FATIGUE BEHAVIOUR OF ZY-4 CLADDING UNDER CYCLIC LOADS USING FINITE ELEMENT MODELLING

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Abstract

The aim of this paper is to analyse the fatigue behaviour of Zy-4 samples worked from CANDU C43 fuel rods ″as received″ metallurgical state, subjected to cyclic loads using finite element modelling. The fatigue analyses of C43 rods were performed by means of reliable and highly used computer programme in nuclear industry, ANSYS 2020R2. Low cycle fatigue simulations have been carried out under total strain amplitudes of 1%, 2% and 3% at room temperature, while in order to determine the lifetime of Zy-4 the Strain-Life approach was used. A comparative analysis between the simulations results and the experimental data was performed and a good agreement for the simulations results with refined mesh comparatively with the experimental data was obtained.

Keywords: *ANSYS, Finite Element Simulation, Cycle Fatigue, Zy-4 Cladding*

Introduction

Choosing the proper structural materials plays an important role in the evaluation of fuel bundle integrity. Since the nuclear materials selected for fuel cladding undergoes a cyclic deformation due to various kind of external and internal parameters such as: coolant temperature, pressure and coolant flow rate, fission gas products build-up, swelling of the fuel pellets etc., they must possess physicochemical properties that enhance the irradiation behavior for a prolonged period of utilization.

Zircaloy alloys have been selected as nuclear materials due to their excellent physicochemical properties such as: low thermal neutron absorption cross section, reasonable mechanical properties at high temperature, high thermal conductibility and excellent corrosion resistance under operating conditions [1].

The fuel element is the basic subassembly of the fuel bundle. The fuel element sheath is one of the protective barriers against the release of fission products into the coolant. During the reactor normal operation power fluctuations emerge and the fuel element sheath is subjected to cyclic, internal and external mechanical loads. These power variations are associated with power ramps that occur during refuelling, reactor shutdowns, reactivity inserts, and so on. Such loads decrease the strength characteristics of the materials [1].

A series of studies available in literature emphasize the appearance of material fatigue phenomenon in such situations [2].

Over the years, there has been a growing interest in RATEN ICN Pitesti Nuclear Fuels R&D Program to assess the fatigue behavior of Zy-4 fuel cladding. In this regard, several experimental and theoretical studies have been conducted [3-5].

The theoretical study assessed the fatigue behavior of thin and thick fuel rods contained in the structure of CANDU fuel bundle with 43 elements, C43, depicted in a 3D representation in Fig.1a. The analysed fuel bundle contains 43 fuel rods, distributed on three circular rings of 7, 14 and 21 elements and one central element. Considering their diameter, the fuel bundle is composed by 8 thick inner elements of about 14 mm in diameter, and 35 intermediary and outer thin elements of about 12 mm in diameter, as shown in Fig.1b [6].

The main feature of C43 fuel bundle resides in adjusting a larger number of elements compared to the CANDU standard fuel bundle with 37 elements, C37. In order to maintain the compatibility with the existing CANDU reactor systems, the basic overall dimensions of C43 fuel bundle are identical with those of C37 fuel bundle [7].

Meantime, C43 fuel bundle configuration provides higher fuel bundle powers, lower element ratings, extended burn-up capability and enhanced load following performance. The C43 fuel bundle uses slightly enriched uranium obtained from the recycling of burnt fuel in LWR reactors. An enrichment of 0.9% - 1.2% in U^{235} is economically attractive for CANDU type fuel, and might help maintain and improve CANDU's competitive edge over LWR [8].

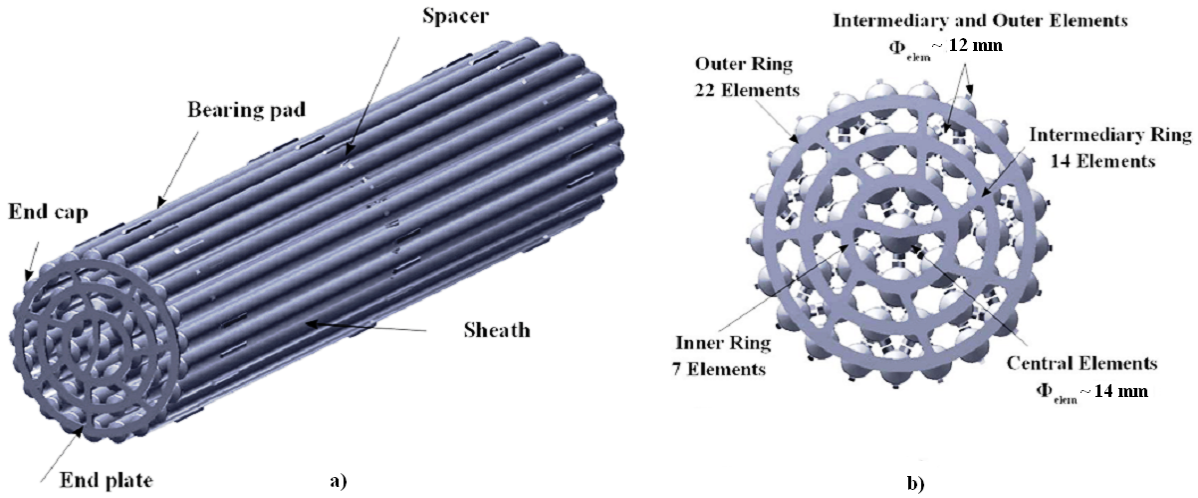


Fig. 1. 3D representation of C43 fuel bundle: a) lateral view and b) frontal view

The fatigue simulations were performed with ANSYS 2020R2 computer program [9]. In this respect, the main stages of finite element analysis: pre-processing (preparation of modelling data), processing (assembly and solution of the equations) and post-processing (visualization of computed results) were conducted. The finite element method, a numerical technique used to perform Finite Element Analysis (FEA) of any given physical phenomena, is commonly used in the nuclear industry.

Material properties of Zy-4

The ANSYS material library does not contain data properties characteristic for Zy-4 so a number of calculations were performed in order to establish the material characteristics required for the present study. Thus, the material properties such as: density, Young's modulus, Poisson's ratio were introduced [10], while the parameters describing the fatigue behavior of Zy-4 were selected from literature [11].

Zy-4 elasto-plastic material properties are determined using the correlations provided by Fisher [10]:

$$E = \left[9.900 \cdot 10^5 - 566.9\left(T - 237.15\right)\right] \cdot 9.8067 \cdot 10^4 \quad (1)$$

where E is the Young modulus (Pa), and T represents the temperature (K).

$$\upsilon = 0.3303 + 8.376 \cdot 10^{-5} \cdot \left(T - 237.15\right) \quad (2)$$

where ν represents the Poisson ratio.

The fatigue material properties of Zy-4 can be determined either by stress-life or strain-life method. For the present study the strain life method (ε-N) was selected. This method is used to evaluate after how many cycles the material will last until failure due to plastic and elastic deformation. The strain-life curves are called Low Cycle Fatigue (LCF) because of the low number of cycles (below 10^5) [12].

As depicted in Fig. 2, at large strains (short life) the plastic strain component is predominant, while at the small strains (longer life) the elastic strain component is predominant. Strain line fatigue curve is plotted on a log-log scale.

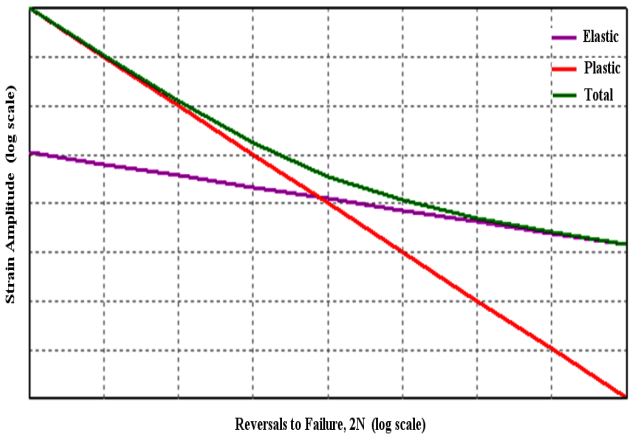


Fig. 2. Strain life diagram (ε-N) [2]

Geometric modelling

In present study were modelled two types of samples worked from CANDU C43 fuel rods. The analysed fuel bundle contains 43 fuel rods, from which 8 thick elements (one central element and 7 elements placed on the inner ring of the bundle) with a diameter of about 14 mm, and 35 thin elements (14 elements placed on the intermediary ring and 21 elements placed on the outer ring of the bundle) with a diameter of about 12 mm (see Fig. 2b).

The samples geometry was created in the SpaceClaim modelling interface programme based on the following dimensions: 14 mm the outside diameter for a ***thick element***, 12 mm the outside diameter for a ***thin element***, wall thickness of 0.4 mm and length of 10 mm for both types of fuel elements. The geometry samples for thin and thick rods are illustrated in Fig. 3, by means of SpaceClaim interface.

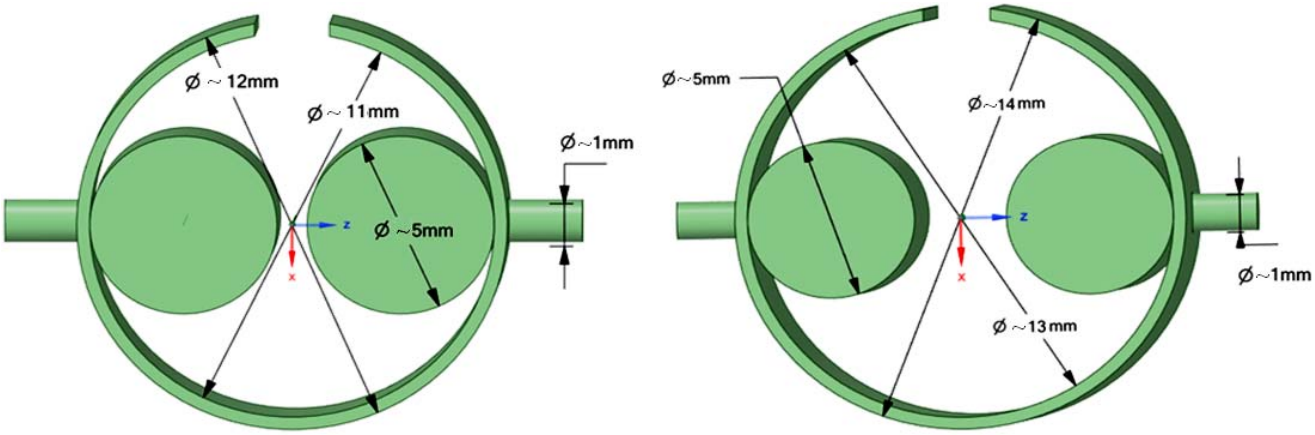


Fig. 3. C43 geometry sample for thin (left) and thick (right) rods

Finite element discretization

The Finite Element Method (FEM) is a numerical technique used to perform Finite Element Analysis (FEA) of any given physical phenomenon. In FEM, the domain of the problem is discretised into small elements.

For the current paper were performed fatigue behavior simulations of Zy-4 C43 samples, in which the number of finite elements was varied with the purpose of highlighting the quality and precision of computations. For the selected thick and thin samples two cases were taken into account. In the first case (*case 1*) the sample thickness was divided in 4 sections, and the element dimension of 0.4 mm was imposed. For the second case (*case 2*), the sample thickness was divided in 6 sections, and the element dimension of 0.2 mm was taken into account.

Figs. 4 and 5 show the number of nodes and elements for each case. The finite element discretization for the two cases is illustrated in Fig. 6.

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Linear
Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
Nodes	11502
Elements	10129

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Linear
Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
Nodes	60420
Elements	51757

Fig. 4. Number of nodes and finite elements for thin rod sample: case 1 (left) and case 2 (right)

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Linear
Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
Nodes	13550
Elements	11582

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Linear
Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
Nodes	71216
Elements	60694

Fig. 5. Number of nodes and finite elements for thick rod sample: case 1 (left) and case 2 (right)

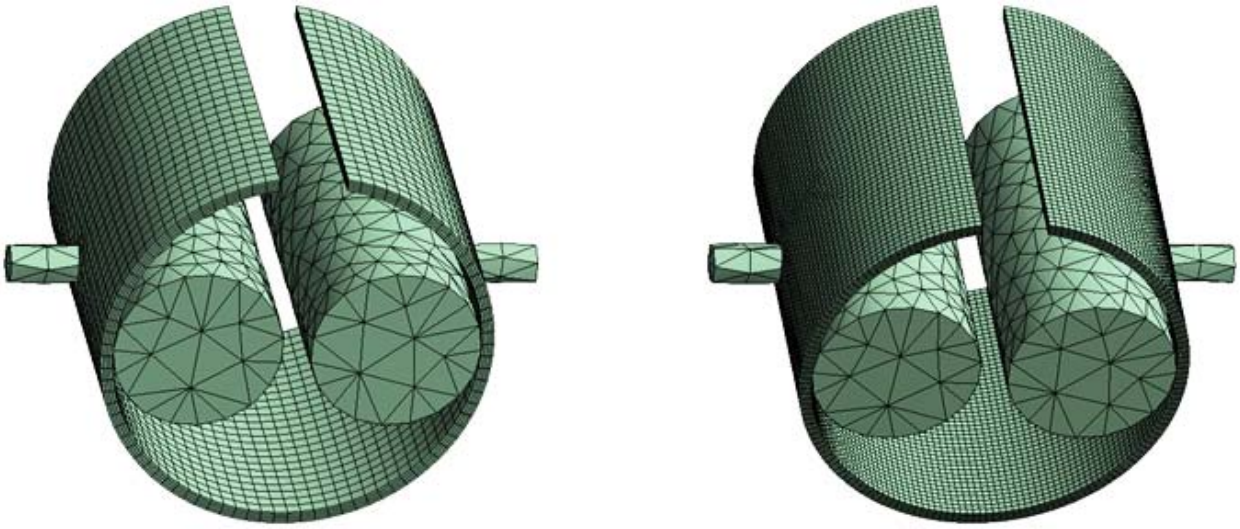


Fig. 6. Rod sample discretization: case 1(left) and case 2 (right)

Boundary conditions

Frictional surface-surface contact pairs with a 0.1 friction coefficient were used to define contact between the holders and sample. For one holder nodes was applied a fixed support constraint, while on the other holder was applied a nodal displacement. Based on tensile tests performed experimentally [13], at room temperature, on C43 Zy-4 samples, and data processing simulations with ANSYS program, the displacements were selected with correspondent total strain amplitude of 1%, 2% and 3%.

Fatigue analysis

In order to estimate the life component, two basic approaches have been developed in ANSYS: Stress-Life method and Strain-Life method [12].

Selecting a certain approach in the case of fatigue analysis depends on the structure failure. The Stress-Life approach is suitable for high-cycle fatigue domain (high durability), while Strain-Life is suitable for low-cycle fatigue domain (low durability) [12].

In the case of mechanical cycling simulation, the Strain-Life method was used to determine the lifetime of Zy-4 [14]. This approach considers plastic deformation and it is often used for low-cycle fatigue analysis. The method principle resides in applying a symmetrical linear load on the sample, with constant amplitude which induces a maximum deformation in the central internal surface. Therefore, a constant amplitude load (Zero-Based) was set (see Figs. 7 and 8).

Details of "Fatigue Tool"

Domain	
Domain Type	Time
Materials	
Fatigue Strength Factor (Kf)	1.
Loading	
Type	Zero-Based
Scale Factor	1.
Definition	
Display Time	End Time
Options	
Analysis Type	Strain Life
Mean Stress Theory	None
Stress Component	Equivalent (von-Mises)
Infinite Life	1.e+009 cycles
Life Units	
Units Name	cycles
1 cycle is equal to	1. cycles

Fig. 7. Fatigue analysis parameters

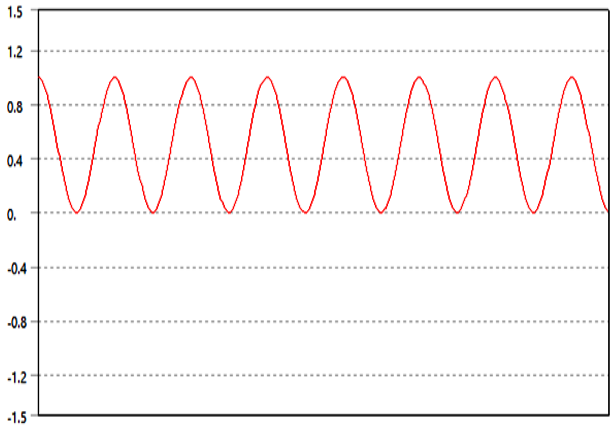


Fig. 8. Constant amplitude load (Zero-Based)

Fatigue tests

The experimental tests [13], conducted for determination of fatigue behaviour were performed on Zy-4 samples at room temperature and a total strain amplitude of 1%, 2% and 3%, respectively. The experimental data determined by constant amplitude tests, on axially required samples are presented in the form of low durability diagrams, namely "total strain amplitude - number of cycles to failure". The fatigue tests were performed on ″as-received″ metallurgical state C-ring samples worked from C43 fuel bundle rods.

Table 1 shows the correspondence between the sample deformation in the central node and the piston displacement.

Table 1. Sample deformation in the central node and the piston displacement correspondence

Sample diameter	**ε- central node (%)**	**Displacement (mm)**
C43 thin rod	1.00	1.66
	2.01	2.98
	3.00	3.74
C43 thick rod	1.00	2.15
	2.03	4.10
	3.03	5.20

In Table 2, the experimental results from the fatigue tests of the C-ring Zy-4 samples, conducted at room temperature [13], are given.

Table 2. Experimental results at room temperature

Total strain amplitude (Δε/2)	**Life**		**Life average**	
	Thin rod	**Thick rod**	**Thin rod**	**Thick rod**
1%	-	223430	-	223430
2%	3210	1790	3093	1926
	2825	2219		
	3064	2541		
	2610	1663		
	3760	1420		
3%	1150	695	993	779
	937	1029		
	816	776		
	1002	681		
	945	718		
	1135			
	1030			
	932			

Results and discussion

C43 fuel bundle thin rod assessment

The fatigue simulations were performed at 1.66 mm, 2.98 mm, 3.74 mm displacement, respectively, varying the number of nodes and finite elements. Every piston displacement is equivalent to a certain deformation (1%, 2% and 3%). The number of cycles obtained in the central node of the sample for both considered cases are shown in Figs 9-11.

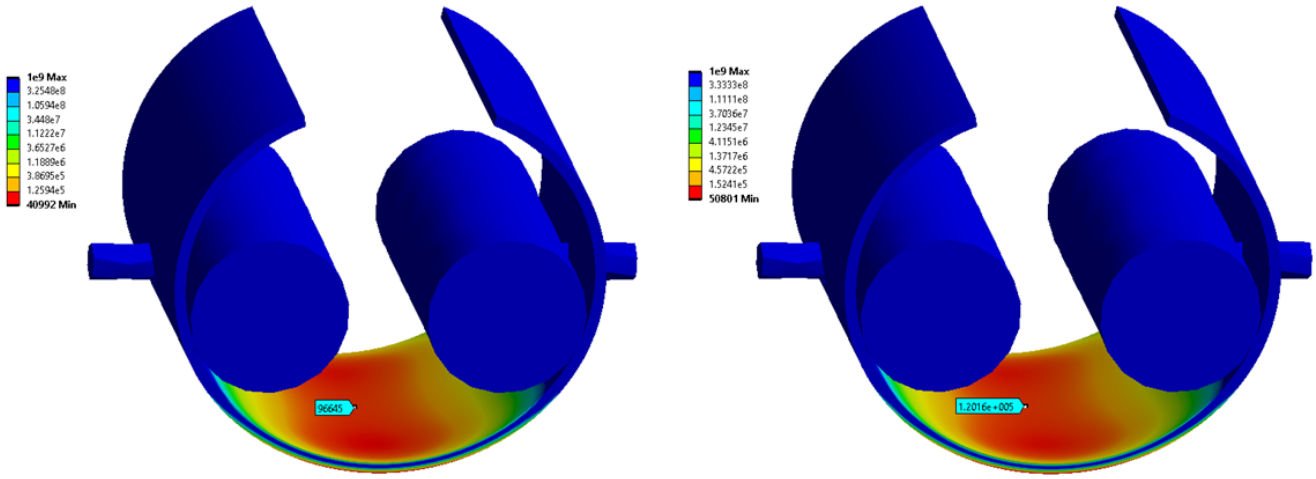


Fig. 9. Number of cycles at 1.66 mm displacement: case 1(left) and case 2 (right)

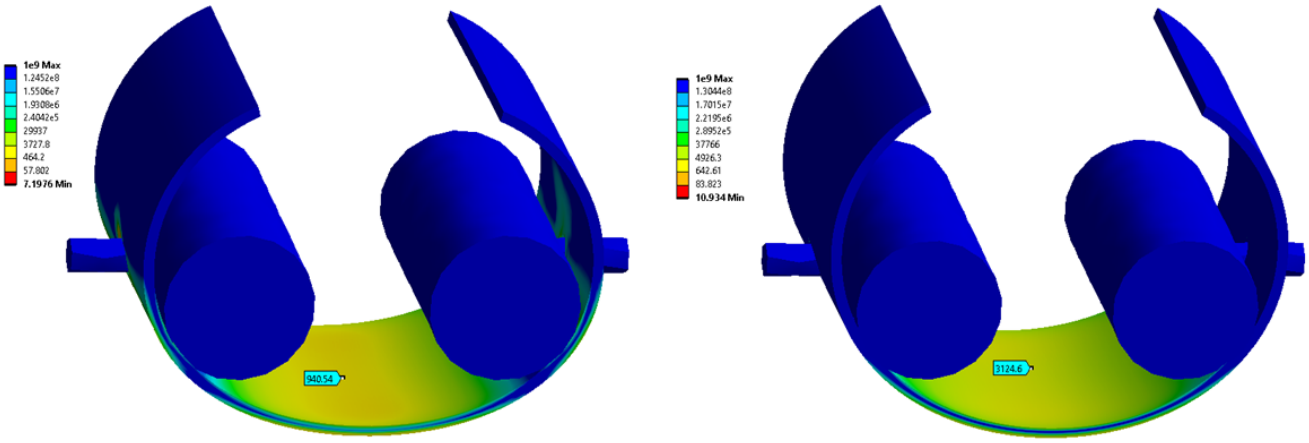


Fig. 10. Number of cycles at 2.98 mm displacement: case 1(left) and case 2 (right)

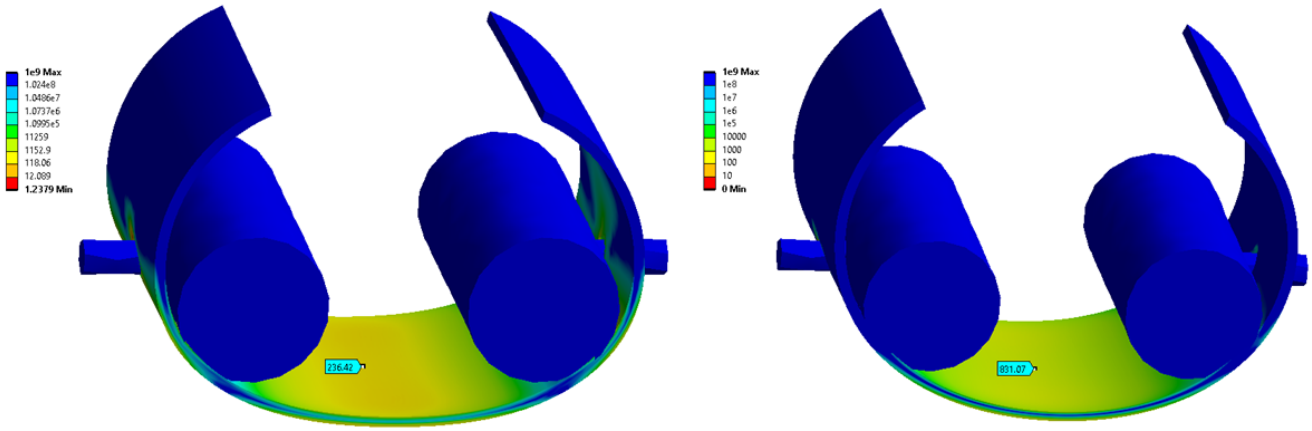


Fig. 11. Number of cycles at 3.74 mm displacement: case 1(left) and case 2 (right)

C43 fuel bundle thick rod assessment

The fatigue simulations were performed at 2.15 mm, 4.10 mm, 5.20 mm displacement, respectively, varying the number of nodes and finite elements. Figs. 12-14 present the number of cycles obtained in the central node of the sample for both considered cases.

Table 3 summarizes all the experimental and simulations data obtained for this study.

In Fig. 15 are comparatively presented ANSYS simulation results and the experimental data for the samples of Zy-4 fuel bundle rods.

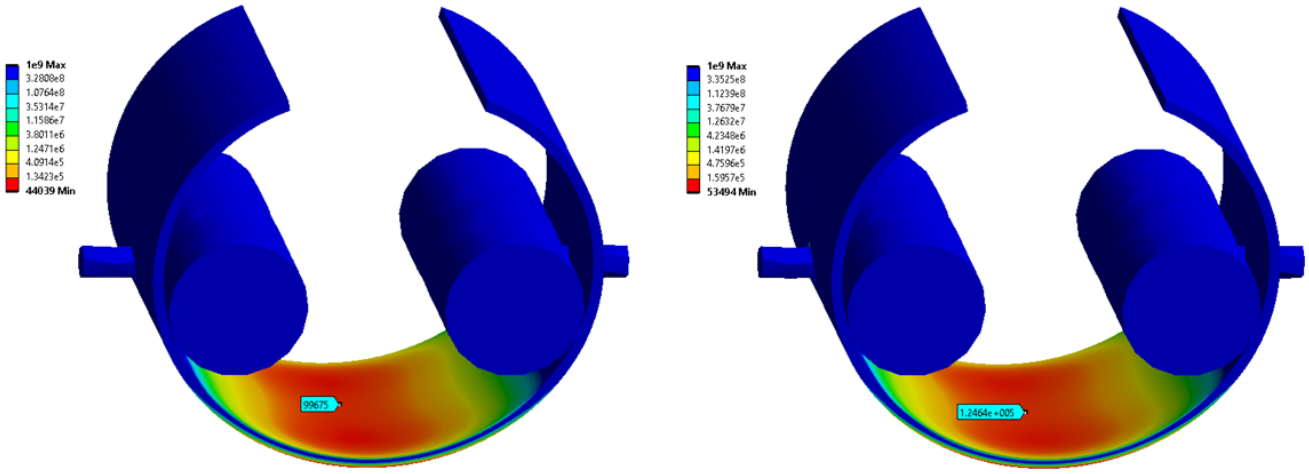


Fig. 12. Number of cycles at 2.15 mm displacement: case 1(left) and case 2 (right)

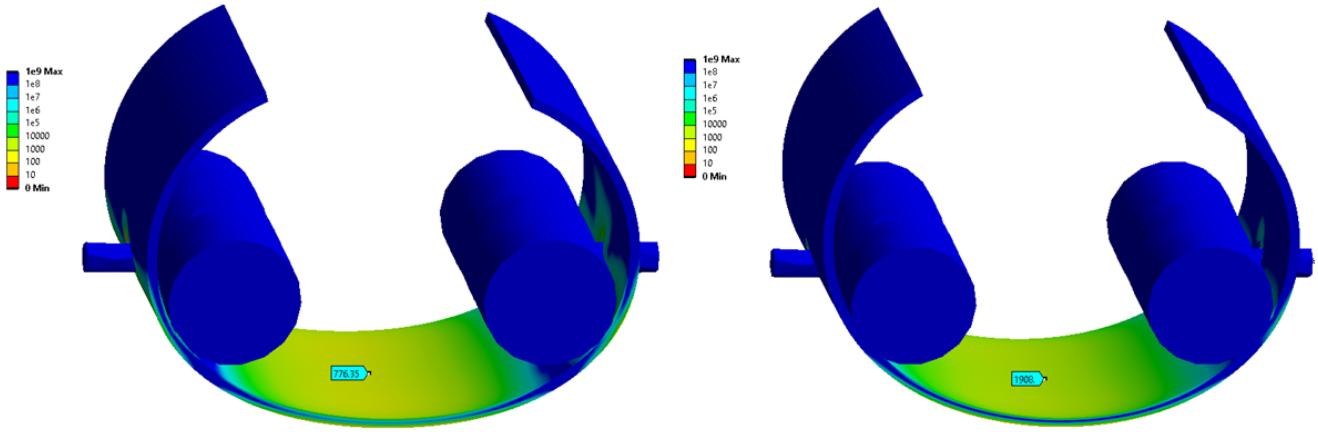


Fig. 13. Number of cycles at 4.10 mm displacement: case 1(left) and case 2 (right)

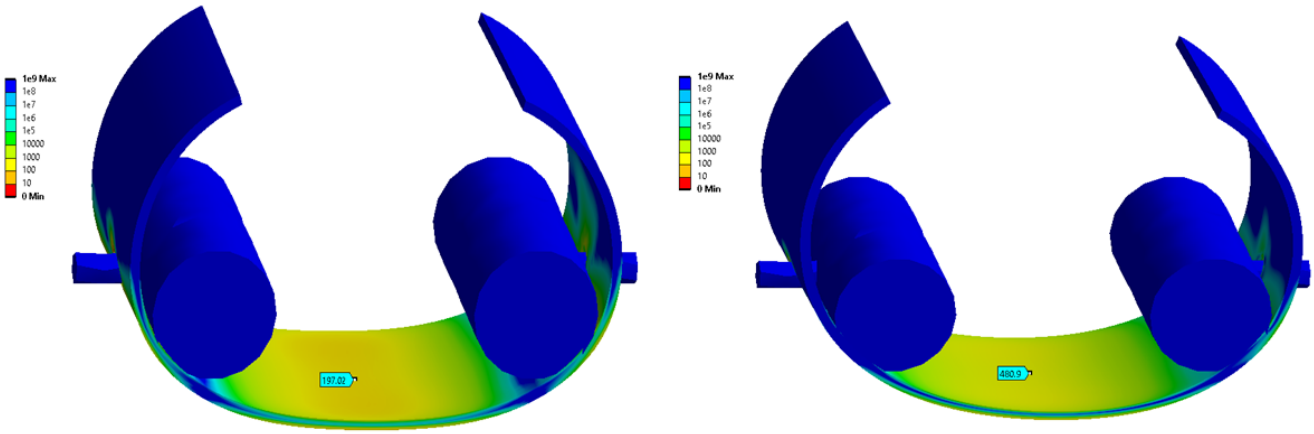


Fig. 14. Number of cycles at 5.20 mm displacement: case 1(left) and case 2 (right)

Table 3. Comparative assessment data

Rod diameter	ε central node (%)	Displacement (mm)	Experimental Results	ANSYS simulation results	
				Case 1	Case 2
Thin rod (φ_{ext} ~ *12 mm*)	1.00	1.66	-	96645	120160
	2.01	2.98	3093	940	3125
	3.00	3.74	993	236	831
Thick rod (φ_{ext} ~ *14 mm*)	1.00	2.15	223430	99675	124640
	2.03	4.10	1926	776	1908
	3.03	5.20	779	197	480

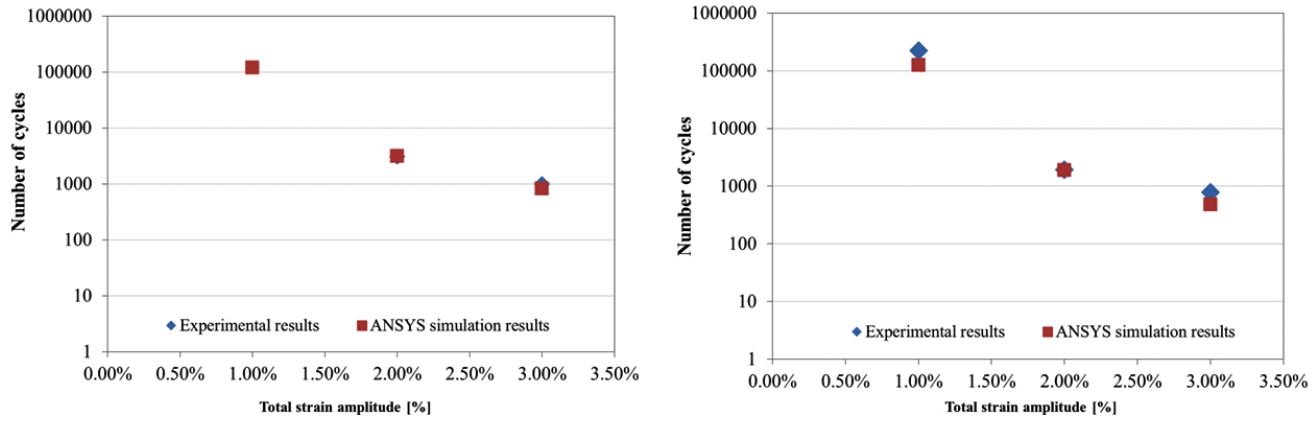


Fig. 15. Comparative results for Zy-4 C43 thin (left) and thick (right) rods

Conclusions

The paper investigated the behaviour of C-ring samples worked from Zy-4 fuel bundle rods subjected to low cyclic loads at room temperature. A comparative analysis between the simulations data and experimental results was performed. Also, an analysis concerning the influence of elements and nodes number was considered.

The use of C43 fuel bundle is expected to exhibit excellent integrity during its lifetime in the CANDU reactors.

The Strain-Life fatigue analysis method was used to determine the lifetime of Zy-4.

The simulations data of Zy-4 C43 thin rod using refined meshing are: 120160 cycles at 1.66 mm displacement, 3125 cycles at 2.98 mm displacement, 831 cycles at 3.74 mm displacement.

The simulations data of Zy-4 C43 thick rod using refined meshing are: 124640 cycles at 2.15 mm displacement, 1908 cycles at 4.1 mm displacement, 480 cycles at 5.20 mm displacement.

The comparative analysis shows a good agreement for the simulations data with refined mesh comparatively with the experimental results was obtained.

The future work will be focused on the development of a finite element model to investigate fatigue behaviour of innovative fuel bundle under accident conditions.

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