Nonlinear finite element studies of the pellet-cladding mechanical interaction in a PWR fuel

Brochard J., Bentejac F., Hourdequin N.
CEA, France

ABSTRACT: After a presentation of the general features of the code TOUTATIS, which is a specific module of the FEM code CASTEM2000 developed in the framework of the CEA project METEOR to describe the local thermomechanical behaviour of PWR fuel rods, results of a parametric study conducted in order to analyse the influence of some modelling assumptions and of the pellet geometry on PCMI intensity are shown. Accurate modelling of the axial pellet-clad constraints and of the pellet fragmentation is proved to be important.

1. INTRODUCTION

In order to simulate accurately the local mechanical behaviour of PWR fuel rods during steady-state or power transient, a specific module of the general purpose finite element computer code CASTEM2000 is in progress. This code, TOUTATIS, based upon 2D or 3D models, is developed in the framework of the C.E.A. research and development project METEOR, as well as the ID1/2 thermomechanical code METEOR/TU which is used to describe the global behaviour of a fuel rod [1]. Up to now, the developments of the code TOUTATIS have been focussed on the prediction of cladding tube failures by pellet cladding interaction (PCI) after an up power excursion (power ramp) [2], especially for fuel rods irradiated for 2 cycles in a power reactor, because for such fuel rods the configuration is favourable to PCI failures: the pellet-cladding gap is closed while the considered power transients occur. Many physical models are available in the global code METEOR/TU and an interface can be used to transfer data from the global code to improve the local modelling.

This paper presents the results of a parametric study conducted in order to quantify the influence of modelling assumptions such as pellet fragmentation or pellet-cladding friction on the amplitude of the predicted cladding ridges after the transient. The calculations were performed with the material properties and the cold pellet-cladding gap of a 2 cycle fuel rod. The influence of the pellet geometry on the pellet cladding mechanical interaction (PCMI) has been analysed also.

2. DESCRIPTION OF MODELS

In a first step, an axisymmetric model has been developed. Usually the mesh is limited to one half of a pellet with the adjacent cladding part (figure 1).

The appropriate boundary conditions on the pellet and the cladding are indicated on fig. 1:

- Contact condition at pellet - pellet interface, dish closure being permitted:
  \[ U_z(r) + h(r) \geq 0 \]
- Condition to treat the pellet midsection plane as a plane of symmetry: \( U_z = \text{const.} \)
- Corresponding symmetry conditions for the cladding: \( U_z = 0 \) and \( U_z = \text{const.} \) respectively at the bottom and at the top of the model.
- Radial contact condition at pellet-clad interface: \( U_{\text{pellet}} \leq \text{gap} + U_{\text{clad}} \)

Two extreme axial constraints are proposed for the pellet-clad interface:
- Locking condition after the initial pellet-clad contact: \( \Delta U_{\text{pellet}} = \Delta U_{\text{clad}} \) at midsection and interface planes.
- No pellet-clad axial constraint.

For steady-state conditions, as well as for ramp transient, the code takes into account:
- The mechanical loads: fuel pellet compression spring force, internal gas pressure (up to now without fission gas release), external coolant pressure.
- The fuel temperatures calculated using the gap conductance updated with the thermally expanded geometry and with or without flux depression.

The stresses and strains are calculated using non-linear resolutions taking into account creep and plasticity for \( \text{UO}_2 \) and Zr4. Fuel swelling is also considered for its contribution to reduce the gap size with burn up [3].

The axisymmetric model can display the typical "diabolo" shape of the pellet due to the quasi-parabolic fuel temperature distribution, nevertheless this model under-estimates the amplitude of the permanent clad ridges after a power ramp.

To improve the prediction of the cladding deformation, it is necessary to take into account the pellet fragmentation. So, in a second step, a tridimensional model, with an idealised fuel fracture pattern, has been developed. Usually the pellet is supposed precracked into four (or eight) equal fragments by four (or eight) radial cracks extending to the fuel center line. The mesh is limited to one fragment using the previously described boundary conditions with additional contact conditions at fragment-fragment planes and corresponding symmetry conditions for the cladding (figure 2). At the pellet-clad interface, the sliding condition is the unique available condition in the current version. This model supposes preexistent pellet fractures before irradiation; this modelling assumption is justified because the oxide fracture occurs at low heat generation level. Furthermore, a previous analysis showed up that the idealised model of the pellet completely cracked to the centerline gives similar results than a more complex model for which the pellet crack pattern is determined by the \( \text{UO}_2 \) fracture stress [4].

3. METHODOLOGY FOR A POWER RAMP CALCULATION

A brief description of the methodology to calculate a power ramp for a 2 cycle fuel rod is given below. At the present state, it is applied with the 2D model.

In order to start the ramp calculation with a correct initial state, the two irradiation cycles are modelled. The calculation is divided in several periods (usually 10 to 15 periods per cycle) during which material properties and loads are supposed constant. At the beginning of a new period thermal resolutions are performed to determine the new temperature distributions taking into account the updated gap conductance and material properties. The internal gas pressure is also updated with the new gap temperature and the reduced free volumes evaluated on the actualised geometry. This estimation is done supposing the behaviour of all fuel rod pellets identical: this assumption is correct for an irradiation in a power reactor because the axial shape factor is almost flat. Therefore the internal pressure evolution can be transferred from a global calculation using the code METEOR/TU. Each period is subdivided in several time steps with successive nonlinear mechanical resolutions to simulate the following mechanisms:
- gap size reduction due to the combined effects of the fuel swelling and clad diameter reduction by creep under the differential external pressure,
• clad ridges at the pellet interface by PCMI when the gap is closed.

The final stress and strain fields at the end of the base irradiation are introduced as initial state for the power ramp calculation. Because of the severe loading during the ramp, plastic strains can't be neglected. To take into account both plastic and creep strains, the linear power increase is approximated by a succession of power steps with plasticity during instantaneous power increments and creep during hold periods. Usually a 200W/cm power increase is divided in 10 power increments with constant hold periods. Hold periods are adjusted to the power rate. A typical input power history is shown in figures 3 and 4. The calculated clad inner surface hoop stress at the interface plane is presented on figures 5 and 6. At the end of the 1st base irradiation cycle, the hoop stress variation indicates that PCMI occurs. During the ramp, for a linear power rate equal to 100W/cm/min, a stress relaxation is observed at high power levels.

This analysis is going on to define a ramp calculation methodology using the 3D model. It has been mentioned previously that a data interface from the 1D1/2 code METEOR/TU to the 2D-3D code TOUTATIS is available. In fact, at the present state, some models, like the fission gas swelling or the fission gas release, are not taken into account in the ramp calculations. Some of these models require a global modelling and a reflection has been engaged to define the set of data it would be useful to transfer from the 1D1/2 code METEOR/TU to improve the numerical predictions using the local FE modelling.

4. SENSITIVITY STUDIES

In the following, results of sensibility studies to modelling assumptions or pellet geometry are presented. Calculations were performed for a power rate of 35 W/cm/min and peak final power 450W/cm kept for 3 min. The material properties and gap size correspond almost to a 2 cycle fuel (table 1). Stresses and strains due to the base irradiation are neglected and calculations simulate only the transient. These conditions might be representative of an irradiation on a fuel rod with a small initial diameter and for which PCMI don't occur during the base irradiation.

Preliminary, based on an average UO₂ fracture stress of about 115MPa, the power level corresponding to radial pellet fragmentation has been evaluated with the isovalues σₕ₀ obtained by a 2D calculation for a standard pellet (H/D = 1) : about 100 W/cm (figure 7).

4.1 Sensitivities to modelling assumptions

Influence of the axial constraint on the PCMI prediction has been analysed simulating, with the 2D module, the two extreme cases described previously (§2) : "locked" condition or sliding condition. Results are presented on figures 8, 9 and 10.

Effect of the biaxiality of the loading is important : there is a multiplicative factor ranging from 2 to 7 on the amplitude of the permanent diameter expansion when the clad axial tension is taken into account.

The very low strain hardening of the clad stress-strain curve explains the equivalent stress saturation on figure 8. The ridge amplitude is reduced with the locked condition. However, approximation of the oxide Zry-4 friction effect by equal axial displacement increments just at the ends of the pellet instead of all along the interface can accentuate this biaxiality effect.

Because it simulates the two following mechanisms :
• hoop stresses are cut at the fragment interface,
• fragments move away each other in the circumferential direction because of the fragment interface bulging,

the 3D model, with pellet fragmentation, gives a better representation, than the 2D one, of the radial expansion of the pellet subjected to the thermal gradient.
The comparison of predicted radial clad displacements using the 2D and 3D models is presented in figure 11. When the pellet fragmentation is taken into account, a significant clad deformation increase is showed up which corresponds to a clad permanent deformation increase after unloading.

4.2 Sensitivities to the pellet geometry

Influence of H/D ratio on PCMI intensity has been studied performing 3D ramp calculations with different pellet heights corresponding to H/D ratio ranged from 0.5 to 3. Figure 12 presents the comparison of the radial clad displacements at the power peak. A remarkable PCMI reduction is observed with a small pellet (H/D = 0.5). The maximal PCMI intensity is yielded for H/D ratio equal to 1 therefore for higher H/D ratios the reduction at pellet interface plane is balanced by an increase at the midsection plane.

Among the different kinds of pellet, we compared:
- a perfectly cylindrical pellet,
- a pellet with dishes,
- a pellet with chamfers,
- a hollow pellet.

The 3D ramp calculations were performed with a H/D ratio equal to 1. Results are presented on figure 13. For an identical thermal flux at the pellet-clad interface, temperatures in the pellet are lower for the hollow pellet. The pellet thermal expansion and consequently the PCMI are reduced for the hollow pellets. Differences between the other cases are minor.

5. CONCLUSION

To complete the 1D1/2 code METEOR/TU which is devoted to the fuel rod global behaviour, the development of the 2D-3D code TOUTATIS, based upon the FEM code CASTEM and devoted to the refined mechanical analyses, is in progress. Efforts are undergone to improve the PCI modelling for fuel rods subjected to a power ramp, especially for 2 cycle fuel.

Among the parameters which can influence the PCMI intensity, the pellet-clad axial constraints and the pellet fragmentation have been identified.

Using the 3D module, parametric calculations have been performed to analyse the influence of the pellet geometry. Important PCMI reductions are identified for short pellets and hollow pellets. These two cases being excluded, the differences are not so significant, therefore a larger effect has been noticed with the H/D ratio.

REFERENCES


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<th>GEOMETRY</th>
<th>H/Dₘₚₛ ratio</th>
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<tr>
<td>Dₘₚₜ/Dₘₜ ratio</td>
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<td>Diagonal pellet-clad gap</td>
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<tr>
<th>THERMAL MODELS</th>
<th>UO₂ conductivity</th>
<th>HARDING and MARTIN correlation [5]</th>
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<tr>
<td>Zr4 conductivity</td>
<td>RESTA code model [6]</td>
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<tr>
<td>Gap conductance</td>
<td>URGAP model [7]</td>
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<tr>
<th>MECHANICAL MODELS</th>
<th>UO₂ plasticity law</th>
<th>Linear cinematic strain hardening [9] yield stress: ( \sigma_{\text{yield}}(\text{Pa}) = 136.10^6 + 4.5.10^7 \varepsilon_u )</th>
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<td>UO₂ creep law</td>
<td>( \dot{\varepsilon}<em>{\text{creep}} = \dot{\varepsilon}<em>0 \lambda(\varepsilon, D, \sigma</em>{\text{eq}}) e^{\varepsilon/T} \sigma</em>{\text{eq}} )</td>
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<td>Zr4 plasticity law</td>
<td>Linear cinematic strain hardening : yield stress: ( \sigma_{\text{yield}}(\text{Pa}) = 435.10^6 + 837.10^6 \varepsilon_u )</td>
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<td>Zr4 creep law</td>
<td>2 cycle irradiated Zr4, short time, high stress : inelastic deformation: ( \varepsilon_q = A_1(\sigma, T)[1 - e^{-B_2(\sigma, T)}] + B_3(\sigma, T) )</td>
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Table 1: Geometrical characteristics and models used for sensitivity studies with TOUTATIS 2D-3D
Figure 1 - 2D Model

Figure 2 - 3D Deformed Model

Figure 3 - Typical Power History: 2 Cycle Irradiation Plus Power Ramp

Figure 4 - Modeled Power History: For a Power Ramp

Figure 5 - Calculated Inner Clad Hoop Stress: 2 Cycle Irradiation Plus Power Ramp

Figure 6 - Calculated Inner Clad Hoop Stress: Power Ramp
FIGURE 7 - HOOPL STRESS ISOVALUES (MPa) FOR A LINEAR POWER LEVEL OF 100 W/cm

FIGURE 8 - CLAD VON MISES STRESS AT POWER PEAK CALCULATED WITH AXISYMMETRIC MODEL FOR LOCKED AND SLIDING CONDITIONS

FIGURE 9 - CLAD RADIAL DISPLACEMENT AT POWER PEAK CALCULATED WITH AXISYMMETRIC MODEL FOR LOCKED AND SLIDING CONDITIONS
FIGURE 10 - CLAD RADIAL DISPLACEMENT AFTER UNLOADING CALCULATED WITH AXISSYMMETRIC MODEL FOR LOCKED AND SLIDING CONDITIONS

FIGURE 11 - CLAD RADIAL DISPLACEMENT AT POWER PEAK CALCULATED WITH AXISSYMMETRIC AND 3D MODELS FOR SLIDING CONDITIONS

FIGURE 12 - CLAD RADIAL DISPLACEMENT AT POWER PEAK CALCULATED WITH 3D MODEL FOR VARIOUS H/D RATIOS

FIGURE 13 - CLAD RADIAL DISPLACEMENT AT POWER PEAK CALCULATED WITH 3D MODEL FOR VARIOUS PELLET GEOMETRIES