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Validation of PWR Core Seismic Models with Shaking Table Tests on Interacting Scale 1 Fuel Assemblies

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ABSTRACT

The fuel assembly mechanical strength must be justified with respect to the lateral loads under accident conditions, in particular seismic loads. This justification is performed by means of time-history analyses with dynamic models of an assembly row in the core, allowing for assembly deformations, impacts at grid locations and reactor coolant effects.

Due to necessary simplifications, the models include "equivalent" parameters adjusted with respect to dynamic characterisation tests of the fuel assemblies. Complementing such tests on isolated assemblies by an overall model validation with shaking table tests on interacting assemblies is obviously desirable.

Seismic tests have been performed by French CEA (Commissariat à l'Energie Atomique) on a row of six full scale fuel assemblies, including two types of 17 x 17 12ft design. The row models are built according to the usual procedure, with preliminary characterisation tests performed on a single assembly. The test-calculation comparisons are made for two test configurations : in air and in water. The relatively large number of accelerograms (15, used for each configuration) is also favourable to significant comparisons.

The results are presented for the impact forces at row ends, displacements at mid assembly, and also "statistical" parameters. Despite a non-negligible scattering in the results obtained with different accelerograms, the calculations prove realistic, and the modelling process is validated with a good confidence level.

This satisfactory validation allows to evaluate precisely the margins in the seismic design methodology of the fuel assemblies, and thus to confirm the safety of the plants in case of seismic event.

1 INTRODUCTION

The analysis of the seismic behaviour of a PWR core is mainly performed to check the integrity of the mixing grids. For this purpose, finite element models are built. Non-linear computations are performed because of the gaps between the different sub-structures which cause impacts between each other. In addition, Interaction between the Fluid (primary coolant) and the Structures (FSI) must be taken into account.

Since the early 90's, FRAMATOME-ANP and EDF have carried out a large research and development program, mainly in association with CEA in order to increase the efficiency of the methods and models used to predict the seismic behaviour of the PWR cores and to quantify the margin in the design methodology.

The main topics studied were (i) fuel assembly modelling, (ii) FSI (especially damping under axial flow), (iii) impact characteristics with and without water and (iv) method of computations. These studies were performed based on both reduced scale and full scale tests.

The study presented in this paper has been carried out in the framework of this R&D program. The objective is to show the effectiveness of computer codes and models to predict the seismic behaviour of a row of assemblies accounting for the phenomena described previously. This is done by comparing numerical results to seismic test results performed on a row of 6 full-scale fuel assemblies.

2 SEISMIC TESTS DESCRIPTION

2.1 Description of the tests

Seismic test on a row of 6 full-scale 12ft fuel assemblies was performed on the CEA shaking table AZALEE [1] in the year 2000. The test program included :

- Characterisation tests as usually performed on FA designs (sine sweep tests, free vibration tests, lateral impact tests, in-air and in-water tests …),
- Seismic tests on CEA AZALEE shaking table on a row of 6 assemblies for different configurations (in-air and in-water, different seismic input levels …).

2.2 Description of the tested designs

The tested FA's correspond to 2 designs representative of 12ft 17x17 fuel assemblies with Zircaloy grids. These designs will be called hereafter design A and design B.

A complete characterisation test has been performed on one assembly of each design (see § 4).

2.3 Seismic excitation

Seismic excitation was consistent with French 900 MW PWR. The corresponding floor response spectrum (SSE) is presented in Figure 1.

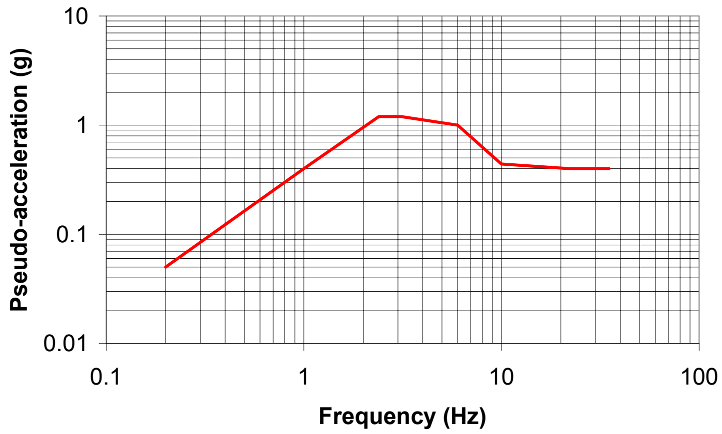


Figure 1: Input floor response spectrum

For the tests, the excitation level (ZPA) has been progressively increased from 0.1 to 0.4 g. For each configuration, 15 synthetic accelerograms were applied in order to get enough statistics to make significant comparisons.

N.B.: The 15 artificial accelerograms come from 3 sets of 5 accelerograms generated by 3 different codes (called X, Y, Z), which allows to identify some different trends between codes if any.

2.4 Test configurations studied

For this study, two test configurations were selected, one configuration in air and one in water. The main characteristics of the selected configurations are presented in Figure 2.

	Row configuration	Gap	Seismic level	Confinement
In-Air	A-B-A-A-B-A	2 mm	0.2 g	wo interest
In-Water	A-B-A-A-B-A	2 mm	0.3 g	Full confinement

Figure 2: Input floor response spectrum

N.B.: Full confinement means that lateral gap between the row and the shroud is low (2 mm) and perfectly tightened which is consistent with in core situation.

3 FUEL ASSEMBLY MECHANICAL MODELLING DESCRIPTION

In this paragraph, the finite element models used respectively by EDF and FRAMATOME are described. These models are those usually used for design analyses.

3.1 EDF model

The finite element model used by EDF is made of 2 beams. The first one (Guide Tubes beam) accounts for the 24 guide tubes and the instrumentation tube. The second one (Fuel Rods beam) accounts for the 264 fuel rods. The characteristics of the model are determined as follows (see Figure 3 a).

- The geometrical and mass characteristics of the beams are directly calculated from the real characteristics of the guide tubes and fuel rods (including Uranium pellets),

- Nozzles are rigid bodies,

- In addition, a rocking stiffness is introduced between two adjacent grids in order to account for the Huyghens term of the inertial characteristics of the tubes which is not taken into account in the guide tubes and fuel rod elements,

- Finally, two springs are introduced in the model between the grid and the fuel rod beam. These springs which account for the internal stiffness of the grid are composed of 2 parameters :

  * A translation stiffness Kt determined based on the spring and dimple characteristics, which enables the lateral impact behaviour of the fuel assembly to be reproduced,

  * A rocking stiffness K_R which enables the lateral behaviour (i. e. natural frequencies) of the assembly to be reproduced: $K_R = q.\ C1 + (1 - q).\ C2$. The q coefficient is scaled to 1 for beginning of life situation and low amplitude of motion and 0 for end of life and high amplitude. C1 and C2 coefficients can be calculated based on the springs and dimples characteristics (see Figure 3 b).

- The external stiffness of the grid (through grid stiffness), determined based on grid crush tests, is added to this model (at each grid level) to account for grid-to-baffle and grid-to-grid impacts,

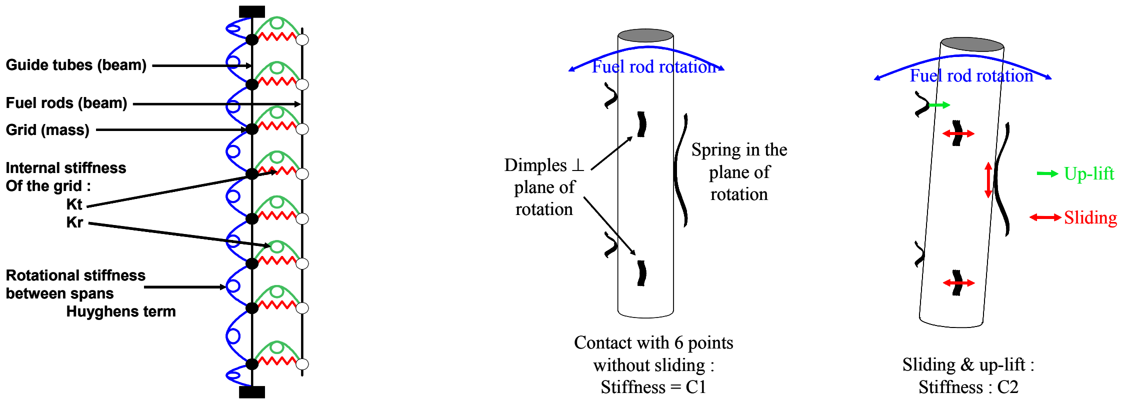


Figure 3: a) Description of EDF FA model **b) Rocking stiffness of the grid – C1 and C2 coefficients**

3.2 FRAMATOME-ANP model

The model used by FRAMATOME-ANP is made of a single beam with shear effect, representing the assembly lateral deformations (see Figure 4 a).

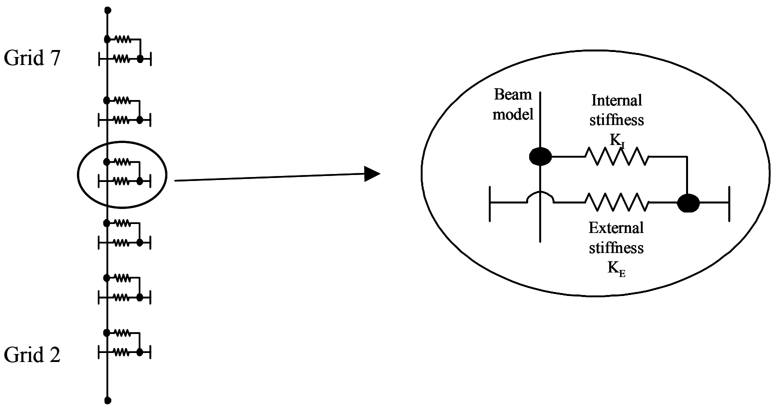


Figure 4 : a) FRAMATOME-ANP model b) Impact model at grid levels

The beam mainly represents the guide thimbles and the rod claddings. It features nodes at assembly bottom, top, and grid levels, excluding the end grids which are close to the nozzles and do not withstand impacts.

The model contains objective parameters (geometry, mass, material properties), and equivalent parameters adjusted to obtain the first modal frequencies and associated damping values supplied by lateral response dynamic tests (sine sweep test or free vibration test). The effective adjustment is performed with modes 1 and 3, which provides the sectional inertia and shear coefficient from the frequencies.

In order to represent impacts at the grid locations, the model covers two types of momentum transfer (see Figure 4 b):

1) from or to the assembly, therefore between the fuel rod bundle (containing most of the mass), and a grid face,
2) through the assembly, therefore through the grid between its opposite faces.

Transfer type 1 is allowed for with an internal stiffness K_I, which is an equivalent parameter reflecting the rod bundle local flexibility; it is determined by lateral response tests with impact against a wall.

Transfer type 2 is represented by the external stiffness K_E, which is a grid-specific parameter determined by dynamic compression tests, together with the grid buckling limit. The buckling limit is the grid strength criterion, with respect to through-grid loads which are found the most limiting.

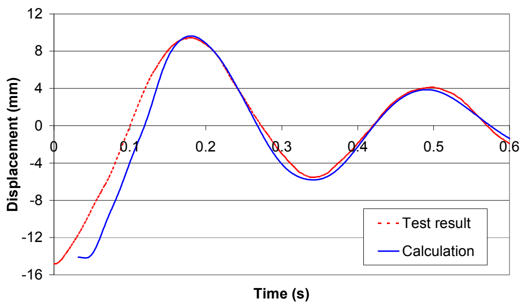
4 IN-AIR CHARACTERISATION TEST RESULTS

In this paragraph, the comparison between the characterisation test results and the computations is performed according to the usual procedure.

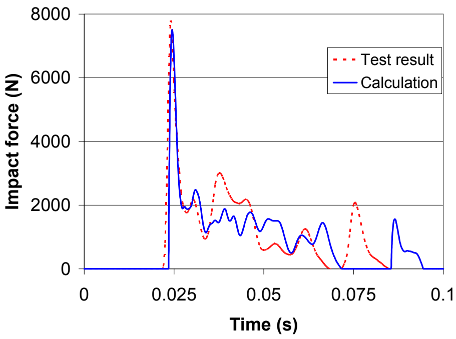
It is known that the fuel assembly has a non-linear lateral behaviour mainly because of the fuel rod to grid contact characteristics (the main consequence of this is an evolution of the first frequency with the lateral amplitude of motion). As the finite element models commonly used for seismic analyses are linear, the characterisation phase follows 2 objectives :

- in a first step, the lateral characteristics of the models are adjusted to reproduce the global average motion of the assembly for the required situation (low or high amplitude of motion for instance, see Figure 5 a),

- in a second step, the impact lateral characteristics of the models are adjusted to reproduce the maximum impact force on the grid (see Figure 5 b).



a) Free vibration test



b) Lateral impact test

Figure 5: Characterisation test results and calculations

5 FLUID-STRUCTURE INTERACTION

Fluid-Structure Interaction is a key factor governing the seismic response of the core. This phenomenon is usually taken into account by means of:

- added mass (and coupling mass between structures),

- added damping.

These two effects can be identified and taken into account separately. Nevertheless, they both strongly depend on the geometrical configuration (i.e. confinement) and the thermal-hydraulic conditions.

5.1 Added mass calculation

The method used to compute added mass coefficients is based on the potential flow theory. The interaction between the fluid and the structure is based on the continuity of the displacement in the fluid and in the structure. This leads to solve Laplace's equation.

This method introduces coupling elements between the considered beams and assigns a mass matrix to these elements. The expression of the mass matrix is :

$$M^A = \begin{pmatrix} m_{11}^A & m_{12}^A \\ m_{21}^A & m_{22}^A \end{pmatrix}$$

where m_{11}^A, m_{22}^A and m_{12}^A represent respectively the added mass of the fluid on the structure 1, on the structure 2, and the inertial fluid coupling between the two structures.

It has been shown [2] that in the case of seismic motion of the core, (i) the predominant coupling term is the coupling between the assembly and the baffle and (ii) this coupling value is independent of the position of the fuel assembly in the row.

According to this theory, an added mass of approximately 35% and a coupling mass of approximately 45% relatively to the mass of the assembly have been calculated for the selected test configuration (full confinement).

5.2 Added damping calculation

Many studies have been performed concerning the evaluation of the additional damping induced by the primary coolant flow on the fuel assembly [3], [4] & [5]. In this situation, damping mainly comes from a lift phenomenon due to axial flow velocity relatively to the assembly lateral velocity and could reach 50 % of critical.

In the case of still water (our test configuration), fluid added damping may also be significant but comes from a drag phenomenon which should be evaluated in a different way than damping from axial flow. An evaluation of the damping in case of still water with full confinement is given in [6]. Based on stationary flow hypothesis, an evaluation of the reduced damping coefficient β of the first mode of the fuel assembly is given by:

$$\beta = \frac{8}{\pi}\frac{\rho_L}{\rho_S}\frac{A}{D}$$

where : ρ_S is the equivalent density of the fuel rod,

ρ_L is the density of the fluid,

A is the amplitude of motion,

D is the diameter of the fuel rod.

This leads to a reduced damping coefficient of 15 % of critical for 6 mm amplitude of motion.

N.B.: One can observe that in this situation (still water), reduced damping is directly proportional to the amplitude of motion. This is different than in the case of flow induced damping.

6 SEISMIC RESPONSE OF THE ROW OF ASSEMBLIES

In this section, the method used to compute the response of the row of assemblies is described. Then the comparison between test results and computations, in terms of displacements and impact forces is presented (the latter correspond to the design parameters).

6.1 Method of solution

Due to impact between assemblies, a non-linear seismic response of the row of assemblies is performed. EDF and FRAMATOME-ANP have two different approaches to solve this problem.

6.1.1 EDF method

The non-linear seismic response of the row of assemblies is based on Non-Linear Modal Synthesis NLMS. This method consists in solving the equation of motion at each time step, in terms of generalised acceleration, velocity and displacement:

$$\Phi^t M\Phi.\ddot{\eta} + \Phi^t C\Phi.\dot{\eta} + \Phi^t K\Phi.\eta = \Phi^t F_{EXT} + \Phi^t F_{NL}(\Phi\eta, \Phi\dot{\eta}, \Phi\ddot{\eta})$$

where F_{NL} represents the non-linear forces (i.e. impact forces) and F_{EXT} the external forces (i.e. seismic excitation).

One can notice that, in that situation, impact loads may excite some higher modes than those usually excited by the seismic motion. Consequently, the modal basis must be properly selected.

The criterion used in EDF finite element computer code *Code_Aster®* is based on an impact softness (inverse of impact stiffness) consideration. In a first step, the local softness S at each impact node is calculated by means of a static calculation : S = Static displacement / Static force. In a second step, the calculated static displacement of the fuel assembly is projected in the modal basis which gives a local modal softness per mode S_i. Finally, the number of modes which are kept is defined by comparing the impact softness (1 / Impact stiffness) to the neglected softness using the following criterion :

$$\frac{Softness_{static} - \sum_{i} Softness_{local(i)}}{Softness_{impact}} < 0.5$$

This criterion means that the neglected softness should be significantly lower than the impact softness. This leads to keep approximately 30 modes per assembly instead of 6 needed for seismic linear computation.

6.1.2 FRAMATOME-ANP method: direct integration

The dynamic equilibrium of the structure is expressed by the equation :

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F(t)\} \tag{1}$$

As the matrix [M] is positive definite, this equation can be written as :

$$\{\ddot{x}\}=[M]^{-1}(\{F(t)\}-[C]\{\dot{x}\}-[K]\{x\}) \tag{2}$$

Taking $\{v\}$ as the velocity vector, relationship (2) is equivalent to :

$$\{\dot{v}\}=[M]^{-1}(\{F(t)\}-[C]\{v\}-[K]\{x\}) \tag{3}$$

$$\{\dot{x}\}=\{v\} \tag{4}$$

By introducing the velocities as independent unknowns, we transform a system of N second order differential equations into a system of 2N first order differential equations.

Insofar as all the dynamic elements in CASAC (FRAMATOME-ANP computer code) have a constant mass matrix, the acceleration of each d.o.f. can be obtained by solving eq. (3) using the pre-factorised mass matrix [M].

The calculation of the complete force vector is the sum of the forces exerted on each d.o.f. by all the different contributions : external, elastic, viscous, kinematic constraints...

Damping can be introduced in two different and complementary ways :

- reduced modal damping values can be taken into account directly on each of a finite set of natural modes (generally the most significant modes), by using a preliminary modal analysis of the structure,
- other modes, that are not controlled by the previous damping technique, can be damped by the very popular Rayleigh technique; the damping matrix is then calculated as a linear combination of the stiffness and the mass matrices.

From the numerical point of view, the integration of the differential equations system (eqs. 3 & 4) is achieved by the HAMMING predictor-corrector method, with an initialisation using a RUNGE & KUTTA algorithm.

6.2 In-air results – 0.2 g seismic excitation

Based on characterisation test results, the following characteristics have been chosen to be representative of the dynamic behaviour of the fuel assemblies (representative of approximately 6 mm amplitude) :

Design A :		Design B :	
1st eigenfrequency:	~3.0 Hz	1st eigenfrequency:	~3.4 Hz
Damping coefficient:	~11 %	Damping coefficient:	~11 %

The comparisons between test results and calculations, in terms of displacements are presented in Figure 6.

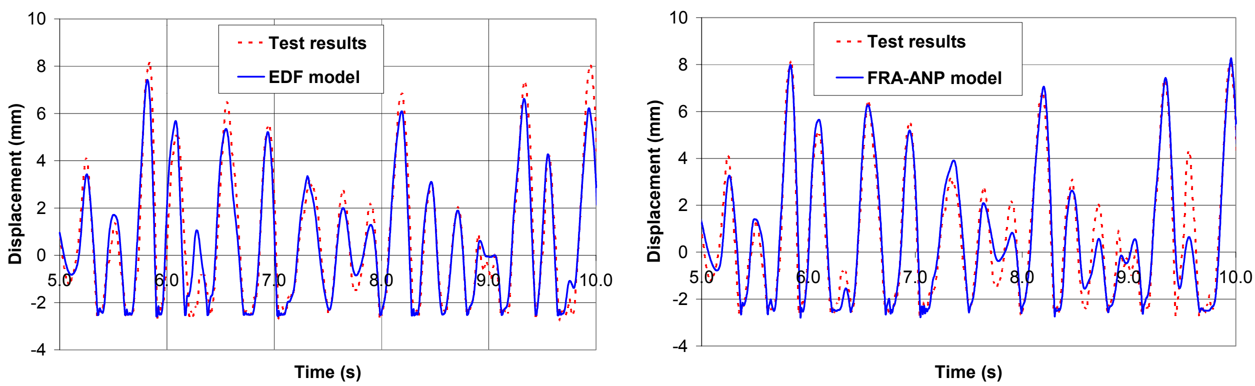
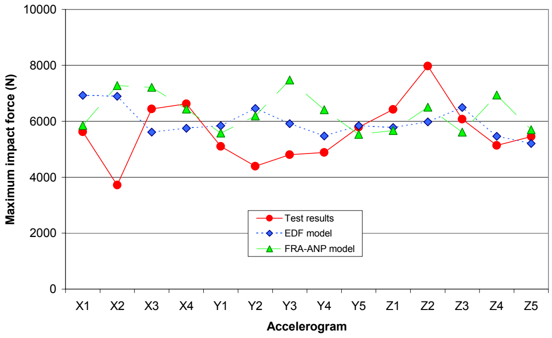


Figure 6: In air - Comparison between test results and calculations (Assembly #6 – Grid 4)

Calculations are in very good accordance with test results in terms of displacements (for phase and amplitude). The differences between measured maximum impact forces and calculated ones are presented in Figure 7.



	Test results	EDF model	FRA-ANP model
Average	5604	5975	6315
Std deviation	1073	528	693

Figure 7: In air - Comparison between test and calculation - Maximum impact forces - Grid 5

Maximum impact forces are in good accordance between test and calculations in most cases. Although some scattering may be observed, calculations are well fitted with test results in terms of average value and standard deviation (differences between average results are below one standard deviation).

6.3 In-water results (full confinement) – 0.3 g seismic excitation

The dynamic characteristics of the fuel assemblies have been determined based on in-air characteristics (see § 6.2), to which has been added FSI (added mass and added damping, see § 5) :

Design A :		Design B :	
1st eigenfrequency:	~2.6 Hz	1st eigenfrequency:	~3.0 Hz
Damping coefficient:	~26 %	Damping coefficient:	~26 %

The comparison between test results and calculations, in terms of displacements, are presented in Figure 8.

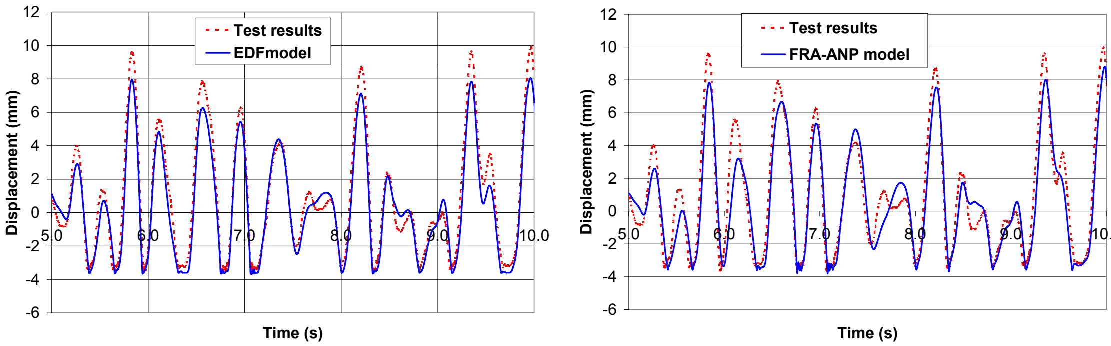
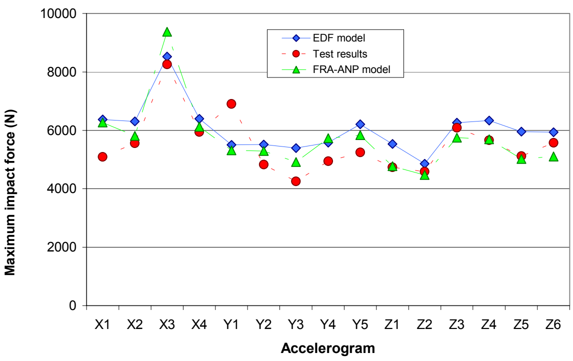


Figure 8: In water - Comparison between test results and calculations (Assembly #6 – Grid 4)

As in the case of the tests in air, calculations are in very good accordance with test results in terms of displacements. The differences between measured maximum impact forces and calculated ones are presented in Figure 9.



	Test results	EDF model	FRA-ANP model
Average	5519	6045	5699
Std deviation	1009	824	1138

Figure 9: In water - Comparison between test and calculation - Maximum impact forces - Grid 5

In this situation (close to in-core situation), maximum impact forces are in very good accordance between test and calculations. In addition, calculations are very well fitted with test results in terms of average value and standard deviation (differences between average results are below ½ standard deviation). It must be specified that the level of acceleration (spectrum ZPA) is different between air and water tests. For the same input level, impact forces in water are of course lower.

6.4 Interpretation of the results

The main comments that can be made on these results are the following:

Displacements at grid location

Calculations reproduce very well the measured displacement in most cases, in terms of phase and amplitude. This confirms the conclusion that the linear modelling of the assembly is appropriate to calculate the seismic response of the row of assemblies - if the dynamic characteristics of the assemblies (i.e. frequency and damping) are properly evaluated of course.

Impact forces

In terms of impact forces, calculations are well in accordance with test results. This shows that, although FRAMATOME-ANP and EDF use two different methods to compute the seismic response of the row of assemblies (direct integration and NLMS respectively), the computations give a value of the maximum impact forces with a high confidence level.

Fluid-Structure Interaction

The comparison between test results and calculations for the in-water test configuration (full confinement) are at least as good as the in-air situation. This confirms the validation of the design method used to account for Fluid-Structure Interaction.

Artificial accelerograms

This study has been performed based on 3 sets of 5 artificial accelerograms generated by 3 different codes. The results show that there is no systematic deviation between sets of accelerograms, which reinforces the design methodology using such artificial accelerograms.

Number of accelerograms

Finally, this study shows that, in order to give proper trends, a relatively large number of accelerograms should be used. 15 accelerograms, as used in this study, allow some proper statistical evaluations to be made.

7 CONCLUSION

FRAMATOME-ANP and EDF have carried out a large research and development program, mainly in association with French CEA (Commissariat à l'Energie Atomique) in order to increase the efficiency of the methods and models used to predict the seismic behaviour of the PWR cores and to quantify the margin in the design methodology.

The study presented in this paper was carried out in the framework of this R&D program. The objective was to show the effectiveness of computer codes and models to predict the seismic behaviour of a row of assemblies by comparing to seismic test results performed on a row of 6 full-scale fuel assemblies.

The comparison between tests and calculations have shown a good agreement in terms of displacements and impact forces which gives additional validation of the design methodology in terms of fuel assembly dynamic characteristics determination and FSI methodology.

In addition, some interesting results concerning the effect of time histories (use of different codes, large number of accelerograms) on the seismic response of the row of assemblies have been obtained.

This allows us to evaluate precisely the margins in the seismic design methodology of the fuel assembly with a high confidence level.

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