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Modelling of PWR Fuel Assembly Deformations During Irradiation

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ABSTRACT - Fuel assembly deformations during irradiation in PWRs are modelled using a finite element method with highly reduced number of degrees of freedom for fuel assembly. In this work the model, called FADA (Fuel Assembly Deformation Analysis), is presented and results from model verification and calibration are presented. Further we present results of simulations performed with FADA on different fuel assembly designs in order to study the deformation susceptibility of a single fuel assembly.

INTRODUCTION

A fuel assembly in a pressurised water reactor (PWR) consists of a skeleton and fuel rods. The skeleton, the main load-bearing structure maintaining integrity of the fuel assembly, consists of a top nozzle, guide thimbles, spacer grids and a bottom nozzle, see Fig. 1. The lower portion of the guide thimbles serves as a hydraulic brake (dashpot) for the control rods. The material in the guide thimbles is Zircaloy. The axial compression from hold-down springs restricting free axial growth of the assembly during irradiation, together with the restriction against rotational deformation at the spacer grid levels, results in a wave-shaped deflection of the fuel assembly. The irradiation-induced axial growth is caused by absorption of fast neutrons (≥ 1 MeV) in Zircaloy. The amount of deformation of individual guide thimbles and fuel rods differ within an assembly due to variations in local irradiation conditions and inherent variations in material and structure from manufacturing of fuel assemblies. The differences in axial growth cause interaction through the mechanical joints, such as spacer grid/guide thimble and spacer grid/fuel rod, initiates local lateral deflections of the individual guide thimbles and fuel rods between the spacer grids. After the initiation of lateral deflections they may be enhanced through irradiation-induced growth, material creep and interaction between surrounding fuel assemblies. These

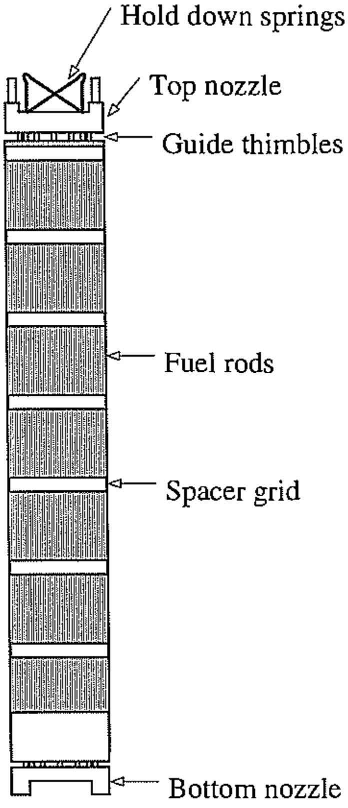


Figure 1 Fuel assembly 17x17 standard

deflections may impair the insertion of control rods into the core. In severe cases it can even prevent full insertion of the control rods.

In Ref. [1] it is shown that it is possible to use a finite element model with highly reduced number of degrees of freedom to describe the mechanical characteristics of a PWR fuel assembly. In this work we present a finite element model for calculation of single PWR fuel assembly deformation under typical reactor conditions. The FADA (Fuel Assembly Deformation Analysis) model is developed in order to provide a tool that can be used to understand and quantify the deformation susceptibility of different fuel assembly designs. Further the detailed in-reactor evolution of the fuel assembly shape and the associated stresses as a function of irradiation time and guide thimble heights are calculated. The driving loads are the fast neutron flux (≥1 MeV) history, the thermal expansion and the interaction between fuel assemblies. The amount of inelastic assembly deflection is assumed to be a combined effect of the irradiation-induced growth and stress relaxation due to material creep.

The fuel assembly skeleton is modelled with two-dimensional beam, spring and coupling elements using small deformation finite element theory. The influence from fuel rods are modelled by forces in the spacer grid positions.

FINITE ELEMENT FORMULATION

The fuel assembly is modelled as an Euler-Bernoulli beam and the potential energy for such a beam may be written as

$$\Pi_p = \frac{1}{2}\int_V (\varepsilon_{xx} - \varepsilon_0)^{\mathrm{T}} E\,(\varepsilon_{xx} - \varepsilon_0)\,dV - \mathbf{u}^{\mathrm{T}}\mathbf{p} \tag{1}$$

where Π_p is the potential energy, ε_{xx} is the total axial strain, $\mathbf{p}$ is the applied nodal forces, $\mathbf{u}$ is the displacement field, E is Young's modulus, ε_0 is the initial strain resulting from thermal expansion, irradiation induced growth and accumulated creep deformation. The superscript $^{\mathrm{T}}$ denotes the transpose operation. The constitutive stress-strain relation is

$$\sigma = E(\varepsilon_{xx} - \varepsilon_0) \tag{2}$$

and the degenerated form of the Green-Lagrangian strain tensor for the problem considered reads as follows

$$\varepsilon_{xx} = \frac{du_o}{dx} - z\frac{d^2 w_o}{dx^2} + \frac{1}{2}\left(\frac{dw_o}{dx}\right)^2 \tag{3}$$

where u_0 and w_0 denote the beam midsurface deformation in the axial and lateral direction, respectively and z is the lateral distance from the beam midsurface.

A matrix formulation of the fuel assembly bending problem is obtained by substituting finite element interpolation formulas for the tension and bending displacement fields into Eqs. (1) and (3). The axial displacement field is linearly interpolated and for the bending displacement field cubic shape functions are chosen. Further details on this can be found in textbooks of finite elements, e.g. Ref. [2].

The variational condition $\delta\Pi_p = 0$ gives then

$$ku = f_0 + f_p \tag{4}$$

where k is the beam stiffness matrix calculated as the sum of three terms, the tensile stiffness term, the bending stiffness term and the contribution from stress stiffening. The applied nodal forces are represented by f_p and the virtual nodal loads resulting from thermal expansion, irradiation growth and accumulated creep strain are represented by f_0. Both the irradiation induced growth and the creep are accounted for throughout the irradiation and both are dependant on time, temperature and fast (≥1 MeV) neutron flux.

THE FADA MODEL

The finite element formulation described in the preceding section has been implemented in a computer program called FADA for prediction of fuel assembly deformation behaviour during irradiation.

The definition of an initially non-straight fuel assembly configuration in FADA is shown in Fig. 2. The initial shape of the structure is created by use of measured deviations (Δ_i) at spacer grid positions. This type of data can be obtained from the fuel assembly straightness test performed on as-fabricated fuel assemblies. The resulting waviness of the structure is taken into account by cubic spline interpolation.

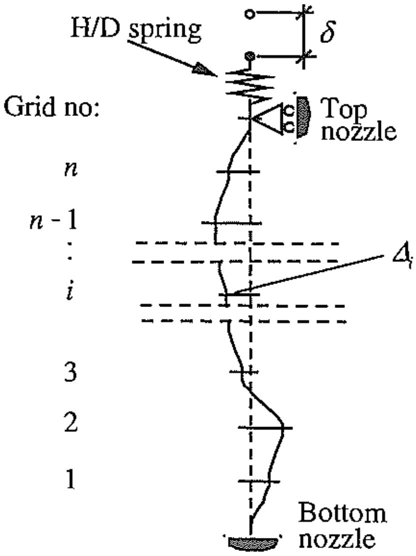


Figure 2 The FADA model

The fuel assembly is foreseen to be represented by a finite element structure of the skeleton including the spacer grids, top and bottom nozzles and the hold-down (H/D) spring, see Fig. 2. The model is based on two-dimensional beam, spring and constraint elements. δ is the initial prescribed axial displacement resulting from mounting of the reactor lid and differential thermal expansion of the fuel assembly (Zircaloy) and the reactor pressure vessel (stainless steel) when the reactor is brought to hot condition.

The restriction against free bending of the structure is mitigated by the stiffening effect of the spacer grids. Moreover, each spacer grid level is modelled by individually adjustable grid heights and torsional spring stiffnesses. The portion of guide thimble that is supported by the spacer grid at each grid level is modelled to maintain a constant inclination angle.

The influence of fuel rods upon the deformation is considered by adding external forces in the spacer grid positions, simulating the spacer grid/fuel rod interaction. These forces are calculated from the difference in thermal expansion of fuel rods and guide thimbles. The axial temperature profile of fuel rod cladding is calculated as a function of burnup using the ABB Atom steady-state fuel performance code STAV7. The temperature of the guide thimble is taken to be the associated temperature of water calculated by STAV7. Further, the relaxation of the normal force between the grid spring and fuel rod is effectively taken into account by decreasing the spacer grid/fuel rod interaction forces as exposure increases. The interaction forces are modelled to follow a linear relationship till an exposure limit is reached where the interaction force vanishes.

The amount of inelastic deflection is assumed to be a combined effect of the irradiation-induced growth and stress relaxation due to material creep. The detailed evolution of the fuel assembly deflection is quantified for a fast neutron flux history (≥1 MeV) consisting of a certain number of axial segments.

MODEL VERIFICATION AND CALIBRATION

The FADA model is verified and calibrated by comparing the model predictions with experimental test results and independent finite element calculations. The test results utilised in this work are extracted from a full-scale test program on ABB Atom PWR 17x17XL fuel assembly, Ref. [3], where the lateral and axial load characteristics for the fuel skeleton and the fuel assembly in unirradiated condition were determined. Characteristic data for this design is shown in Table 1. In the lateral tests, spacer grid number 5, from the bottom end, was laterally deflected and the resulting shape was determined by measuring the deflections in the spacer grid positions.

Table 1 Characteristic data for ABB Atom 17x17XL fuel assembly

Number of fuel rods		264
Number of spacer grids		10
Fuel assembly length	mm	4790
Square width dimensions	mm	214
Fuel assembly weight	kg	785
Guide thimble inner diameter (upper part)	mm	11,38
Guide thimble outer diameter (upper part)	mm	12,19
Guide thimble inner diameter (lower part)	mm	10,11
Guide thimble outer diameter (lower part)	mm	11,00

Skeleton Model

First the skeleton model is verified against independent finite element (FE) calculations performed with the general purpose FE program ANSYS Ref. [4]. A 17x17XL fuel assembly skeleton with an initial as-fabricated non-straight shape is axially loaded via the hold down springs. The resulting normalised lateral deflections calculated with FADA and ANSYS respectively, are shown in Fig. 3.

The slightly smaller deflections calculated by FADA, see Fig. 3, shows that FADA behaves somewhat stiffer compared to the used ANSYS model. The reason to this deviation is that FADA models the guide thimble portions guided by the spacer grid as rigid whereas the ANSYS model does not model this feature. The above comparison shows very good agreement and the conclusion is that the basic mechanical skeleton model in FADA is correct.

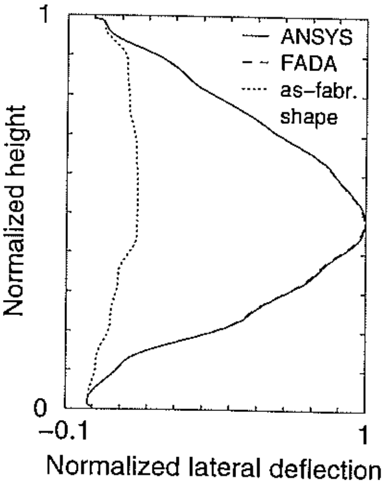
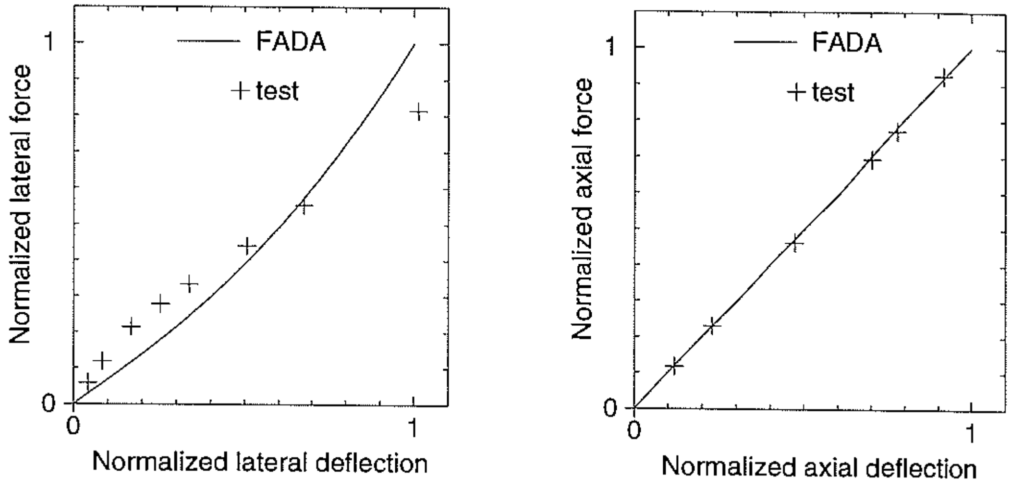


Figure 3 Calculated deflections of axially loaded 17x17XL skeleton

Further verification of the skeleton model is performed by comparing model predictions with results from experiments. Comparison of the calculated and measured load-deflection characteristics for lateral and vertical loading on ABB Atom PWR 17x17XL skeleton are shown in Figs. 4a and 4b respectively. The skeleton in the FADA simulations has been taken to be perfectly straight. In Fig. 5a the calculated lateral deflection shape of the skeleton is compared with test results.

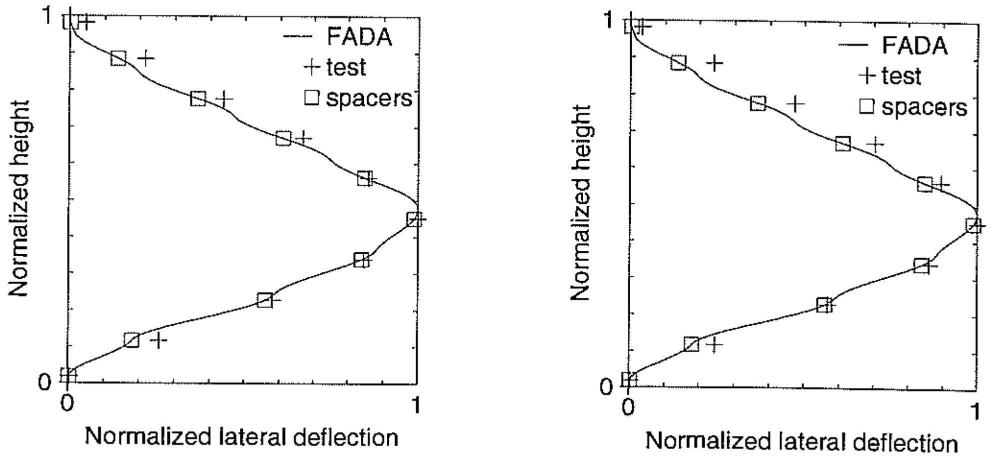


(a) (b)

Figure 4 Measured and calculated load-deflection characteristics of 17x17XL skeleton due to (a) lateral and (b) axial loading

Assembly Model

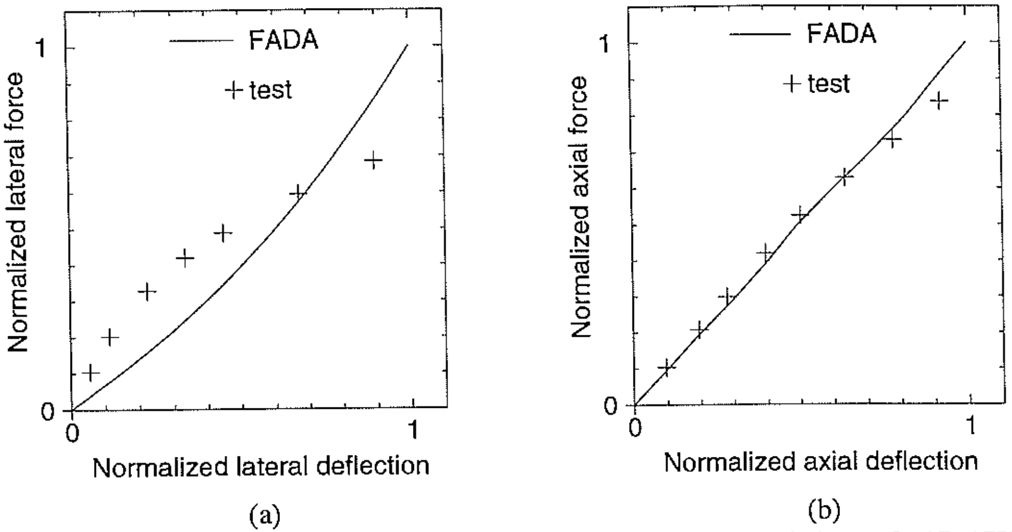
Verifications of the assembly model is performed by comparing model predictions with experimental results. Comparison of the calculated and measured load-deflection characteristics for lateral and vertical loading on ABB Atom PWR 17x17XL fuel assembly are shown in Figs. 6a and 6b respectively. In Fig. 5b the calculated lateral deflection shape of the assembly is compared with test results.



(a) (b)

Figure 5 Measured and calculated lateral deflection shapes of 17x17XL (a) skeleton and (b) fuel assembly

The deviations seen between calculated and measured skeleton and fuel assembly shapes in Figs. 5a and 5b are mainly at the top of the fuel assembly. This may come from the fact that in the tests the top nozzle experienced a small rotation contrary to the calculations where the nozzles are rigid.



(a) (b)

Figure 6 Measured and calculated load-deflection characteristics of 17x17XL fuel assembly due to (a) lateral and (b) axial loading

The load-deflection characteristics in the axial direction show a very good agreement between measured and calculated values for both skeleton and fuel assembly. In the lateral direction the deviations between measured and calculated values are more pronounced. The lateral deflections are higher than the axial and therefore the more complicated phenomena such as sliding between fuel rods and spacer grids are more predominant. In a rather simplified model such as FADA the sliding phenomena can not be fully taken into account in the whole deformation range of interest. However, FADA is developed in order to provide a tool for understanding and quantifying deformation susceptibility of different fuel assembly designs, the agreement between measured and calculated values are fully satisfactory.

INFLUENCE FROM DESIGN MEASURES

In this section results from FADA simulations on different PWR fuel assembly designs are presented. We focus our study on quantifying the deformation susceptibility of a single fuel assembly for different design measures relative to the ABB Atom PWR 17x17 standard design fuel assembly with eight spacer grids. To reduce assembly deformation in reactor service one can increase the fuel assembly stiffness, decrease the initial deformed shape and reduce the driving load producing fuel assembly deformation.

The different design parameters investigated in this study are:

- grid cell rotational stiffness
- initial as-manufactured bow amplitude of fuel assembly
- hold-down spring force
- new guide thimble design
- intermediate flow mixer grids (IFM)
- irradiation induced growth rate

The main difference between the ABB Atom standard and the new guide thimble design is the increase in outer diameters, primary in the dashpot region but also in the upper part. The intermediate flow mixers are, if present, located in the upper part of the fuel assembly.

The study consists of two parts. First the static lateral stiffness of a fuel assembly with realistic axial load is evaluated using FADA. The reference fuel assembly is loaded laterally at spacer grid number 5 from bottom and the corresponding deflection is scaled to unity. After design measures have been introduced the fuel assemblies were loaded in accordance with the reference fuel assembly. The results of the study are shown in Table 2, where the relative lateral deflections at the loaded spacer grid are given.

Table 2 Impact of certain design measures on deformation susceptibility

Design/design measure	**Relative lateral deflection**	
	lateral force	in-reactor conditions
Standard design (reference)	1	1
Grid cell rot. stiffness increased 10 %	0,94	0,84
As-manufactured bow decreased 10 %	0,99	0,91
Hold-down force decreased 10 %	0,92	0,80
Irradiation growth decreased 10 %	-	0,92
No irradiation growth	-	0,41
New guide thimble design	0,63	0,73
Standard design + 3 IFM	0,91	0,62
New guide thimble design + 3 IFM	0,59	0,48

In the second part of this study a single PWR fuel assembly is exposed to realistic in-reactor conditions. An as-manufactured non-straight fuel assembly is axially compressed via the hold-down springs. The fuel assembly is further exposed to axially varying hydraulic lift force, temperature and fast neutron flux (≥ 1 MeV) histories coming as a result of a representative PWR power history shown in Fig. 7. The calculated relative maximum lateral deflections after approximately 22000 h of in-reactor service with various design measures are also stated in Table 2. The relative deflections in Table 2 represent the values at spacer position of maximum lateral fuel assembly deflection.

The design parameters in this study showing the highest potential for decreasing the deformation susceptibility are reduction of irradiation induced growth and introduction of new stiffer guide thimble design and intermediate flow mixer grids.

The reason for performing calculation with vanishing irradiation induced growth is to show the strong influence on fuel assembly deformations. ABB Atom is now testing some new advanced materials with substantially reduced growth. These materials have a very high potential as guide thimble material due to the strong influence of irradiation induced growth on fuel assembly deformation susceptibility.

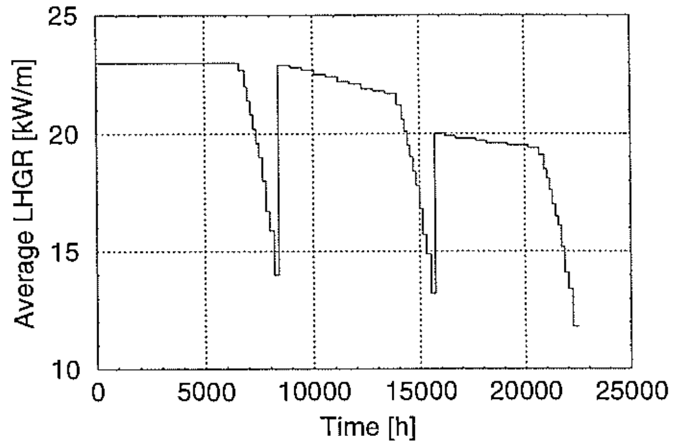


Figure 7 Power history

CONCLUDING REMARKS

The FADA model for calculations of single PWR fuel assembly deformations under typical reactor conditions is presented in this paper. The results show sufficient agreement between calculated and measured quantities. The FADA model will be further verified and calibrated against in-reactor data and extended to cover a row of fuel assemblies.

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