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HOLTEC'S METHODOLOGY FOR SEISMIC/STRUCTURAL ANALYSIS OF REINFORCED CONCRETE ISFSI PADS FOR FREESTANDING CASKS

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A Presentation to NRC

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Presentation Overview

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- Meeting Objective
- Design Requirements for ISFSI Pads Supporting Freestanding Casks
- Analysis Background
- Soil-Structure Interaction (SSI) Analysis
  - Input Time Histories
  - Strain Compatible Soil Properties (SHAKE2000)
  - Coupled Model of Soil/Pad/Cask (LS-DYNA)
- ACI Code Strength Evaluation (ANSYS)
- Open Discussion

Meeting Objectives

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- To present to the NRC Staff Holtec's methodology for analyzing reinforced concrete ISFSI pads for freestanding casks
- To secure Staff's input on Holtec's methodology refined over the past 3 years
- To establish a standard analysis process for future pad designs and eliminate the uncertainty associated with NRC's inspection of ISFSIs prior to first fuel loading

Design Requirements for ISFSI Pads Supporting Freestanding Casks

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- Per 10CFR72.212, ISFSI pad shall be “designed to adequately support the static and dynamic loads of the stored casks, considering potential amplification of earthquakes through soil-structure interaction”
- ISFSI pad must have an effective target stiffness that is low enough to prevent violation of regulatory reactivity limit under the non-mechanistic tip over event
  - Meeting the non-mechanistic tip over requirement calls for a “softer” target
- ISFSI pads used for freestanding casks are designated as “not important to safety” (NITS) per Section 2.0.4.1 of HI-STORM 100 FSAR
  - NITS designation is based on the fact that the HI-STORM cask system is qualified for a non-mechanistic tip over

Design Requirements for ISFSI Pads Supporting Freestanding Casks (cont.)

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- Per Section 2.0.4.1 of HI-STORM FSAR, structural qualification of the ISFSI pad must consider the following three governing load combinations (which are taken from NUREG-1536):
  - Load Combination # 1: $U_c > 1.4D + 1.7L$
  - Load Combination # 2: $U_c > 1.05D + 1.275(L+F)$
  - Load Combination # 3: $U_c > D + L + E$ (or W_t)
  - U_c = Ultimate strength, D = Dead load, L = Live load, F = Hydrological Load (i.e., Flood), E = Earthquake load, and W_t = Tornado load
- Load Combination # 1 typically controls the ISFSI pad design due to the increased load factors and the effects of long-term settlement

Design Requirements for ISFSI Pads Supporting Freestanding Casks (cont.)

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- FSAR Table 2.0.5 permits ACI 318 and ACI 349 as acceptable reference codes for ISFSI pad design for freestanding casks
  - Future ISFSI pad analyses will be performed using ACI 318-05 (except for the governing load combinations which are defined above)

Analysis Background

- Prior to 2007 Holtec analyzed ISFSI pads using the so-called Classical Non-linear Dynamics (CND) method implemented via the Holtec computer code DYNAMO
  - Soil substrate represented by a series of discrete spring-mass-damping elements
  - DYNAMO has been used in over 50 license applications and ASLB hearings since 1986
- In 2007 Holtec began to analyze ISFSI pads using the nomograms published in NUREG/CR-6865 (because of its evident built-in conservatisms) in lieu of performing an explicit SSI analysis

Analysis Background (cont.)

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- In 2010, after the NRC's response to a TAR discouraged the use of the NUREG/CR-6865 based approach, Holtec developed an LS-DYNA based approach for performing SSI analysis of ISFSI pads (which is the focus of this presentation)
  - Similar to the Design Basis Seismic Methodology used to qualify the HI-STORM 100U system (which has been approved by the NRC)
- It is noted that all three methods are non-linear, i.e., they all allow for the cask to lift off the pad
  - Linear analysis codes such as SASSI are not capable of predicting cask lift off and subsequent slap down
- The following table shows the peak cask-to-pad impact loads for an ISFSI pad site where all three methods were used to establish utmost confidence

Analysis Background (cont.)

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Table 5.1
MAXIMUM CASK-TO-PAD IMPACT LOADS FOR BEST ESTIMATE SOIL PROPERTIES USING THREE CALCULATION MODELS

Calculation Method	Maximum Cask-to-Pad Vertical Impact Load,F, lbf	Reference
Classical Non-Linear Dynamics (Holtec Proprietary Code DYNAMO)	919,700	Holtec Report HI-2094484 Rev. 1
NUREG/CR-6865 and Visual-Nastran (Public Domain)	1,050,000	Holtec Report HI-2094398 Rev. 1
LS-DYNA (Public Domain)	950,600	Holtec Report HI-2104767 Revision 0

- The peak impact loads agree within 15% of one another.
- The maximum load results from the NUREG/CR-6865 based method, which is not surprising since the nomograms were developed to bound a wide range of soil conditions

SSI Analysis – Input Time Histories

- Acceleration time histories will be developed in accordance with Section 2.3 of ASCE 4-98.
  - Unlike stack-up analyses which are under the purview of Part 50, SRP 3.7.1 is not applicable for ISFSI pad analyses since the ISFSI pad is a Part 72 structure
  - Use of ASCE 4-98 is appropriate considering the ISFSI pad's NITS designation
- For non-linear analysis, ASCE 4-98 requires the following:
  - Use of more than one set of acceleration time histories
  - Use of recorded, modified recorded, or synthetic time histories
  - Mean spectrum (calculated from individual time history sets) shall envelope target spectrum with no one point of the mean spectrum falling more than 10% below the target spectrum
  - Input motions in the 3 orthogonal directions shall be statistically independent (correlation coefficient < 0.3)

SSI Analysis – Input Time Histories (cont.)

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- In order to meet the ASCE 4-98 requirements, Holtec plans to use a minimum of 3 sets of acceleration time histories (synthetic or modified recorded) for future ISFSI pad analyses

SSI Analysis – Strain Compatible Soil Properties

- Strain compatible soil properties for the best estimate and upper bound soil profiles are calculated for the ISFSI pad site using the computer code SHAKE2000 for each time history set
  - Input to SHAKE2000 is based on available soil data for site location (e.g., soil borings)
  - Lower bound soil profile will not be explicitly analyzed since previous analyses show that the cask-to-pad impact loads are governed by the best estimate or upper bound soil profiles (due to the stiffer target surface)
- Strain compatible soil properties from SHAKE2000 are used to characterize the soil in the LS-DYNA SSI model
  - Same soil layering (i.e., number of layers and layer thicknesses) analyzed in SHAKE2000 will be reflected in the LS-DYNA SSI model

SSI Analysis – Strain Compatible Soil Properties (cont.)

- SHAKE2000 is also used to deconvolute the design basis ground motion to the base of the soil column for each combination of time history input and soil profile (i.e., best estimate and upper bound)
  - Seismic motion at the base of the soil column from SHAKE2000 is subsequently used as input to the LS-DYNA SSI model
- A total of 18 SHAKE2000 runs are performed
  - 9 time history inputs (3 sets x 3 component directions)
  - 2 soil profiles

SSI Analysis – Coupled Model of Soil/Pad/Cask

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- LS-DYNA is used to obtain the seismic response of the coupled soil/pad/cask system
  - LS-DYNA model is similar to the coupled dynamic model described in NUREG/CR-6865 (which is constructed using Abaqus)
- ISFSI pad is modeled as flexible structure based on the minimum concrete compressive strength
- LS-DYNA model includes a single freestanding cask positioned in the farthest permissible storage location from the centroid of the pad to maximize torsional effects
  - An isolated cask in the extreme corner of the ISFSI pad is generally avoided based on the findings by Dr. Bjorkman [1]

[1] Bjorkman, G.S., "Influence of ISFSI Design Parameters on the Seismic Response of Dry Storage Casks", PATRAM Conference, London, U.K., 2010.

SSI Analysis –
Coupled Model of Soil/Pad/Cask (cont.)

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- Boundary conditions are the same as those employed in NUREG/CR-6865 for the dynamic coupled model
  - Each ring of perimeter nodes defining the boundary edge of the soil volume is rigidly constrained such that all nodes that comprise the ring move together
  - Acceleration time histories are applied simultaneously in three directions to the bottom surface of the soil volume

SSI Analysis – Coupled Model of Soil/Pad/Cask (cont.)

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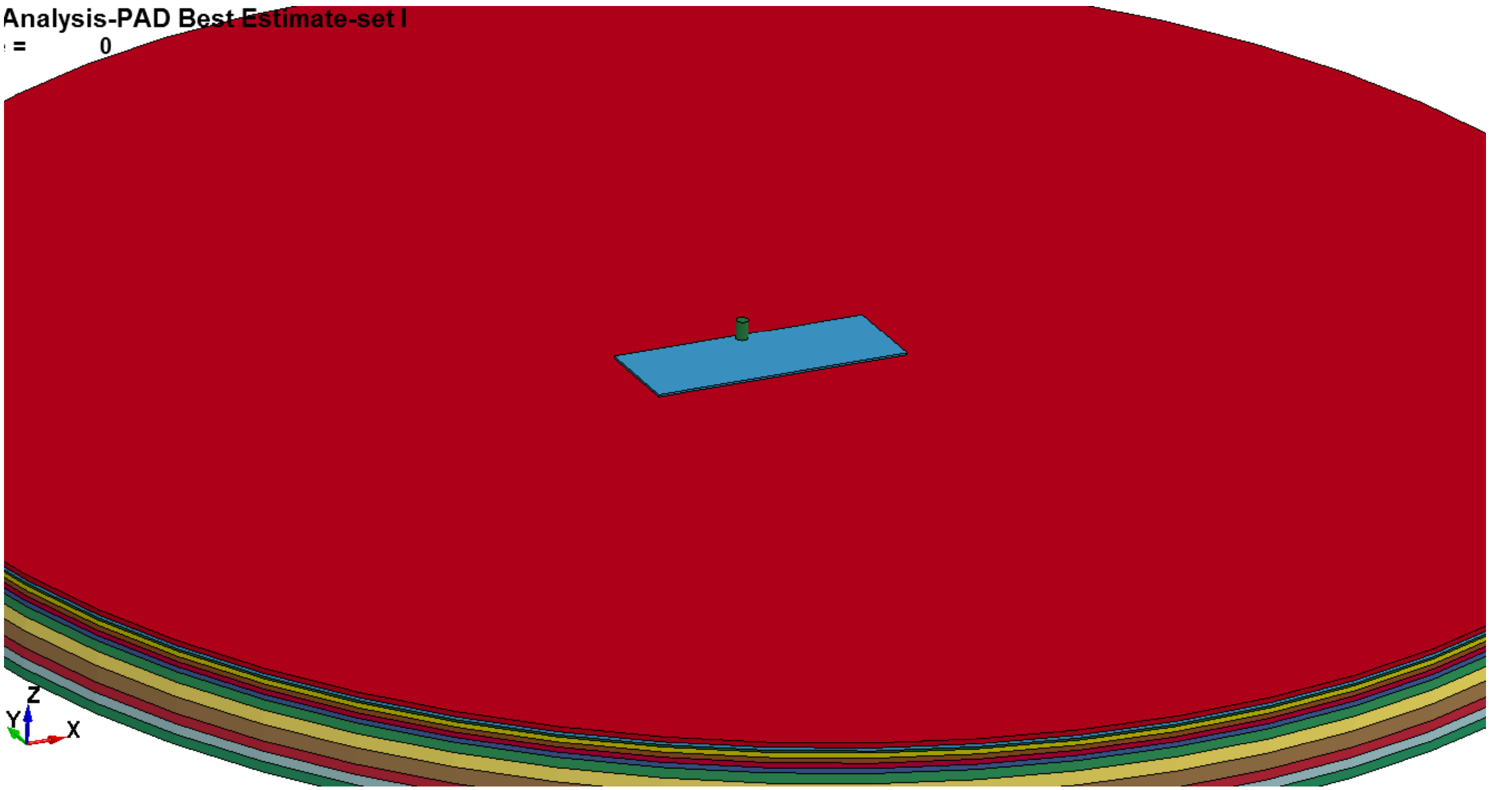
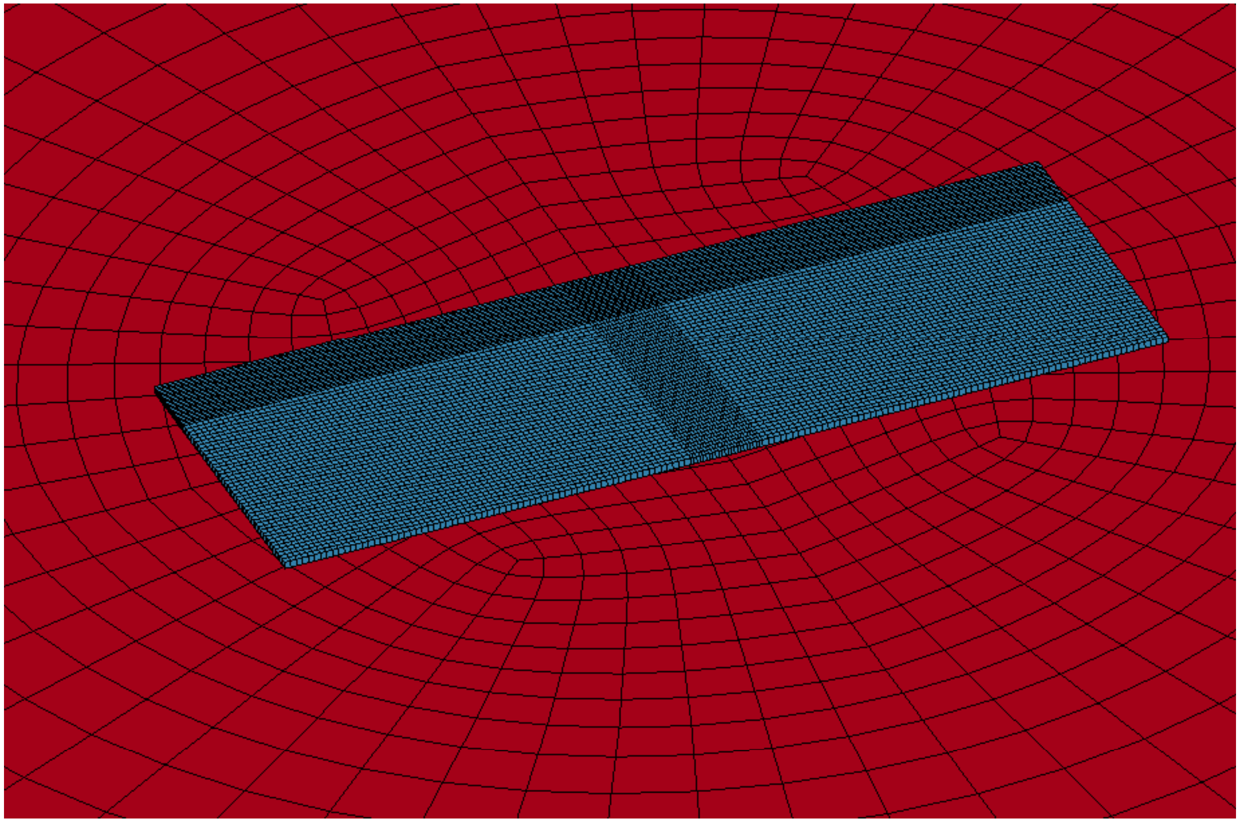
Overall Model



SSI Analysis –
Coupled Model of Soil/Pad/Cask (cont.)

Close-Up View of ISFSI Pad and Soil Finite Element Mesh



SSI Analysis –
Coupled Model of Soil/Pad/Cask (cont.)

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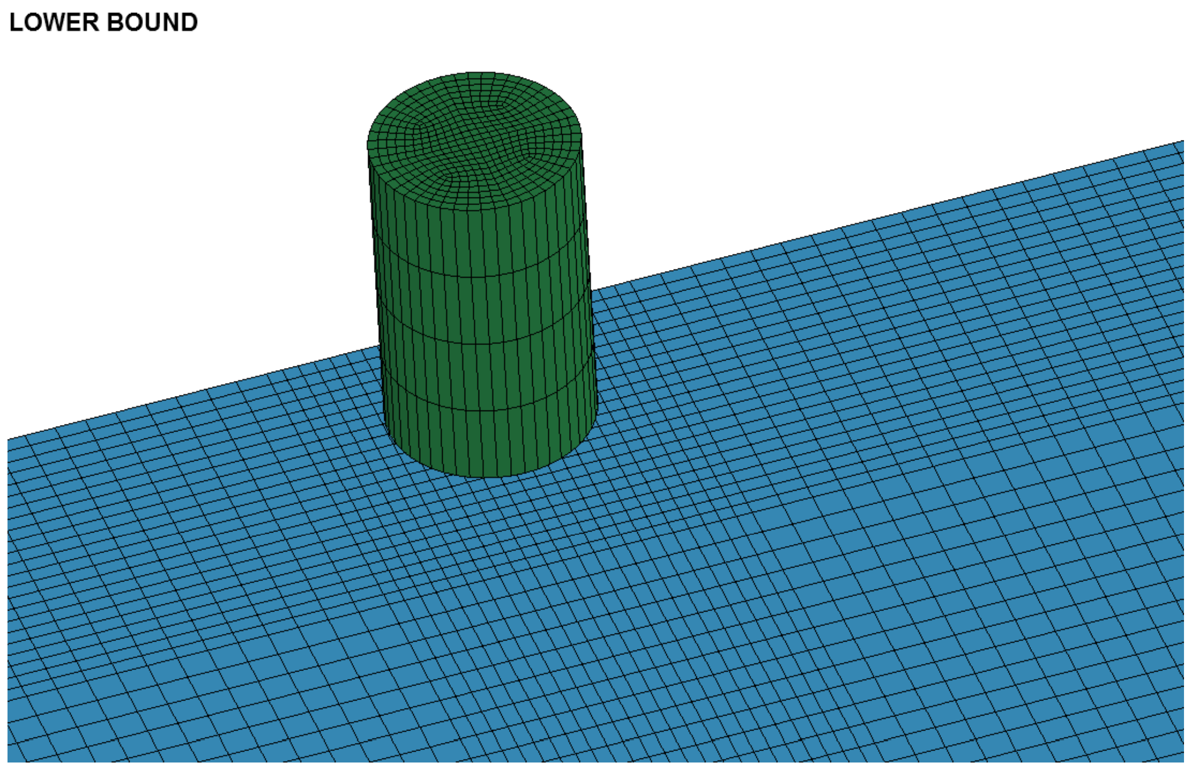
Close-Up View of Cask and ISFSI Pad Finite Element Mesh



SSI Analysis –
Coupled Model of Soil/Pad/Cask (cont.)

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- Friction contact interfaces are defined between cask and ISFSI pad, and ISFSI pad and soil
  - An upper bound coefficient of friction (COF) of 0.8 is used at the cask/pad interface to maximize cask rocking
  - A COF value of 1.0 is used between the pad and the soil to simulate the effect of the embedded pad (same approach used in NUREG/CR-6865)

SSI Analysis – Coupled Model of Soil/Pad/Cask (cont.)

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- Coefficient of restitution for the freestanding cask as it rocks on the ISFSI pad will be treated using one of the following two approaches:
  - 1) Include a detailed model of the loaded HI-STORM, which accounts for geometric and material non-linearities, within the LS-DYNA SSI model
    - Pros: Analyst does not have to specify any damping values, energy losses due to material hysteresis and MPC rattling are computed directly by LS-DYNA
    - Cons: Computationally more expensive, significantly longer run times and larger output files
  - 2) Represent the loaded HI-STORM as a solid rigid cylinder within the LS-DYNA SSI model and specify an appropriate contact damping percentage at the cask/pad interface to account for material hysteresis and internal gaps associated with loaded HI-STORM
    - Pros: Computationally more efficient
    - Cons: Requires independent model of deformable HI-STORM (with MPC inside) rocking on an essentially rigid target surface to establish contact damping percentage

SSI Analysis – Coupled Model of Soil/Pad/Cask (cont.)

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- A total of 6 LS-DYNA runs are initially performed
  - 3 time history sets
  - 2 soil profiles (i.e., best estimate and upper bound)
- The limiting run in terms of the maximum cask-to-pad vertical impact load is then re-analyzed assuming that the pad is fully cracked
  - Elastic modulus of the concrete is multiplied by a factor of 0.5 based on the guidance from ASCE 43-05

ACI Code Strength Evaluation

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- ACI Code strength evaluation of the ISFSI pad is performed using ANSYS
- The following cask loading patterns are analyzed:
  - First loading campaign
  - Quarter loaded pad condition (25% of storage locations occupied)
  - Half loaded pad condition (50% of storage locations occupied)
  - Fully loaded pad condition (100% of storage locations occupied)
- The average of the maximum cask-to-pad impact loads from the SSI analysis (from either the best estimate or upper bound soil profile) is statically applied at all cask locations simultaneously
  - Use of average response value for demand-to-capacity checks is consistent with ASCE 4-98

ACI Code Strength Evaluation (cont.)

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- Overturning moment due to horizontal inertia force is accounted for by applying a linear varying pressure over the footprint area of the HI-STORM
  - Applied pressure gradient is equivalent to maximum vertical seismic force plus the overturning moment due the maximum horizontal inertia force from the SSI analysis
- The effects of long-term settlement are incorporated in the finite element solution using the methodology described in Holtec Position Paper DS-338
  - Soil modulus used for dead load case is degraded such that the elastic deflection of the fully loaded pad equals the estimated long-term settlement for a fully loaded pad
  - Same methodology used in HI-STORM 100 FSAR to qualify HI-STORM 100U

ACI Code Strength Evaluation (cont.)

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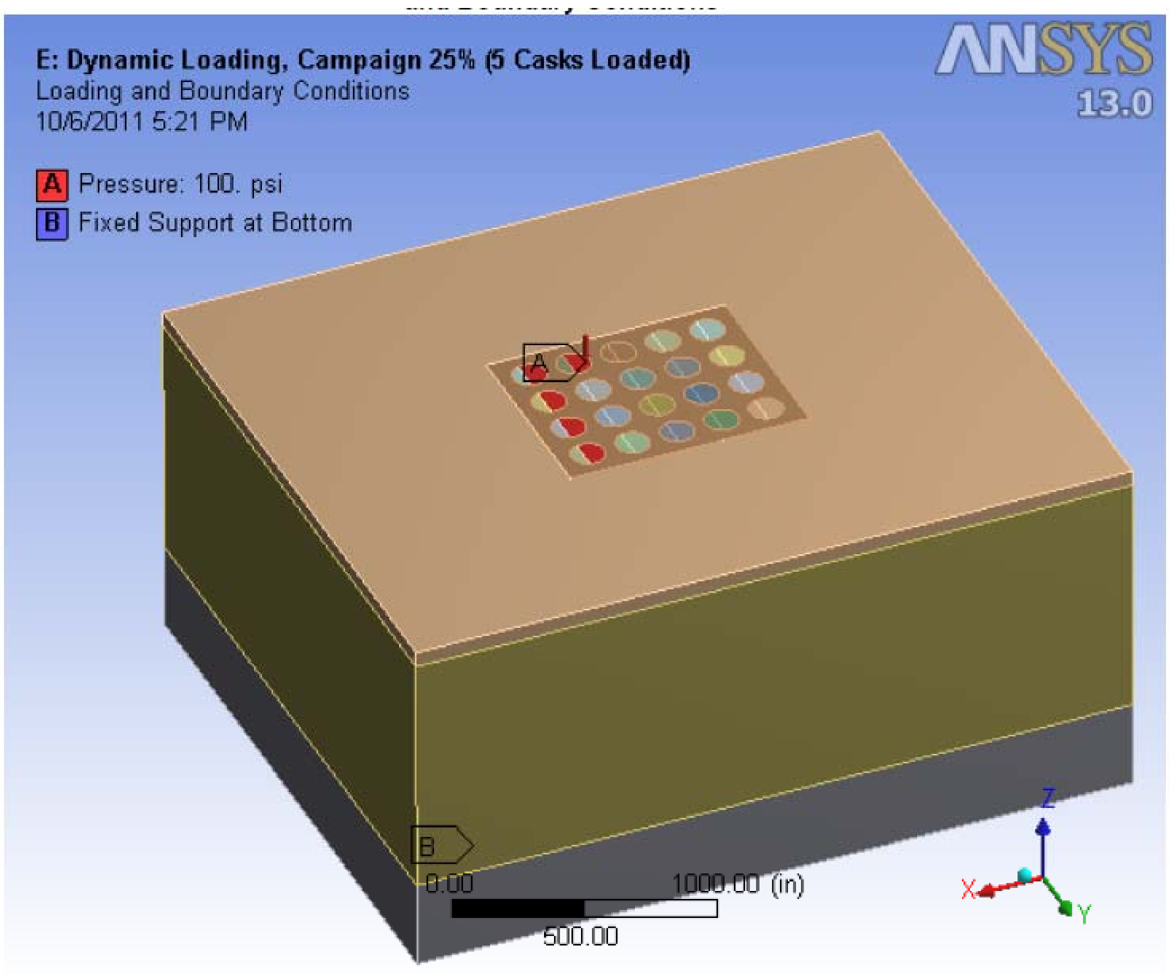

Open Discussion