C06/3

Seismic Behaviour of PWR Fuel Assemblies Model and Its Validation

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1 INTRODUCTION

The validity of the models simulating the seismic behaviour of PWR cores can only be exactly demonstrated by seismic testing on groups of fuel assemblies. Shake table seismic tests of rows of assembly mock-ups, conducted by the CEA in conjunction with FRAMATOME, are presented in reference /1/. This paper addresses the initial comparisons between model and test results for a row of five assemblies in air.

Two models are used: a model with a single beam per assembly, used regularly in accident analyses, and described in reference /2/, and a more refined 2-beam per assembly model, geared mainly towards interpretation of test results.

The 2-beam model is discussed first, together with parametric studies used to characterize it, and the study of the assembly row for a period limited to 2 seconds and for different excitation levels. For the 1-beam model assembly used in applications, the row is studied over the total test time, i.e twenty seconds, which covers the average duration of the core seismic behaviour studies, and for a peak exciting acceleration value at 0.4 g, which corresponds to the SSE level of the reference spectrum.

2 DESIGN AND ADJUSTMENT OF 2-BEAM MODEL

2.1 Outline of assembly model

The assembly is finite element-modelled by means of two equivalent beams, masses and springs (see SMIRT 9 paper reference /3/), as presented in Fig. 1.Beam # 1 represents the guide thimbles and beam # 2 the rods . Their cross-sections and inertias are respectively equal to the sum of the guide thimble and rod cross-sections and inertias. The grids are modelled by lumped masses on the guide thimble beam and by translation springs between the two beams. Rotation springs on each beam interconnect the grids . They model the connections (fully clamped or clamped + slippage) of the grids and rods (KCR) and those of the grid and guide thimbles (KTU).

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Though the finite element model is a linear one, non-linearity is taken into account by varying the rotation springs between grids of the rod beam . The KCR values, calculated without slippage, are decreased by a coefficient Q determined from measurements of the assembly natural frequencies for different amplitudes.

2.2 Assembly natural frequencies

Table 1 gives the values of the first four frequencies of the 6x6 assembly in air, calculated and measured at a very low excitation level on three different mock-ups. Note the close agreement of the results. The scatter of the test results originates mainly from differences between the rod restraint values inside the grid cells.

TABLE 1

	Frequencies in Hz			
Modes	Calculation (Q = I)	Tests (3 mock-ups)		
		N°1	N°2	N°3
1	4.60	4.43	4.56	4.24
2	10.93	10.50	10.50	10.10
3	19.29	18.00	17.70	17.80
4	27.36	26.30	27.20	26.60

2.3 Snap-back on a single grid - Parametric study

For impact calculations , springs and shock absorbers are added at each grid elevation.

The calculations use the non-linear modal superposition method. The shock is simulated by introducing a force proportional to the deflection of an impact spring Kc as soon as the gap between grid and impact plate becomes zero.

Parametric studies were conducted on :

- the number of modes to be allowed for (study for 3-9 modes); the results (Fig. 2) show that although calculation test differences are small for displacements, this does not hold true for the impact forces. It can be seen that with three modes the level is much too low and the frequency content is insufficient. It seems that at least four modes are needed to find the correct main peak shape and the maximum level of the impact force peaks;
- the influence of the shock absorber (Cc). For the very low shock absorber Cc values (0 N/ms^{-1}), only the impact stiffness Kc, contributes to the impact force (the peak is very wide). For high Cc values (5000 N/ms^{-1}), the force due to the shock absorber is predominant. In this case, the main peak is much narrower. The optimized shock absorber value is 1650 N/ms^{-1};
- the influence of modal dampings. Their effect is to reduce impact velocity and therefore the maximum force level, and also to decrease fluctuations during the time the grid is in contact

with the impact plate. It seems appropriate to take for the first mode $\beta = 13$ % and for the other modes $\beta = 8$ % for amplitudes on the order of 9-12 mm. The β value for the first mode matches the damping measured during sine sweep tests in this amplitude range ;

- the influence of inter-assembly gaps. An increase in gaps has the effect of reducing impact force.

2.4 Calculation/test comparison - Snap-back on a single grid

After completion of the parametric study , fitting to the tests leads to the following values being adopted for all calculations:

- modal damping : those measured during sine sweep tests for the natural frequency search ;
- impact springs : 1.6×10^7 N/m ;
- shock absorbers : 1650 N/ms^{-1} ;
- nine modes.

Table 2 gives the numerical values measured and calculated for a 12 mm static deflection snap-back with impact on a single grid.

Table 2

	Test	calculation
Impact duration (ms)	36.67	43.00
Start of impact (ms)	81.67	81.70
Time of peak (ms)	84.67	84.80
Maximum impact force (N)	583	581
$\int$ fdt (Ns)	7.369	7.456
Tensile force (N)	191	200
Initial amplitude (mm)	12.83	12.86

2.5 Snap back on six grids

In this case, the assembly impacts against the test wall at all its grids ; there is a need to input into the calculation actual gaps between each grid (and not the theoretical gaps) to have the correct force values. Even a very small gap change causes wide variations in impact forces.

Table 3 gives the values of the computed parameters and the values measured during testing for the 9 mm static deflection snap back test with impact on all the grids. The force integral is calculated for all the grids.

Table 3

	Test	calculation
Tensile force (N)	133	146
Drop amplitude (mm)	9.01	8.87
Max force (N) on grid 4	439	439
$\int$fdt (Ns) on all the grids	6.23	6.38

Fig. 3 shows impact force trends calculated and measured at the grid 4 location.

3 CALCULATION OF A ROW OF 5 ASSEMBLIES WITH THE 2 BEAM MODEL

To calculate a row of five assemblies in air, the initial model was extrapolated.

The impact stiffness, modal damping and shock absorbers correspond to the calculation values determined during the study of the single assembly. The responses to earthquakes with maximum accelerations of 0.2 g, 0.4 g and 0.6 g were calculated.

For this configuration, the total cumulative gap between assemblies is about 8 mm. Coefficient Q applied to spring KCR is the one determined for 8 mm amplitude.

The calculation are run for the first two seconds of excitation , allowing for 5 modes. At this point it is clear that it is vital to input the actual gaps between the assemblies. Since these gaps could not be measured exactly before the tests (high mock-up flexibility), they are determined from the analysis of measured displacements. By taking these randomly distributed actual gaps , and not theoretical gaps uniformly distributed between the assemblies, agreement is achieved with the displacements and peak forces measured during testing, as shown in figure 4 and table 4, which give some measured and calculated value at 0.2 g, 0.4 g and 0.6 g. These parameters relate to all the end grids. For these calculations, β = 8 % and all gaps are identical to the real gaps measured during the 0.4 g reference test.

Table 4

Level	0.2 g		0.4 g		0.6 g	
	test	calculation	test	calculation	test	calculation
Total $\int$ fdt (Ns)	71.4	85.7	186.1	206.8	358.9	390.3
Maximum impact force (N)	2276	2679	3475	3552	3836	3741
Total number of impacts	31	39	80	72	75	90
Total contact duration (0.01 s)	94.6	96	177.6	183.6	219	249.9

4 CALCULATION OF A ROW OF 5 ASSEMBLIES WITH 1-BEAM MODEL

The model is built under the same conditions as those described in reference/2/ for accident analyses, but the adjustment is limited to cold in-air conditions. As a reminder, this model uses the direct explicit integration method.

Since the calculation is performed under conditions simulating those of the seismic studies (time 20 s, SSE level 0.4 g), uniform gaps are used as a first approximation (see reference /1/) with nominal value 1 mm. The calculation is also made with the real gap values deduced from the test results, which provides confirmation, as for the 2-beam model, that the impact times match those of the tests. (figure 5).

The test calculation comparison is shown in table 5 for the same reference test as above.

In addition to the parameters in table 4, relative to all the grids of the assemblies at the row ends, this table gives the average peak force of impact, and the range of maximum forces obtained from several tests conducted under identical conditions.

Table 5

	Test	Calculation uniform gaps	Calculation real gaps
Total $\int$Fdt (N.s)	2102	2642	2531
Maximum impact force(N)	1142 (980-1270)	1255	1640
Average peak force (N)	254	230	297
Total number of impacts	912	1019	775
Total contact duration(s)	17,1	17,6	13,0

The results show that despite its greater simplicity, this model also yields realistic results.The less satisfactory results obtained with real gaps in the model arise from amplification of the asymmetry effects related to gap distribution (the forces are only really overestimated at one end of the row, and the impact duration underestimated at the opposite end), when this asymmetry disappears with the uniform gaps. A more precise interpretation of the model behaviour is underway.

CONCLUSION

The two models described herein seem capable of supplying a realistic estimate of the behaviour of a row of assemblies. The 2 beam model is probably and logically more precise: this means it is better suited to test interpretation and can serve as a reference for simpler models.

These encouraging results were obtained in air on a 5 assembly row, yet they already reflect the consistent behaviour of the model from the point of view of assembly structural characteristics. Allowance for a higher number of assemblies,and for the effects of the reactor coolant, more complex and often simplified in the current models, will be addressed in latter studies.

REFERENCES

/1/ SMIRT 11 TOKYO C06/2 .Experimental studies on seismic behaviour of PWR fuel assemblies.

/2/ SMIRT 11 TOKYO C06/1 .Status of methods for justifying fuel assembly lateral strength during an earthquake.
/3/ SMIRT 9 LAUSANNE.VOL K2 .Analyses of impact phenomena between PWR fuel assemblies in earthquakes situation.

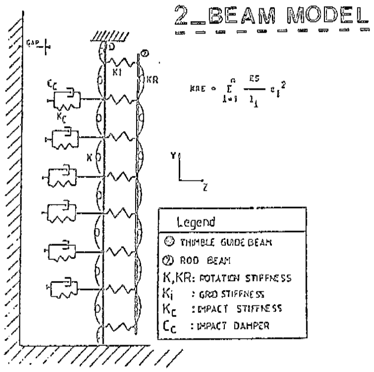


FIG 1

12 MM IMPACT TEST ON ONE GRID

IMPACT FORCE COMPUTATIONS WITH 3 AND 9 MODES

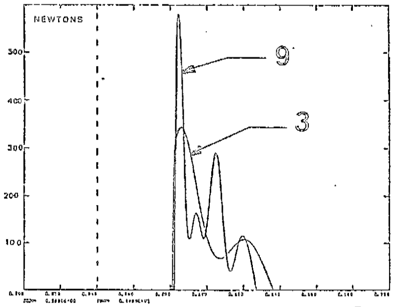
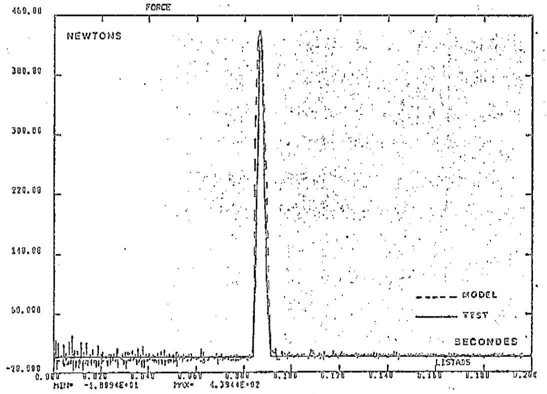


FIG 2



9 MM IMPACT TEST AGAINST ALL GRIDS

IMPACT FORCE GRID N°4 (MID-LEVEL)

FIG 3

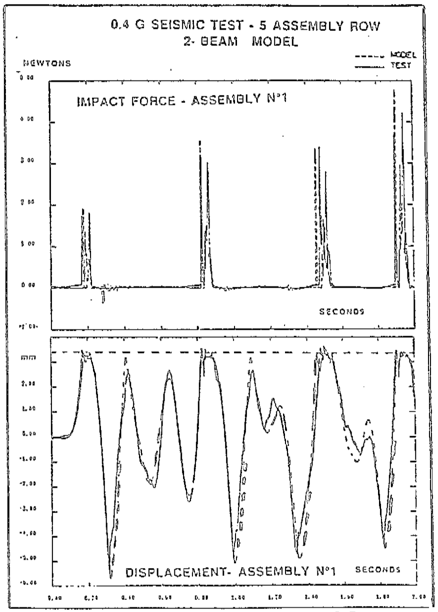


FIG 4

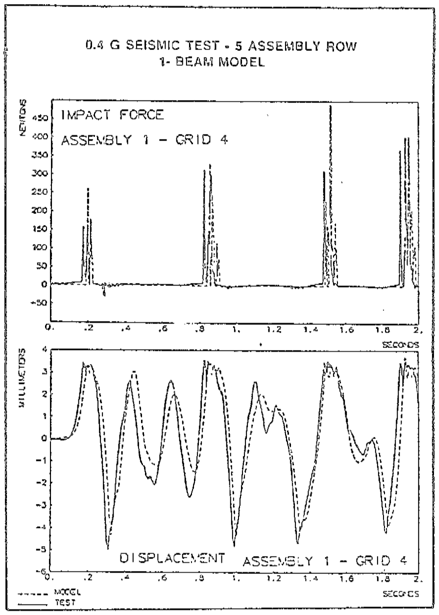


FIG 5