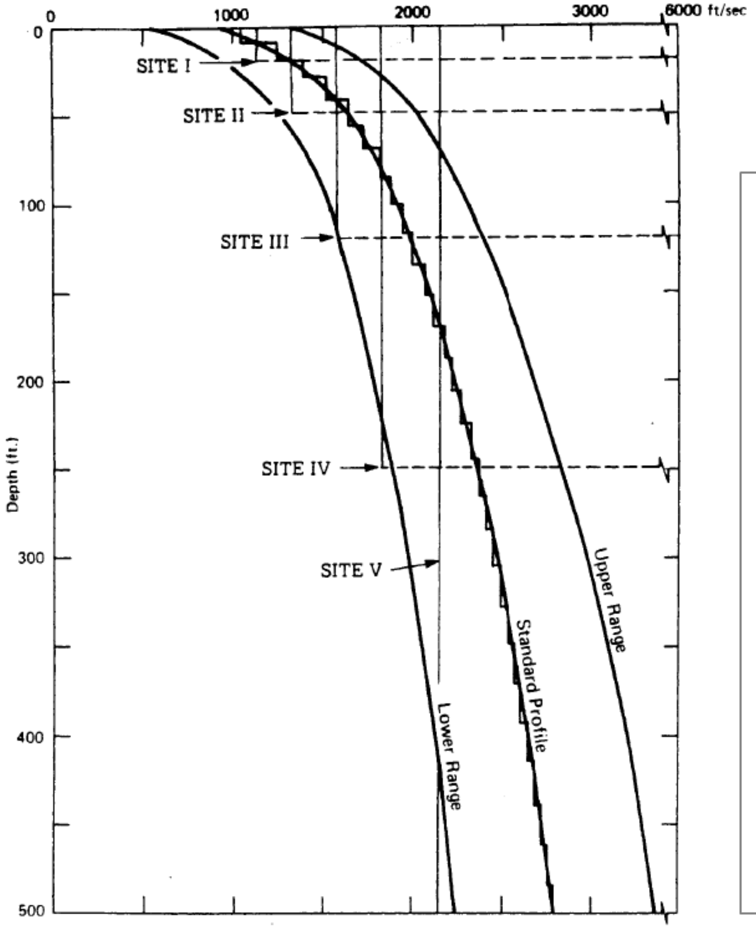
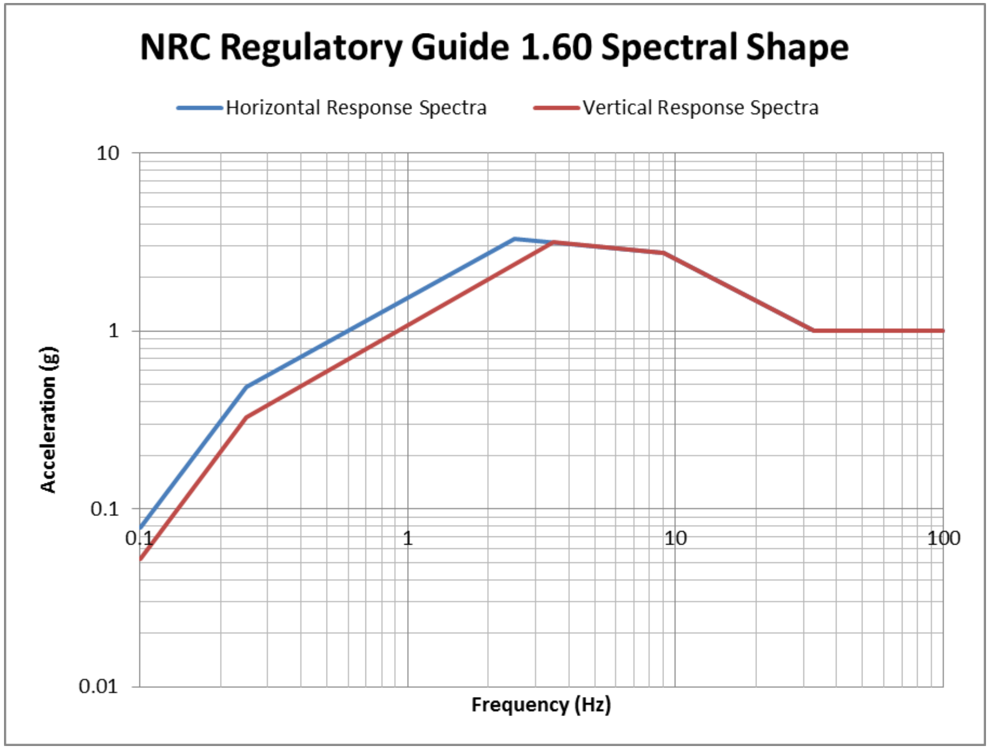
Standard Nuclear Site and Spectrum

NUREG-CR-6865 Standard Nuclear Site IV



Design Spectrum:



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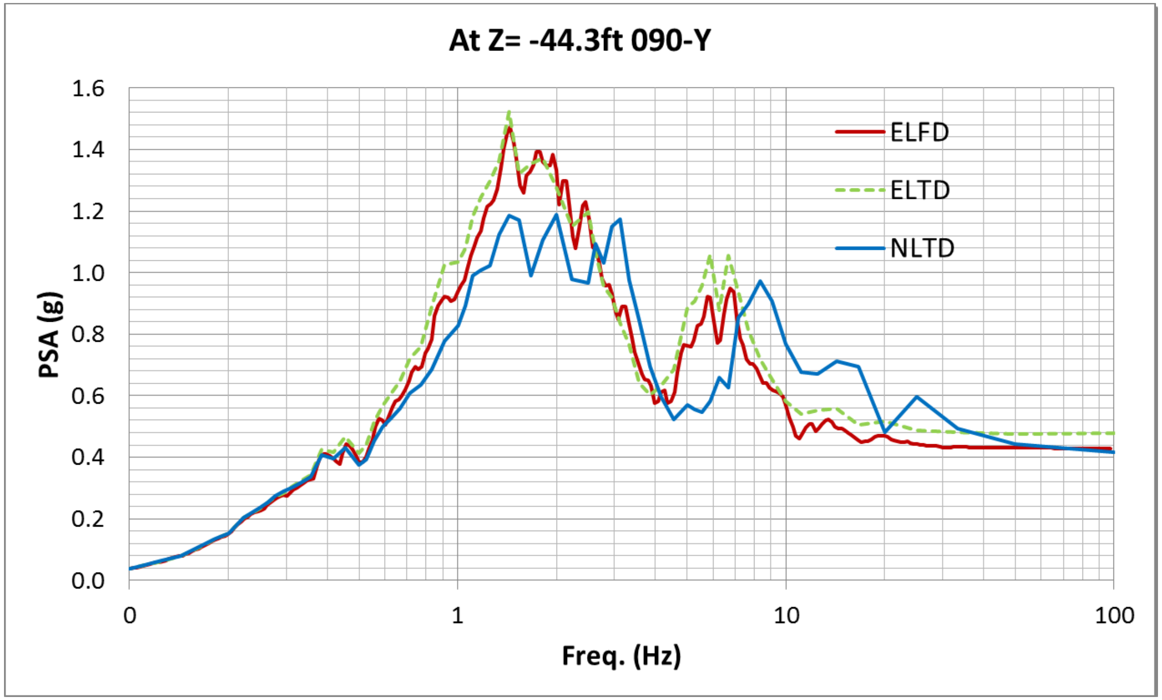
Site Response Verification – Different Approaches



Soil hysteretic damping beyond 20%

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RESULTS

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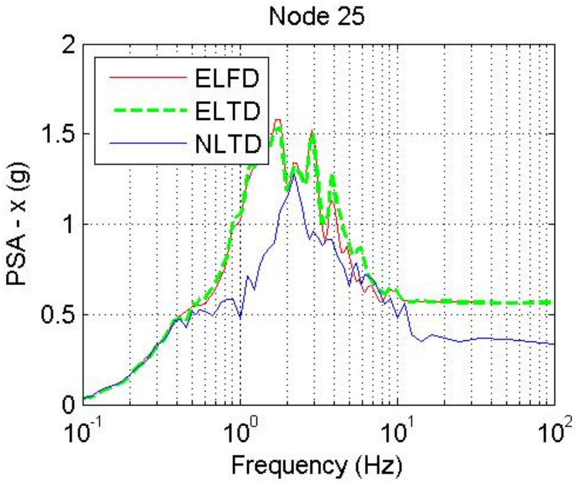
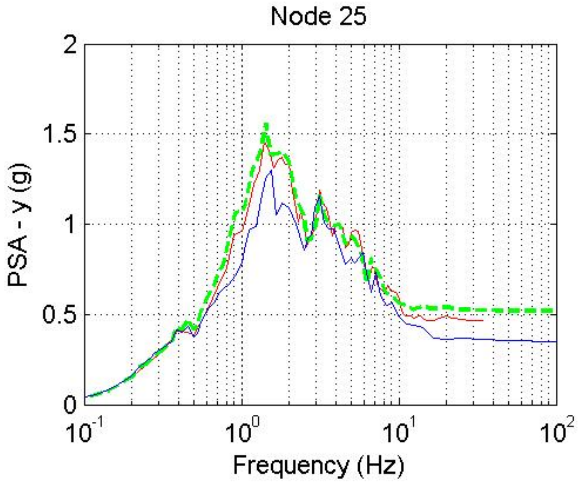
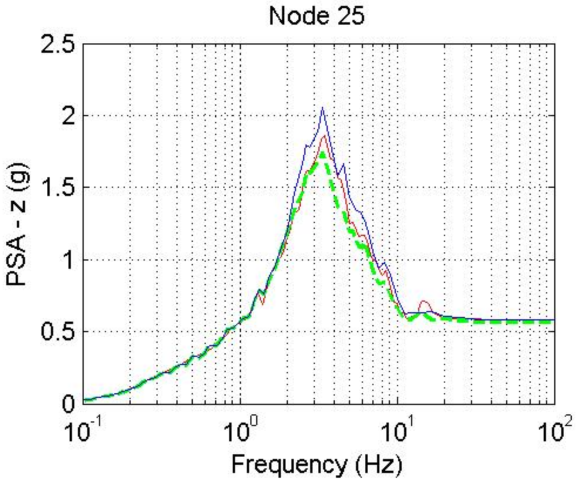
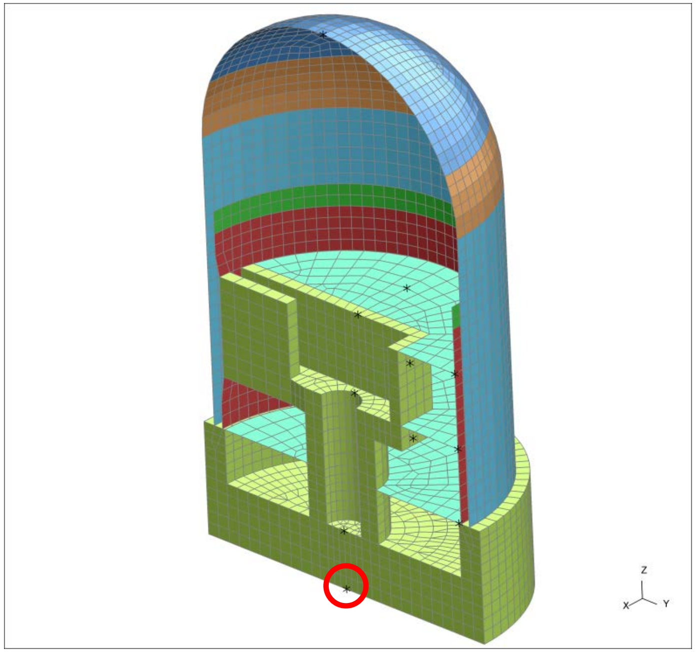
Response: Below Reactor









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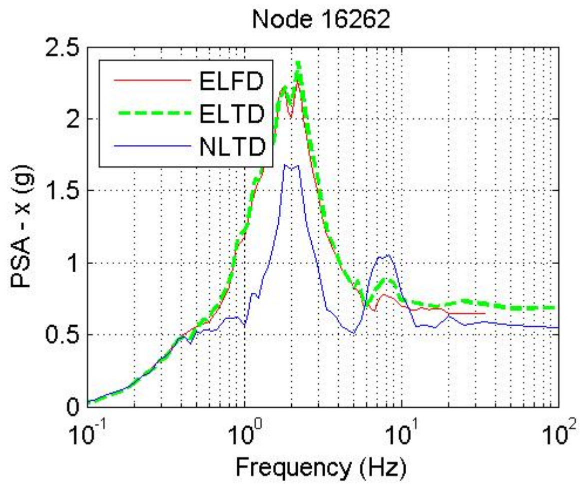
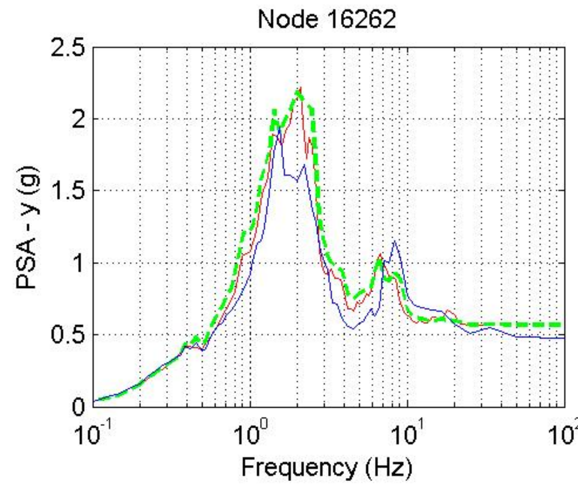
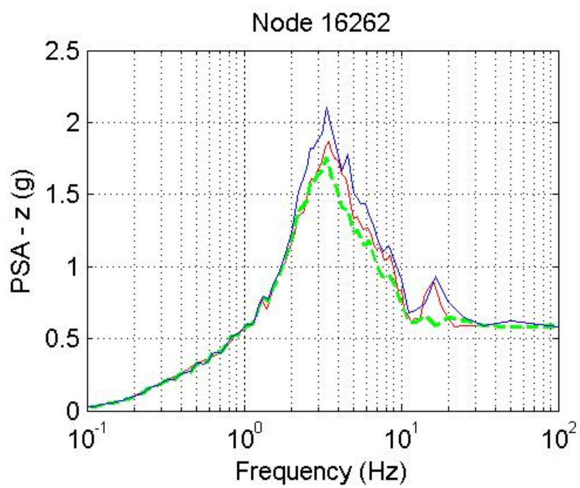
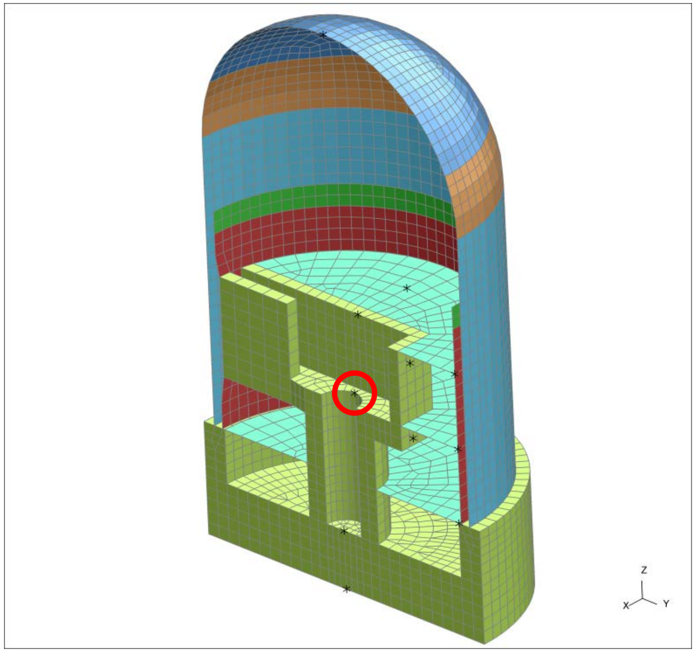
Response: Above Core









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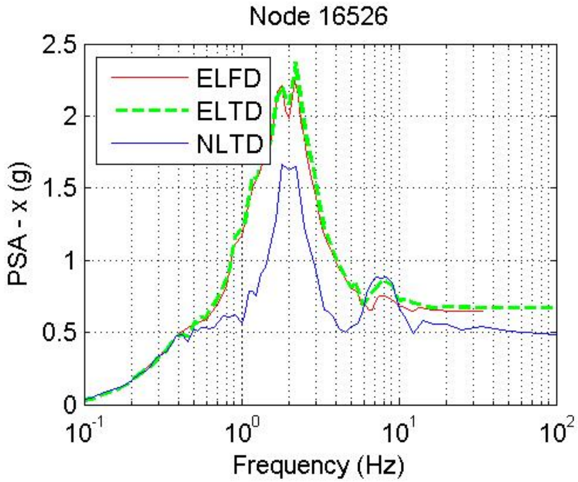
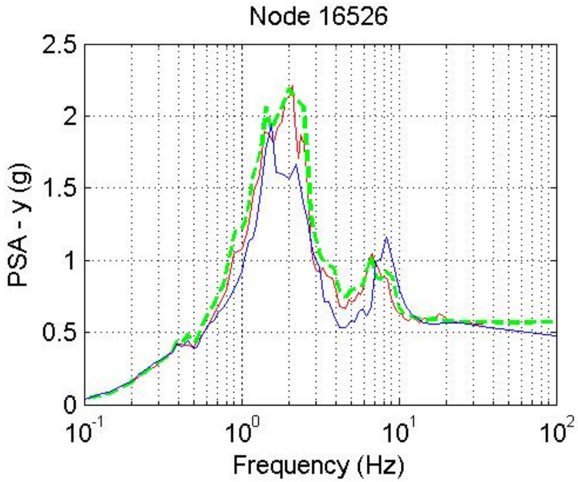
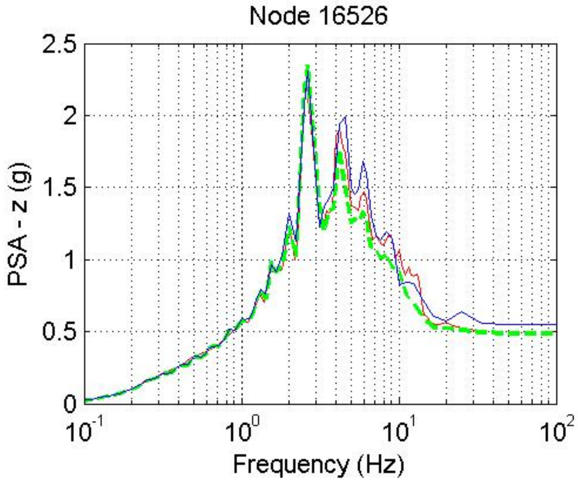
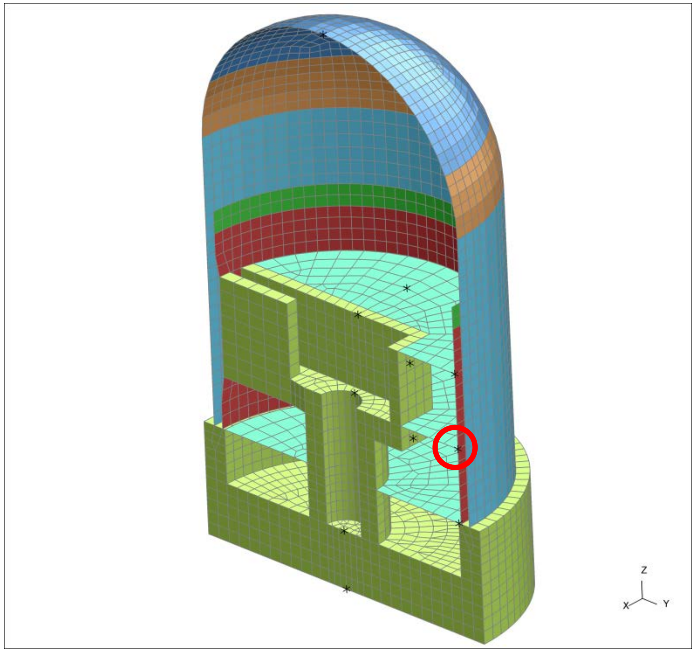
Response: Inner Wall Mid-Floor









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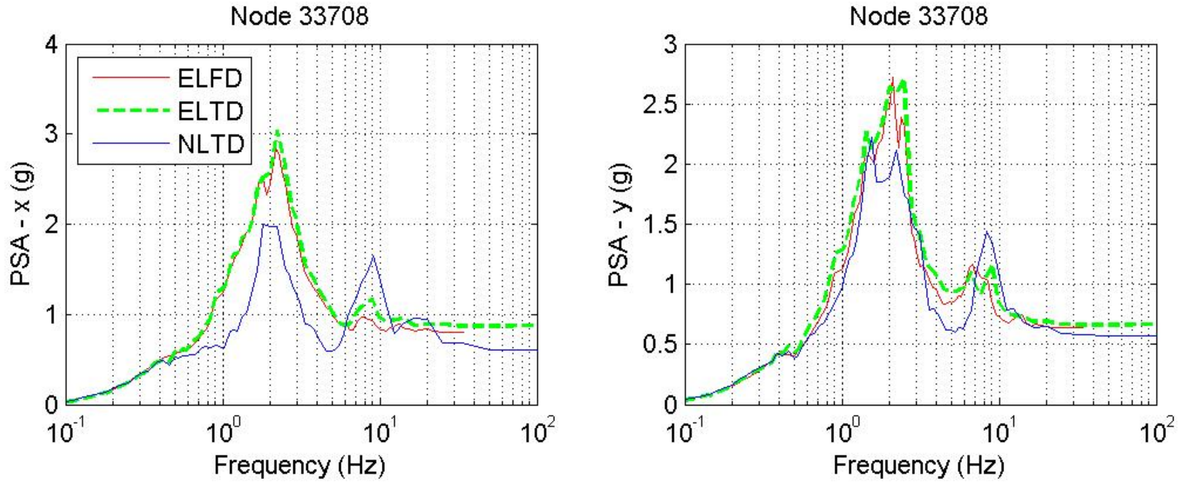
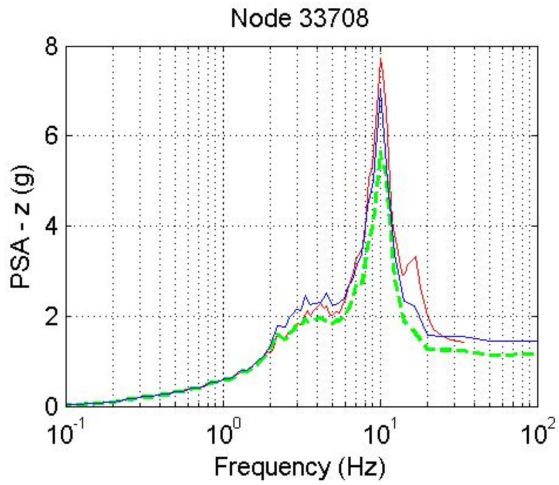
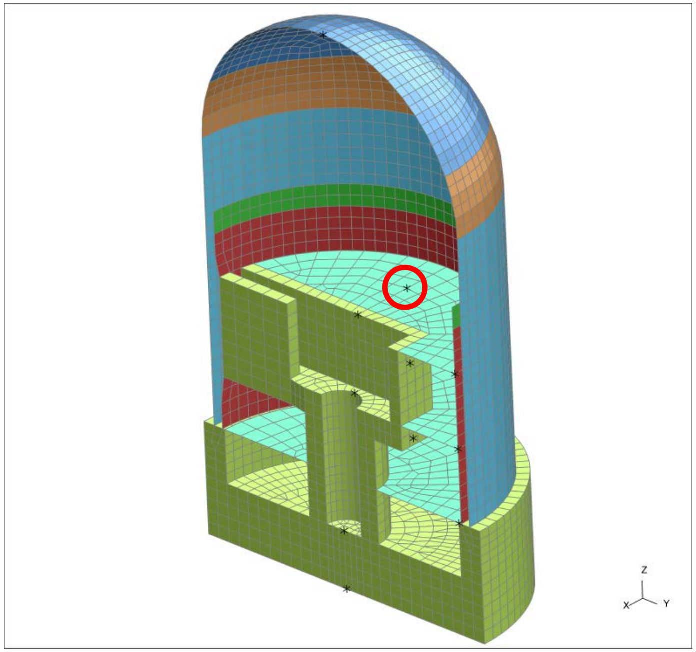
Response: Mid-Slab Top Floor







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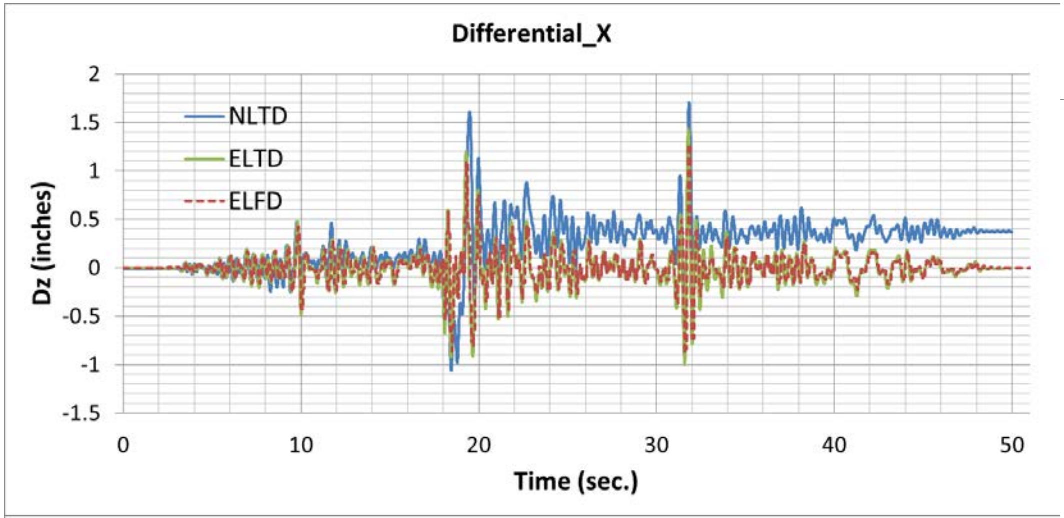
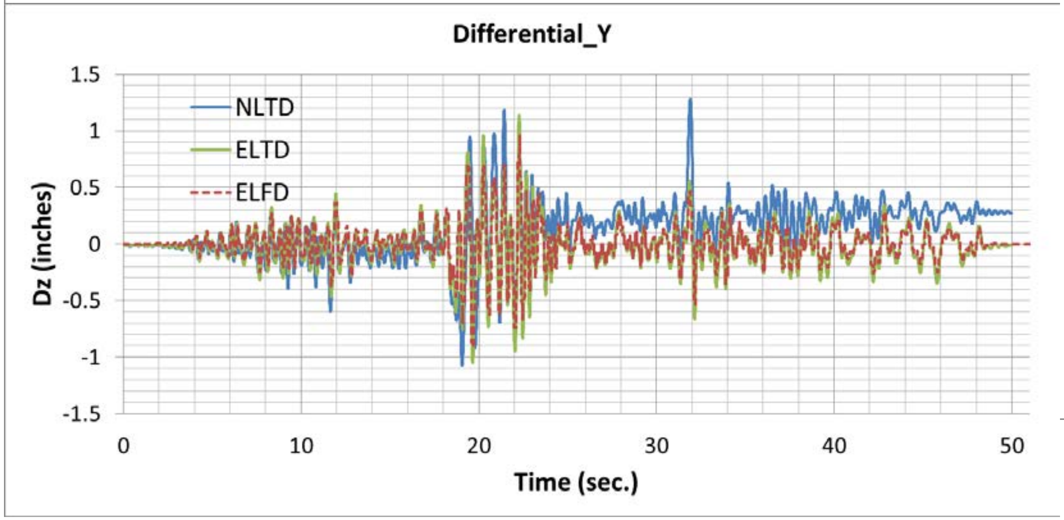
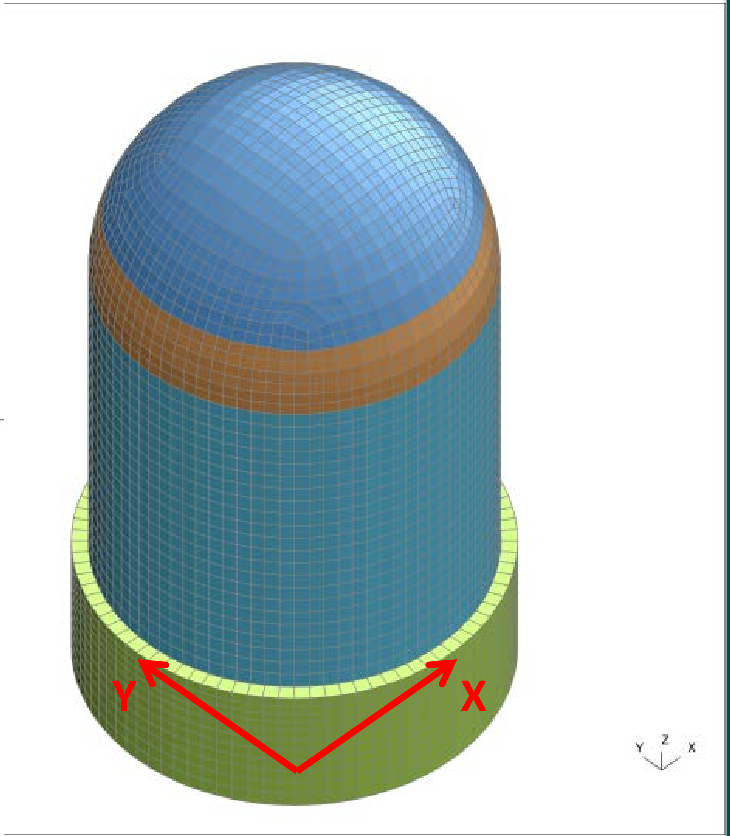
Response: Foundation Rocking







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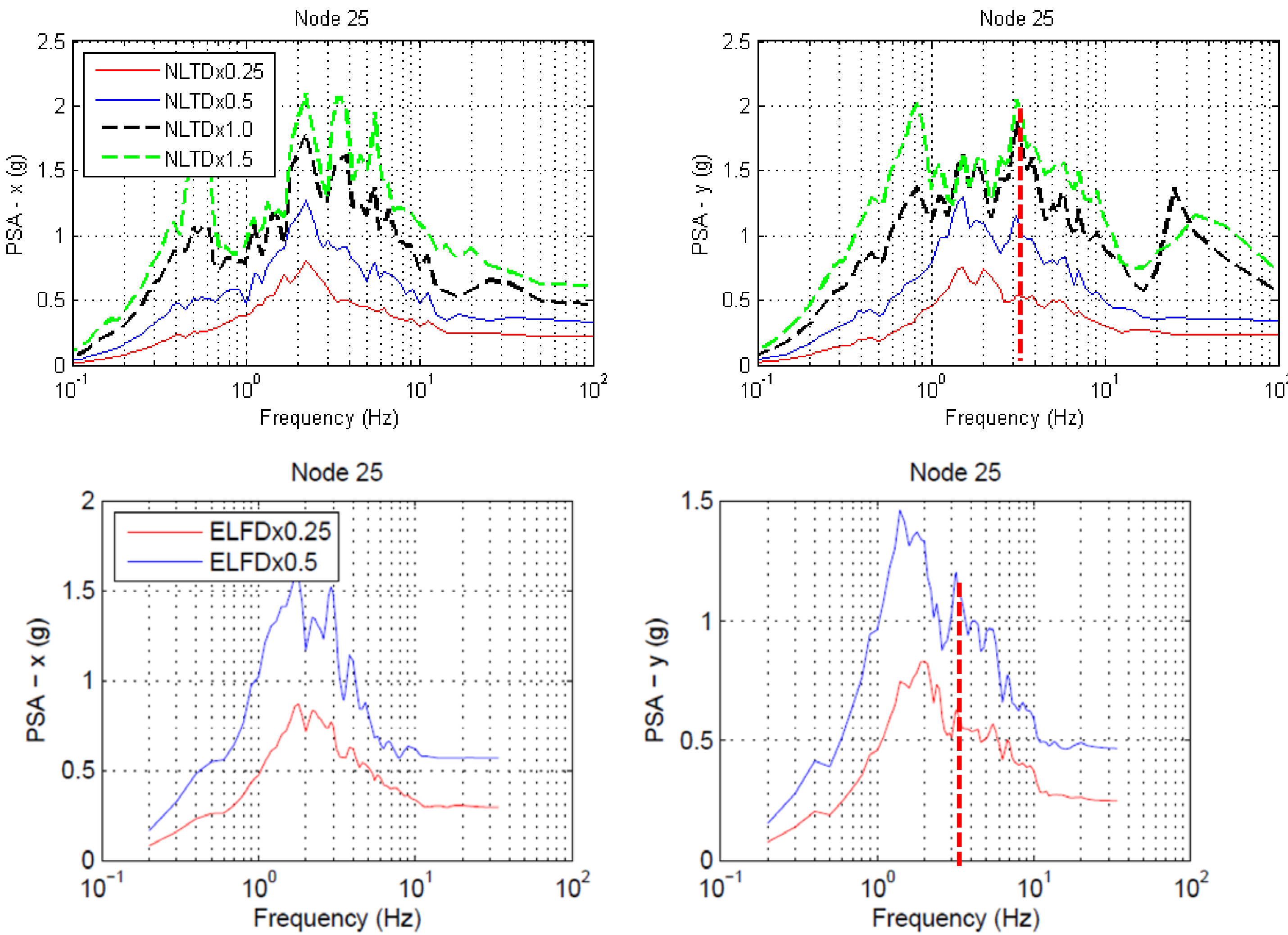
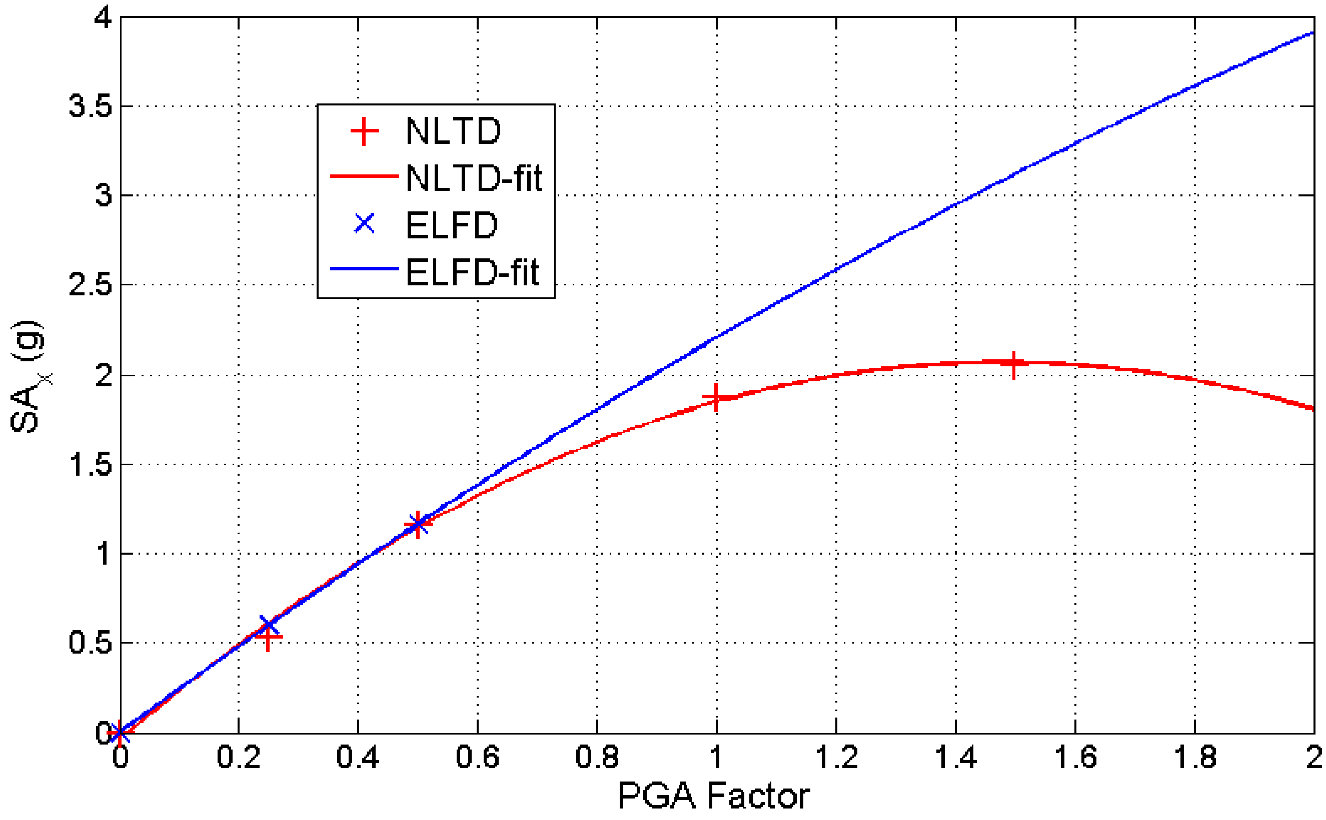
Scaled Response: Below Reactor



EL-SRA did not converge when large factors were applied to the ground motion.

Scaled Response: Below Reactor



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EFFECT OF SLAB CRACKING ON VERTICAL RESPONSE

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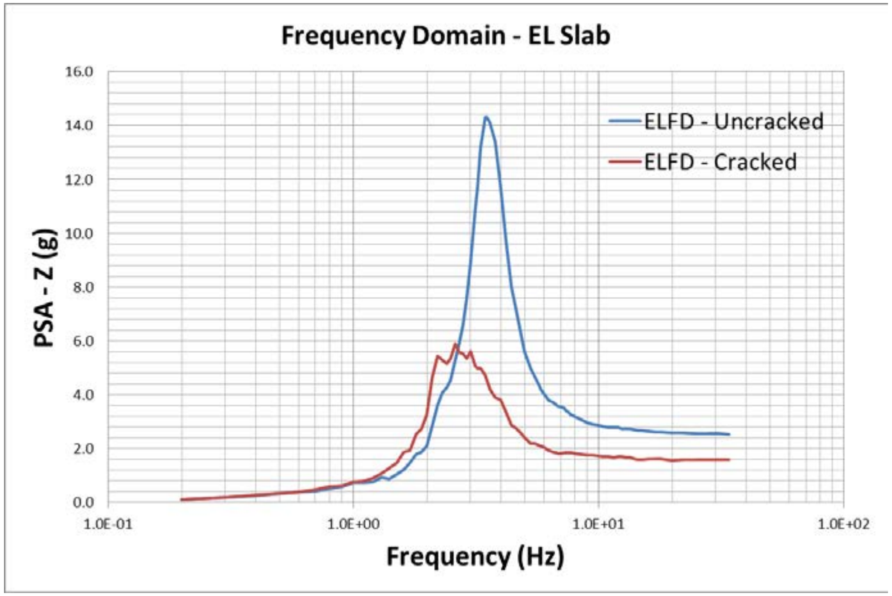
Slab Cracking and Vertical Response - FD

Equivalent linear assumptions for the cracked section in FD (ASCE 4):

- 50% Cracked Section
- Damping increase from 4% to 7%



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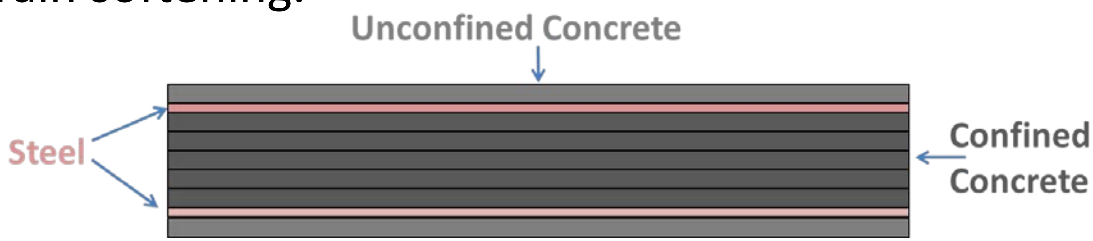
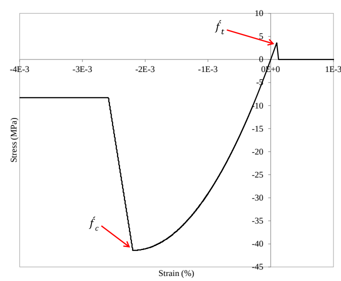
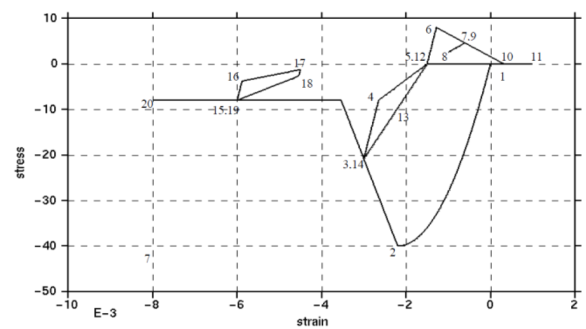
Modeling Nonlinear Response of RC Slab

- Layered composite shell finite elements
- Mander or Kent-Park model used for concrete layers/fibers
- concrete model : Cracking in tension, Crushing under compression, and post-peak strain softening.

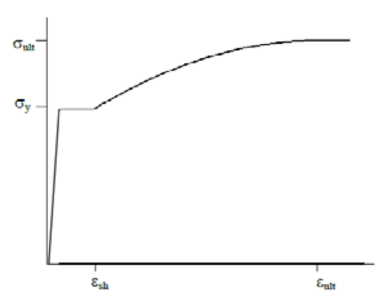


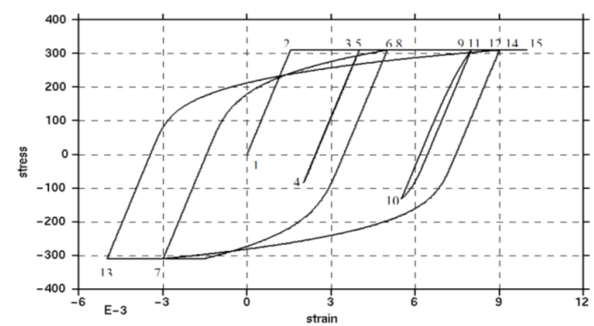
Concrete:





Steel:





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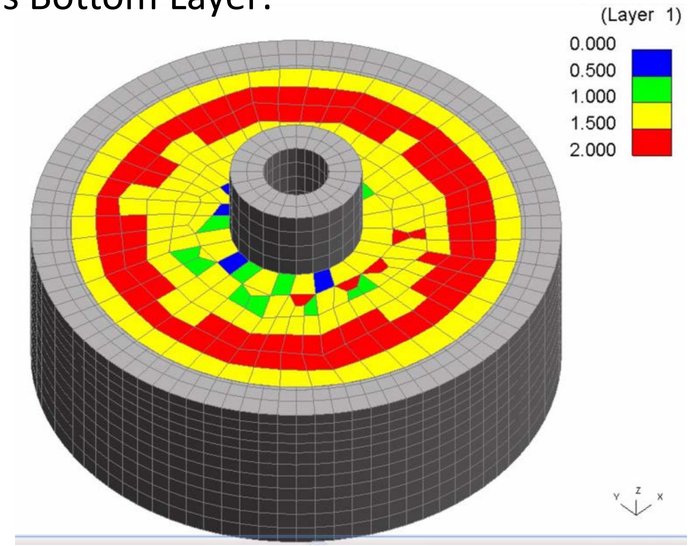
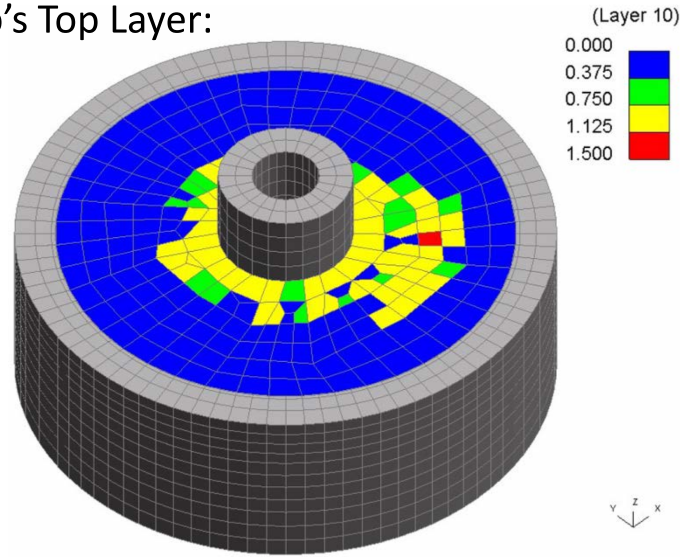
Modeling Nonlinear Response of RC Slab

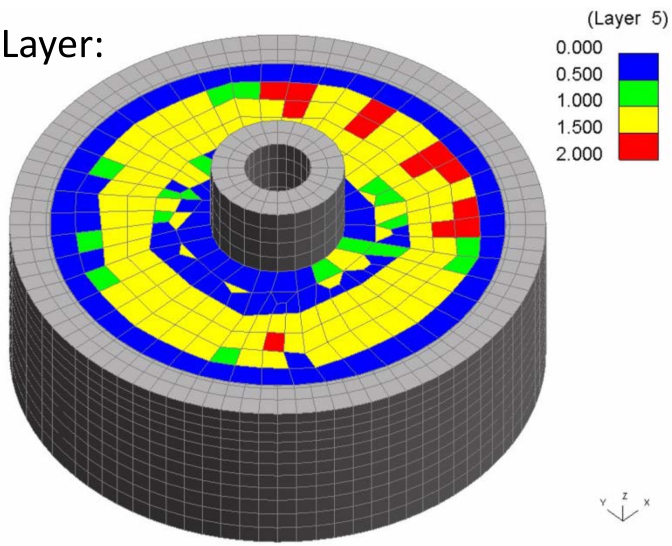
Slab's Bottom Layer:



Slab's Top Layer:



Slab's Middle Layer:



12" thick slab
0 in contours = No crack
2 in contours = Heavily cracked

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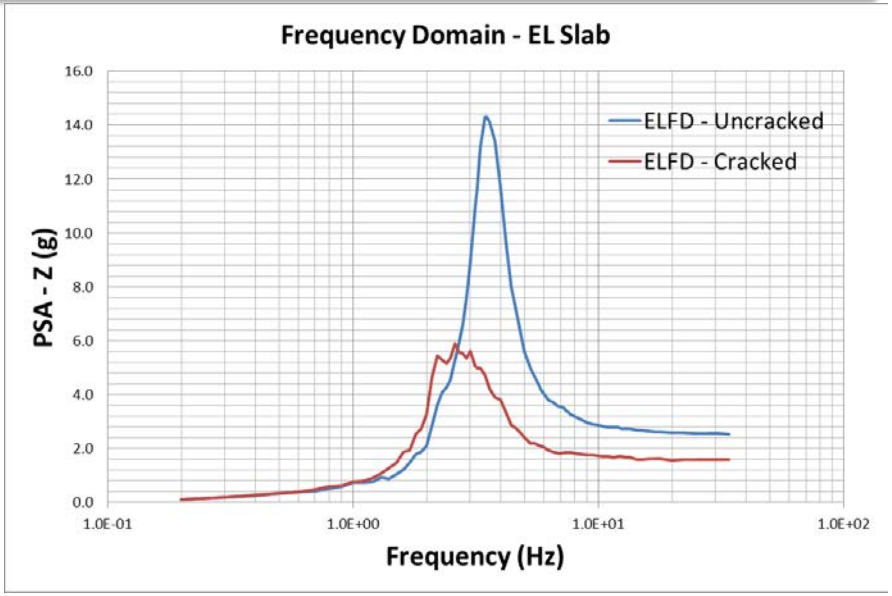
Slab Cracking and Vertical Response

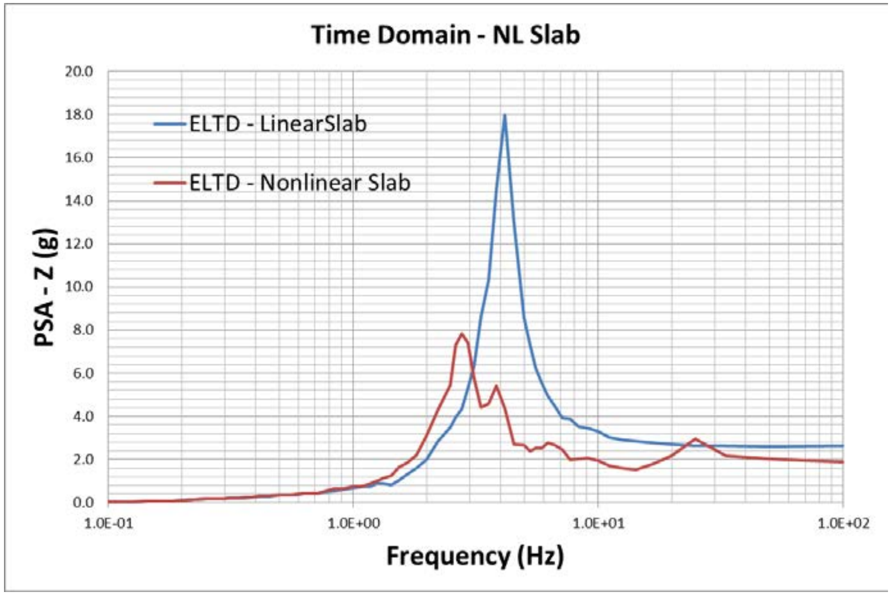
Equivalent linear assumptions in FD (ASCE 4):

- 50% Cracked Section
- Damping increase 4% to 7%



Observation from NL slab in TD:

- Period shift corresponding to 50% stiffness reduction
- Similar peak accelerations ratio



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SUMMARY / CONCLUSIONS

ELFD → ELTD → NLTD

- SSI is a key component to seismic evaluation of nuclear facilities and other critical infrastructure
- ELFD has been the long-accepted state-of-practice and has evolved to efficiently handle large and complex SSI problems
- TD approaches provide attractive alternatives to FD →
  Risk analyses and beyond-design-basis evaluations necessitate realistic response evaluations under large and varied seismic events
- ELTD with frequency-independent damping produces equivalent response as ELFD, thus verifying TD as legitimate tool
- NLTD analysis demonstrates ELFD can over-predict response for large intensity ground motions
- NLTD is versatile and can efficiently incorporate a variety of nonlinear response features in projects across multiple industries
- Selection of approach should be based on the applicability of the inherent technical assumptions, rather than limitations of tools and precedence

THANK YOU

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