STRUCTURAL ANALYSIS OF MOX FUEL ELEMENTS

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Abstract

This article aims to present the attempts of modelling the stress and strain distribution within MOX fuel elements, using finite element method. For this purpose, ANSYS software was used for the simulation of two experimental fuel elements, irradiated in the HBWR Halden reactor and containing MOX pellets, with different geometries. The model and simulation were made taking into account fuel elements geometry, material properties, boundary conditions and loads. For structural analysis, first thermal analysis was performed to assess the temperature distribution, which is used as a thermal load in the structural analysis. The results from the three-dimensional analysis, performed with ANSYS, shown the most stressed areas in the analyzed fuel elements.

Keywords: *Finite element method, MOX fuel, Stress and strain distribution*

Introduction

The development of Generation IV nuclear reactor concepts foresees the utilization of mixed-oxide uranium-plutonium fuel (MOX) to be irradiated under fast neutron flux. However, MOX fuel implementation must be done in safety conditions, being thus mandatory to demonstrate its compatibility with the reactor systems.

Generally, there are many issues to be investigated; amongst them pellet-cladding interaction (PCI) is a prevailing one. Therefore, the assessment of the stress, strain and displacement distribution within the pellet and cladding is an important aspect in terms of fuel safety.

Most of the published papers focus on predicting the temperature inside MOX fuel elements. Therefore, in order to assess the mechanical behavior of MOX fuel under normal operating conditions, a structural analysis must be performed.

One of the ways to design and evaluate the behavior of such fuel elements is to perform analyses through specific computer codes [1].

Present study aims to assess the mechanical behavior of two experimental fuel elements, irradiated in Halden Reactor, and containing MOX pellets surrounded by a zircaloy-4 cladding. In this regard, ANSYS APDL 7.1 (ANSYS Parametric Design Language) was used.

The ANSYS model requires definition of the material data of each component, the geometry and mesh specification as well as the thermal and static structural loads. The structural analysis computes mechanical parameters, such as elastic and plastic strains or stresses, under static load conditions [2].

First, a steady-state thermal analysis is performed and the thermal results are used as input in the structural model. For the sake of brevity, the current study presents only the results from the structural analysis, but ANSYS predictions for temperature distribution can be find in [3].

Material properties and finite element modelling

The main goal of the study was to perform a mechanical analysis of two experimental fuel elements, with different geometries, using the finite element method. In this respect, IFA597 experiment was selected from NEA's IFPE database. This experiment consisted in irradiation of two fuel elements loaded with MOX pellets and zircaloy-4 cladding, during normal operating conditions. The difference between the analyzed fuel elements is given by the different pellet geometry: an experimental fuel element contains two types of MOX pellets (solid and hollow pellets), while the other fuel element contains only pellets with a central hole (hollow). All the geometrical data and irradiation conditions were taken from [4, 5].

For the ANSYS simulations [6], fuel material properties have been used in the input file. Therefore, a short review of MOX material properties [7] is given in the following.

Density

The theoretical density of UO_2 (TD_{UO2}) is 10.96 g/cm^3 and that of PuO_2 fuel (TD_{PuO2}) is 11.46 g/cm^3. Therefore, MOX theoretical density (TD) is obtained with Vegard law, as follows:

$$TD = TD_{UO_2} \cdot f_{UO_2} + TD_{PuO_2} \cdot (1 - f_{UO_2}) \quad (1)$$

where f_{UO2} represents UO_2 fraction in the MOX fuel.

Thermal conductivity

The Halden correlation for MOX fuel was selected and used in the ANSYS simulation:

$$K = \frac{K_{MOX} \cdot a_1}{a_2 + a_3 \cdot BU \cdot (1 - a_7 \cdot BU) + a_4 \cdot Gd + (a_5 - a_6 \cdot BU) \cdot T_C} \cdot F(p) \quad (2)$$

where $K_{MOX} = \begin{cases} 1.0 & pentru\ UO_2 \\ 0.92 & pentru\ MOX \end{cases}$,

$a_1 = 40.4$ $a_2 = 464.0$ $a_3 = 18.4$ $a_4 = 1.16$
$a_5 = 1.0$ $a_6 = 0.0032$ $a_7 = 0.003$

$$F(p) = \left(\frac{1-p}{1+2\cdot p}\right) \Big/ \left(\frac{0-0.05}{1+2\cdot 0.05}\right)$$

with K = thermal conductivity, [W/m·K], p = porosity, T = temperature, [ºC], BU = burnup, [MWd/kgMOX].

Young's modulus

The Young's modulus is given by the formula:

$$E = 2.334\cdot 10^{11}(1\text{-}2.752(1\text{-}D)\cdot(1\text{-}1.0915\cdot 10^{-4}\cdot T)\cdot(1+0.15 f_{Pu})) \quad (3)$$

where E = Young's modulus for MOX fuel, [Pa], D = fraction of TD, T = temperature, [K], f_{Pu} = Pu fraction in MOX fuel.

Thermal expansion

The following correlation for the thermal expansion of MOX fuel was used in present study [6]:

$$\left.\frac{\Delta L}{L_0}\right|_{MOX} = \left.\frac{\Delta L}{L_0}\right|_{UO_2} \cdot (1-f) + \left.\frac{\Delta L}{L_0}\right|_{PuO_2} \cdot f \quad (4)$$

where

$$\left.\frac{\Delta L}{L_0}\right|_{UO_2} = -4.972\cdot 10^{-4} + 7.107\cdot 10^{-6}\cdot T + 2.581\cdot 10^{-9}\cdot T^2 + 1.140\cdot 10^{-13}\cdot T^3$$

$$\left.\frac{\Delta L}{L_0}\right|_{PuO_2} = -3.9735\cdot 10^{-4} + 8.4955\cdot 10^{-6}\cdot T + 2.1513\cdot 10^{-9}\cdot T^2 + 3.7143\cdot 10^{-13}\cdot T^3$$

with T = temperature, [ºC], f = Pu fraction in MOX fuel.

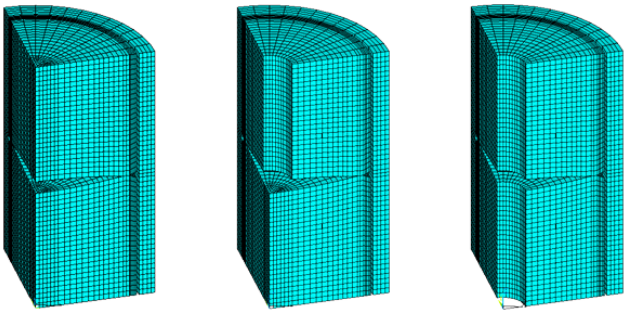
MOX fuel plasticity

In the absence of specific data for MOX fuel, the simulations were performed using UO_2 correlation for plastic deformation:

$$\sigma_Y = \begin{cases} 66.9 - 0.0397\cdot T + (520.0 - 0.386\cdot T)\cdot \bar{\varepsilon}_p & T \le 1200\ ^oC \\ 36.6 - 0.0144\cdot T + (139.5 - 0.06875\cdot T)\cdot \bar{\varepsilon}_p & T > 1200\ ^oC \end{cases} \quad (5)$$

where σ_Y represents the yield strength [kg/mm^2], and T is the temperature [ºC].

The three-dimensional analysis of MOX fuel elements was performed using ANSYS APDL [6]. First, the finite element type for the structural analysis was defined (in our case *SOLID45*) and the geometric model (*pellet* and *clad*) was created, followed by the finite element discretization. The modelled geometry consists of two eights of adjacent pellets and the corresponding clad. For the sake of clarity, in Fig. 1 is depicted the finite element modelling of pellets and clad. It can be noticed that, for the experimental fuel element with both solid and hollow pellets, two different sections were subjected to analysis (see Figs. 1a and 1b), while for the second fuel element only one section was considered (see Fig. 1c).



a) b) c)

Fig. 1. Finite element modelling of pellet and clad

The results from the simulation performed in the steady-state thermal model [3] are used as input to the static structural solution. The next step was to define the boundary conditions applied to the geometry.

Due to the modelling symmetry, all nodes located in the midplane of the bottom pellet (for both clad and pellet) are fixed in the axial direction, the nodes located in the XZ plane are fixed on Y direction, and those located in the YZ plane are fixed on X direction. The nodes located in the axial upper side of the clad are coupled to have the same displacement in axial direction.

Fuel element internal pressure is applied at the pellets external surface and at the clad internal surface (values extracted from TRANSURANUS and presented in [8]). At the clad external surface, coolant pressure was applied [4].

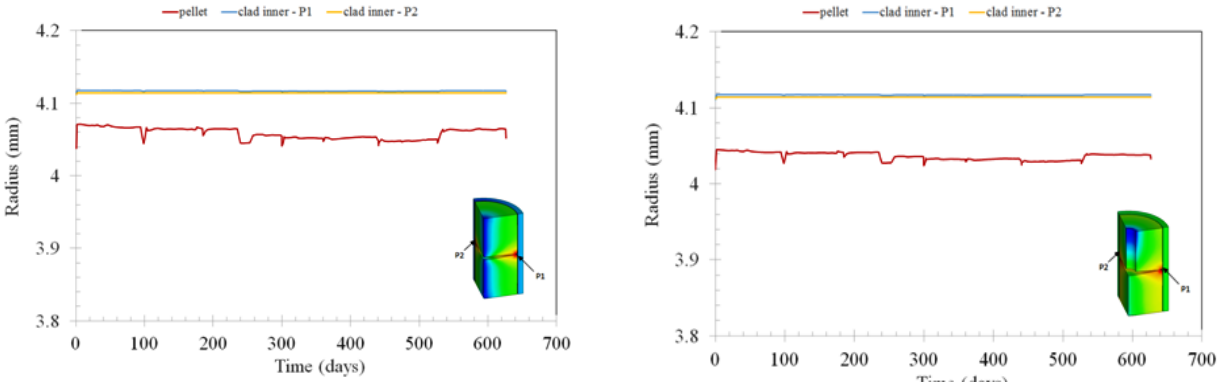
On the clad upper surface, pressure $p = (p_i - p_0)\frac{\delta^2}{\delta^2 - 1} - p_i$ is applied, with p_i = fuel element internal pressure, p_0 = coolant pressure and δ = ratio between outer and inner clad radius. All these loads are applied at each time step.

Results and discussion

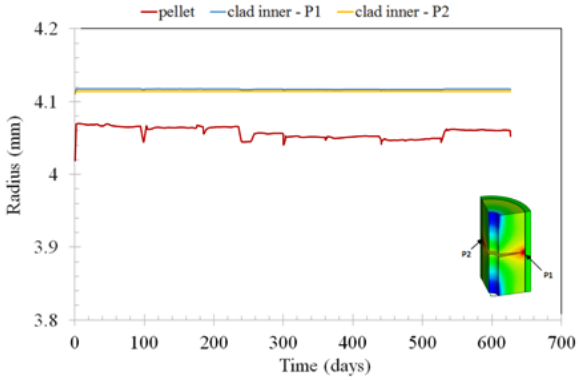
The objective of this work was to carry out a structural analysis of two MOX fuel elements, irradiated in normal operating conditions.

A significant aspect to be taken into account and investigated is the PCMI (pellet-cladding mechanical interaction). The pellet outer radius variation during the irradiation time is represented in Fig. 2, along with clad inner radius at pellets midplane position. It can be noticed that, in all studied cases, there is no contact between pellets and clad, and the radial gap remains open during the whole irradiation period.

The strain behavior is depicted in Figs. 3 and 4, both from the radial and axial perspective, the values being extracted for the last time step. ANSYS results show that the maximum radial strain is reached across the pellet chamfers (see Fig. 3). From the axial perspective, the maximum strain is observed at pellets dish, although the pellets are not in contact (see Fig. 4). From these results we can agree that the pellet and clad expanding is within the safety limits.

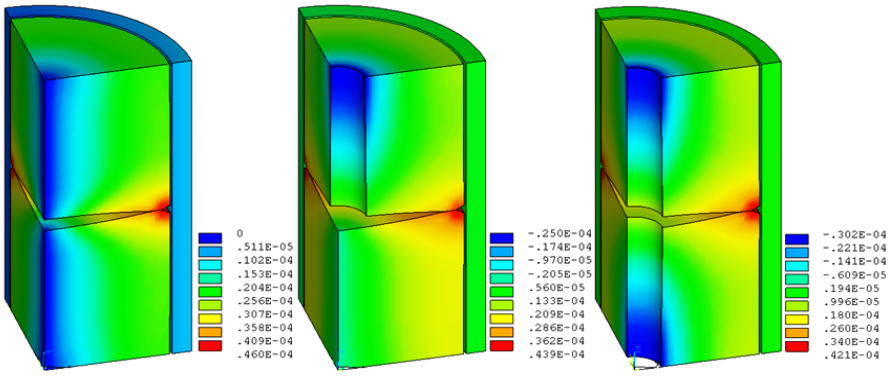


a) section with solid pellets b) section with solid and hollow pellets



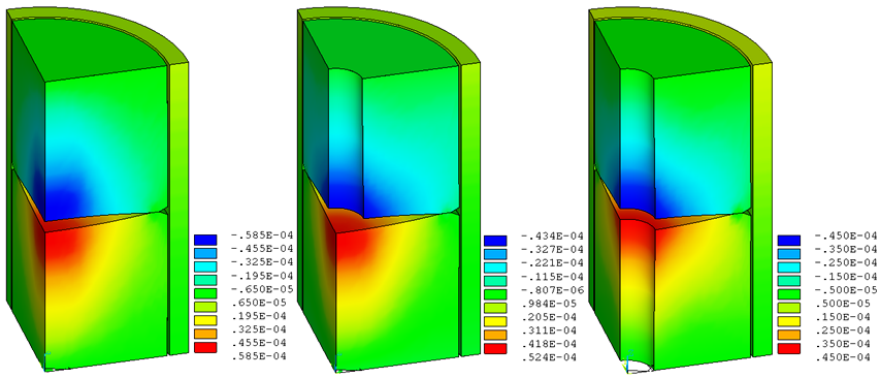
c) section with hollow pellets

Fig. 2. Evolution of pellet outer and clad inner radius



a) b) c)

Fig. 3. ANSYS strains [m] obtained in the radial direction at the end of the irradiation period
a) solid pellets; b) solid and hollow pellets; c) hollow pellets



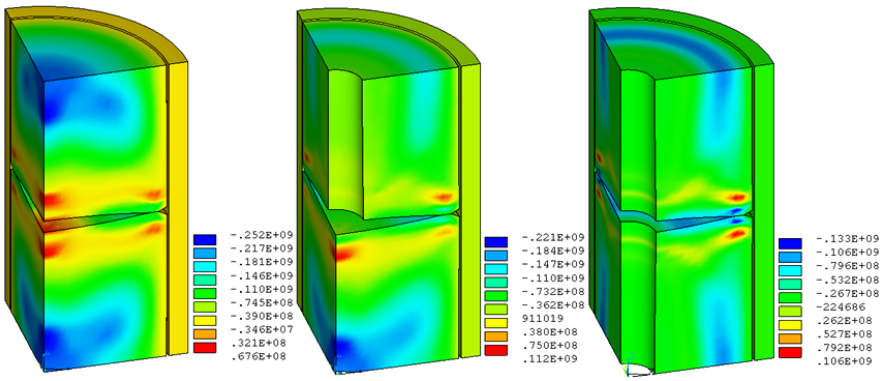
a) b) c)

Fig. 4. ANSYS strains [m] obtained in the axial direction at the end of the irradiation period
a) solid pellets; b) solid and hollow pellets; c) hollow pellets

Regarding the radial stress distribution, it was found that the maximum stress is developed near pellet chamfer and dish, as it can be seen in Fig. 5.

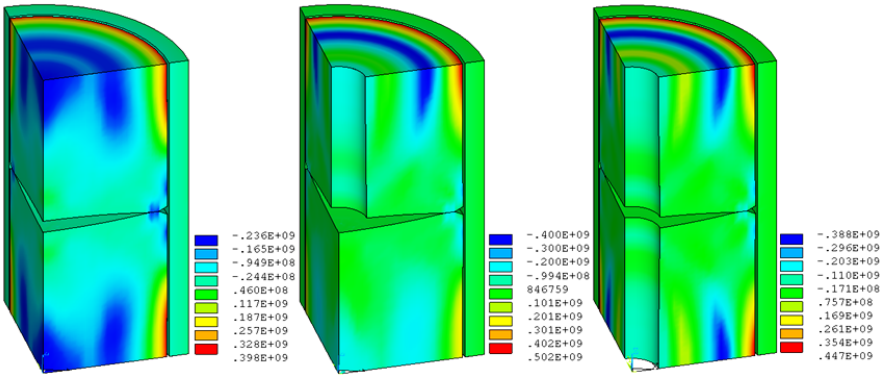
In order to obtain more complex results, the axial and hoop stresses were represented, along with the equivalent stress, for all studied fuel elements and the corresponding sections (see Figs. 6, 7 and 8).

The results shown that the most stressed areas are at the outer pellet surfaces towards their midplane positions (middle of the pellet on the axial direction).



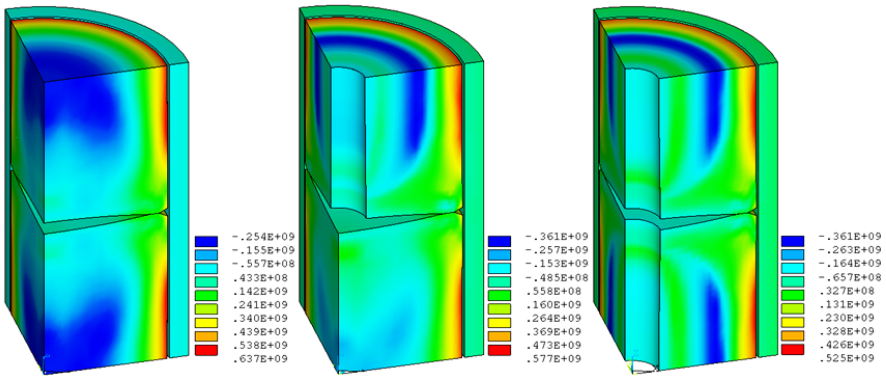
a) b) c)

Fig. 5. ANSYS stresses [Pa] obtained in the radial direction at the end of the irradiation period
a) solid pellets; b) solid and hollow pellets; c) hollow pellets



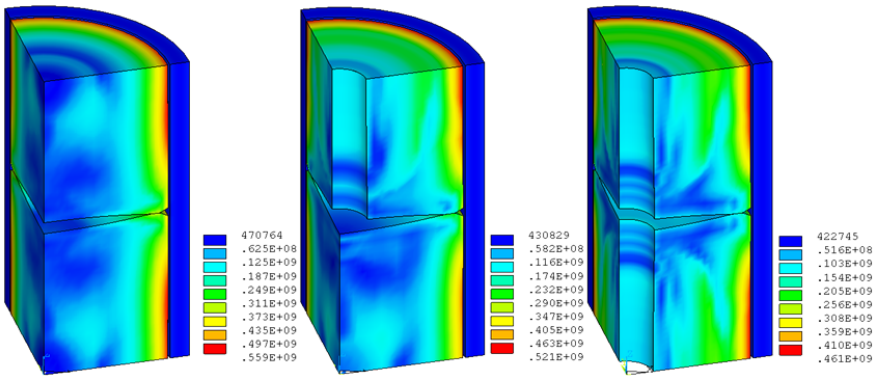
a) b) c)

Fig. 6. ANSYS stresses [Pa] obtained in the axial direction at the end of the irradiation period
a) solid pellets; b) solid and hollow pellets; c) hollow pellets



a) b) c)

Fig. 7. ANSYS hoop stresses [Pa] obtained at the end of the irradiation period
a) solid pellets; b) solid and hollow pellets; c) hollow pellets



a) b) c)

Fig. 8. ANSYS equivalent stresses [Pa] obtained at the end of the irradiation period
a) solid pellets; b) solid and hollow pellets; c) hollow pellets

Conclusions

The main goal of the study presented in this work was to determine the mechanical behavior of two experimental fuel elements, loaded with MOX pellets surrounded by a zircaloy-4 cladding. A main outcome of the paper was also to develop a complex finite element method, suitable for future simulation of different types of fuel elements and/or various operating conditions.

The finite element method was used in ANSYS v7.1 program to assess the most stressed areas in the studied fuel elements.

Two experimental fuel elements irradiated in the Halden reactor were considered. More precisely, the analyzed fuel elements contain MOX pellets, with different geometries, surrounded by a zircaloy-4 cladding and irradiated in Halden reactor considering normal operation conditions.

From ANSYS simulations, it was emphasized that the stress developed in the MOX fuel elements is within the safety limits, and the radial gap remains open for the whole irradiation period. The cladding strain and stress distribution is also in the elastic domain. Therefore, the pellet-cladding interaction is not taken into consideration in this scenario.

Future perspective will be focused on the assessment of MOX fuel elements mechanical behavior, irradiated in lead fast reactor operation conditions, such as ALFRED LFR demonstrator.

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