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FINITE ELEMENT MODELING OF SPENT FUEL ROD SEGMENTS UNDER BENDING LOADS

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ABSTRACT

Transport packages for spent nuclear fuel have to be assessed with respect to specific transport conditions which are defined in the regulations of the International Atomic Energy Agency. The physical state of the spent fuel and the fuel rod cladding as well as the geometric configuration of the fuel assemblies are important inputs for the evaluation of the package capabilities under these conditions. Cracks or failures in the fuel rod cladding can cause the release of gas, volatiles or fuel particles into the cavity. The amount of substances in the cavity has to be considered in the assessment of the activity release and criticality safety.

The mechanical analysis of the compound system formed by the fuel rod cladding and the spent fuel pellets is very difficult due to the limited knowledge of the material properties and the insufficient understanding of the interaction between pellets and cladding and between adjacent pellets. The variation of fuel assembly properties regarding cladding material, burn-up and the history of usage makes reliable predictions of the fuel rod behavior even harder.

For a better understanding about the behavior of spent fuel rods, JRC and BAM have started a joint research project. In this context, JRC has developed a test device which allows quasi-static 3-point-bending test on fuel rod segments in the hot cell. The loads are applied with respect to the boundary conditions of the activity release assessment. This paper deals with the numerical calculation of a single fuel rod segment under bending load. The aim is to identify the governing mechanical parameters by the variation of constitutive assumptions, contact conditions, inner constraints, etc. This knowledge helps for the interpretation of the experimental results. Furthermore, the improved understanding about the behavior of the cladding-pellets system will be beneficial for the assessment of spent fuel transport conditions.

INTRODUCTION

The Federal Institute for Materials Research and Testing (BAM) is one of the two German competent authorities with responsibilities for mechanical, thermal and containment safety assessment within package design approval procedure. The assessment of shielding and criticality safety is incumbent on the Federal Office for the Regulation of Nuclear Waste Management (BfE). But BAM also examines the geometrical and material assumptions of the fuel assemblies under the specific transport conditions which are applied as input data in the shielding and criticality safety analysis. The assessment work of BAM within the design approval process of such packages brings up two issues which involves the behavior of the fuel assemblies. In the containment analysis the activity release compliance with the regulatory limits are verified. The second issue refers to the criticality safety analysis. The potential cladding failure followed by the release of gas, volatiles, fine fuel particles or fragments into the cask cavity is highly relevant for both safety functions. BAM assesses the physical and geometrical state of the spent fuel under transport conditions, e.g. the deformations or failure modes of the fuel rods, which can influence the correspondent analysis. Assumptions about the mechanical behavior of fuel rods are needed for both issues of the assessment. The mechanical behavior of spent fuel depends on the design of the fuel assemblies but also on their operational and storage history. It results in a wide range of material properties which are decisive for the mechanical behavior of the fuel rods such as the cladding alloys (Zircaloy-2, Zircaloy-4, ZIRLO, M5, etc.), the burn-up, the thickness of the oxide layer on the cladding, possible hydride reorientations, etc., see e.g. Billone et al. (2013). The deterioration of the mechanical properties of the cladding materials due to burn-up makes it nearly impossible to calculate the mechanical problem precisely. On the other hand, the complexity of interactions between the fuel rods as well as between fuel assemblies, basket, and cask containment under transport conditions presents additional challenges to experimental or numerical verification of forces acting on the rods. In conclusion the assessment of the fuel assemblies and rods is governed by knowledge gaps, both for the definition of the load as well as for determination of covering material properties. Therefore, BAM applies and accepts enveloping approaches for the containment assessment and the assumptions for the criticality safety analysis. A detailed description of the BAM approaches can be found in Ballheimer et al. (2012) and Linnemann et al. (2015).

Experimental testing and mechanical analyses of spent fuel with respect to transport loads has been in the focus in the past and today. The Fuel Integrity Project, a joint project between TN International and International Nuclear Services (INS) in the early 2000s had the aim to develop a methodology to assess the response of fuel assemblies during 9 meters regulatory drops. Among others the amounts of fissile material released in static bending tests with irradiated fuel rod specimens were measured during this test campaign. The experimental force-deflection curves as reaction of specimens to bending were used then as basis for verification of post-test finite element calculations, see e.g. Dallongeville et al. (2010). Experimental results about the release of fissile material from spent fuel rods under transversal impact loads are presented in Papaioannou et al. (2009). The release of fissile material for transversal and axial load cases on fuel rod segments are investigated in Hirose et al. (2015). Worthy of mention is also the GRS project in Schrödl et al. (2010), in which some methodical investigations concerning the bending loading of fuel rods were conducted, but unfortunately this project was not extended to the tests with irradiated rod segments. Multiply aspects of spent fuel under transport loads are covered in the Used Fuel Disposition Campaign in the US. The vibration loads and impact loads onto a fuel rod are investigated experimentally with an instrumented surrogate fuel assembly on a shaker table and during a truck measurement run, see McConell et al. (2013) and (2014). The experiments were supported by bending fatigue tests of spent fuel rods in the hot cell and finite element analyses, see Wang et al. (2013) and Adkins et al. (2013).

The focus of the presented joined research project performed by ITU and BAM is the mechanical testing of fuel rod segments in the hot cell. The primary goal is a better understanding of the failure mechanism with respect to the activity release for loads in range of normal conditions of transport. In this context, ITU has developed a 3-point bending test device. The spent fuel rod segments are pressurized and the pressure is measured during the tests. The tests are performed with quasi-static loads to determine the point of pressure drop and thereby the failure initiation in the cladding precisely. Fuel rod segments with high burn-up of around 65 GWd/tU are planned to be tested in the hot cell. BAM provides boundary conditions based on the experiences of the approval work and will also contribute by numerical analysis of the tests and associate the results with the load conditions in the cask. In the future, dynamic tests are also planned to investigate the fuel rod behavior under accident conditions of transport.

EXPERIMENTAL SETUP

A 3-point quasi-static bending test was developed by ITU to investigate the bending behavior of spent fuel rod segments. The specimen can be pressurized. The sensors applied allow the measurement of the bending displacement, the force and the pressure. The testing device as shown in Figure 1 is designed to be inserted in a hot cell at ITU. The geometry of the support and the former which applies the load is based on the ISO 7438 standard. A cold test campaign was performed to test the performance of testing device and the sensors. The distance between the supports is 140 mm. Zircaloy-4 (Zr4) claddings and surrogate pellets from Al2O3 were used for the cold tests. The claddings have an outer diameter of 10.75 mm and a wall thickness of 0.725 mm. The pellets have a diameter of 9.27 mm and a length of 10 mm. This gives a radial gap between cladding and pellets of 0,015 mm. The specimens are pressurized with 4 MPa. The claddings are artificially hydrogenated to reduce the ductility of the material. Four different hydrogen levels are used of the testing. Since the hydrogen concentration varies over the length of the specimen, it is measured after the test in area of the fracture. A detailed description of the test setup and the experimental results can be found in Nasyrow et al. (2016).

MODELING AND CALCULATION

The aim of the finite element model is to identify decisive parameters and an appropriate material model based on the cold test results. The estimate approach shall be the basis for the numerical analysis of the spent fuel tests in the hot cell, which will be performed hereafter. The intention is not to reproduce the mechanical interaction between surrogate pellets and cladding (PCMI) and between adjacent pellets (PPMI) of the cold tests precisely since the state of spent fuel rods and their interactions change significantly during operation. The pellets tend to swell, close the gap to the cladding and form a compound between each other and with the cladding. Furthermore, cracks occur in the pellets and the cladding change their mechanical properties by embrittlement. Consequently, an understanding about the PCMI and PPMI of the cold tests cannot be transferred to the ones about spent fuel rods. In the present approach, spent fuel rods are mainly considered as compound that modelled by beam elements. The advantage is that the number of parameters is low. A more detailed model usually requires more parameters which are not always known, e.g. the friction coefficient between cladding and pellets. Nevertheless, a detailed finite element model is used to investigate some of these parameters in a second step. The FE-code ABAQUS is used for all calculations presented.

A finite element model using Timoshenko beam elements for the fuel rods is applied in the first step. The circular supports and the former which applies the load are included in the model. The contact formulation for the surfaces cladding/support respectively cladding/former considers the beam surface. The elastic model was verified with a geometrical nonlinear analytical beam solution based on elliptical parameters, see Popov (1986). In the next step, an elastic-plastic material model with linear hardening was used to reproduce the test results of the cold tests. The material parameters as Young's modulus and yield stress were chosen for a better correlation with the cold test results (E_{clad} = 85000 MPa, $R_{e,clad}$ = 560 MPa). The plastic hardening modulus affects the nonlinear behavior of the fuel rod gravely. The influence of the pellets on the bending response is not taken into account in the beam model. Therefore the stiffness influence of the pellets (if there is any) has to be included in the hardening modulus $E_{tc,clad}$ of the cladding. The value of $E_{tc,clad}$ = 2600 MPa was derived from literature. In a parameter study $E_{tc,clad}$ = 5200 MPa was used. The calculation was performed displacement-controlled with a maximum displacement of the former of 35 mm. The results in Fig. 3 show that the bending reaction of the fuel rods can be approximated pretty well with the beam model. The stiffer model with $E_{tc,clad}$ = 5200 MPa fits better to the results with a hydrogen concentration of 340 ppm, 400 ppm and 700 ppm. The experiments do not include the statistical scattering of the material yet. In principle the beam model with a rather simple bilinear elastic-plastic material law is suitable to reproduce the force-displacement-curves of the quasi-static 3-point bending test.

A model with solid elements was used to analyze effects of the pellet-cladding interaction and the influence of the pellets on the stiffness of the compound. An elastic-ideal-plastic material model is assumed for the Al_2O_2 - pellets (E_{pel} = 380 GPa, $R_{e,pel}$ = 350 MPa). The material model for the cladding is taken from the beam calculation above with the same variation of the hardening modulus. The friction coefficient between cladding and pellets is varied in two calculation cases with μ_{cp} = 0.05 and μ_{cp} = 0.15. The friction coefficient between the pellets is assumed to μ_{pp} = 0.10. The FE-model is depicted in Fig. 4. The results for the force-displacement-curves are shown in Fig. 5. The pellets increase the stiffness of the fuel rod only after the exceedance of the elastic limit. This stiffening effect seems to behave similar to the constant hardening. The calculation with μ_{cp} = 0.15 and $E_{tc,clad}$ = 2600 MPa shows nearly equal results as the beam calculation with $E_{tc,clad}$ = 5200 MPa. So the modelling of the pellets does not give an additional more complex or precise behavior in this case.

The movement of the pellets during the bending can be seen in Fig. 4. It can be noticed, that only the inner 3 pellets in the area of the highest curvature are twisting against each other. These pellets do also apply a substantial contact pressure onto the inner surface cladding, resulting in imprints which can also be observed in the experiments. Such effects can obviously not be modelled with a beam model. On the other hand, the solid model has a much higher computational costs and the convergence behavior is much more sensitive.

It seems to be reasonable to start with a simple model and to increase its complexity successively in order to separate the effects of the governing parameters. Such a gradual approach can be especially advantageous for the analysis of the hot cell tests because the information about the mechanical properties of spent fuel specimens is usually not sufficient to describe the complex numerical models uniquely.

CONCLUSIONS

Two different FE-models are presented to simulate the results of the quasi-static 3-point bending cold tests performed at ITU. In the first model, the cladding is meshed with beam elements and the pellets are neglected to reproduce the bending behavior. In the second case, cladding and pellets are modelled with solid elements to identify influence of the PCMI and PPMI effects in the cold tests. As a result of the calculations it can be noted that the beam model with a bilinear elastic-plastic material model is sufficient to reproduce the force-displacement-curves measured in the cold tests. The calculations with solid elements can be used to investigate local effects like the imprints the pellets leave in the cladding. But the approximation of the force-displacement-curves is generally not more precise than the one of the beam model. So beam elements seem to be a sufficient method for the modelling. In particular, with regard to the complete different PCMI and PPMI characteristics of spent fuel rods in comparison with the cold test rods, the numerical models have to be adapted. Nevertheless, the approach outlined in this paper with the successively increasing complexity of the model can be efficiently used to analyze the parameters governing the behavior of spent fuel specimen in the hot cell tests.

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FIGURES

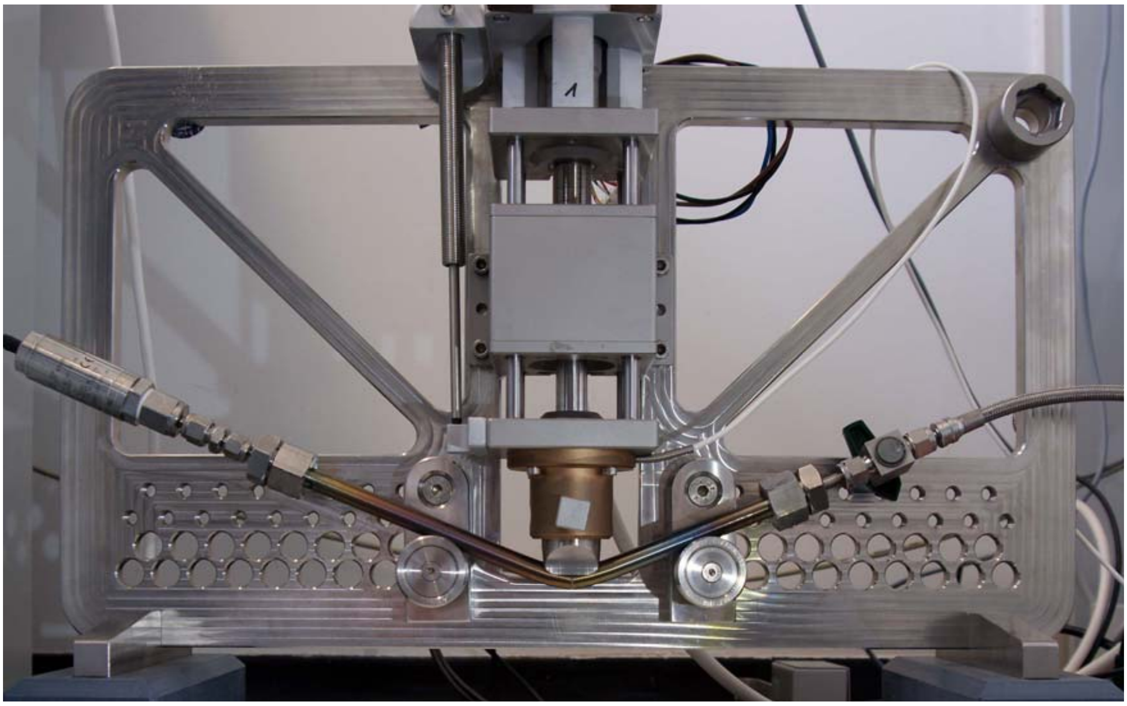

Figure 1. Test setup for quasi-static 3-point bending test

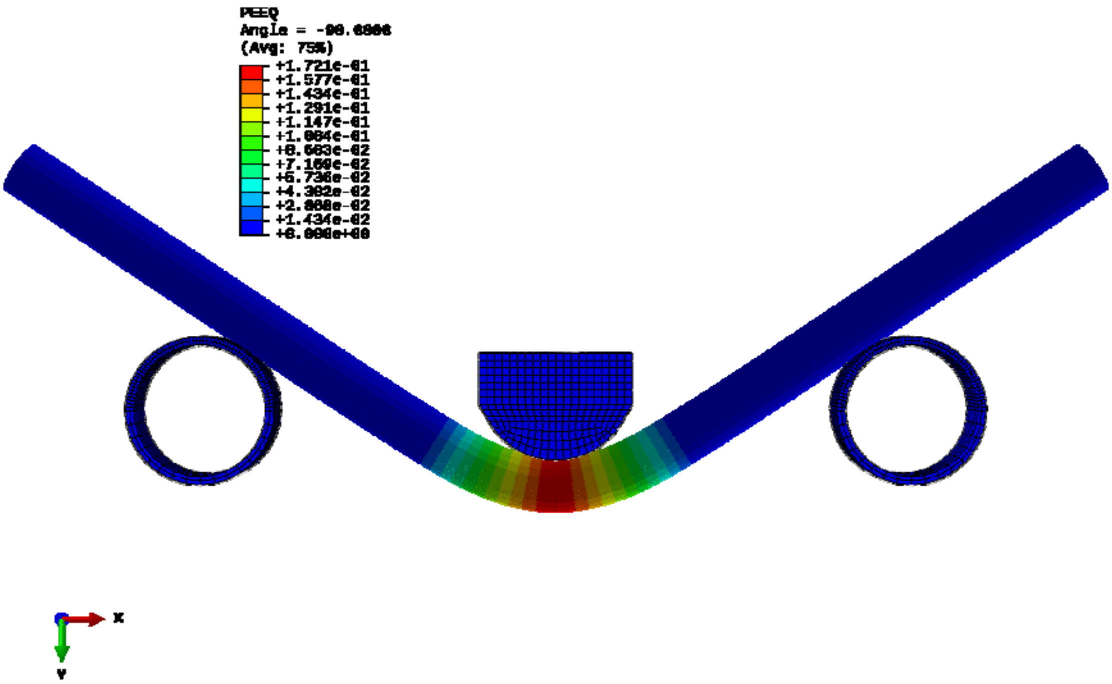

Figure 2. Finite element model of 3-point bending test with beam elements: plastic strains in the last calculation step

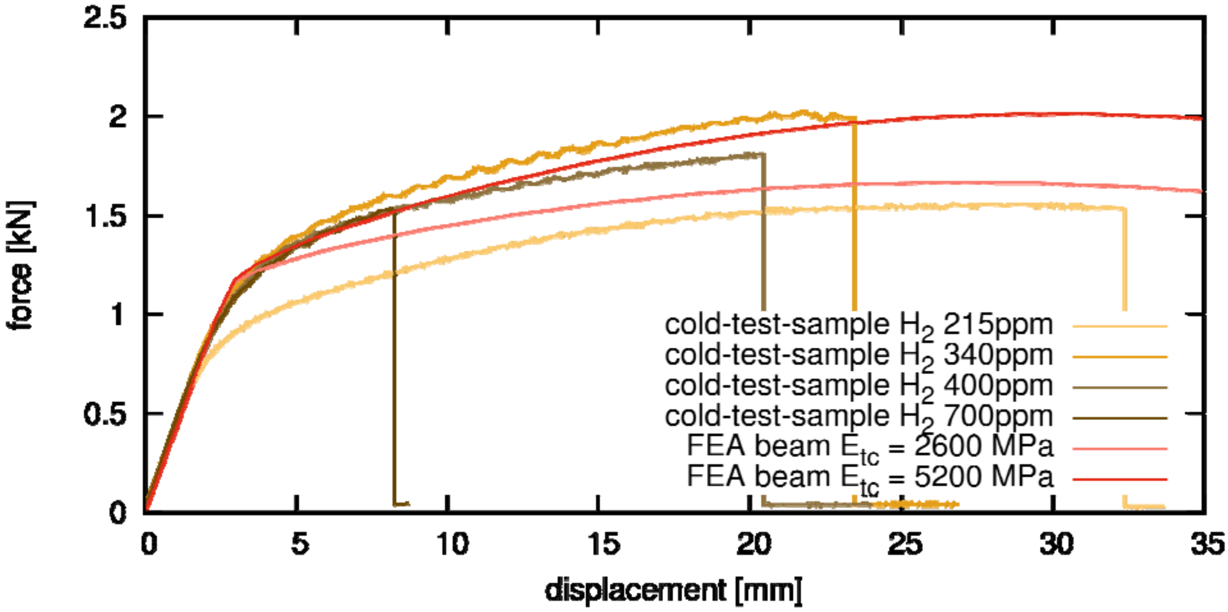

Figure 3. Results of beam element calculation in comparison with cold test results

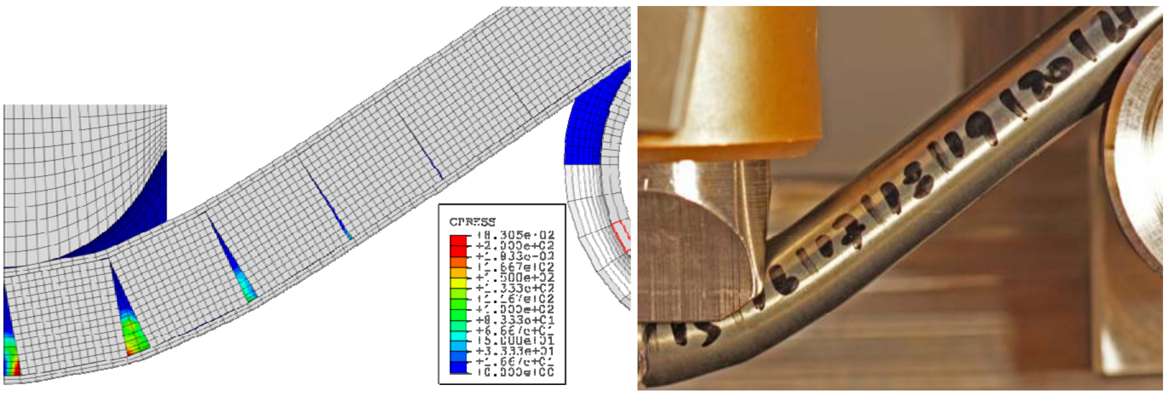

Figure 4. Finite element model of 3-point bending test with solids elements: contact pressure in the last calculation step in comparison with experimental results

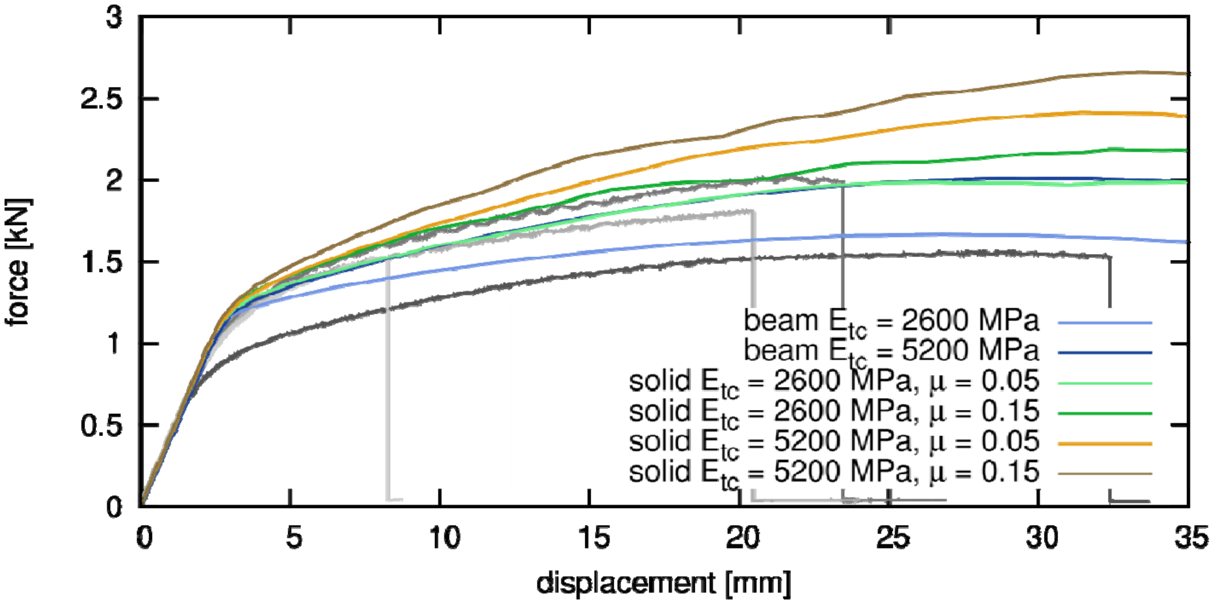

Figure 5. Results of solid element calculation in comparison with beam calculation