Rail Shock and Vibration Pre-Test Modeling of a Used Nuclear Fuel Assembly

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The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology, has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development activities related to storage, transportation, and disposal of used nuclear fuel (UNF) and high-level radioactive waste (HLW). The mission of the UFDC is to identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and HLW generated by existing and future nuclear fuel cycles. The Storage and Transportation staff within the UFDC is responsible for addressing issues regarding the long-term or extended storage (ES) of UNF and its subsequent transportation.

Available information is not sufficient to determine the ability of UNF, including high-burnup fuel, to withstand shock and vibration forces that could occur when the UNF is shipped by rail from nuclear power plant sites to a storage or disposal facility after extended storage. There are three major gaps in the available information – 1) the forces that UNF assemblies would be subjected to when transported by rail, 2) the mechanical characteristics of fuel rod cladding, which is an essential structure for controlling the geometry of the UNF, a safety related feature, and 3) modeling methodologies to evaluate multiple possible degradation or damage mechanisms over the UNF lifetime.

In order to address the first gap, options for tests to determine the physical response of surrogate UNF assemblies subjected to shock and vibration forces that are expected to be experienced during normal conditions of transportation (NCT) by rail must be identified and evaluated. The objective of the rail shock and vibration tests is to obtain data that will help researchers understand the mechanical loads that UNF assemblies would be subjected to under normal conditions of transportation and to fortify the computer modeling that will be necessary to evaluate the impact those loads may have on the integrity of the UNF assembly. The shock and vibration testing along with computer modeling is a vital part of research to achieve closure of a gap in information related to the ability of UNF to maintain its safety function when subjected to NCT.

In support of this effort, preliminary structural dynamics modeling was conducted. The modeling investigates the rigidity of a hypothetical cask and cradle structure by comparing it to a monolithic concrete mass. The concrete mass represents a practical option for achieving the necessary cask and cradle mass on a flatbed railcar, but this comparative modeling study investigates whether or not the dynamic loads transmitted through a monolithic concrete configuration are adequately representative of a realistic cask and cradle system. This modeling highlights the need for rail testing by reporting the phenomenon of structural transmissibility. As shown herein, this structural transmissibility can cause an amplification of shock and vibration loads through the structure, which could potentially lead to accelerated mechanical degradation of UNF under NCT.

I. INTRODUCTION

The mission of the Used Fuel Disposition Campaign (UFDC) is in part to develop the technical bases needed to support extended storage of used nuclear fuel and associated transportation. The objectives of the transportation activities are to address identified high-priority technical issues as well as to support the Nuclear Fuels Storage and Transportation Planning Project efforts to prepare for the large-scale transportation of UNF and high-level radioactive waste (HLW) with an initial focus on removing UNF from the shutdown reactor sites. This includes developing the technical basis for the transport of high-burnup used nuclear fuel (HBU UNF) and the transport of all used nuclear fuel after extended storage. This work will focus on planned field-testing to assess realistic loading on the fuel rods and assemblies during NCT in order to obtain data needed to evaluate the integrity of the UNF. This data will be used to inform the computer modeling of railcar/cask and fuel assembly components.

As discussed in a report by Adkins et al. (Ref. 1) on used nuclear fuel performance characterization under U.S. Nuclear Regulatory Commission (NRC) regulations, it is not sufficient for UNF to simply maintain its integrity during the storage period. It must maintain its integrity in such a way that it can withstand the physical forces of handling and transportation associated with restaging the fuel and moving it to a different location (such as an interim storage site, a geologic repository, or a treatment/recycling facility). Hence, understanding mechanical performance under cumulative loading stemming from storage , transfer (from storage container to transport container if needed), and normal conditions of transport (NCT) is necessary as it establishes part of the safety basis by maintaining the fuel confining boundary (geometry) and criticality safety. Because of this, an understanding of the mechanical loads on used nuclear fuel, cladding, and key structural components of the fuel assembly during normal conditions of transport, and the mechanical response of the UNF and assembly components to these loads is essential.

The purpose of this paper is to present preliminary modeling results which will inform testing. Preliminary modeling is necessary because conveyance systems are complex dynamic systems and no single test of one particular system would be representative of all combinations of fuel/cask/conveyance designs. Fuel response data from the test series, such as strain measurements, need to be considered in the context of the conveyance system in which they were generated. Two hypothetical conveyances are presented herein, which highlight the dynamics of these systems. These conveyances are a realistic cask/cradle system, and an equivalent mass. The equivalent mass system is evaluated in this study to determine if it would be an adequate replacement for a realistic cask/cradle system due to the high cost and limited availability of existing systems.

II. PRELIMINARY MODELING TO INFORM TESTING

Each conveyance has a different structural configuration, and this raises the question of how much the configuration affects the loading transmitted to the fuel. At one extreme, the cask or representative mass configurations are sufficiently rigid that the only components to affect the dynamic response of the system are the railcar truck and suspension, which can be easily modified for test purposes by swapping in different spring/damping packages. Another possibility is that the cask or representative mass configuration has a strong influence on the loads transmitted from the track to the fuel, such that any test configuration needs to be carefully constructed or vetted to match existing or expected railcar behavior. A limited modeling campaign was conducted to determine whether or not the structural configuration of the test system was important, or if it was only necessary to capture the correct mass on the railcar. The results of this modeling campaign suggest that the test system configuration is vitally important to ensuring representative loading on the fuel.

II.A. Two-Dimensional Railcar Modeling

The initial modeling effort was performed using simplified representations of the railcar system to model two-dimensional (2D) motion. Two different cask surrogates were modeled on identical flatbed railcars: 1) an approximate PWR cask system and 2) a concrete block monolith of equivalent mass (Figure 1). Each model contained a point mass on a spring and damper to approximate an individual fuel assembly. When the models were subjected to the same dynamic disturbance at the trucks, the fuel assembly point-mass of the PWR cask system responded more strongly than the fuel assembly point-mass attached to the monolithic concrete block by about 30 percent. These relatively simple models suggested the structural configuration of the test system could be important.

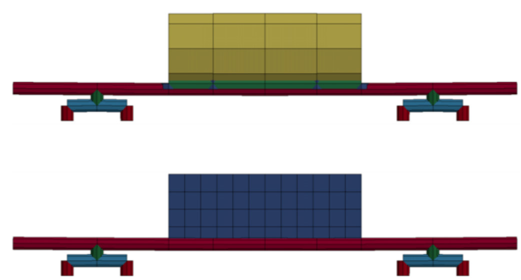

Fig 1. 2D Railcar System Dynamic Models (Top: PWR Cask, Bottom: Monolithic Concrete Block).

II.B. Comparative Stiffness

Detailed three-dimensional (3D) structural models were created to evaluate the stiffness of a realistic cradle supporting a PWR cask (Figure 2) and a concrete block of equivalent mass and footprint (Figure 3). The design of the cradle was inspired by photographs of actual cradles, but does not correspond to a known design. The stresses caused by the weight of a fully loaded cask were determined to be well within the yield strength of structural steel, so the simulated cradle design appears to be viable and a reasonable approximation of a realistic system.

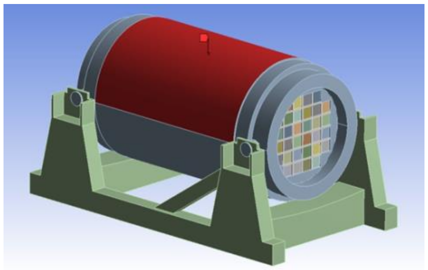

Fig 2. Realistic Cradle/Cask System

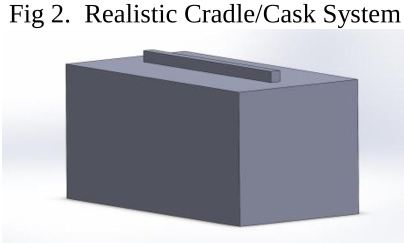

Fig 3. Equivalent Mass Concrete Block with Basket/Assembly Test Unit

The effective vertical stiffness of the two structures was calculated by applying a vertical downward load to the top of the cask and topmost surface of the concrete block and dividing by the resulting displacement. The cask system was determined to have a representative stiffness of 1E8 lb/in. The concrete block was found to have a stiffness of 1E9 lb/in. when the load was distributed across the top face of the concrete (without the representative fuel basket block) and 3E8 lb/in. when the load was localized on the fuel basket block visible in Figure 3. Lower effective stiffness for the cask would tend toward a lower resonant frequency which is more susceptible to amplification for the low-frequency excitations expected under rail transportation. The dynamic difference is further evaluated using a frequency response analysis and a time history comparison for a shock pulse.

II.C. Frequency Domain Evaluation

Dynamic systems are often evaluated in the frequency domain because the dynamic response of structures depends on the frequency characteristics of the load. When a structure is loaded with a cyclical excitation that has a frequency near its natural frequency, a small magnitude load can be amplified to a large magnitude response to the extent that the structure may be damaged. Modal analysis is used to determine the natural frequencies of vibration of a structure, and frequency response analysis is used to determine the amount of response amplification over a range of frequencies.

II.C.1. Modal Analysis

A modal analysis for the concrete block and cask/cradle systems was performed in ANSYS R15.0. The total weight for both systems is approximately 255,000 lb, the length for both systems is approximately 228 in, and the width for both systems is approximately 122 in. The modal analysis for each system was performed with the displacements of each base fixed.

The results of the modal analysis for the concrete block system and the cask/cradle system are shown in Tables 1 and 2, respectively. The natural frequencies of vibration of the structure and the corresponding deformation shapes associated with the first eight vibration modes were calculated. The relative strength of each mode is ranked by the amount of mass that participates in the deformation mode shape. The ratio value reported in Tables 1 and 2 is a normalized mass participation value with the strongest listed mode frequencies assigned a value of 1.0 and the other values normalized to that value. In the case of the concrete block, the strongest mode is 318.1 Hz, with another relatively strong vibration mode at 338.2 Hz. The corresponding vibration frequencies for the cask/cradle system were far below those of the concrete block, with the strongest frequency at 52.4 Hz and other relatively low strength vibration modes between 10.5 and 154.2 Hz. Based on previous analytical work, the range of interest for a fuel assembly is below 100 Hz (Ref. 2). This analysis shows that the concrete block system does not have any normal vibration modes below 144.3 Hz, while the cask/cradle system's fundamental mode is within the range of interest at 52.4 Hz. From modal analysis, we expect a cask/cradle system to behave in a significantly different manner to a concrete block system.

Table 1. Modal Analysis of Concrete Block

Concrete Block System		
Mode	Frequency	Ratio
1	144.3	0.0002
2	174.3	0.0000
3	179.0	0.0000
4	285.9	0.0004
5	318.1	1.0000
6	338.2	0.6429
7	347.9	0.0000
8	354.1	0.0000

Table 2. Modal Analysis of Cask/Cradle Systems

Cask/Cradle System		
Mode	Frequency	Ratio
1	10.52	0.0004
2	27.72	0.0269
3	28.75	0.0012
4	52.40	1.0000
5	66.76	0.0033
6	73.06	0.0419
7	153.5	0.0503
8	154.2	0.0245

II.C.2. Frequency Response Analysis

The modal analysis identifies the normal vibration frequencies of a structural system. Frequency response analysis calculates the response of the system when subjected to cyclical loads over a range of frequencies. In this case, the response spectra were calculated assuming a vertical acceleration load applied to the base of both systems with amplitude of 1 m/s^2 and a frequency range of 1 to 100 Hz. The response of the concrete system was measured at the basket, while the response of the cask and cradle system was measured at the top of the cask. For simplicity, it is assumed that the two locations are representative of the acceleration response of the fuel carried by each system. The modal analysis model of the cask and cradle case did not include an internal basket structure, so a point on the outside surface of the relatively rigid steel cask was chosen for comparison. The same models used for modal analysis were used in the frequency response analysis (the modal results are used in the frequency response calculation).

Figure 4 shows the frequency response spectra for both cases. A response value of 1.0 indicates that the peak acceleration response equals the input amplitude. A response value less than 1.0 indicates that the response is relatively lower than the input, and a response value greater than 1.0 indicates a relative amplification of the input. At about 35 Hz and higher the cask/cradle system exhibits amplification, with a maximum amplification of 10 times near 50 Hz. The modal analysis predicts a natural vibration frequency at 52.4 Hz, so the frequency response analysis is appropriately showing resonance around that frequency. Conversely, the concrete block shows a low transmissibility through the entire frequency range of interest. Comparing the two curves, the cask/cradle response is more than an order of magnitude higher than the concrete block response. This indicates that the loads transmitted to the fuel assembly are potentially much greater in the cask/cradle case than the concrete case.

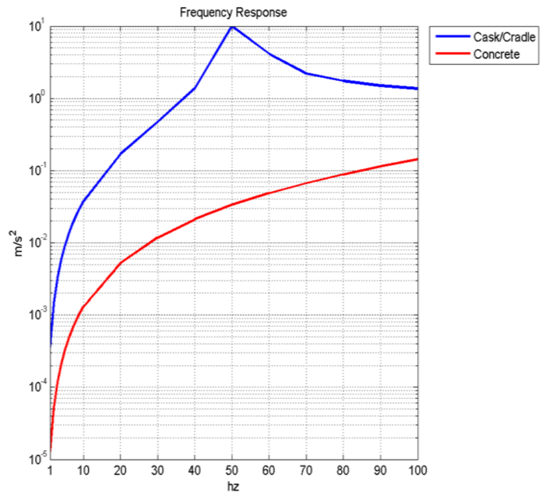

Fig 4. Frequency Response Spectra

II.C.3. Time Domain

The frequency domain evaluations used linear methods, but the fuel represents a nonlinear system because it has the freedom to move independently in the basket subject to friction and contact forces. One way to evaluate the nonlinear transmission of loads is through a time-domain model. For the two configurations of interest—cradle/cask and concrete block—a detailed fuel assembly model is added to the basket, and an identical shock acceleration load is applied to the base. A direct comparison can be made between the responses of the fuel assembly in both configurations.

The two nonlinear time-domain models were evaluated using the LS-DYNA code. Figure 5 shows a cutaway view of the cask and cradle system, which approximates a PWR cask with a 32 fuel assembly capacity. A number of elements at the near end are removed to show the detailed basket contents within, including one detailed fuel assembly model. Figure 6 shows the monolithic concrete system, which has an aluminum channel used as a basket surrogate. Part of the channel is cut away to show the detailed fuel assembly within.

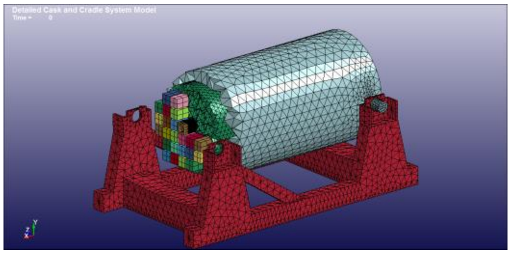

Fig 5. Detailed Cradle System Model with Detailed Fuel Assembly in One Fuel Compartment

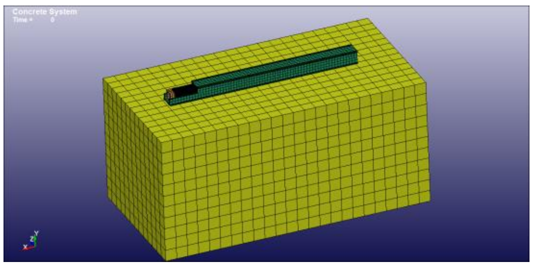

Fig 6. Concrete System Model with Detailed Fuel Assembly in Channel

Figure 7 summarizes the difference in response that is observed when the cradle system and concrete mass system are subjected to the same shock acceleration load. The excitation curve shows the triangular acceleration pulse that was applied to the base of both systems in the vertical direction as the input load. The fuel assembly center of gravity (FA CG) – Cradle curve shows the response acceleration of the centrally located detailed fuel assembly center of gravity, while the FA CG – Concrete shows the response of the CG of the fuel assembly in the concrete system case. The two response curves are filtered with a Butterworth filter to eliminate frequency content above 100 Hz.

The initial negative acceleration of the fuel assemblies is due to the settling of each structure under the initial gravity load (-9.8 m/s^2), which did not quite reach equilibrium in a quasi-static preload step. The motion associated with this settling is relatively small and is not expected to have a significant effect on the metrics of interest. In this case, an excitation pulse with a peak of 6.4 m/s^2 caused a peak response of 31.4 m/s^2 in the fuel assembly of the cradle system and a peak response of only 4.9 m/s^2 in the fuel assembly of the concrete system. So, the cask and cradle system effectively amplifies the response of the fuel (relative to the input) while the concrete system reduces the fuel assembly response (relative to the input). This analysis further demonstrates the loads transmitted through the cask/cradle structure, and shows that the concrete monolith option could potentially underrepresent the loads on the fuel assembly.

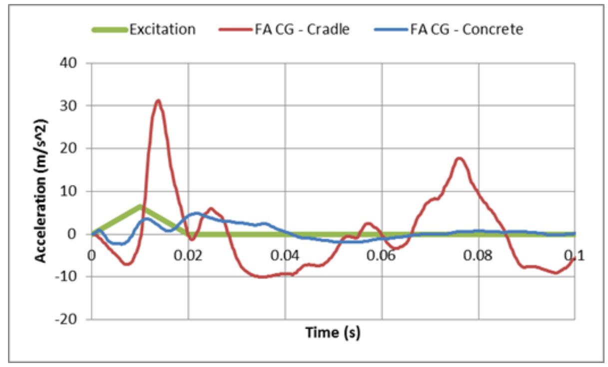

Fig 7 - Nonlinear Analysis of Load Transference

III. CONCLUSIONS

In every analysis, a significant difference is found between the dynamic characteristics of the concrete block monolith and a realistic cask/cradle system. In the comparison of effective vertical stiffness, the concrete block is found to be 3-10 times stiffer than the realistic cask/cradle system. It is concluded that the monolithic concrete block is not a viable alternative to using a realistic cask and cradle system in future UNF transportation testing.

In the frequency domain analyses, the concrete block was found to have fundamental vibration modes with a much higher frequency than the cask/cradle, which notably had vibration modes within the range of interest for fuel assemblies while the concrete block did not. The frequency response spectra showed that cask/cradle amplified the response of the cask between 35-100 Hz, while the concrete block attenuated the response in the range of 1-100 Hz. Comparatively, the response of the realistic cask/cradle system is more than an order of magnitude higher than the concrete block throughout the range of 1-100 Hz.

In the time domain analyses, simplistic models of the whole railcar system predicted a stronger response for the cask/cradle system than the concrete block system. A more detailed mechanical shock response analysis was made using the concrete block and cask/cradle models used in the first analyses and a used fuel assembly model that was developed for the UFDC Structural Uncertainty task (Ref. 3). The results show that the loads transmitted through the system to the fuel assembly were lower in the concrete monolith case and significantly higher in the detailed cask/cradle case.

These analyses support the conclusion that the composition of the cask/cradle structure has a strong influence on the response of the fuel assembly. In addition, the results of this analysis series indicate that any proposed test configuration needs to be evaluated in the structural dynamic realm as was presented here. Modal analysis, frequency response analysis, and time domain shock analysis are needed to characterize the proposed test platform. Even when using an actual cask/cradle system, this analysis and characterization is necessary to interpret the results of testing. Because the cask/cradle design affects the transmission of loads to the fuel, we have to be able to identify the characteristics of the test system so the results can be extended to other cask/cradle designs. Variations in cask/cradle design will likely affect the loads transmitted to the fuel, so any one test series using a single cask/cradle configuration is not sufficient to characterize the loads across all possible cask/cradle configurations.

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