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CAST3M modelling of a spent fuel assembly bending during a handling accident
Rod failure risk evaluation from the experimental results of spent fuel rod bending test

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Abstract – The fuel handling operating rules exclude any accidental risk. However in the framework of the PRECCI R&D project, the bending of a spent fuel assembly resulting from its locking during a translation displacement is taken into account. This enabled us to develop an approach based on experiments and calculations that allows us to simulate the behaviour of an assembly under such loading. This study was carried out in CEA laboratories with the funding and the technical support of EDF. A three points bending test on a spent fuel rod segment was performed at the Laboratory for Mechanical Behaviour of Irradiated Materials (LCMI). From the experimental strength-displacement curve, a maximum failure strain, a maximum failure curvature and an equivalent constitutive equation were determined. CAST3M modelling of the fuel rod taking into account the elasto-plastic behaviour of the clad and the cracking of the UO_2 fuel pellets was verified by the experimental results. Consequently, the identification of the respective contributions of the clad and of the pellets to the rod global behaviour was made possible. A two dimensional assembly with beam elements was modelled with CAST3M. The properties of the beams modelling the different parts of the assembly (top and bottom nozzle, grids) were chosen and adjusted according to their materials (zirconium alloys, steel) in order to obtain stiffness, tensile and shear behaviour, sliding and holding functions close to the experimental ones. Assembly bending calculations were performed. In order to obtain a rod integrity estimator, their maximum calculated strains and curvatures as a function of the bending angles can be compared to the failure experimental ones.

Key words: Spent fuel rod / assembly bending / rod integrity / CAST3M

1 Introduction

The spent fuel assembly remote handling in spent fuel storage facilities follows processes excluding any accident. However, we developed an approach based on experiments and calculations that allows us to simulate the behaviour of a spent fuel assembly under a mechanical load leading to its bending. This study was performed in the framework of the PRECCI R&D project. The assembly was modelled using the finite element solver CAST3M [1]. The equivalent constitutive equation for the bending of spent fuel rod as well as the maximum strain and curvature at failure were obtained from experiment and from CAST3M calculations. The constitutive equation was applied to the beams modelling rods in the spent fuel assembly model. The maximum strains and curvatures calculated in the rods of the bended assembly were compared to the maximum experimental ones at failure in order to study the fuel rods integrity. This is of particular interest since cladding constitutes the first confinement barrier.

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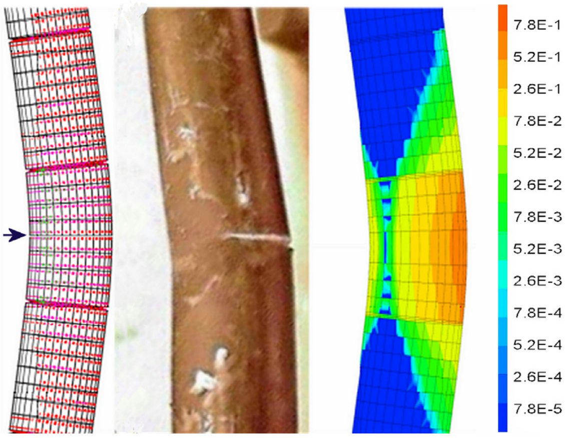

Fig. 1. Qualitative comparison of the experimental and calculated three points bending results. From the left to the right, calculated cracks openings in the pellets, photo of the fuel rod in the hot cell after bending test and calculated inelastic strains in the clad normalized to their maximum value.

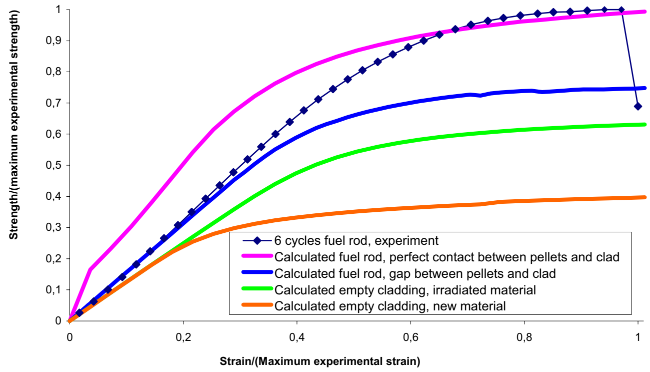

Fig. 2. Experimental and calculated strength as a function of the strain for three points bending tests on rod and empty cladding (normalized to their respective maximum values).

2 Bending of a spent fuel rod, an experimental and numerical study

Three points bending tests were carried out on a six-cycle fuel rod segment at the LECI Facility in Saclay: laboratory for studies on irradiated materials. The segment ends were sealed with welded plugs. In order to study the behaviour of the clad and pellets system and to avoid specific effects at the inter-pellet singularity, the load was applied at the mid-plane level of a pellet as indicated by an arrow Figure 1. CAST3M modelling of the rod bending was performed taking into account the elasto-plastic behaviour of the clad. For the pellets, the Ottosen fictitious crack model [2] which fits well for brittle material was used with parameters corresponding to the UO_2 characteristics. The three dimensional mesh included the cladding and the pellets. Unilateral support was considered between successive pellets. Two different boundary conditions were considered between the pellets and the clad. Firstly, tight contact due to high burn up was modelled, merging the maximum diameters points of the pellets with the cladding inner mesh. Secondly, residual gap between the clad and pellet was modelled with (unilateral) support between the nodes of the two meshes. Figure 1 shows the calculated final cracking in the pellets as well as the experimental and the calculated final deformed shape of the rod. The calculated inelastic strain in the clad (normalized to its maximum value) is also reported on the deformed shape. The experimental results for fuel rod were satisfactorily compared to experimental data. Important cracking was experimentally confirmed by the ejection of few small fuel particles from the rod at failure. The load-displacement curves obtained are shown in Figure 2. For cladding that contains pellets, the applied load level is much higher than in the case of the empty cladding. Concerning the behaviour of the empty cladding, irradiation affects the zirconium alloy properties, resulting in an increase of the bending strength as can be seen from the orange and green curves displayed in Figure 2. When the pellets are taken into account, the experimental results on the spent rod (dark blue curve with symbols) are bounded by the calculations taking into account the two different boundary conditions between the pellets and the clad. When the bending displacement is weak, the experimental behaviour is better reproduced by taking into account a gap between the pellets and the clad (blue curve) since the cooling of the rods after irradiation has caused the opening of the gaps between the fuel fragments and between the fuel and the cladding. When bending increases, the fragments lock and the fuel rod behaviour is better reproduced by the merging of the point of internal clad surfaces and external pellet diameter ones (pink curve).

3 Fuel assembly model and fuel rod equivalent behaviour

Models of fuel assemblies allowing to determine their behaviors under irradiation (growth and creep) [3] but also to determine their deflections loads and vibrations characteristics [4] were already reported in literature. For the present study, a two dimensional assembly meshed with 4144 beam elements was modelled with CAST3M. The beam element is a two-nod line-element with six degrees of freedom at each node (translations and rotations along the x, y, and z directions). The mesh and details of the modelling are displayed Figure 3. Without particular optimization, the CPU time is less than 100 seconds per millimeter of pole displacement on 20 cores and 32 Go computers.

The properties of the beams simulating the different parts of the assembly (top and bottom nozzle, grids) were chosen and fitted according to their materials (zirconium alloys, steel) in order to obtain stiffness, tensile and shear behaviour close to the experimental ones. Interaction between grids and rods were modelled by a node-to-node link between the grid and the rod node located at the mid-plane of the grid. For this purpose an equivalent beam with elasto-plastic characteristics reproducing

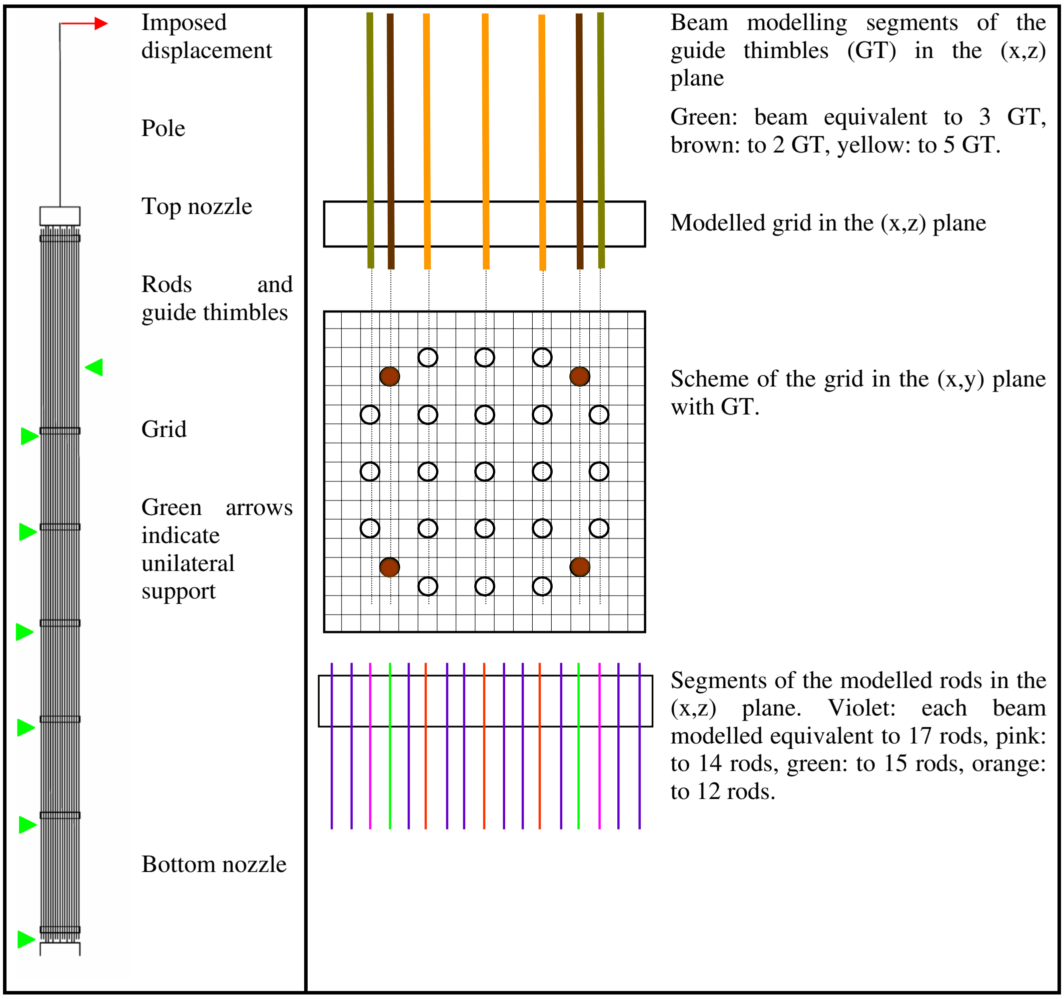

Fig. 3. Two dimensional modelling of the fuel assembly. Left: mesh of the assembly in the (x,z) plane. Right: schemes for the equivalent behaviour of the beams representing the guide thimbles and rods.

the axial friction strength between rod and grid and a large inertia (in order to lock rotational degrees of freedom (DOF)) was used. Guide thimbles (GT) DOF were fully linked to those of the grids. Conditions of relative in-plane displacement between the rods and between the guide thimbles and the rods were chosen in order to allow an arrangement in staggered rows. Since the model is bi-dimensional, each row of fuel rods and guide thimble is modelled by an equivalent beam having the real rod geometrical properties (thickness, cross sectional area) and strength values multiplied by the number of rods (or GT) in the row (see Fig. 3 right). All elements except rods and guide thimbles have an elastic behaviour. GT follow the irradiated elasto-plastic law of their zircaloy alloy. Plenums of the rods follow the elasto-plastic law of the irradiated cladding zirconium alloys. A one meter long handling pole linked to the top nozzle was also included in the model. The displacement is imposed along the x direction (horizontal) at the top of the pole as displayed by the red arrow on Figure 3 left while unilateral supports shown with green arrows are imposed at the locations the assembly is restrained by surrounding framework.

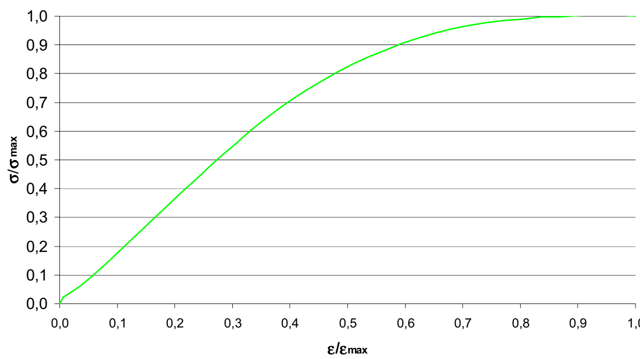

Fig. 4. Normalized strain-stress law for irradiated fuel rod deduced from the experimental three points bending test.

The constitutive law of the beams which models the fuel rods was drawn from the experimental three points bending strength-displacement $F(d)$ data. The strength-displacement function was first converted in stress strain curve $\sigma(\varepsilon)$ considering a circular shape of the rod between the two supports. The strain is expressed from the rod radius, r, and the distance between the supports, L,

Table 1. Maximum calculated inelastic strain/curvature in the rod fuel column region normalized to the maximum experimental strain/curvature at failure as a function of the pole displacement.

Pole displacement	500 mm	600 mm	700 mm	800 mm
Angle (°) between the highest external and right top nod of the highest grid	33	40	47	54
Maximum curvature in the rods in the fuel column region/maximum curvature at failure	0.34	0.42	0.51	0.64
Maximum strain in the rods in the fuel column region/maximum strain at failure	0.22	0.29	0.37	0.54

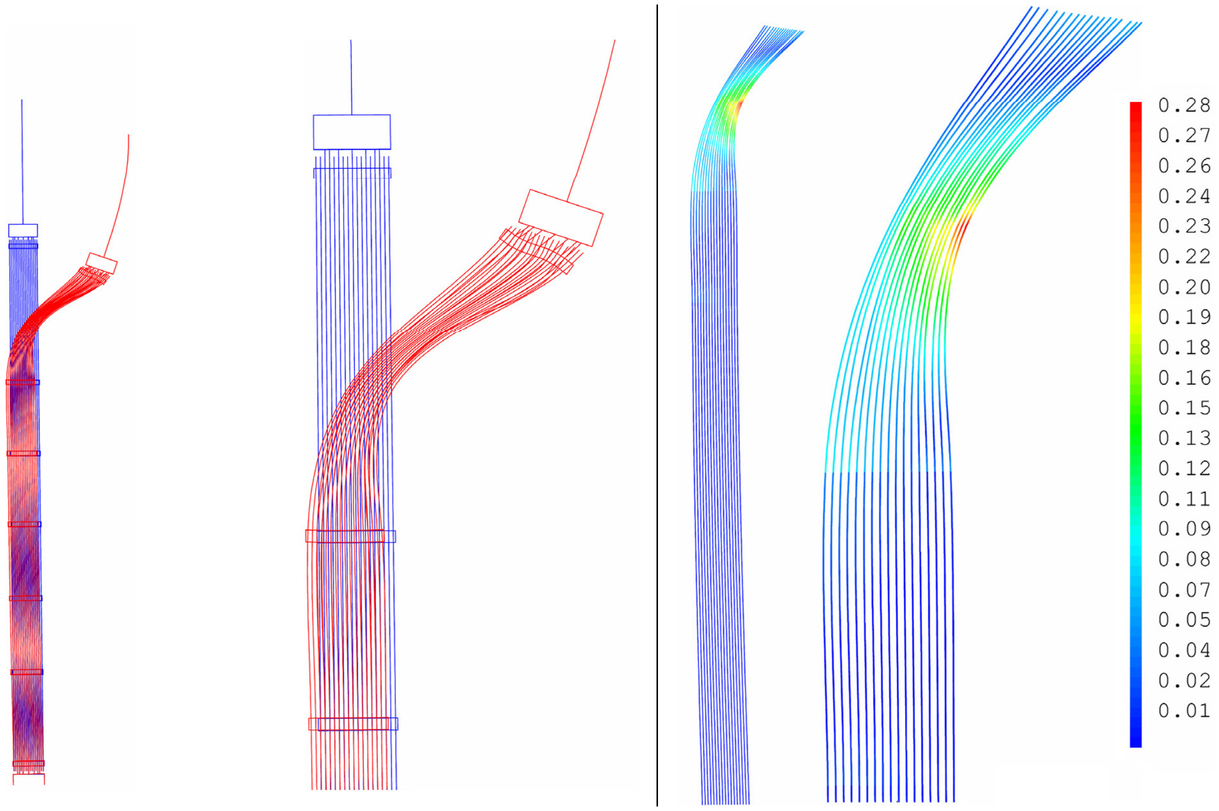

Fig. 5. Assembly calculations results. Left: initial and final shape for a displacement of the pole of 800 mm, whole system and zoom of the upper region. Right: for a displacement of the pole of 600 mm, inelastic strain in the fuel rods normalized to the maximum failure strain, whole rods and zoom in the upper region.

as follows:

$$\varepsilon = \frac{r}{\frac{d}{2} + \frac{L^2}{8d}} \tag{1}$$

The stress is calculated from:

$$\sigma = \frac{F\,L}{\pi\,r^3} \tag{2}$$

It was necessary to modify the stress strain curve $\sigma(\varepsilon)$ obtained by this way since the circular flexion hypothesis is not good enough to recalculate experimental strength displacement curve from this $\sigma(\varepsilon)$ constitutive equation. Corrective factors to apply to the strains (and subsequently to curvatures) were determined from an optimisation process using the Levenberg-Marquardt method. The correction is a multiplicative factor applied on the strains and increasing linearly from the lower to the higher strain of the stress strain curve. The functional minimised is the difference between the calculated and experimental strength displacement curves. The final constitutive equation obtained by this way is displayed in reduced units Figure 4. It allows to recalculate the experimental strength-displacement curve but also to obtain the maximum strain and curvature at rod failure.

4 Fuel assembly behaviour

The shapes of the assembly as well as the normalized inelastic strains in the rods are given in Figure 5. As displayed in Table 1, the failure strain and curvature of the rod are not reached even for the highest pole displacement studied corresponding to a bending angle higher than 50°. The strength necessary to bend the assembly was moreover estimated.

5 Conclusions

The experimental and modelling of three points bending tests of spent fuel rods segments have allowed us to determine the rods equivalent constitutive equation, as well as their failure strains and curvatures. The constitutive equation was included in a CAST3M fuel assembly mechanical model. The goal of this study, consisting in developing a program that could be used to model the assembly behaviour under external loading leading to fuel rods plastic strains and in evaluating the fuel rods integrity was reached. Further development could reside in refining the fuel rod behaviour modelling from new experimental data or detailed calculations taking into account its response to other loadings than 3 points bending.

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