Accidental Fuel Drop on Spent Fuel Pool Storage Racks

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1 Introduction

Spent Fuel (SF) storage racks are fully submerged in water and stand freely at the bottom of the Spent Fuel Pool (SFP). The water column acts as a coolant for residual heat removal from nuclear fuel and provides radiation shielding. Due to the storage of large quantities of nuclear material, Appendix D to NUREG-0800 Section 3.8.4 [1] specifies that the functionality of the SF racks be demonstrated for the D + L + Fd load combination, where Fd is the force caused by the accidental drop of the heaviest load from maximum height. D and L are the dead and live loads acting on the SF racks.

SF racks are designed to store both Fuel Assemblies (FA) and Non-Fuel Assemblies (NFAs) that get irradiated inside a power reactor. Depending on the design basis of a SF rack being evaluated, multiple analysis scenarios involving a) deep drops where the FA or NFA drops through an empty storage cell and impacts the base plate and b) shallow drops where the FA or NFA drops in vertical or horizontal orientation striking the top of the SF rack needs to be evaluated.

The goal of the analyzes for a deep drop is to show that the base plate will absorb the total drop energy without a fracture (piercing) or contact with the pool floor liner (secondary damage). The actual stiffness of the SFP floor with stainless steel (SST) liner and embedded leak chases is not calculated or considered in the accidental drop analyzes. The support leg loads shall be distributed by base plates sized to ensure that there is no damage to the liner or floor concrete. The worst-case support leg forces from the accidental drop analyzes are extracted and documented so that the SFP floor concrete, SST liner and leak-chases can be qualified by others. The gap between the bottom of the baseplate and the SFP liner is approximately 5”. Therefore, the maximum deflection of the baseplate should be less than 5” for the deep drop. In order to prevent penetration of the dropped FA/NFA, the baseplate must not exceed true ultimate stress or strain over a wider area upon impact. Stresses in the support leg and bearing plate components are evaluated under the maximum impact load. A load drop analysis may also cause crushing of the fuel configuration and result in criticality. However, damage to FA / NFA that involves modeling with actual stiffness is not investigated in this article.

The fuel storage rack modules shall be designed to meet the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NF, Reference [2]. The fabrication and installation of spent fuel racks shall be performed based on ASME Section III, Division 1, Subsection NF Class 3 component supports, Reference [1].

This paper investigates the deep drop (center strike case) which has the tendency to cause maximum deflection and nonlinear deformation.

2 Modeling Assumptions and Simplifications

A hypothetical 10×10 rack configuration that is applicable for storing small modular reactor FAs (or NFAs when applicable) is investigated. This model is created such that drop or impact analysis on one of the cells near center creates eccentric loading that induces more demand on one of the support legs. A FA with square cross section (typical of a PWR or BWR fuel) is considered as the drop missile. To simplify the drop analysis, the upper portion of the SF rack geometry is excluded. Because the combination D + L + F_d need to be considered, a weight equal to the dead weight of the excluded portion of the SF rack is applied to the baseplate as pressure loading. Conservatively, the applied dead weight load includes that of corner angles, HSS vertical posts and bottom supports explicitly included in the deep drop model. The dead load due to the 99 bounding FA/NFAs (excluding the one FA that is dropped) is also added to the base plate. Material properties assigned to the FE model are taken at a reference temperature of 120ºF. The operating temperature has very small to insignificant effect on material property values used.

The SF rack sits on the top of SFP SST liner and concrete floor. Leak chases are embedded into the concrete structure of the SFP floor and walls for collecting, measuring, and examining any liquid leak activity in the SFP. This article idealizes the SFP floor as a flat rigid surface wherein the actual stiffness of concrete floor with embedded leak chases and SST liner are ignored. A rigid surface provides conservative reaction forces for later qualification of the SFP floor and liner.

Nominal center line dimensions are used to create the finite element models. Minor adjustments are made to the geometry in center line or shell mid-surface idealization. This may include adjustments up to ½ the thickness of some members. These changes help to simplify the model geometry without the use of contact elements. The simplifications reduce computer runtime without affecting the results and are therefore appropriate. The circular openings in the baseplate are replaced by equivalent square openings. This may result in higher stresses in the corners but improves the mesh shape. Fluid elements are not included in the load drop analysis onto underwater fuel racks. Instead, the LS-DYNA model applies a uniform gravity load to all bodies and considers the FA/NFA at an initial velocity before impact that accounts for buoyancy forces. Upward forces due to drag and water flow through the bottom holes of the baseplate are not considered. This results in higher impact energy and is conservative. Minor geometric details such as corner radii on formed shapes, the flow holes in the foot support rings, and chamfers on the support plates are neglected.

3 Finite Element Model

The dimension of the model is approximately 102”×102” in plan with 100 storage cells (10x10 configuration). Each storage cell has a clear dimension of approximately 8.7” allowing for the placement of a small modular reactor fuel. The racks are mostly made of ASME SA-240, Type 304/304L SST material that are modeled using material models **`*MAT_PIECEWISE_LINEAR_PLASTICITY`** and **`*MAT_PLASTIC_KINEMATIC`** with true stress-strain properties. The hypothetical FA missile is 7.5” x 7.5” x 200” in dimension and 900 lbf in weight. The FA/NFA accidental drop missile is modeled as a rigid body using **`*MAT_RIGID`** or **`*MAT_020`**. Rigid material properties of **`RO`** = 2.070e-004 lb-s^2/in^4, **`PR`** = 0.31 and **`E`** = 2.74e+007 lbf/in^2 (Type 316 SST) are set. The clearance or tolerance between the walls of the fuel rack cells and FA is controlled by fuel configuration and irradiation performance of fuel. A generous gap tolerance (about 0.5” on all sides) was provided for the hypothetical model presented in this article. A mesh size of 0.5” inch is used for all parts of the FEM. For areas in the immediate vicinity of results of interest, a refined mesh size of 0.25” is used. Two separate models were created: one with a shell element baseplate and the other with solid element baseplate.

3.1 Shell Base Plate Model

All shell elements are modeled using 7 integration points and the fully integrated shell element modified for higher accuracy element formulation (**`ELFORM = -16`**) with full projection warping stiffness (**`PROJ=1`** and **`IHQ=8`**). This is noted as the base shell model in this article.

The impact surface is modeled using the **`RIGIDWALL_PLANAR_FINITE_ID`** option in LS-DYNA. The **`RIGIDWALL`** option (called as rigid wall) provides a simple way of treating contact between a rigid surface (SFP liner) and nodal points of a deformable body (foot support circular disc). The rigid wall acts as a plane which is not deformable but still can interact with other parts in the model. The rigid wall is set to stationary and acts as ground component for the simulation. The rigid wall enables the reflective shock waves that bounces back after the impact. Modeling using **`RIGIDWALL`** option provides a numerically rigid surface, while allowing the uplift of the feet. Eight rigid walls numbered #1 to #8 are modeled (one for each foot) so that resultant foot reactions can be calculated individually. The rigid wall #5 is closest to the impact location considered in this model and generates controlling reactions.

The bottom nodes of the eight simplified foot support cylinders are rigidly connected to the nodes in the circular footprint of the foot adjuster support bar (approx. diameter of 4.25”) using **`*CONSTRAINED_NODAL_RIGID_BODY`** command. Eight massless nodes (one for each foot support) are used as part identifiers. Solver mass is added to all eight nodes using **`*ELEMENT_MASS`** command for stability.

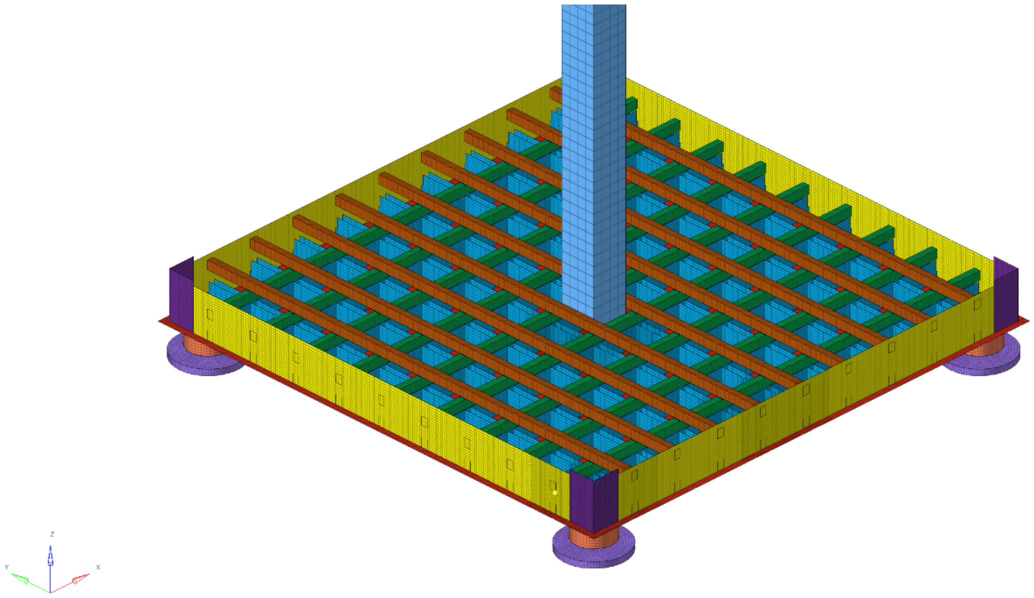

Fig.1: FE Model Isometric View with FA Missile shown

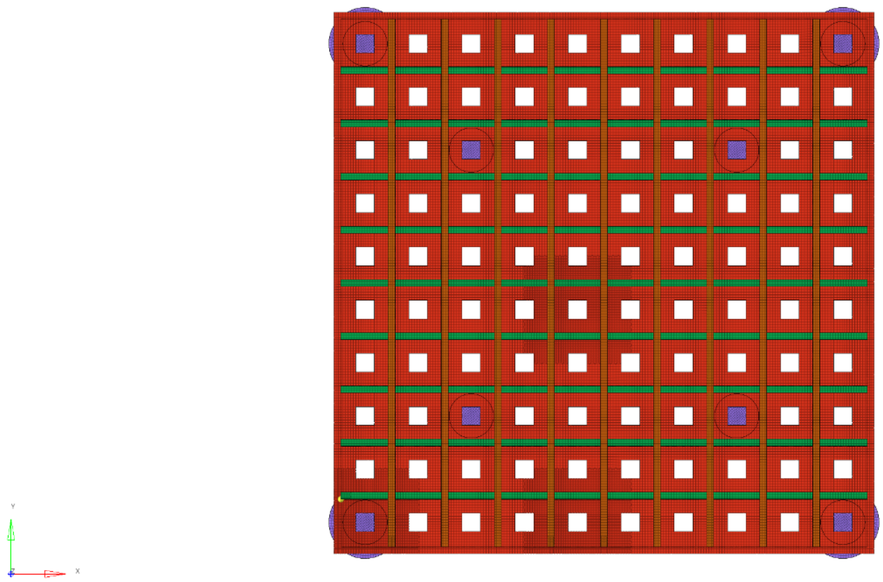

Fig.2: Top View of the Model

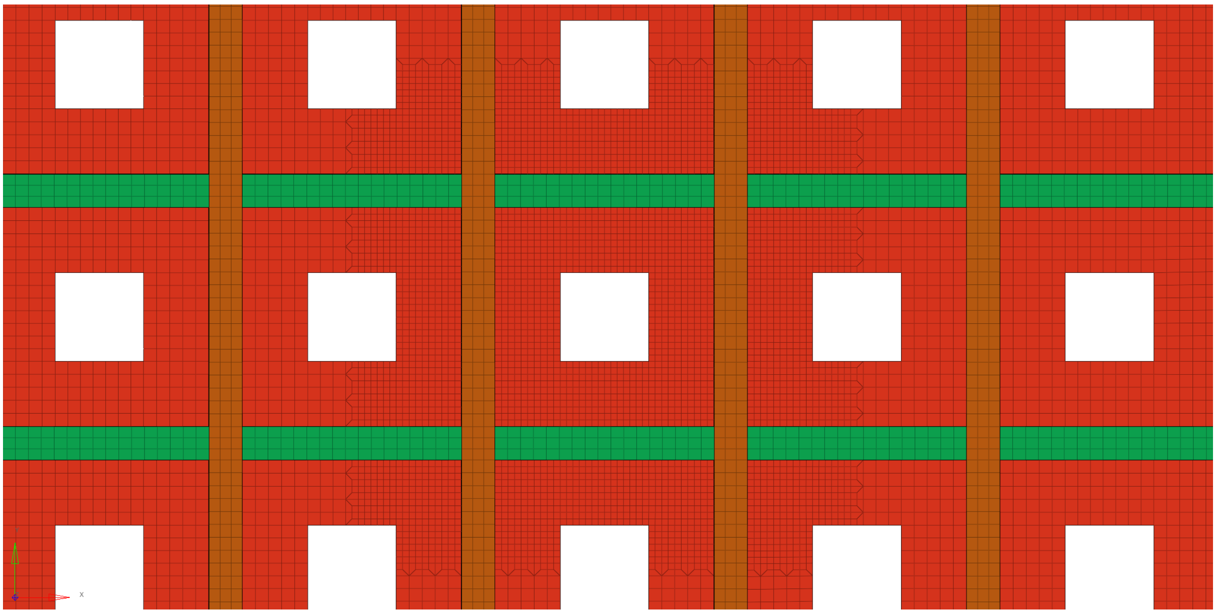

Fig.3: Center Mesh Refinement around FA Missile Drop Area

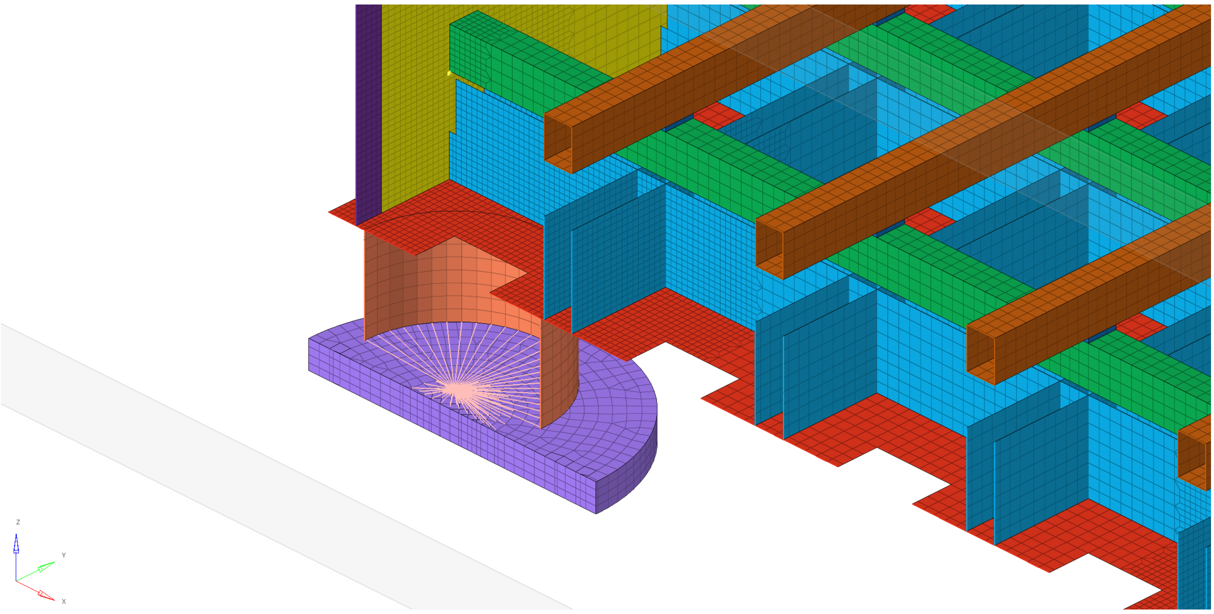

Fig.4: Cut Section View of Tied Contact Foot Assembly Idealization and Mesh Detail

3.2 Solid Base Plate Model

In the solid model, the shell element baseplate is replaced with a solid element baseplate with 8 layers of elements across the thickness direction. One layer of vertical shells is embedded into the solid baseplate to address shell-to-solid connectivity. All other components of the model are the same as the shell element model discussed earlier.

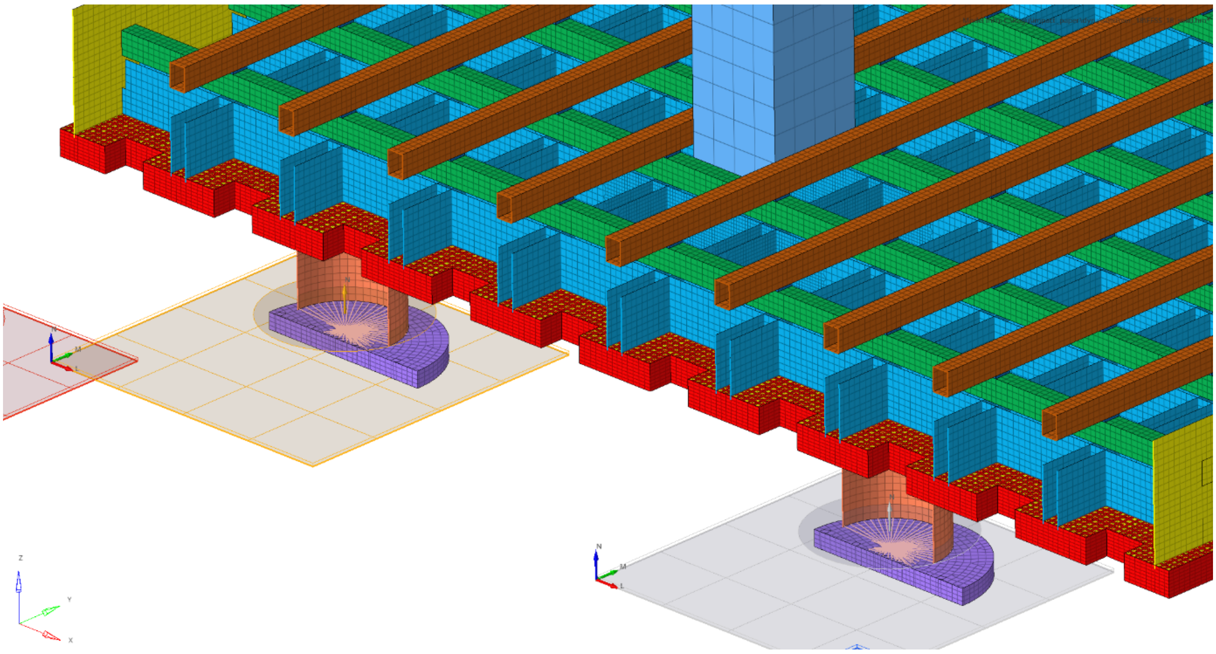

Fig.5: Cut Section View of Solid Element Model with Pressure Loads and Rigid Walls Shown

4 Results for Base Shell Element Model

The results for the base shell element model (`ELFORM=-16` and `SHRF = 5/6`) are presented below. Fig.6: shows the energy profile plot for the finite element solution. Hourglass energy is near zero due to the use of fully integrated shell elements and the contact energy is a small fraction of total energy. The energy profile suggests that the computer run results are stable and adequate for the purposes of this analysis. Fig.7: shows the min and max displacement profile results of all the baseplate nodes. The maximum downward vertical deflection is 0.908 inch at t = 0.015 seconds, which is much less than the gap to the SFP liner of approximately 4.0". The maximum upward deflection of the baseplate is 0.34 inch. Fig.8: shows the displacement contour at t = 0.015 seconds, max negative Z displacement timestep.

Since LS-DYNA does not calculate stress intensity, the maximum stress intensity is calculated by multiplying the maximum unaveraged shear stress by two. Fig.9: shows the maximum shear stress envelope of all the baseplate elements over time. The max shear stress of 23.3 ksi occurs at t = 0.015 seconds. The maximum stress intensity is 46.6 ksi. This is higher than the yield stress (f_y = 30 ksi) of SA-240 Type 304 SST and hence positive effective plastic strains are observed. However, the stress is about 46.6 ksi/67.5 ksi = 69% of the stress limit (0.9×Su). Stresses in all other regions of the model including the bottom stiffeners and vertical support plates are insignificant.

Fig.11: shows the resultant force in all the rigid walls #1 to #8 over time. A maximum resultant force of 573.1 kips is observed on rigid wall #5. Fig.12: shows the cross-sectional reaction forces over time. The max reaction at support #5 is 277.3 kips, which is less than half of the reaction from rigid wall entity. The cross-sectional forces are realistic when compared to the artificial spikes seen in the results from the rigid wall idealization.

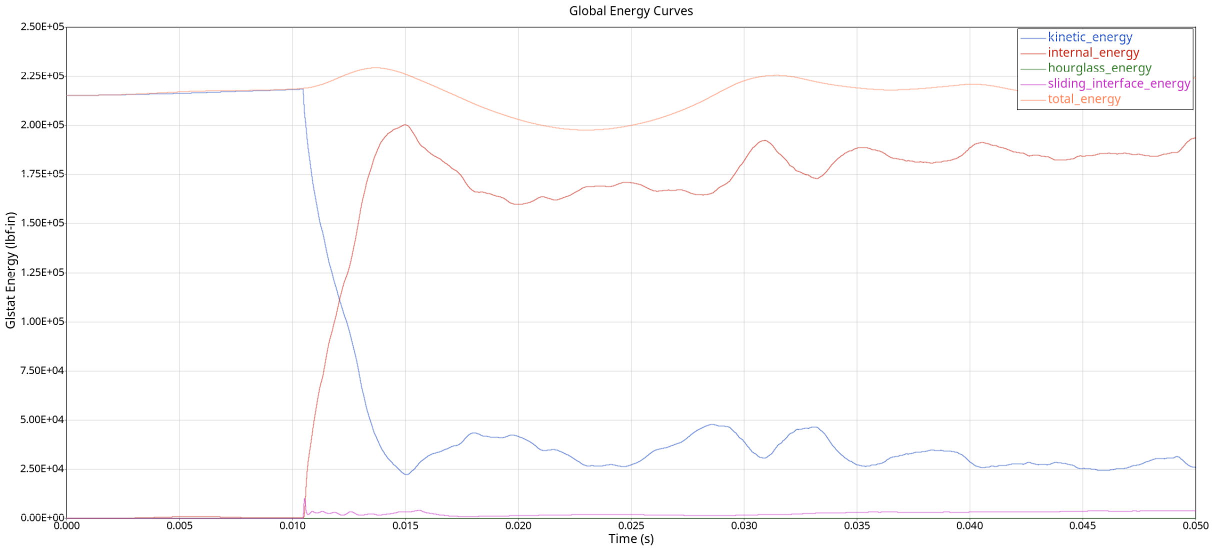

Fig.6: Energy Curves (ELFORM = -16, SHRF = 5/6)

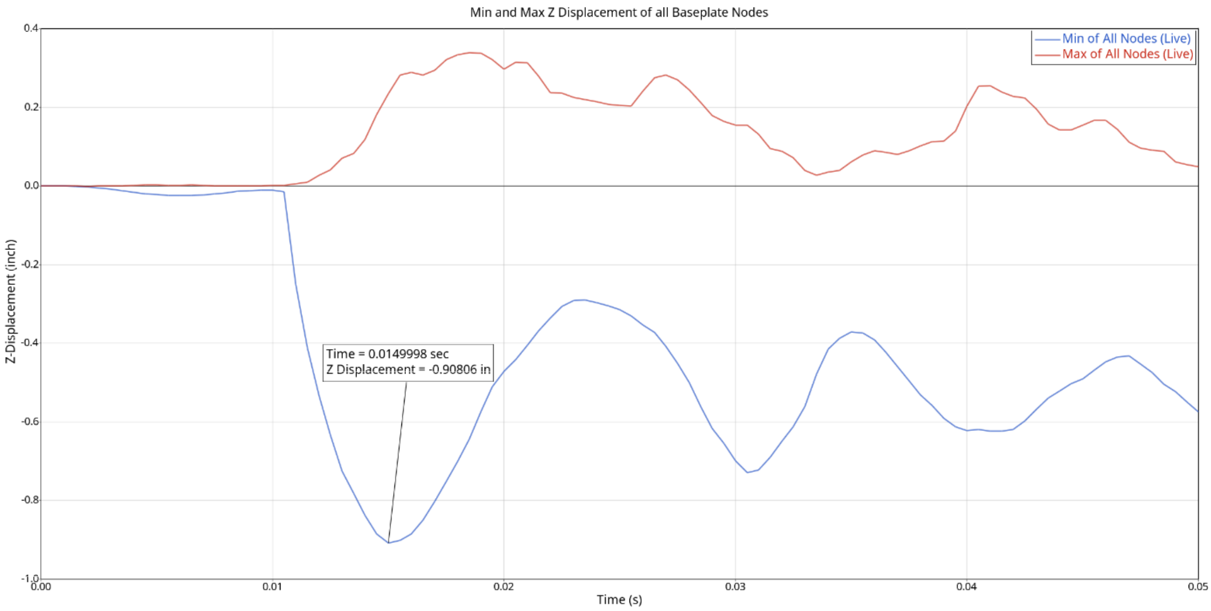

Fig.7: Baseplate Min and Max Vertical Displacements Over Time (ELFORM = -16, SHRF = 5/6)

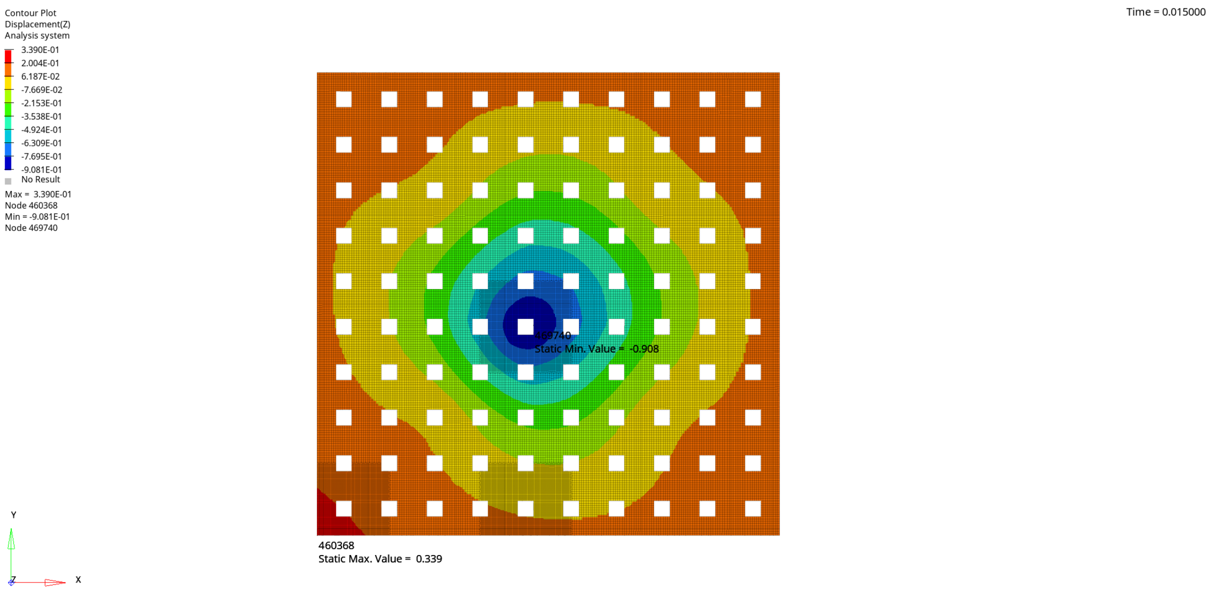

Fig.8: Baseplate Max Vertical Displacement Contour (ELFORM = -16, SHRF = 5/6)

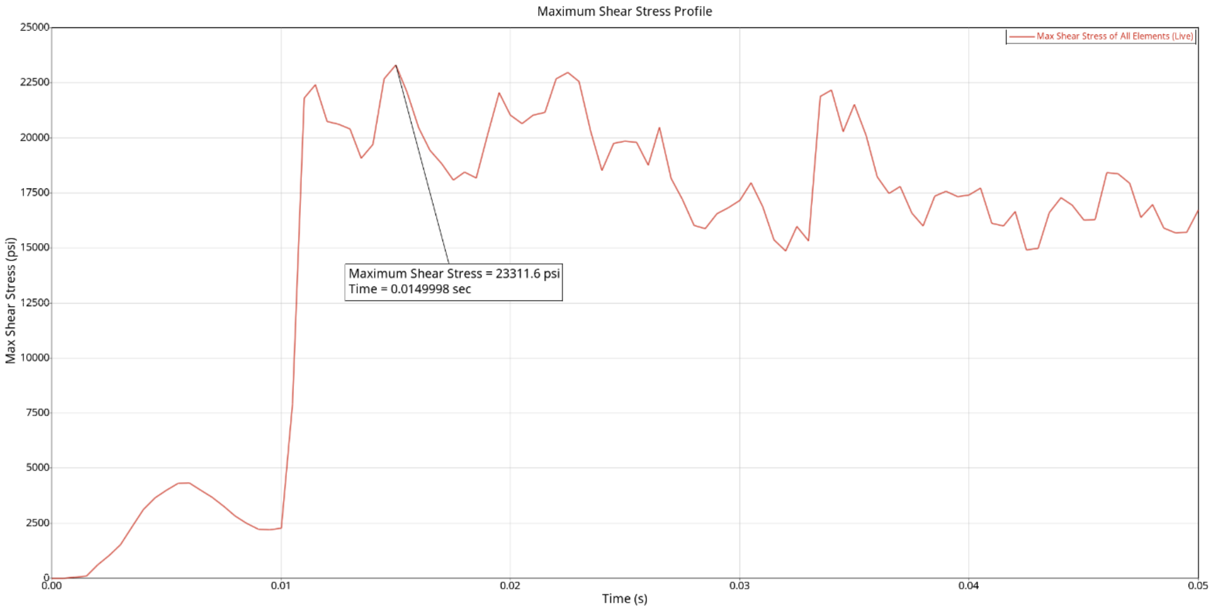

Fig.9: Baseplate Max Shear Stress Over Time (ELFORM = -16, SHRF = 5/6)

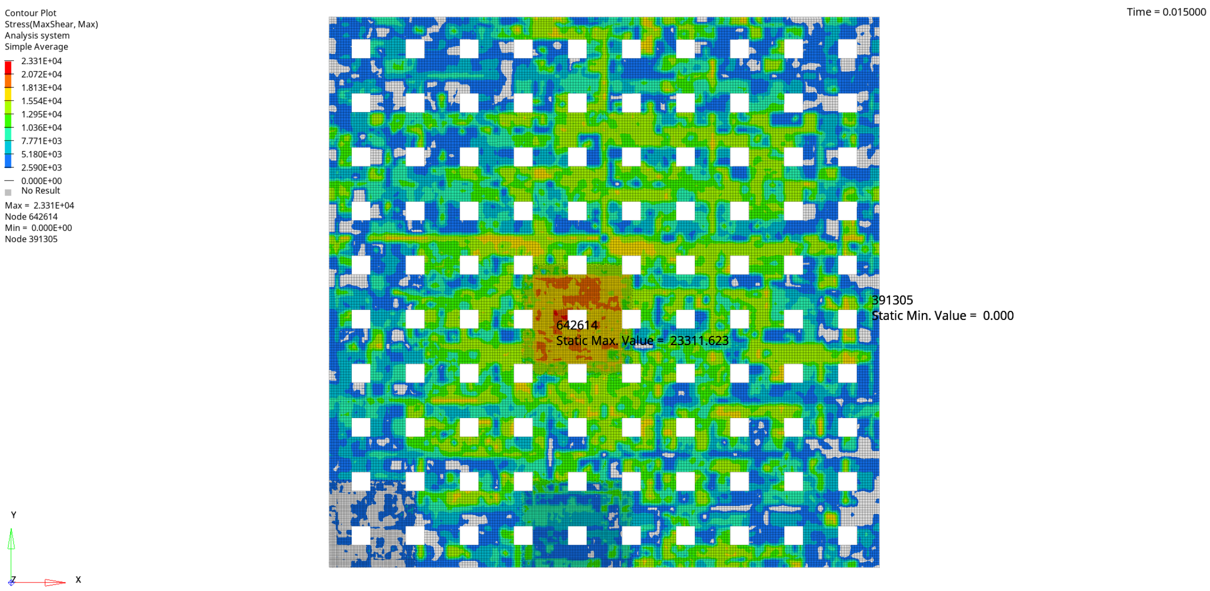

Fig.10: Baseplate Max Shear Stress Contour (ELFORM = -16, SHRF = 5/6)

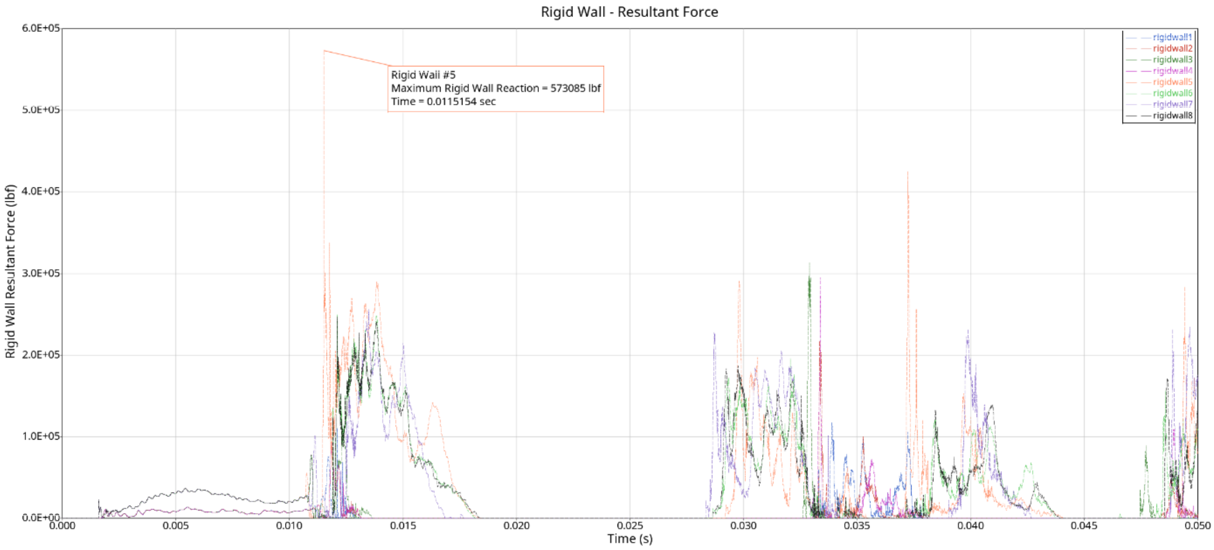

Fig.11: Rigid Wall Resultant Force Over Time (ELFORM = -16, SHRF = 5/6)

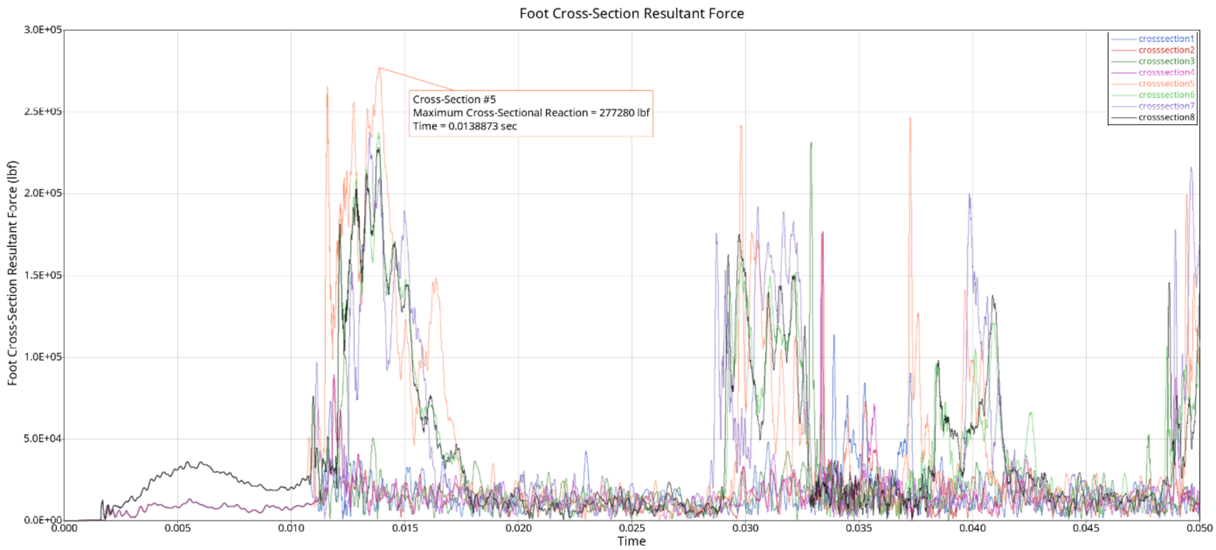

Fig.12: Foot Cross-Sectional Reaction Over Time (ELFORM = -16, SHRF = 5/6)

5 Parametric Study Results

Shear deformations tend to be important when the shell thickness Is greater than approximately 1/5 to 1/10 of the span of plate-bending curvature. The baseplate is 2" thick and the thickness to span ratio of the model varies from 1/25 to 1/45. For classical static or dynamic load applications, the use of thin shell elements is acceptable. Short duration missile impact is a 3-D punching shear problem that sometimes requires sophisticated 3-D models (or solid element models). Thick shell elements are a refinement over thin shells wherein the transverse shear deformation is included in plate bending behavior.

The first order shear deformation (FOSD) elements have a shear correction factor (denoted by SHRF in LS-DYNA) to alleviate their weakness while handling moderately thick to thick shell element situations. LS-DYNA has a default value of 1.0 assigned to shell elements, although 5/6 is recommended in the user manual. Hence, a parametric study was conducted to investigate the sensitivity of SHRF on the results of the model. Per literature, the shell **`ELFORM=16`** shells require more than 2.5 times the computational power of **`ELFORM=2`** shells. Alternatively, a reduced integration element formulation by Belytschko-Wong-Ching (**`ELFORM=10`**) was also investigated for speed and robustness. This element formulation is the same as the default with better mitigation of warped area configurations. For the solid element baseplate, **`ELFORM=1`** (constant stress solid element) and **`ELFORM=3`** (fully integrated quadratic 8 node element with nodal rotations) were selected for the parametric study. Six configurations listed in Table 1: are analyzed.

Model No	Base Plate Element	ELFORM	SHRF
1	*SECTION_SHELL	-16	5/6
2	*SECTION_SHELL	-16	1
3	*SECTION_SHELL	10	5/6
4	*SECTION_SHELL	10	1
5	*SECTION_SOLID	1	NA
6	*SECTION_SOLID	3	NA

Table 1: Parametric Study Analysis Configurations.

Table 2: presents the analysis summary results for the six models considered. It can be immediately noticed that the shear correction factors do not have any effect on the shell element results both for fully integrated and reduced integration elements. The changes to the SHRF from 5/6 to 1.0 change the results by 0% to 3%. For the shell element models the rigid wall reactions have sharper spikes, thus resulting in rigid wall reaction to be almost twice that of foot cross-section reactions. In an idealized model, these two reactions are expected to be closer to each other.

The solid element model is more flexible and produces about 30% higher deformation when compared to the shell element models. The solid element models also produce higher stresses. This is expected as the failure or overstressing is observed mostly in the top or bottom layer of solid elements only. The middle six layers of solid elements have lower stress profiles and only the max stresses along the profile (and not average stresses) are presented. A correct method may be to linearize the stresses across the thickness and then compare it to the shell element results. The foot and cross-sectional reactions are almost similar for the solid element model and no sharp peaks are observed. Overall, both types of elements produce consistent results.

Model No	ELFORM	SHRF	Max Deflection (in)	Max Shear Stress (psi)	Max Foot CS Reaction (kip)	Max Rigid Wall Reaction (kip)
1	-16	5/6	-0.908	23,312	277	573
2	-16	1	-0.908	23,472	278	554
3	10	5/6	-0.915	23,927	278	585
4	10	1	-0.915	23,924	277	562
5	1	NA	-1.188	32,985	403	393
6	3	NA	-1.165	27,761	405	405

Table 2: Parametric Study Results.

6 Summary and Conclusions

This article presents a simplified analysis model of spent fuel racks when subjected to the accidental drop of fuel assemblies. The model is computationally efficient as only the relevant portions of the SF rack are analysed instead of the entire rack model. The results show that variations in shear correction factor (SHRF) have minimal to no impact on the shell element results. The shell element idealization is adequate and provides good results for qualification of the racks to FA drop loads. The shell element base plate underpredicts the deflections by 30% when compared to eight-layer solid element base plate idealization. As there is always a sufficient margin in deflection results of typical SF rack models, it is recommended that shell element idealization be used. The solid element modelling is recommended only when the missile punctures the baseplate or when the deflections are sufficiently large and closer to the design margin.

7 Literature

[1] NUREG-0800 Section 3.8.4 Appendix D, “Guidance on Spent Fuel Pool Racks”, Rev. 4, September 2013.

[2] ASME, “ASME Boiler and Pressure Vessel Code”, Section III, Division 1, Subsection NF and Appendices, 2017 edition.