Seismic Behavior of a Fast Reactor Core.
Application on SUPER PHENIX 1

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Summary

The code CORALIE, which calculates the non-linear seismic response with shocks of a fast reactor core, was used for the first time within the framework of the design study of an industrial reactor : SUPER-PHENIX 1.

CORALIE is a dynamic FEM code for the calculation of beams, whose the main part is to account for shocks between the beams. The main hypotheses are presented, and then the mathematical models selected to take into account some specific parameters such that damping, fluid effect, or non-linearities such that shocks.

The application of CORALIE to the SUPER-PHENIX 1 core response is showed, first to the "seisme de base" (SB), then to the "seisme majoré de sécurité" (SMS), just as some complementary tests performed in scale 1 during these studies, especially about modal damping.

Finally, we describe the consequences of the core seismic response within the framework of the design studies : in particular on the mechanical design of the subassemblies as to the response to SB, and on the diverse operation and safety studies as to the response to SMS, mostly the reactivity effects and the behavior of the core control rods.
1 - INTRODUCTION

After the presentation at SMIRT-6 of the history of the different models developed for the calculation of the seismic behavior of a fast reactor core (Ref.1), this paper describes the calculations performed on the SUPER-PHENIX 1 core. These calculations represent the first application, within the framework of a design study of an industrial reactor, of the most recent model: CORALIE, seismic core model with shocks.

2 - PRESENTATION OF THE SUPER-PHENIX 1 CORE

The SUPER-PHENIX core consists of about 24 rings of subassemblies, whose the 16 inner ones are supported by a diagrid, and the 8 outer ones by a dummy diagrid. Every subassembly is composed of an hexagonal wrapper tube above the diagrid and a pole which fits in the diagrid-pipe. It stands on the diagrid by means of its spherical seat at the lower end of the hexagonal tube. Pads are located at one single intermediate level between the seat and the head.

There are 4 types of subassemblies, fuel, blanket and steel (RAC) ones, supported by the diagrid, and lateral neutron shielding ones (PNL), supported by the dummy-diagrid.

3 - PRESENTATION OF CORALIE PHYSICAL MODEL

CORALIE is a static or dynamic FEM code for the 2-dimensional beam analysis. In dynamics, two methods are possible: either direct integration by $\delta$-NEWMARK method, or modal analysis with the vibration modes. The second one is used in the SUPER-PHENIX 1 core seismic analysis. Neglecting shear forces, 2 d.o.f. - elements are used. The beams are submitted to an uniform acceleration at the base level as well as local forces, initial conditions of displacements or forced contacts. The main part of the code is to account for the shocks between neighbouring beams, or between a beam and a rigid wall (to describe the interaction between the subassembly pole and the diagrid pipe), which occur under a dynamic excitation. The hypotheses and mathematical models to account for such phenomena that shocks and damping, are presented in the following subsections.

3.1 - Shock model

We assume that, between 2 beams coming into contact, a spring-damper system acts as soon as the contact starts. The solution method of the displacements along time (Duhamel integrals) assumes the contact force at mid-timestep $[t_{i-1}, t_1]$ to be known. This force depending on the displacements, an iterative process must be used. We assume that an interpenetration between two beams is possible: this value has no actual physical meaning, but is used to calculate the shock force. At every iteration, the dynamic interpenetration between the beams, at the nodes where the shock occurs, is computed with the help of the arithmetic average of the displacements at the beginning and the end of
the timestep, and with the help of the average velocity, evaluated in the previous iteration. If this interpenetration is greater than the static one (introduced in order to simulate a static contact), the shock force can be computed at time \( t_{j-1/2} \) with shock parameters such that a shock spring constant and a shock damper constant. Then, we iterate until a relative convergence on the displacements of each beam is obtained.

The modal analysis uses only the \( N \) first modes of every beam; thus, for every possible shock level, it is necessary to add, to the shock spring local flexibility (for instance, at the pad level: the pad flexibility), that of a spring due to the neglected modes, and connected in series to the shock one. This local flexibility can be evaluated at every shock node by means of a static calculation of the displacement of the beam \( i \), submitted to a unit force at the shock node in the shock direction: with this direct calculation, we obtain a displacement \( X(z) \). By summing the modal series on the \( N \) first modes, we obtain \( X'(z) \). The difference \( X(z) - X'(z) \) corresponds to the part due to the neglected modes in the structure flexibility. Finally, for every possible shock level, if \( K_L \) is the shock spring local stiffness, the total stiffness \( K_{ij} \) for a shock between the beams \( i \) and \( j \) is such that:

\[
\frac{1}{K_{ij}} = \frac{1}{X_i(z) - X_i'(z)} + \frac{1}{X_j(z) - X_j'(z)} + \frac{1}{K_L}
\]  \hspace{1cm} (1)

3.2 - Damping

The damping consists in two parts:

- modal damping \( \eta_{in} \) which appears in the equilibrium equation of the beam \( i \), projected on the base of the mode shapes \( \phi_n \):

\[
\ddot{\alpha}_n + 2 \eta_{in} \omega_n \dot{\alpha}_n + \omega_n^2 \alpha_n = \frac{F_{in}}{M_{in}} \]  \hspace{1cm} (2)

Where

\( \alpha_n \) : modal coefficient such that \( X_i(t) = \sum_{n=1}^{N} \phi_n \alpha_n(t) \)

\( \omega_n \) : angular frequency

\( M_{in} \) : generalized mass

\( F_{in} \) : generalized force

- shock damping

By setting equal, on the one hand, the kinetic energy variation during the shock and the energy absorbed by the damper, and, on the other hand, the initial kinetic energy and the potential energy corresponding to the maximal interpenetration, we obtain the shock damper constant:

\[
C = (1 - \varepsilon^2) \frac{k}{\omega_0} \]  \hspace{1cm} (3)
Where

\[ e : \text{restitution coefficient steel over steel} \]
\[ k : \text{shock stiffness} \]
\[ \omega_0 : \text{shock "angular velocity" (roughly estimated with the 1st beam period in flexion, considering the shock node as an extra support point).} \]

It is noticeable that such a damper yields a damping coefficient proportional to the frequency; so, the low frequency modes are little damped.

3.3 - Algorithm stability

The integration time-step may be constant, or reduced during the shock.

A first conservative criterion is \( \Delta t \leq 1/40 \) of the smallest vibration period. In the most general case, with several modes for every beam, the half-period of the 1st neglected mode gives a good approximation of the shock-time; then, at least 3 points are necessary during the shock to get a correct convergence.

3.4 - Validation test program

These tests were carried out on a mock-up in geometry RAPSODIE at scale 1, and in similitude of about 1/3 with respect to SUPER-PHENIX 1. They consisted in harmonic and seismic tests, on a shaking table, in air and in water. Their main conclusion, beside the good agreement with the code results, is the equivalence of the dynamic behavior, first between the whole core and a diameter of subassemblies, and secondly, between shocks over flats and shocks over angles.

4 - PRESENTATION OF THE SUPER-PHENIX 1 CORE CALCULATIONS

4.1 - Seismic characteristics of the SUPER-PHENIX 1 core

In the preliminary calculation of the vibration modes, each type of subassembly is modelized by a series of beam elements, with 2 d.o.f. per node. The stiffness of the fuel pins is neglected, but their mass is added to the subassembly one, in the zone where they are.

The limit conditions are the following ones (Fig 1):

- for the 3 first types; a pin at the pole lower end, and a pin at the subassembly seat.
- for the PNL : 2 unilateral supports with a gap at the centers of the lower and upper slabs of the dummy diagrid, and 1 support with friction on the base at the pole lower end.

The other types of subassembly such that the control rods (main : SGP, backup : SAC) are not modeled because of their small number : we can assume they don’t modify the core motion. Their movement in the core can be obtained with the help of the movements of the surrounding subassemblies.

The modulus of elasticity and the density of the materials account for temperature. The densities are increased of 15% to account for the decrease of the eigenfrequencies due to fluid motion between the subassemblies : this effect of added mass appeared during the seismic tests on the RAPSODIE mock-up.

Because of the varying PNL limit conditions, it is necessary to use the 2 rigid body modes of translation and rotation. Four modes are used for every subassembly type when limiting the frequencies up to 200 Hz.

4.2 - Complementary tests on damping

Two programs of tests were run at scale 1 : one in the SUPER-PHÉNIX 1 geometry on a small group of subassemblies, the other one in the PHÉNIX geometry on a larger group.

The SUPER-PHÉNIX 1 mock-up consists of a diagrid of 4 pipes and 4 dummy subassemblies. The tests, static and dynamic, were performed in air and in water.

The static one consisted to draw the plots force vs. displacement with hysteresis, in order to determine damping due to the foot gaps and to friction in the subassembly seat. A viscous damping coefficient, equivalent to this hysteretic one, was obtained for diverse displacement values : damping varies from 18 to 5% for displacements from 10 to 50 mm.

The dynamic one consisted to move one of the four subassemblies apart of its equilibrium position and then release it. The results were the following ones : damping decreases when the motion amplitude increases ; for initial displacements from 10 to 50 mm, damping keeps above 5%. These release tests allowed also to achieve the shock model validation, and to check the calculation method of the shock damper.

In the PHÉNIX geometry, release tests in air were run on groups of 7 to 19 subassemblies, free or constrained at their periphery by an elastic strip.

The results showed an increase of damping with the group size (from 1,3 % for 1 subassembly to 5 % for 19 subassemblies) and with the interaction forces between the subassemblies.
To sum up, these 2 tests programs showed that the modal damping coefficient was above 5% in the core (all the more as the inner pins create a supplementary damping by their individual motions).

4.3 - Calculations of the SUPER-PHENIX I core seismic response

From the conclusions of the validation tests of CORALIE on the RAPSIDIE mock-up (see § 3-4), the calculation was run on a SUPER-PHENIX I core diameter over flats, that is 47 subassemblies (Fig.2) : 8 PNL, 2 RAC, 3 fertile, 21 fuel, then 3 fertile, 2 RAC and 8 PNL ones. Some shock possibilities were introduced at the head level, at the pad level, and at one level in the pole between the pole and the diagrid-pipes.

The pad shock flexibility was obtained by means of FEM calculations, checked by tests : the value is high enough to neglect the flexibility due to the neglected modes.

The shock flexibilities, at the head level, and at the pole-diagrid interaction level, correspond to the flexibility of the neglected modes.

The core is subjected to a diagrid accelerogram corresponding to the "séisme de base" (S.B.), then to the "séisme majoré de sécurité" (SMS) (Fig.3), both 20 s. long. The time step is 0,8 ms. The code yields the displacements, the bending moments, the shear forces, and the shock forces at every axial level at any time during the earthquake, just as their maximal values.

The figures 4 and 5 show respectively, in SMS, the evolution of the maximal head and pad displacements along the diameter, then of the maximal shock forces between the subassemblies at the head and pad levels. The highest displacement takes place at the fuel core periphery ; the highest shock force is located at the blanket-steel interface.

The figures 6 and 7 present in SMS, the variation along time of the head displacement of respectively the blanket subassembly located at the fuel core periphery, and the external PNL. One notices on the Fig. 7 that the PNL eigenfrequency depends on the motion amplitude.

5 - CONSEQUENCES OF THE CORE SEISMIC BEHAVIOR WITHIN THE FRAMEWORK OF THE PROJECT STUDIES

The SB and SMS earthquakes are two of the contractual situations of operation of the subassemblies, for which some criteria, related to the mechanical design of the subassemblies or to operation and safety studies, must be fulfilled within the framework of a project study like the SUPER-PHENIX I one.
5.1 - Mechanical design of the subassemblies

The SE belongs to the 3rd category "emergency operating conditions". Within the framework of the mechanical design of the subassemblies, among all the situations in the 3rd category, it is the most penalizing situation for most structures, such that:

- the pads of the fuel blanket or steel subassemblies, subjected to high shock forces repeatedly in SE.

- the poles of all the subassemblies, subjected to alternate bending moments, due to the shock forces at the head and pad levels, and damaging from the point of view of fatigue.

The SMS is one of the situations of the category 4 "faulted conditions". It concerns mainly the safety studies.

5.2 - Safety problems

The field of the horizontal displacements of the subassemblies under an earthquake modifies the core reactivity, because of the spatial redistribution of the neutronsically active materials, mainly fuel blanket and control rods. This effect upon the core reactivity is most important for the operation and safety analyses.

Besides, the role of the core control rods, i.e. main (SCP) and backup (SAC) control rods, must be fulfilled in case of an earthquake. We must check that the fall of the mobile structure keeps possible in spite of the core deformations and that the falling time is suitable.

6 - CONCLUSION

The evolution of the different core models, from the linear one to the non-linear one with shocks, developed in CORALIE, allowed to reach a fine analysis of the seismic behavior of a fast reactor core. Within the framework of the SUPER-PHENOIX I project studies, the CORALIE results were used, on the one hand, in the mechanical design studies of the subassemblies, and on the other hand, in the studies related to operation and safety, such that the effects upon the reactivity of the behavior of the core control rods.

The future development of CORALIE will concern the fluid-structures coupling, which is taken into account in the present version only approximatively in the calculation of the vibration modes of the subassemblies.
FIGURE 1: LIMIT CONDITIONS OF THE SUBASSEMBLIES

FIGURE 2: SUPER-PHENIX 1 CORE MODELIZATION

FIGURE 3: SUPER-PHENIX 1 DIAGRID ACCELERATION RESPONSE SPECTRUM IN S.M.S.

FIGURE 4: MAXIMAL HEAD AND PAD DISPLACEMENTS IN S.M.S.

FIGURE 5: MAXIMAL HEAD AND PAD SHOCK FORCES IN S.M.S.

FIGURE 6: HEAD DISPLACEMENT OF THE BLANKET SUBASSEMBLY LOCATED AT THE FUEL-BLANKET INTERFACE DURING THE S.M.S.

FIGURE 7: HEAD DISPLACEMENT OF THE EXTERNAL PNL SUBASSEMBLY DURING THE S.M.S.