Fuel Integrity Project: Analysis of Light Water Reactor Fuel Rods Test Results

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1. ABSTRACT

BNFL Nuclear Sciences and Technology Services and COGEMA LOGISTICS started in the year 2000 a joint project known as FIP (Fuel Integrity Project) with the aim of developing realistic methods by which the response of LWR fuel under impact accident conditions could be evaluated. To this end BNFL organised tests on both unirradiated and irradiated fuel pin samples and COGEMA LOGISTICS took responsibility for evaluating the test results.

Interpretation of test results included simple mechanical analysis as well as simulation by Finite Element Analysis. The first tests that were available for analysis were an irradiated 3 point bending commissioning trial and a lateral irradiated hull compression test, both simulating the loading during a 9 m lateral regulatory drop.

The bending test span corresponded roughly to a fuel pin intergrid distance. The outcome of the test was a failure starting at about 35 mm lateral deflection and a few percent of total deformation. Calculations were carried out using the ANSYS code employing a shell and brick model.

The hull lateral compaction test corresponds to a conservative compression by neighbouring pins at the upper end of the fuel pin. In this pin region there are no pellets inside. The cladding broke initially into two and later into four parts, all of which were rather similar. Initial calculations were carried out with LS-DYNA3D models.

The models used were optimised in meshing, boundary conditions and material properties. The calculation results compared rather well with the test data, in particular for the detailed ANSYS approach of the 3 point bending test, and allowed good estimations of stresses and deformations under mechanical loading as well as the derivation of material rupture criteria.

All this contributed to the development of realistic numerical analysis methods for the evaluation of LWR fuel rod behaviour under both normal and accident transport conditions.

This paper describes the results of the 3 point bending tests and of the hull compression tests. The subsequent Finite Element analysis and interpretation are also presented.

2. FUEL PIN BENDING TEST

2.1 INTRODUCTION

This study follows previous finite elements studies made for the same loading with un-irradiated fuel rods, which gave preliminary indications on the models, and optimisations that are necessary.

Two models are developed to simulate the lateral commissioning bending test (figure 1) of an irradiated fuel rod and are compared with the test results. Constitutive material laws are determined for Zircaloy 4 and for the pellets. The main differences between the two calculation models are the accuracy of the model and material laws of the pellets:

- Simplified irradiated models: the pellets are cylindrical, and modelled with an asymmetrical material law,
- Cracked irradiated models: the pellets are modelled with a bilinear material law; some sliding and cracking planes are also modelled.

In the end, the two models were found to be equivalent, so only the simplified irradiated model is presented here.

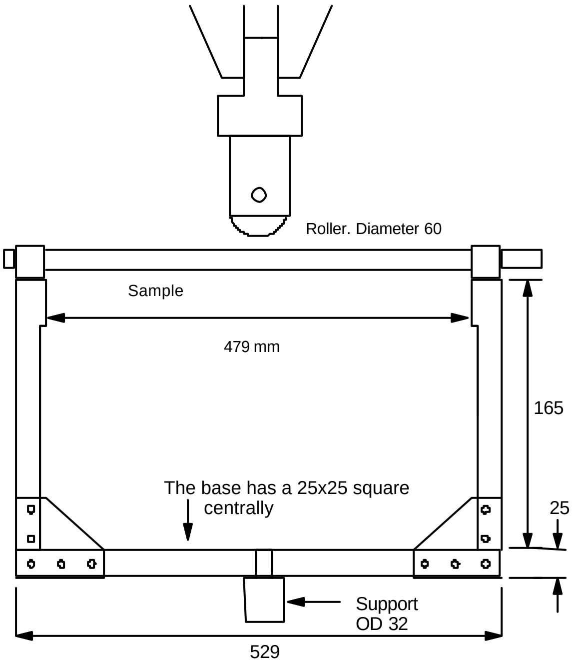

Figure 1 : Test appliance

2.2 ASSUMPTIONS

- The test device is sufficiently stiff to be considered as perfectly rigid.
- The fuel pin sample is part of an irradiated pin with a burnup rating of 50,000 MWj / tU.
- The fuel pin cladding modelled is engaged at each end in supports with small radial gaps. A pulley wheel at the middle of the span loads it laterally.
- Irradiated pellets are bounded to the cladding and initially cracked by in-reactor thermal loading.
- The model takes into account only ductile deformation and rupture is not calculated but deduced from the comparison between the FE calculation and the test results.
- The material constitutive laws used have to be optimised to correlate well the test results.

2.3 MODEL DESCRIPTION

2.3.1 Geometry

The PWR fuel pin sample (figure 1) consists of a cylindrical irradiated zircaloy cladding containing cracked fuel pellets. Its length corresponds approximately to the intergrid distance of a current fuel PWR assembly. The intermediate grids are simulated by partially sliding supports that are linked by a steel frame. These frame deformations are neglected.

An external corrosion thickness existing on the cladding has no significant material strength.

The pulley wheel has a circular external groove with slightly larger radius than the cladding radius manufactured so as to apply the load correctly.

2.3.2 Meshing

The ANSYS mesh, shown in figure 2, is for a representative section of the test piece and takes account of symmetry along the fuel pin axis and at mid- span. It consists of standard 3D-shell elements (4 nodes, 6 degrees of freedom per node, 5 integration points through thickness) for the cladding and 3D volume elements (8 nodes, 3 degrees of freedom per node, 8 integration points) for the pellets, pulley wheel and supports. Contact is also simulated by 3D surface to surface elements.

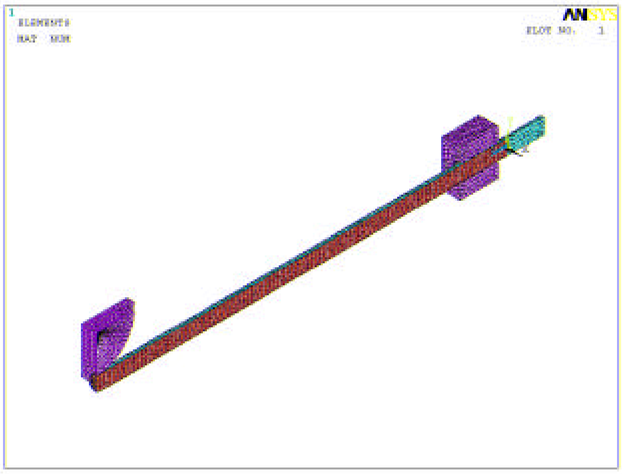

Figure 2 : Finite Element Mesh

2.3.3 Materials

The Zircaloy 4 elastic-plastic material law considered in the calculation is the following non-linear Voce material law described by the following mathematical expression:

$s = s_e + R \times (1 - \exp(-b \times e^{pl}))$ where e^{pl} is the plastic strain.

The reference elastic-plastic material law (figure 3) considered in the calculation for the pellets is the following asymmetrical one:

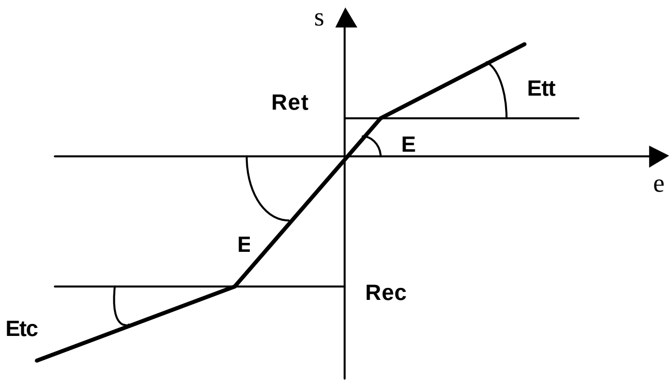

Figure 3 : Asymmetrical material law of pellets

An asymmetrical material law simulates the material of the pellets in order to minimise as much as possible the traction stiffness. Effectively, the pellets are regarded as only working in compression with a perfect plastic behaviour.

The parameters E, σ_e, R, b, Ret, Ett and Etc were optimised in order to respect both the material assumptions and not to overly penalise the calculation time until convergence. This is possible since their respective effects on the force / displacement curves do not occur simultaneously.

2.3.4 Boundary conditions

As the models correspond to a fourth of the fuel pin sample, symmetry boundary conditions are applied in the vertical planes containing the fuel pin axis, and perpendicular at the fuel pin axis at middle span.

As the model has several contact surfaces, friction coefficients are assigned between the cladding and the supports, between the cladding and the pellets, and between the pellets themselves.

2.4 RESULTS

The test / FE comparison of force / displacement curves is presented on figure 4 for the optimised values of constitutive material laws and friction coefficients. At a given displacement the difference of force is less than 1% of the measured force, except at the beginning of the test curve where the gaps in the supports are not yet closed. The equivalent maximum displacement at first failure is about 35 mm for sliding supports without radial gap.

The axial total elongation in the cladding is presented on figure 5. The final values are about 3 % for the tensile side where pellets have no effects, and about 2 % for the compressed side where the pellets supplement the cladding strength.

The cladding longitudinal sliding at the support is presented on figure 6 and the final maximum value is only a few millimeters. The figures 7 and 8 show the deformed cladding with axial plastic strain map and the displaced pellets stuck with equivalent Von Mises Stress map, respectively.

Conclusion: these results are encouraging and will provide a good basis for the future exploitation of the whole bending test series 11.

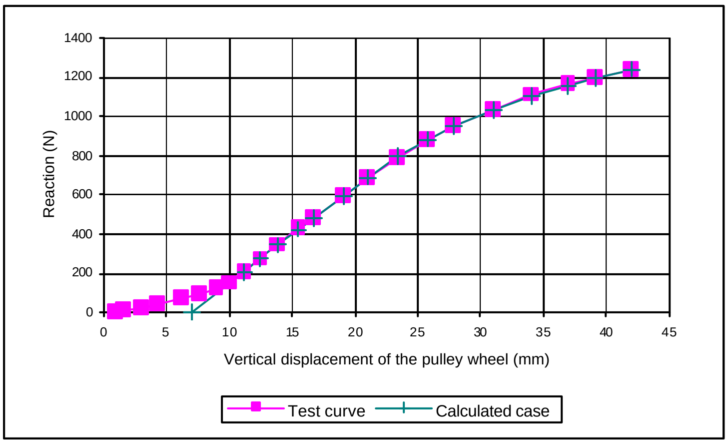

Figure 4 : Curve reaction/displacement

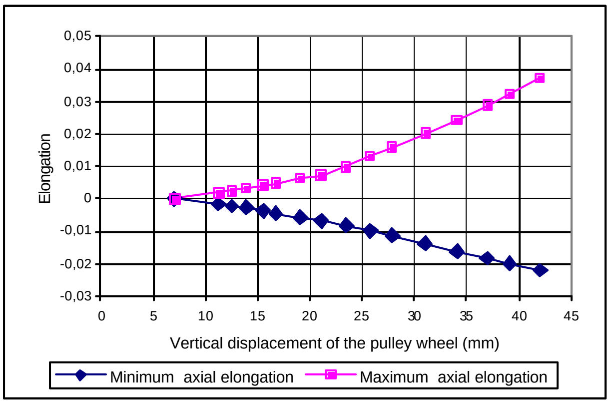

Figure 5 : Axial elongation in the cladding

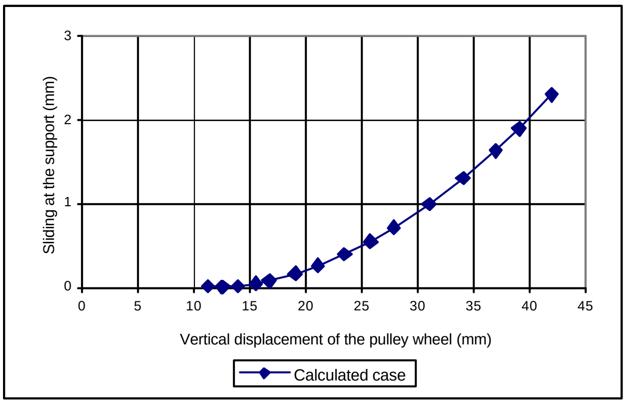

Figure 6 : Sliding at the support

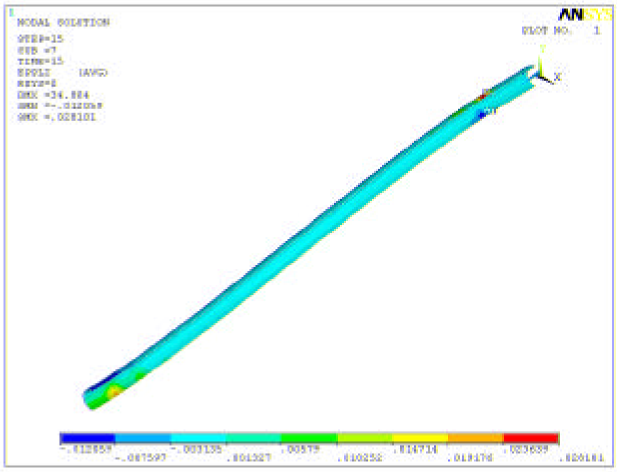

Figure 7 : Axial plastic strain in the cladding

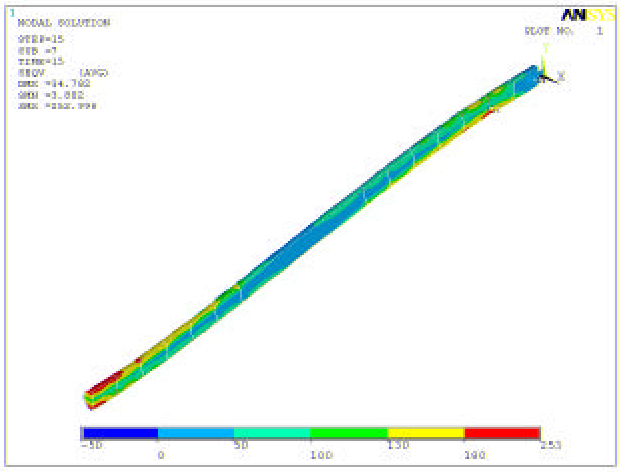

Figure 8 : Equivalent Von Mises stress in the pellets

3. HULL COMPACTION TESTS

3.1 INTRODUCTION

Lateral compression tests have been carried out on irradiated samples of BWR cladding. The non-linear finite element code LS-DYNA3D has been used to simulate the measured load/displacement curves. Good agreement with peak load has been obtained and the overall shape of the load displacement curves is similar. The finite element results suggest that there is little post-yield hardening of irradiated zirconium and that the material is essentially elastic-plastic. Accurate simulation of these curves provides confidence in the material properties which is an essential step in predicting the response of fuel rods to impact loads.

3.2 DESCRIPTION OF LATERAL COMPRESSION TESTS

The ten tests are lateral compression tests on irradiated BWR cladding [1] with wall thickness of about 0.73 mm and outer diameter 10.72 mm. A range of fuel burnups from 30 GWd / tU to 60 GWd / tU was tested and load displace-

ment curves of a few millimetres long obtained. The maximum loads were in the range from 3.8 kN to 5.2 kN and the corresponding displacements at peak load were of about 1.0 to 1.8 mm.
The load displacement curves exhibit a similar collapse characteristic. The load increases with displacement until a peak load occurs, thereafter the load gradually decreases to zero (Fig. 9). In all the tests the tube fragmented into 4 pieces and Fig. 10 shows the test-rig and the test pieces after test 7.

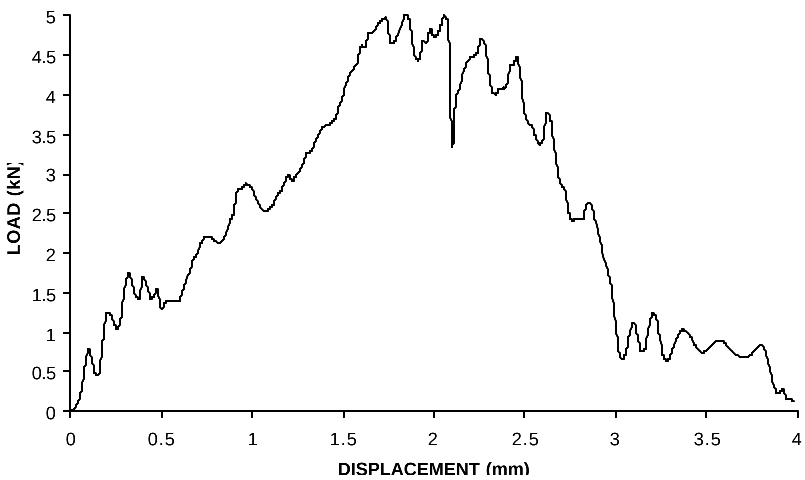

Figure 9 : Load displacement curve

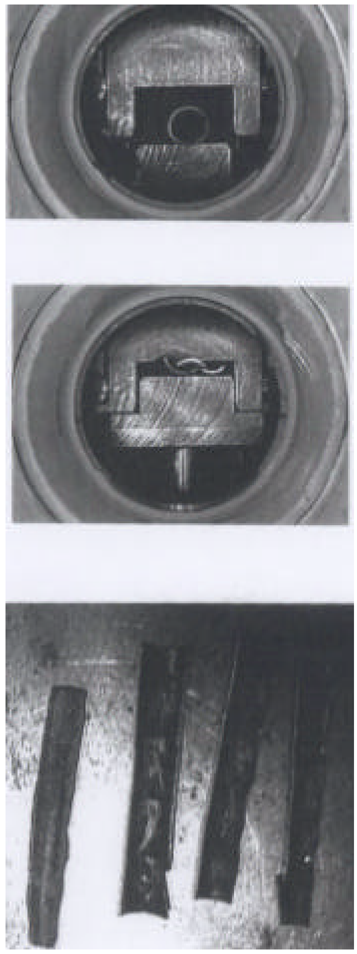

Figure 10 : Test rig

3.3 MODEL DESCRIPTION

3.3.1 Geometry

The cladding test pieces are 50mm long with diameters and wall thicknesses as mentioned in section 3.2.

3.3.2 Meshing

The initial finite element (fe) model of the tube (Figure 11) comprises 500 shell elements and is quarter-symmetric with appropriate boundary constraints. The model has been loaded by two opposing rigid walls with zero friction. (These are not shown in the diagram but their normals lie along the diameter.) One wall was moved inwards at a rate of 1 m/s, the other was kept static. The reaction force on the static wall was monitored as the tube collapsed in order to give a load-displacement curve.

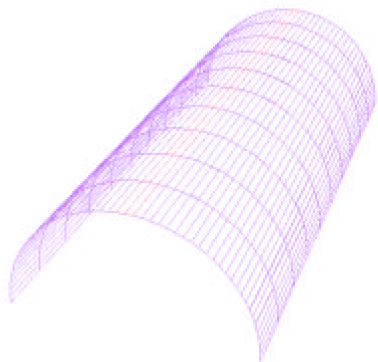

Figure 11 : Finite element mesh of cladding

3.3.3 Materials

The material properties of the test pieces are not known and have to be estimated from the literature [2].

E = Young's Modulus = 87023 N/mm2   Uniaxial Yield strength = 820 N/mm^2 Poisson's ratio = 0.3

Plane strain yield strength,Y = 820 x 2/v3 = 947 N/mm^2 (as plane strain conditions prevail)

Hardening modulus = 2264 N/mm^2 (Hardening modulus is the slope of the stress strain curve beyond yield.)

3.3.4 Preliminary estimate of collapse load

The collapse load at yield, P_O, can be estimated by assuming that four plastic hinges develop in the tube [3].

P_O = 4 Mp/R this gives: P_O = 4.7kN for a 50mm tube length

Where: Mp =plastic hinge moment per unit length = $Yxt^2/4$ (N-mm/mm)

3.3 RESULTS

The predicted load displacement is compared with that measured in Figure 12. The peak loads agree well and also align well with the preliminary estimate of 4.7 kN. The measured loads agree well up to displacement of 0.4 mm and thereafter the predicted load increases at a greater rate than that measured. This may be due to cracking of the test piece as this is not simulated in the finite element model.

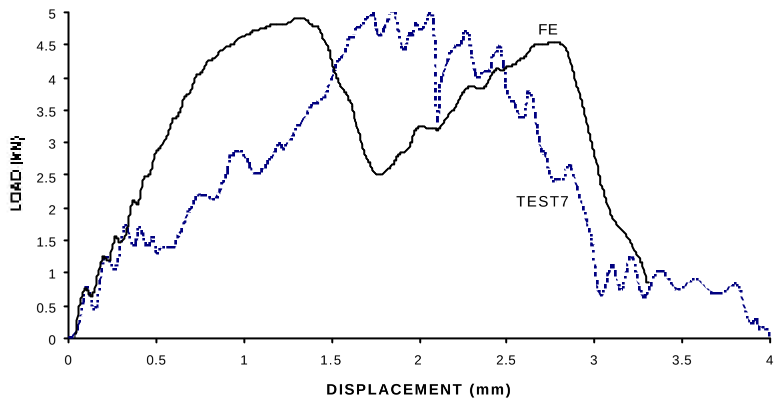

Figure 12 : Measured and predicted loads

It was also thought that the post yield hardening may contribute to the difference in load so the analysis was re-run without post-yield hardening (ie as an elastic - perfectly plastic material). The results with and without post-yield hardening are shown in Figure 13. As the two curves are very similar they confirm that the material is essentially elastic plastic. This is consistent with the findings in the simulation of fuel rod bending.

Conclusion: For lateral compression of irradiated tubes the peak load and the overall shape of the load-displacement curve can be predicted using LS-DYNAD shell elements and an elastic-plastic material law.

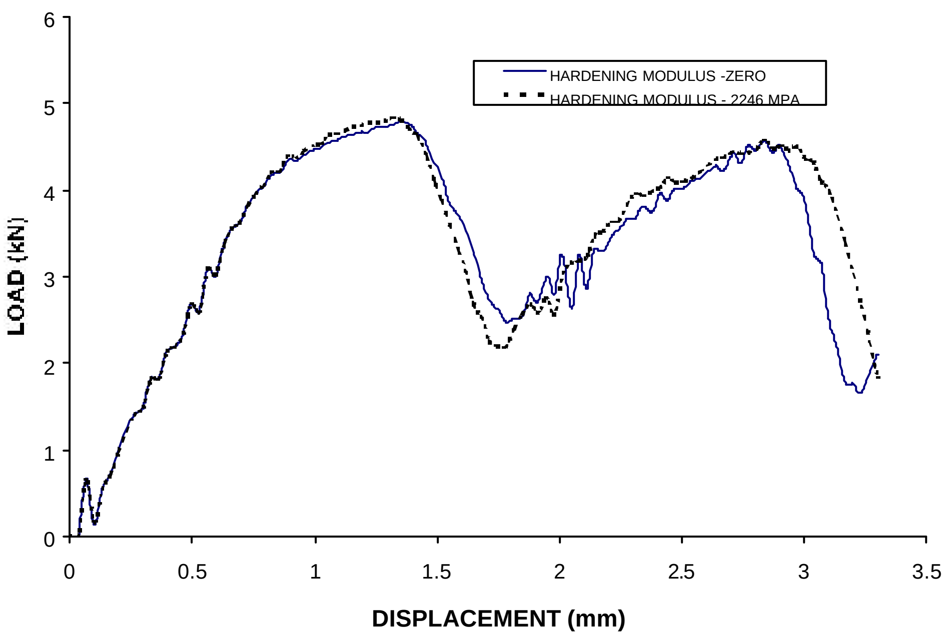

Figure 13 : Predicted loads with and without post yield hardening

3.4 REFERENCES

[1] AEAT – 1595 Issue 1 THORP Hull Compaction Trials

[2] Thermal Reactor UO2 data sheet number 5, UKAEA report ND-R-622(W)ZyBPC/P(88)

[3] T Y Reddy & S R Reid On obtaining material properties from the ring compression test. Nuclear Engineering and Design 52 (1979) 257-263

4. CONCLUSIONS

This paper describes simulations of a 3 point bending test and of hull compression tests both of which are related to a lateral 9 metres regulatory drop. The subsequent mechanical Finite Element analysis and interpretation are also presented.

The models used were optimised in meshing, boundary conditions and material properties. The calculation results compare rather well with the test data and allowed good estimations of stresses and deformations under mechanical loading as well as the derivation of material rupture criteria.

This is particularly the case for the detailed ANSYS approach of the 3 point bending test that simulates fuel pin intergrid bending occuring in a regulatory lateral drop.

The DYNA3D analysis of hull compression tests gives a peak load which agrees well with that measured and with the theoretical peak load. It also confims that an elastic perfectly plastic material law is appropriate in that case.

All this contributed to the development of realistic numerical analysis methods for the evaluation of LWR fuel rod behaviour under both normal and accident transport conditions.