

Detailed PWR Fuel Rod and Grid Finite Element Analysis to Provide Equivalent Rod Stiffness and Damping and Equivalent Grid Shell Thickness to PWR Used Nuclear Fuel (UNF) Assembly – 14525

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ABSTRACT

U.S. Nuclear Regulatory Commission (NRC) rules require that used nuclear fuel (UNF) rods maintain their integrity during handling, transportation, and storage to ensure maintenance of the fuel retaining boundary, safety against criticality, and long term fuel retrievability for processing and disposal. Consequently, understanding the mechanical performance of UNF rods under cumulative loading stemming from handling, normal conditions of transport (NCT), and normal conditions of storage (NCS) is necessary as their performance under these conditions establishes part of their safety basis.

This paper focuses on work performed by Idaho National Laboratory (INL) as part of a larger collaborative effort between Sandia National Laboratory (SNL), Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and the Transportation Technology Center Inc. (TTCI) focused on assessing the performance of a typical UNF assembly subject to NCT loads generated by rail transport. The work described pertains specifically to the detailed fuel rod level modeling and analyses performed by INL.

The knowledge and characterization of material states for high burnup fuel, cladding, and the pellet-clad interface is based on limited experimental data and subject to additional complex behaviors such as chips, voids, primary ridging (from thermal expansion and clad creep-down and often termed “bambooing” from the cladding’s similar appearance to a bamboo stalk), secondary ridging (from fuel fracturing/swelling and differential thermal expansion), and local stresses due to pellet edge-clad interactions. For the effort to provide effective mechanical properties of a fuel rod, model evaluations will only consider the effect of complete bonding

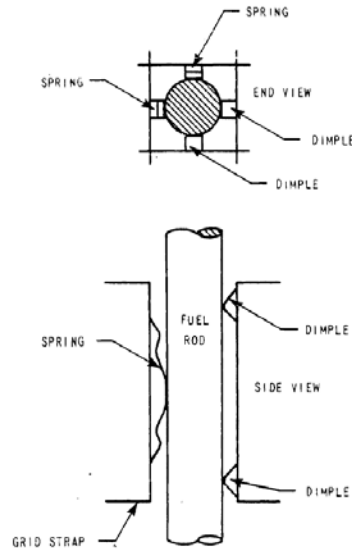


Figure 1. Typical Spring and Dimple Support of Fuel Rod in Fuel Assembly Grid

versus frictional sliding. The single rod sub-modeling effort includes a detailed three-dimensional representation of the fuel pin and cladding to investigate the influence of possible gaps between the pellet and cladding on structural dynamic performance. The effort also includes a detailed submodel of one individual fuel rod slot in a grid spacer (Figure 1).

This sub-modeling effort provides equivalent beam properties (i.e., stiffness and damping) and spring and shell properties for the grid spacers, springs, and dimples to the assembly model. Additionally this effort investigates the stress concentrations in the cladding due to the pellet-pellet-clad interface and provides a stress concentration multiplier to the assembly level analysis.

Given the potential for geometric nonlinear behavior (i.e., contact between the pellets and cladding) and potential variation in material properties in the actual fuel rods, detailed rod evaluation is necessary to develop the equivalent beam properties. The intent of the detailed fuel rod evaluation is to establish reasonable lower bound (LB), best estimate (BE), and upper bound (UB) properties that could be used to define the fuel rod equivalent beam properties in the PNNL PWR assembly model. The intent of establishing this material property LB, BE, and UB “window” is to account for uncertainty in material properties and material state of the PWR assemblies. More explanation of this approach is provided in “Broadening of Assembly Level Response Spectra to Account for Material Property Uncertainty and Generation of Modified Time Histories.”

INTRODUCTION

The knowledge and characterization of material states and material properties for high burnup fuel, cladding, and the pellet-clad interface is limited. These material states and material properties will change the dynamic behavior of PWR assemblies due to rail transportation excitation. In light of the limited material state and material property input data for numerical modeling, an alternate and conservative approach is used in the analysis of nuclear structures. This deterministic approach which is based on ASCE, (2013) captures uncertainty in material properties by using three estimates on the material properties to provide a working window:

lower bound (LB), best estimate, and upper bound (UB). The input rail vibration response used in the PWR assembly analysis is broadened by this material property uncertainty such that the first mode response of the PWR assembly is “tuned” to the peak of the input motion thus providing conservative results. This paper also provides a method for developing equivalent fuel rod stiffness and damping values using detailed fuel rod finite element analysis to study a variety of sensitivities.

DESCRIPTION

This project selected a WE 17x17 type PWR OFA assembly to use for the finite element analysis. PNNL performed the PWR assembly level analysis with the fuel rods being represented by beam elements. To appropriately capture the structural dynamics of the PWR assembly level behavior the following parameters are important: stiffness (linear elastic material properties) and damping (Rayleigh damping). Given the potential for geometric nonlinear behavior (i.e. contact between the pellets and cladding) and potential variation in material properties in the actual fuel rods, detailed rod evaluation is necessary to develop the equivalent beam properties for the PNNL assembly level model. As discussed above the intent of the detailed fuel rod evaluation is to establish reasonable LB, BE, and UB properties that could be used to define the fuel rod equivalent beam properties in the PNNL PWR assembly model. Material nonlinearity (elastic/plastic response) is not evaluated in this detailed model because significant material nonlinearity is not expected during NCT.

The basic approach to the detailed fuel rod evaluation can be summarized in the five steps below:

- Generate a simply supported finite element model for a portion of a fuel rod that accurately considers geometric nonlinearity
- Apply a distributed load to excite a first mode response
- Establish optimization that best relates the displacement equation to the finite element model data using nonlinear regression
- Modify the modeled length, the modeled interaction (tied or in contact), and friction coefficient (where contact is defined) and repeat the above steps to establish viscous damping versus natural frequency, flexural rigidity, and friction
- Define linear beam mass, flexural rigidity and Rayleigh damping parameters equivalent to the nonlinear fuel rod model. This data is provided to the PNNL PWR assembly model.

The conclusions of the detailed fuel rod modeling effort documented below are that damping in the fuel rod due to pellet clad interaction is low. Also there is a large change in beam flexural rigidity that occurs when going from the non-tied beam case (i.e. the pellets and clad are all modeled in contact with various coefficient of friction values) to the tied beam case. The coefficient of friction values used here-in have little effect on the flexural rigidity.

In addition to the developing the stiffness and damping properties it is important to consider the peak stress increase that the pellet-pellet clad interface has on fuel cladding bending stress. This interface concentrates the bending stress at this interface location.

Once the stiffness and damping parameters and the stress concentration multiplier on the fuel cladding due to pellet-pellet clad interface are determined, these values are provided to PNNL for the PWR assembly level analysis. The next step is to broaden the input rail vibration to account for material property uncertainty.

FUEL ROD FINITE ELEMENT MESH, MATERIAL PROPERTIES, AND GEOMETRY

The fuel rod finite element meshes are each a simply supported portion of the fuel rod as shown in Figure 2. This model includes fuel pellets (shown with the red and orange elements) and cladding (shown with the light blue elements). The model uses nominal dimensions for the fuel pellet and cladding from DOE (1987), pages 2A-349 to 2A-354. The cladding length is modeled to match the length of the enclosed fuel pellets.

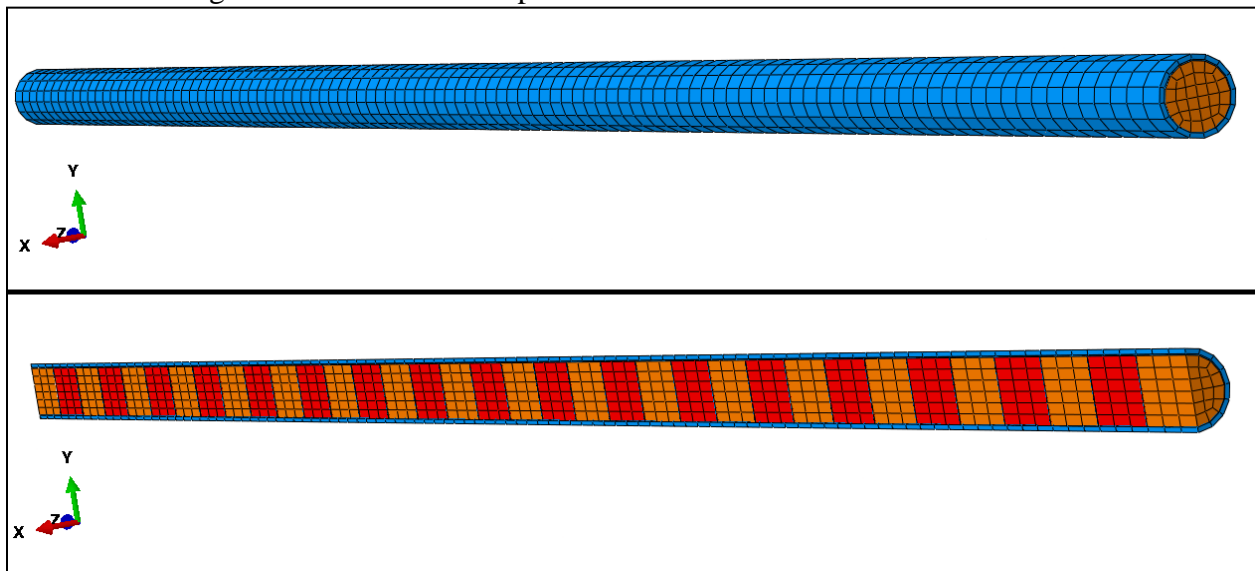


Figure 2. Full 35 Fuel Pellet Mesh for the Fuel Rod (Top) and Cut Away of the Mesh to Show the Internal Structure (Bottom)

The mesh shown in Figure 2 is generated with solid linear continuum shell elements for the cladding and solid reduced integration linear brick elements for the fuel pellet elements. When pellet-to-clad surfaces are tied, the outer nodes of the fuel pellets move with a strain free displacement to the inner surface of the cladding. Otherwise, the contact definition does not affect the geometry. The boundary conditions necessary for the simply supported beam behavior are enforced with coupling constraints attached to the ends of the clad. (as shown in Figure 3). A coupling definition is more desirable than a rigid connection because a coupling does not artificially stiffen the cross section by forcing it to stay round. The boundary condition on one coupling node is fixed translation in all directions and fixed rotation along the axis of the fuel rod. The boundary condition on the other coupling node is fixed translation in the two directions perpendicular to the axis of the fuel rod. Allowing one end of the fuel rod to displace along the axis of the fuel rod prevents the fuel rod from being artificially stiffened by having to elongate the fuel rod to allow a simply supported displacement.

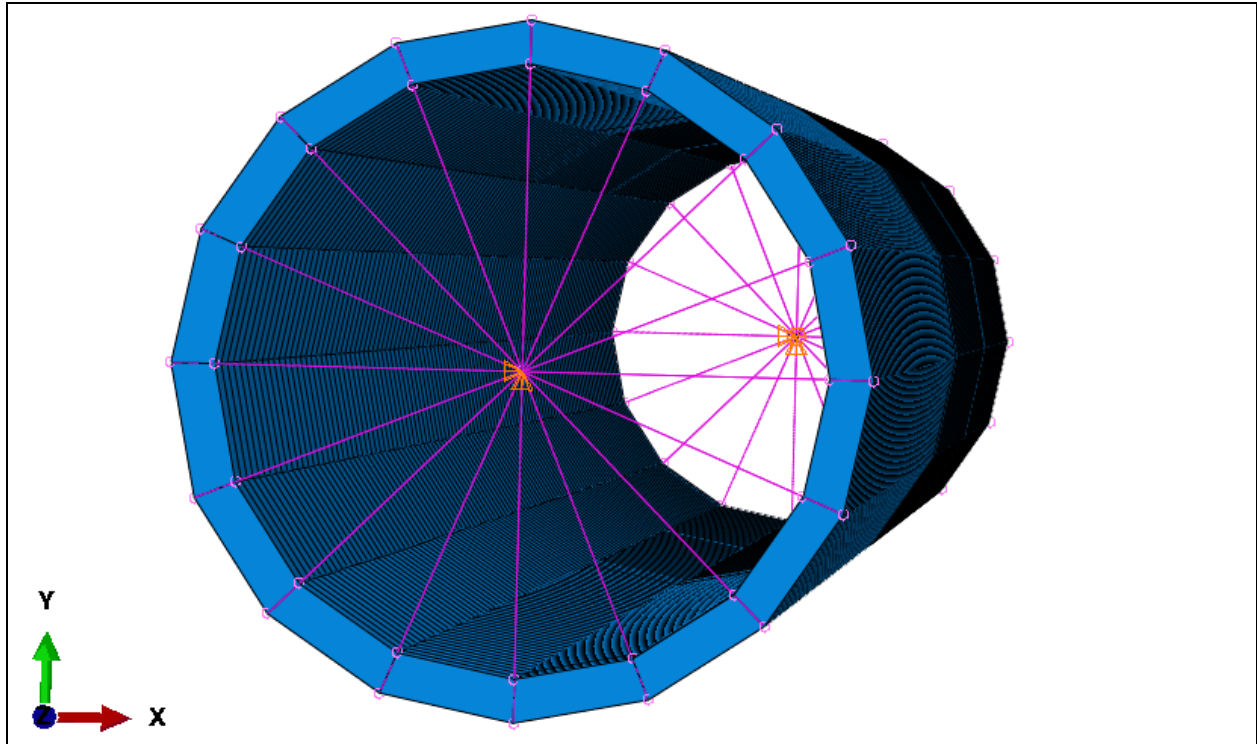


Figure 3. Couplings, Cladding, and Cladding Restraints

The UB response occurs when all of the fuel pellets along with the cladding are tied together thus acting as a continuous beam. The LB response occurs when all of the fuel pellets along with the cladding are in contact (i.e. nodes not tied) thus the cladding is primarily responsible for the stiffness of the model. The best estimate response occurs when the fuel pellets are tied to the cladding but in contact with each other. Given the significant variability associated with possible deformation and cracking, the UB and LB are intended to reasonably envelope possible fuel rod response. The BE gives an initial guess as to actual fuel rod response. However, the final PNNL PWR assembly model runs will be based on selecting best estimate fuel rod stiffness, and using input motion that fits a broadened response spectrum.

FUEL ROD LOADING AND RESPONSE

In the finite element model, the first mode fuel rod response is excited by applying loading over two steps. In the first step, the loading is applied statically as a constant 1g load and a superimposed 0.4g sine wave load as shown in Figure 4. The sine wave load is zero at the fuel rod model ends and 0.4g in the center. This value is considered reasonable and relatively conservative as higher loading can be expected in actual motions. Having the motion slightly lower than expected tends to make the calculated damping value be conservatively low. In the second step, the sine wave portion of the load is removed to produce first mode, free vibration response that is evaluated dynamically. The response is tracked using the vertical motion of a node midway along the cladding length.

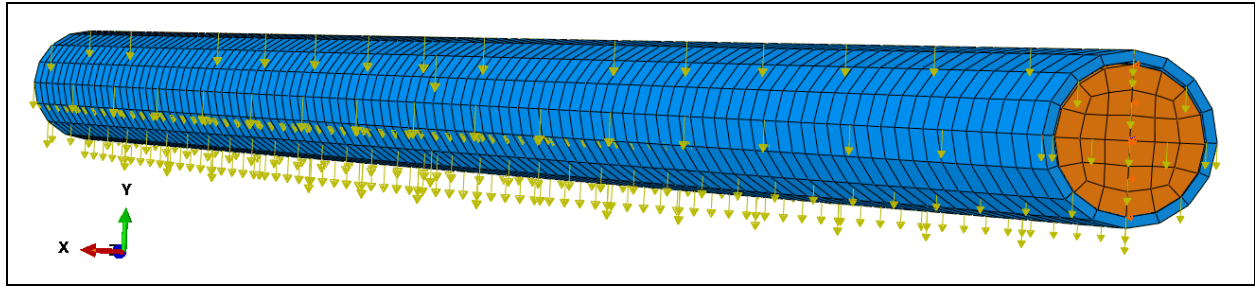


Figure 4. Distributed Load on the Fuel Rod

Figure 5 shows example vertical motions for the center of a fuel rod. These motions are from a single fuel rod mesh that has fuel pellets that are free to move. The difference in the curves is the friction coefficient that is used. The red curve is for a friction coefficient of 0.1, the blue curve is for a friction coefficient of 0.75, and the brown curve is for a friction coefficient of 1.5.

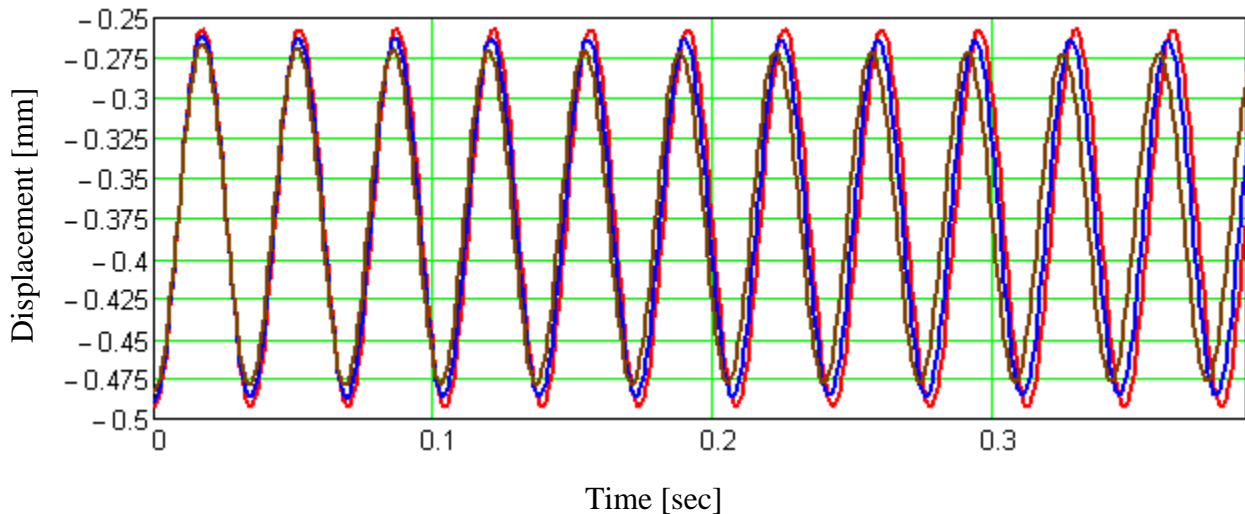


Figure 5. Three Example Vertical Motions for a Single Fuel Rod Mesh Defined with Different Friction Coefficients

Detailed fuel rod stiffness and damping are determined by using the displacement equation (below) and a nonlinear regression to fit the finite element response shown in Figure 5. And provide optimized values for viscous damping, angular natural frequency, wave amplitude, phase angle, and wave offset.

$$y(t, \zeta, \omega, Y_a, \phi, y_g) := Y_a \cdot e^{-\zeta \cdot \omega \cdot t} \cdot \sin(\sqrt{1 - \zeta^2} \cdot \omega \cdot t + \phi) + y_g$$

Displacement equation of a single degree of freedom system.

where:

- | | | | |
|---------------------------|--------------------------------------|-------------------------|------------|
| ζ - Viscous damping | ω - Angular natural frequency | y - Vertical position | t - Time |
| ϕ - Phase angle | Y_a - Wave amplitude | y_g | |

Using these values, optimized natural frequency and flexural rigidity can also be defined as follows:

$$(\zeta \ \omega \ Y_a \ \phi \ y_g)^T = A \quad \text{Optimized values output from the nonlinear regression.}$$

$$f = \frac{\omega}{2 \cdot \pi} \quad \text{Optimized value for natural frequency.}$$

$$f = \frac{\pi^2}{2 \cdot \pi \cdot L_c^2} \cdot \sqrt{\frac{E \cdot I}{m_{cp}}} \quad \text{Natural frequency of the first mode of a simply supported beam.}$$

Solving for flexural rigidity:

$$E \cdot I = \frac{4 \cdot f^2 \cdot L_c^4 \cdot m_{cp}}{\pi^2} \quad \text{Optimized value for flexural rigidity.}$$

Time [sec]

The results from the finite element model runs show that damping is minimal. Also, the results provide the flexural rigidity as given in Table 1.

Table 1: Fuel Rod Finite Element Model Input and Results

Model number	Contact Definition	Length [mm]	Friction Coefficient	Viscous Damping	Frequency [Hz]	E·I [Pa·m ⁴]
1	No Ties	1287.9	0.1	0.0000821	3.5	8.29
2	No Ties	901.53	0.1	0.0000936	7.2	8.33
3	No Ties	901.53	0.75	0.000522	7.2	8.36
4	No Ties	643.95	0.1	0.000164	14.1	8.34
5	No Ties	643.95	0.75	0.000877	14.2	8.39
6	No Ties	450.76	0.1	0.0000844	28.8	8.32
7	No Ties	450.76	0.75	0.000548	28.9	8.36
8	No Ties	450.76	1.5	0.00105	29.1	8.5
9	Clad-Pellet Tie	450.76	0.1	0.0000136	67.1	45.06
10	All Tied	450.76	0.1	0.00000181	70.1	49.29

Given the evaluation for the geometrically nonlinear, simply supported fuel rod model, the following properties can be used to define linear beam element properties that generate similar results.

$$m_{cp} = 0.599 \frac{\text{kg}}{\text{m}} \quad \text{Modeled mass of the cladding and fuel pellet.}$$

$$EI_{LB} = 8.3 \cdot \text{Pa} \cdot \text{m}^4 \quad \text{Evaluated lower bound flexural rigidity.}$$

$$EI_{BE} = 45.1 \cdot \text{Pa} \cdot \text{m}^4 \quad \text{Evaluated best estimate flexural rigidity.}$$

$$EI_{UB} = 49.3 \cdot \text{Pa} \cdot \text{m}^4 \quad \text{Evaluated upper bound flexural rigidity.}$$

$$\alpha(EI, fn) := \frac{(49.3 \text{ Pa} \cdot \text{m}^4 - EI) \cdot (3.39 \times 10^{-2} \cdot fn)}{41.0 \text{ Pa} \cdot \text{m}^4} \quad \text{Mass damping factor for Rayleigh damping}$$

$$\beta(EI, fn) := \frac{(49.3 \text{ Pa} \cdot \text{m}^4 - EI) \cdot (3.07 \times 10^{-6} \cdot fn)}{41.0 \text{ Pa} \cdot \text{m}^4} \quad \text{Stiffness damping factor for Rayleigh damping}$$

where

El - Flexural rigidity

fn - Friction coefficient (the damping factors were evaluated for a range of $0.1 < fn < 1.5$)

PELLET-PELLET CLAD STRESS INCREASE

A finite element sensitivity study was performed to understand the stress concentration at the pellet-pellet clad interface. The study is performed with nominal cladding and fuel pellet dimensions except the fuel pellet diameter which is expanded to make contact with the inside diameter of the cladding. There is no friction and essentially no axial restraint. These parameters are selected because they represent one bound of the possible scenarios and they produce a conservatively high stress state as compared to having friction and/or an axial restraint defined.

Figure 6 shows the full mesh and a cut-away of the mesh for the simply supported beam.

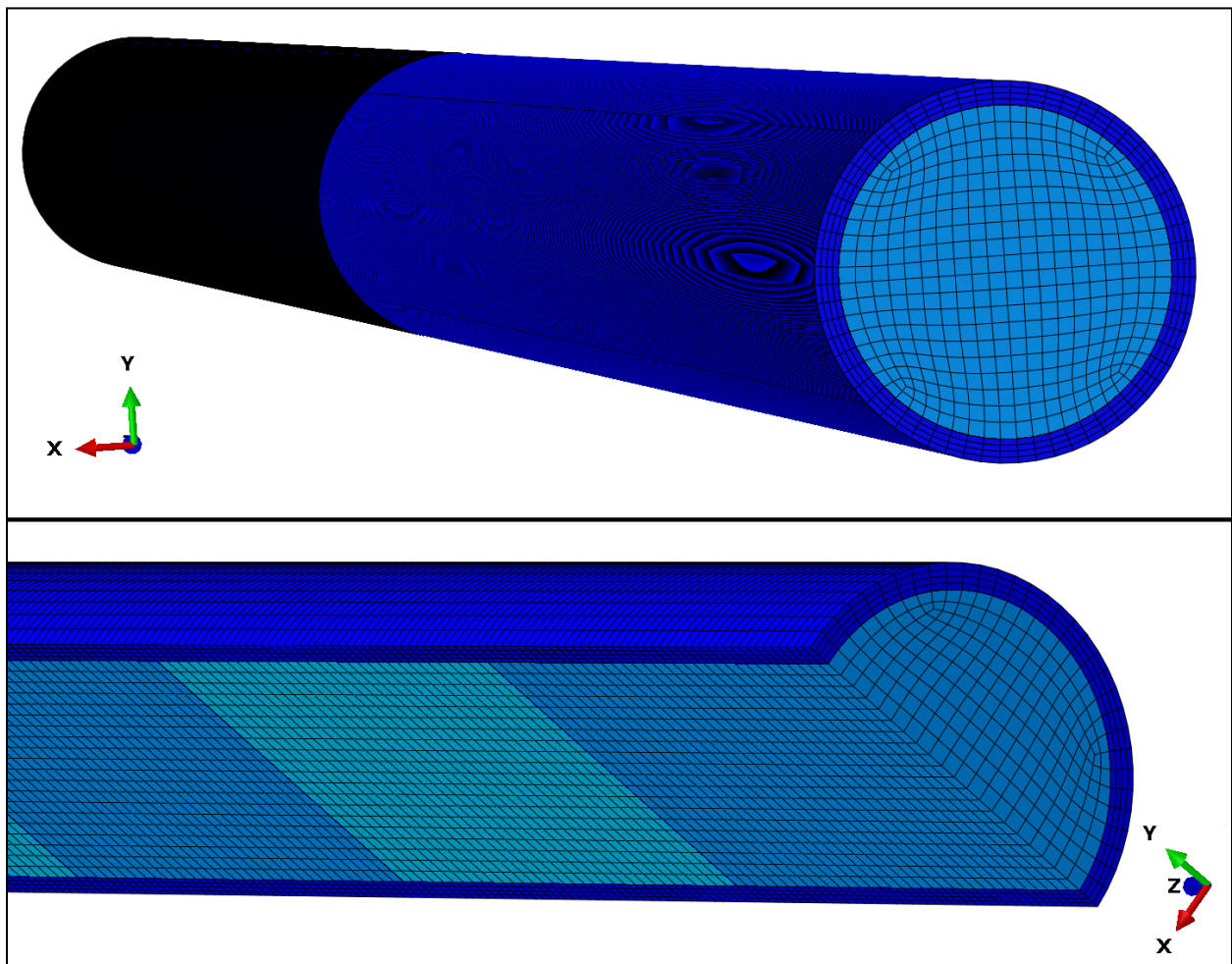


Figure 6. Full Mesh and Cut-Away Mesh for the Simply Supported Beam.

The stress results for the simply supported beam are shown in Figure 7. The three plots show the full model with the overall maximum stress identified.

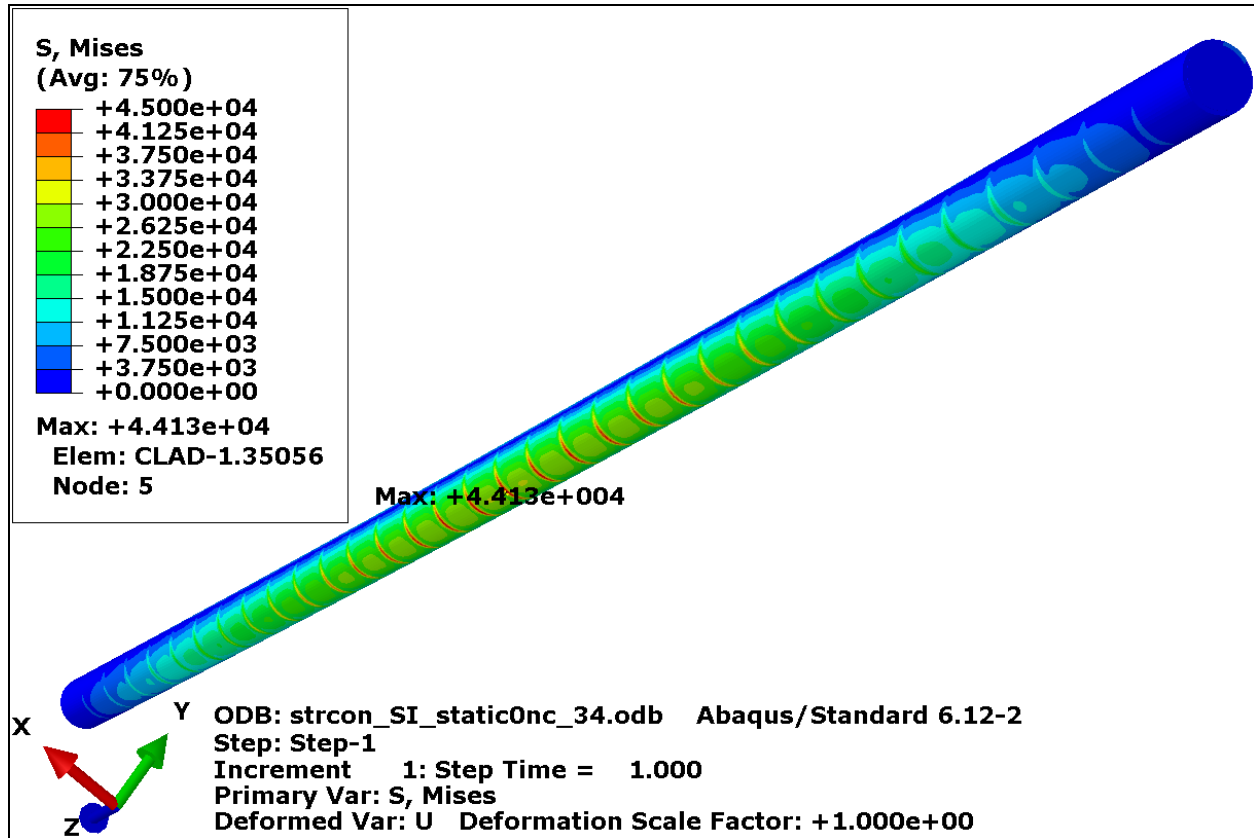


Figure 7. Full Model Stress Results for the Simply Supported Beam.

The high stress in the simply supported beam model (shown in Figure 7) occurs at the center of the cladding. The moment in the cladding at this location is $9.949 \cdot 10^5 \text{ kg} \cdot \text{mm}^2/\text{s}^2$. Below is a calculation of the beam stresses that would be expected with no stress concentration:

$$M_v := 9.949 \cdot 10^5 \cdot \text{kg} \cdot \frac{\text{mm}^2}{\text{s}^2} \quad \text{Moment at the center of the cladding.}$$

$$\sigma_v := \frac{M_v \cdot \frac{d_{co}}{2}}{I_c} \quad \text{Cladding bending stress.}$$

$$\sigma_v = 3.203 \times 10^4 \cdot \frac{\text{kg} \cdot \text{mm}}{\text{s}^2 \cdot \text{mm}^2} \quad \sigma_v = 3.203 \times 10^4 \cdot \text{kPa}$$

This produces a stress concentration multiplier of 1.35.

DEVELOPMENT OF MODIFIED INPUT TIME HISTORIES FIT TO FLAT AND BROADENED RESPONSE SPECTRA TO ACCOUNT FOR MATERIAL PROPERTY UNCERTAINTY

The NCT modeling effort documented herein accounts for the uncertainty in the material properties and material state by using “best estimate” fuel rod properties and broadened input PWR response spectra. Figure 8 shows the unmodified and broadened response spectra. The broadened response spectrum is broadened relative to the unmodified response spectra based on the percentage of uncertainty in the material properties. This is done to ensure that the PWR assembly will respond in a manner that is possible even if the best estimate finite element model tunes to a valley in the actual response spectra. For example, Figure 8 provides a hypothetical PWR assembly first mode response which is around 15 Hz (black line). If the unmodified response spectra (shown as the blue curves) are used, the PWR assembly response will have a low response that is not conservative. Given the variation in the material properties, the actual response could occur at the peak response of the unmodified response spectra. Using the broadened response spectrum ensures that the worst response that could occur is captured by the best estimate PWR assembly finite element model.

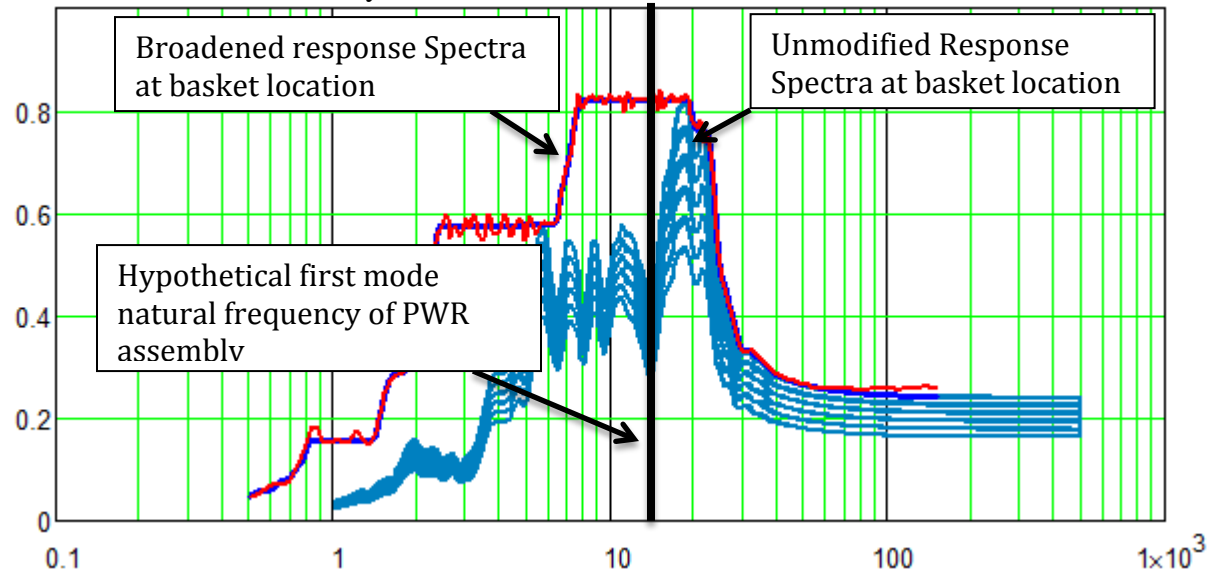


Figure 8. Unmodified and broadened response spectra at basket location

This approach should produce conservative results. Additional sensitivity studies could be performed on the pellet-pellet-clad interface to reduce this conservatism and provide a better estimate on high burn-up fuel rod flexural rigidity and fuel rod natural frequency.

CONCLUSIONS

The finite element analysis at the detail fuel rod level provided stiffness, damping, and a pellet-pellet-clad stress multiplier to PNNL for the assembly level analysis. Also provided were broadened time histories to account for material property uncertainty.

REFERENCES

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