Modelling of WWER fuel rod during LOCA conditions using FEM code ANSYS

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The report presents the results of the computer simulation of the IFA-650.6 experiment, the sixth test in Halden LOCA test project series, performed in May 18, 2007 with a pre-irradiated WWER-440 fuel with maximum burnup of 56 MWd/kgU.

The thermo-mechanical analysis was fulfilled with the license finite element ANSYS code package.The calculation was carried out with the 2D axisymmetric and 3D problem definitions.

Analysis of the calculational results shows that the ANSYS code can adequately simulate thermo-mechanical behavior of cladding under IFA-650.6 test conditions.

INTRODUCTION

The report presents the results of the computer simulation of the refabricated fuel rod behavior under IFA-650.6 LOCA test conditions. Test was conducted within the framework of the Joint Program of the Halden Reactor Project (HRP).

The sample for refabricated test fuel rod was cut out from fuel-scale fuel rod of AA29 assembly, irradiated on the first unit of NPP "Loviisa". J13 fuel rod with average burnup of 50 MWd/kgU was delivered at Studsvik, where it was cut to pieces for post-irradiated examinations (PIE) and segments for in-pile tests, in particular, for LOCA-type test in Halden reactor. For the LOCA test a segment of 500 mm length was cut from the central part of the fuel rod J13. The maximum burnup of refabricated fuel rod amounted to 56 MWd/kgU. After that the segment was transported in IFE hot cells for further refabrication and preparation for the LOCA experiment.

Simulation of the experiment was carried out with the finite element ANSYS code license (customer number – 662129). At this stage the simulation of the cladding thermo-mechanical behavior without fuel was performed. Due to axially symmetric shape of cladding this task can be solved using the 2D axisymmetric formulation. Calculations at those conditions allow to save computer time and resources owing to small number of finite elements. Also this statement permits to simulate the problem more detailed using very small size of the finite element.However, the problem has a significant geometric nonlinearity (circumferential strain can be up to 20%). That is, the simulation results will depend on the deformed shape of the model (ballooning). This can lead to non-equivalence of 2D and 3D problems. Also the 3D formulation allows to research the influence of non-uniform azimuthal temperature distribution on the simulation results.

The report presents the results of test simulation with the 2D-statement and 3D definitions with the uniform and non-uniform tangential temperature distributions.

1 Short description of the IFA-650.6 LOCA experiment

Test with refabricated fuel rod was carried out under standard Halden reactor conditions: coolant is heavy water, temperature is about 235 °C and pressure is 34 bar. Instrumented fuel rod was located in a high-pressure flask connected to the heavy water loop (Figure 1). Test fuel rod was instrumented with inlet/outlet coolant pressure transducers, internal rod pressure transducer, fast neutron detectors to indicate fuel rod power, thermocouples to determine inlet/outlet coolant temperatures, thermocouples to measure cladding temperature at two elevations, thermocouples at electrical heated shroud, cladding elongation detector, gamma monitor to indicate coolant radioactivity. Parameters of experimental fuel rod are shown in Table 1.

Table 1 – Parameters of experimental fuel rod in IFA650.6 test

Fuel stack height, mm	480
Cladding outer diameter, mm	9.13
Cladding thickness	0.679
Cladding material	E110 (Zr1%Nb)
Total free gas volume, cm^3	16 - 18
Gas volume at active part, cm^3	7
Gas plenum length, cm	14
Initial fuel rod pressure, MPa	3
Average burnup, MWd/kgU	49
Maximum burnup, MWd/kgU	56

At the preliminary stage of the experiment the steady-state operation at high power with the outer loop connected and forced circulation coolant flow during ~20 days was performed. Power calibration was done during this period. After that, fuel rod linear power was decreased to test level by declining reactor power. Then the electrical heater of was switched on. At the beginning of coolant blowdown the linear heat rate for the fuel was measured to be 12.0 W/cm and the electrical heater power was about 13.5 W/cm.

After stabilization of temperature distribution, forced circulation regime was changed to natural circulation phase by mean of valve VA6303 opening and valve VA6305 closure, at the same time valve VA6304 stayed open. The LOCA blowdown phase was modeled by appropriate re-switching of valves. When blowdown period was started, valves VA6333 and VA6334 were opened whereas VA6304 was closed. At that moment time keeping during IFA-650.6 test was started at zero point. The test rig was empty about 2 minutes after the beginning of blowdown as the rig inlet pressure reached a minimum.

The coolant spray was started in pulse regime at 440 s from the upper part of test flask when thermocouple TCC1 reached ~800 °C (~1 minute before the cladding burst). The cladding deformation was assumed to have been started when the rod pressure reached a maximum ~470 s after blowdown, then internal rod pressure was slowly declining.

The fast pressure drop indicating fuel rod cladding burst started at 526 seconds as cladding temperature reached 832 °C before the heater was switched off at the time of ~556 s. Test was finished with slow reactor scram at ~ 7.5 minutes after completion of the blowdown. Experimental rig was not refilled. Afterwards the rig was filled with helium to prevent any further corrosion etc. until PIE.

2 Material properties definition

The simulation of cladding mechanical behavior was performed in visco-elastic formulation. At this formulation it is necessary to specify the elastic constants and creep rate for E110 cladding.

Dependence of the Young's modulus vs. temperature for E110 alloy is represented in Figure 3. To specify cladding creep rate the Norton model was used in following form:

$$\dot{\varepsilon} = C_1 \cdot \sigma^{C_2} \cdot e^{-C_3/T} \qquad (1),$$

where $\dot{\varepsilon}$ – creep rate, s^{-1}; σ – cladding effective stress, MPa; T – temperature, K; C_1,C_2, C_3 – experimental constants given in Table 2:

Table 2 - C_1, C_2, C_3 parameters in formula (1)

Parameter number	Value
C_1	$1.3947 \cdot 10^8$
C_2	2.55
C_3	$3.5 \cdot 10^4$

3 Simulation of the LOCA experiment with 2D axisymmetric definition

3.1 Finite element modeling scheme

A full-size test fuel rod cladding without fuel was simulated with the use axisymmetric 2D formulation. The length of specimen equals to 480 mm, outer cladding diameter – 9.13 mm, cladding thickness – 0.679 mm. Cladding was divided into finite elements PLANE223 (the eight-node quadratic elements with median nodes, which provide more accurate results that support plasticity, creep, and stabilization of the solution). The finite-element researches demonstrated that the optimal size of the finite element at this formulation is 1/4 of the cladding thickness. The nodal scheme consists of 11312 elements and 39601 nodes. Finite element scheme is shown in Figure 4.

3.2 Boundary and loading conditions

The boundary conditions of the simulated cladding are given below:

- on the top and bottom of the modeled cladding all translational degrees of freedom were fixed: $U_X=0$, $U_Y=0$, $U_Z=0$;
- the variation of temperature versus time and height was specified as body forces;
- at the inner and outer cladding surfaces the time-dependent pressure was specified.

To specify time-dependent function for cladding temperature the smoothed interpolation data from thermocouple registrations was used. The data from three pressure sensors (two outer located in coolant and one internal in fuel rod) were used for the cladding pressure drop specification.

3.3 Calculation results

Computational results are presented in Figure 5. Figure shows the distribution of radial displacement and tangential stresses at the time of the fuel rod cladding failure (527 s). The maximum radial displacement reached the value of 1.69 mm and was realized at the axial level of 107 mm. The measured maximum radial displacement was 1.86 mm and occurred at 95.7 mm. A good agreement between calculational and experimental data was obtained. The maximum circumferential stresses were 40.4 MPa at the height of 109 mm.

4 Simulation of the LOCA experiment using 3D definition

4.1 Geometrical part

A full-size test fuel rod cladding without fuel was simulated in the three-dimensional definition. For the simulation a three-dimensional quadratic 20-node element SOLID186, supporting plasticity and stabilization during solution, was selected. The total number of elements was 230400. Finite element model is shown in Figure 6.

4.2 Boundary conditions and loading

The boundary conditions were the same as for 2D definition (see section 3.2).

4.3 Solution results

The calculational results are presented in Figure 7. The figure shows the distribution of radial displacement and circumferential stresses at the time of cladding burst (time 527 sec obtained at IFA-650.6 test). The maximum radial displacements were 2.36 mm and occurred at the level of 107 mm. The computed peak circumferential stress amounted to 49.6 MPa and was realized at the level of 109 mm. The time and stress/strain conditions of cladding failure weren’t determined at this stage of calculations. Comparison between computational, experimental data and independently obtained results with the FRAPTRAN code [1], is shown in Figure 8. As in the case of 2D calculation, a good agreement between computational and experimental data was obtained.

5 LOCA test simulation with non-uniform azimuthal temperature distribution

At this block of calculations the influence of a non-uniform circumferential temperature distribution on computed results was investigated. For this purpose, non-uniform temperature field was specified, which was increased linearly by 1 ºC to 180º circumferential angle and was decreased linearly to the initial angle. Obtained distributions of radial displacements and circumferential stresses are shown in Figure 9.

The maximum radial displacement of the cladding in the case of non-uniform circumferential temperature distribution was 2.6 mm, that greater by 0.24 mm (10%) than in the case of uniform circumferential temperature distribution.

6 Discussion of the results

Comparison between calculational results obtained by 2D axisymmetric definition, 3D calculation with uniform circumferential temperature distribution, 3D simulation with non-uniform circumferential temperature distribution and experiment is shown in Table 3:

Table 3 – Results of the comparison between calculational results using 2D axisymmetric and 3D definitions

Formulation	Maximum radial displacements, mm	Maximum circumferential stresses, MPa
2D	1.69	40.4
3D uniform	2.36	49.6
3D non-uniform	2.6	53.3
Experiment	1.86	–

Table 3 shows that all three formulations adequately describe the results of the test with account for uncertainty of the material properties data. The maximum error of the displacement calculation was 40%. The analysis of computational results showed that maximum radial displacements are increased by 40%, hoop stresses – by 23% in the case of calculations with 3D task definition in comparison with 2D calculations under the same conditions.

Introduction of the circumferential non-uniformity of 1^{o} leads to increase the maximum radial displacements by 10%. Figure 10 shows a comparison between results of the experimentally obtained gamma-scanning of the failed cladding [2] with computational results of cladding deformation. Figure 10 shows a good agreement between experimental and calculational data.

CONCLUSIONS

In this work a numerical simulation of the cladding thermo-mechanical behavior under IFA-650.6 test conditions with the use of ANSYS finite-element computational complex was performed. The calculational results in frame of following task definitions are presented:

- 2D axisymmetric formulation;
- 3D formulation with uniform azimuthal temperature distribution;
- 3D formulation with non-uniform azimuthal temperature distribution.

Results of the cladding behavior simulation were analyzed. It was shown that:

- all three definitions adequately describe the experimental results with the uncertainty in material properties data with except of cladding failure. The maximum error of the cladding displacement was 40%;
- In the case of 3D definition calculated maximum radial displacements increase by 40%, circumferential stresses - by 23% as against computed results, obtained in frame of 2D definition;
- Input deck specification of the circumferential non-uniformity of 1º increases the maximum radial displacements by 10%.

It was shown that the developed technique can be used to simulate thermo-mechanical aspects of LOCA tests.

Further it is planned to carry out the following works:

- Thermo-mechanical calculations of LOCA experiments, in particular, IFA-650.11 test;
- To predict cladding rapture at LOCA-type tests the cladding failure criterion for E110 alloy should be analyzed and adopted to ANSYS code;
- The revision and implementation of the high-temperature E110 cladding material property data for the more accurate simulation of LOCA tests.

REFERENCES

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2. LOCA IFA650-6: PIE of the high burnup (56 MWd/kgU) VVER segment. B.C.Oberländer, M.Espeland, N.O.Solum, H.K.Jenssen. Nuclear Safety and Reliability Division Nuclear Materials Technology Department POB 40, NO-2027 Kjeller. EHPG-Meeting, Storefjell, March, 2009.

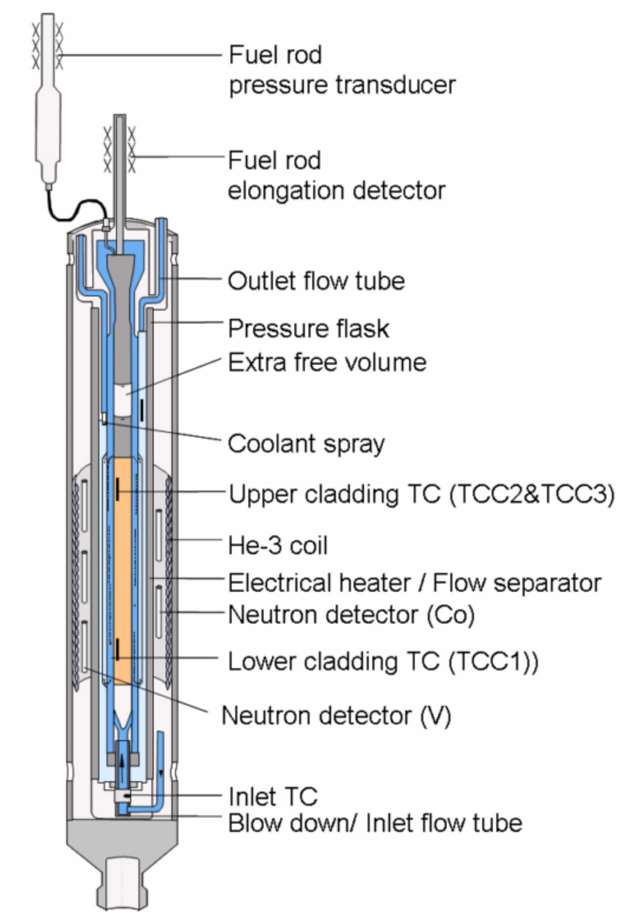


Figure 1 – Scheme of test rig

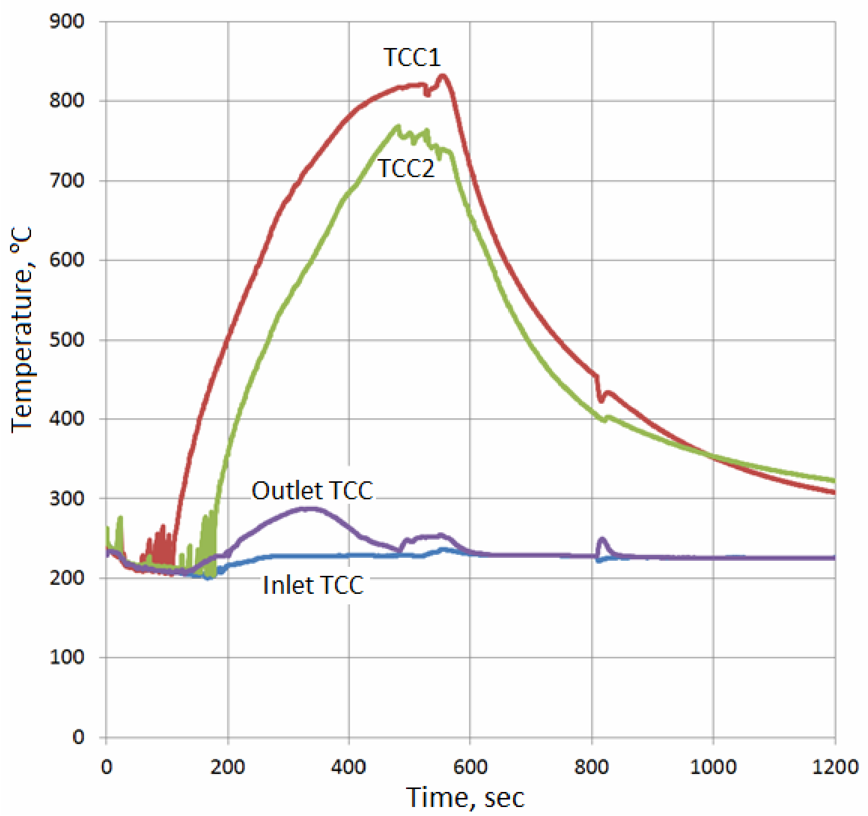


Figure 2 – Thermocouple data (TCC1, TCC2, Inlet TCC, Outlet TCC)

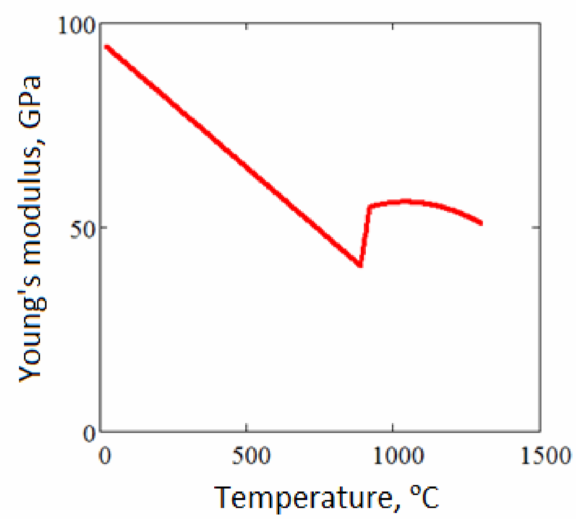


Figure 3 – Young's modulus of E110 alloy

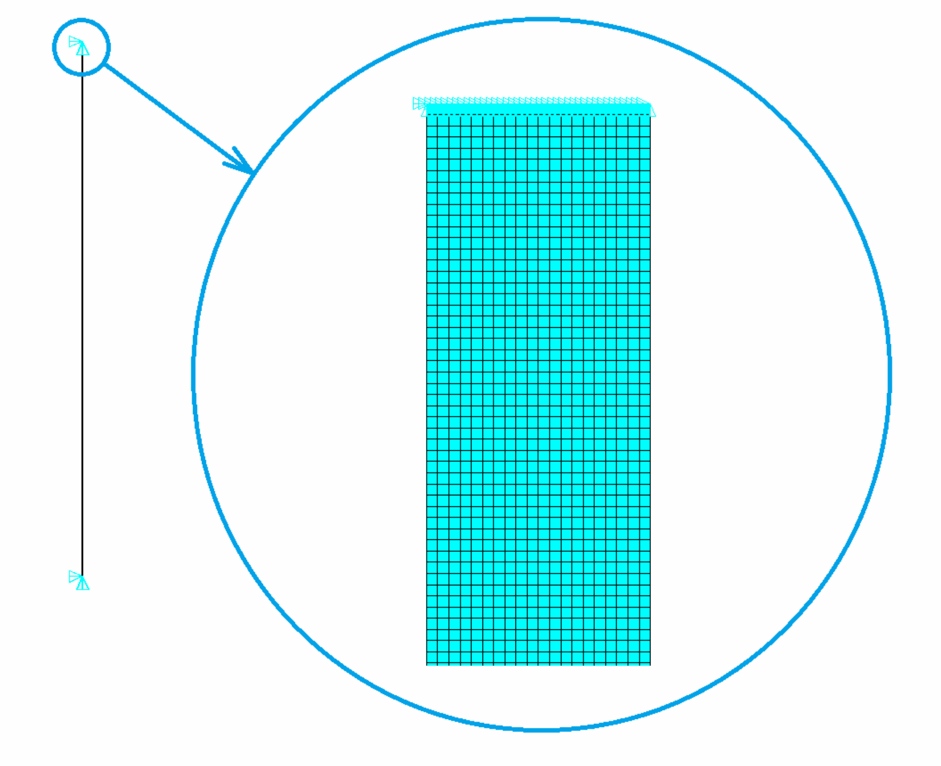


Figure 4 – 2D axisymmetric finite element model with fixings (at the left) and enlarged image (at the right)

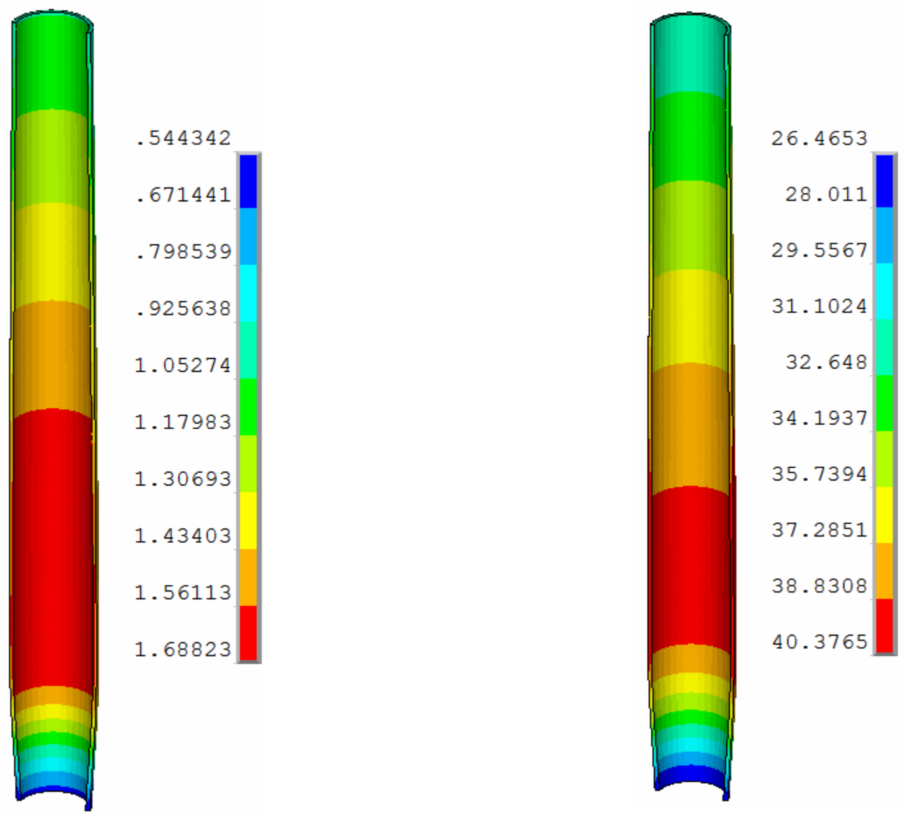


Figure 5 – Distribution of radial displacements (mm) (at the left) and cladding circumferential stresses (MPa) (at the right) (½ turn around the axis)

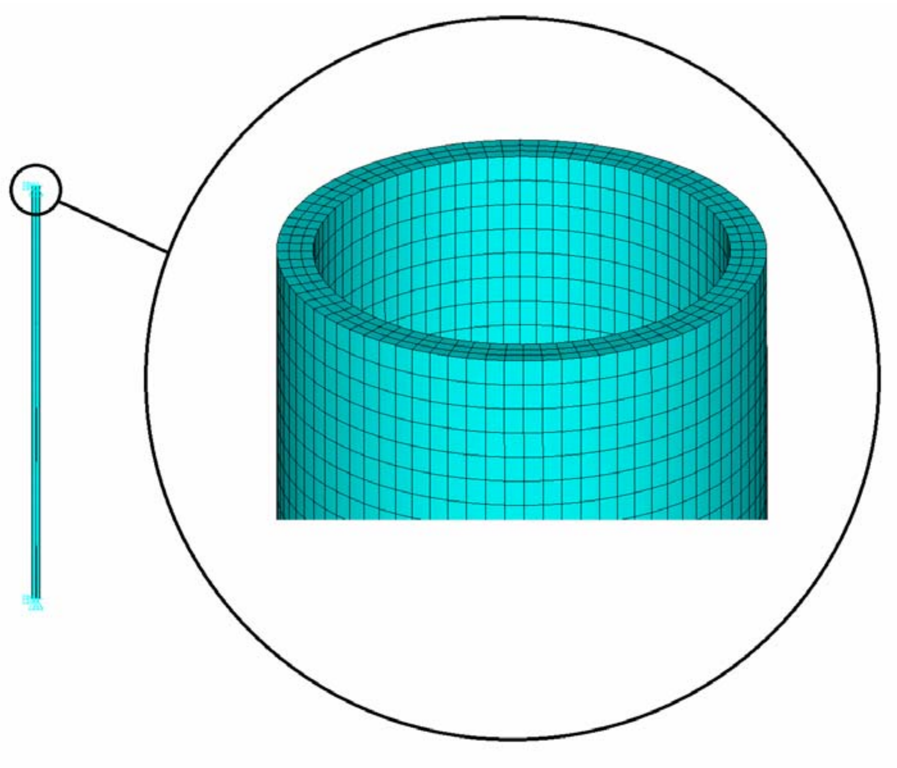


Figure 6 – 3D cladding volumetric subdivisions for finite element model with fixing fixings (at the left) and enlarged image (at the right)

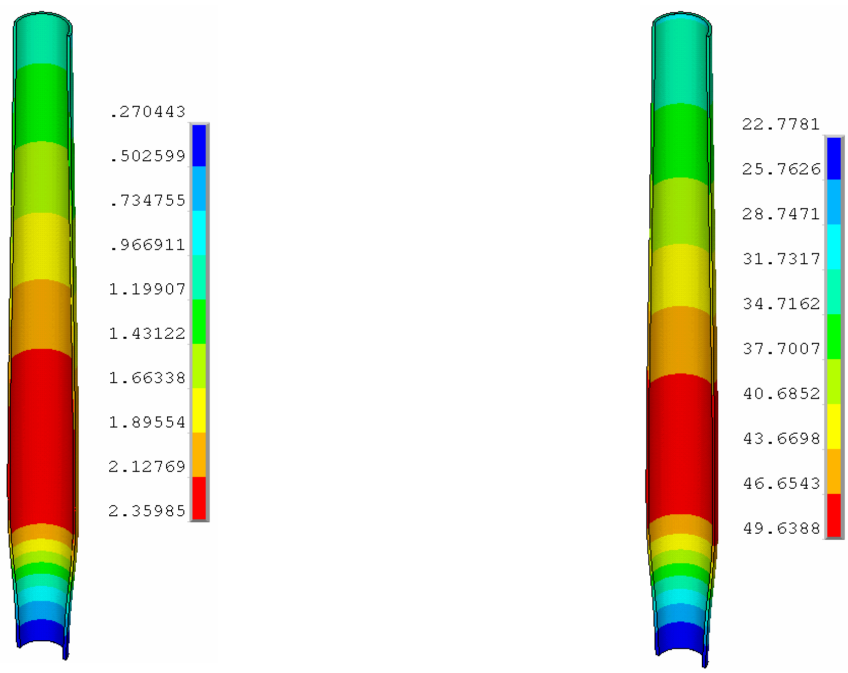


Figure 7 – Distribution of radial displacements (mm) (at the left) and circumferential cladding stresses (MPa) (at the right)

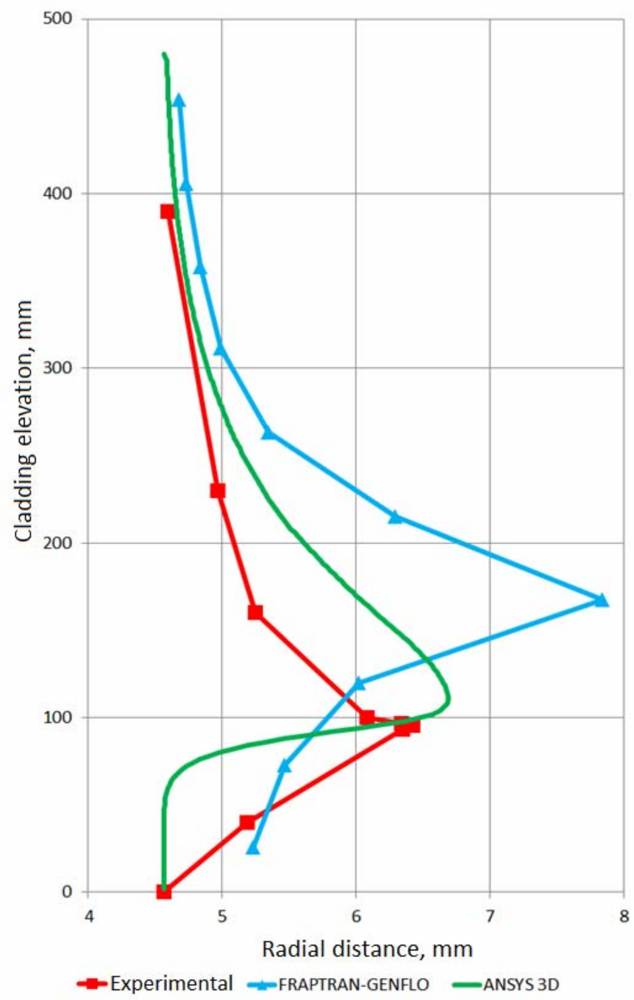
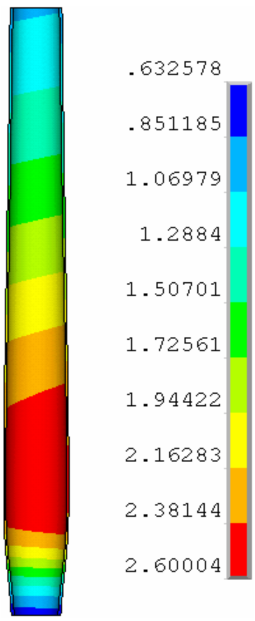


Figure 8 – Comparison between experimental and computational results



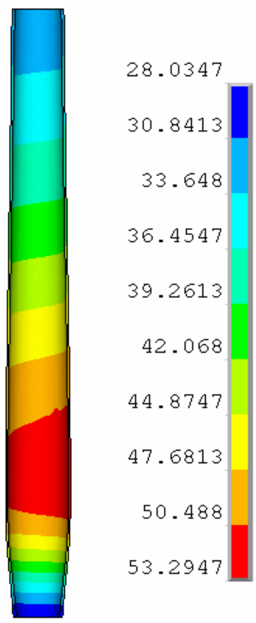


Figure 9 – Distribution of radial displacements (mm) (at the left) and circumferential cladding stresses (MPa) (at the right) at the bottom part of the cladding

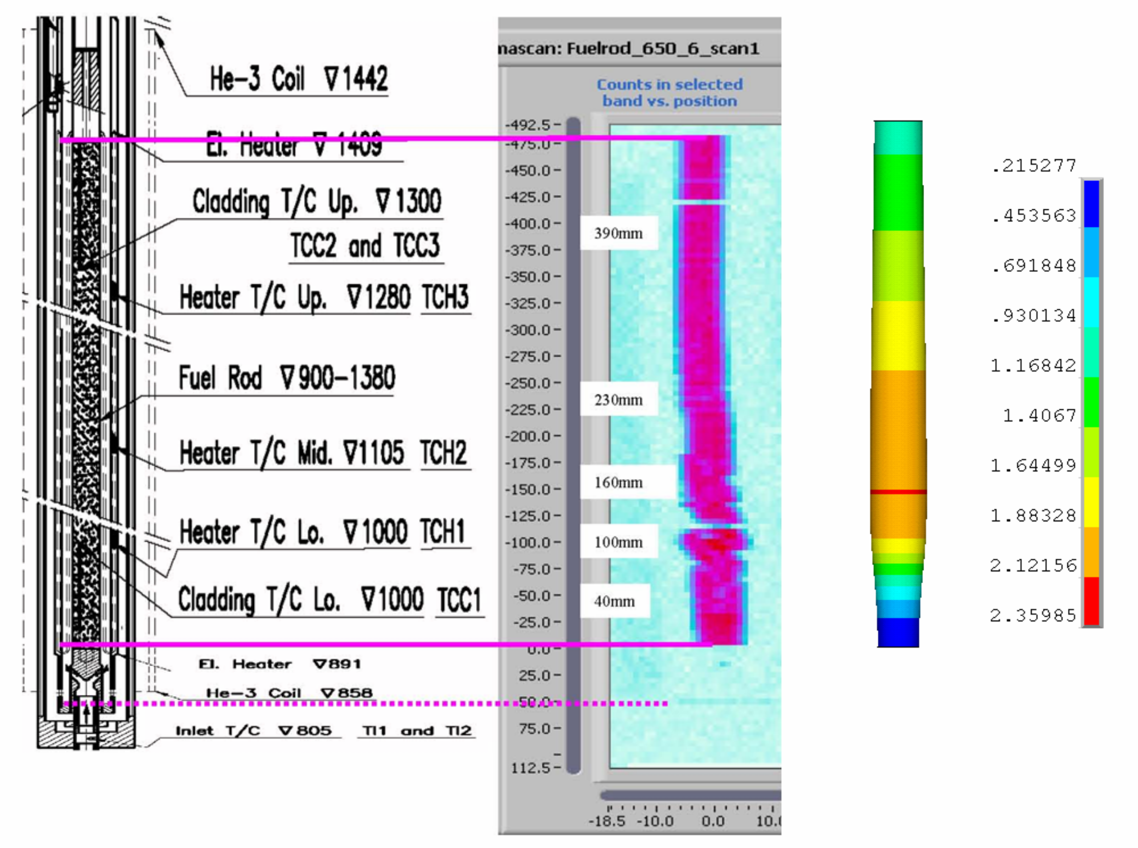


Figure 10 – Comparison between results of the experimentally obtained gamma-scanning of the failed cladding (at the left) with computational results of cladding deformation (at the right)