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NONLINEAR ANALYSES OF THE BUCKLING LOAD AND THE EIGENVALUES IN A 17x17 PWR FUEL ASSEMBLY

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ABSTRACT

In this work a finite element model has been developed to enable analysis of an ABB Atom PWR 17x17 fuel assembly regarding both static and dynamic behaviour. In the model stiffnesses and masses of the fuel assembly have been lumped together to reduce the number of degrees of freedom. The analysis is nonlinear since sliding with friction occurs with a consequent loss of energy. This nonconservative problem (load-path dependent) is solved by incrementing the load and for each load step iteratively finding the solution by the Newton-Raphson procedure. The model has been verified against full scale assembly static tests and is presently under verification against dynamic tests. The model can be used to describe behaviour at different operating conditions and to study the influence of design changes on the static and dynamic behaviour.

1. INTRODUCTION

Nuclear fuel assemblies in light water reactors are designed to withstand a variety of loads (shipping and handling, flow-induced loads, seismic, etc) under both normal and abnormal conditions. Thus the knowledge of dynamic behaviour of the assembly and of its structural stability is essential for fuel system design. As a complement to assembly mechanical tests a theoretical model is needed for evaluation of design changes and of the effect of different operating conditions. A finite element model of the ABB Atom PWR 17x17 fuel assembly has been developed for analysis regarding static deflection characteristic, critical buckling load, and eigenfrequencies. This paper presents the assembly model and discusses verification of the model by comparison with results from full-scale mechanical tests.

2. ABB ATOM PWR FUEL ASSEMBLY DESIGN

The fuel design chosen for the present analysis is the ABB Atom PWR 17x17 XL fuel assembly. The fuel assembly consists of 264 fuel rods, 24 guide thimble tubes, one central instrumentation tube, all arranged in a 17x17 lattice. The fuel assembly also embodies 10 spacer grids and top and bottom nozzles, see Figure 1. The spacer grids are fixed to the Zircaloy guide thimble tubes, except for the bottom grid, which is positioned by inserts between the grid and the bottom nozzle. The top and bottom nozzles are connected to the guide thimbles and are removable. Nozzles, guide thimbles and spacer grids form the structural skeleton of the assembly.

There are two main types of spacer grids in the fuel assembly: one bottom end Inconel grid and nine all-Zircaloy grids. The fuel rods are supported by the grids, which maintain the lateral space between the rods. Each rod cell in the grid is provided with two springs and four arches, oriented so that the rod is pressed against two arches in two perpendicular directions, Figure 2. The fuel rods consist of cold-worked Zircaloy-4 tubing and encapsulate the fuel column of UO_2 pellets. In the upper end there is a plenum for axial expansion of the fuel column and for accommodation of released fission gas. The top nozzle is provided with four holddown spring packs, which resist the hydraulic lift force during operation and press the assembly against the bottom core plate.

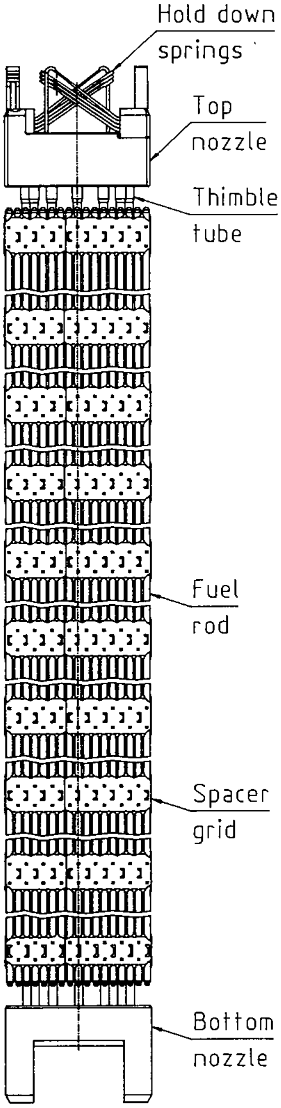

Figure 1 Fuel assembly design 17x17

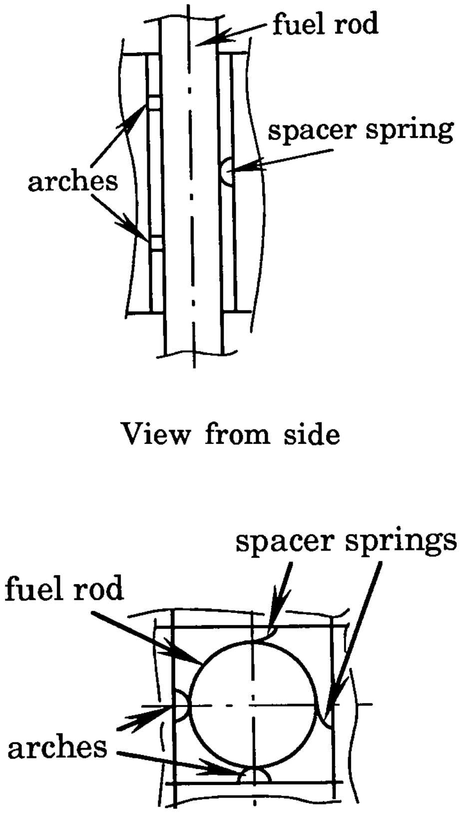

Figure 2 Sketch of one rod cell in a spacer grid.

3. MODEL

3.1 The Finite Element Model

A simplified finite element model of fuel assembly has been developed to describe the axial and lateral static as well as the dynamic behaviour of a fuel assembly. The model consists of two main parts: the skeleton part, representing guide thimbles, spacer grids, and nozzles; and the fuel rod part. In order to reduce the number of degrees of freedom stiffnesses and masses of the fuel assembly have been lumped together. The finite element program ANSYS 4.4 [1] is used to model this system. The model consists of beam, gap, spring, mass, and torsional elements. Figure 3 shows the finite element model used in this analysis.

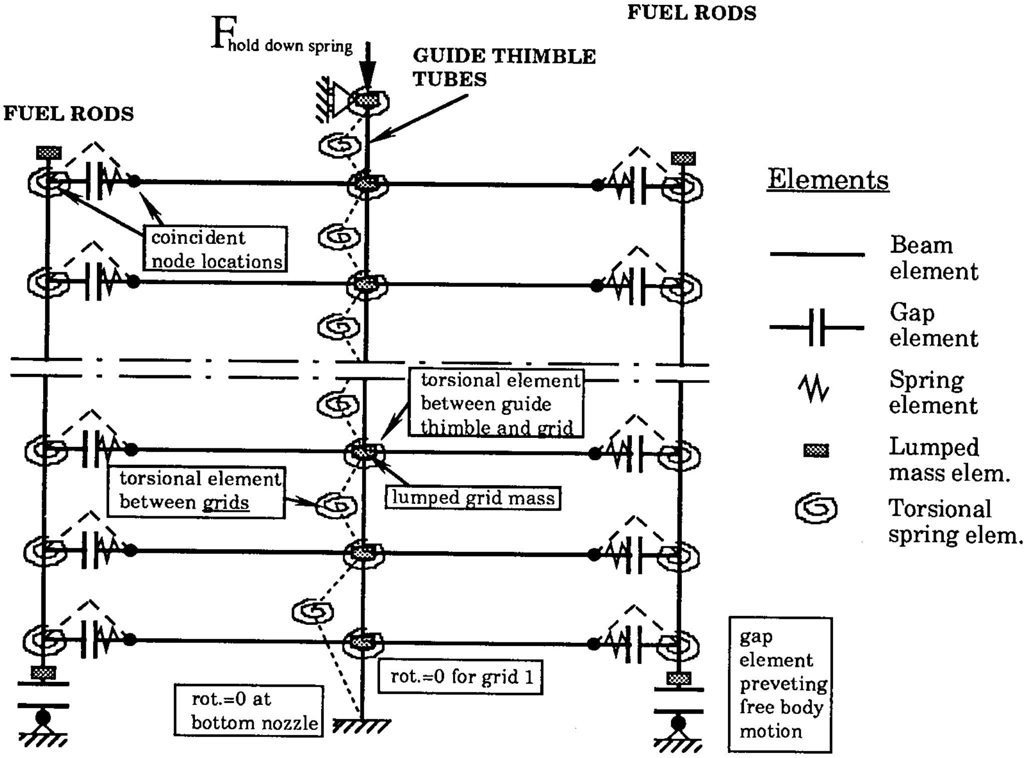

Figure 3 Finite element model of fuel assembly

The guide thimble tubes are represented by a string of beam elements with a stiffness (moment of inertia) which is equal to the sum of all thimble tube stiffnesses. The mass of the thimble tubes is linearly distributed along the beam elements. Each spacer grid is described as two symmetrical stiff horizontal beams, coupled to the thimble tubes in the lateral and axial directions. Moreover, in rotational direction the guide thimble elements are connected to the spacers by one dimensional (1-D) torsional spring elements restricting rotation of the guide thimble in the spacer cell. The spacer grid rotation, on the other hand, is restricted by torsional springs inserted between adjacent grids. These represent the restriction caused by the fixed connection between grids and thimble tubes. Their stiffness is calculated by taking into account the deformations of all thimble tubes between two grids. The mass of each spacer grid is lumped and described by a mass element positioned on the thimble tube. The connections of thimble tube to top and bottom nozzles, and top nozzle to core plate are also modelled with torsional springs. However, the bottom nozzle is not allowed to rotate.

The rods are lumped together into two symmetrical positions and are modelled with 2-D elastic beam elements. The connection between the fuel rods and spacer grid is modelled by 2-D spring and nonlinear gap (friction & contact) elements resisting both compressive and tensile stresses. The gap element describes frictional sliding of the rod in the spacer cell, possible loss of contact between fuel rod and spacer spring, and enables sliding of the fuel rod in axial direction. The spring element gives the transverse preload from the spacer spring to the fuel rod. Due to the axial spacing of grid spring and arches the spring also causes a moment, resisting rotation between rod and spacer. Rotation will not occur until the moment from the rod exceeds the preload moment, Figure 4. This behaviour is modelled with a 1-D nonlinear torsional spring element.

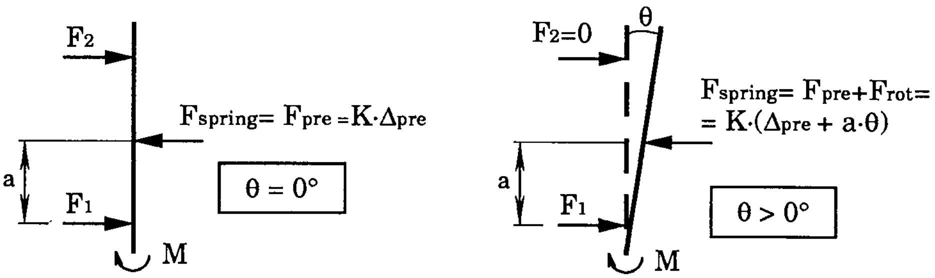

Figure 4 Moment-rotation characteristics of a fuel rod in a spacer cell

3.2 Solution Technique

The static deflection, buckling and natural frequency analyses are solved using the finite element code ANSYS 4.4. Since the model includes nonlinear elements the buckling and natural frequency problem must be solved by other methods than the direct solution of an eigenvalue problem. Both the lateral deflection and buckling problems are solved iteratively by full Newton-Raphson procedure, i.e. the stiffness matrix is updated at each iteration step. They are treated as a large deflection problem with the axial load imposed in small steps to avoid numerical problems. In the buckling problem the displacement response is studied to get the load when the structure turns unstable. The basic equation for this nonlinear static problem is:

$$[K]\{\Delta u\} = \{F_{app}\} - \{F_{el}\} \qquad (1)$$

where

$[K]$ = total stiffness matrix
$\{\Delta u\}$ = nodal displacement increment vector
$\{F_{app}\}$ = applied nodal force load vector
$\{F_{el}\}$ = element elastic vector.

The first cumulative iteration is performed as for the linear problem, i.e. without the elastic load vector. For subsequent iterations, the element elastic vector is computed and the stiffness matrix is updated to account for non-linearities.

The natural frequency problem is solved by studying the dynamic response of the structure released from a deflected shape but also under the action of a harmonic (sinusoidally varying) load of known amplitude and varying frequency. The basic equation of motion for this problem is:

$$[M]\ \{\ddot{u}\} + [C]\ \{\dot{u}\} + [K]\ \{\Delta u\} = \{F(t)\} \tag{2}$$

where

$$\{F(t)\} = \{F_{app}\} + \{F_{ma}\} - \{F_{el}\}$$

and

$[M]$ = total mas matrix
$[C]$ = structure damping matrix
$\{F_{ma}\}$ = applied element body force load vector
$\{\ddot{u}\}$ = nodal acceleration vector

$\{\dot{u}\}$ = nodal velocity vector,
other terms in (2) are described below equation (1).

An implicit direct integration scheme, based on the Newmark method [1], is used to solve the unknown displacements at a given time point.

4. MODEL VERIFICATION

Verification of the model is performed by comparing the model predictions with experimental test results. A full scale assembly test program has been performed to determine lateral and axial load deflection, free vibration, and forced vibration characteristics. Simulation of the tests is presently under evaluation. Before simulating these tests one should verify that the correct stiffnesses have been used for the thimble tube-to-spacer, spacer-to-spacer and thimble tube elements. The calculated deflection shape of the skeleton is compared with the test results in Figure 5. In the test, grid number 5, from the bottom end, was laterally deflected in both directions and all spacer grid deflections as well as strain distribution along the thimble tubes were determined. The reaction force at grid 5, corresponding to the skeleton stiffness, is calculated and compared with the test results. The agreement between the experiment and the calculation is within 2-3%, which is quite satisfactory. The calculated moment on the guide thimble tube, caused by the rotational restriction from the spacer grid, is compared with the moment obtained from tests at each grid location. The distributions of the moment along the thimble tube showed a good agreement, but the calculated moments were slightly higher than the measured (10-20%). The calculated rotation of the top nozzle was consistent with the test results (< 0.3°).

The lateral load deflection test of the fuel assembly shows a pronounced hysteresis due to the sliding in the grids and this is used to calibrate the parameters of the gap elements. The deflected shape of the fuel assembly is also compared with tests. Calculations are performed to establish the buckling load and then calculated pre-buckling deformations are compared with results from fuel assembly axial test.

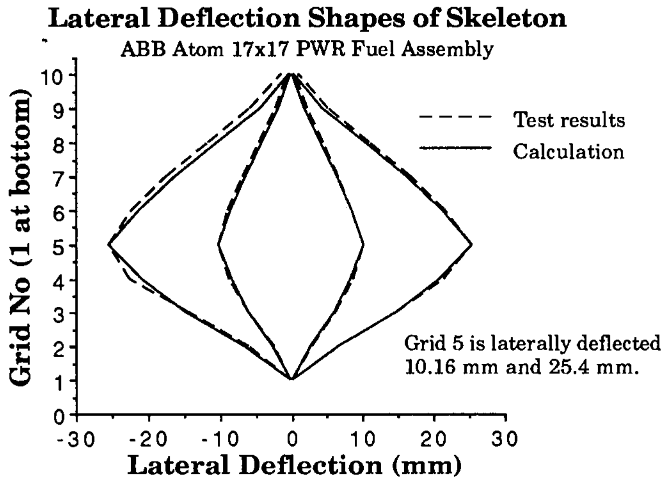

Figure 5 Lateral deflection shape of skeleton

In the free vibration test one of the central grids of the assembly is laterally deflected and then released allowing the assembly to vibrate to its rest position. This gives information on natural frequency and damping behaviour of fuel assembly system. Finite element simulation of this test verifies the dynamic properties of the model.

In the forced vibration test the bottom end of the assembly is sinusoidally excited with varying frequency. Comparison with this test confirms that the natural frequencies of the model, including higher modes, are correct.

5. APPLICATION

The model described above can be used to evaluate the effect of possible design changes on eigenfrequencies and buckling stability. It can also be used for evaluation of dynamic and buckling behaviour at different operating conditions. Assembly mechanical tests are performed at room temperature, and evaluation at operating temperature requires a model simulation. The model can also calculate the guide thimble tube stresses for different deflection shapes.

6. CONCLUSIONS

It is possible to use a finite element model with highly reduced number of degrees of freedom to describe the static and dynamic characteristics of a PWR fuel assembly and thereby predict buckling load and natural frequencis. The nonlinear sliding of the fuel rods in the spacer grids can be simulated by employing nonlinear gap elements.

REFERENCE

[1] Kohneke, P.C., (1989), ANSYS Engineering Analysis System, Theoretical Manual Division 4.4, Houston, Swanson Analysis System