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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Résumé :

Les opérations de manutention des assemblages combustibles irradiés sont réalisées selon des modes opératoires adaptés qui excluent tout risque d'accident. Néanmoins, dans le cadre du projet de R&D PRECCI, le cas hypothétique d’un blocage de l’assemblage durant une étape de translation, conduisant ainsi à sa flexion a été utilisé pour mettre en œuvre une démarche, qui, couplant expérience et modélisation, permet de représenter le comportement d’un assemblage soumis à un chargement externe. Cette étude a été réalisée au CEA avec le support technique et financier d’EDF. La flexion 3 points de segments de crayons combustibles irradiés a été réalisée au laboratoire LCMI. A partir des courbes effort-déplacement obtenues, une déformation et une courbure maximales ainsi qu’une loi de comportement équivalente ont été déterminées. La modélisation à l’aide du code E. F. CAST3M (avec loi de comportement élasto-plastique pour la gaine irradiée et comportement en fissuration avec des paramètres adaptés à l’UO\textsubscript{2} pour les pastilles de combustible) a été validée grâce aux résultats expérimentaux permettant alors de dissocier l’influence du gainage et des pastilles sur le comportement des crayons. Un modèle 2D d’assemblage en éléments poutres a ensuite été réalisé à l’aide de CAST3M. Les propriétés des poutres modélisant les différentes parties de l’assemblage (tête, pieds, grilles) ont été choisies et ajustées en fonction leur nature (Alliages de zirconium, acier) afin de retrouver les caractéristiques connues de leur comportement (rigidité, réponse en traction et cisaillement, fonctions de maintien et de glissement…). Les calculs de flexion ont été réalisés. Afin de disposer d’un estimateur de l’intégrité des crayons, les valeurs maximales calculées de leurs déformations et de leurs courbures en fonction de l’angle de flexion imposé peuvent être comparées aux valeurs limites issues de l’expérience...

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 allow to represent 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 LCMI laboratory. 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 for the clad and cracking of the UO\textsubscript{2} fuel pellets was validated with 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 following 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.

Mots clefs : 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 allow to represent 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.

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

Three points bending tests had been carried out on a 6 cycles 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 FIG. 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 adopted with parameters corresponding to UO$_2$ characteristics. The three dimensional mesh includes 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 nods of the two meshes. FIG. 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 FIG. 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 FIG. 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 allowed to open 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).
FIG. 1 – Qualitative comparison of the experimental fuel rod bending and the calculated one by 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).
3 Fuel assembly model and fuel rod equivalent behaviour

A two dimensional assembly with beam elements was modelled with CAST3M. The mesh and details of the modelling are displayed FIG. 3.

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, steal) 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 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 FIG. 3 left.
while unilateral supports shown with green arrows are imposed at the locations the assembly is restrained by surrounding framework.

The constitutive law of the beams which model 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, $L$, and the rod radius from:

$$\varepsilon = \frac{r}{d \left( \frac{L^2}{2} + \frac{d^2}{8d} \right)}$$  \hspace{1cm} (1)

The stress is calculated from:

$$\sigma = \frac{F L}{\pi r^3}$$ \hspace{1cm} (2)

It was necessary to modify the stress strain curve $\sigma(\varepsilon)$ obtained 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 curvatures were determined from an optimisation process. The final constitutive equation obtained this way is displayed in reduced units FIG. 4. It allows to recalculate the experimental strength-displacement curve but also to obtain the maximum strain and curvature at rod failure.

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

4 Fuel assembly behaviour

The shapes of the assembly as well as the normalized inelastic strains in the rods are given in FIG. 5.

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.

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

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

5 Conclusions
The experimental and modelling of three points bending tests of spent fuel rods segments have allowed 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 allowing to perform bending calculations and fuel rod integrity evaluation.

References