Impact Strength Analysis of CANFLEX Fuel During LOCA Condition

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ABSTRACT

A structural analysis was performed to simulate the impact of the fuel bundle string on the inlet shield plug during a 100% Reactor Inlet Header (R.I.H) brake accident in a CANDU-6 Reactor. Any significant damage to either the fuel or the fuel channel due to the collision could result in coolant flow blockage, and thus pose additional safety related concerns beyond those addressed for the initial loss-of-coolant accident. A finite-element (FE) model for simulating the collision was developed using the structural analysis computer code ABAQUS. The FE model was validated against the test results that have been obtained during the normal refueling impact test performed at KAERI in 1996. With use of the FE model, dynamic behavior of the fuel bundle string impacted on the shield plug was investigated and its effects on the fuel bundles and pressure tube were evaluated. The overall integrity of the fuel bundles as well as the possibility of bundle sticking or coolant flow blockage in the pressure tube 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. Due to the flow, a significant amount of the header-to-header pressure drop occurs in the fuel bundle string.

The hydraulic drag exerted by coolant flow past fuel bundles in a fuel channel forces the entire fuel string against the down-stream shield plug during normal reactor operations. If a break should occur in the upstream feeder, then the channel flow would rapidly reverse, forcing the string of bundles to accelerate and impact on the upstream shield plug. Should such an accident occur, the potential exists for bundle and channel damage, depending primarily on the velocity of the bundles at impact.

Energy considerations of moving fuel bundles impacting a stationary shield plug show that damage could occur to the fuel bundles, or the channel components, or both. Any significant damage to either the fuel or the fuel channel could result in coolant flow blockage, and thus pose additional safety related concerns beyond those addressed for the initial loss-of-coolant accident. Thus, the fuel bundles and the channel components are required to withstand these impact forces during a break accident of inlet piping.

A finite-element (FE) model for simulating the collision was developed using the structural analysis computer code ABAQUS [1]. The FE model was validated against the impact test results that were obtained during the normal refueling impact test performed at KAERI in 1996. The FE model was found to be in reasonable agreement with experiment results. With use of the FE model, the dynamic behavior of the fuel bundle string impacted on the shield plug was investigated and its effects on the fuel bundles and pressure tube were evaluated. The overall integrity of the fuel bundles as well as the possibility of bundle sticking or coolant flow blockage in the pressure tube was assessed.

2. MODEL DESCRIPTION

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. Pressure tube and bearing pads are not modeled, 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 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°C are used for the analysis, which is the reactor inlet header temperature (See Table 2).

The FE model of the fuel bundle string is made by its actual alignment in the reactor fuel channel. A fuel bundle string is modeled as a row of twelve fuel bundles (Figure 2). The endplates of adjacent bundles are assumed to be in complete contact each other and their concavities are ignored. The twelve bundles are modeled to have an angle of 28 degrees clockwise, when viewed from the inlet, relative to the adjacent downstream bundle. The angle of 28 degrees is the bundle alignment angle in which the most probable pressure drop can be achieved in the pressure drop test with the CANFLEX fuel bundle string [2]. In such a manner, the actual random alignment of the twelve bundles in the fuel channel is simulated. 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.

During normal reactor operations, the hydraulic drag exerted by coolant flow past fuel bundles in a fuel channel forces the entire fuel string against the down-stream shield plug. If a break should occur in the upstream feeder, then the channel flow would rapidly reverse, forcing the string of bundles to accelerate and impact on the upstream shield plug. The severity of the impact increases with the velocity of the bundle string. In this analysis, the velocity of the bundle string at impact was assumed to be 4.0 m/sec. This is a maximum velocity that is based on a 100% Reactor Inlet Header (R.I.H.) break during channel normal operation [3].

Damping by the coolant is simulated by specifying a damping factor that defines a damping contribution proportional to the mass matrix for a finite element. The damping forces that are introduced 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. 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. 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.

With the use of the bundle FE model described in section 3, the normal refueling impact test was simulated. The FE model of the fuel bundle string is made by its actual alignment in the test. The endplates of adjacent bundles are assumed to be in complete contact with each other and their concavities are ignored. A fuel bundle string is modeled as a row of eleven fuel bundles, ten stationary bundles and one moving bundle. The simulated outlet shield plug supports the ten stationary bundles. The one moving bundle impacts the ten stationary bundles by hitting the upstream bundle endplate-to-endplate. The velocity of the moving bundle at impact is 2.8 m/sec, which is the actual impact speed at the test.

In the 1996 normal refueling impact test, accelerations of test bundles were not measured. 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 3 shows endplate waviness of three test bundles. They are the moving bundle, the impacted bundle and the downstream bundle supported by the shield plug. Analysis results show quite good agreement with the measurements for the moving and the impacted bundles whereas the downstream bundle shows a fairly bigger value of prediction over the measurement. This might be attributed to the imperfect simulations of the boundary condition and the damping effect by the coolant.

Figure 4 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. Negative values of the displacement mean that it was pushed into the bundle. Magnitude of waviness shows quite a big difference between the measurements and the predictions but analysis results trace the measurements very well.

4. RESULTS AND DISCUSSIONS

4.1 Dynamic Behavior of the Fuel Bundle String

Figure 5 presents energy contents of the whole model as a function of time. The deformation of the fuel bundle string transfers energy from kinetic energy to internal energy. It is seen that the internal energy increases as the kinetic energy decreases. However, much of the kinetic energy dissipates due to the damping by the water. 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 continues to rise as the fuel bundle is deformed permanently.

Figure 6 shows axial acceleration at midpoints of outer ring elements in bundles #1, #2 and #3 as a function of time. It reaches a peak of 610 g at approximately 1 ms in bundle #1. The maximum acceleration at the point decreases as the bundle is placed upstream and so does the impact force.

Figure 7 shows the histories of Von-Mises stress at six points along the length of the fuel bundle string. The stress data are taken from a point of fuel element at similar radial and circumferential locations in the bundles of #1, #3, #5, #7, #9 and #11. 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 zero. The time difference between the steep stress rise in each bundle shows that it takes about 0.5 ms to transfer the impact to the adjacent bundle. The stress intensity reduces as the bundle places upstream because crushing of the downstream bundles and the water absorbed part of the impact energy.

4.2 Interaction between Fuel Bundle and Pressure Tube

Figure 8 shows the history of radial deflection at the midpoint of an outer ring element that shows the largest deflection in bundle #1. Magnitudes of radial deflections show a peak of 11.7 mm at approximately 14.5 ms. The radial displacements become smaller as the bundle locates upstream and the maximum displacement in bundle #3 is approximately 1.5 mm. However, radial deflection of the fuel element is constrained by the pressure tube and adjacent fuel elements in the actual CANDU reactor. Diametral clearance between the pressure tube and the bearing pad of the outer ring element is about 1 mm and the gap between the fuel elements is less than 1 mm [4]. Therefore, the fuel elements of these bundles are predicted to collide with the pressure tube or the adjacent fuel elements. The impact between fuel elements or the impact on the pressure tube is not simulated in this model. Instead, magnitudes of maximum radial velocities at midpoints of the fuel elements are calculated.

Figure 9 shows the history of radial velocities at the midpoint of an outer ring element that shows the largest velocity in bundle #1. It reaches a peak of 1.1 m/s at approximately 18 ms. In reality, however, fuel elements impact the pressure tube at a far lower velocity due to the narrow gap between the pressure tube or the adjacent fuel elements. Considering the energy balance, much of the lateral kinetic energy would be transferred to the axial kinetic energy. Therefore, damage of the pressure tube is not expected due to the impact by the reverse flow during a 100% RIH brake accident.

To investigate the possibility of bundle sticking in the pressure tube, radial displacements of the upstream and the downstream endplate of bundle #1 are calculated. Its time history showed peaks at approximately 14 ms. Figure 10 shows radial displacements of the upstream and the downstream endplate of bundle #1 at 14 ms. Upstream endplate shows a decrease of radius because the inner ring and center fuel elements bulge out and the plane figure of the endplate reduces in diameter after the impact. However, in the downstream endplate, a minor increase in diameter is observed in a part, in spite of the decrease in its diameter as a whole. Radial displacement at the location of 130 degree shows radial outward deflection of 0.3 mm, but it is smaller than the diametral clearance between the pressure tube and the outer ring element. Therefore, it can be concluded that there is a weak possibility of bundle sticking in the pressure tube.

4.3 Fuel Integrity

Figure 11 shows the stress contour of the downstream end plate at 5 ms. High stress appears at the junctions of the intermediate ring and the webs. Because the diameter of the shield plug inner ring is slightly smaller than the diameter of endplate intermediate ring, the shield plug cannot provide complete support for the intermediate ring. Therefore, the shield plug tends to penetrate into the intermediate ring, and junctions of the intermediate ring and the webs show large deformations. Figure 12 shows the history of the Von-Mises stress at the high stress point on the downstream end plate of bundle #1 that impacts the shield plug due to the reverse flow. The stress reaches a maximum of 281 MPa at approximately 1 ms and maintains the intensity for the rest of the calculation time. The magnitude of 281 MPa corresponds to the ultimate tensile strength of the material and the equivalent plastic strain at those points exceeded 30%. Therefore, localized failure is expected at the high stress points.

Figure 13 shows stress contour of the downstream endplate of bundle #2, which appears different from that of bundle #1. Highest stress occurs at the outer ring of the endplate because the outer ring supports a large portion of the impact load. Figure 14 shows the maximum Von-Mises stress of the downstream endplate of bundle #2 as a function of time. The stress reaches a peak of 281 MPa at approximately 14 ms and two more peaks follow afterwards. Therefore, it is not expected that the downstream endplate is wholly free from failure.

Maximum Von-Mises stress in the fuel element is as high as 320 MPa. However, the fuel element is predicted to maintain better integrity than the endplates considering its high yield strength.

5. CONCLUSION

(1) An impact analysis FE model was developed to simulate the impact of the fuel bundle string against the inlet shield plug during a 100% R.I.H brake accident in a CANDU-6 reactor 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 reasonable agreement with the measurements.

(2) The deformation of the fuel bundle string transfers energy from kinetic energy to internal energy and much of the kinetic energy dissipates due to the damping by water. The impact force in bundle #1 shows a steep rise just after the impact and decays as time passes. Axial acceleration at the midpoint of outer ring elements reaches a peak of 610 g at approximately 1 ms. The impact force of the individual bundle reduces as the bundle places upstream and so does the stress intensity.

(3) Interaction between the fuel bundle and pressure tube is investigated. Lateral impact to the pressure tube by the fuel element will be small and the pressure tube damage is not expected. The deformation shape of the endplates in bundle #1 assures that the sticking of the bundles or coolant flow blockage in the pressure tube will not occur.

(4) Stress contour of the endplates in bundles #1 and #2 showed high stress intensity that corresponds to the ultimate tensile strength of the material at some points. The equivalent plastic strain at those points exceeded 30%. Therefore, failure of the endplates is expected in bundles #1 and #2.

Acknowledgement

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References

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

[2] 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.

[3] Component Verification Specification -- CANFLEX Fuel Bundle Impact Test during LOCA Condition, To be issued in 2001.

[4] 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

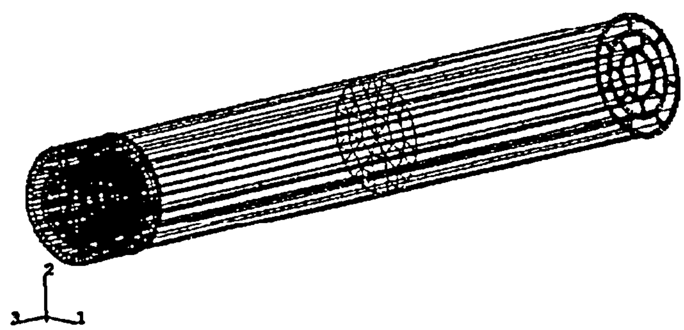


Figure 1. FEM model for CANFLEX fuel bundle and shield plug

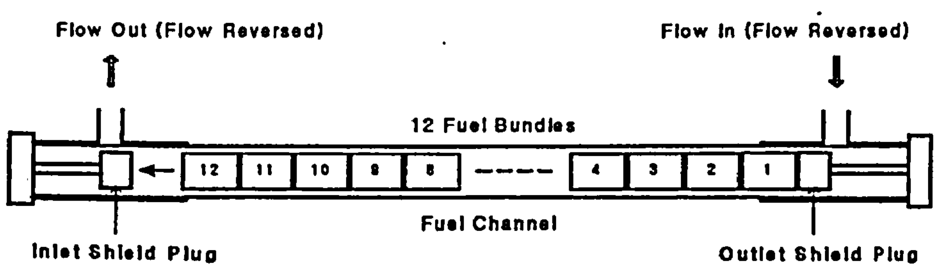
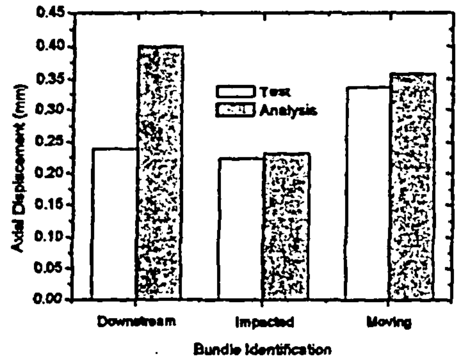


Figure 2. Schematic diagram of fuel string impact to the inlet shield plug



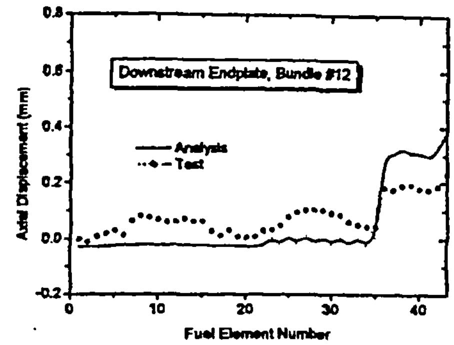
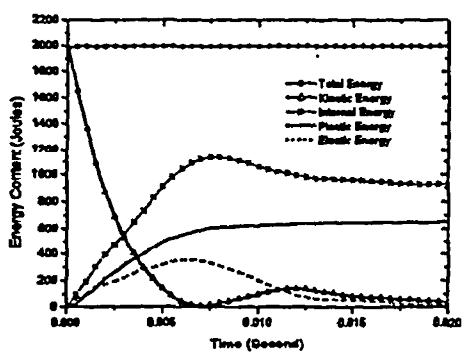


Figure 3. Predicted vs. measured waviness in downstream endplates of three test bundles

Figure 4. Predicted vs. measured axial displacement in endplate supported by shield plug



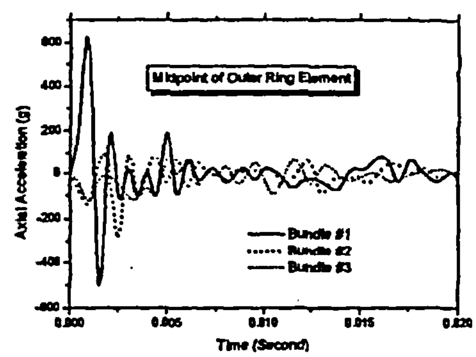
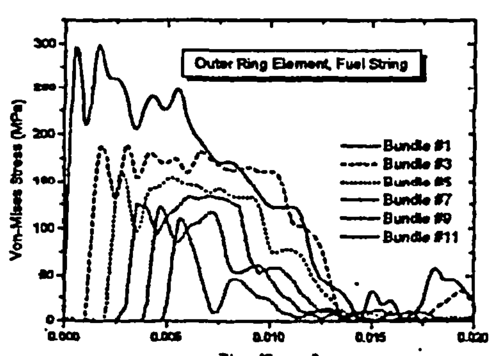


Figure 5. Energy terms as a function of time

Figure 6. Axial acceleration history of bundle #1 ,#2 and #3



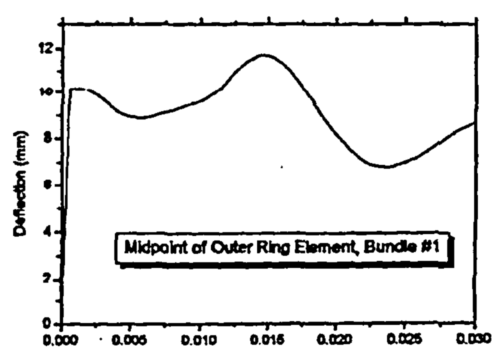


Figure 7. Time history of stress at six points along the fuel string

Figure 8. Radial deflection of bundle #1 outer ring element as a function of time

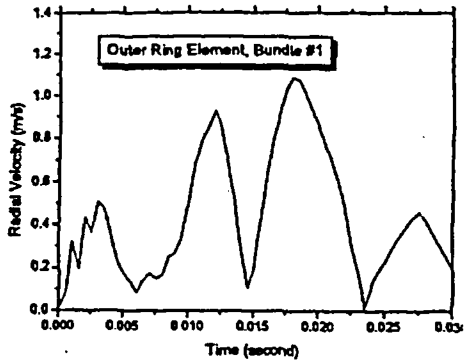


Figure 9. Radial velocity of bundle #1 outer ring element as a function of time

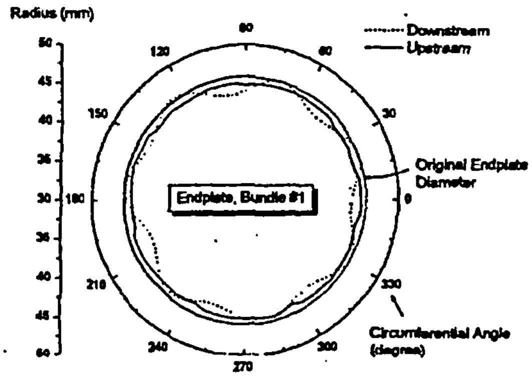


Figure 10. Radial displacement of endplates in bundle #1

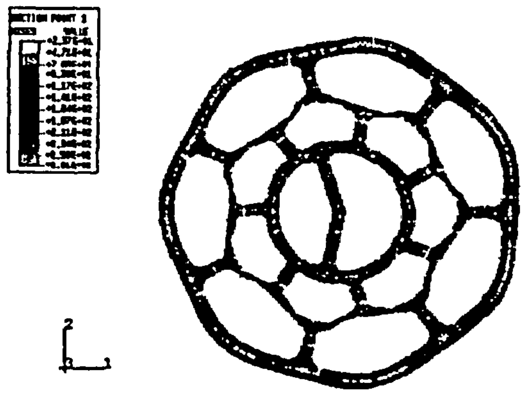


Figure 11. Stress contour of bundle #1 downstream endplate

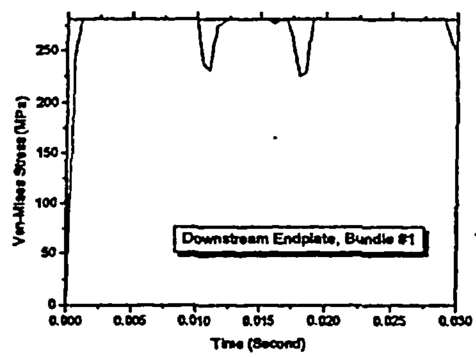


Figure 12. Time history of Von-Mises stress at high stress area in bundle #1 downstream endplate

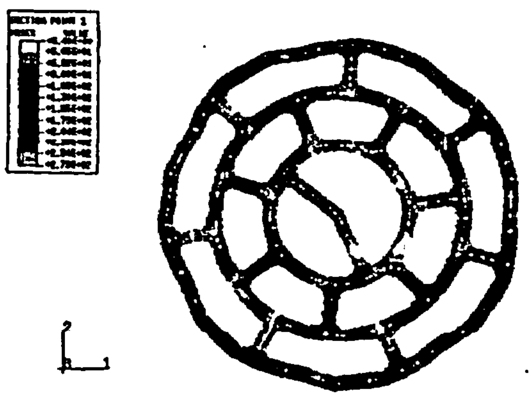


Figure 13. Stress contour of bundle #2 downstream Endplate

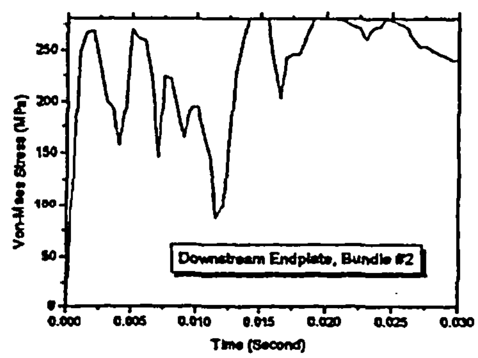


Figure 14. Time history of Von-Mises stress at high stress area in bundle #2 downstream endplate