Impact Strength Analysis of CANFLEX Fuel During CANDU-6 Normal Refueling

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ABSTRACT

A finite-element (FE) model was developed to simulate out-reactor CANDU fuel string impact tests with use of the structural analysis computer code ABAQUS. The FE model takes into account the deflection of fuel elements, and stress and displacement in endplates that are subjected to the normal refueling impact in CANDU-6 reactor. It was adapted to the conditions of the out-reactor impact tests performed with CANFLEX 43-element bundles. In overall judgment, the three dimensional analysis results are well agreed with the test results. With use of the FE model, the dynamic behavior such as stress propagation along the fuel string, whole model energy history and acceleration history of the fuel bundle string subjected to the normal refueling impact was investigated, interaction between the fuel elements was estimated and the overall integrity of the fuel bundles was assessed.

1. INTRODUCTION

There are 380 fuel channels in a CANDU-6 reactor, and twelve fuel bundles are loaded into each fuel channel. Heavy water coolant passes through the fuel bundle string to remove heat generated from the fuel.

The reference-fueling scheme of a CANDU-6 reactor is an eight-bundle shift at power. Eight new fuel bundles are inserted in the flow direction at one end of a fuel channel, and another eight fuel bundles are discharged at the other end of the same channel. For this purpose, the CANDU reactor uses identical, remote-controlled fueling machines at each face of the reactor. The fuelling machine has a revolving tubular magazine. It has twelve tubes or stations corresponding in length to two fuel bundles. Five of the twelve stations are used to store internal components of the fuel channels and fuelling machine; five stations are for fuel (total capacity of ten bundles) and the remaining two stations are for a spare channel closure and spare shield plug. The machines clamp onto the end fittings of the same fuel-channel during a refueling operation, and work together. That is, one inserts new bundles and the other receives irradiated fuel bundles, two bundles at a time.

During a normal refueling sequence, the first bundle loaded is accelerated a short distance by the coolant flow as it passes through the upstream liner hole region and hits the fuel bundles already loaded in the channel. The severity of the impact increases with the bundle velocity that depends on the acceleration distance and coolant flow. The impacting bundle and the stationary bundles in the channel are required to withstand these impact forces without any significant damage or degradation of performance.

In order to verify whether the fuel bundles would resist the impacting load during the normal refueling operation, a refueling impact test was performed for the CANFLEX 43-fuel element bundle under conservative in-reactor conditions at the KAERI CANDU Hot Test Loop facility in 1996 [1]. The result demonstrated sufficient strength of the bundle against the normal refueling impact.

In this study, a finite-element (FE) model for simulating the normal refueling impact test was developed using the structural analysis computer code ABAQUS [2]. The FE model was validated against the impact test results that were obtained from the normal refueling impact test. The FE model was found to be in reasonable agreement with experiment results. With use of the FE model, the dynamic behavior such as stress propagation along the fuel string, whole model energy history and acceleration history of the fuel bundle string subjected to the normal refueling impact was investigated, interaction between the fuel elements was estimated and the overall integrity of the fuel bundles was assessed.

2. MODEL DESCRIPTION

2.1 FE model for fuel bundle

The 43-element CANFLEX fuel bundle consists of eight components [3]. Each of fuel elements contains a controlled-length stack of natural UO_2 pellets in a Zircaloy-4 sheath. A graphite layer is coated inside the sheath and separates the sheath and the pellet to reduce pellet-sheath interaction. End caps are resistance-welded to the sheath extremities to seal the element. Endplates are welded to the end caps to hold the elements in a bundle configuration. Spacers are brazed to the adjacent elements at their mid-planes to ensure the desired minimum inter-element separations. The bundle is spaced from the pressure tube by bearing pads brazed on near both the end surfaces and the middle surface of each outer element. Another component, the so-called button is brazed on the three planes of all the elements for the enhancement of critical heat flux

(CHF).

The FE model of a fuel bundle is presented with shell, beam and truss elements. The endplates are discretized into a series of four-noded 3-D shell elements, fuel sheathes into beam elements, and spacers into truss elements. The oblong buttons are not modeled in the analysis because they hardly affect the analysis result. Pressure tube and bearing pads are not modeled either, and they are built into the analysis model by establishing appropriate boundary conditions. The interaction between them can be predicted by investigating the behavior of fuel elements at bearing pad locations. Figure 1 and 2 illustrates the FE model of a bundle and a shield plug. A specific description of the FE model for each component is presented in Table 1.

Regarding material properties, tensile properties at 266 ^{O}C are used for the analysis, which is the reactor inlet header temperature (See Table 2). Endplate is made of annealed Zircaloy-4, and fuel sheath and spacer are made of stress-relieved & cold worked (SRCW) Zircaloy-4. Therefore tensile properties for these components are different from each other, as represented in Table 2. Besides, tensile properties of these components are different from those of LWR fuel components because of different material specifications, regardless the same use of Zircaloy-4. The material property data on Table 2 are the representative for CANDU fuel components.

2.2 FE model for fuel bundle string

A fuel bundle string is modeled as a row of eleven fuel bundles, ten stationary bundles and one impacting bundle (Figure 3). The endplates of adjacent bundles are assumed to be in complete contact each other and their concavities are ignored. The FE model of the fuel bundle string is made by its actual alignment in the reactor fuel channel. The bundle #1 and #11 are modeled to have a misalignment of 75 degree, respectively with the adjacent bundle #2 and #10 to produce the worst conditions for the endplate webs during the impact [2]. The shield plug is modeled with three-dimensional solid elements. An FE model of the shield plug is shown in Figure 1. The shield plug is fixed by restraining all degrees of freedom of the nodes on the other side of the contact with the fuel string. The velocity of the impacting bundle at impact was assumed to be 2.8 m/sec, which is the actual impact speed at the test.

The coolant induced damping is simulated by specifying a damping factor that defines a damping contribution proportional to the mass matrix for a finite element. The damping forces are caused by the absolute velocities of the nodes in the model. The resulting effect can be likened to the model through a viscous "ether" so that any motion of any point in the model triggers damping forces.

3. APPLICATION TO OUT-REACTOR IMPACT TESTS

3.1 Validation of the FE analysis model

The FE model was validated against the test results that were obtained during the normal refueling impact test performed at KAERI in 1996[1]. The refueling impact test set-up, as shown schematically in Figure 3, consisted of a pressure tube with the inlet and outlet closure flange, eleven test bundles, and the downstream shield plug. The shield plug simulator was designed and fabricated to fit into the outlet end fitting of the rig. The simulated outlet shield plug supports the ten stationary bundles. During the normal refueling sequence, a new bundle is accelerated a short distance by the coolant flow as it passes through the upstream liner hole region and hits the stationary bundles that are already in the channel.

All the system parameters (pressure, temperature and flow rate) were measured by the Hot Test Loop data acquisition system (HP3054A, Hewlett Packard). To measure the velocity and displacement of the impacting bundle, the cable extension linear position and velocity transducer (Celesco, PT9301) was used. The high-speed motion analyzer (Kodak, Ekta Pro-1000) was also used to visualize and record the movement of the sensing wire with a ball indicator. The charge type force sensor (PCB, M218B) was attached to the outlet closure flange for detecting the impact force.

In this test, impact force of test bundle could not be measured. The signals from the force sensor were completely unacceptable because the force sensor that was exposed to hot condition for a long time was damaged by the high temperature. Therefore, for the verification of this FE model, permanent deformations of test bundle endplates predicted by this FE model were compared to the measurements.

Figure 4 shows endplate waviness of three test bundles. They are the impact bundle, the impacted bundle, and the downstream bundle supported by the shield plug. The differences between measurements and predictions are within 3% for all of the three endplates. Analysis results show very good agreement with the measurements.

Figure 5 shows axial displacements in the downstream endplate of the bundle that rests on the shield plug. Test results are measurements relative to the axial displacement at the location of fuel element #1. (The location of each fuel element on the endplate is shown in Figure 2.) Negative values of the displacement mean that it was pushed into the bundle. The prediction agrees well with the measurements in both trace and magnitude.

3.2 Dynamic Behavior of the Fuel Bundles

Figure 6 presents energy contents of the whole model as a function of time. At the start of the simulation bundle # 1 moves at the velocity of 2.85 m/s, and the kinetic energy is large. However, much of the kinetic energy dissipates due to the damping by the water. The deformation of fuel bundle string due to the impact transfers some energy from kinetic energy to internal energy. The internal energy stops increasing at approximately 4 ms and maintains the level from that time on. The internal energy is the sum of the recoverable elastic energy and the plastically dissipated energy, both of which are plotted in the figure. Elastic energy rises to a peak and then falls as the elastic deformation recovers, but the plastically dissipated energy keeps its level as the fuel bundle is deformed permanently. The kinetic energy rises abruptly at around 2 ms because the impact bundle (bundle #1) starts to move backward in reverse to the original direction after hitting the ten-fuel bundle string.

Figure 7 shows contact normal force on the endplate surfaces of the ten stationary fuel bundles. Fractional length of 0.0 represents a position of contact between the shield plug and the downstream bundle (bundle #11) and 1.0 represents a position of contact between bundle #2 and the impact bundle (bundle #1). The contact area at position 0.0 is small compared to other contact position because the shield plug supports only the outer and intermediate rings of the downstream endplate. The contact areas at positions 0.1, 0.9 and 1.0 are relatively small due to the intentional miss-alignment between the contacting bundles as explained in section 2.2. The normal force decreases, in general, as the bundles are placed downstream. This phenomenon happens due to the bundle deformation and the water damping as mentioned above.

Figure 8 shows axial acceleration of the stationary ten-fuel string as a function of time at its both ends, upstream endplate of bundle #2 and downstream endplate of bundle #11. It reaches a peak of 205.6 g at approximately 0.15 ms in bundle #2. Acceleration decreases, as the bundle is placed downstream. The refueling impact reaches bundle #11 at approximately 13.5 ms and shows a peak of 46.1 g at approximately 14.5 ms.

Figure 9 shows the histories of Von-Mises stress at five points along the length of the fuel bundle string. The stress data are taken from the endplate of the bundles #2, #4, #6, #8 and #10 at similar radial and circumferential locations. The stress propagates through the bundle string. The stress at the point increases as the stress travels through the point. Once the stress wave has passed completely through the point, the stress at the point oscillates about a constant value. The stress intensity reduces as the bundle places downstream because deformation of the downstream bundles and the water absorbed large part of the impact energy.

3.3 Interaction between Fuel Elements

As the impacting bundle hits the fuel bundle string in the channel, the fuel elements of the impacting or the impacted bundles interact with adjacent elements. Because this FE model cannot simulate the contact between elements, the interaction between elements can be predicted by reviewing the radial displacement and the radial velocity of the fuel elements that are calculated without considering the inter-element contacts.

Figure 10 illustrates histories of an element radial displacement at a specific point in each bundle of the fuel string. These results are obtained without considering the inter-element contacts. Bundle #11 showed the biggest radial displacement among the eleven bundles because of its worst boundary condition, two-ring support from the shield plug. Magnitude of radial displacement is bigger in intermediate ring element than in the outer ring element because the shield plug supports only the inner-edge of the intermediate ring. Magnitude of radial displacement shows a peak of 0.23 mm in the intermediate ring and 0.13 mm in the outer ring at approximately 25.5 ms. Considering that the radial clearance between elements do not exceed 0.13 mm in outer ring and intermediate ring of CANFLEX fuel [4], fuel elements in those rings are predicted to collide with the adjacent fuel elements as a consequence of the fuel loading impact. Radial velocity is investigated to estimate the inter-element interaction. Magnitude of radial velocity shows a peak of 145 mm/s in the intermediate ring and 79 mm/s in the outer ring at approximately 23.5 ms. Therefore, the inter-element interaction due to the normal refueling impact has a negligible effect on the fuel element integrity.

3.4 Fuel Integrity

Figure 11 shows the stress contour of the impacting bundle downstream endplate at the time of its stress peak. High stress appears in the inner ring and webs. Because the shield plug supports the outer and the intermediate ring only, large strain occurs in the inner ring and the webs and consequently results large stress in the region. Figure 12 shows the history of the Von-Mises stress at the point of highest intensity on the endplates of the bundle #1 and the bundle #2. The stress on both endplates reaches a maximum of 180 MPa at approximately 1.5 ms and oscillates about 130 MPa afterwards. The magnitude of 180 MPa is bigger than the material yield strength (165 MPa) and results in a permanent deformation of 0.36 mm in waviness.

Figure 13 shows the stress contour of the impacting bundle fuel elements at the time of its stress peak. High stress appears on the impact side (+3 direction) of the fuel elements. Fuel elements in the outer and the intermediate ring elements show higher stress than those in the inner ring. Figure 14 shows the history of the principal stress at points of highest intensity in the fuel elements of the bundle #1 and the bundle #2, respectively. The element stress of the impacting bundle reaches a peak of -60 MPa (Compressive stress) at approximately 1.5 ms. That is much lower than its material yield strength (314 MPa) and the stress diminishes showing oscillations about zero MPa .

4. CONCLUSION

(1) An impact analysis FE model was developed to simulate out-reactor fuel string impact tests with use of the structural analysis code ABAQUS. This model was verified against test results on endplates axial displacements and waviness obtained from a normal refueling impact test for CANFLEX and the 37-element fuel. The predictions were in good agreement with the measurements.

(2) The deformation of the fuel bundle string transfers energy from kinetic energy to internal energy. However, most of the kinetic energy dissipates due to the damping by water. Axial acceleration reaches a peak of 205.6 g at approximately 0.15 ms in bundle #2. Acceleration decreases, as the bundle is placed downstream. The refueling impact reaches bundle #11 approximately at 13.5 ms and shows a peak of 46.1 g at approximately 14.5 ms.

(3) Interaction between fuel elements was investigated by reviewing the radial displacement and the velocity of the fuel elements. Magnitude of radial displacement shows a peak of 0.23 mm in the intermediate ring and 0.15 mm in the outer ring at approximately 18.5 ms. Radial velocity shows a peak of 156 mm/s in the intermediate ring and 102 mm/s in the outer ring. Therefore, the inter-element interaction due to the normal refueling impact has a negligible effect on the fuel element integrity.

(4) The maximum stress appears on the endplate of the bundle #1 and it reaches a peak of 180 MPa in Von-Mises stress, and results in a permanent deformation of 0.36 mm in waviness. The element stress of the impacting bundle reaches a peak of − 60 MPa, much lower than its material yield strength (314 MPa). Therefore it is concluded that CANFLEX fuel withstand the normal refueling impact without neither significant bundle deformation nor degradation of performance.

Acknowledgement

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References

[1] S. K. Chang, J. S. Park, C. H. Chung, H. C. Suk, P. Alavi, I. E. Oldaker and W.W. Inch, "Test Report - CANFLEX Fuel Bundle Impact Test", KAERI/TR-CX-301, 1997 April.

[2] Hibbitt, Karlson & Sorensen, Inc., "ABAQUS/Standard User's Manual", Ver. 5.8, 1998

[3] Fuel Bundle Design Drawing, "Joint AECL-KAERI CANFLEX 43 Element Bundle (CANDU-6) Reference Drawing", CANFLEX-37000-1-1-GA-E, Rev. 5, KAERI/AECL, 2000 October.

Table 1. Description of FE model for each component

Component	ABAQUS element type	Element description	Remark
Endplate	**S4R**	**4-Node, 3D Shell 6 DOF**	**422 elements per plate**
Fuel sheath	**PIPE31**	**2-Node, 3D Pipe 6 DOF**	**6 elements per rod**
Spacer pad	**T3D2**	**2-Node, 3D Truss 3 DOF**	

Table 2. Material properties at 266 °C [a]

Component	Young's modulus	Yield strength	Ultimate tensile strength	Poisson's ratio
Endplate	**79,706 MPa**	**165 MPa**	**281 MPa**	**0.4**
Cladding tube	**83,882 MPa**	**314 MPa**	**421 MPa**	**0.4**
Spacer	**83,882 MPa**	**-**	**-**	**0.4**

[a] Engineering Manual, DE-13(5.3-1), "Zirconium Alloys – Mechanical Properties and Corrosion Resistance", Chalk River Nuclear Laboratories Engineering Manual, 1969

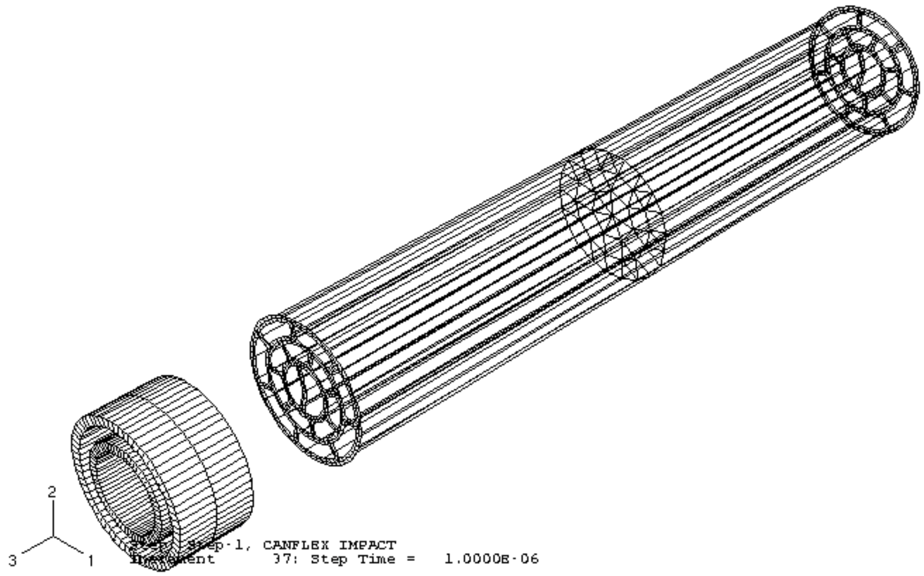

Figure 1. FE model for CANFLEX fuel bundle and shield plug

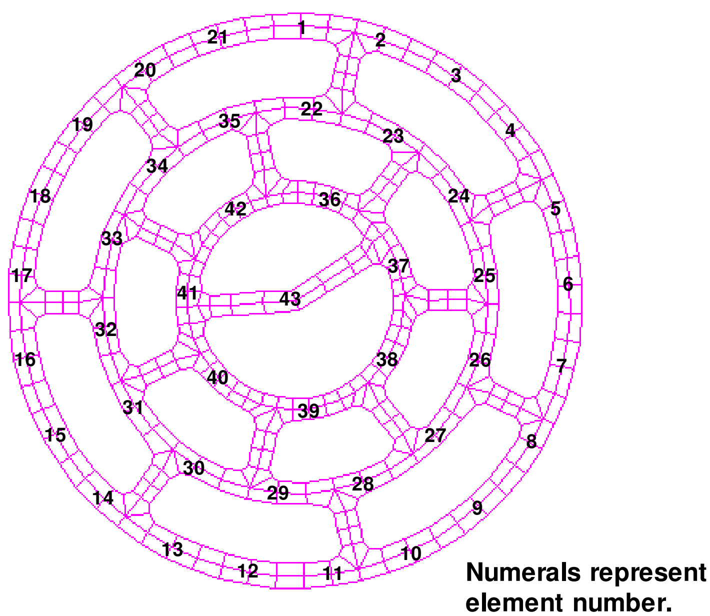

Figure 2. Illustration of FE model for endplate

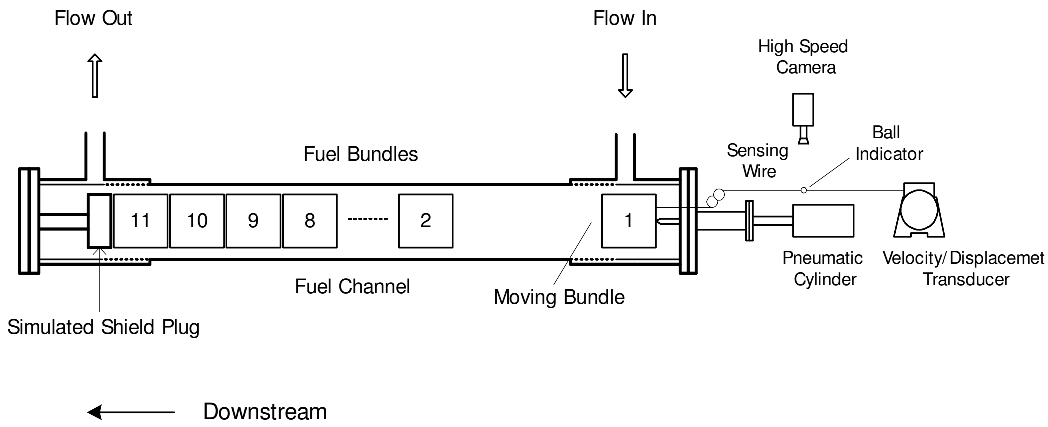

Figure 3. Schematic diagram of refueling impact test set-up

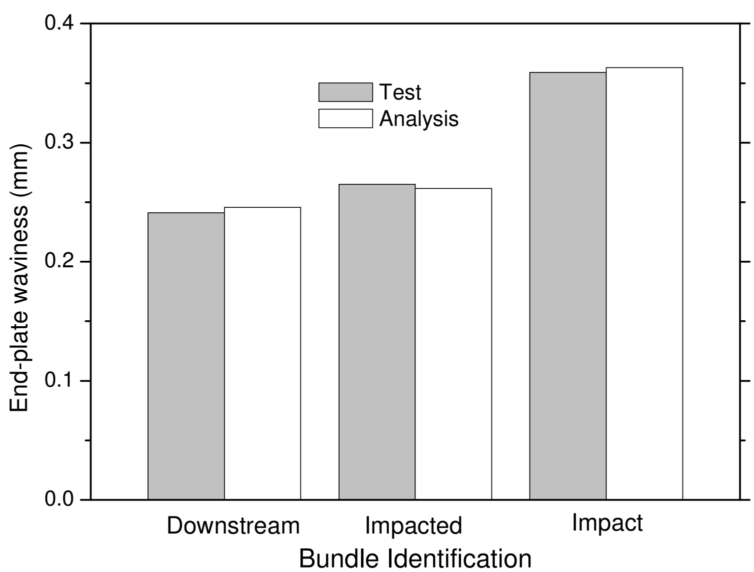

Figure 4. Predicted waviness vs. measured one in endplates

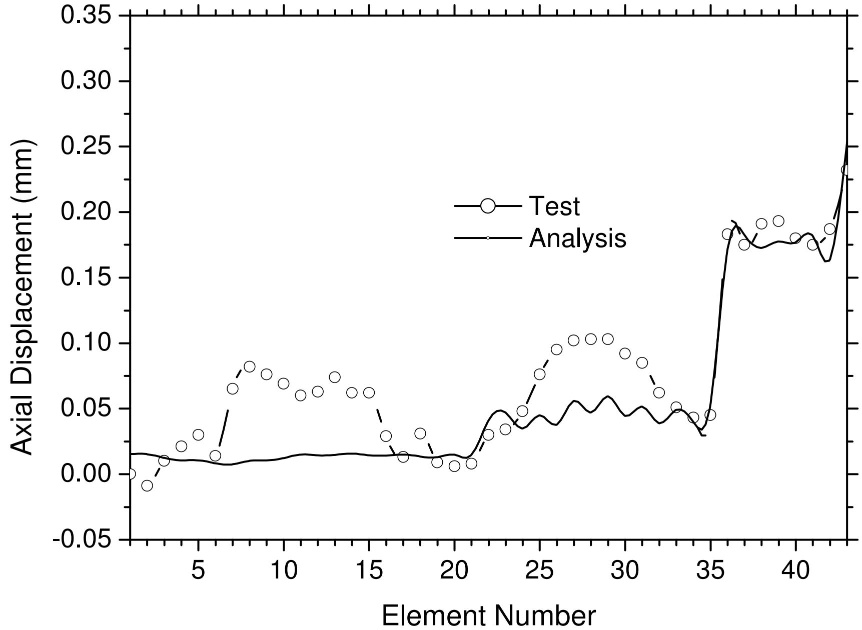

Figure 5. Predicted axial displacement vs. measured one in downstream endplate

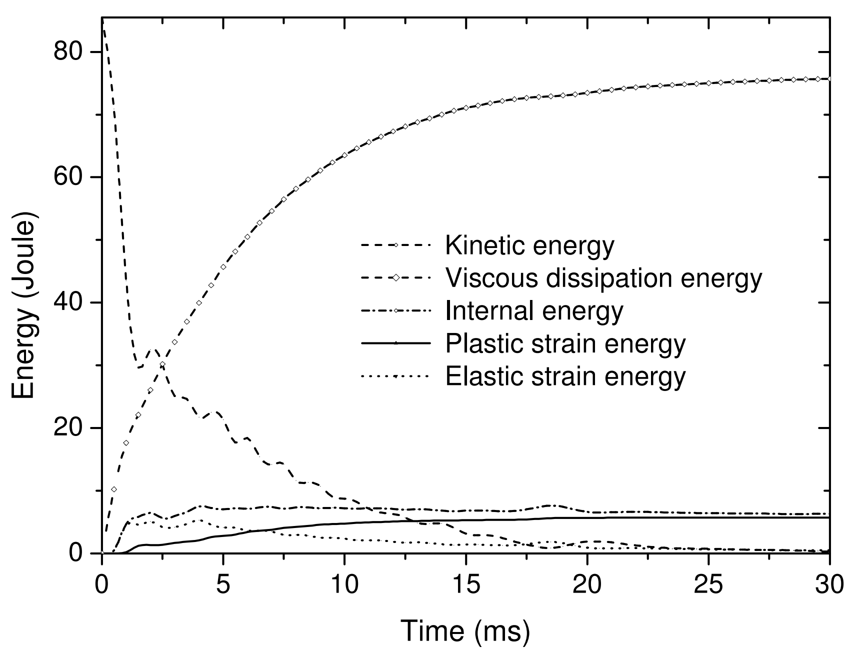

Figure 6.   Energy terms as a function of time

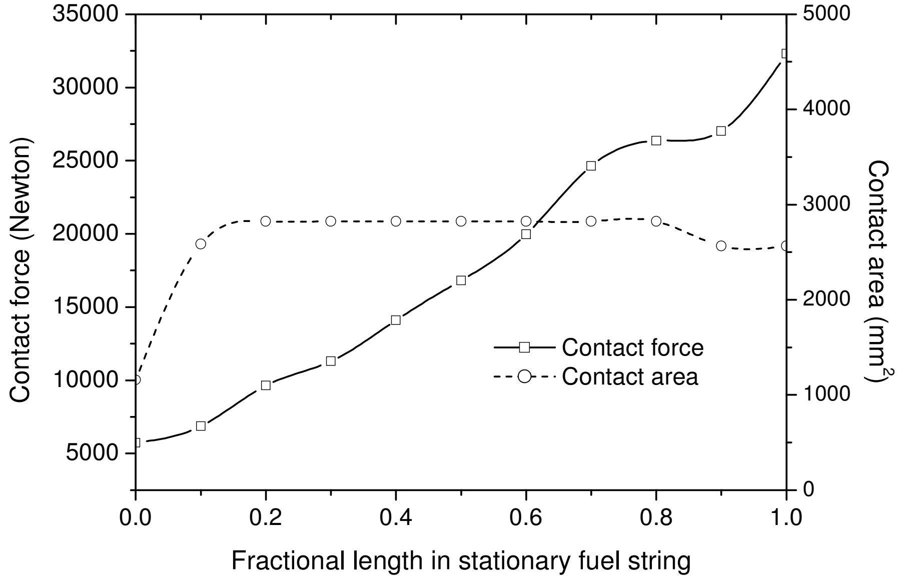

Figure 7. Contact normal force and contact area in fuel string

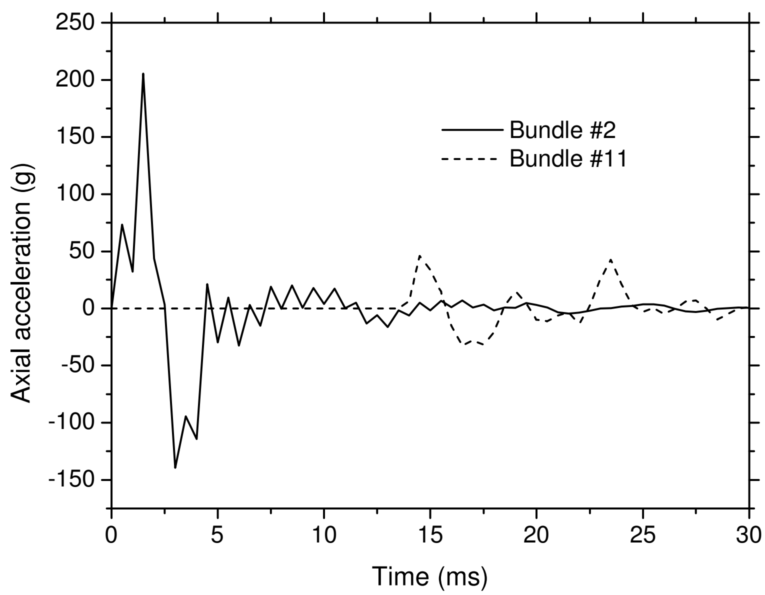

Figure 8. Axial acceleration histories of bundle #2 and #10

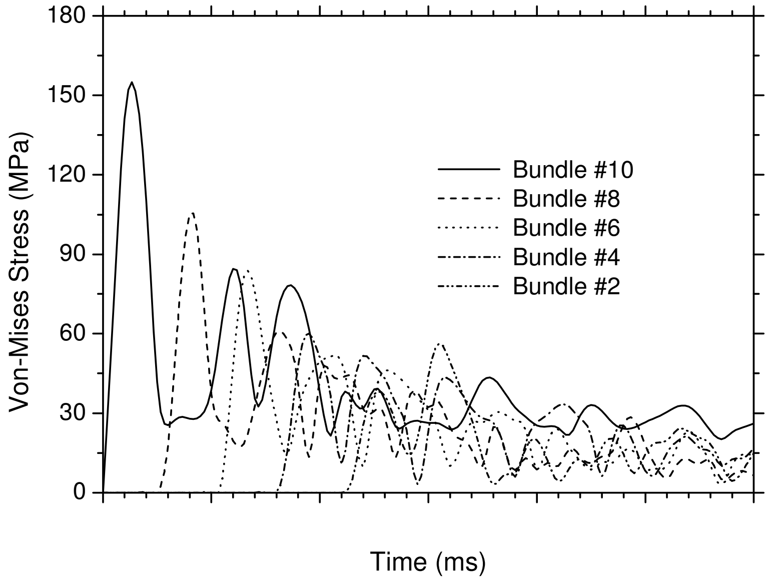

Figure 9. Time histories of stress at five points in fuel string

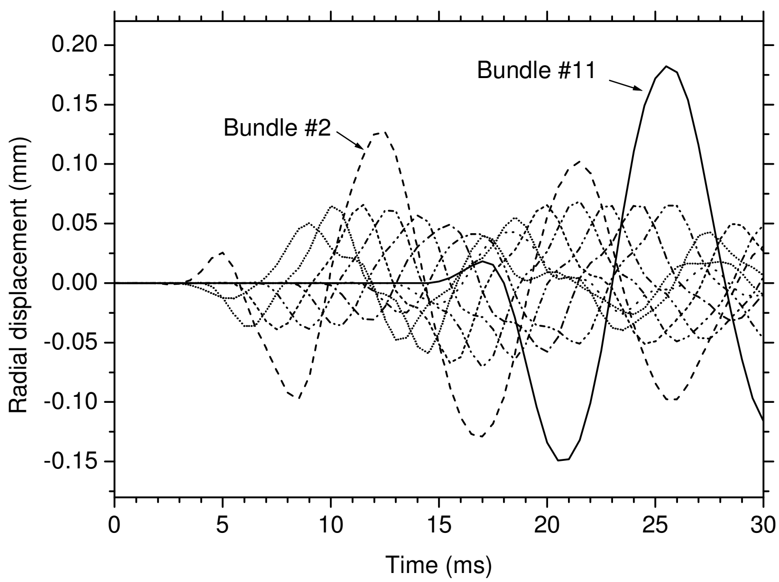

Figure 10. Element radial displacement histories of the ten-fuel string

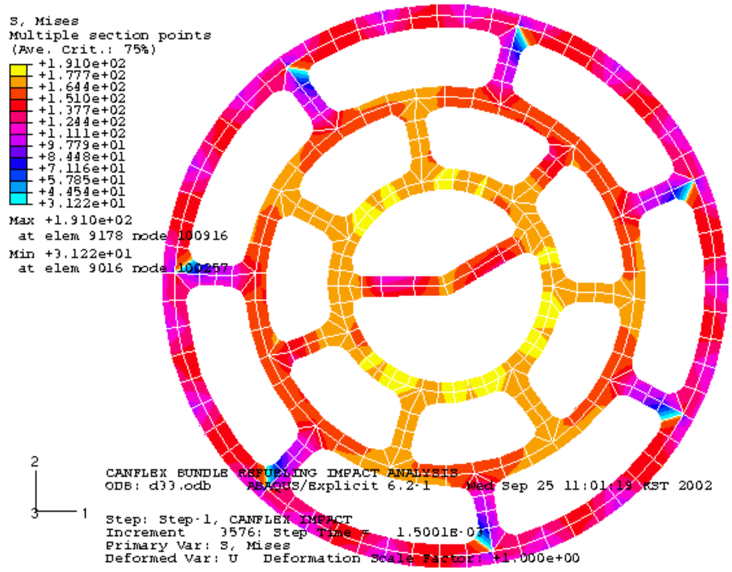

Figure 11. Stress contour of impacting bundle downstream endplate

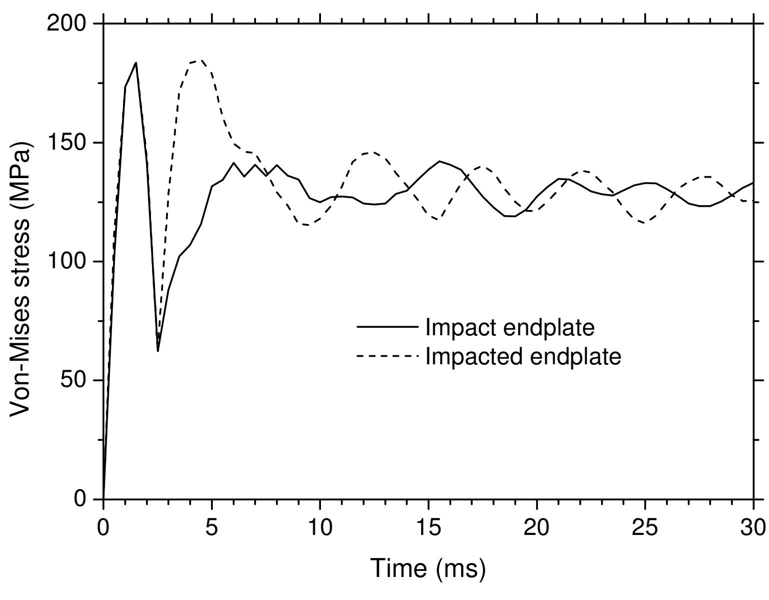

Figure 12. Time history of Von-Mises stress on endplate of impacting bundle

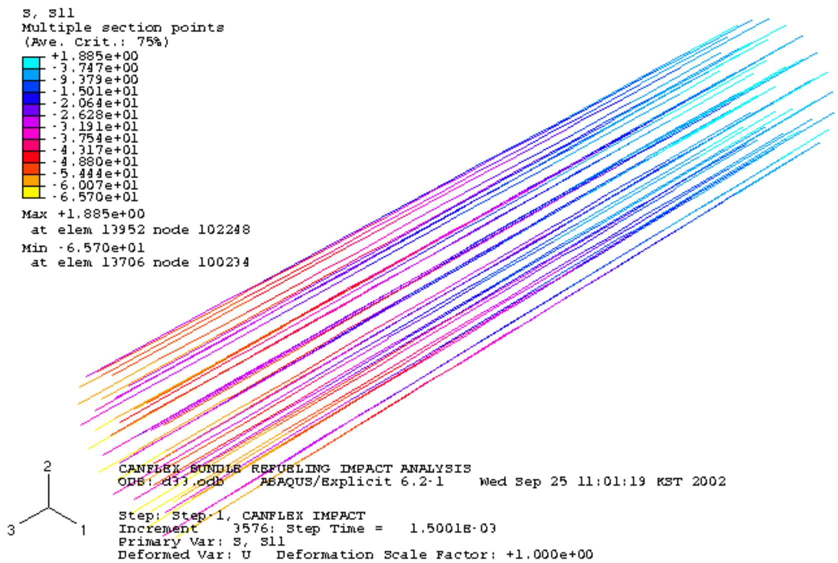

Figure 13. Stress contour of impacting bundle fuel element

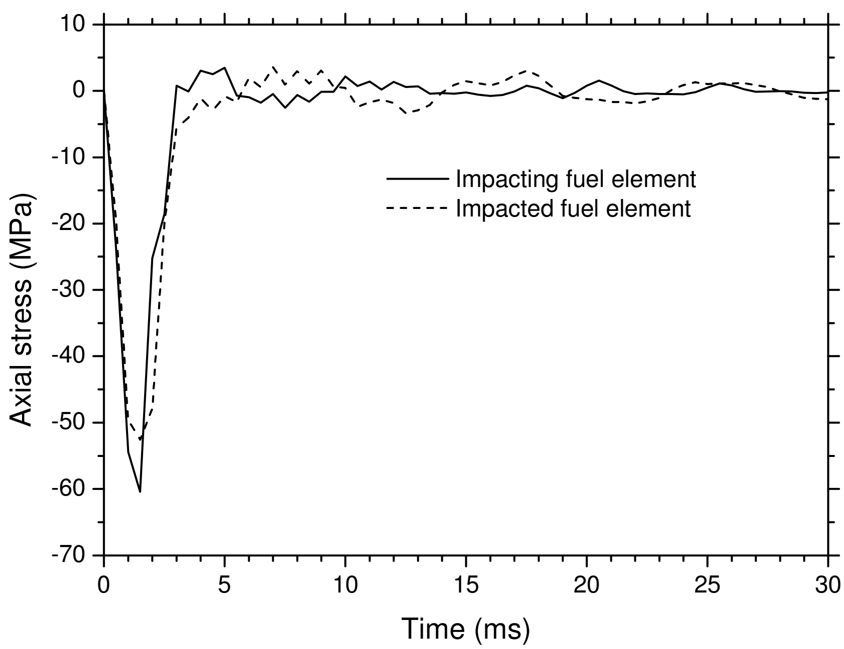

Figure 14. Time history of Von-Mises stress in fuel element of impacting bundle