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Modeled Structural Transmissibility of a Used Nuclear Fuel Conveyance Applied to Over the Road Test Data and Finite Element Modeling

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ABSTRACT

The Used Fuel Disposition Campaign (UFDC) has been established by the U.S. Department of Energy Office of Nuclear Energy (DOE-NE), to conduct research and development activities related to storage, transportation, and disposal of used nuclear fuel (UNF). The Storage and Transportation staff within the UFDC are responsible for addressing issues regarding the long-term or extended storage (ES) of UNF and its subsequent transportation. Current information is insufficient to determine the ability of UNF, including high-burnup fuel, to withstand shock and vibration loads that could occur when UNF is shipped by rail from nuclear power plant sites to a storage or disposal facility after extended storage. In order to make this determination, the magnitude of the transportation loads transmitted to the UNF must be quantified. Previous preliminary modeling work has shown how the structural transmissibility of the transport system can affect the magnitude of these loads and the importance of modeling all aspects of the transport system (i.e. rail car, transport cradle, cask, canister, and fuel). The work presented herein proposes a methodology for determining the structural transmissibility of a hypothetical transport system, this is then used to scale existing OTR data. The utility of this, is that the resultant scaled data can then be used to compare the as tested configuration to an untested hypothetical configuration. This work will be relevant in creating models of UNF during transport. As such, this paper also presents finite element modeling of the response of a fuel assembly for the existing OTR data and the scaled OTR data. The finite element modeling indicates that the strains in both cases are low, and that no rod to rod interaction is likely to occur.

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 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 Normal Conditions of Transport (NCT) and modeling which supports this testing effort, in order to obtain data needed to evaluate the integrity of the UNF.

As discussed in a report by Adkins et al. [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).

Hence, understanding mechanical performance under cumulative loading stemming from storage, transfer from storage container to transport container, and NCT is necessary. This 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.

As presented previously, the conveyance design may greatly affect the loads transmitted to the fuel [2]. To better understand this, staffs at Pacific Northwest National Lab (PNNL) have begun examining how existing OTR data, which contains information about the magnitude of the input loads, can be scaled with the modeled structural transmissibility of an untested conveyance design. This will provide information concerning how the modeled system would perform when subject to the same input loads as the tested conveyance.

In addition, the input loads that the conveyance experiences will affect the loads transmitted to the fuel. These input loads are generated at the rail/wheel interface during transport, and may differ greatly depending on the speed of the train and the condition of the rail. PNNL is in the process of developing a modeling methodology which will allow the user to couple the rail vehicle dynamics code NUCARS© with existing models of UNF during transport [3]. This methodology will allow the user to subject a UNF conveyance to various track conditions and train speeds and predict the response in the fuel.

BACKGROUND

In 2014, Sandia National Laboratories (SNL) provided valuable information regarding the loads transmitted through the conveyance system to the fuel assembly [4]. For practical reasons, the testing could not be performed on an actual used nuclear fuel conveyance system, so a surrogate test conveyance system was configured using a flatbed trailer and large blocks of concrete to achieve a realistic mass representation. The system was intended to mimic the total mass of an existing used fuel highway conveyance.

Analysis of the 2014 OTR data showed that there may be an attenuation or amplification of the input loads, due to the structural transmissibility of the system. The results from this testing, showing the effects of structural transmissibility are shown in Figure 1.

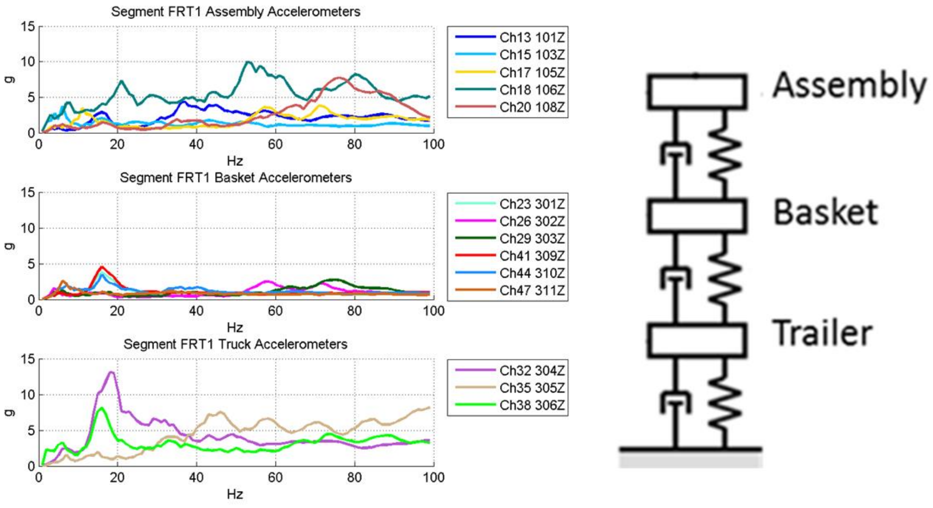


Figure 1: Conveyance Accelerometer Responses

The results from this work and subsequent modeling of the system indicated that the structural design of the conveyance may greatly affect the magnitude of the loads transmitted to the fuel [5]. Thus, it is necessary to develop techniques for determining how a different design may behave under the similar loading conditions. Specifically, a method for scaling the OTR data above with the modeled frequency response of a hypothetical system is described.

HIGHWAY CONVEYANCE COMPARATIVE TRANSMISSIBILITY

Previous work has shown that the dynamic characteristics of a UNF conveyance may affect the magnitude of the loads transmitted through the conveyance to the fuel. The phenomenon, which is responsible for the amplification or attenuation of base input loads which travel through a structure, is known as the structural transmissibility [6].

In order to better understand how structural transmissibility affects a UNF conveyance, two models have been developed. The first model represents a system which was used for preliminary over the road (OTR) testing by SNL [4, 7]. A simplified model of this system is shown in Figure 2. It consists of two concrete blocks, a simulated basket, and a blended mass surrogate representing the fuel assembly.

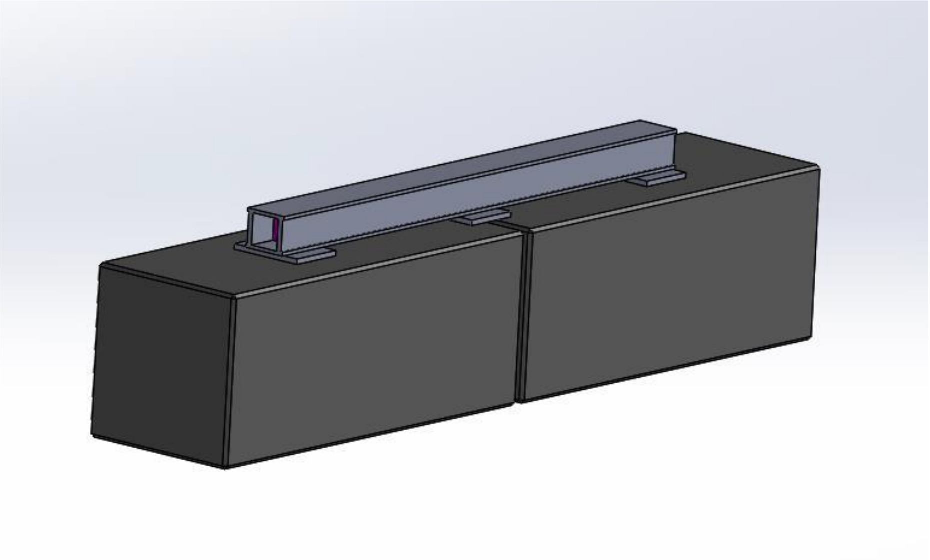


Figure 2: Sandia Test Conveyance

The SNL conveyance was compared to a currently used UNF conveyance; this conveyance represents a realistic transport system [7]. It consists of a transport cradle, cask, basket, and blended mass surrogate representing the fuel. A simplified model of the realistic conveyance is shown in Figure 3.

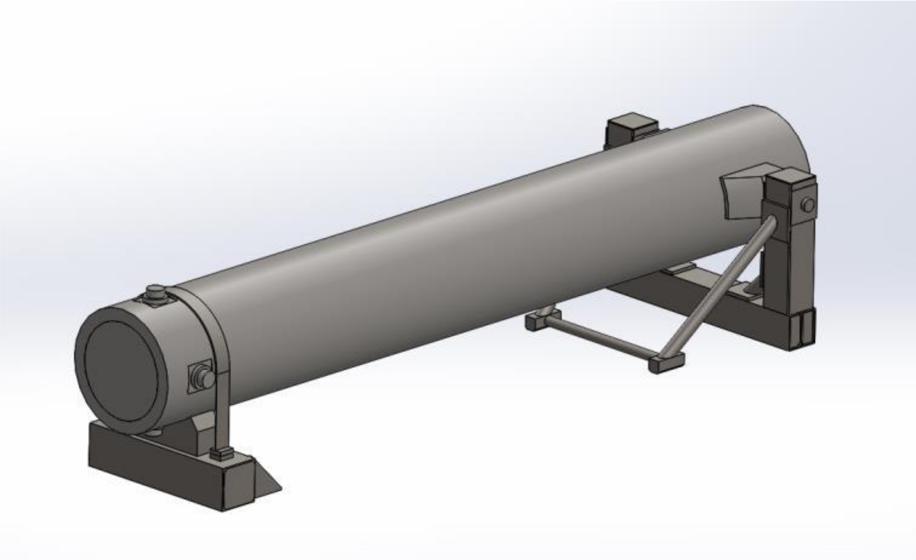
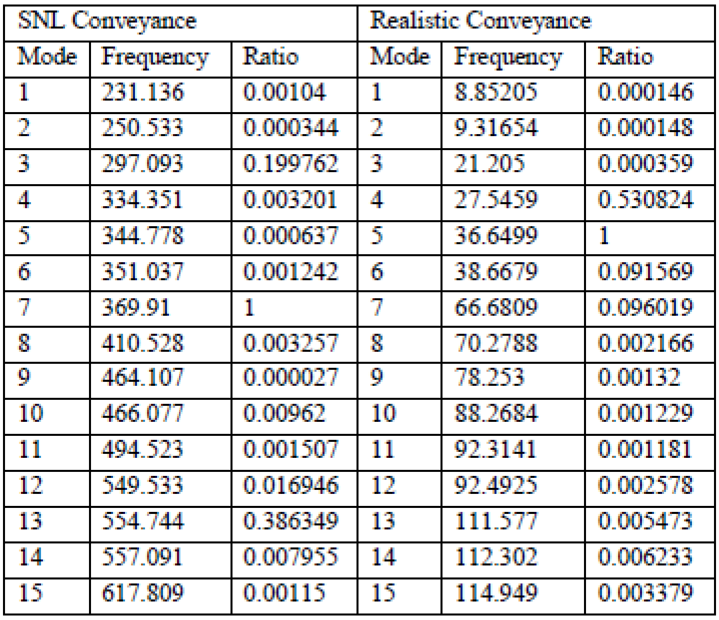


Figure 3: Realistic Conveyance

For comparison, each model had nearly equivalent total masses. The SNL conveyance had a total mass of approximately 48,000 lbs, and the realistic conveyance had a total mass of approximately 52,000 lbs.

In each case, the models were subjected to a modal analysis and random vibration analysis in ANSYS Workbench 15. A modal analysis involves the study of a structures dynamic performance, the goal of this type of analysis is to determine the natural frequencies and mode shapes of an object. The first 15 modes in the vertical direction are shown in Table 1. The modal results show that no significant modes exist for the SNL conveyance below 231 Hz and that the largest mode occurs at 369.9 Hz. Contrasting this, the realistic conveyance has a large mode at 36.6 Hz with a second important mode at 27.5 Hz.

Table 1: Modal Results



SNL Conveyance			Realistic Conveyance		
Mode	Frequency	Ratio	Mode	Frequency	Ratio
1	231.136	0.00104	1	8.85205	0.000146
2	250.533	0.000344	2	9.31654	0.000148
3	297.093	0.199762	3	21.205	0.000359
4	334.351	0.003201	4	27.5459	0.530824
5	344.778	0.000637	5	36.6499	1
6	351.037	0.001242	6	38.6679	0.091569
7	369.91	1	7	66.6809	0.096019
8	410.528	0.003257	8	70.2788	0.002166
9	464.107	0.000027	9	78.253	0.00132
10	466.077	0.00962	10	88.2684	0.001229
11	494.523	0.001507	11	92.3141	0.001181
12	549.533	0.016946	12	92.4925	0.002578
13	554.744	0.386349	13	111.577	0.005473
14	557.091	0.007955	14	112.302	0.006233
15	617.809	0.00115	15	114.949	0.003379

The random vibration analysis allows the user to compare the response Power Spectral Density (PSD) at any location in the structure for a given base input PSD. The base input PSD is shown in Figure 4 and was used in previous shaker table work performed by SNL [8]. The base input PSD was applied in the vertical direction

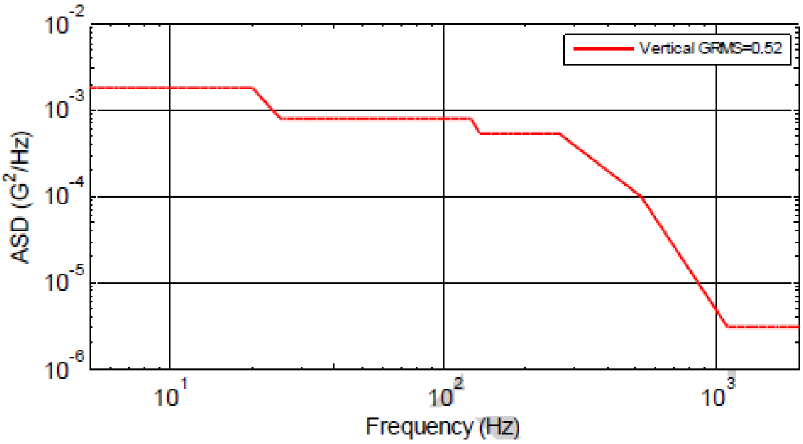


Figure 4: Input PSD

For the SNL conveyance and realistic conveyance, the response PSD was measured at the center of the basket at the interface between the blended mass fuel surrogate and the bottom surface of the basket. The measured response PSDs and input PSD are shown in Figure 5. This analysis shows that the realistic conveyance shows an amplification of input loads from 5-68 Hz, and a large attenuation above 68 Hz. The SNL conveyance tracks the input PSD from 5-100 Hz, amplifies the input from 100-350 HZ, and attenuates the input loads above 350 Hz.

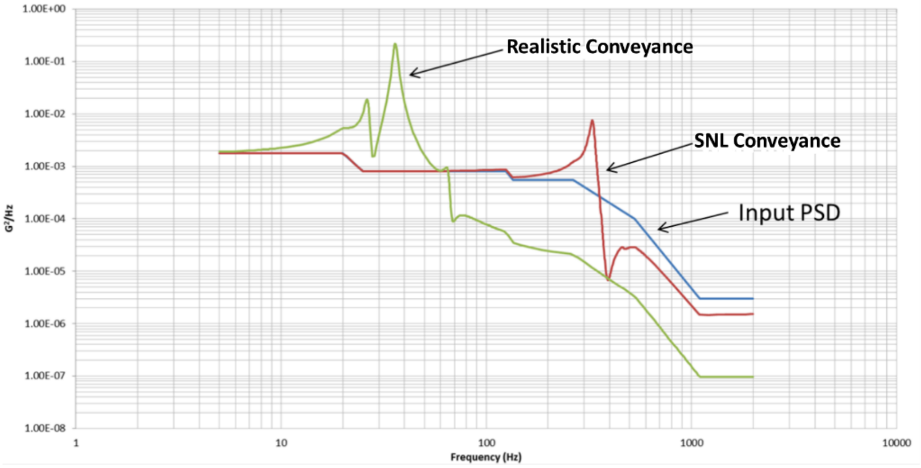


Figure 5: Response PSDs

The results from the modal analysis and random vibration analysis demonstrate that the realistic conveyance behaves in a distinctly different manner from the SNL conveyance. This indicates that the structural characteristics of the conveyance may play an important role and affect the magnitude of the loads transmitted to the fuel.

HIGHWAY CONVEYANCE COMPARISON

The previous section has demonstrated that the dynamic characteristics of the conveyance structure can affect the magnitude of loads experienced by UNF during transport and that each conveyance is likely to have different transmissibility characteristics. OTR testing can be used to determine the loads transmitted to the UNF under various transport circumstances.

However, it would be impractical to perform OTR testing for every conveyance design, under all known road or rail transport condition. To address this issue, PNNL staff have developed a methodology for scaling existing OTR data with the modeled dynamic characteristics of a hypothetical conveyance. To demonstrate this methodology, the scaling of OTR test data for the SNL test conveyance with the modeled dynamic characteristics of the realistic conveyance is presented in this section.

Figure 6 shows a portion of the measured acceleration time history from OTR testing that was performed in FY14 [4, 5], which will be scaled by the modeled structural transmissibility of the untested realistic conveyance.

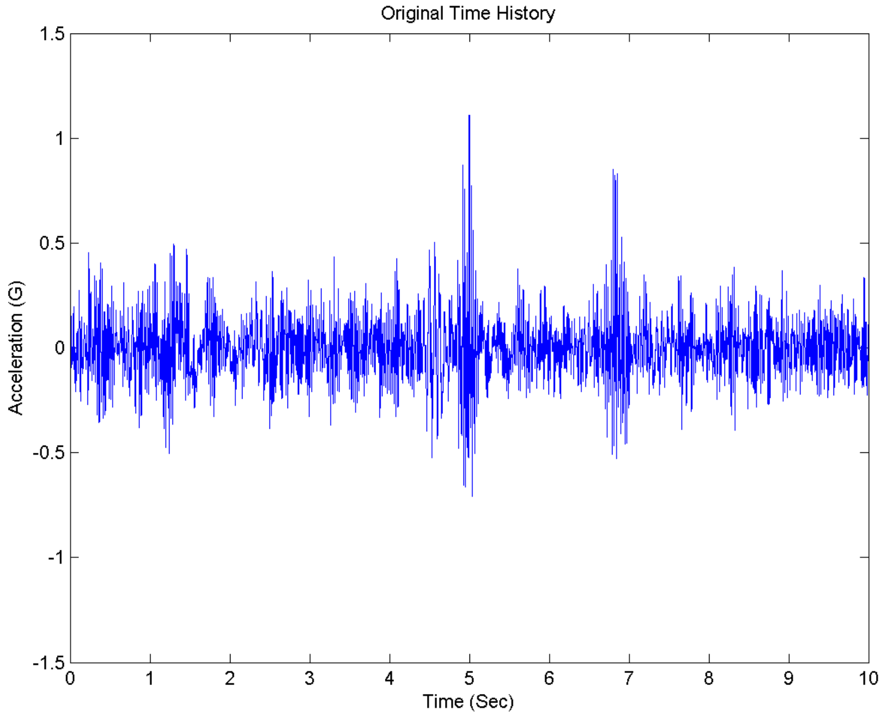


Figure 6: OTR Acceleration Data

For both the SNL conveyance and realistic conveyance, a harmonic analysis was performed in ANSYS Workbench 15. In each case, a 9.806 m/s^2 base excitation was applied from 0-500 Hz, and the system damping was set to 0.03. This frequency range was chosen because the OTR data shown in Figure 6 was filtered with a low pass filter with a 500 Hz cutoff frequency. The harmonic analysis was used to generate the amplification ratio of the realistic conveyance to the SNL conveyance. The results from the harmonic analysis are shown in Figure 7, and the amplification ratio is shown in Figure 8.

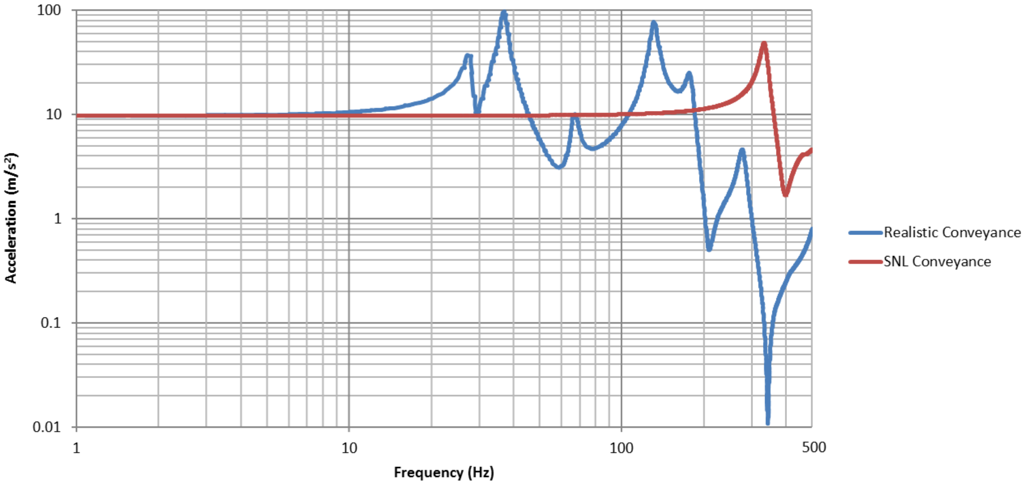


Figure 7: Harmonic Analysis of the SNL & Realistic Conveyance

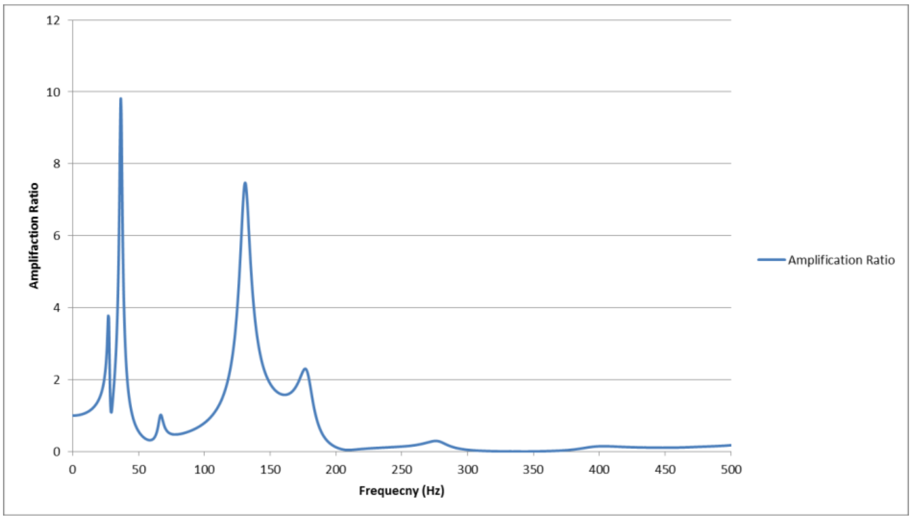


Figure 8: Amplification Ratio

A Fast Fourier Transform (FFT) was then performed on the original time history shown in Figure 6. In the frequency domain, between the 0 and 500 Hz the OTR test data was scaled with the amplification ratio. An overlay, in the frequency domain, of the original OTR data and the scaled OTR data is shown in Figure 9.

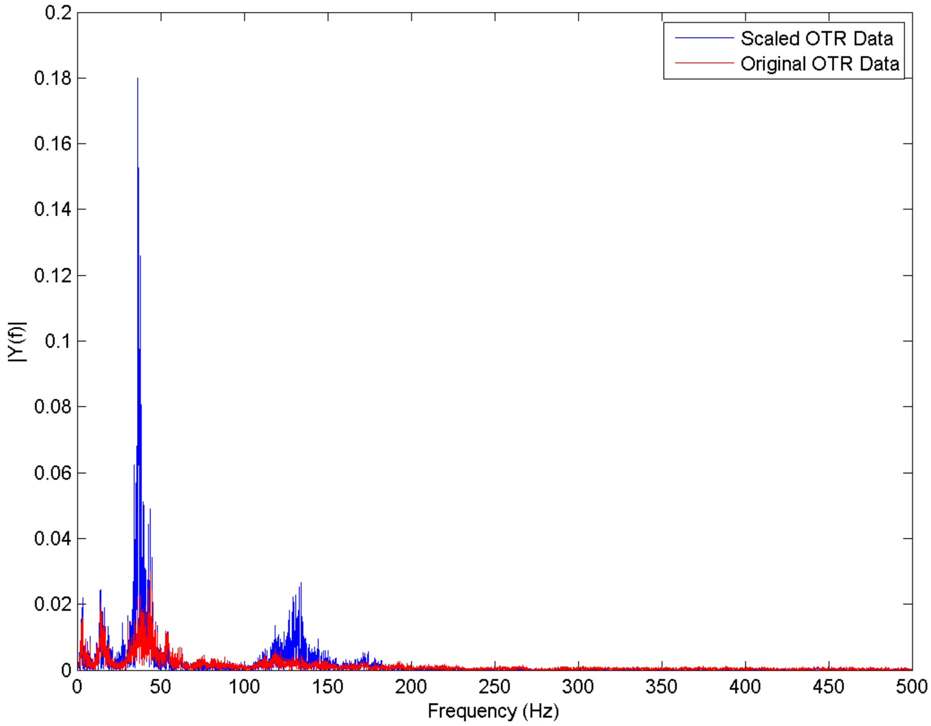


Figure 9: Original and Scaled OTR Data

The inverse transform was then performed on the scaled OTR data, yielding a new time history that incorporates the dynamic characteristics of the realistic conveyance. An overlay of the new scaled acceleration time history and the original acceleration time history is shown in Figure 10. Figure 10 clearly shows that the magnitude of the loads in the acceleration time history has been amplified by the modeled structural transmissibility of the realistic conveyance.

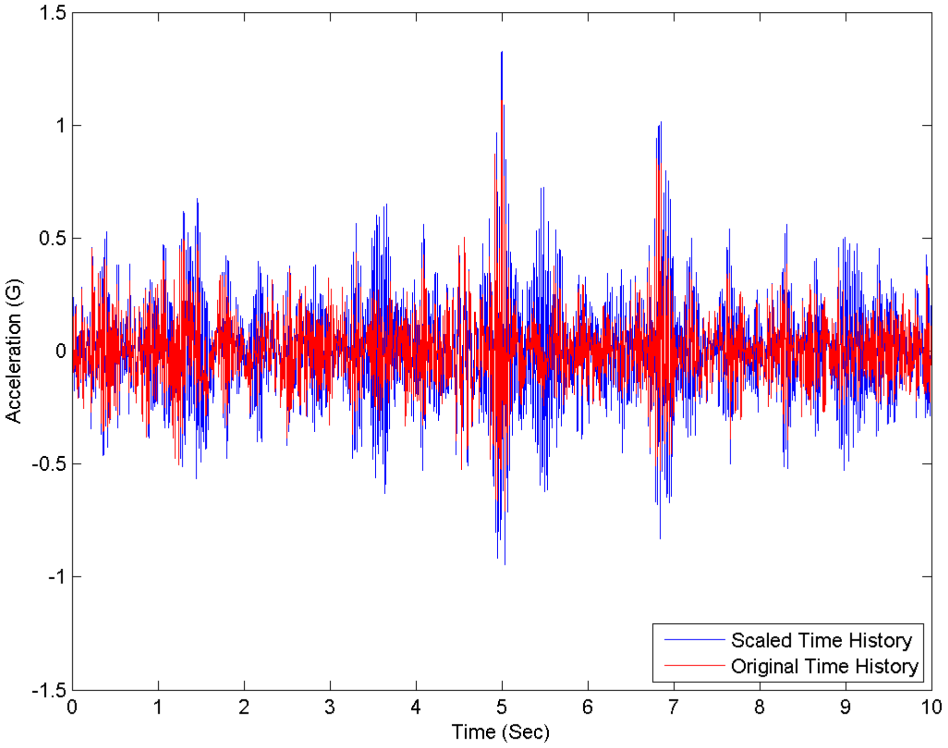


Figure 10: Scaled and Original Acceleration Time History

The scaled acceleration and original acceleration time history from Figure 10 was used as base excitation in a finite element model of the basket and fuel assembly that was developed in 2013-2014 [7].

FUEL ROD FINITE ELEMENET MODELING

PNNL uses a detailed full fuel assembly finite element model in a number of dynamic loading applications, such as transportation package free drop impact evaluation [10, 11], shock loading and short duration vibration testing. The full fuel assembly model is not well suited to modeling behavior beyond 2 seconds of solution time because of the long computation times necessary to run it. This study considers a 10 second basket loading window, which makes it a challenging problem for the full detailed fuel assembly model. It would take on the order of 100 hours of calculation time to solve the model for 10 seconds of solution time. This study uses a limited finite element model of one fuel rod to determine if using the full fuel assembly is necessary or not. In this case, the loads are ultimately determined to be so small that using the full fuel assembly model is not necessary to determine the loads on the UNF.

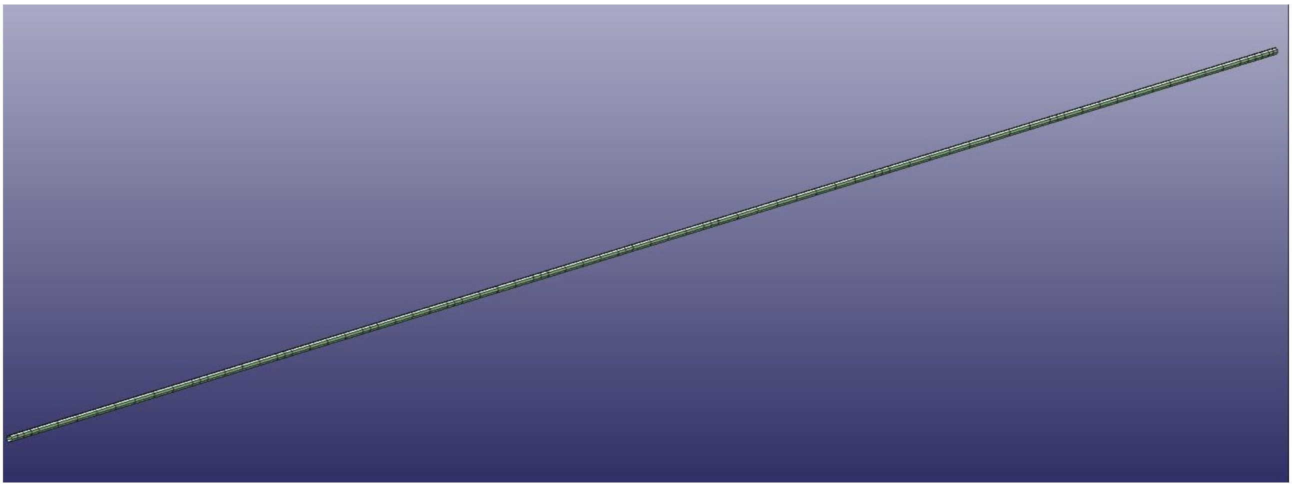


Figure 11: Isometric View Showing Mesh

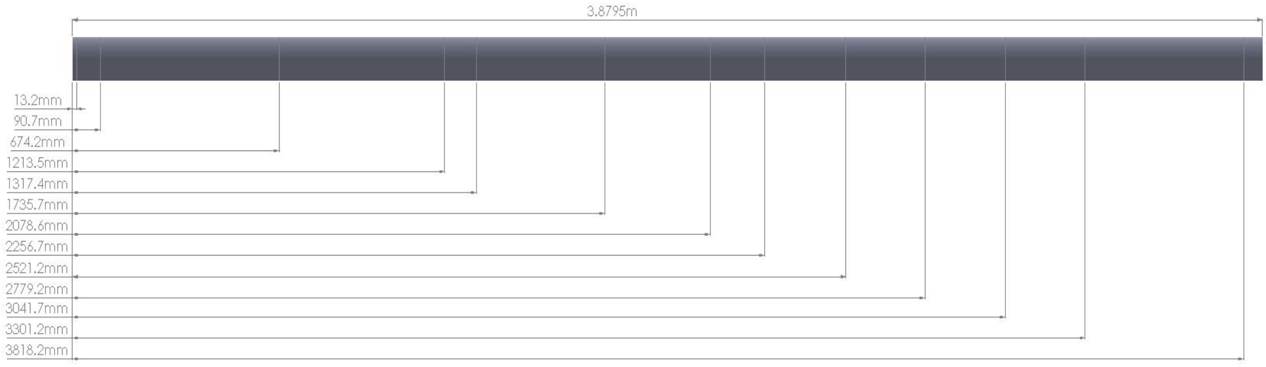


Figure 12: Rod Length and Loading Locations

The single fuel rod finite element model is sketched in Figures 11 & 12. The full length of one fuel rod is represented with beam elements. Prescribed motion is applied at the nodes that are indicated in the sketch. A key assumption in this analysis is that the basket motion is directly applied to the fuel rod at the grid locations, which is a simplification that neglects the transmission of loads through the complex fuel assembly structure. This model also assumes the loaded fuel rod nodes maintain a horizontal orientation.

All of the prescribed motion histories used in this study were derived from the SNL truck test. The raw acceleration load was filtered with a bandpass filter, with 1 Hz and 500 Hz cutoff frequencies to determine the acceleration history of interest. The peak acceleration was identified, and a ten second window was taken from the filtered data. The applied motion causes transient inertia loads to develop in the fuel rod, causing the fuel rod to bow and vibrate in the unsupported spans between grid spacers. Gravity is active in the model, and is applied and initialized over the first 0.1 seconds of solution time, prior to starting the applied motion histories.

The baseline model has a beam flexural rigidity (EI) that represents empty zirconium alloy cladding, which approximates the as-tested cladding case that has lead rope within the cladding to represent the mass of fuel. This study also models the UNF with a beam EI that represents real used nuclear fuel with a fraction of the fuel bonded to the cladding and contributing to the total EI. The cladding EI is 14.29 N-m^2 and the realistic used fuel is considered to have an EI of 31.38 N-m^2, which is a rough approximation of UNF with a burnup of 45 GWd/MTU.

The maximum axial strain calculated in the baseline model is 0.000597. This is the maximum integration point value through time. The LS-DYNA beam model uses the default Hughes-Liu element formulation with 3x3 Lobotto quadrature. The maximum integration point value is expected to be a close indicator of the local maximum cladding strain. This is generally comparable to the maximum strain gage data of approximately 0.000150 that was recorded during testing [3]. However, some differences are expected because the strain gage data is at fixed points on certain fuel rods and the current model only represents one fuel rod that is decoupled from interaction with spacer grids and neighboring fuel rods. Comparing 0.000150 to 0.000597, the single rod model provides a conservative estimate of the actual recorded response to truck transportation loads. The difference between 0.000150 and 0.000597 is an indicator of the relative significance of the fuel assembly details that were not modeled in this simplified analysis.

Another result that is reported is the maximum nodal deflection that occurs relative to the rigid body motion of the fuel rod grid locations. The nodes at the spacer grid locations all experience the same rigid body motion, but the nodes associated with the unsupported fuel rod span lengths are free to bow under gravity and the imposed dynamic loading. The maximum relative deflection is an indicator of the amount of mid-span bowing that occurs (i.e. the longest span is expected to have maximum deflection). The peak deflection in the baseline case is

1.66 mm. This is small relative to the distance between fuel rods, which is generally reported to be 12.6 mm [12]. This indicates that rod to rod interaction would not occur.

The highway amplified load was applied to the as-tested cladding model and the 45 GWd/MTU burnup UNF model. The peak strains were 0.000607 and 0.000137, respectively. The results show that adjusting the system dynamics to more closely represent an actual UNF conveyance results in a slight increase in the expected strains. Also, when the EI for high burnup UNF is used in the model, the peak strain is significantly reduced because the larger EI results in less rod deflection which in turn results in lower axial strain.

Because the highway amplified load did not result in significantly higher strains or mid-span deflections than the baseline case, the amplified load was scaled up by a factor of 10 to demonstrate an unrealistically severe loading case. In this case, the resultant strains are increased to 0.004172 for the cladding case and 0.001616 for the UNF case. The cladding case results are less than half the strain necessary to cause UNF to yield [4]. For the cladding the peak mid-span deflection indicates that rod to rod interaction may occur if two adjacent rods deflected in opposing directions.

Table 2: Flexural Rigidity(EI) and Elastic Moduli

	EI N-m^2	E in model GPA
Cladding as tested	14.29	89.3
UNF 45 GWd/MTU	31.38	196.1

Table 3: Axial Strains and Peak Deflections

	EI	Load	Peak Axial Strain	Peak Deflection (mm)
Baseline	cladding	Baseline	0.000597	1.66
Amplified	cladding	Amplifiedx1	0.000607	1.75
Amplified	UNF	Amplifiedx1	0.000137	0.38
Major Amp.	cladding	Amplifiedx10	0.004172	8.60
Major Amp.	UNF	Amplifiedx10	0.001616	3.26

FUTURE WORK

In FY 17, PNNL will continue using some of the methods described to couple existing models of UNF during transport to specific rail car models in the NUCARS© modeling suite [9]. NUCARS© is a general multi-body rail vehicle dynamics simulation package which allows the user to model different rail car configurations, track geometries, conveyance transportation speeds, and other factors that would affect the ride quality of a UNF conveyance [13]. This coupled modeling methodology will allow the user to test a hypothetical UNF conveyance under various rail conditions. The ENSA/DOE transportation test described in Ross et al. [14] will provide data to validate the model assumptions on transmissibility.

CONCLUSIONS

Described herein are methods for modeling how UNF performs during transportation. A frequency scaling methodology was presented to better understand how the structural transmissibility of the conveyance components affects the loads. This method allows the user to better understand the accelerations seen by the conveyance due to changes in transmissibility predicted by modeling. The results from the frequency scaling were then used in a single rod finite element model. The results from this finite element model show that the predicted strains and mid-span deflections are very low. In addition, plans for developing a coupled model of a UNF rail conveyance were presented.

These models and future OTR testing of a rail conveyance [9, 15] are being pursued by the UFDC program, and will aid in developing a strong technical basis for the safe transportation of UNF.

REFERENCES

1) Adkins HE et al. 2013. “Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport – Method and Approach.” FCRD-TIO-2011-00050. U.S. Department of Energy, Washington D.C.

2) Ross SB, NA Klymyshyn, PJ Jensen, RE Best, SJ Maheras, PE McConnell, and J Orchard, “Rail Shock and Vibration Pre-Test Modeling of a Used Nuclear Fuel Assembly”, *American Nuclear Society International High Level Waste Management Conference*, Charleston, South Carolina, April, 2015.

3) Ross SB, R Best, PJ Jensen, NA Klymyshyn, W Shust, D Garrido, R Walker, S Gurule, R Pena, 2016, “ENSA/DOE Transport Shock and Vibration Test Plan”, PNNL-25720, Pacific Northwest National Laboratory, Richland, WA.

4) PE McConnell, Wauneka R, Saltzstein S, Sorenson K, 2014,“Normal Conditions of Transport Truck Test of a Surrogate Fuel Assembly”, Sandia National Laboratory, Albuquerque, NM

5) Klymyshyn NA, PJ Jensen, SE Sanborn, and BD Hanson, 2014. “Fuel Assembly Shake and Truck Test Simulation” PNNL-23688, Pacific Northwest National Laboratory, Richland, WA.

6) Piersol AG, and Paez TL, “Harris’ Shock and Vibration Handbook – 6th Edition”, McGraw Hill, 2010

7) Klymyshyn NA, PJ Jensen, and NP Barret, 2015. “Shaker Table Modeling Support Task 2015”, PNNL-24735, Pacific Northwest National Laboratory, Richland, WA.

8) PE McConnell, Wauneka R, Koenig G, Ammerman D, Bignell J, Saltzstein S, Sorenson K, 2013, “Fuel Assembly Shaker Test for Determining Loads on a PWR Assembly under Simulated Normal Conditions of truck Transport”, Sandia National Laboratory, Albuquerque, NM

9) Ross SB, W Shust, PJ Jensen, RE Best, NA Klymyshyn, and SJ Maheras, 2015, “FY15 Used Fuel Rail Shock and Vibration Testing Planning Summary”, PNNL-24772, Pacific Northwest National Laboratory, Richland, WA.

10) Klymyshyn NA, Jensen PJ, and Barrett NP, “Modeling Used Fuel Response to Normal Codition of Transportation Package Drops to Assess Geometric Sensitivities”, *American Nuclear Society Top Fuel 2016*, Boise, ID, 2016

11) Klymyshyn NA, Jensen PJ, and Barrett NP, “Used Fuel Response 30 cm Package Drops”, *PATRAM 2016*, Kobe, Japan, 2016

12) Todreas NE and Kazimi MS, “Nuclear Systems 1: Thermal Hydraulics Fundamentals”, Taylor & Francis, 1990

13) Transportation Technology Center, Inc., 2015, “NUCARS© User Manual”, Version 2015.2, Transportation Technology Center, Inc., Pueblo, CO.

14) Ross SB, R Best, PJ Jensen, NA Klymyshyn, P McConnell, S Saltzstein, K Sorenson, B Hanson, W Shust, D Garrido, R Walker, S Gurule, and R Pena, “ENSA/DOE Transport Shock and Vibration Test Plan”, *PATRAM 2016,* Kobe, Japan, 2016

15) Ross SB, RE Best, NA Klymyshyn, PJ Jensen, and SJ Maheras, 2014, “Used Fuel Rail Shock and Vibration Testing Option Analysis”, PNNL-23709, Pacific Northwest National Laboratory, Richland, WA.