Technical Paper
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Evaluation of Functional Capability for Spent Fuel Drops in PWR Spent Fuel Rack

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The spent nuclear fuel, combusted and released in the nuclear power plant, is stored in the spent fuel pool (SFP) located in the fuel buildings interconnected with the reactors. In Korea, spent fuel has been stored exclusively in SFPs, prompting initiatives to expand storage capacity by either installing additional SFPs or replacing them with high-density spent fuel storage racks. The installation of these fuel racks necessitates obtaining a regulatory license contingent upon ensuring safe fuel handling and storage systems. Regulatory agencies mandate the formulation of various postulated accident scenarios and assessments covering criticality, shielding, thermal behavior, and structural integrity to ensure safe fuel handling and storage systems. This study describes an evaluation method for assessing the structural damage to storage racks resulting from fuel dropping as a part of the functional safety evaluation of these racks. A scenario was envisaged wherein fuel was dropped onto the base plates of the upper and lower sections of the storage racks, and the impact load was analyzed using the ABAQUS/Explicit program. The evaluation results revealed localized plastic deformation but affirmed the structural integrity and safety of the storage racks.

Keywords: Spent fuel rack, Shallow drop, Deep drop, Spent fuel drop

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1. Introduction

Spent fuel generated in PWR is stored in the pool filled with water. Dropping accidents of a fuel element on top of the rack may occur during fuel handling in SFP. In the NUREG-0800 APPENDIX D 3.8.4, it requires that a review of the functional capability of the racks and the fuel pool, including the fuel pool liner, be performed for hypothetical accidents that could occur during the handling of spent nuclear fuel [1]. In the NUREG-0800, functional capability refers to the ability of structures, systems, or components (SSCs) to perform their intended safety functions under various conditions, including normal operations, postulated accidents, and structural integrity concerns the physical condition of the SSCs being sufficient to prevent structural failure that could lead to safety hazards. Structural integrity ensures that SSCs remain intact and serviceable under all anticipated loadings, including environmental impacts and operational stresses. Among the two evaluation methods, the structural integrity of the racks and the fuel pool, including the fuel pool liner was evaluated in the technical reports (Pool liner qualification report for spent fuel storage racks and Seismic, Structural and Fatigue Evaluation of the Spent Fuel Racks) according to ASME B&PVC, Section III, Division 1, Subsection NF [2-4].

This study evaluated the critical effects and additional damage caused by rack failure and the functional capability of the racks for postulated fuel drop accidents using the tresca stress basis.

2. Dropping Accident of Spent Fuel

2.1 Evaluation Conditions

The accident of spent fuel dropping on the storage racks is assumed to occur in the following three scenarios.

- Shallow Drop: Vertical drop causing collision with the upper part of the storage rack cell.
- Deep Drop-1: Vertical drop passing through an empty cell and colliding with the base plate between support structure and span.
- Deep Drop-2: Vertical drop passing through an empty cell and colliding with the base plate directly above the support structure.

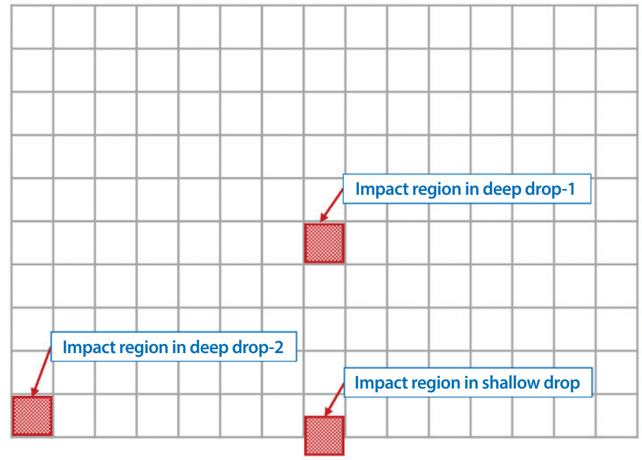


Fig. 1. Impact regions of Postulated fuel-dropping accidents.

The consideration of an inclined drop scenario, where the impacting spent fuel assembly falls in a sloped manner, is conceivable. However, in such instances, the spent fuel assembly undergoes a redistribution of its center of mass during the initial collision with the upper part of the storage rack, leading to subsequent collisions with multiple cells and secondary impacts. Consequently, the kinetic energy of the spent fuel assembly is dissipated and absorbed across the entirety of the storage rack cells. Therefore, due to the significantly lower amount of energy absorbed by a single cell compared to vertical drop accidents, this scenario has been omitted from the evaluation. The assessment focused on a storage rack measuring 15×10 in its horizontal dimension, chosen for its largest size, with postulated fuel-dropping accidents impact regions depicted as illustrated in Fig. 1. The CE16×16 PLUS with the largest weight among the stored spent fuels was selected. The weight of spent fuel is 640 kg.

2.2 Shallow Drop

The shallow drop accident assumes that fuel assembly and handling tools fall vertically together, colliding with the upper surface of the outer cells of the storage rack module. Since the storage rack has a square grid structure, parts, where displacement occurs, are restricted to the impact part. Additionally, the depth of damage to the cell walls after the drop accident should be less than that of the upper part of the effective fuel area. Therefore, the permissible range of plastic deformation on the cell walls of the storage rack should be less than 187.5 mm from the top of the cell, where the neutron absorber is installed.

2.3 Deep Drop-1

The deep drop-2 scenario involves fuel assembly passing through an empty cell of the storage rack and striking the center of the base plate. Consequently, it could cause damage to the concrete plate is penetrated or deformed significantly. Therefore, the functional capability of the base plate is essential in the event of a drop accident. Additionally, evaluation should be conducted to assess the potential damage to the concrete plate due to secondary collisions between the base plate and the concrete plate when maximum displacement occurs.

2.4 Deep Drop-2

In the deep drop-2 scenario, fuel assembly pass through an empty cell of the storage rack and strike the support structure directly. As the base plate is supported by the support structure, the impact load is transmitted directly to the concrete plate of SFP, potentially causing damage. Therefore, functional capability of the base plate and support structure is crucial in the event of a drop accident, and assessment of potential damage to the concrete plate of SFP is necessary.

3. Criteria for Mechanical Accidents

- Permanent damage should not occur to the effective fuel area of the basket cell due to collisions resulting from drop accidents.
- Impact on the base plate caused by drop accidents should not induce significant deformation (cracking or penetration), and such deformation of the base plate should not lead to secondary impacts on SFP concrete plate.
- Impact on the bearing pad of the support structure resulting from drop accidents should not cause significant damage to the concrete plate of the lower part of SFP.

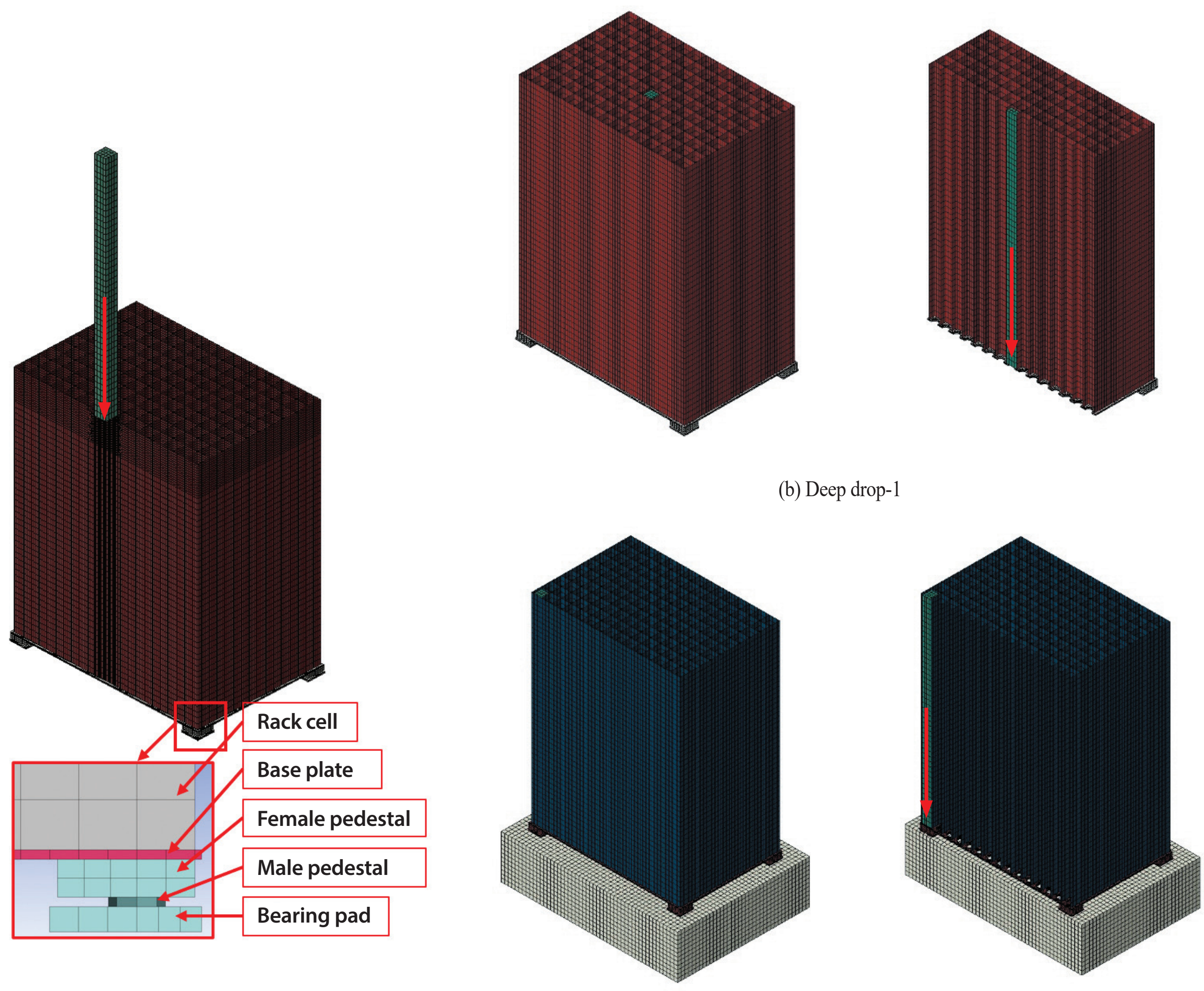
4. Analysis of Accidents

4.1 Assumptions

- Before impact, the storage rack is stationary, and any movement of the rack is solely due to seismic activity. Mechanical accidents do not coincide with earthquakes.
- The longitudinal axis of the spent fuel assembly aligns with the vertical direction.
- The spent fuel assembly is assumed to be a rigid body with a cuboid shape.
- The material properties of the storage rack are assumed to be bilinear elastic, referencing ASME B&PV Code, Sec.II, Part A and Part D. These properties are detailed in Table 1 [5, 6].
- For the shallow drop scenario, it is assumed that the spent fuel assembly falls onto the outer surface of the cell wall of the storage rack. This is considered the most hazardous scenario for the storage rack, making it a conservative assumption.
- During the drop accident, the impact velocity of the impacting object is calculated considering the water resistance and the loss coefficient due to changes

Table 1. Mechanical properties of the material

Category	Material	Elastic modulus (MPa)	Density ($ton \cdot mm^{-3}$)	Yield strength (MPa)	Tensile strength (MPa)	Poisson's ratio	Elongation (%)
rack cell/ base plate/ female pedestal/ male pedestal	SA-240 304 L	195,000	8.03×10^{-9}	172.0	483.0	0.3	40
Pedestal	SA-564 630	195,000	7.75×10^{-9}	795.0	965.0	0.3	14



(a) Shallow drop

(b) Deep drop-1

(c) Deep drop-2

Fig. 2. Finite element analysis models.

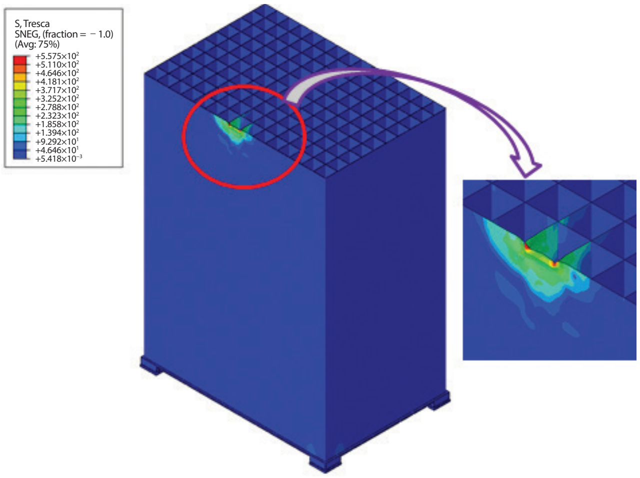


Fig. 3. Deformation shape and stress distribution for shallow drop.

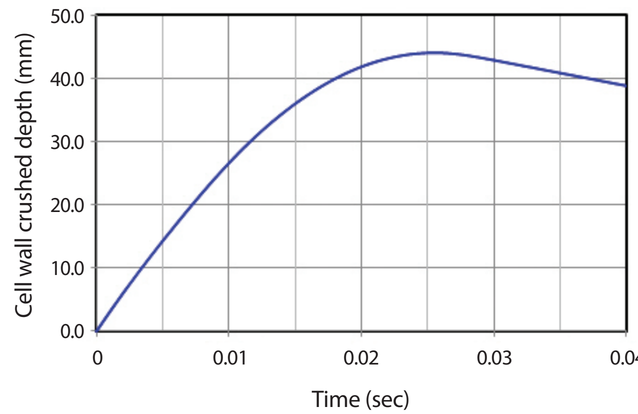


Fig. 4. Deformation depth of rack cell for shallow drop.

in cross-sectional area as the impacting object passes through the storage rack cell.

4.2 Analysis Method

Drop impact analysis used the ABAQUS/Explicit computational program for the Region II 15×10 module [7].

4.2.1 Analysis model

The base plate, pedestal and bearing pad were modeled using 8-node solid elements, while the rack cells were modeled using 4-node shell elements. The spent fuel assembly was modeled as a rigid body, conservatively assuming no energy absorption. Detailed geometric shapes were used to model the impacting objects, including the rack cell, base plate, pedestal and bearing pad. Contact conditions were applied to areas where contact with the spent fuel assembly was expected. Tie constraints shared nodes between the rack cell and the base plate. For the shallow drop scenario, the analysis model was partially refined for the cell involved in the collision, with a total of 177,527 nodes and 168,089 elements. The analysis model for the deep drop-2 scenario included the concrete plate supporting the storage rack to evaluate stresses. It was based on the deep drop-1 model, with a total of 179,193 nodes and 165,356 elements. Material properties of concrete were considered. The geometric configurations of the finite element models for shallow drop, deep drop-1, and deep drop-2 structural analyses are depicted in Fig. 2.

4.2.2 Boundary and initial conditions

For the shallow drop and deep drop-1 analysis models, the boundary conditions constrained the vertical and horizontal degrees of freedom of the nodes on the underside of the support structure. For the deep drop-2 analysis model, the boundary conditions constrained the vertical and horizontal degrees of freedom of the nodes on the underside of the concrete slab supporting the storage rack. The initial conditions applied a drop velocity to the spent fuel assembly, considering water resistance, with velocities of 3,142, 6,978, and 6,585 mm·sec^{-1} for the shallow drop, deep drop-1, and deep drop-2 scenarios, respectively.

5. Analysis Results

5.1 Shallow Drop

The deformation shape and stress distribution at the collision area are illustrated in Fig. 3. The maximum deformation depth, as shown in Fig. 4, is 44.0 mm in the rack cell. The maximum Tresca stress at the collision area is 557.5

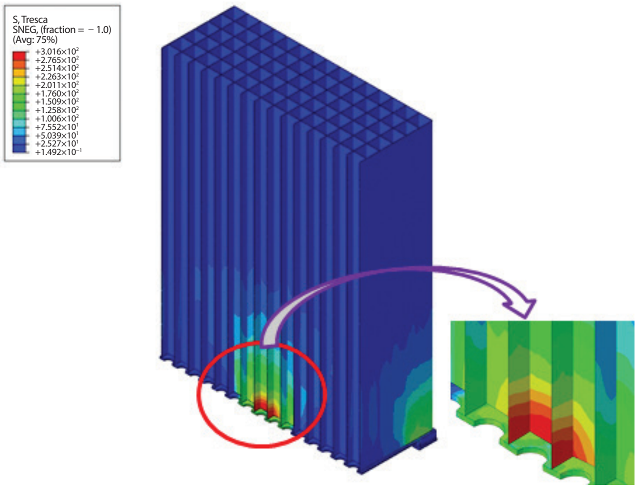


Fig. 5. Deformation shape and stress distribution for deep drop-1.

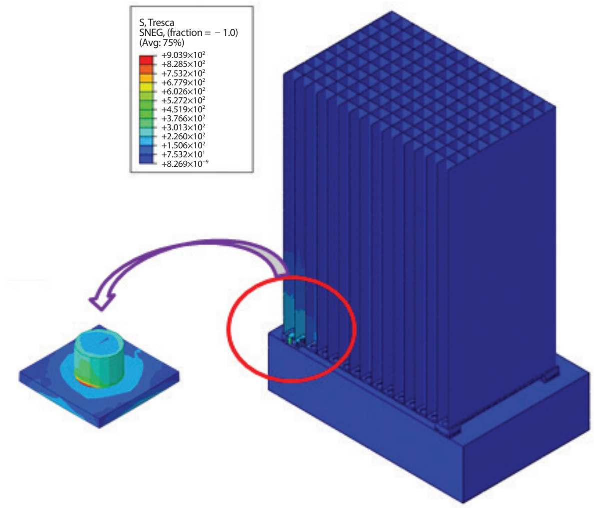


Fig. 7. Deformation shape and stress distribution for deep drop-2.

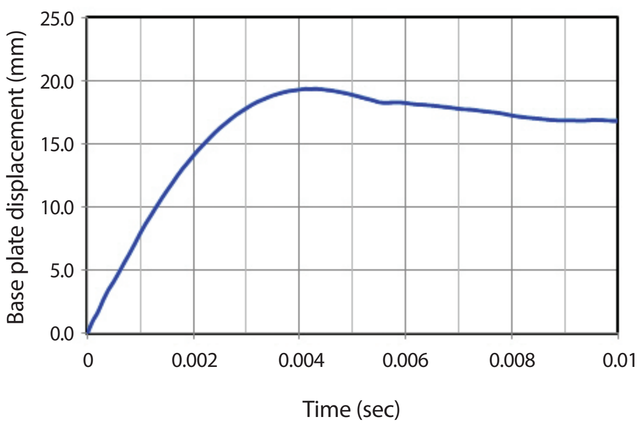


Fig. 6. Displacement of base plate for deep drop-1.

MPa in the rack cell colliding with the spent fuel assembly, which does not exceed the yield strength (676.2 MPa). Plastic deformation is observed in the upper part of the storage rack cell, extending to a depth of 261 mm from the top. However, it does not reach the effective fuel area starting from a depth of 625 mm.

5.2 Deep Drop-1

The maximum vertical displacement of the base plate directly impacted by the spent fuel assembly is 19.3 mm, as shown in Fig. 6. This deformation does not exceed the threshold (150 mm) to cause damage to the concrete plate. The maximum Tresca stress at the collision area is 301.6 MPa in the rack cell and 213.6 MPa in the base plate. Although yielding occurs in the rack cell and base plate, the stress does not surpass the ultimate strength (676.2 MPa), indicating no fracture.

5.3 Deep Drop-2

The deformation shape for the deep drop-2 collision analysis is depicted in Fig. 7. The maximum Tresca stress at the collision area is 903.9 MPa at the male pedestal, indicating localized plastic deformation around the bolt bottom and bearing pad top. However, it remains below the ultimate strength (1,100.0 MPa), suggesting no failure. Additionally, the maximum stresses of 201.4 MPa and 237.5 MPa are observed in the base plate and bearing pad, respectively, below the ultimate strength of 676.2 MPa.

The axial maximum stress on the concrete plate supporting the storage rack reaches 76.9 MPa, exceeding the design compressive strength of 28 MPa. This is expected to cause localized surface cracking within the thickness of the concrete plate, with no significant impact on the overall

Table 2. Maximum deformation for drop accidents

Category	Allowable deformation (mm)	Maximum deformation (mm)	Safety ratio
Shallow drop	625	261	2.4
Deep drop-1	150	19.3	7.8
Deep drop-2	150	6.8	22.1

Table 3. Maximum stress for drop accidents

Category	Yield strength (MPa)	Ultimate Strength (MPa)	Maximum stress (MPa)			Safety ratio		
			Shallow drop	Deep drop-1	Deep drop-2	Shallow drop	Deep drop-1	Deep drop-2
Rack cell	172.0	676.2	557.5	301.6	220.4	1.2	2.2	3.1
Base plate	172.0	676.2	27.1	213.6	201.4	25.0	3.2	3.4
Female pedestal	172.0	676.2	25.2	107.6	204.2	26.8	6.3	3.3
Male pedestal	795.0	1,100.0	32.8	135.2	903.9	33.5	8.1	1.2
Bearing pad	172.0	672.2	23.0	78.6	237.5	29.2	8.6	2.8

functional capability of the base plate.

A summary of the collision analysis results for the virtual drop accidents is presented in Tables 2 and 3.

6. Conclusion

The evaluation of potential mechanical accidents on the storage rack yields the following results:

(1) In the shallow drop scenario, plastic deformation occurred at the top of the rack cells. However, no permanent damage occurred to the effective fuel area, indicating that it does not affect the criticality of the storage rack.

(2) In the deep drop-1 scenario, the impact on the storage rack base plate did not induce significant deformation (cracking or penetration), thereby avoiding secondary impacts on the SFP concrete plate. The horizontal deformation of the rack cell is very small, so it is not expected to affect the critical analysis results.

(3) For the deep drop-2 scenario, the collision analysis revealed that the contact pressure on the support bracket exceeded the design compressive stress, resulting in localized surface cracking on the concrete plate of the lower part of the SFP. However, it is anticipated that this area will not significantly affect the damage of the concrete plate, as it is less than the thickness of the protective coating.

(4) For all drop conditions, the rack cell experienced permanent plastic deformation but it is not fracture. The horizontal deformation of these rack cells is very small and it is not expected to affect the critical analysis results.

In conclusion, the storage rack is deemed to maintain functional capability against all anticipated mechanical accidents.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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