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Computing PWR fuel assemblies behaviour under seismic solicitations

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ABSTRACT: This paper describes a complete numerical study of the dynamical behaviour of PWR fuel assemblies. A complete finite element model is described for modal analysis and a simplified two beams model is compared. Added and coupling mass effects on the assembly due to coolant fluid are computed. A final 15 assembly line is subjected to a seismic sollicitation and impact forces computed.

1. INTRODUCTION

The nuclear PWR core must remain within safe operating conditions after the occurrence of an earthquake. The electric nuclear producer has to make sure with the most accurate numerical tools that the fuel assemblies composing the core will not collapse due to the impacts caused by the solicitation. EDF Research and Development Division has undertaken a 3 year development project (MASSIC 94-96) in order to build such numerical tools. Many disciplines are involved in the project, including fluid-structure coupling, sub-structuring to reduce the size of the structural models studied, and non-linear dynamics to account for the impacts between the structures.

This paper presents part of the results already obtained in this project, dealing with the computation of French 900 MW fuel assemblies under seismic solicitations.

2. PWR FUEL ASSEMBLY DESCRIPTION

The 900 MW fuel assembly studied is composed of a set of 25 guide thimbles clamped at each extremity, a set of 8 grids, welded to the guide thimbles, these two sets build the assembly skeleton and a set of 264 fuel rods, containing UO_2 pellets, secured in the grids by spring.

The approximate length of a fuel rod is 3,85 m, the total weight of this structure is 670 kg. The rods and tube thimbles are arranged in a 17x17 array, which pitch is 12,6 mm. The nominal gap between each assembly in the core is about 3,67 mm.

3. FUEL ASSEMBLY COMPLETE FINITE ELEMENT MODEL

The complete model, which is thought to be a reference model, aims at representing almost precisely every part of the structure. Each tube thimble and fuel rod has been discretized into beam elements. For the fuel rod, the flexural stiffness accounts only for the cladding stiffness, the UO_2 pellets are supposed to participate only to a linear mass addition to the rod.

The grids have been modelled by homogenised rectangular beams and the rod to grid junction by translational (K_n, K_t) and rotational (C) stiffnesses. The normal stiffness

K_n accounts for the spring and dimples horizontal effect. A tangential spring (K_t) accounts for a vertical stiffness of the junction. It should actually be non-linear if possible sliding between the fuel rods and the grids could occur. In this paper K_t was chosen equal to the limit sliding state $\mu.K_n$ which means that relatively large displacements for the assembly were considered for the modal analysis.

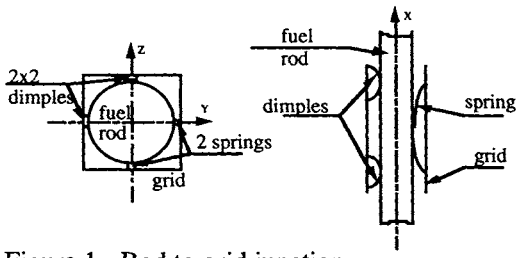

Figure 1 - Rod to grid junction

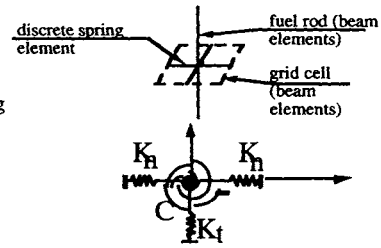

Figure 2 - Rod to grid model

The complete model is assumed to be linear and it contains about 15.000 nodes.

4. IN AIR MODAL COMPUTATION

A modal computation has been carried out with Aster finite element code [1]. The first eigenfrequencies and the effective masses are reported in the table 1.

The six first modes are global modes with deformed beam shape (fig. 6 in the appendix). Their eigenfrequencies range from 2,9 Hz to 25 Hz. These modes carry almost 90 % of the complete assembly mass. Beyond the sixth frequency, the modal density tends to be very large, due to multiple local modes (see fig. 7 in the appendix). A Sturm procedure estimated that more than a thousand modes were present between 30 and 45 Hz. This fact makes it almost impossible to use a modal superposition method covering the seismic bandwidth [0-50Hz]. However, these modes have a small effect on the total assembly response due to their small modal participation. A good correlation with experimental measurement is obtained on the first and third modes (<2% difference). A parametric study has showed that the model frequencies are mostly sensitive to rotational stiffness C.

Mode Number	Freq. (Hz)	Mass (kg)	Cumul. Mass (%)
1	2,92	515,78	77,96
2	6,19	0,29	78,00
3	9,98	55,54	86,40
4	14,44	0,19	86,42
5	19,62	18,84	89,27
6	25,41	0,02	89,27
7	28,73	/	89,27
8	30,07	/	89,27
9	30,17	/	89,27
10	31,40	/	89,27

Table 1 - Eigenfrequencies and effective masses in air

5. FUEL ASSEMBLY ADDED MASS

The fuel assemblies are immersed in coolant fluid which modifies their dynamical properties. One of the effects of the fluid is to bring an added mass which must be accounted for in the numerical model. A special development was carried out in the Aster code to compute 2D added mass effects in general geometries. Recent

publications [2] propose a "row" determination of the added mass. This section compares the calculation of a row of tubes and of a complete array in ambient water. The numerical study was conducted with the nominal pitch listed above and a half gap between row and the border (see figure 3).

Figure 3 - Row calculation

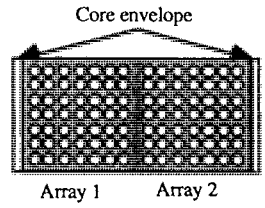

Figure 4 - Array calculation

The added mass of one single fuel rod was calculated for 3 to 7 tube rows for water at an arbitrary temperature of 20°C and are listed on table 2.

A logarithmic extrapolation to the 17x17 array of the assembly leads to a "row" [2] linear added mass of 189,7 g/m.

Number of tubes	Added mass per tube (kg/m)	Number unknowns	CPU Time (s) CRAY C98
3	0,19321	5800	3
5	0,19204	9500	4
7	0,19153	13000	5

Table 2 - Added mass by "row" calculation

Calculations were then carried out for an array from 3x3 to 9x9 with the same gaps. The added mass seems to be somewhat over-estimated in the row calculation.

The final 17x17 "array" linear added mass extrapolated for a fuel rod is 187 g/m.

Number of tubes	Added mass per tube (kg/m)	Number unknowns	CPU Time (s) CRAY C98
3x3	0,160	12000	6
5x5	0,170	32000	17
7x7	0,174	40000	20
9x9	0,177	47000	22

Table 3 - Added mass by "array" calculation

A procedure was carried out to evaluate fluid coupling between assemblies as well as with the core envelope (see figure 4 in the appendix). The added and coupling masses calculated for 2 arrays from 3x3 to 7x7 gave the results listed in Table 4. No coupling mass effect will be considered between assemblies but a strong coupling effect between each assembly and the envelope must be taken into account in the numerical model. It was extrapolated to a linear coupling mass of -250 g/m per fuel rod for a 17x17 array.

Number of tubes in array	Added mass array 1 per tube (kg/m)	Coupling mass array 1 / array 2 per tube (kg/m)	Coupling mass array 1 / envelope per tube (kg/m)	Added mass array 2 / tube (kg/m)	Coupling mass array 2 / envelope per tube (kg/m)	Added mass envelope (kg/m)
3x3	0,160	-8,74e-4	- 0,229	0,160	- 0,229	7,570
5x5	0,169	-5,51e-4	- 0,239	0,169	- 0,239	20,84
7x7	0,174	-3,85e-4	- 0,244	0,174	- 0,244	40,76

Table 4 - Added and coupling masses between array and core envelope

6. IN WATER MODAL COMPUTATION

A modal computation has been carried out with Aster finite element code for the complete model with the added mass effect in cold water (at an arbitrary temperature of 20° C). The added mass for the tube thimbles must also be computed with the same procedure as described above. It was found of approximately 665 g/m. The linear added mass on an assembly is estimated at 66 kg/m, which makes a global mass increase of 38 % due to fluid added mass. The first six eigenfrequencies and the effective masses are listed in the table 5. A global decrease of 16% of the frequencies compared to table 1 is observed.

Mode Number	Freq. (Hz)	Mass (kg)	Mass (%)
1	2,48	714,90	76,7
2	5,26	0,41	76,7
3	8,50	76,72	84,93
4	12,32	0,27	85,0
5	16,76	25,65	87,7
6	21,71	0,03	87,7

Table 5 - Eigenfrequencies and masses in cold water

7. A SIMPLIFIED FUEL ASSEMBLY BEAM MODEL

The complete finite element model is not very well suited to transient calculations because of its size. Many simplified models can be found in literature [3], [4] and were compared as regards predicted frequencies and participation factors to the complete and so precise model. The simplified model retained in the project is due to [3]; it is a two beam model, the first one represents the tube thimbles, the other one accounts for the fuel rods. Translational (K) and rotational springs (C) represent the tube thimbles to fuel rods junctions. Special rotational springs joining the grid levels, on both beams (C_{TT} and C_{FR}) are added. The table below shows that a fairly good correlation between the complete model and the simplified model is achieved for the eigenfrequencies as well as for the effective masses which are an important factor for the seismic calculation.

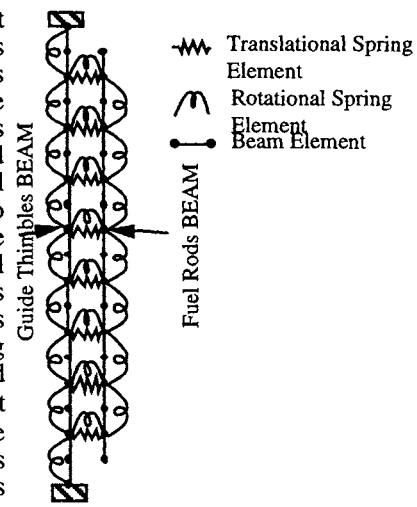

Figure 5 - Simplified beam model

Mode Number	F. (Hz) Compl. Model	F. (Hz) Simpl. Model	Error (%)
1	2,92	2,97	-1,71
2	6,19	6,35	-2,58
3	9,98	10,59	-6,11
4	14,44	15,38	-6,51
5	19,62	20,72	-5,61
6	25,41	26,29	-3,46

Table 6 - Eigenfrequencies Comparison

Mode Number	Eff. Mass Compl. Model	Eff. Mass Simpl. Model	Error (%)
1	515,78	507,01	1,70
2	0,29	0,20	n. s.
3	55,54	64,53	-16,19
4	0,19	0,32	n. s.
5	18,84	17,54	6,90
6	0,02	0,06	n. s.

Table 7 - Effective masses Comparison

8. A 15 FUEL ASSEMBLY ROW SIMULATION

Using the above primary conclusions, a finite element model for a 15 assembly row was built. The simplified model was used for each assembly and added and coupling masses were introduced in the model. A modal basis containing 10 modes per fuel assembly was used to calculate the system response. Seismic solicitation ranging from 0.1 g to 0.4 g were tested. Figure 8 in the appendix shows an example of a synthetic accelerogram used for the simulation. An arbitrary modal damping of 23% on first mode and 10% for the others was used in the calculation.

Non-linear impact conditions were considered at the grid levels between assemblies and between peripheral assembly and the core envelope. The modal superposition problem has 150 unknowns and 75 localised non-linearities. The aim of this study is to establish the impact force experienced at the grid levels in order to evaluate the crushing risk for a seismic level. Transient force and displacement curves computed with this model are given in figure 9 in the appendix. They show the grids impact force level and shape as well as the displacement amplitude. The maximum impact force is experienced at the 4th grid level for the peripheral assemblies.

The table below shows the variation of impact maximal force and mean impact force for the different seismic levels computed.

Seismic Level (g)	Maximum Impact Force (kN)	Mean Impact Time (ms)	Number Impacts/s
0,1	5,36	4,86	1
0,2	10,65	5,96	5
0,3	16,79	7,79	8
0,4	22,67	8,85	9

Table 8 - Impacts for various seismic levels

The maximum impact force on the grid is then compared to limit crushing load to establish the behaviour of the fuel assemblies under an given seismic level.

9. CONCLUSIONS

A complete study for fuel assembly computations was presented in this paper. Many tools developed in the MASSIC project are now available in the Aster Code. An added mass calculation strategy based on a tube array computation was chosen. A simplified model was retained which shows good agreement with a complete finite element model as regards modal characteristics. These stages permitted to simulate the consequences of an earthquake on a 15 assembly row and to evaluate the maximal impact forces on the grids.

Further developments have still to be done, to complete this study. A specific fluid damping effect under axial flow is to be incorporated as well as squeeze film effect for the grid impacts. Experimental comparisons on a real fuel assembly under specific transient loads will also provide a lot of complementary information to this task.

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[2] TROLLAT C., BEZIAT L., "Computation of the hydrodynamic forces on the fuel assemblies in a PWR core" *ASME Pressure Vessel and Piping proceedings* (1994)

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[4] J. C. LEROUX et Al "Structural analysis of PWR fuel assemblies in loca and seismic conditions" *7th SMIRT, Chicago (1983) - Vol C 6/2*

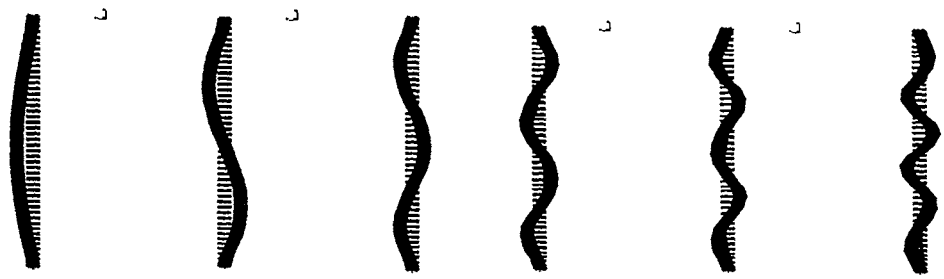

Figure 6 - 6 first global modes (n°1 to 6)

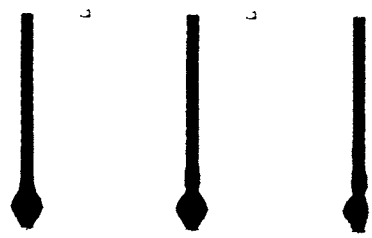

Figure 7- Local modes (n°7 to 9)

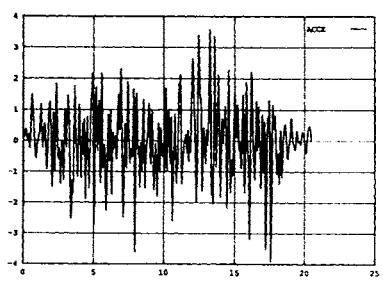

Figure 8 - Synthetic accelerogram for 0.4 g

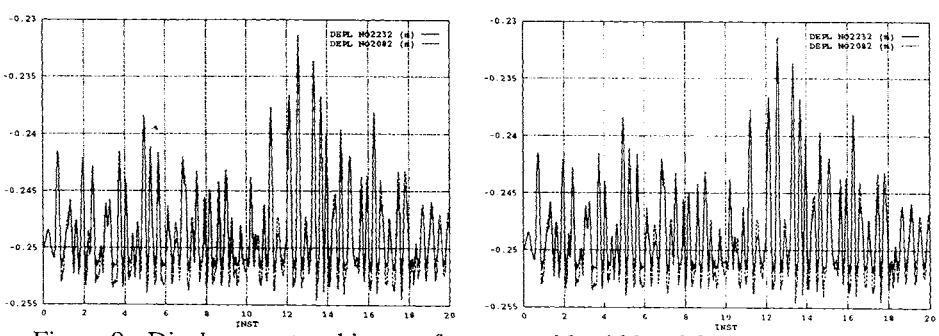

Figure 9 - Displacement and impact forces at mid-grid level for 0.4 g acceleration