

Status of Methods for Justification of Fuel Assembly Lateral Strength during an Earthquake

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1. INTRODUCTION

The core design of a PWR nuclear reactor must satisfy the design requirements for class 4 events /1/. These include earthquakes, for which the designer must demonstrate that the reactor can be restored to and maintained in safe shutdown. During such an event, ground motions are transmitted to the vessel through the building, then to the fuel assemblies (F/A) through the vessel and the internals. Their main effects are lateral core displacements, producing lateral distortion of the fuel assemblies and impacts between the latter or with the baffles at the grid locations.

Demonstration must be provided that distortions and impact forces remain at a level compatible with control rod drop and core cooling, i.e. that limit values are respected. It is the task of fuel assembly designers to develop and implement a methodology for making this demonstration.

2. METHODOLOGY

Exhaustive research has been made on this topic since the early 1970's. Progress in numerical methods and the increased computing speed have enabled a rapid advance in the techniques used. However, the models built until now generally correspond to a single row of F/A excited in its own direction, assuming that the longest row in the core represents the worst case.

The first studies on the dynamic behavior of a F/A row used an assembly model of the mass-spring type with a single degree of freedom, determined by the "Far Coupled Method", and a numerical integration method of the direct implicit type /2/. Loading was generally single, with the assembly row considered to be inside a non-deformable "box".

These models have given way to models built from beams and springs with gaps to represent inter-assembly impacts /3/ /4/. The direct explicit integration method was used together with the non-linear modal superposition method, the latter allowing more detailed assembly modelling. The loading was also determined more precisely by applying different motions to the upper core plate, the different core baffle elevations and the lower core plate. A number of tests accompanied these developments, some aiming to validate the overall model/computing method approach /3/, others to better characterize full-scale F/A mock-ups /5/. Full-scale shaker table tests were even performed up to grid buckling /6/.

FRAMATOME Fuel Division's current policy is to use a model consisting of beams and impact springs, in conjunction with a direct explicit integration method, and with multiple excitation from the core internals. The method for building this model is outlined in section 3, and section 4 addresses the verification of overall model validity.

3. FUEL ASSEMBLY ROW MODEL

3.1. F/A beam model

The model shown in figure 1 features a single beam of length equal to F/A height between nozzles and restrained at both ends. The nodes are situated at the grid locations, each element representing a grid span ; however, the end grids are generally not represented, since they are close to the nozzles and do not impact.

This model contains both actual physical parameters and equivalent parameters adjusted for optimum reproduction of dynamic behaviour. The physical parameters are the beam cross-section, which corresponds to that of the guide thimbles and of the rod envelopes, the mechanical properties of the material (Zircaloy), and finally the total F/A mass between nozzles, from which the beam equivalent in-air density is deduced.

The other parameters are determined from out of core full-scale assembly tests, under cold in-air and in-water conditions, then corrected for PWR conditions. Study of F/A free or forced oscillations supplies the first natural frequencies and the related reduced damping. The values obtained are amplitude-dependent, due to rod slippage in the grid cells, and the results corresponding to an amplitude significant for accident analyses are selected.

For the non-damped model, the determination is performed by the following sequence :

- a) Cold, in air :
The cross-sectional inertia and the equivalent shear coefficient are determined to obtain a best estimate of the test frequencies. The use of two parameters only enables adjustment of two frequencies (f_1 and f_3 are usually chosen), but experience shows that satisfactory values are yielded for the first 4 or 5 F/A natural frequencies.
- b) Cold, in-water :
The reduction in the first frequency determines the mass added to the F/A. This linear mass is represented by lumped masses on the nodes, proportional to the height assigned to each node.
- c) Under PWR conditions :
The Young's modulus is set to the value corresponding to the average core temperature. Likewise, the added mass is corrected by the ratio of the reactor coolant average density to the cold water density.

The model uses RAYLEIGH proportional damping, where the damping matrix is a linear combination of mass and stiffness matrices ($C = \alpha M + \beta K$). This form of damping proves satisfactory for representing a mode 1 reduced damping higher than that of the following modes, due to its predominance and as a result of higher associated amplitudes. The two coefficients are therefore determined by applying the mode 1 reduced damping on the one hand and that of a close higher mode (generally mode 3) on the other.

The frequencies used are computed by the model under PWR conditions ; the related reduced dampings are deduced from the cold, in-water assembly tests, but can be revised to fit PWR-related conditions : in-reactor measurements by neutronic noise, damping under flow conditions (section 5).

3.2. Grid impact model

This model is represented on figure 2 for one grid of a single assembly and on figure 3 for the set of grids with the same vertical level in the assembly row, i.e. in its final form.

Stiffness K_C and damping C_E are the "external" characteristics of the grid, when it is compressed between its two opposing faces (outer straps). These parameters are determined under hot conditions by dynamic compression tests, which also supply the buckling limit.

The "internal" stiffness K_I reflects, in series with the stiffness $2K_E$, the "equivalent local dynamic stiffness" K_{eq} of the assembly when it impacts on a single side. Its value depends on the fineness of discretization of the mass in the F/A beam model ; for a span mass concentrated at a single node, it is much lower than K_E (therefore $K_I = K_{eq}$).

This stiffness is determined by assembly impact tests against a wall, cold in water ; the value is adjusted to obtain the maximum experimental impact load, but satisfactory values are also obtained for other impact parameters (duration, timing and amplitude of rebound). The value under PWR conditions is then obtained by correcting with the hot/cold ratio of Zircaloy Young's moduli.

The related damping C_I is relatively arbitrary and its influence is low. Its reduced value is taken to be identical to that of C_E , on the basis of the span mass and corresponding stiffnesses.

The intermediate mass m has a value close to that of the grid, slightly higher for numerical reasons ; note that this mass is included in the beam model for its qualification, then removed and placed in the impact model.

Finally, in the row model, gaps in the spring elements between assemblies or between assemblies and baffles correspond to the average value in the core ; the gap value is therefore uniform between assemblies, but it may be slightly different for the baffles.

4. CHECK ON VALIDITY OF ACCIDENT MODELS

The model qualification method outlined in the foregoing is a fair guarantee of validity. However, analytical tests on isolated assemblies do not yield exact knowledge of the behaviour of a row, still less of the entire core.

Against this background, FRAMATOME has undertaken with the CEA a large-scale test program using representative F/A mock-ups to simulate dynamic behaviour, arranged in one or even several rows and subjected to seismic excitation on a shaker table. The main results for one row are given in reference /7/, and the first test / calculation comparisons in reference /8/. These first comparisons, made in air, are highly encouraging and later analyses will be mainly devoted to the more complex effects of the presence of water, particularly fluid-structure interaction with confinement.

These tests are not suitable for the study of damping induced by coolant axial flow, and this phenomenon has given rise to a specific study /9/. The results demonstrate the existence of a very high damping under flow, whose influence is eliminated or minimized in the model damping values.

Finally, the realism of the models must be matched by that of the grid strength criterion. The detailed interpretation of the grid compression test results, which promoted a precise evaluation of grid stiffness /10/, is currently being pursued for buckling limit.

The above-mentioned studies should lead to better evaluation of model realism, with improvements where necessary. It is noteworthy that, given the current computing capability, the predictive accuracy of the accident models is probably limited as much by the availability of experimental data as by practical considerations (case of deployment and running cost).

5. CONCLUSION

The current methods are sufficient for meeting the safety targets. However, the development of methods for predicting more realistic behaviour will make it possible on the one hand to make better allowance for earthquake effects at the fuel assembly design stage and on the other to provide margins for the product.

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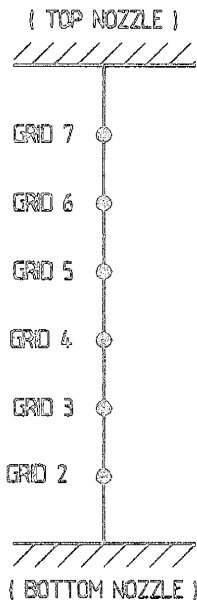


FIGURE 1 : BEAM MODEL FOR AN 8-GRID ASSEMBLY

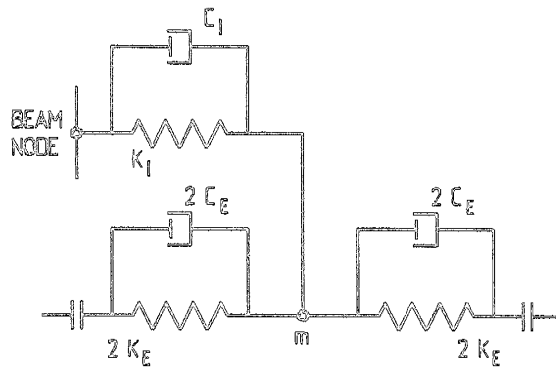


FIGURE 2 : IMPACT MODEL AT GRID LOCATION FOR A SINGLE ASSEMBLY

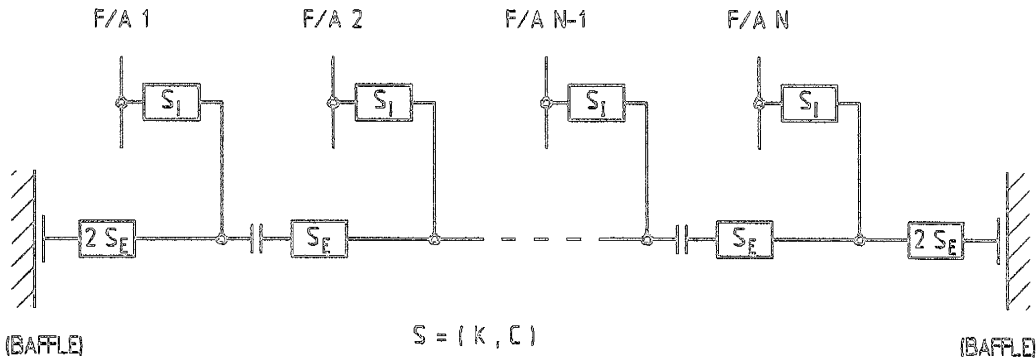


FIGURE 3 : ROW MODEL FOR A SINGLE GRID ELEVATION

