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QUALIFICATION OF INDUSTRIAL MODELS FOR THE JUSTIFICATION OF FUEL ASSEMBLY LATERAL STRENGTH DURING AN EARTHQUAKE

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1. INTRODUCTION

The nuclear PWR core must satisfy class 4 design requirements, which include earthquakes ; the main seismic effects are lateral core displacements leading to lateral distortion of Fuel Assemblies (F/A), and impact between the latter and with core baffles at grid locations. In order to demonstrate that distortions and impact forces respect the limit values (compatible with control rod drop and core cooling), F/A designers must develop appropriate models to represent F/A flexural response and impacts on grids.

These models should allow for various and complex phenomena, such as non linearities resulting from impacts and from fuel rod bundle behaviour, and PWR core conditions, mainly the hydraulic effects of reactor coolant. However, the model sophistication should remain acceptable for industrial use, since a large number of calculations have to be performed at a limited cost. Compromise between such opposing requirements is achieved in the current F/A row models described in reference /1/. The purpose of this paper is to present the complete qualification procedure of the methodology used for model building, according to the large-scale test and modelling program undertaken by FRAMATOME Fuel Division, in cooperation with the Commissariat à l'Energie Atomique (CEA).

2. QUALIFICATION METHODOLOGY

Let us briefly recall the model basic features. A F/A single row is considered (longest row in the core), each F/A being modelled by a single beam, with nodes located at grid levels only. A set of spring elements with gaps allows either for impact on one side of F/A (equivalent impact stiffness), or for impact on both sides (external stiffness, i.e. between grid opposite outer straps).

As stated in model description /1/, the preliminary step in model building is the introduction of F/A geometrical characteristics, material mechanical properties and mass distribution. Then the complete qualification of the model building methodology is summarized hereafter :

- F/A characterization tests for flexural response and impacts on grids, on scale 1 and reduced scale (6 x 6 fuel rod array) mock-ups (cold, in air and water).
- Specific parameter determinations, when not available from previous tests : grid external stiffness, and hydraulic coupling for confined conditions.
- Overall validation from shaker table tests on sets of 6 x 6 array mock-ups (cold, in air and water).
- Estimate of F/A damping under axial coolant flow, from cold in-loop tests on a reduced scale (8 x 8 array) mock-up.

Apart from relatively straightforward cold / hot changes in material and coolant properties, all the significant aspects of seismic response under PWR conditions are covered by this methodology.

3. FUEL ASSEMBLY CHARACTERIZATION TESTS

They consist mainly of snap-back tests, i.e. release after a lateral tension at middle grid level, without or with impact against a wall ; impact may occur either on a single middle grid or on several grids. Loading with an actuator has also been used. Tests have been performed on a wide range of F/A designs (17 x 17, 18 x 18), and on the 6 x 6 mock-ups whose model is needed in the overall validation (§ 5). Typical results are presented in ref. /2/ for scale 1 F/A's, and in ref. /3/ for 6 x 6 mock-ups.

As frequencies decrease and damping increases when motion amplitude increases (non linear effect of rod slippage), the linear beam model qualification, i.e. frequency and damping adjustments, has to be achieved for an average amplitude, significant for seismic response. In-water tests provide a first estimate of fluid coupling and damping, which may be revised in further qualification steps (§ 4.2 and § 6).

Since the results for impact on several grids are very dependent upon the precise impact sequence (and therefore upon the exact gap values at rest), the impact model qualification is performed for impact on a single grid. The equivalent impact stiffness is adjusted to obtain the test maximum impact force, which also leads to satisfactory values of impact duration and rebound amplitude. Finally, the tests with impact on several grids, more representative of the seismic response situation, provide a supplementary check for model consistency, which is found acceptable.

In the previous references, the F/A model is a 2-beam one with a larger number of nodes, designed for test interpretation. The industrial model displays very similar features in a free oscillation response (the first mode is predominant), and although its description of impact force vs. time is simpler, it is possible to obtain satisfactory values of impact parameters, displayed on the table below for the 6 x 6 mock-up model characterization (with release middle grid lateral displacement 9 mm and maximum impact force 302 N).

PARAMETERS	MODEL	TEST
Force Integral (N.s)	4.32	3.76
Rebound Amplitude (mm)	3.63	3.71
Time in milliseconds from release instant :		
Impact Beginning	74.5	74.7
Maximum Force Instant	81	78.7
Impact End	113	112
Rebound Amplitude Instant	213	220

4. SPECIFIC PARAMETER DETERMINATIONS

4.1. External grid stiffness

This stiffness cannot be determined from previous tests, in which the equivalent impact stiffness allows for the local flexibility of a rod bundle modelled by a single beam. Therefore it is obtained from dynamic crush tests before the crush limit is reached, i.e. from impacts of a mass at increasing velocities, together with the damping associated to grid deformation /4/. The resulting stiffness value is a "tangent" upper bound, thus conservative in the seismic model, and consistent with static determinations.

4.2. Fluid coupling between fuel assemblies and core baffles

Allowance for the in-water frequency reduction can be made by introducing an added mass to the beam model, which is derived from the characterization tests /1/. However, physical consistency calls for actual coupling terms between core structures, the F/A added mass itself being dependent upon in-core confinement effects.

A coupling model has been developed, which is found to be limited to the F/A added mass and coupling term with core baffles only, which are independent of F/A position /5/. Although theoretical, such a model is certainly more realistic than the previous one ; moreover, the added mass value in confined conditions is confirmed by frequency measurements in the overall validation tests, which also provide a check for coupling model consistency (§ 5.2).

5. OVERALL VALIDATION FROM SHAKER TABLE TESTS ON SETS OF INTERACTING FUEL ASSEMBLY MOCK-UPS

5.1. Test conditions and representativity

Test conditions are described in ref. /6/, together with experimental results. The mock-up design is based on a significant reduction in fuel rod array size (6 x 6) and therefore in mass (scale about 1/10), but grid number (6) and total height (3 m) are moderately reduced, and fuel rod diameter, pitch, and restraining by grids are typical of 17 x 17 F/A's. This leads to a good representativity, which is displayed by a similar behaviour to that of scale 1 F/A's in characterization tests (including grid crush tests).

Test program is also designed for optimal representativity or extrapolation capabilities. The configurations of the 13 available mock-ups are as follows :

- 5-mock-up row, for complete parametric tests : gaps, confinement, accelerograms,
- 13-mock-up row (close to maximum row F/A number), laterally confined,
- 13 mock-ups in lozenge pattern, i.e. a "core-mock-up" with 5 mock-ups in the longest rows, with confinement similar to that of core baffles.

All tests are performed cold, in air and water, with seismic load direction along the row, or bi-axial for the core-mock-up pattern. Accelerograms correspond to a spectrum used in the French nuclear program, with maximum acceleration from 0.1 g to 0.6 g (SSE level 0.4 g), with a 20 s duration.

5.2. Test-model comparison

Concerning the in-air response of the 5-mock-up row, a detailed comparison is given in ref. /3/, but for the 0.4 g loading level only ; fig. 1 and 2 display the maximum impact forces, and the force integrals on all grids at row ends, for the different loading levels. All these results show that the model is realistic, with a tendency towards conservatism, more especially when loading level increases. This is confirmed by the 13-mock-up row results (fig. 4 and 5, in-air results), although there is no longer a limitation of experimental maximum force at high loading levels (which enhances model conservatism for 5 mock-ups).

The mock-up single row configuration representativity can be verified by comparing the test or model results relative to the 5-mock-up confined single row with the test results for the longest 5-mock-up rows in the biaxial OX-OY response of the "core-mock-up" configuration. Fig. 3 displays the maximum impact forces obtained in water, with either complete coupling /5/ or single added mass in the model. It is shown first that the different row end impact forces levels are very similar, and secondly that the model results remain conservative, although more realistic with actual F/A - baffle coupling than with the single added mass. The latter trend is confirmed by the 13-mock-up row results (fig. 4 and 5, in-water results).

Another trend which is displayed is the in-water experimental response decrease with the respect to in-air response, which is reflected by the model with the effective fluid coupling, but not with the single added mass ; then, this coupling model is found consistent both with experimental results, and with the predicted reduction in F/A equivalent loading forces /5/.

6. ESTIMATE OF FUEL ASSEMBLY DAMPING AXIAL FLOW

All the previous in-water tests are performed in still water. Influence of axial coolant flow on F/A damping is studied on a 8 x 8 mock-up placed in a flow channel. The first results from snap-back tests presented in ref. /7/ are confirmed with loading by an actuator, and by further parametric studies. Damping is systematically and largely increased when flow velocity increases, up to twice the still water value when velocity reaches that of core coolant flow. Such results justify the use of larger damping values than those derived from the scale 1 F/A characterization tests. However, as the results correspond to a mock-up, in cold flow , and even though large damping values under axial flow have also been obtained by HOTTA et al. /8/, a significant conservatism margin is applied in seismic F/A models.

7. CONCLUSIONS

A complete qualification procedure during model building leads to a model behaviour which appears to be reasonably conservative in the overall validation under seismic loads. A supplementary conservatism margin is brought by damping under axial coolant flow, depending upon the accepted damping value in model applications. Then the industrial model building methodology is thoroughly qualified, and the models may be considered as both efficient and reliable.

Use of interacting scale 1 F/A's in the seismic tests may be envisaged, yet this would not necessarily bring a significant improvement, since the reduced scale mock-ups are proved representative, and because representativity is also related to the F/A number in seismic tests, which cannot be made comparable to that of core. Progress is more likely to be achieved in model refinement and accuracy, made compatible with industrial use from numerical method improvements, and in further analysis of coolant effects, since they reduce the response. Then reliable conservatism margin reductions could be performed, for the design of more efficient products under severe seismic loads.

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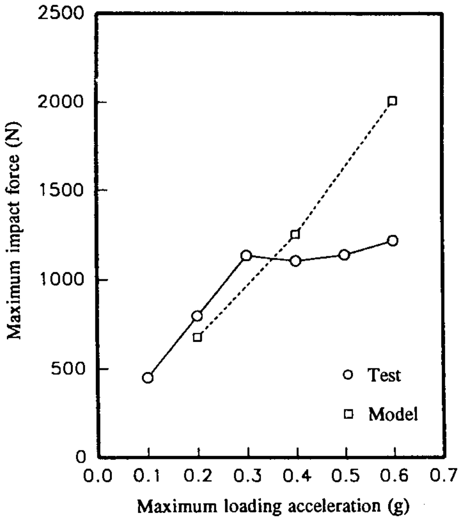

FIG.1 : MAXIMUM IMPACT FORCES, IN-AIR 5-MOCK-UP ROW

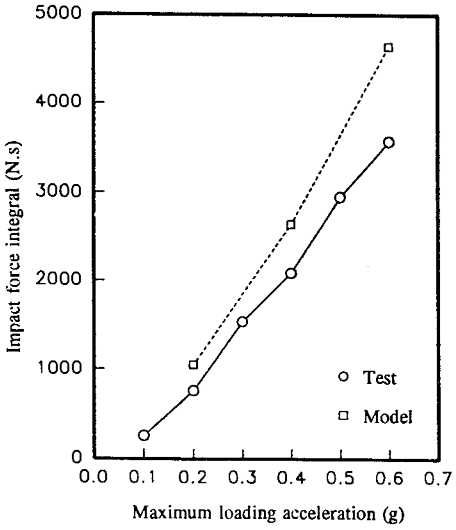

FIG. 2 : IMPACT FORCE INTEGRALS, IN-AIR 5-MOCK-UP ROW

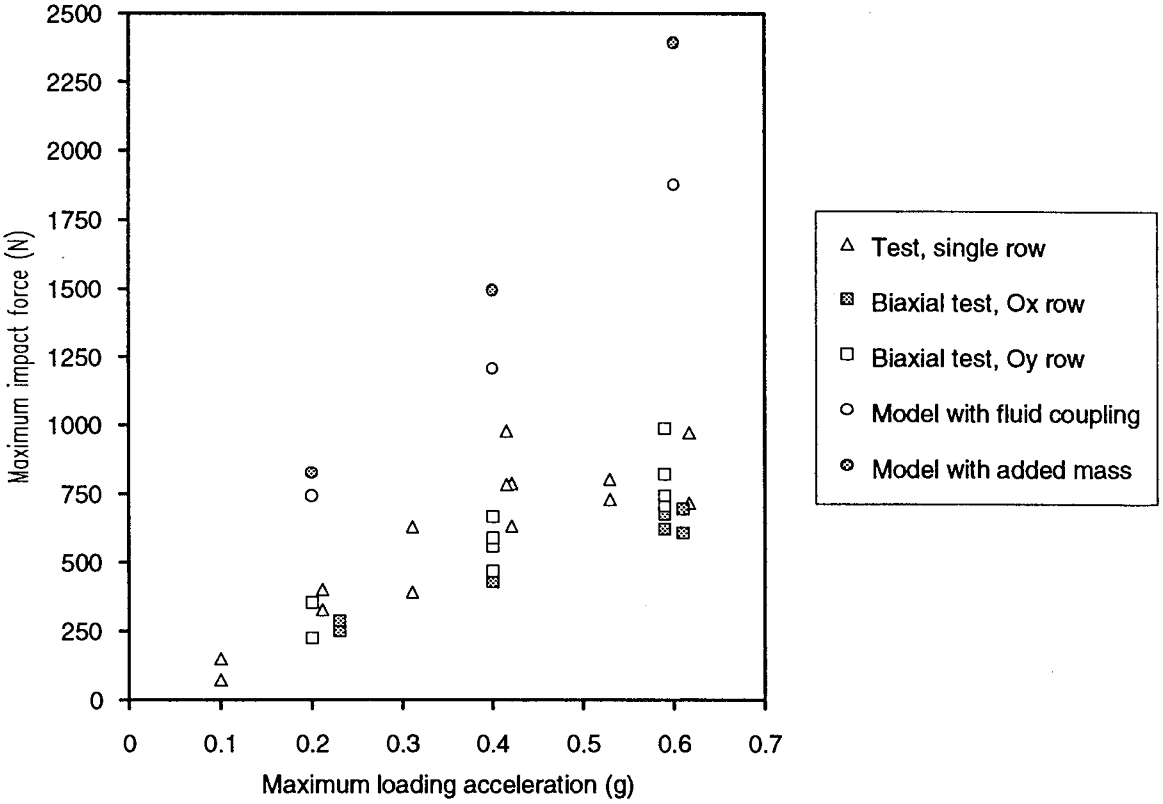

FIGURE 3 : MAXIMUM IMPACT FORCES FOR IN-WATER 5-MOCK-UP ROWS

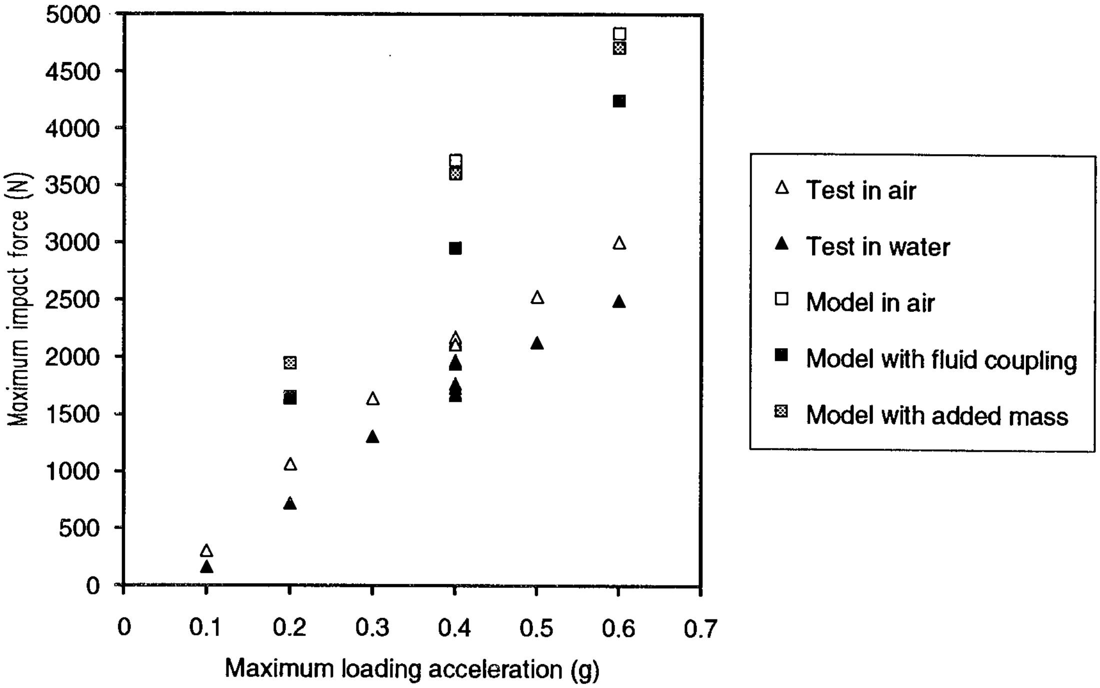

FIGURE 4 : MAXIMUM IMPACT FORCES FOR A 13-MOCK-UP ROW

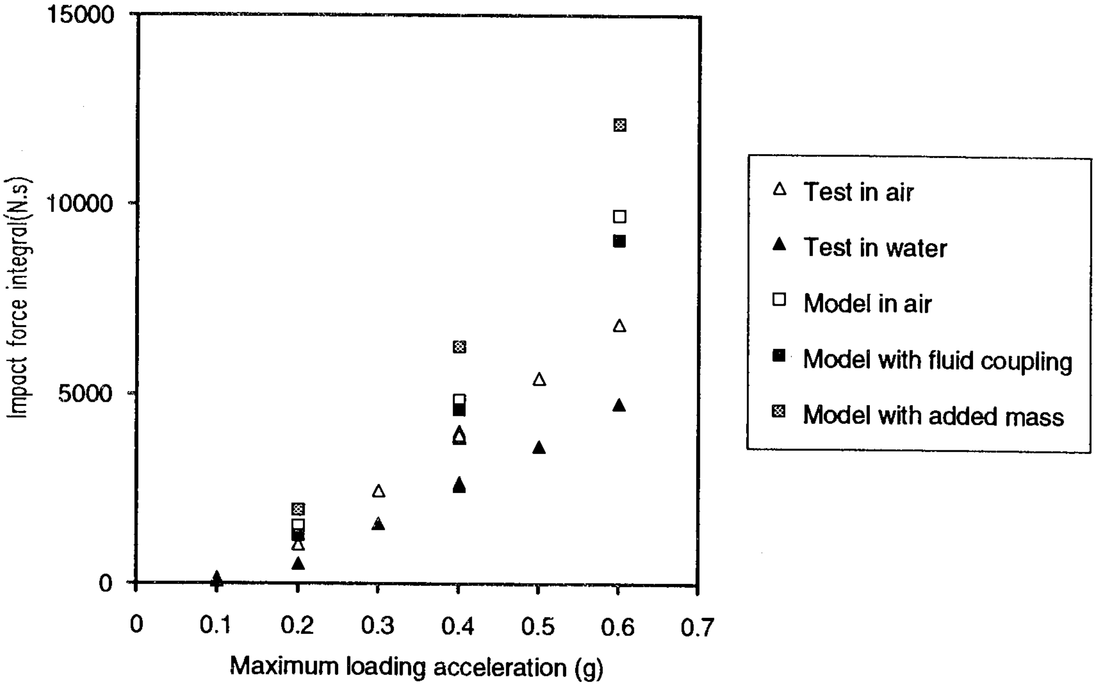

FIGURE 5 : IMPACT FORCE INTEGRALS FOR A 13-MOCK-UP ROW