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Modeling Used Fuel Response to 30 cm Package Drops

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Abstract
The US Department of Energy Used Fuel Disposition program is performing research to determine the loading conditions that used nuclear fuel (UNF) experiences during normal conditions of transportation (NCT). Materials research is being done to study the mechanical behavior of used fuel, with a particular interest in the high burnup state, when the fuel cladding is expected to have degraded material properties. This study uses numerical models to estimate the mechanical response and the peak strain that occurs in used nuclear fuel cladding during a postulated 30 cm package free drop event to help inform test programs of the anticipated range of response of used fuel. The 30 cm drop scenario represents a normal condition of transportation free drop test specified by 10 CFR 71.71 for the packages modeled in this study. The LS-DYNA explicit finite element analysis code is used to model used nuclear fuel packages impacting an unyielding surface. A detailed 17x17 pressurized water reactor (PWR) fuel assembly is modeled within a generic rail package and a generic truck package. The primary fuel assembly model is represented in enough detail to study the fuel assembly dynamic response and extract local cladding strains. This paper studies the dynamic response of used fuel, estimates the peak cladding strain, and evaluates sensitivities of some of the parameters that influence the cladding strain response, such as temperature, burnup, and variations in fuel rod flexural rigidity due to bonding between the fuel and cladding.

Introduction
Finite element modeling and analysis is being used to estimate the loads that are experienced by used nuclear fuel (UNF) under normal conditions of transport (NCT) to support the Used Fuel Disposition program sponsored by the U.S. Department of Energy. An estimate of fuel loading is critical to determine the materials testing needs of the program by identifying the range of loading that is relevant and to determine when sufficient understanding of material properties have been obtained. Structural dynamic modeling is being used along with experimental testing to develop a technical basis for demonstrating the safe transportation of UNF from the utility site to a final repository. This paper documents a set of analyses that estimates the range of loads UNF cladding may experience during package free drop test conditions defined according to 10 CFR 71.71 (c) (7) for normal conditions of transport. It is assumed that the NCT package drop scenarios represent the upper limit of mechanical shock loading that can occur to a package and the fuel it carries in realistic NCT service, with any higher drop heights representing accident conditions.

This study uses the commercial software LS-DYNA to perform explicit finite element analyses (FEA) on generic rail and truck UNF transportation package systems that contain a single highly detailed 17x17 pressurized water reactor (PWR) fuel assembly model and equivalent fuel assembly masses occupying the other fuel compartments where necessary. The free drop height for both rail and truck systems is 30 cm, and the impact orientation in all cases is assumed to be horizontal. This study evaluates the effect of changes in the mechanical properties of UNF on the loads that develop during impact.

The package models used in this study do not precisely match any existing commercial package system design and the response behavior of the system is not intended to match any particular system. The impact limiter behavior in the rail and truck package models is tuned to provide an approximate 12 *g* peak deceleration in the horizontal impact orientation. This deceleration value is expected to be in the range of realistic package performance but does not necessarily bound it. The intent of modeling both packages with similar deceleration loads is to provide a comparable loading environment for the UNF.

The results provide an estimate of UNF loads under horizontal NCT free drop conditions. This analytical work is intended to compliment experimental work on quantifying dynamic loads [1,2] and other analytical work [3]. Any physical phenomena that are not mentioned in this study (such as internal pressure in the fuel cladding) need to be considered when evaluating the response of real UNF to the dynamic loads that are calculated in this study.

Detailed PWR Finite Element Model

The PWR fuel assembly model used in this study consists of beam elements to represent the UNF and guide tubes, shell elements to represent the grid spacers, and nonlinear spring elements to represent the leaf springs and contact points where the fuel rods interact with the grid spacers. The top and bottom nozzles of the fuel assembly are represented by solid (hexahedral) elements. The model is described in more detail in [4]. Figure 1 shows the fuel assembly model with certain elements removed to show the guide tubes.

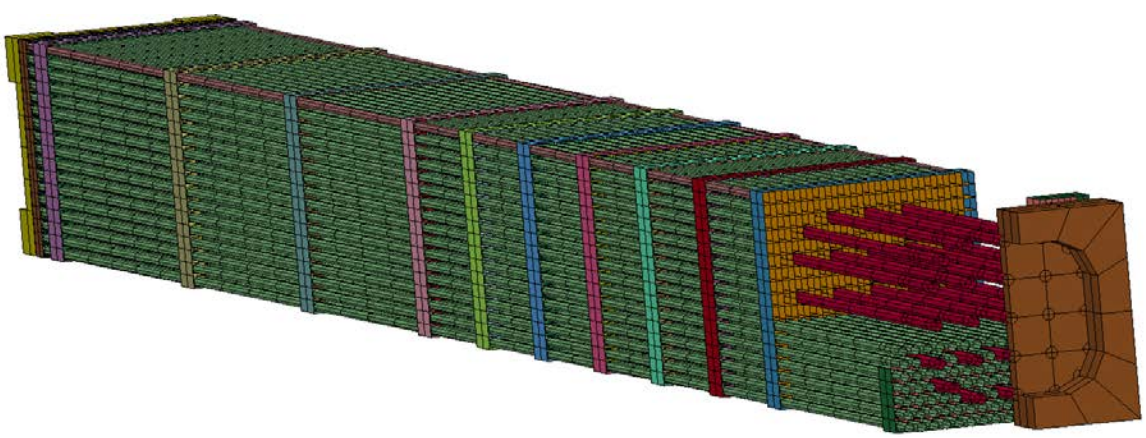


Figure 1: Detailed PWR 17x17 Fuel Assembly (Cutaway View)

The UNF rod is modeled as a composite material to represent the realistic interaction between the fuel pellet and the cladding. This study considers a variation in beam flexural rigidity (EI) to account for a range of temperatures, burnups, fuel-to-cladding bonding, and fuel pellet-to-pellet bonding. The range of temperature considered is 22 °C to 300 °C. The range of burnup is 10 GWd/MTU to 90 GWd/MTU. The range of fuel pellet and cladding bonding is 0% (no stiffness contribution of the fuel at all) to 100% (fuel pellets are assumed to be fully bonded to each other and to the cladding). The base material properties are determined from [5] for Zircaloy-4 cladding and fuel with a 95% density. The cladding inner and outer diameters are modeled as 8.36 mm and 9.50 mm, respectively. The diameter of the fuel is assumed to be 8.36 mm, to match the cladding inner diameter with no gap. The fuel rods are modeled as homogenous rods along their entire length, which does not account for realistic features such as end plugs and plenum space. The minimum cladding yield strain for the range of conditions considered in this study is 0.009395, and all of the calculated strains remain well within this value.

Materials research on UNF is ongoing. CIRFT (Cyclic Integrated Reversible-Bending Fatigue Tester) bend testing of UNF segments [6] measured the equivalent EI of a number of fuel types, and found that fuel stiffness contribution varies, but is typically closer to 50% than it is to 0% or 100%. This study varies EI to determine how significantly the change in EI can affect the response of the fuel. The four values for UNF EI used in this modeling study are 11.63, 21.50, 31.38, and 54.94 N-m^2. Table 1, Table 2, and Table 3 provide EI estimates for the 0% fuel stiffness contribution, 50% fuel stiffness contribution and 100% fuel stiffness contribution, respectively. Three of the EI values chosen for use in this study were chosen to be a bounding minimum, bounding maximum, and average EI for the range of interest, and they generally represent the 0%, 50%, and 100% fuel stiffness contribution assumptions. The exception is 21.50 N-m^2, which was chosen based on the initial results of this study to obtain another point of data roughly between the 0% and 50% fuel stiffness contributions to explore the trends in the calculated results.

Table 1: Estimated UNF EI (N-m^2), Zero Fuel Contribution

Burnup (GWd/MTU)	**22 °C**	**100 °C**	**200 °C**	**300 °C**
10	14.29	13.55	12.59	11.63
30	14.66	13.89	12.90	11.92
50	14.66	13.89	12.91	11.94
70	14.66	13.89	12.91	11.94
90	14.66	13.89	12.91	11.94

Table 2: Estimated UNF EI (N-m^2), 50% Fuel Contribution

Burnup (GWd/MTU)	**22 °C**	**100 °C**	**200 °C**	**300 °C**
10	34.43	33.52	32.33	31.14
30	33.97	33.04	31.83	30.63
50	33.15	32.22	31.04	29.85
70	32.33	31.41	30.23	29.06
90	31.51	30.59	29.43	28.26

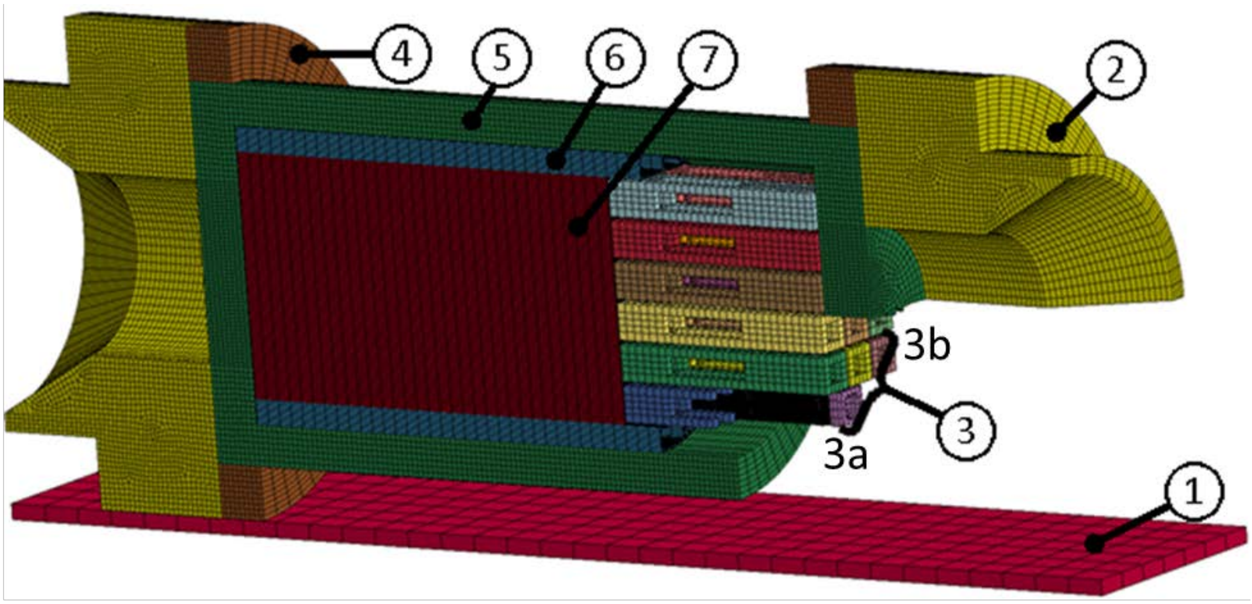
Table 3: Estimated UNF EI (N-m^2), 100% Fuel Contribution

Burnup (GWd/MTU)	**22 °C**	**100 °C**	**200 °C**	**300 °C**
10	54.57	53.48	52.06	50.65
30	53.29	52.18	50.76	49.35
50	51.65	50.56	49.16	47.77
70	50.00	48.93	47.55	46.18
90	48.36	47.30	45.94	44.58

LS-DYNA's default Hughes-Liu beam element formulation is used, which locates the integration points of the beam element in the mid-thickness of the cladding. Integration point strains are a convenient way to evaluate the UNF response to dynamic loads. With a fixed geometric cross section, the area moment of inertia (I) of the beam is fixed. The elastic modulus (E) of the beam is selected to match the target EI. This representation of the fuel is intended to provide realistic bending behavior for a loading scenario that is dominated by beam bending. Other beam formulations, quadrature rules, and other beam modeling options are available in LS-DYNA. The default settings were used in this study because they have been shown to provide reasonable agreement with experimental shaker table testing of a fuel assembly [2]. The minimum cladding yield strain for the range considered in this study is 0.009395 based on [5], and all of the calculated strains remain well within this value, so the use of elastic material properties to represent the UNF is justified.

Generic Rail Package Model

The rail package model used in this study is based on the Equipos Nucleares, S.A. (ENSA) ENUN 32P package design and has the capacity to carry 32 PWR fuel assemblies. The finite element model, shown in Figure 2 with sections cut away to show the various components, is not a precise representation of the real design. The package model is sufficient to transmit realistic impact loads to the fuel basket and fuel assemblies within, but it does not have the level of detail necessary to, for example, perform a stress evaluation on the package. The outer package body (5) has been approximated as a thick-walled right circular cylinder. The impact limiter materials, (2) and (4), have a crush strength that was selected to provide a desired peak deceleration (12 *g*). The basket material (7) is homogenized to provide a mass and stiffness in the finite element model that is representative of a more complex basket structure. The basket rails (6) share common nodes with the basket. This creates a bonded connection between the two components. The basket and rails were modeled with a limited number of finite elements with the intent of providing a reasonable but computationally efficient approximation of the basket geometry and stiffness. The model uses a half-symmetry assumption, and as-modeled has a mass of about 70,000 kg, representing a fully loaded package of about 140,000 kg. The package strikes the rigid ground (1) with an initial velocity of 2.45 m/s, to represent a drop height of 30 cm. One detailed fuel assembly (3a) is located in the package as pictured. The other fuel compartments in the basket are filled with dummy assemblies (3b) that approximate the mass and volume of a real fuel assembly. It was determined in reference [4] that the chosen location provided the most limiting response for the detailed fuel assembly. All of the package and dummy assembly components are represented with hexahedral elements that use LS-DYNA's selectively reduced integration formulation.



1) Rigid Ground
2) Impact Limiter Material 1
3) Fuel Assemblies
   a) Detailed PWR Assembly
   b) Dummy Assemblies
4) Impact Limiter Material 2
5) Outer Package Body
6) Basket Rail
7) Basket

Figure 2: Rail Package Finite Element Model

Generic Truck Package Model

The generic truck package model is a hypothetical design with the capacity to carry 1 PWR fuel assembly. The total mass of a loaded system is 21,500 kg. The package model is intended to represent a legal weight truck cask without precisely matching an existing design. The model is described in more detail in [3], but key parameters are listed in

Table 4. The impact limiter material is selected to provide a 12 *g* peak deceleration under a 30 cm free drop to match the generic rail package. The generic truck package model is shown in Figure 3, with sections of the model cut away to show the fuel assembly inside. The same materials and finite element formulations were used in both rail and truck package models.

Table 4: Generic Truck Package Characteristics

Part	OD (m)	ID (m)	Length (m)	Mass (kg)
Impact Limiters	1.524	0.731	0.762	4,540
Cask	0.731	0.340	5.075	15,200
Basket	.340	-	4.521	860
Total Loaded	-	-	5.837	21,500

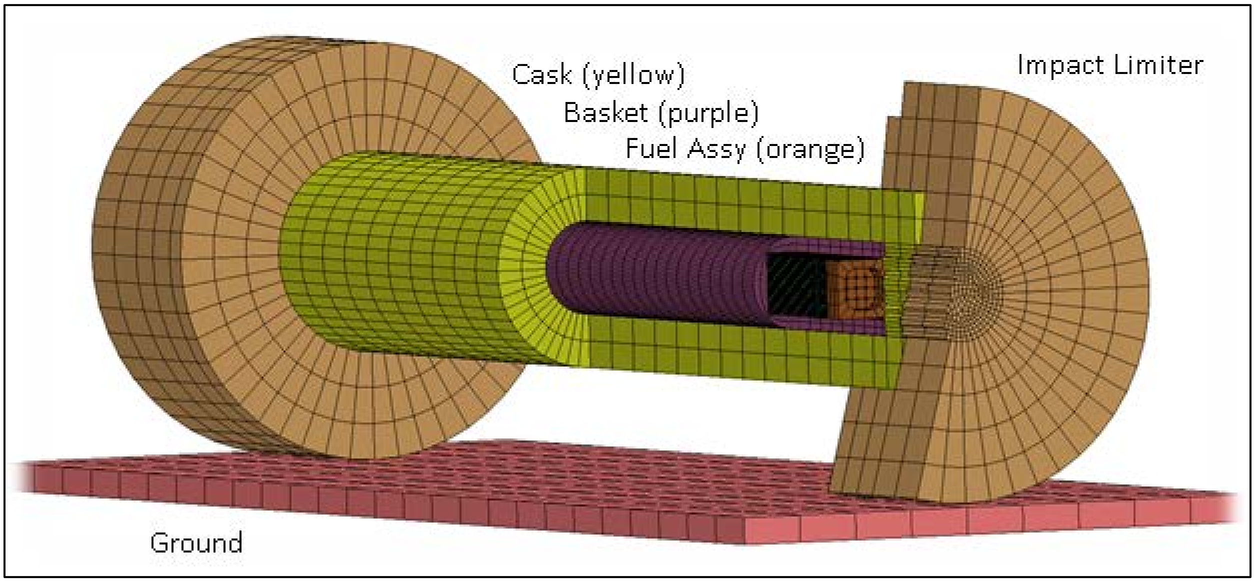


Figure 3: Truck Package Finite Element Model

Loading Conditions

The fuel baskets in the rail and truck package models form fuel compartments with a square cross section. Each fuel compartment is slightly larger than the fuel assembly, which allows the potential for gaps to form during a realistic drop event. The initial configuration of the model locates the fuel assemblies within 1 mm of the basket wall closest to the impact surface, so gap effects and secondary impact phenomena are minimized. The effect of initial gaps using the same finite element models was studied in [7].

Calculated Results

The key finite element model results are presented in Table 5. These values are considered to be nominal values because they are reported directly from the composite fuel rods and do not account for all of the realistic phenomena that affect the cladding stress state. For example, fuel rod internal pressure is not considered, but is expected to be present in realistic fuel rods and contribute to the cladding stress state. As a second example, stress concentrations are expected to occur in the cladding at the pellet-to-pellet interface, but are not accounted for in the nominal strain values calculated here. Furthermore, this study uses raw explicit dynamics results data and does not attempt to condition the time history response with frequency filtering. The results might include high frequency transient components that have insufficient duration to cause any structural damage, so this implies the reported peak results are conservative. Cladding strains are reported to six digits for comparison against related work but, the limits of the model accuracy and precision are expected to be in the range of three to four digits after the decimal based on validation against experimental data [1]. In addition to the primary results of interest, the Peak Fuel Assembly Rigid Body Acceleration (RBA) is listed for each case. The RBA represents the peak instantaneous acceleration of the center of mass of the detailed fuel assembly. For comparison, the peak acceleration of the package as a whole was set to equal 12 *g* (118 m/s^2). The fuel assembly RBA values show two clear groupings of fuel assembly peak deceleration for the rail and truck cases, which demonstrates that the loading conditions are approximately the same for all four EI cases of each package type.

Table 5: Nominal Results

Package Type	**EI** ($N\text{-}m^2$)	**Cladding Peak Axial Strain**	**Peak Bending Moment** (N-m)	**Peak Shear Force** (N)	**Peak Fuel Assembly RBA** (m/s^2)
Rail	11.63	0.001024	3.62	275	213
Rail	21.50	0.000489	3.34	297	237
Rail	31.38	0.000434	4.29	301	229
Rail	54.94	0.000349	6.01	54	225
Truck	11.63	0.001325	4.90	595	318
Truck	21.50	0.001077	6.83	1069	329
Truck	31.38	0.000672	6.70	634	327
Truck	54.94	0.000393	6.80	517	331

Axial Strain Response

The cladding peak axial strain is the maximum tensile integration point strain recorded in the UNF beam element results database. The integration points are located in the mid-thickness of the cladding, so the integration point values represent a reasonable estimate of strain at the outer surface of the relatively thin cladding. Figure 4 plots the maximum (tensile) axial cladding strain that was recorded in each of the eight models of this study. The truck response tends to have higher peak strain than the rail response, which can be attributed to the difference in package geometry and design. The lower EI cases tend to have higher strains than the higher EI cases, which is reasonable because a lower stiffness beam is expected to deflect more than a higher stiffness beam under equal transverse loading. The total range of calculated strains for the 30 cm drop is 0.000349 to 0.001325, which indicates a certain level of sensitivity to the bending rigidity of the fuel rod. However, the minimum cladding yield strain for the range of conditions considered in this study is 0.009395, which is nearly an order of magnitude higher than the calculated range of response for the 30 cm drop. This suggests that while fuel rod EI can affect the response, the potential variation is not strong enough to threaten the fuel cladding integrity.

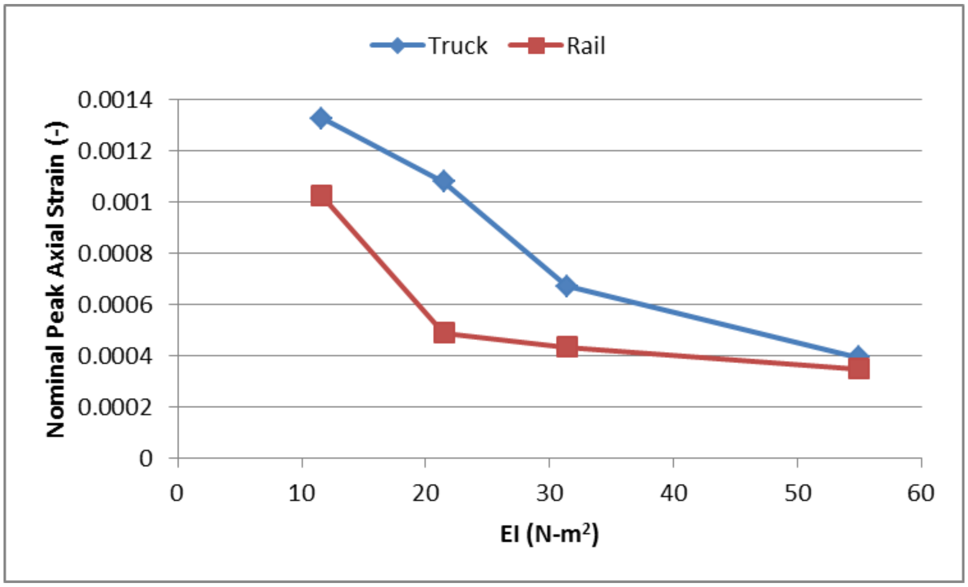


Figure 4: Nominal Peak Axial Strain vs. EI

Bending Moment Response

The peak bending moment is the maximum instantaneous bending moment that occurs in any of the discrete UNF beam elements throughout the model. The bending moment is useful to quantify the load that is acting on the fuel rod for comparison against experimentally-determined bending strength. Figure 5 plots the peak bending moment for each of the models of this study against the corresponding EI. The trend in the bending moment data is not as strong as the axial strain trend, but the lower EI cases tend to have lower peak bending moments than the higher EI cases. Increases in EI lead to a beam that has increased resistance to bending, but it also leads to an increase in natural frequency, which might also be significant to the dynamic response of the UNF. The range of peak bending moment in the fuel rods was calculated to be 3.34 N-m to 6.83 N-m, which is a narrower range than the axial strain results. It can be concluded that the bending moment that develops in the fuel rod has a minor sensitivity to EI.

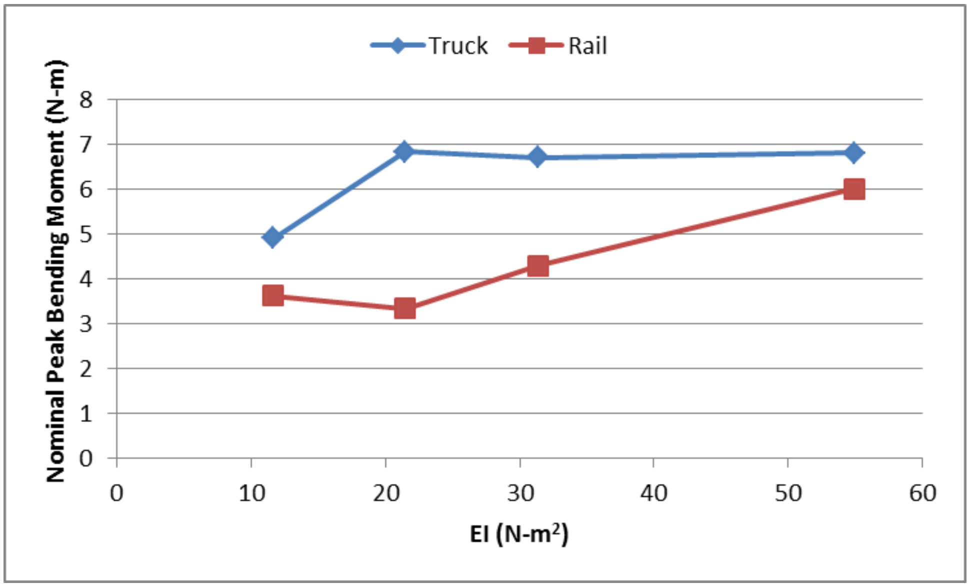


Figure 5: Peak Bending Moment vs. EI

The bending moment results data can be used to estimate the local cladding strain on the outer cladding surface under a state of pure bending. The integration point axial strains calculated by LS-DYNA also include an axial extension or contraction component related to the change in length of the beam element. The pure bending strain calculated from the peak bending moment provides a check on the calculated strains, and can potentially provide a more bounding cladding strain estimate. The peak fuel rod bending moment was calculated to be 6.83 N-m with an EI of 21.5 N-m^2, and using these values in Equations 1 and 2 the pure bending cladding strain is calculated to be 0.001509. This pure bending cladding strain is 40% higher than the 0.001077 integration point strain calculated by LS-DYNA. A small part of the difference (about 6%) can be explained by a difference in geometry, as the beam element integration points are located in the middle of the cladding wall thickness while Equation 2 calculates strain at the cladding outer diameter. The rest of the difference could be explained by dynamic effects or numerical noise, but this issue was not explored in detail because the strains are still well below the minimum cladding yield strain of 0.009395.

$$\varepsilon = \frac{Mc}{EI} \tag{1}$$

$$\varepsilon = \frac{(6.83N \cdot m)(.00475m)}{21.5N \cdot m^2} = 0.001509 \tag{2}$$

The pure bending cladding strain was calculated from the peak bending moment for all cases of the study, as presented in Table 6. Interestingly, the highest pure bending strain in the study was determined to be 0.002001 for the minimum EI truck case. The bending moment for that case was in the middle of the range, but low EI led to the highest strains. The pure bending strain is consistently between 40% and 51% higher than the integration point strain, so these strain values are used as the basis to establish the upper bound of cladding strain response to the 30 cm drop load cases of this study. Future work will explore the difference between integration point strain and pure bending strain calculated from the bending moment results.

Table 6: Pure Bending Strain Compared to Integration Point Strain

Package Type	**EI** ($N\text{-}m^2$)	**Bending Moment** (N-m)	**Cladding Integration Point Strain**	**Cladding Surface Pure Bending Strain**	**Difference**
Rail	11.63	3.62	0.001024	0.001479	44%
Rail	21.50	3.34	0.000489	0.000738	51%
Rail	31.38	4.29	0.000434	0.000649	50%
Rail	54.94	6.01	0.000349	0.000520	49%
Truck	11.63	4.90	0.001325	0.002001	51%
Truck	21.50	6.83	0.001077	0.001509	40%
Truck	31.38	6.70	0.000672	0.001014	51%
Truck	54.94	6.80	0.000393	0.000588	50%

Shear Force Response

The peak shear force is the maximum shear force resultant at any UNF integration point. The shear force range was calculated to be 54 N to 1069 N. Figure 6 plots the maximum shear force magnitude for each case in the study. The data does not illustrate a clear relationship between shear force and EI. The peak shear force of 1069 N appears to be the result of numerical noise that occurs during the rebound and free vibration phase of the impact response. The shear force at the location remains below 50 N until a strong high-frequency oscillation in the shear force begins about 40 milliseconds after impact. While the peak shear force is likely an artifact of the model, it can be considered an upper bound limit on the true shear force response. Applying the upper bound shear force limit of 1069 N to the cladding cross sectional area of 1.6E-5 m^2 yields an instantaneous shear stress on the cladding of 66.8 MPa. This estimate of the shear stress on the cladding ignores any support from the fuel or stress concentrations that might be present in the cladding at the interface between fuel pellets. Irradiated cladding is expected to have a shear strength that is much higher than 66.8 MPa (the minimum cladding yield strength is 683 MPa for the conditions of this study, based on [5]) so this result suggests a significant margin. However, material research for high burnup fuel cladding is still ongoing, and issues like hydride reorientation could potentially reduce the effective shear strength to a value that is lower than currently expected.

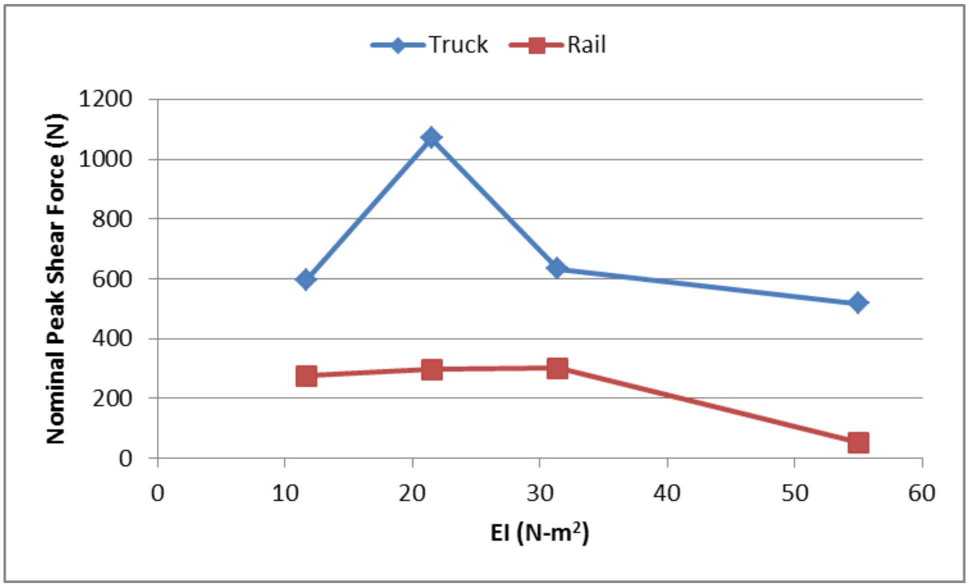


Figure 6: Peak Shear Force vs. EI

Conclusions

This study used explicit finite element models to estimate the range of response of UNF during a 30 cm drop event for generic rail and truck packages. A detailed finite element model of a PWR fuel assembly was used to calculate the UNF response. The fuel assembly model has been validated against test data from a full scale NCT shock and vibration testing program, which has approximately same the range of response that is calculated in this study.

The UNF was modeled to represent a range of temperatures, burnups, and fuel pellet contribution to the overall fuel rod flexural rigidity. The UNF EI was varied between 11.63 N-m^2 and 54.94 N-m^2 to cover the anticipated range of commercial 17x17 PWR fuel assembly configurations that are expected to be transported in the USA. The results of this study suggest that the UNF response to impact is somewhat sensitive to the choice of fuel rod EI in terms of peak cladding strain, put the calculated strains in all cases are well below the expected cladding yield limit. This study finds that the value used for EI has a larger effect on the cladding strain than it does on peak bending moment in the UNF. The relationship between EI and peak shear force is not clear, and there are signs that the shear force response is dominated by outliers and numerical noise in the model.

The peak cladding strains that were calculated at the finite element integration points ranged from 0.000349 to 0.001325. Strains were additionally derived from the calculated peak beam bending moments to estimate the cladding strain that would occur in a pure state of bending. The pure bending strains tended to be 40% to 51% higher than the integration point values, ranging from 0.000540 to 0.002001. The higher values of the pure bending strains are considered to be the upper limit of the cladding strain response for the horizontal 30 cm drop. This study only considers the nominal stress and strain state of the composite fuel rod surface; it does not include stress concentrations at the pellet-to-pellet interface, fuel rod internal pressure, or any other phenomena that might increase the stress or strain beyond what the model is attempting to capture.

There is a strong trend in the cladding strain response that the lower EI cases have higher strain. The same trend is present whether the strains are based on integration point data or derived from bending moments. This suggests that low burnup fuel or UNF that has degraded fuel and pellet bonding can be expected to experience higher nominal cladding strains during a 30 cm drop than other UNF. However, all of the strains calculated in this study are well below the minimum cladding yield strain of 0.009395 for these conditions, so the sensitivity to EI is potentially outside the range of interest.

The range of peak bending moment was calculated to be 3.34 N-m to 6.83 N-m. The higher EI values tended to produce higher bending moments, but when the moments were translated back to cladding strain the lower EI cases tended to have higher strains than the higher EI cases, which matches the trend observed in the integration point strain results. Better agreement between strains derived from the bending moments and integration point strains were expected, and future work will investigate the discrepancy.

The range of peak shear force in the fuel rods was calculated to be 54 N to 1069 N. The maximum value of 1069 N is thought to be an outlier that is associated with numerical noise in the finite element model, but it is considered to be an upper bound limit on the shear force. When this is applied to the fuel cladding cross sectional area, ignoring any contribution of the fuel, the shear stress is calculated to be 66.8 MPa. This shear stress is much lower than the anticipated shear strength of irradiated cladding, but it does not consider realistic effects like hydride reorientation, stress concentrations at the pellet-to-pellet interface, or other phenomena that might alter the effective shear strength of the cladding. There was no clear relationship between EI and peak shear force.

This study provides an estimate of UNF response to a 30 cm horizontal free drop onto an unyielding surface. Additional modeling studies have considered the effect of gaps between the fuel assemblies and the basket at impact and small changes in impact angle. Future work will focus on other aspects of NCT loading on UNF, including the transport shock and vibration environment of rail packages experiencing multi-modal transportation by rail, heavy haul truck, barge, and open ocean transport.

Acknowledgments

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References

[1] McConnell PE, R Wauneka, G Koenig, W Uncapher, C Grey, C Engelhardt, S Saltzstein, and K Sorenson, "Surrogate Fuel Assembly Multi-Axis Shaker Tests to Simulate Normal Conditions of Rail and Truck Transport". *FCRD-UFD-2015-000128*, Sandia National Laboratory, Albuquerque, New Mexico, (2015).

[2] Klymyshyn NA, PJ Jensen, SE Sanborn, and BD Hanson, "Fuel Assembly Shaker and Truck Test Simulation," *PNNL-23688*, Pacific Northwest National Laboratory, Richland, Washington, (2014).

[3] Adkins H, K Geelhood, B Koeppel, J Coleman, J Bignell, G Flores, J-A Wang, S Sanborn, R Spears, and N Klymyshyn. "Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport – Demonstration of Approach and Results on Used Fuel Performance Characterization," *FCRD-UFD-2013-000325*, (2013).

[4] Nicholas A Klymyshyn, Philip J Jensen, "Used Nuclear Fuel Rail Package Normal Conditions Of Transport (NCT) Drop Analysis," *FCRD-UFD-2016-000421*, PNNL, Richland WA, (2016).

[5] Geelhood KJ and CE Beyer. "Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport – Supporting Material Properties and Modeling Inputs," *FCRD-UFD-2013-000123*. (2013).

[6] Wang JA, H Wang, H Jiang, Y Yan, and BB Bevard. *"FY 2015 Status Report: CIRFT Testing of High-Burnup Used Nuclear Fuel Rods from Pressurized Water Reactor and Boiling Water Reactor Environments," M2-FCRD-UFD-2015-000101*, *ORNL/SPR-2015/313*, Oak Ridge National Laboratory, Oak Ridge, Tennessee, (2015).

[7] Klymyshyn NA, PJ Jensen, NP Barrett, "Modeling Used Fuel Response to Normal Conditions of Transportation Package Drops to Assess Geometric Sensitivities," to be presented at *TOPFUEL 2016.*