

Simulations of CANDU® Fuel Bundle Under Static Mechanical Loads and Refuelling Loads Using LS-DYNA Finite Element Models¹

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Abstract

LS-DYNA is a commercial general purpose finite element code for analyzing static and dynamic response of structures. It is used by Candu Energy in the analysis of CANDU^{®2} fuel bundles subjected to static mechanical loads, and refuelling loads when the fuel bundle string is supported by Fuelling Machine side-stop separators to resist the hydraulic loads from coolant flow in the fuel channel. The analysis calculates deflections and local stresses / strains in the bundle. When modelling these conditions, the LS-DYNA fuel models consider the non-linear mechanisms for the following phenomena: mechanical driving forces (gravity, hydraulic drag and friction force etc.), contact constraints on bundles at side-stops, inter element contacts through the mating spacers, fuel elements to pressure tube contact at bearing pads, endplate to endplate contacts in fuel bundle string, and relative bundle misalignment in fuel string etc. This paper describes the LS-DYNA models and simulations of CANDU fuel bundles under static mechanical loads and refuelling loads.

1. Introduction

The CANDU 37-element fuel bundle design has been proven to be very successful, with very low cumulative bundle defect rate [1] of less than 0.1%, in CANDU power reactors with accumulated operation of approximately 140 reactor years over three decades.

The CANDU fuel bundles (similar to fuel assemblies in other power reactors) were designed to perform reliably in the reactor cores during normal operations (NO) and anticipated operational occurrences (AOOs) [2][3]. These conditions include certain static or quasi-static mechanical or/and hydraulic loading conditions of the bundles during their residence in the reactor or during transfer out of the reactor channel to the Fuelling Machine in the process of on-power refueling. During NO, coolant flow in the fuel channel produces hydraulic drag forces on the fuel bundle string in the channel. The drag forces result in mechanical loads in fuel bundle components (fuel elements, endplates and assembly welds) that are transferred from one bundle to the adjacent bundle in the fuel string in the flow direction. The last fuel bundle experiences the highest load that is transferred to the shield plug, which supports the fuel bundle string in

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the channel. During refuelling, the fuel string travels to the downstream end of the fuel channel and the fuelling machine separator side-stops are inserted into the fuel string to restrain the fuel bundles upstream of the side-stops, while the downstream bundles are discharged into the Fuelling Machine. The side-stops support the bundle over only a few outer elements of the bundle at their endcaps. This configuration results in high stresses and strains in the irradiated downstream bundle resting against the side-stops and thus is considered as one of the key scenario for static loading.

To understand the mechanical behaviour of CANDU fuel bundles under static loading, significant effort on numerical simulations has been expended by CANDU fuel designers since the 1970s. The governing behaviour of CANDU fuel bundles under static loading is characterized by the following key parameters:

- Fuel element lateral force and deflection, stress and strain;
- Fuel element /bundle axial force, length change and strain;
- Deflection, stress and strain in endplate;

This paper describes the modeling and simulation of CANDU fuel bundles under static mechanical loadings and refueling load using LS-DYNA computer program [4]. It covers descriptions of the finite element models and methods used for simulation and simulation results.

2. Modelling of Fuel Bundles under Static Loadings

Two typical static mechanical loading conditions on fuel element / bundle are selected for LS-DYNA modelling and simulation: a) lateral pull load of an outer ring fuel element in a bundle, and b) bending (i.e., peel) or torque load on an assembly weld (endcap-endplate weld) of a fuel element. The schematic of loading and the LS-DYNA model for the single fuel bundle is shown in Figure 1. In this model, fuel sheathes, bearing pads, spacers are modelled using shell elements, endplates and endcaps are built with solid elements, nonlinear material properties are used for Zircaloy components. Pellets are modelled with solid elements inside sheath, and they automatic contact with the inner surface of sheath, a friction coefficient between pellets and sheath is specified. The bundle was placed horizontally and simply supported at bottom of endplates near six o'clock position. A lateral load was applied in small increments at midplane of fuel element near 12 o'clock position. The LS-DYNA model for bending or/and torque load on an assembly weld (endcap-endplate weld) of a fuel element is shown in Figure 2. The model consists of sheath, endcap and endplate strip, weld diameter varies from 3.0 mm ~5.0 mm. Sheath is constrained; bending and/or rotational loading (relevant to the weld centre) are applied on endplate. LS-DYNA code calculates the displacement, stress and strain in assembly weld region.

The simulation result for the pull test of an outer ring element is shown in Figure 3. It can be seen that maximum stress (normalised) occurs at the surface of middle portion of fuel element, or near the pull loading location, as this portion bears high bending moment. Also the endplate and endcap weld region presents high stress, as this area endures high shear force plus moderate bending moment.

In the bending load simulation case for assembly weld, finite element model employs weld diameter weld diameter at 3, 4, and 5 mm (these weld diameters are used in sensitivity studies, the actual actual weld diameter may vary from these). LS-DYNA calculated stress in weld region, and failure and failure bending moment (failure moment is identified as the maximum bending moment when moment when the stress level reaches ultimate tensile strength). The predicted normalized stress is normalized stress is shown in Figure 4. The maximum bending stress is found at the edge of weld section, which is consistent with the observation in CANDU fuel. The failure bending moments versus the cube of weld diameter is plotted in

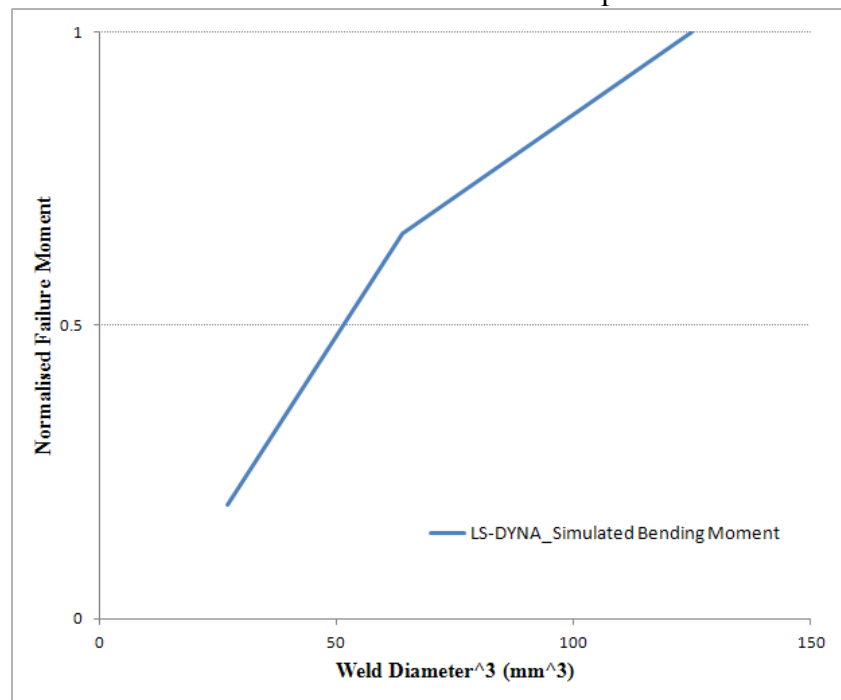


Figure 5. The predicted failure moment changes approximately linearly with the cube of weld diameter. For torque loading on assembly weld, the similar simulation can be done, and the failure torque can be calculated.

3. Modelling of Three Fuel Bundles Under Compressive Loading at High Temperature

A three bundle string is modelled under compressive load and simulated high temperature of 282°C. The bundle is supported at one end by simulated side-stops. The schematic of LS-DYNA model of fuel bundle strength simulation are given in Figure 6. The predicted normalised displacement in endplate is shown in Figure 7, it can be seen that the displacement of endplate in the areas near side-stops is much less than the displacements in other areas of endplate. The element lengths (before and after loading) are calculated on the bundle immediately supported by side-stops. The element length was computed over the endplates and any bending of the endplates is included in the length increments. Permanent plastic deformations in fuel elements are obtained by the length change between the computed length during pre-loading and post-loading. The average plastic strain (over element length) is calculated using the length change divided by initial length of the element. The average normalised plastic strains for various elements of the bundle are given in Figure 8. The curves in the figure demonstrate a trend: i.e., those elements

supported by side-stops bear large plastic strain; these elements are 2, 3, 5, 6, 13, 14, 16 and 17. Those elements away from side-stops experience less plastic deformation, the average plastic strain for these elements could be about 10-20% of the maximum predicted value. Under axial compressive loads and constraints from side-stops, some elements (for example, elements 1 to 6, elements 12 to 17), together with endplates permanently deform in “W” shape at side-stops supports; “S” shape at the interface areas between those element supported by side-stops and unsupported elements such as elements 4 to 8, and element 15 to 19. These shapes are consistent with the observations of CANDU fuel experience.

4. Modelling of A String of Twelve Fuel Bundles under Refuelling Loading

Modelling of a fuel string of twelve fuel bundles under refuelling hydraulic drag loads and constrained by side-stops were carried out on CANDU 6 fuels, the deflection and strain results were calculated. The schematic of fuel bundle string is illustrated in Figure 9 and modelling detail focus on downstream endplate of downstream bundle (supported by side-stops). The most downstream bundle supported by side-stops is modelled by shell elements (for sheath, bearing pads, spacers) and solid elements (for endplates, endcaps and welds). The pellets are not included, but sheath thickness is adjusted to match equivalent stiffness of fuel element. In the remaining eleven upstream fuel bundles of the twelve bundle fuel string, beam elements are used to represent the sheaths and shell elements are used to represent the endplates. The weld area in the eleven upstream bundles is modelled as rigid to avoid causing unanticipated local deformation at the joints between the endplate and the fuel elements. The modelling simplification in the eleven upstream bundles is made because main focus of simulation is on the most downstream endplate, and there are constraints of computer's random access memory, storage capacity and computational speed. Hydraulic drag load is applied uniformly on all fuel elements of the twelve bundles. Non-linear contact constraints are modelled between endcaps and side-stops, among elements through the mating inter-element spacers, between fuel element bearing pads and pressure tube, between endplate to endplate contacts in fuel string corresponding to the bundle misalignment between adjacent bundles specified for the desired scenario, or set as most probably bundle misalignment angle between adjacent bundles.

The LS-DYNA calculations of strain in endplate for a typical case under refuelling hydraulic drag load are given in Figure 10. It is observed that the normalized predicted strains show high values in the areas near side-stops, which agree with the previous observation.

5. Conclusions

Fine Element Modelling and simulation using LS-DYNA program for CANDU fuel bundles under static mechanical loads and refuelling load have been performed. The models include single CANDU fuel bundle and a string of CANDU fuel bundles. All major components including sheathes, bearing pads, spacers, endplates and endcaps are built within the model, and nonlinear contact constraints as well as non-linear material properties are incorporated in the models. Static loads applied include mechanical loads,

and refuelling hydraulic drag load. The simulation results are presented, the predicted displacements, stress and strains demonstrate good consistency, and match with the observations of CANDU fuel experience, indicating that the Candu Energy models using LS-DYNA are suitable for simulating non-linear phenomena involved in static mechanical and refuelling loading of CANDU fuel bundles.

6. Acknowledgements

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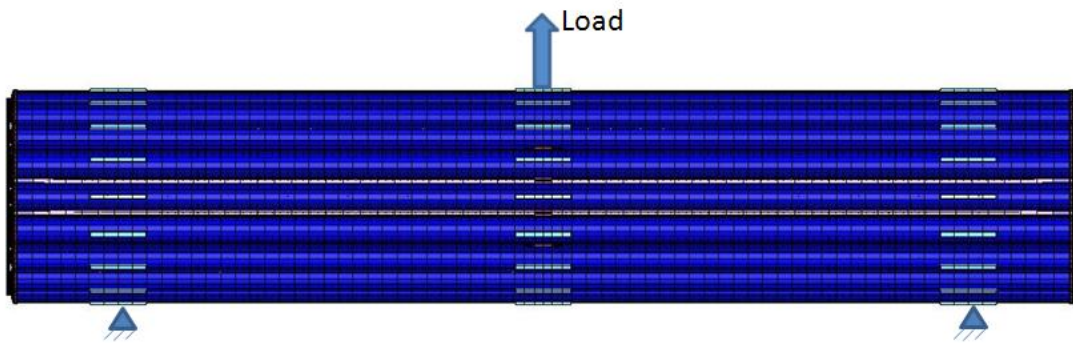


Figure 1 Model for A Bundle under Lateral Pull Load

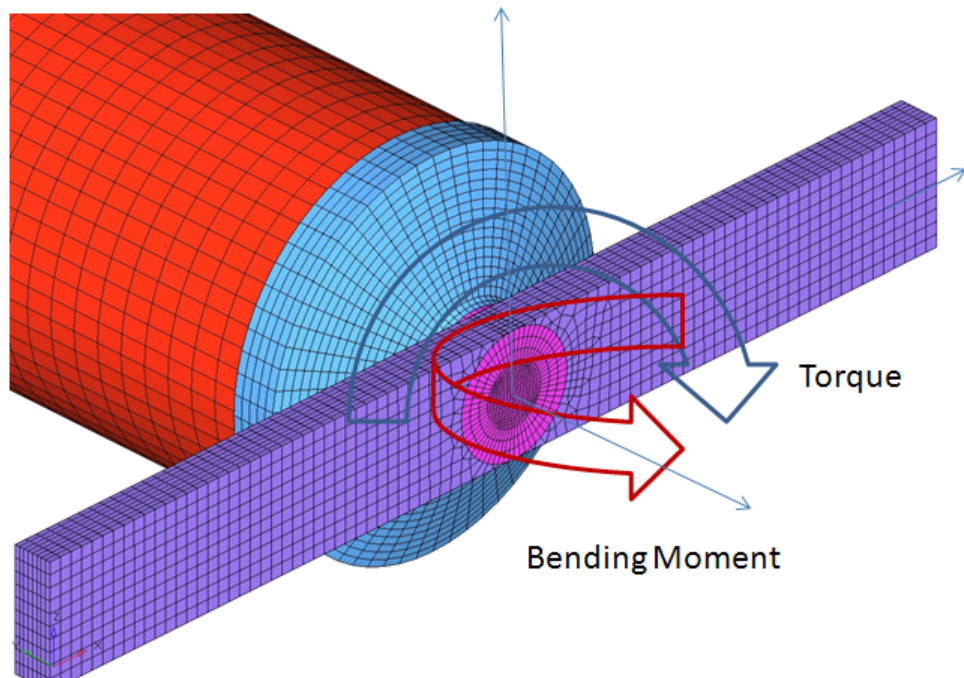


Figure 2 Model of Fuel Assembly Weld Subjects to Torque and Bending Moment

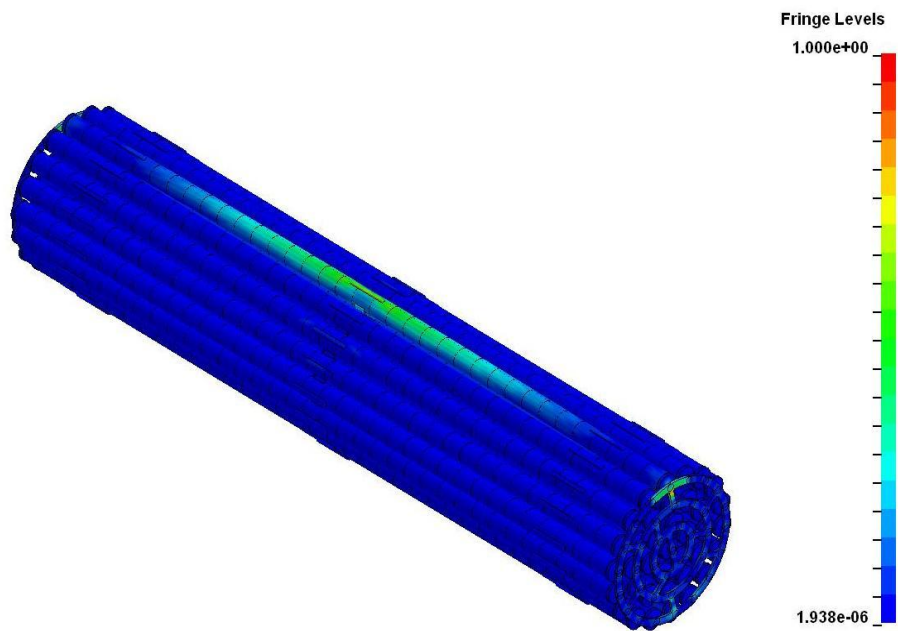


Figure 3 Normalised Stress Contour in Bundle under Pull Loading

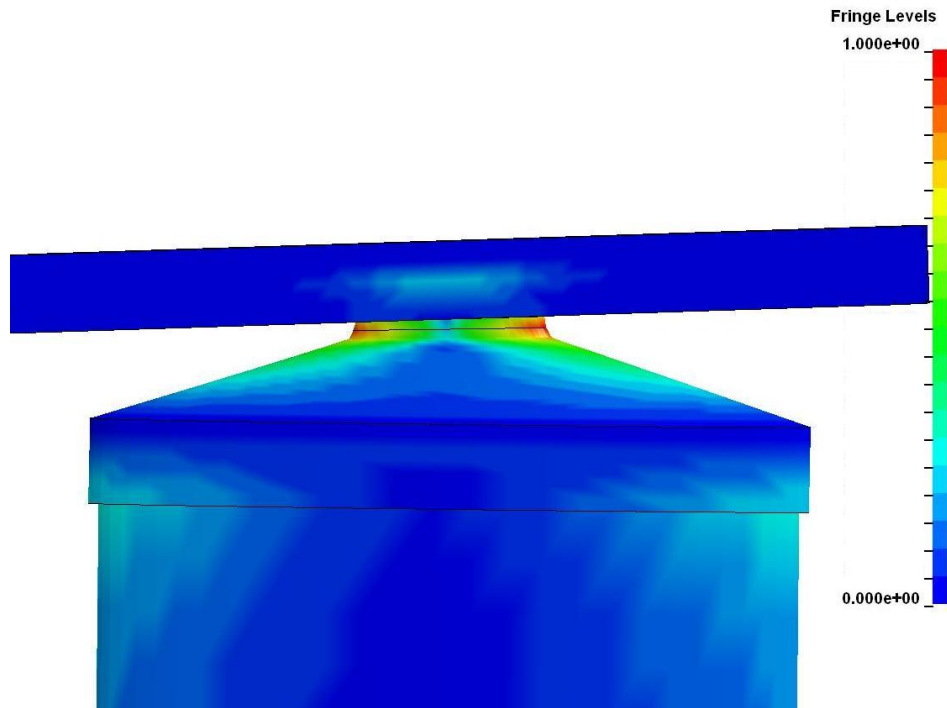


Figure 4 Normalised Stress Contour in Assembly Weld under Bending Load

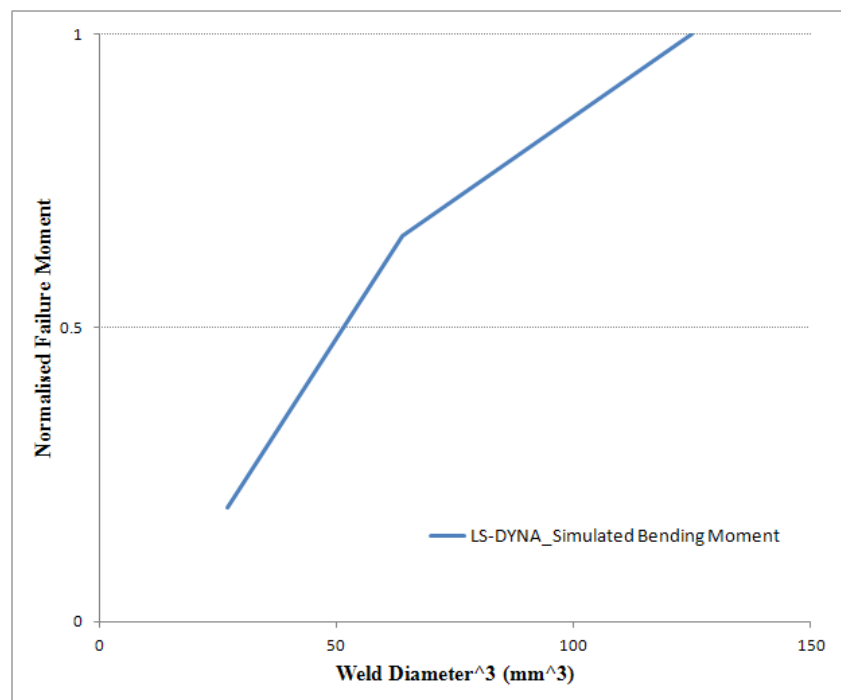


Figure 5 Normalised Failure Bending Moment vs. Cube of Weld Diameter

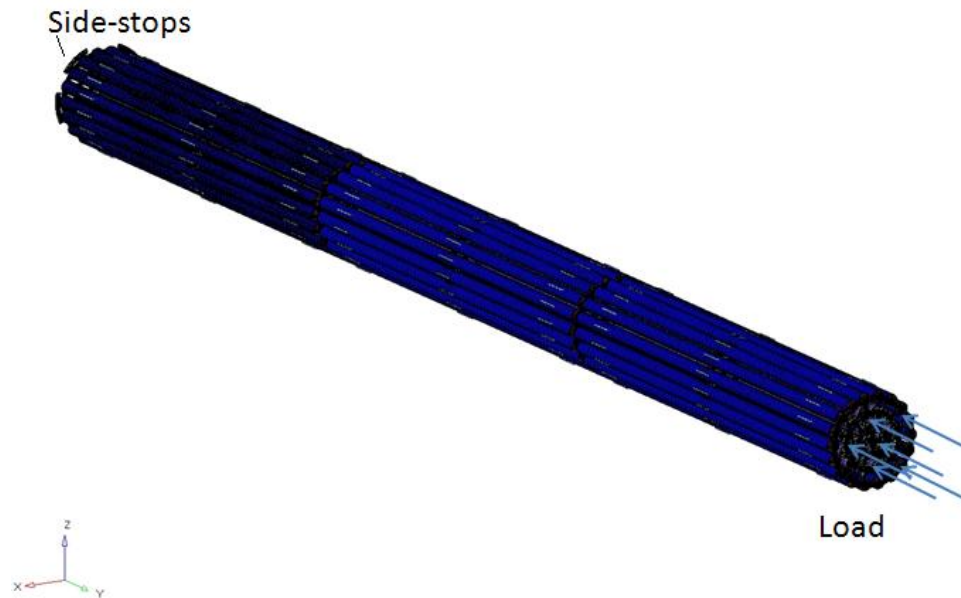


Figure 6 Model for Three Bundle String Simulation

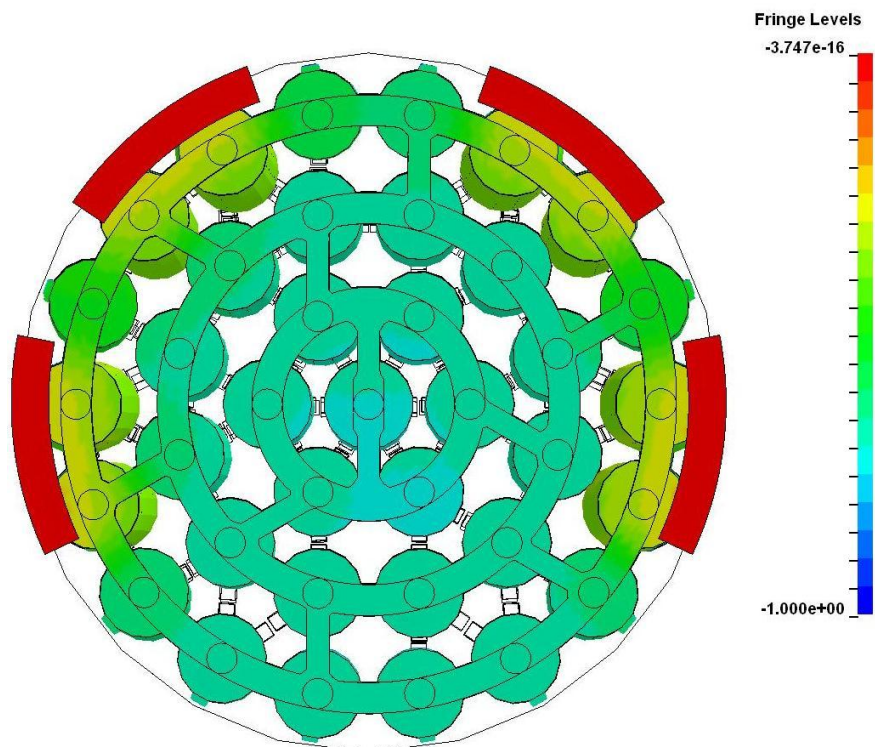


Figure 7 Normalised Displacement in Endplate near Side-stops for Three Bundle String

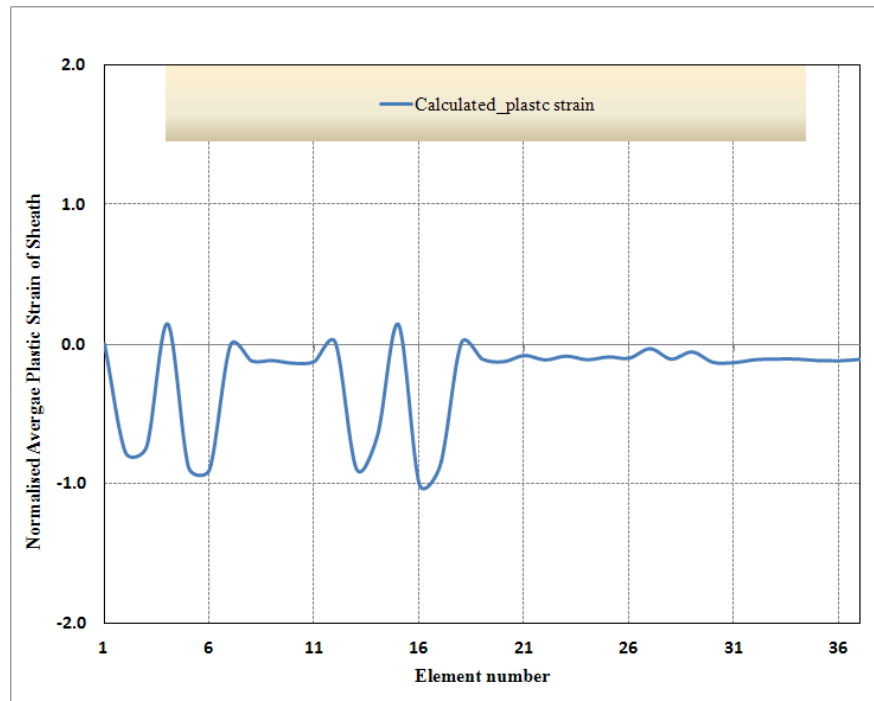


Figure 8 Normalised Average Plastic Strain in Fuel Elements in the Bundle Supported by Side-stops at High Temperature

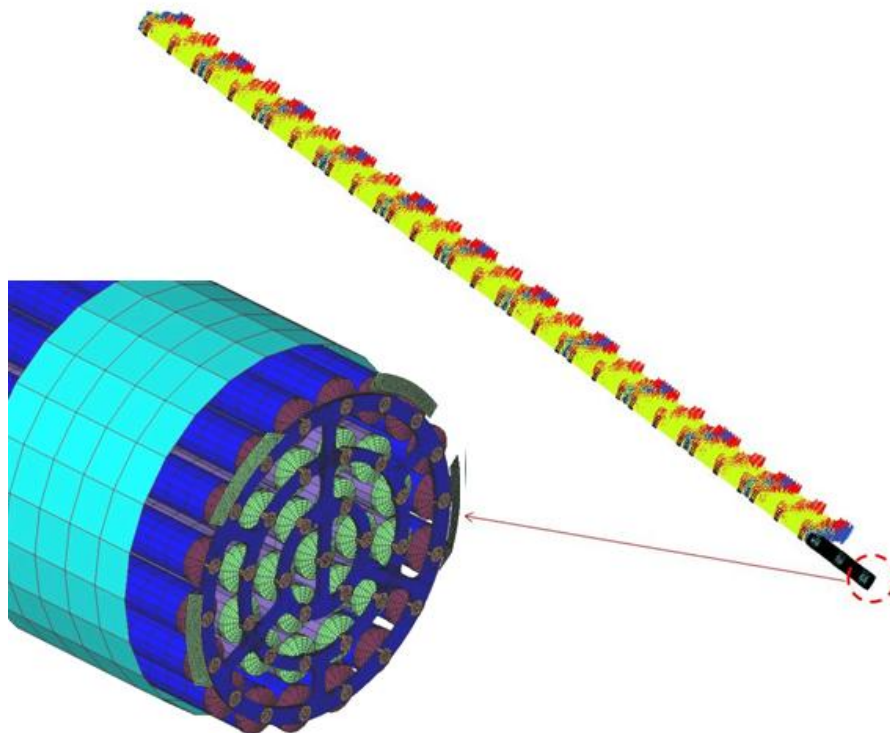


Figure 9 Model of Refuelling Load Test for a Fuel String of Twelve Bundles

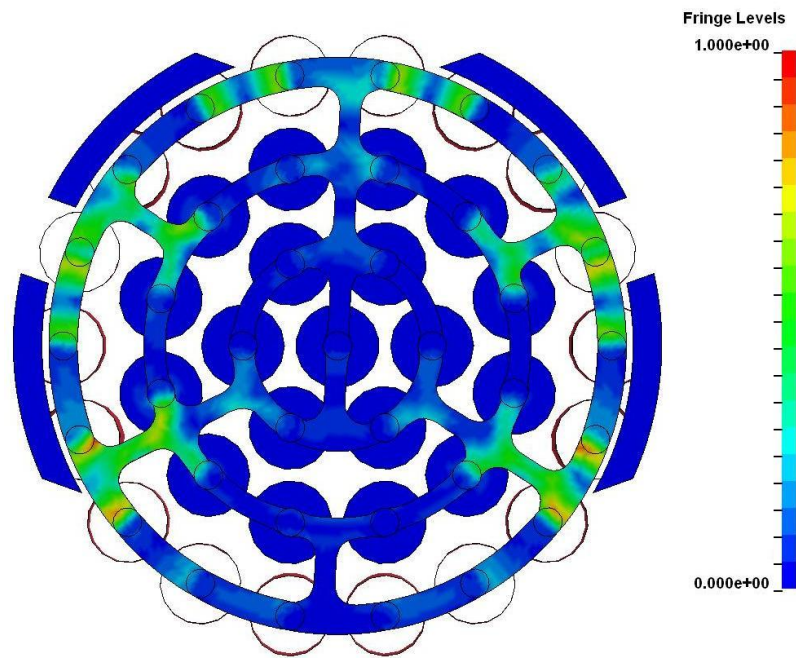


Figure 10 Normlaised Strain on Endplate During Refueling under Hydraulic Drag Load