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Analysis of Mechanical Cumulative Damage of Dry Storage Container

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1. Introduction

As wet storage facilities for Spent Nuclear Fuel (SNF) near capacity, the demand for independent dry storage solutions is rising. Dry storage systems, which store SNF in containers after over six years of cooling in wet storage, are being rapidly developed globally. In Korea, versatile containers for transportation, storage, and disposal are under consideration. Ensuring safety during transport, particularly against accident drops, is crucial for the canister that seals the fuel [1], [2], [3]. While evaluating cumulative damage is challenging due to analytical limits, this paper addresses these issues by performing free-fall penetration drop tests with orientation changes in dry storage containers.

2. FE Model and Results

In this study, a finite element model of a dry storage container was developed, as depicted in Fig. 1, to analyze the structural response to impact under cumulative accident scenarios during transportation. To account for orientation changes, the model was constructed to simulate a 9-meter vertical drop followed by a 1-meter horizontal penetration drop.

2.1 Dry Storage Containers Model

The dry storage containers consist of internal components such as fuel, a canister, a cask, and a impact limiter. Each of these components was modeled in detail, focusing on those structures that are likely to significantly influence the system's dynamic behavior and response to impact loads.

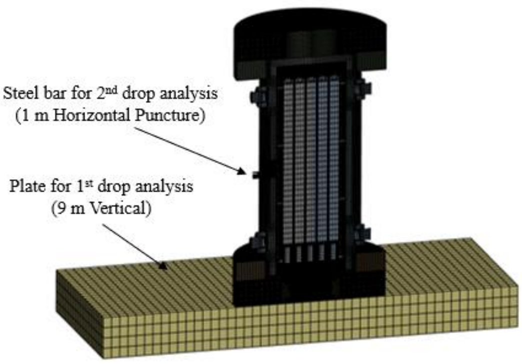

Fig. 1. Analysis model for cumulative scenarios

2.2 Material Properties

The material properties used in the analysis were derived from the characteristics of the dry storage containers. These properties were then applied to create an analytical model, incorporating specific data for the cask, canister, and impact limiter components. For the wood material in the impact limiter, the stress-strain curve obtained from actual test results was utilized and incorporated into the analysis.

Table 1 Material properties of Dry Storage System

Component	Material	Density [kg/m^3]
Cask	SA-350 GR. LF3	8030
	SA-182 GR. F6NM	7850
	SA-240 TP.304	8030
	NS-4-FR	1760
Canister	SA-240 TP. 316L	8030
	SA-240 TP. 304	7850
Impact Limiter	Balsa Wood	120
	Red Wood	380

2.3 Cumulative damage analysis

Figure 1 illustrates the establishment of the analysis model, which simulates the ground impact following a 9-meter vertical free fall. After this, the ground was removed from the analysis, and a Steady State analysis was performed, allowing adequate time for system stabilization. The longitudinal velocity at the moment of impact with a steel rod was simulated by inputting the velocity corresponding to a 1-meter height during a horizontal fall onto a dry storage container. Both the ground and the steel rod were considered rigid, resulting in conservative estimates since penetration and energy absorption were not permitted. In the overall analysis, the Hourglass Energy, which reflects numerical errors in relation to the total energy, was found to be below 5% as shown in Figure 2. With total energy consistently conserved, it was determined that there were no errors in the analysis.

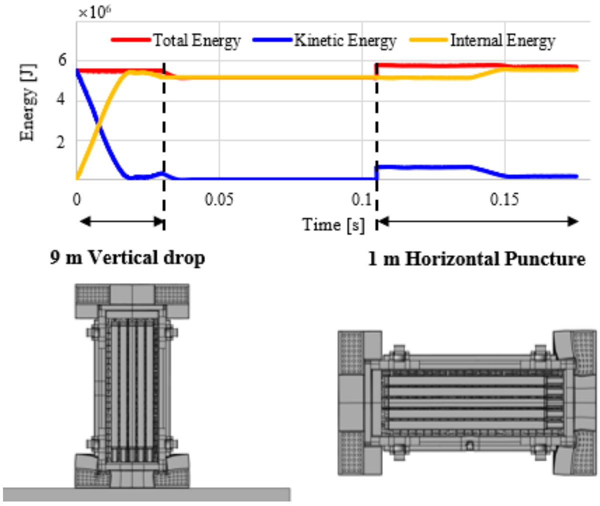

Fig. 2. Energy plot for cumulative damage analysis

2.4 FE Results

Following the cumulative damage incident analysis, we compared the results of individual accident scenarios involving a 9-meter vertical free fall and a 1-meter horizontal penetration drop. During each individual scenario, certain element deletions that did not occur were observed in the cumulative damage analysis, as shown in Figure 3. Specifically, the cumulative damage analysis revealed element erosions in the cask structure due to failure, as highlighted in Figure 3.

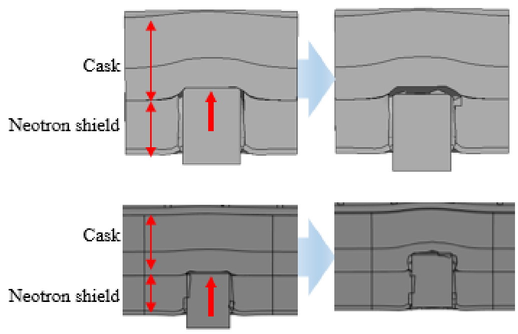

Fig. 3. Cask changes in puncture drop (Upper) and Cumulative damage (Lower)

To assess the increase in response within the cask, the stress in the penetration area was analyzed immediately before the collision between the steel rod and the dry storage container. The impact and stress from the free fall caused the fuel rod to experience higher residual stress than observed in individual damage analyses, as shown in Figure 4. Consequently, it was concluded that the response within the cask is elevated.

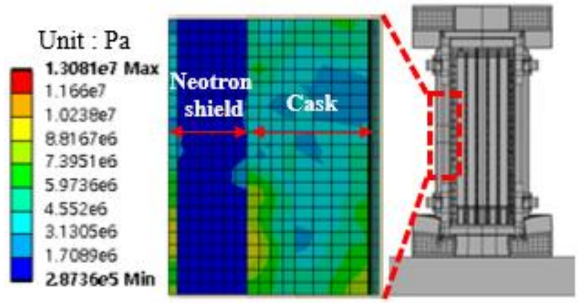

Fig. 4. Residual stress in cumulative damage

Furthermore, conducting the 9-meter vertical free fall first causes a shift in the weight distribution of the dry storage container due to the yielding deformation of the impact limiter. In cumulative damage analysis, this results in the center of gravity shifting closer to the cask lid and canister lid, leading the the steel rod colliding at an inclined angle, which creates high stress in a confined area and causes failure.

3. Conclusions

In this study, finite element analysis was performed on a 9-meter free fall followed by a 1-meter penetrating drop, simulating various accident scenarios for dry storage containers. The model included stabilization time after the free fall to reflect real experimental conditions. Results showed higher responses in combined accident scenarios compared to individual ones. Future work will evaluate more severe accident combinations for dry storage systems in line with ASME Code stress-based evaluations.

4. Acknowledgements

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