STUDY TO ASSESS CN43 END PLATE STRESSES AND STRAINS USING FINITE ELEMENT ANALYSIS

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Abstract

The paper presents the results of a static analysis with ANSYS 7.1 computer code simulating axial compression in CN43 CANDU-type fuel bundles subject to hydraulic drag loads, in various refuelling conditions (supported by two side stops or by only one side stop). Different cases were considered in the structural analysis, for a maximum load of 7300N (corresponding to reactor operating conditions) and 12000N, respectively. The finite element method used in ANSYS Mechanical APDL assumed: pre-processing (modelling of fuel bundles and end plates), processing (analysis of the stresses and strains distribution), and post-processing (visualization of computed results). The main outcomes were: deflection of fuel elements, stresses, strains, and displacements in the CN43 fuel bundle end plate. The results were compared to those corresponding to the standard C37 fuel bundle. The comparative analysis highlighted that the stress and strain values for CN43 fuel bundle end plate are in good agreement to the results obtained for the C37 fuel bundle.

Keywords: *CN43 fuel bundle, End Plate Deformation, ANSYS Finite Element Analysis*

Introduction

Currently, burnup extension is one of the most well-known practical methods for enhancing fuel cycle efficiency and reducing the radioactive waste volume. Extended burnup may require changes to fuel element and assembly designs.

In order to study the possibility to reach the nuclear fuel extended burnup in Cernavoda NPP reactors, a new CANDU type of fuel bundle with 43 elements (CANDU New 43 - CN43) has been designed within the Institute of Nuclear Research (RATEN ICN Pitesti) [1]. The new fuel bundle design must withstand the combined axial loads caused by the hydraulic drag and the fuelling machine, and also must be able to withstand crossflow in the liner tube for short periods of time without damage.

There are two types of tests performed on innovative CANDU type fuel bundles before they can be used in a CANDU reactor, namely irradiation tests conducted on experimental fuel elements in test reactors and out-of-reactor tests conducted on prototype fuel bundles. Among the second category, the strength test stands out, which provides information regarding the fuel's capability to withstand longitudinal compressive mechanical stresses and the action of hydraulic drag loads [2].

In addition to previous mentioned tests, the calculation-based determination of stresses and strains distribution, under fuel channel loading conditions, provide useful information. The technical specification for the strength test includes the following situations:

• test with two side stops – simulates the normal operating conditions of the fuel bundle in the fuel channel;
• test with one side stop - simulates the operation conditions when one side stop is blocked (side stop failure conditions) [3].

In this work, the stress and strain distribution within the CN43 fuel bundle end plate, under fuel channel loading conditions, were determined through simulations using the finite element method. By means of the ANSYS APDL (ANSYS Parametric Design Language) code [4], a static analysis was developed to assess the mechanical strength of the new fuel bundle design during refuelling conditions.

The main stages of the analysis were, as follows:
- Development of the geometric models for C37 and CN43 fuel bundles using the ANSYS Mechanical APDL finite element program.
- Simulation of the normal operating conditions for the fuel bundles support on both side stops, and also for the specific loading conditions in the fuel channel in the event of a side stop failure (blockage). A maximum load of 7300 N was considered.
- Simulation of operating conditions for the fuel bundles supported on both side stops, when the maximum load of 12000 N is considered.
- Determination of the stress and strain distribution in CN43 fuel bundle end plate
- Comparison of the results obtained for CN43 fuel bundle with those corresponding to the standard CANDU fuel bundle with 37 elements and natural UO_2 fuel, C37.

Fuel bundles description

The C37 fuel bundle contains 37 fuel elements with the same diameter, of about 13 mm, disposed on 3 concentric rings (of 6, 12 and 18 fuel elements, respectively) around a central element.

The CN43 fuel bundle contains 43 fuel elements with the same diameter, of about 12 mm [5], disposed also on 3 concentric rings (of 7, 14 and 21 fuel elements, respectively) around a central element.

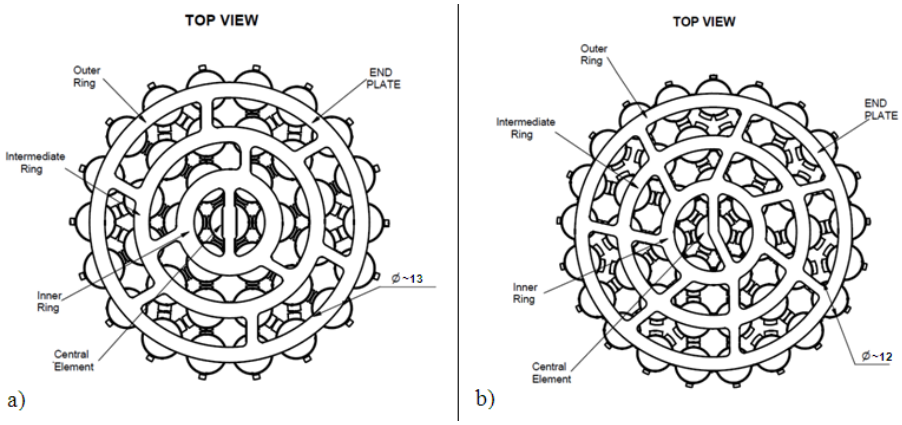


Fig. 1. Top view of C37 (a) and CN43 (b) Fuel Bundles with the corresponding end plates

In normal operating conditions, the last fuel bundle in a CANDU 6 reactor fuel channel is supported by the shield plug; during refuelling conditions, the last fuel bundle is supported by the side stops. More precisely, only some fuel elements are supported by the side stops. The shield plug supports the outer and intermediate rings of the end plates, and partially supports the outer and intermediate radial ribs of the end plates. Fig. 2 shows the interaction between two fuel bundles and side stops during refuelling. In addition, it should be mentioned that the side stops generate eccentric loading on these fuel elements [6].

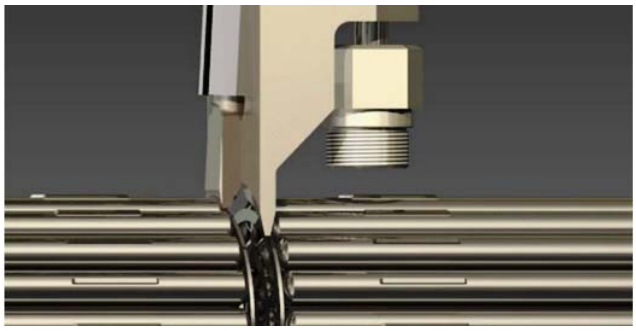


Fig. 2. Interaction between CANDU fuel bundle and a side stop during refuelling [6]

To get a better understanding of the refuelling conditions for CANDU 6 reactors, the fuel channel loading scheme is the following: 8 fresh fuel bundles are inserted at one end of the pressure tube in the direction of the coolant flow, while 8 irradiated bundles are discharged at the other end. During this time, the column of fuel bundles is supported by the side stops of the refuelling machine. Thus, the stops prevent axial displacement of the fuel bundles column, due to the coolant flow in the fuel channel.

The hydraulic drag load varies during refuelling according to the number of fuel bundles, so the maximum force in the fuel channel occurs before the first fuel bundle is discharged (when all 12 bundles from the fuel channel are supported by the side stops) [7].

To carry out the proposed analyses, ANSYS Mechanical APDL finite element code was used to simulate the CN43 bundle thermo-mechanical behaviour. Additionally, using the Autodesk Inventor specialized design program, main geometric parameters of the C37 and CN43 fuel bundles were determined.

Finite element modelling

For any structural analysis performed using the ANSYS finite element code, the material properties should be given as input data. The elastoplastic properties of the Zircaloy-4 material (used both for fuel rod claddings and end plates), under normal operating conditions of the reactor, are described using the correlations provided by MATPRO [8]. Therefore, in ANSYS simulations, the elastic modulus and Poisson's ratio are required, along with the stress-strain curve.

The geometric modelling in ANSYS finite element simulations must, first and foremost, be as realistic as possible and enable a suitable discretization into finite elements. Based on the fuel bundle geometric modelling, a fine discretization into finite elements should be possible, depending on the type of finite element, producing several nodes and elements that make computer analysis feasible. The finite element discretization is depicted in Fig. 3, for both analysed fuel bundles end plates.

Given that discretization into finite elements affects result accuracy, a larger number of finite elements lead to more accurate results, but requires longer processing/ computing time. In the present study, a column of 12 fuel bundles was considered, the following discretization being used:

- 6699 nodes and 8009 elements for CN43 end plate, and 46479 nodes and 41477 elements for the column of fuel bundles;
- 5391 nodes and 6920 elements for C37 end plate, and 40527 nodes and 36104 elements for the column of fuel bundles.

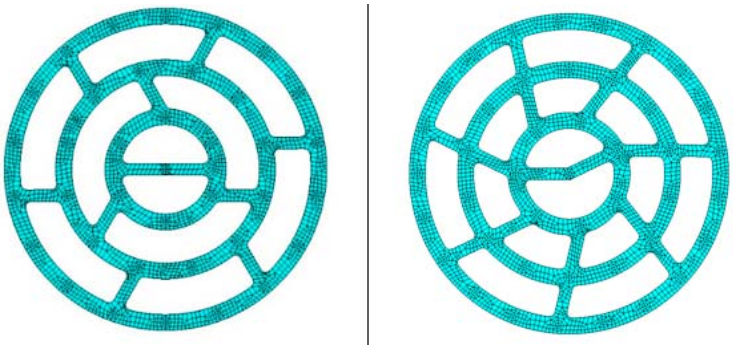


Fig. 3. Finite element modelling of C37(left) and CN43 (right) fuel bundle end plates

Regarding the boundary conditions that were imposed, the corresponding contact nodes were established at the points where the fuel bundles and the end stops come into contact. These nodes were fixed on the Z direction, and the fuel bundles displacement was restricted in the coolant flow direction.

Results and discussion

For this study, under normal operating conditions, the simulation was carried out with a maximum estimated force of 7300 N, for a reference value of coolant flow of 24 kg/s. Even if one of the side stops fails to function, the maximum force remains at 7300 N.

In Figs. 4 and 5, the radial displacements occurring in studied fuel bundles column are represented. The lowest values of radial displacements are obtained for the CANDU standard fuel bundle, C37, in both considered cases (column of fuel bundles supported by one side stop and by two side stops). For CN43 fuel bundle, the smallest value of radial displacements (0.82 mm) was obtained when the column of fuel bundles is supported by two side stops, compared to 1.28 mm obtained for the case with one side stop support. In this case, the value obtained does not fit within the distance from the fuel elements located on the outer ring to the inner diameter of the pressure tube (which is about 1 mm).

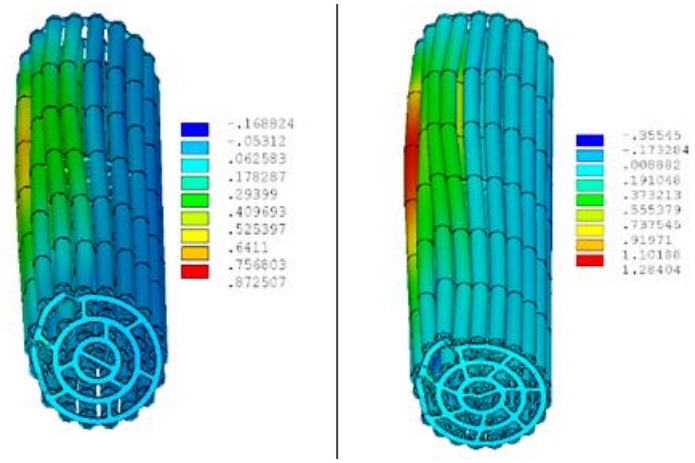


Fig. 4. Radial Displacement [mm] in C37 (left) and CN43 (right) fuel bundles supported by one side stop

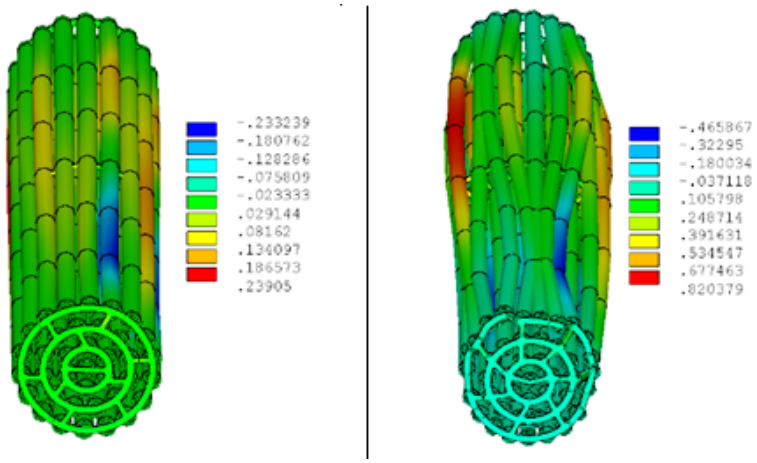


Fig. 5. Radial Displacement [mm] in C37 (left) and CN43 (right) fuel bundles supported by two side stops

Fig. 6 shows the Von Mises equivalent stresses (from different angles) for C37 and CN43 fuel bundles end plate, in the case of a single side stop support. The maximum values are obtained near the weld zone. The stress results are nearly identical, with a slightly lower value in the case of CN43 fuel bundle end plate (a difference of 0.4 MPa versus the one obtained for C37 fuel bundle end plate).

The plastic deformation of the analysed fuel bundles end plates is depicted in Fig. 7 for single side stop support. The areas of plastic deformation are located near the weld zone, similar behaviour being noticed for both fuel bundles. The maximum value was obtained for CN43 fuel bundle.

Fig. 8 presents the axial displacement in the C37 and CN43 fuel bundles end plates for the scenario with one side stop support. The evolution of axial displacements, as well as the maximum values, are similar for both analysed fuel bundles, namely 3.68 mm for C37 fuel bundle and 3.84 mm for CN43 fuel bundle.

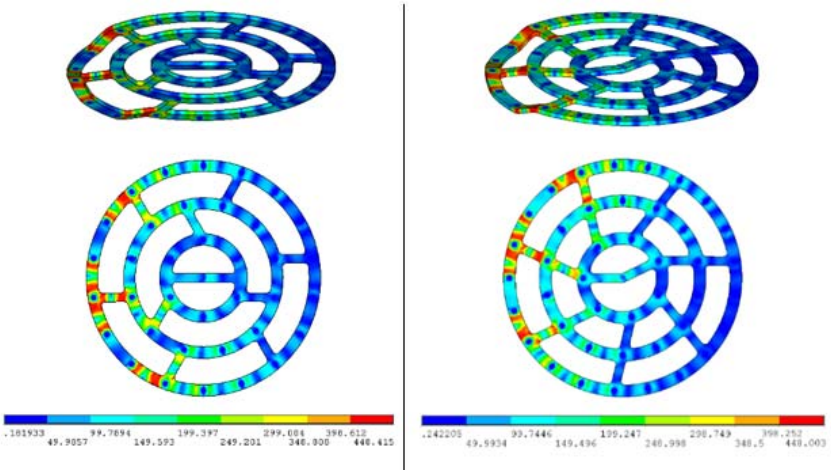


Fig. 6. Equivalent Von Mises stress [MPa] in C37 (left) and CN43 (right) fuel bundles end plate

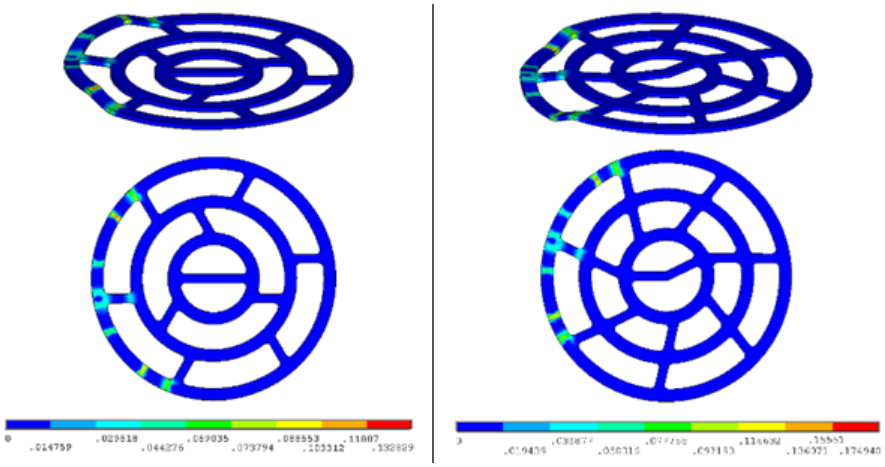


Fig. 7. Equivalent Von Misses plastic deformation [%] in C37 (left) and CN43 (right) fuel bundles end plate

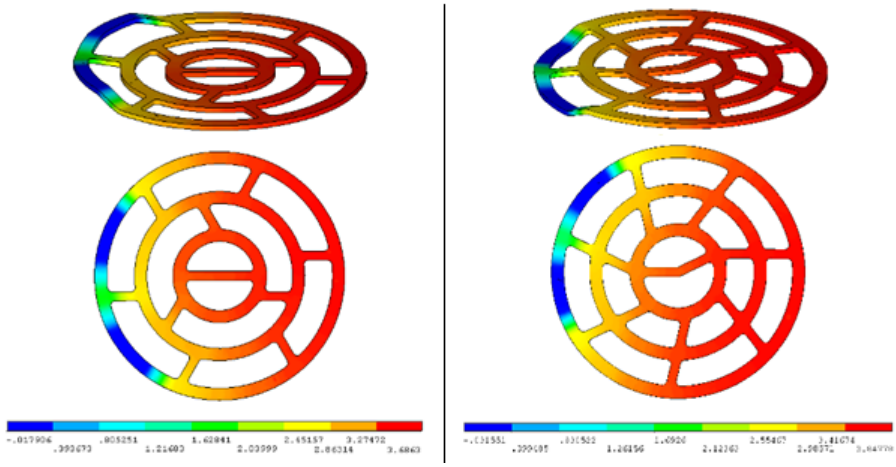


Fig. 8. Axial displacement [mm] in C37 (left) and CN43 (right) fuel bundles end plate

The radial displacement for the two considered fuel bundles is depicted in Fig. 9, with the highest maximum value of 0.24 mm for the CN43 end plate, compared to 0.14 mm for the C37 end plate.

Using the same methodology, a structural analysis was performed on C37 and CN43 fuel bundles end plate for the scenario when the fuel bundles column is supported by two side stops and is subjected to a force of 7300 N. For the sake of conciseness, only the top view results are displayed.

In Fig. 10, the equivalent Von Mises stress for the two fuel bundles is illustrated, considering the two side stops support for the fuel bundles column subjected to a force of 7300 N. The maximum values were located near the weld zone, with very small differences between obtained values: 445 MPa for C37 fuel bundle and 447 MPa for CN43 fuel bundle. It can also be noticed that CN43 fuel bundle has multiple stress zones on its intermediate and inner rings compared to C37 fuel bundle, with less stressed zones.

Fig. 11 presents the end plates plastic deformation of the two analysed fuel bundles; the lower values were obtained for the C37 fuel bundle.

The axial and radial displacements are represented in Figs. 12 and 13, with the higher values obtained for the CN43 fuel bundle end plate. Both axial and radial displacements were higher for the fuel bundle CN43 fuel bundle end plate (1.404 mm and 0.097 mm) compared to the C37 fuel bundle end plate (0.562 mm and 0.041 mm).

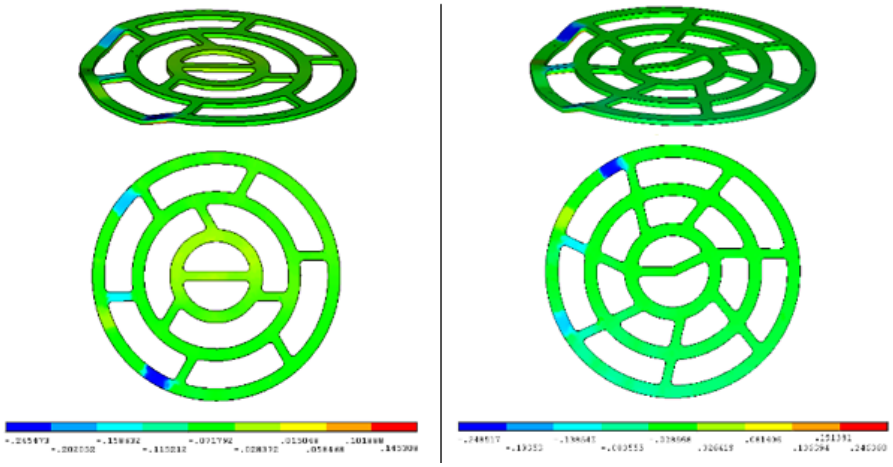


Fig. 9. Radial displacement [mm] in C37 (left) and CN43 (right) fuel bundles end plate

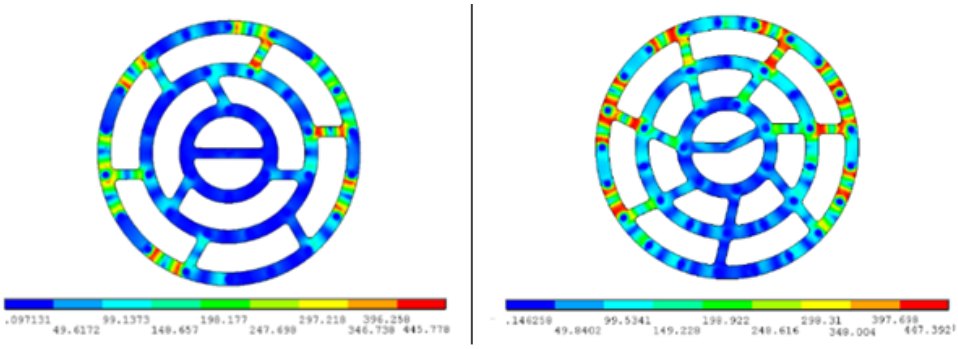


Fig. 10. Equivalent Von Mises stress [MPa] in C37 (left) and CN43 (right) fuel bundles end plate

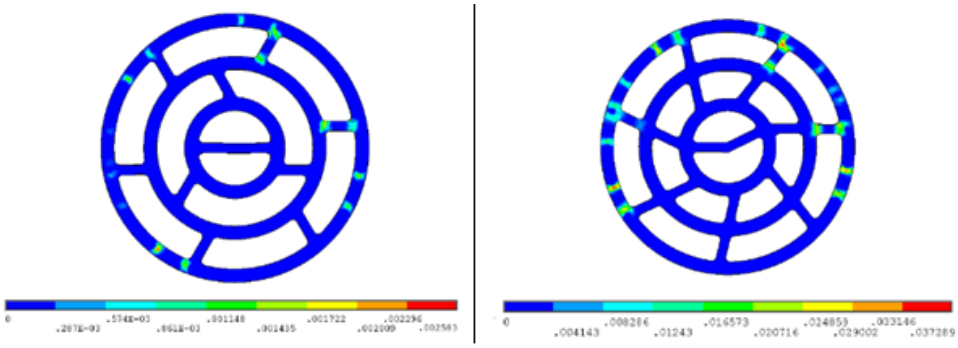


Fig. 11. Equivalent Von Mises plastic strain [%] in C37 (left) and CN43 (right) fuel bundles end plate

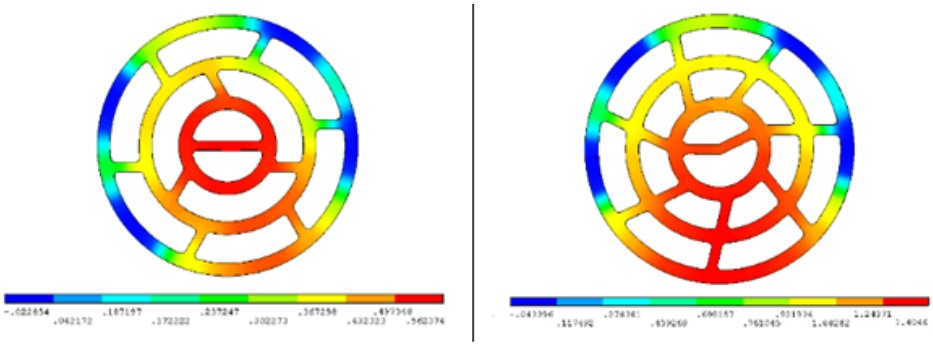


Fig. 12. Axial displacement [mm] in C37 (left) and CN43 (right) fuel bundles end plate

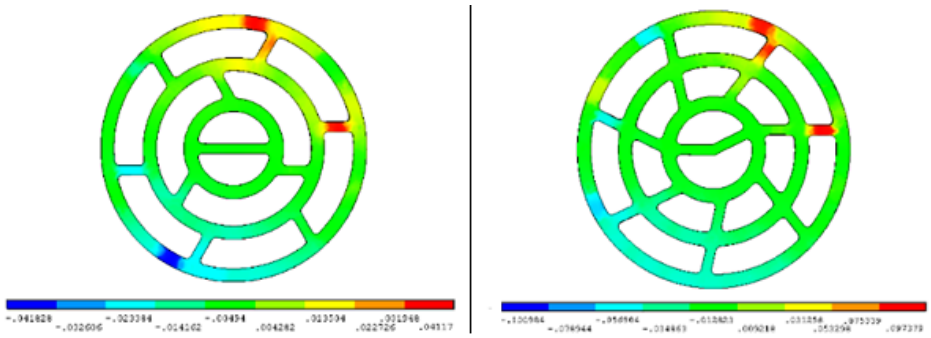


Fig. 13. Radial displacement [mm] in C37 (left) and CN43 (right) fuel bundles end plate

The last step of the study was the assessment of fuel bundles behaviour when using a maximum drag force of 12000 N and the two side stops support for fuel bundles column.

The analysis showed that the maximum values for the equivalent Von Mises stresses are obtained for both fuel bundles near the weld zone. The stress results are comparable, with a slightly lower value for C37 fuel bundle end plate (446 MPa) in comparison with CN43 fuel bundle end plate (448 MPa). The maximum equivalent plastic deformation was also obtained for CN43 fuel bundle end plate.

In the case of the axial displacement, the highest value was achieved for the CN43 fuel bundle end plate (0.22 mm). The highest radial displacement was also obtained for CN43 fuel bundle end plate compared to C37 fuel bundle.

Table 1 summarizes the minimum and maximum values of all studied parameters, using the ANSYS finite element analysis, for the two fuel bundles subjected to a maximum drag force of 12000 N and both side stops support for the fuel bundles column.

Table 1. The interest parameters maximum and minimum values for C37 and CN43 fuel bundles end plates
ANSYS finite element analysis, 12000 N drag force, two side stops support

Parameter /Fuel bundle	**C37**		**CN43**	
	Min	Max	Min	Max
Displacement [mm]				
UX	- 0.0690	0.0680	- 0.2028	0.2221
UY	- 0.0430	0.0717	- 0.2786	0.1677
UZ	- 0.0306	0.9581	- 0.3739	2.6174
Plastic stress [%]				
EPPLX	- 0.0118	0.0117	- 0.08473	0.0852
EPPLY	- 0.0103	0.0103	- 0.81924	0.0819
EPPLZ	- 0.0129	0.0128	- 0.09383	0.0937
Deformations [%]				
EPPTX	- 0.0176	0.01748	- 0.0901	0.0906
EPPTY	- 0.0154	0.01547	- 0.0868	0.0868
EPPTZ	- 0.0166	0.01660	- 0.0981	0.0980
Stress [MPa]				
SX	- 492.71	492.808	- 506.205	506.127
SY	- 488.24	487.959	- 516.735	516.734
SINT	0.07787	499.990	0.262579	517.016
SEQV	0.07093	446.891	0.239630	448.175

Conclusions

The present paper investigated the mechanical behaviour of the CN43 fuel bundle end plate, on various refuelling conditions, by means of the finite element method.

For the parameters of interest (deflection of fuel elements, stresses, strains, displacements), a comparative analysis between the CN43 fuel bundle and the C37, CANDU standard fuel bundle, was performed.

The results of the structural analysis, performed by means of the ANSYS code, were analysed and it was noticed that both fuel bundles have similar behaviour.

The comparative assessment reveals that the CN43 fuel bundle can withstand a high flow rate without showing significant geometric instability.

Future perspective will foresee the utilisation of ANSYS Workbench for three-dimensional analyses in order to simulate the contacts between fuel bundles, spacers and fuel bundle side stops. This feature will enable a more in-depth analysis of the fuel bundles behaviour.

References

[1] Olteanu, G., Ionescu, D.V., Roman, M.R., Răduț, A.C. (2020) "Preliminary design of CN43 fuel bundle for use in CANDU reactors", Technical Note NT-358, Institute for Nuclear Research (RATEN ICN) Pitesti, Romania (in Romanian).

[2] Cotter, J.K. (1988) "Design Manual: Nuclear Power Enterprise - Cernavoda Unit 1. Fuel Design Manual", Atomic Energy of Canada Limited, No 79 - 37000 - DM - 000, Rev.1, AECL, Canada.

[3] Ionescu, D.V., Horhoianu, G., Zvanciuc, F. (2005) "Mechanical behaviour of the SEU43L fuel bundle under CANDU fuel channel stress conditions", Internal Report RI-7313, Institute for Nuclear Research Pitesti, Romania (in Romanian).

[4] *** (2003) ″ANSYS 7.1 - User Manual″, ANSYS Release 7.1, Help System, ANSYS Mechanical APDL, ANSYS Inc, USA.

[5] Oproiu, D.F., Ionescu, D.V., Olteanu, G., Roman, M.R., Răduț, A.C., Florea, S. (2018) "Preliminary designs of fuel bundles potentially usable in CANDU Reactors", Internal Report RI-11662, Institute for Nuclear Research (RATEN ICN) Pitesti, Romania (in Romanian).

[6] Oproiu, D.F., Ionescu, D.V., Răduț, A.C., Matei, E. (2022) "Analysis of stresses and strains distribution in CN43 fuel bundle end plate on various refuelling conditions", Internal Report RI-13092, Institute for Nuclear Research (RATEN ICN) Pitesti, Romania (in Romanian).

[7] Horhoianu, G., Ionescu, D.V. (2005) "A Finite Element Model for Static Strength Analysis of CANDU Fuel Bundle", IAEA Techn. Meet. on Fuel Behaviour Modelling under Normal, Transient and Accident Conditions, and High Burnups, Kendal, United Kingdom.

[8] United States Nuclear Regulatory Commission (1976) "MATPRO-09: A Handbook of Material Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior", US NRC, TREE NUREG-1005.