Static Strength Analysis of CANFLEX Fuel Bundle for CANDU 6 Reactor

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ABSTRACT

A static analysis, finite-element (FE) model was developed to simulate out-reactor fuel–string strength tests with use of the well-known, structural analysis computer code ABAQUS. The FE model takes into account the deflection of fuel elements, and stress and displacement in endplates subjected to hydraulic drag loads. It was adapted to the strength tests performed for CANFLEX 43-element bundles and the existing 37-element bundles. The FE model was found to be in good agreement with experiment results. With use of the FE model, static behavior of fuel bundle string, such as load transfer between ring elements, endplate rib effects, hydraulic drag load incurring plastic deformation in fuel string and high flow rate effects were investigated.

1. INTRODUCTION

There are 380 fuel channels in a CANDU-6 reactor, and twelve fuel bundles are loaded in 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 reference-fuelling scheme of 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. The fuel bundle string is temporarily supported by side-stops in the fueling machine, and eight bundles are discharged, two at a time. The side-stops contact the fuel bundle on the conical surfaces of the endcaps of eight or nine outer elements. Thus, the side-stops prevent an axial movement of the fuel bundle string, which might otherwise occur due to the hydraulic drag caused by the channel flow. The hydraulic drag varies during refueling according to the number of bundles in the flow, and therefore, the maximum force occurs before the first bundle is discharged, i.e., when the old bundle 12 is against the side-stops. In normal conditions, the maximum side-stop load is estimated to be 7,300

N at the reference flow 24 kg/s. Even in case one of the two side-stops fails to engage, the maximum force reacted against a single side-stop is the hydraulic drag only, and its magnitude is 7,300 N.

The fuel bundles developed for use in CANDU-6 reactors must withstand all fuel handling loads described above. Out-reactor experiments, so called double side-stop strength and single side-stop strength tests have been performed to demonstrate that the 37-fuel element bundle and CANFLEX 43-fuel element bundle[1] satisfies this requirement. The results were excellent, even though double side-stop tests were performed with the load as high as 1.6 times of the maximum load (7,300 N) in normal conditions.

A static analysis finite-element (FE) model for simulating out-reactor strength tests was developed with the use of a well-known, structural analysis computer code ABAQUS[2]. This FE model takes into account the deflection of fuel elements and contours of stress and displacement in endplates subjected to hydraulic drag loads. In this paper, the FE model is adapted to the strength tests performed for CANFLEX 43-element bundles and existing 37-element fuel bundles to analyze the experiment results in terms of physical parameters such as load transfer between ring elements, endplate rib effects, hydraulic drag load incurring plastic deformation in fuel string and high flow rate effects.

2. MODEL DESCRIPTION

2.1 FE Model for Fuel Bundle and String

The FE model of a fuel bundle is presented with shell, beam and truss elements. Pressure tube and bearing pads are not modeled, but they are built into the analysis model by establishing appropriate boundary conditions, as described in Section 2.2. Figures 1 and 2 illustrate the FE model of a bundle. A specific description of the FE model for each component is presented in Table 1. Regarding material properties, tensile properties at 120°C are used for the analysis because out-reactor strength tests were performed at 120°C (See Table 2).

A fuel bundle string is modeled as a row of thirteen fuel bundles. This is to simulate 13 fuel bundles being affected by flow among twenty bundles (12 old bundles and 8 new bundles) loaded in the fuel channel on refueling (Figure 3). The endplates of adjacent bundles are assumed to be in full contact each other and their concavities are ignored. The FE model of the fuel bundle string is made in accordance with its actual alignment in the test rig. The ten bundles in the upstream, which are in random alignment in the test, are modeled to have an angle of 28° for CANFLEX and 31° for the 37-element fuel in clockwise, when viewed from the inlet, relative to the adjacent downstream bundle. The angles of 28° and 31° are the bundle alignment angles with which the most probable pressure drop can be achieved in the pressure drop test with fuel bundle strings[3].

2.2 Boundary Conditions and Applied Loads

The downstream bundle (bundle #13) is supported by side-stops, each of which contacts four outer fuel elements. Each contact of a fuel element with side-stop is modeled by means of 2-node beam elements. Therefore, eight 2-node beam elements are used to simulate the contact between side-stops and eight outer fuel elements. One end of the beam element has all degrees of freedom restrained, while the other end supports fuel elements of the downstream bundle, as shown in Figure 2. Therefore, the downstream bundle has axial displacement restrained only in its +z direction.

The center node on each of the two endplates of all fuel bundles have their transverse displacements (Ux, Uy) restrained to fix these nodes in space. The rotation about z-axis is also restrained to avoid spinning and causing any singularities during the solution.

Hydraulic drag force was the controlling parameter in the strength tests and is shown in Table 3. The hydraulic drag force is assumed to be uniform over the whole fuel string and over the whole length of the fuel element. Therefore, the hydraulic drag force 12,010 N over the 13 CANFLEX fuel bundle string is represented by 0.04338 N/mm along each fuel element.

3. APPLICATION TO OUT-REACTOR STRENGTH TESTS

3.1 Description of Out-Reactor Tests [3]

The strength test setup consists of 15-fuel bundle string and fuelling machine side-stop simulators. The side-stop simulators were designed and fabricated to fit correctly into the outlet end fitting of the rig. The fuel bundle string of 3 test bundles plus 12 filler bundles was placed in the fuel channel. The channel flow rate was adjusted to establish a specified fuel string pressure drop, resulting in the desired hydraulic drag force against the side-stop. The specified pressure drop corresponded to the maximum number of fuel bundles (13.1 bundles) which reside in the axial flow region of the fuel channel during refueling. For each of these tests, the coolant temperature and the inlet pressure were set to 120 °C and 11.2 MPa, respectively, and held for 15 minutes. After that, the test bundles were unloaded and measured to obtain any dimensional changes due to the testing.

3.2 Validation of the FE Analysis Model

3.2.1 Displacement in Downstream Endplate

Figure 4(a) shows axial displacements in the downstream endplate of the CANFLEX bundle that rests on double side-stops. 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(a).) Calculations trace the measurements very well. Negative values of the displacement correspond to the part of the endplate that was against the side stop, and means it was pushed into the bundle. Some discrepancy in the magnitude between the prediction and the measurement are found in this part. This might be attributed to the existing waviness of the test bundle endplates, which was not taken into account of in the model.

Figures 4(b) shows the axial displacements of the downstream endplates of the CANFLEX fuel bundles supported by single side-stop in the downstream of the fuel channel. Generally, the predictions agree well with the measurements in both trace and magnitude.

3.2.2 Deflection of Fuel Elements

Figure 5(a) shows the radial deflection of element #8 for the CANFLEX bundle that rests on single side-stop. Both the measurement and the prediction show maximum value near the middle of the element. Figure 5(b) shows the radial deflections of twenty-one outer elements in the mid-plane. The measurements and the predictions show similar trends in variations.

3.3 Analysis of Fuel Bundle String Behavior

3.3.1 Double Side-Stop Strength Test with CANFLEX Fuel Bundle String

Figure 6 shows drag load carried by each ring element of the CANFLEX fuel bundle string in the double side-stop test. Drag load carried by outer elements becomes bigger as bundles are placed in downstream, and eventually 93% of the drag load was carried by outer elements in the downstream bundle (#13). (Figure 7) This is because inner elements were not supported. The slope of the load curve for outer elements was rapidly increased from bundle #8.

Figure 7 also shows comparative load-transfer mechanisms between the CANFLEX and the 37-element fuel bundle strings. The load carried by outer elements in upstream bundles is bigger in the 37-element fuel bundle string than in the CANFLEX. This is due to a different design of the endplate. The endplate of the CANFLEX bundle has more ribs. They lessen the load concentration in the outer ring by providing inner ring elements with better support.

Figure 8(a) presents the maximum stress at each bundle in the 13-CANFLEX fuel bundle string supported by double side-stops. A big change in the slope of the stress curve occurred in bundle #8. This tendency was shown in the load transfer curve of Figure 6, and indicates that the rapid increase in stress occurred due to the load transfer from inner elements to outer elements. Stress stopped increasing in bundle #10, indicating plastic deformation occurred. A slight increase in bundles #12 and #13 was due to the contact between eight outer fuel elements of the downstream bundle and side-stops.

Figure 8(b) shows maximum displacement in each bundle in the CANFLEX fuel bundle string supported by double side-stops. The axial displacement is higher as bundles are placed downstream, due to load transfer and material plasticity as discussed in Figure 8(a).

3.3.2 Comparison of Fuel-String Behavior Between CANFLEX 43-Element Bundle and Existing 37-Element Fuel Bundle

Figure 9 compares the maximum local stresses that occurred in each bundle of both CANFLEX and the 37-element fuel bundle strings under the condition of the double side-stop strength test. The general trend of variation in the stress is the same in both cases. But, the 37-element bundle shows higher stress in the elastic region, and thus shows earlier plastic deformation in bundle #9 where the drag load was 8,000N, while in CANFLEX plastic deformation begins in bundle #10 where the drag load was 9,200N. This could be predicted from the curves in Figure 7 in which the 37-element fuel bundle showed a higher load transfer than CANFLEX in the elastic region. A relatively uneven distribution of load causes a higher maximum local stress in the 37-element fuel bundle endplate. As a CANFLEX bundle begins plastic deformation, the two curves go together.

With regards to the stresses in outer elements against side-stops, higher stress occurred in CANFLEX because its outer elements have a smaller diameter (11.5mm) than the 37-element fuel bundle (13mm). However, the maximum stress in CANFLEX elements is far less than the material yield strength.

3.4 Influence of high flow rate

Figure 10 presents calculation results of axial displacement and maximum stress in the endplate of bundle #13, which rests on double side-stops, under the condition of extremely high flow rates. The hydraulic drag load is in proportion to flow rate, and therefore the flow rate 40kg/s corresponds to the drag load 12,310 N, and the flow rate 60 kg/s to the drag load 27,700 N. Both curves increase as the flow (i.e., load) increases. The ultimate tensile stress of the endplate material occurred at a flow rate of 61 kg/s, which corresponds to the drag load 28,600 N.

CONCLUSION

(1) A static analysis FE model was developed to simulate out-reactor fuel-string strength tests with use of the structural analysis code ABAQUS. This model was verified against test results on endplate displacement and element bowing obtained from strength tests for CANFLEX and the 37-element fuel. The predictions were in good agreement with the measurements.

(2) The initial deflection of fuel elements, which had occurred during the braze-welding of appendages on the thin sheathing, was found to significantly affect the radial deflection along the fuel length in tests.

(3) The load transfer mechanism between ring elements was affected by endplate design. Because of more ribs in the CANFLEX endplate than in the 37-element fuel endplate, maximum stress and displacement were lower in the CANFLEX fuel string than in the 37-element fuel string. Moreover, plastic deformation in the CANFLEX endplate occurred with higher hydraulic drag than in the 37-element fuel endplate. However, the threshold loads causing plastic deformation in endplates, 9,200 N for CANFLEX and 8,000 N for the 37-element fuel, were much higher than the maximum drag load 7,300 N in the CANDU-6 fuel channel. Stress in the endplate exceeded the ultimate tensile stress at the drag load of 28,600 N which corresponds to the flow rate 61 kg/s. This reveals that the CANFLEX fuel bundles are able to withstand extremely high flow rate without showing a significant geometric instability.

Acknowledgement

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References

[1] W. W. R Inch, P. Thompson and H. C. Suk, "CANFLEX from Development Concept to a Proven Fuel", Presented at the 13th KAIF/KNS Annual Conference, Seoul, Korea, 1998 April 15-16

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

[3] C. H. Chung, S. K. Chang, H. C. Suk, P. Alavi and I. E. Oldaker, "Performance of the CANFLEX fuel bundle under mechanical flow testing", Proceedings of the 5th International Conference on CANDU Fuel, Vol.1, pp.10-69, September 21-25 1997, Toronto, CANADA

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 ea. for CANFLEX 328 ea. for CANDU
Fuel sheath	PIPE31	2-Node, 3D Pipe 6 DOF	6 elements per rod
Spacer pad	T3D2	2-Node, 3D Truss 3 DOF	
Side-stop simulator	B31	2-Node, 3D Beam 6 DOF	4 elements consist one side-stop

Table 2 Material properties at 120 °C

Component	Young's modulus	Yield strength	Ultimate tensile strength	Poisson's ratio
Endplate	87,980 MPa	228 MPa	378 MPa	0.4
Cladding tube	89,015 Mpa	403 MPa	443 MPa	0.4
Spacer	89,015 MPa	-	-	0.3

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

Table 3 Axial hydraulic drag in strength tests

Boundary condition	Load in CANFLEX	Load in CANDU
Double side-stops	12,010 N	11,559 N
Single side-stop	7,300 N	7,468 N

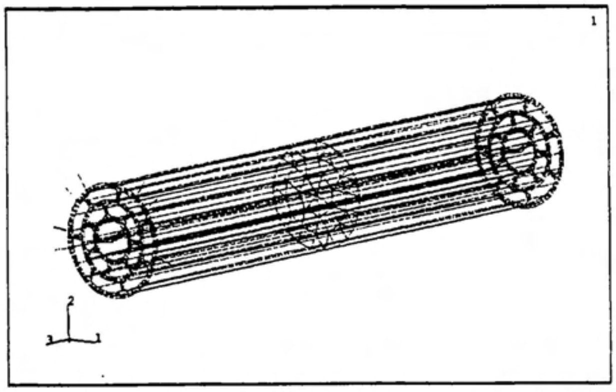
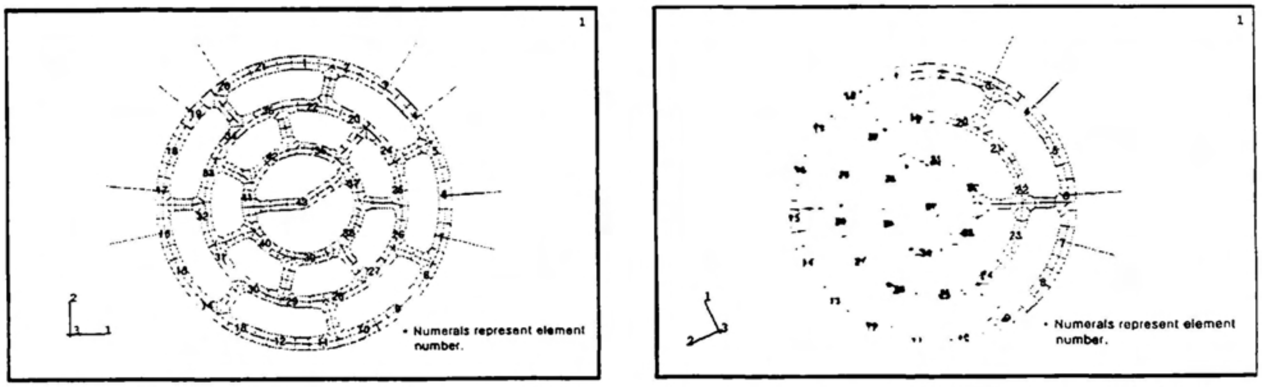


Figure 1 FEM Model for CANFLEX Fuel Bundle



2(a) CANFLEX endplate against double side-stops

2(b) 37-element fuel endplate against single side-stops

Figure 2 Illustration of FE model for endplate

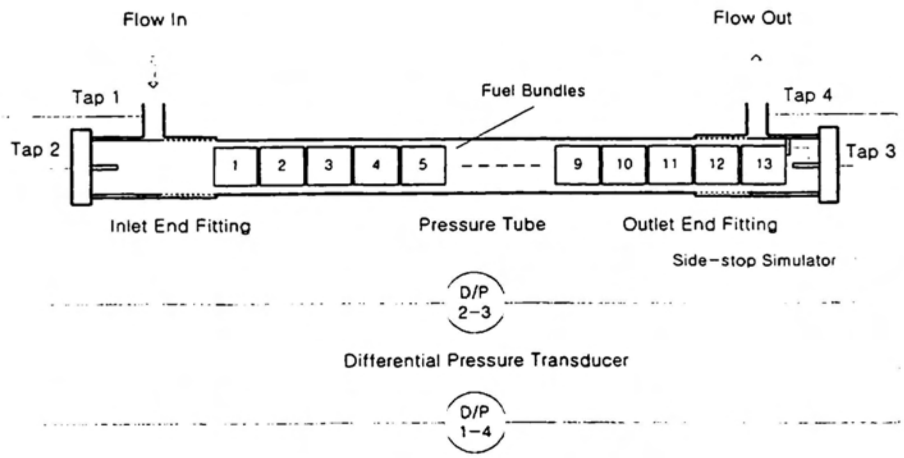
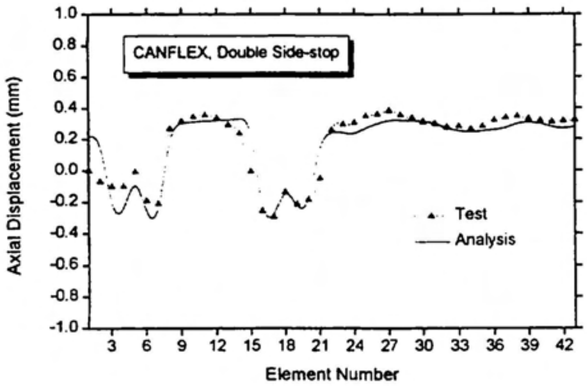
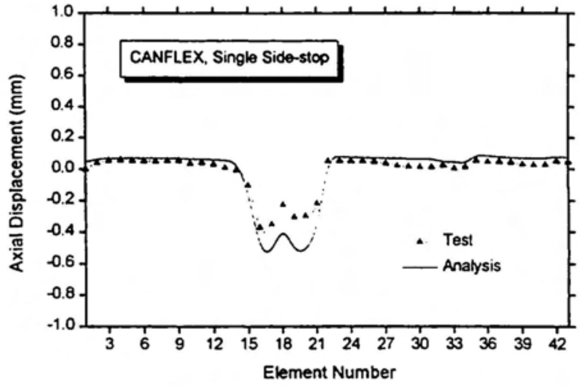


Figure 3 Schematic diagram of strength test set-up

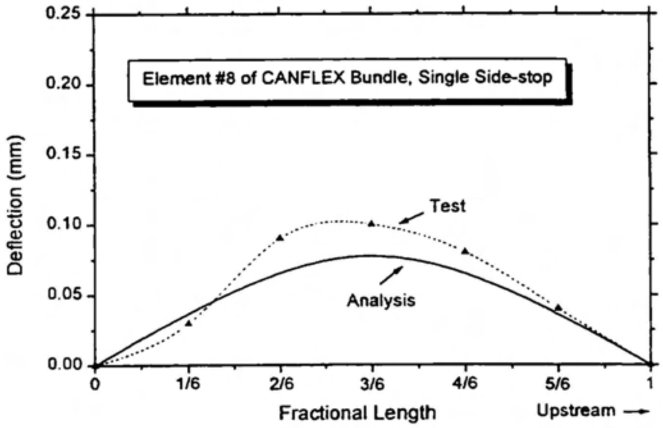


4(a) Double Side-stops

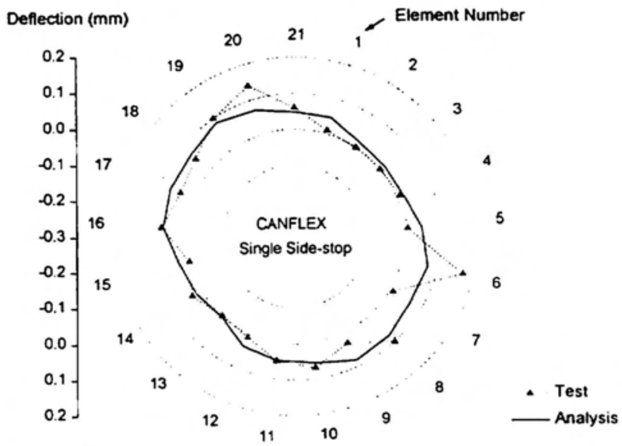


4(b) Single Side-stop

Figure 4 Predicted vs. measured axial displacement in endplate



5(a) Radial deflection along fuel element #8



5(b) Radial deflection in 21 outer elements at mid-plane

Figure 5 Predicted vs. measured radial deflection in CANFLEX bundle #13 (Single side-stop)

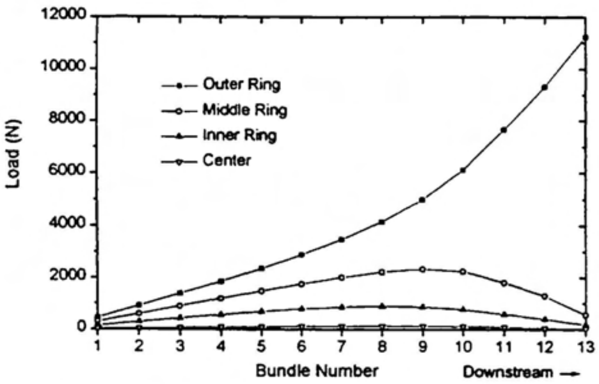


Figure 6 Drag load carried by ring elements in CANFLEX fuel bundle string

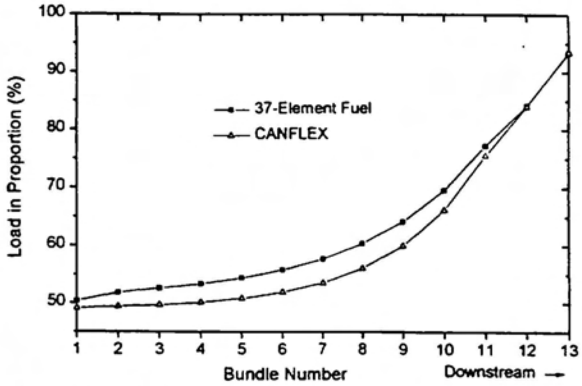
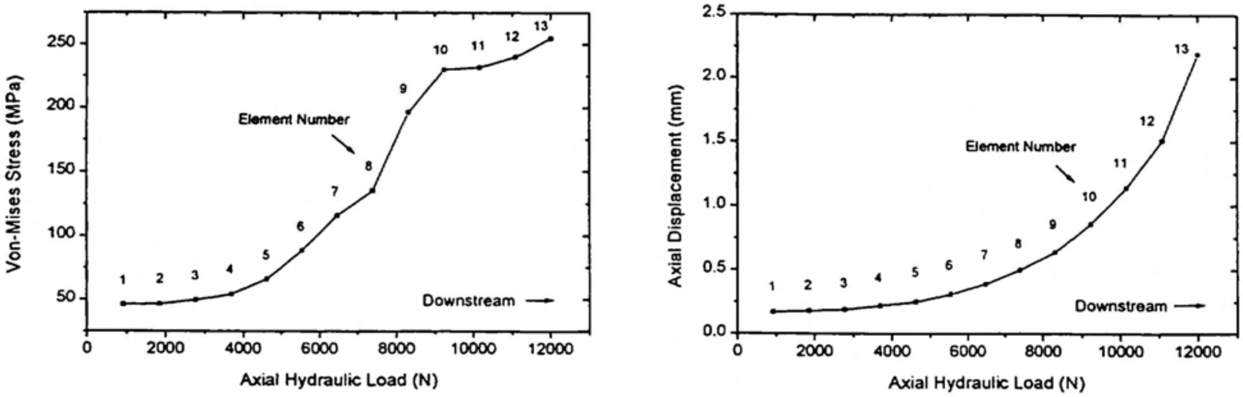


Figure 7 Comparison of the load carried by outer ring elements



8(a) Stress **8(b) Displacement**

Figure 8 Maximum stress and displacement in endplates (CANFLEX, Double side-stops)

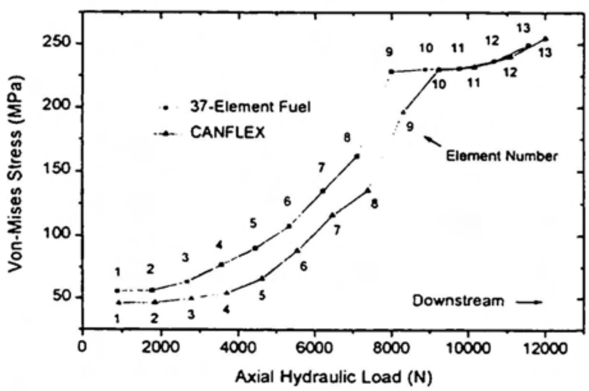


Figure 9 Comparison of maximum stress in endplates (double side-stops)

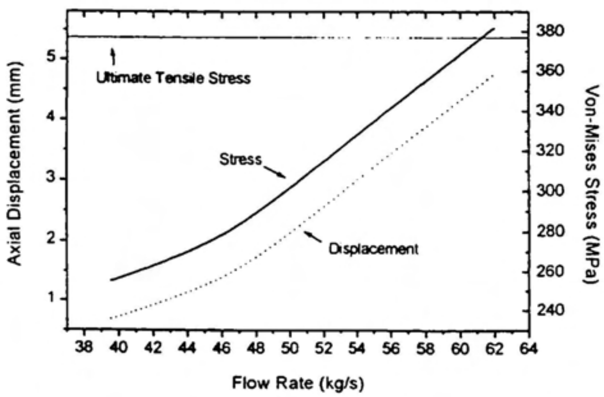


Figure 10 Max. stress and displacement under extremely high flow rate