Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Structural analysis of PWR fuel assemblies

Macedo, L.V.S.
Emgepron, São Paulo, Brazil
Perrotta, J.A.
IPEN/CNEN, São Paulo, Brazil

ABSTRACT: It is presented a program of analysis which was developed to evaluate the structural integrity of PWR fuel assemblies. The static and dynamic structural models implemented in computer programs are discussed and the experimental program is briefly presented.

1 INTRODUCTION

When idealizing project and analysis of nuclear fuels it is necessary to have knowledge in areas such as materials and its behavior under in-core conditions, mechanical design for the fuel to satisfy functional requirements, establishing analytical models useful for the analysis and the utilization of experimental facilities in order to get information, proof and validation of analysis items.

Based on these principles we have elaborated an analysis program concerned with the study of the structural behavior of typical PWR fuel assemblies. Both theoretical and experimental subjects were covered.

2 STATIC STRUCTURAL ANALYSIS OF A SINGLE FUEL ASSEMBLY

The static structural behavior of the fuel assembly is calculated by the ELCOM (ELemento COMbustível) . ELCOM uses a model developed by Pimenta and Perrotta (1984). It models the fuel assembly as an array of tubes (fuel element's cladding and thimble tubes) held together by rigid spacers (fuel assembly's grids and bottom and top nozzles). It assumes that the spacers have rigid body movement and that the coupling between each tube and the spacers may be of variable rigidity. The typical loading are distributed loads in the tubes, concentrated loads in the spacers and loads due to differential thermal expansions. The results obtained are the rigidity of the hole structure and forces, moments and nodal displacements of the tubes at the spacer's locations.

A complete matrix analysis of the fuel assembly's structure becomes complex because the great number of degrees of freedom involved. A typical fuel assembly consists of 235 fuel elements, 21 thimble tubes, 8 spacer grids, 2 nozzles resulting in 2090 nodes, 12540 degrees of freedom.

Thus, the main point in the ELCOM's implementation is the hypothesis of rigid body movement on the spacers and bottom and top nozzles, which is supported by the much greater rigidity of those compared with that presented by the tubes.

Each node in the structure (fuel element-spacer coupling, thimble tube-spacer coupling and thimble tube-nozzles coupling) has its degree of freedom related to the degree of freedom of the corresponding spacer or nozzle. The global stiffness of the structure is then obtained through the summation of these transformations, reducing a lot its size. (In the above example we have now 10 nodes, 60 degrees of freedom.)

For the coupling between the thimble tubes and the spacers and nozzles it's assumed a rigid connection. For the coupling between the fuel elements and the spacers a variable rigidity is allowed. A bilinear model is currently implemented in ELCOM.

The solution is then obtained through classical methods of nonlinear structural analysis, allowing the consideration of variable rigidity in the coupling between the fuel elements and the spacers.

At the end of the solution the displacements, rotations, forces and moments at each node in each substructure (fuel element or thimble tube) are recovered through an inverse transformation of that used to reduce the global stiffness matrix of the structure.

Another ability of ELCOM is to calculate the natural frequencies of the fuel assembly's structure, with its modal matrix, utilizing the reduced global stiffness matrix calculated and a given diagonal mass matrix.

Thus ELCOM is a very useful tool for the design and analysis of typical fuel assemblies, allowing the parametrization of its structural behavior versus, for example, the number of spacer grids, the rigidity of the coupling between tubes and spacers and the fuel assembly's boundary condition, considered in the analysis, in its mounting into the core (if clamped-clamped, clamped-hinged or hinged-hinged).

Some conclusions about the structural behavior of typical fuel assemblies can be shown using ELCOM (Macedo & Perrotta, 1990):

- the variation of the lateral stiffness of the fuel assembly with the variation of the rigidity of any one of the degrees of freedom of the coupling between the fuel elements and the spacers is almost linear. The better results in order to enhance the lateral stiffness of the fuel assembly is, in descending order, to increase the rotary stiffness of the coupling, increase the axial stiffness and last increase the perpendicular stiffness;
-to increase the number of spacers contributes highly to increase the lateral stiffness;
-increasing the rigidity of the coupling between the fuel elements and the spacers, there is a distribution of the loading from the fuel elements to the thimble tubes.

2.1 *Formulation*

The equilibrium equations for all the fuel elements are

$$\{R_E\}+\{R_C\}=[K_E]\{r_E\} \tag{1}$$

where $\{R_E\}$ is a vector of external forces acting over the fuel elements, $\{R_C\}$ is a vector of reaction forces, given by the coupling system between the fuel elements and the grids, acting over the fuel elements, $[K_E]$ is the stiffness matrix of the fuel elements and $\{r_E\}$ is a vector of the nodal displacements of the fuel elements.

The equilibrium equations for all the thimble tubes are

$$\{R_T\}+\{R_S\}=[K_T]\{r_T\} \tag{2}$$

where $\{R_T\}$ is a vector of external forces acting over the thimble tubes, $\{R_S\}$ is a vector of reaction forces acting over the thimble tubes, $[K_T]$ is the stiffness matrix of the thimble tubes and $\{r_T\}$ is a vector of the nodal displacements of the thimble tubes.

The forces acting in the coupling system between the fuel elements and the grids are a nonlinear function of the relative displacements between the nodes of the fuel elements and its corresponding location on the grid; i.e.,

$$\{R_C\}=\{R_C\}(\{r_C\})=\{R_C\}(\{r_R\}-\{r_E\}) \tag{3}$$

where $\{r_R\}$ is a vector of the displacements of each fuel element location on the grid. If we assume a bilinear model we obtain

$$\{R_C\}=([K_1]-[K_2])(\{r_{R0}\}-\{r_{E0}\})+[K_2](\{r_R\}-\{r_E\}) \tag{4}$$

where $[K_1]=[K_2]$ for $(\{r_R\}-\{r_E\})\leq(\{r_{R0}\}-\{r_{E0}\})$ and $[K_1]\neq[K_2]$ for $(\{r_R\}-\{r_E\})\rangle(\{r_{R0}\}-\{r_{E0}\})$ and the index 0 indicates the breaking values of the bilinear model.

As the grid acts like a rigid body, these displacements can be written as a function of the displacement of the center of gravity of the grids; i.e.,

$$\{r_R\}=[A_C]\{r_G\} \tag{5}$$

where $[A_C]$ is a matrix with unity elements in its diagonal and coordinate differences in other positions. The same can be made for the thimble tubes,

$$\{r_T\}=[A_T]\{r_G\} \tag{6}$$

Then, the equilibrium for the grids and the nozzles are

$$\{R_G\}=[A_C]^T\{R_C\}-[A_T]\{R_T\}+[A_T]^T[K_T][A_T]\{r_G\} \tag{7}$$

Thus, (1) and (7) are a nonlinear equation system from which, using an iterative scheme, we obtain the final equation

$$
\begin{aligned}
&\{R_G\}-[A_C]^T([K_1]-[K_2])([A_C]\{r_{G0}\}-\{r_{V0}\})-[A_C]^T[K_2]([A_C]\{r_G\}_m-\{r_V\}_m)+\\
&[A_T]^T[K_2][A_T]\{r_G\}_m+[A_T]^T\{R_T\}+\\
&[A_T]^T[K_2]([K_2]+[K_E])^{-1}*\\
&\{\{R_E\}+([K_1]-[K_2])([A_C]\{r_{G0}\}-\{r_{V0}\})+[K_2]([A_C]\{r_G\}_m-\{r_V\}_m)-[K_E]\{r_E\}_m\}+\\
&\{[A_C]^T[K_2]\big[[[K_2]+[K_E]]^{-1}[K_2]-[I]\big][A_C]-[A_T]^T[K_T][A_T]\}(\{r_G\}_{m-1}-\{r_G\}_m)=0
\end{aligned}
\tag{8}
$$

where de subscript "m" indicates the number of the iteration.

3 DYNAMIC STRUCTURAL ANALYSIS OF A ROW OF FUEL ASSEMBLIES

The lateral dynamic structural response of a row of fuel assemblies mounted in the reactor's core is obtained with the STYCA (STructural DYnamics - Core Analysis) computer program. STYCA uses the Modal Superposition Method with the Duhamel integral in order to obtain a time-history response of the lateral displacements and impact forces, that may occur between the fuel assemblies, because the existence of gaps between them. STYCA can use the fuel assembly's spectral and modal matrices obtained by ELCOM or use experimental results. STYCA was developed by Macedo (1990, 1991) based mainly upon woks of Nuno et al. (1977), Preumont (1981) and Grubb (1979).

Some simplifying assumptions are made, i.e., only lateral displacements are considered; the problem is linear, the only non linearity is concerned with the impacts between adjacent assemblies; the baffle and the upper and lower core plates are assumed rigid; impacts are admitted only at the grid's elevations.

The dynamic response is obtained separately for each fuel assembly at each time-step, with the impact forces being treated as external forces at the next time increment.

The input for STYCA are the fuel assembly's modal and spectral matrices, the magnitude of the gaps between fuel assemblies and between them and the baffles, the impact characteristics between the fuel assemblies and between them and the baffles and a base excitation time-history. The results are the nodal displacements of the fuel assemblies and the impact forces amog them.

The modal superposition method is well known and its numeric implementation using the Duhamel integral can be found in Clough & Penzien (1975).

4 EXPERIMENTAL PROGRAM

The experimental program covered tests needed to confirm analytical models and those necessary for the structural characterization of the fuel assembly and its parts. Those tests include modal analysis on a prototype fuel assembly, static lateral loading in a prototype fuel assembly, grid stiffness testing (static and impact tests) and clad to spacer stiffness investigation tests.

4.1 Fuel element-grid coupling tests

The fuel element clad to spacer grid connection is modeled in ELCOM by rotary, axial, perpendicular and torsional springs. In order to get these information, tests were made. The main results on typical grids are (Peres, 1994):

- the load versus displacement curves are nonlinear, with a softening behavior, due to a geometric effect;
- the unloading curves are lower than the loading curves, plasticity occurs in working conditions;
- the rotary stiffness is a function of the distance between the dimples.

4.2 Static grid crush tests

Static crush tests were made in spacer grids in order to get information about its stiffness, useful as input data for STYCA (Peres, 1994). Another important information is the critical load supported by the grid. We confirm results obtained by Preumont et al (1982), such as that the loading characteristic is nonlinear, the ruin occurs by instability and that the grid stiffness is much larger when provided with fuel elements, as compared with a grid with empty cells.

4.3 Fuel assembly's modal tests

An experimental facility was built in order to perform in-air modal tests on the fuel assembly, similar to that performed by Stokes & King (1978). Dynamic excitation was applied at various grids locations and the response monitored using displacement transducers. These results are important in the validation of ELCOM models and as input for STYCA. The experimental facility and procedures were described by Trindade (1992). Theoretical results obtained by ELCOM are in good agreement with the experimental results.

5 CONCLUSIONS

This paper has presented an analysis program developed in order to evaluate the structural integrity of PWR fuel assemblies. The primary conclusions are that the models which were implemented as computer programs are very useful as design and analysis tools and that the experimental facilities mentioned above are able to give us the necessary input data and validation of results.

REFERENCES

Clough, R.W. & J. Penzien 1975. *Dynamics of structures.* Singapore: McGraw-Hill International Editions.

Grubb, R.L. 1979. *Pressurized water reactor lateral core response routine, FAMREC (Fuel Assembly Mechanical Response Code).* EG&G Idaho Inc. (NUREG/CR1019).

Macedo, L.V.da S. & J.A. Perrotta 1990. O programa computacional ELCOM no projeto e análise estrutural de ECs típicos de reatores PWR: Um caso exemplo. *Proc. 3rd Congresso geral de energia nuclear.* Rio de Janeiro, RJ, Brazil.

Macedo, L.V.da S. 1990. Metodologia de análise estrutural dinâmica do núcleo de reatores PWR. *Proc. 3rd Congresso geral de energia nuclear.* Rio de Janeiro, RJ, Brazil.

Macedo, L.V.da S. 1991. *Análise estrutural dinâmica de um conjunto de elementos combustíveis no núcleo de um reator PWR.*. MSc. dissertation. São Paulo, SP, Brazil: Escola Politécnica da Universidade de São Paulo.

Nuno, H.; M.Mizuta & N.Isumura 1977. Development of advanced methods for fuel seismic analysis. *Proc. 4th Smirt.* San Francisco, Cal., USA.

Peres, C.R. 1994. Programa experimental para qualificação do elemento combustível de um reator PWR. Ensaios estáticos com grades espaçadoras. *Proc. 5th Congresso geral de energia nuclear.* Rio de Janeiro, RJ, Brazil.

Pimenta, P.M. & J.A. Perrotta 1984. Análise matricial de estruturas compostas de tubos interligados por espaçadores. *Proc. 5th Congresso latino-americano de métodos computacionais para engenharia.* Salvador, BA, Brazil.

Preumont, A. 1981. A two-time step algorithm for seismic analysis of a PWR core. *Nuclear Engineering and Design* 65:49-62.

Preumont, A.; P. Thomson & J. Parent 1982. Seismic analysis of PWR-RCC fuel assemblies. *Nuclear Engineering and Design* 71:103-119.

Stokes, F.E. & R. A. King 1978. PWR fuel assembly dynamic characteristics. *Proc. International conference in BNES vibration in nuclear plant.* Keswick, U.K.

Trindade, C.E. 1992. *Determinação das propriedades modais de elementos combustíveis utilizados em reatores do tipo PWR.* MSc. dissertation. São Paulo, SP, Brazil: Instituto de Pesquisas Energética e Nucleares/CNEN.