Modeling Nuclear Fuel Rod Drop with LS-DYNA®

W. Zhao, J. Liu, W. Stilwell, B. Hempy, and Z. Karoutas
Westinghouse Electric Company LLC
Hopkins, SC 29061, USA

Abstract

As a primary barrier to the fission product release, maintaining the structural integrity of fuel rod cladding has been a topic of great importance. To help better understand the structural behavior of the fuel rod in shipping and handling incidents, a detailed model for a typical pressure water reactor (PWR) fuel rod is being developed using LS-DYNA. The paper describes an on-going model development effort. For efficiency of the development process, a shortened version of the fuel rod is considered. Nevertheless, the model contains all the structural features of the fuel rod, thus can be easily extended to obtain a full length fuel rod model. A few typical fuel rod drop orientations have been simulated using the model to demonstrate its capability, including weld failure events. The results are discussed.

1. Introduction

As a primary barrier to the fission product release, maintaining the structural integrity of fuel rod cladding has been a topic of great importance. In the events of nuclear fuel handling incidents, or, in hypothetical shipping accidents, it is necessary to evaluate the structural integrity of fuel rod cladding. It is also important to assess the integrity of the fuel pellets, as damaged pellets may result in excessive pellet-cladding mechanical interactions, causing leaking fuel rods during operations.

Figure 1 shows a typical PWR fuel rod (shortened), consisting of UO_2 pellets enclosed in Zirconium alloy cladding. Its major components include bottom end plug, pellets, tube, plenum spring, and top end plug. The bottom and top end plugs are welded to the tube, which is pressurized with Helium gas.

Figure 1 - Typical PWR fuel rod (shortened).

Towards better understanding the structural behavior of the fuel rod in shipping and handling incidents, a detailed model for a typical pressure water reactor (PWR) fuel rod is being developed using LS-DYNA, which has been used previously in simulating fuel shipping packages [1, 2], and fuel spacer grid impact tests [2, 3]. The paper describes an on-going model development effort. For efficiency of the development process, a shortened version of the fuel rod is considered. Nevertheless, the model contains all the structural features of the fuel rod, thus can be easily extended to obtain a full length fuel rod model. A few typical fuel rod drop orientations have been simulated using the model to demonstrate its capability, including weld failure events. The results are discussed.

2. Model Development

All the structural features of the fuel rod are included, which are bottom end plug, pellets, tube, plenum spring, and top end plug. The weld connection of the tube to the bottom end plug is also included along with the heat-affected zone (HAZ). Figure 2 shows a 10-pellet model designating the components.

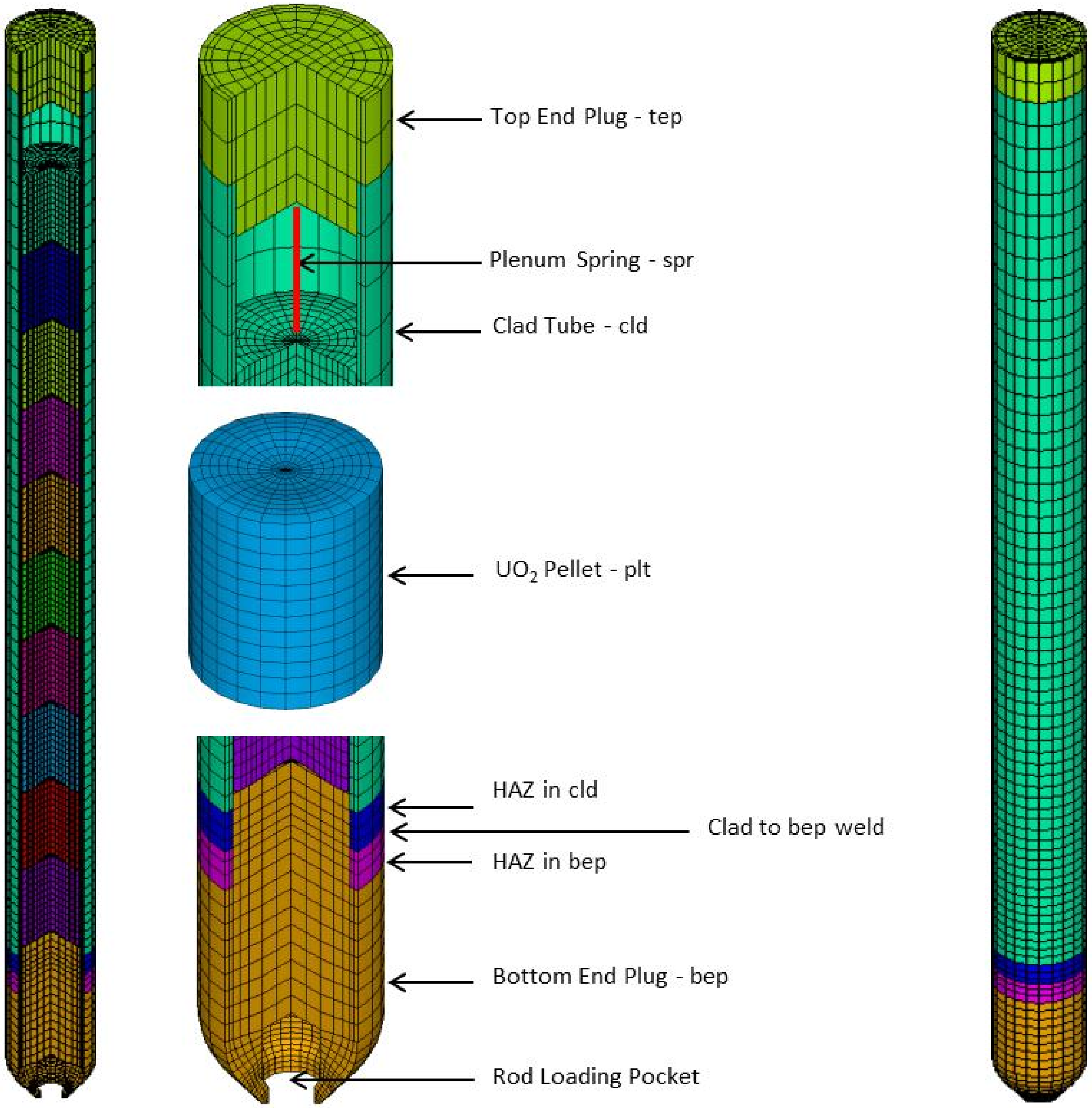

Figure 2 – Fuel rod model - components.

Figure 3 shows the finite element model details in section view, which is for a 5-pellet model and used to run all the simulations presented in this paper to further speed up the model development process. The initial velocity represents a drop height of one meter. Individual surface-to-surface contact definitions are used to obtain contact forces at specific interfaces of interest, while automatic contact is used to capture the remaining contact interactions. It is also noted that pellet 5 (plt5) is modeled as a rigid body to eliminate its appreciable contribution to hourglass energy. The remaining pellets behave linearly elastic. The plenum spring is modeled using keyword `*MAT_SPRING_ELASTIC,` along with `*SECTION_DISCRETE.` The Zirconium alloys used for the end plugs and the tube are modeled using Piecewise Linear Plasticity. The ground is modeled as a rigid surface. It is assumed that the pellets are centered in the tube, though off-center positions can be considered easily. Using the model, a few drop orientations are simulated to examine the model, and to gain some understanding of the phenomenon. The results are discussed in the next section.

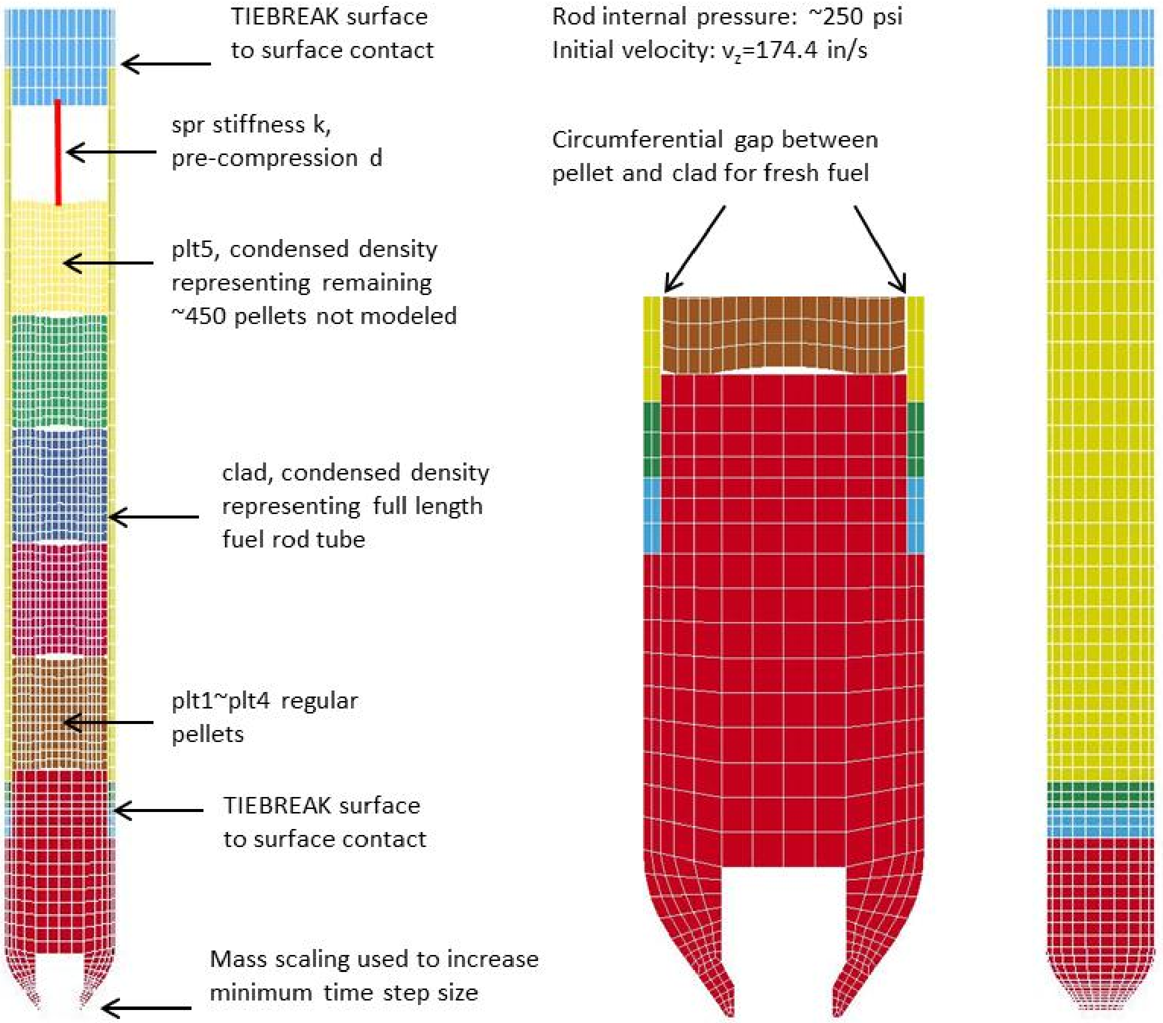

Figure 3 – Fuel rod model – finite element details.

3. Results and Discussions

Although the model is much shorter than the real fuel rod, it can still provide useful information and understanding to the behavior, especially on comparative bases. Furthermore, for vertical and horizontal drop orientations, the short model is expected to have good representation of full length fuel rod, as the length effect is less significant in such orientations.

3.1 Overall Deformation

The overall deformed shape for each drop angle is summarized in Figure 4 in section views, with the contour representing the effective stress at a state when it reached the maximum value. The model behaved as expected based on the following observations. (1) The tip of the bep is highly deformed for the high angle drops (90° and 80°). (2) The fuel rod bends for the 45° angle drop, with pellet-to-pellet gaps noticeable at the lower, or the right-hand side. (3) For the horizontal drop, the maximum effective stress occurred in the clad beneath the pellet 5, which is ~450 times more massive than the other pellets.

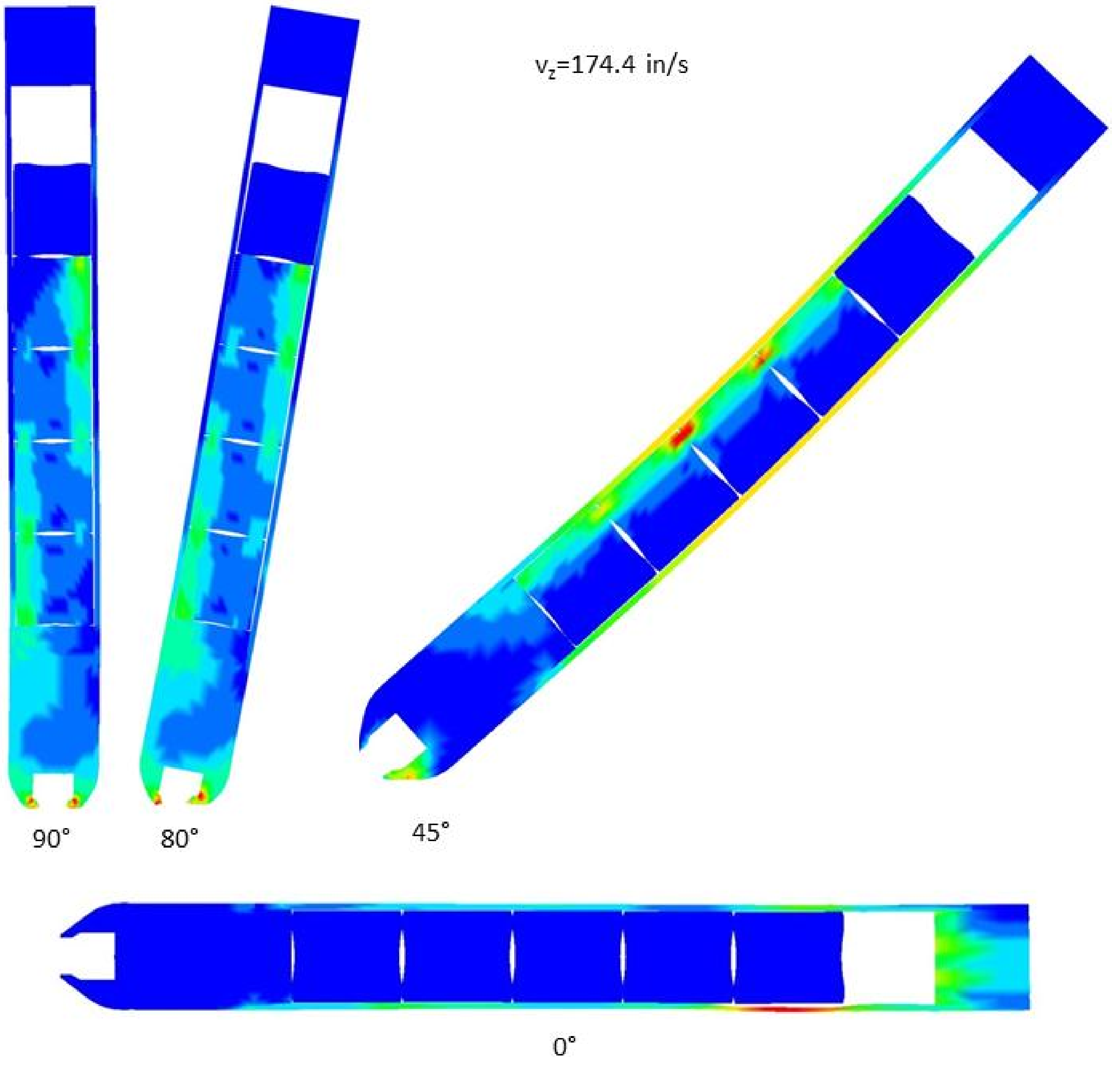

Figure 4 – Overall deformed shapes.

3.2 Deformation of Bottom End Plug (bep)

The deformed shape of bep for each drop angle is summarized in Figure 5 in section views, with the contour representing the effective stress at a state when it reached the maximum value. The clad HAZ is also included. It can be seen that both the degree of deformation and the magnitude and location of the effective stress show reasonable trend, with the maximum occurring in the case of vertical drop.

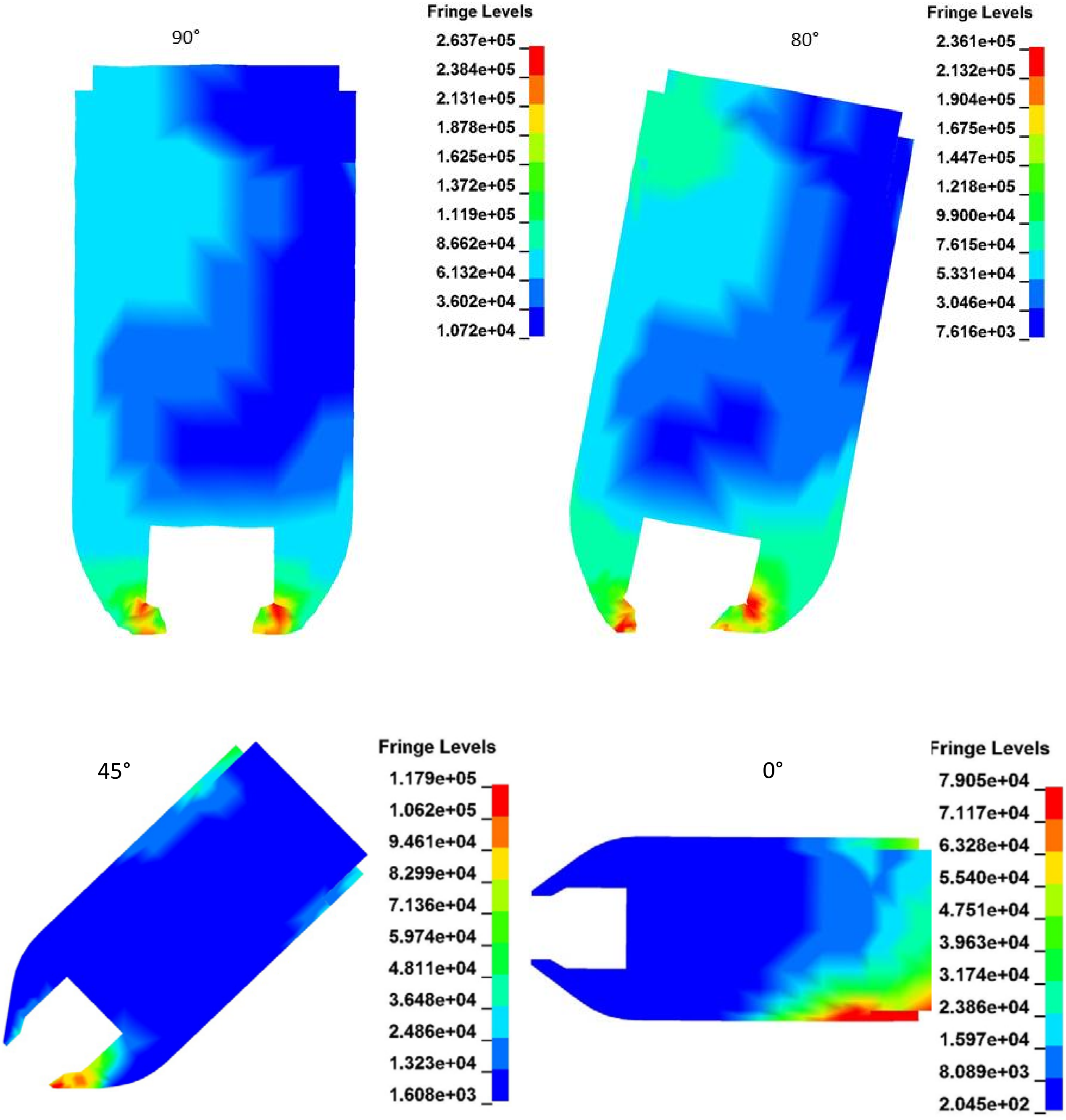

Figure 5 – Deformation and effective stress in the Bottom End Plug.

3.3 Maximum Shear Stress in the Pellets

The maximum shear stress in pellets is examined at a state when it reached the maximum value, as ceramic materials are generally more prone to fail in shear than in compression. It can be seen that the highest maximum shear stress occurred in the case of vertical drop.

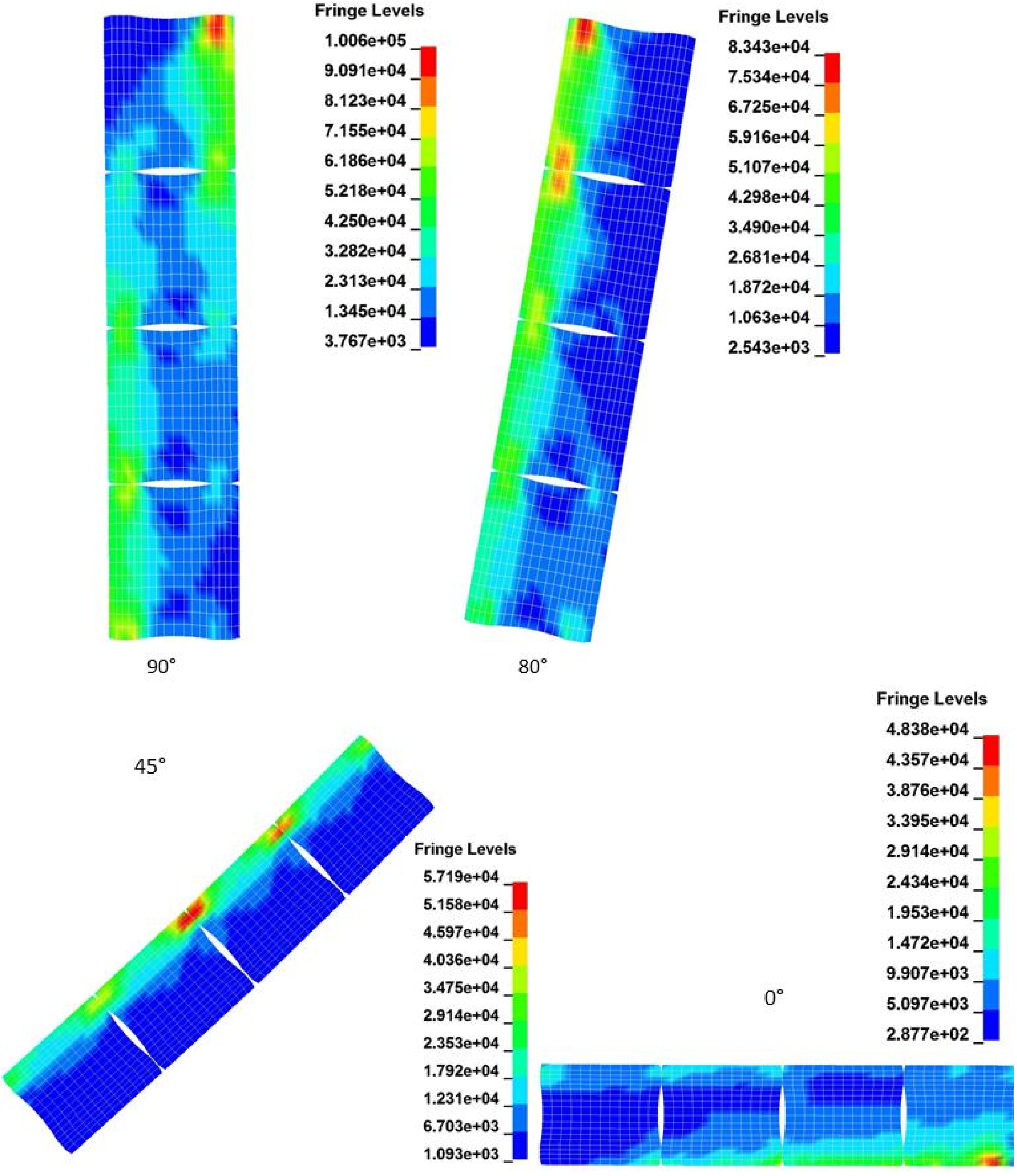

Figure 6 – Maximum shear stress in pellets .

3.4 Simulating Weld Failure between Clad Tube and Bottom End Plug

Failure of the weld between the fuel rod clad tube and the bottom end plug has been observed in various drop tests involving fuel assembly shipping packages. Figure 7 shows some examples of failed welds from such drop tests.

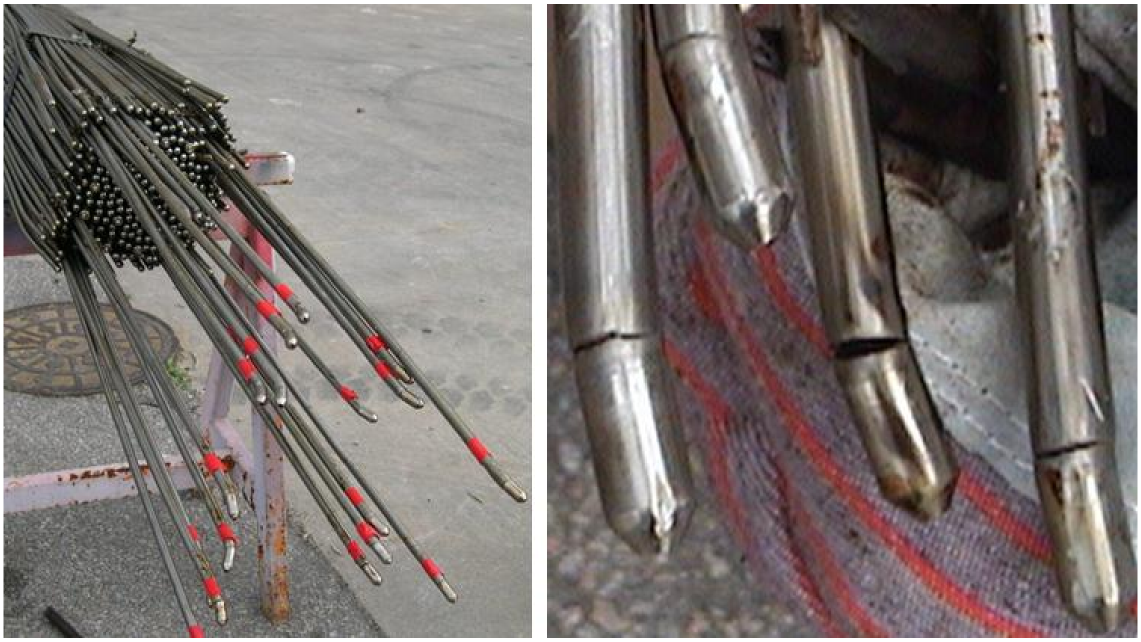

Figure 7 – Examples of failed welds from drop tests of fuel assembly shipping packages.

To test of the model’s capability of simulating weld failure, the case of 45° drop was rerun using reduced weld joint strengths.

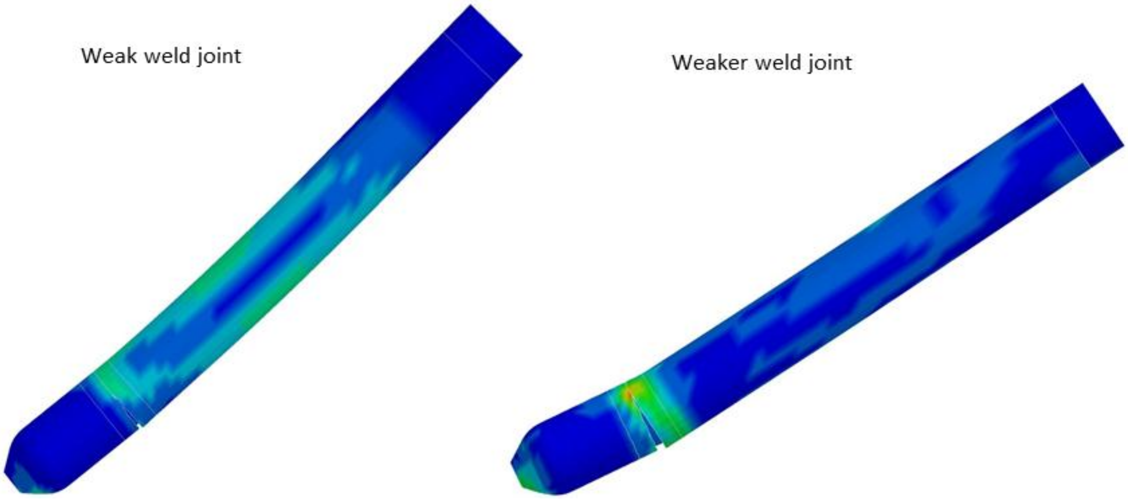

Figure 8 –Partial separated weld for weakened joint.

It is noted that the purpose is to test the model's capability of simulating weld failure process, not to predict the actual failure loads or stresses, as the loading conditions of the fuel rods supported in a fuel assembly inside shipping package are not well known for characterization and comparison. Nevertheless, the exercises are useful in confirming the model, and in understanding the phenomenon. As can be seen in Figure 8, the weld failure process is properly represented.

3.5 Effect of Plastic Deformation of Bottom End Plug on Pellet Loading Severity

As shown in Figures 4 and 5, significant plastic deformation occurs at the tip of bep for high angle drops, where the pocket, designed for rod loading tool to grab on, also creates a weak spot in the bep. On the other hand, this plastic deformation should help alleviate the loading severity on pellets for high angle drops, thus provides a design opportunity to facilitate plastic deformation if such needs arise. To assess the beneficial effects, a special case for the 80° drop is considered where the bep is modeled as a rigid body, thus eliminating its deformation. Figure 9 provides a comparison of the overall deformed shapes between rigid and deformable bep for the 80° drop at the same time instant as shown in Figure 4. To quantify the effect, Figure 10 compares the magnitudes of the acceleration vector of pellet 5 for the two cases. It shows that the maximum acceleration experienced by pellet 5 for the rigid bep is more than 2.5 times higher than that for the deformable bep, indicating that increasing the bep plastic deformation capacity may significantly reduce the pellet loading severity in high angle drop events.

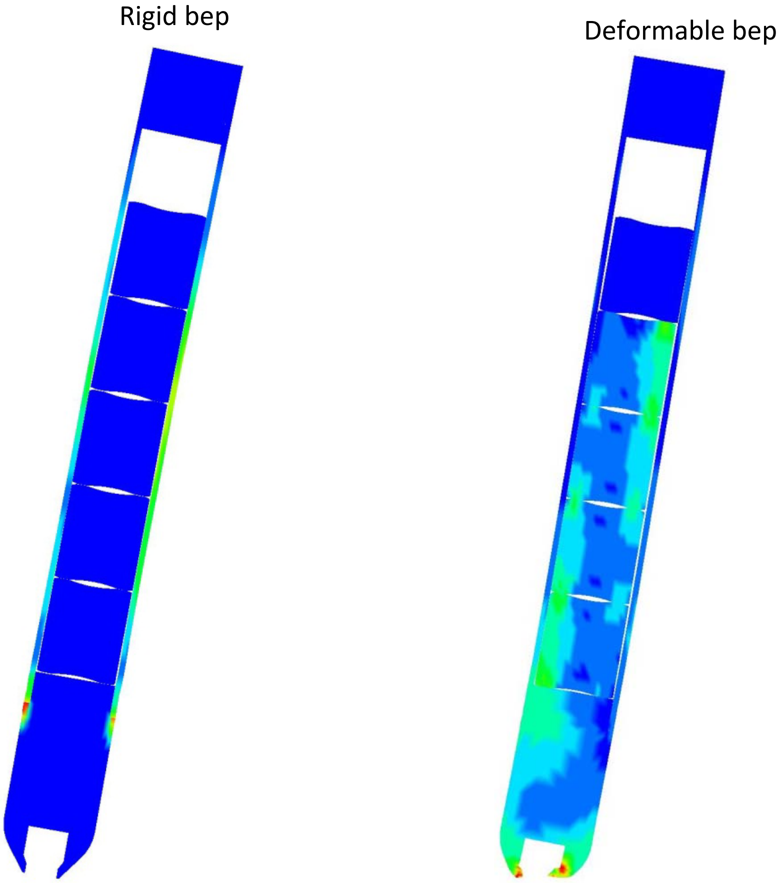

Figure 9 – Comparison of overall deformed shapes between rigid and deformable bep for 80° drop.

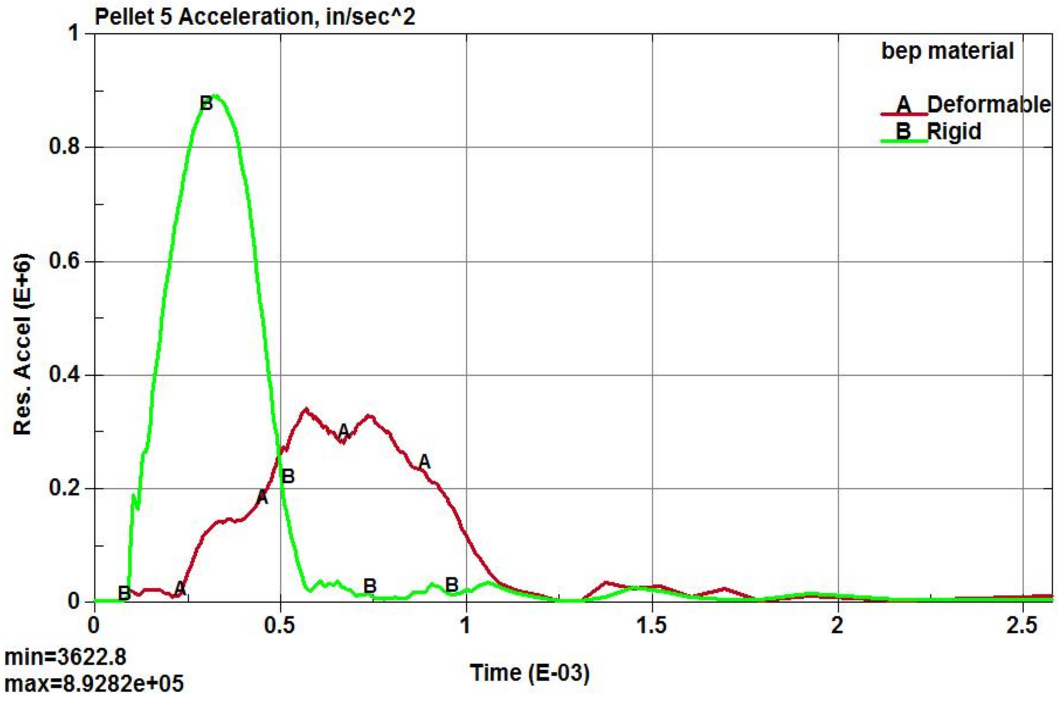

Figure 10 – Comparison of acceleration experienced by pellet 5 for 80° drop.

3.6 Clad Tube Deformation for Horizontal Drop

For the horizontal drop, the clad tube experiences direct impact, representing a severe loading case for the clad. Thus the clad deformation is examined below for this case.

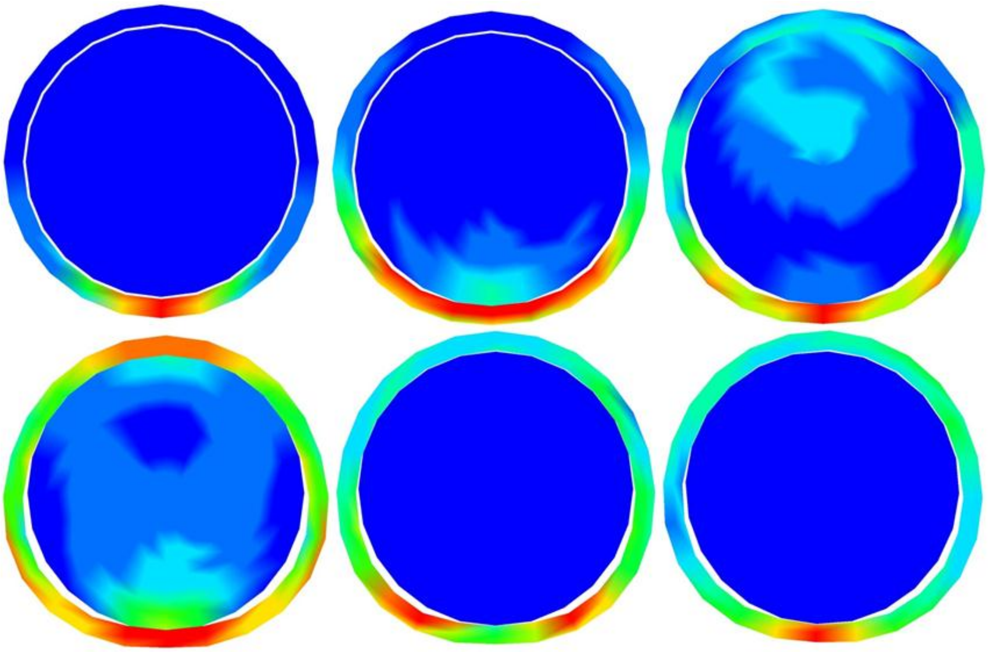

Figure 11 – Clad tube deformation for 0° drop.

Figure 11 shows a series of section views cut through pellet 2 at various time instants in increasing order, with the contour representing the effective stress. It shows that the tube became oval shaped after impact.

4. Concluding Remarks

A PWR fuel rod FEA model with full fuel pellet stack represented by five pellets has been developed. Example analyses with the model demonstrate its versatile capability and usefulness, such as characterizing the pellet loading severity and potential weld failure. The model can be used to evaluate other design parameters, such as the effect of the plenum spring stiffness and pre-compression, pellet stack eccentricity, rod internal pressure, and irradiated fuel, etc. Having included all the features of the fuel rod, the model can be easily extended to obtain a full length fuel rod model.

References

[1] W. Zhao, B. Hempy, J. Liu and W. Stilwell and R. Rochow, *Development and validation of an LS-DYNA model for simulating vertical drop test of a nuclear fuel shipping package,* ICONE18-29313, Proceedings of the 18th International Conference on Nuclear Engineering ICONE18,May 17-21, 2010, Xi'an, China.

[2] Wei Zhao, Zeses Karoutas, Paul Evans and Olin McRae, *LS-DYNA Applications in Simulating Impact Tests of Nuclear Fuel Spacer Grids and Drop Tests of Fuel Shipping Packages*, 12th International LS-DYNA Users Conference, 2012.

[3] W. Zhao, Z. Karoutas, P. Evans and O. McRae, Simulating Impact Tests of Fuel Assembly Spacer Grids, LWRFuel Performance Meeting TopFuel 2013, September 15-19, 2013, Charlotte, NC, USA.