Seismic Design of a Spent Fuel Storage Rack

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ABSTRACT

This paper deals with the design analysis of a spent fuel storage rack performed by FRAMATOME for its type N325 PWR. It concerns the aspect of the problem related to the possible out of phase motion of adjoining modules, whether partially or fully loaded, in case of seismic event.

The spent fuel storage rack consists in a certain number of independent rectangular modules free-standing on the pool floor and immersed in water. For studying the seismic behaviour of the system, each module is considered as a flexible beam pinned to the pool floor through a rotational stiffness. Using the finite element method, it may indeed be shown that the main vibration mode of a module corresponds to its rotation around the neutral axis of the base plate. As clearance between modules is small for increased pool storage capacity, one of the main concerns is the possible out of phase swaying of a line of modules. This is studied with attention focused on fluid-structure interaction. The method is again based on finite elements. Additional hydrodynamic masses related to a row of five modules are determined for an excitation in the longitudinal row direction. This is achieved through resolution of an equivalent thermal problem.

For the geometry under consideration, the additional masses are important, thus indicating a trend towards a rigid motion of the entire row. Indeed, this is confirmed when these masses are used in the computation of the modal then spectral responses of the partially loaded system. In the seismic domain, five modes are present. Each of these is shown to maximize the rotation of one of the modules in the row. Among these modes, when the row is partially loaded, the fifth is shown to correspond to the in-phase motion of the five modules. It exhibits the greatest modal coefficient and the entire spectral modal response remains close to this pure modal response.

The study reported here allows to rule out the possibility of important out of phase motions of two adjoining modules in a partially loaded row of a spent fuel storage rack. This conclusion is also valid for a fully loaded row. Moreover, in case of seismic event, the module displacements are shown to remain small due to the effect of the surrounding water. Thus, it is demonstrated that, under the assumptions used, there is no possibility of two modules interfering with each other in case of earthquake.

INTRODUCTION

The spent fuel storage rack designed by FRAMATOME for its type N325 PWR consists in 15 identical modules arranged in 3 parallel rows of 5 modules each in the
spent fuel storage pool (see Fig. 1 and 2). Each module is free-standing on the pool floor and is coupled to its neighbours only through the surrounding water. The lateral walls of a module consist in solid plates preventing water to flow in the horizontal direction. Also, clearance between two modules of a row as well as between two adjacent modules in different rows is small (140 mm between casings) for increased storage capacity. The seismic behaviour of this arrangement must be studied and one of the concerns is the possible independent motion of each individual module that could perhaps lead to their mutual impact. This may especially happen when the modules are not identically loaded; conversely, it is intuitively felt that the coupling effect of water is beneficial and therefore must be taken into consideration in a realistic analysis.

Fig. 1 Spent Fuel Pool Layout.

Fig. 2 Row of Spent Fuel Storage Rack Modules.
ANALYTICAL PROCEDURE

A simplified approach approximating the global response of the array of modules immersed in water is undertaken. To keep the problem simple, a single row of five modules is studied under the occurrence of a horizontal seismic excitation in the row direction.

A finite element analysis of an isolated module in air is first conducted in order to gain knowledge on the deformation behaviour of the structure. The computer code used in this calculation as in subsequent ones is SYSTUS. This 3-dimensional analysis is performed with a relatively high degree of accuracy as it is actually also used for the basic design mechanical calculations of the structure. The present purpose, however, is to be able to derive a simple yet acceptable model for an individual module. As a matter of fact, this study shows that the main vibration mode of a module corresponds to its rotation around the neutral axis of the base plate. Indeed, the solid sides of a module are responsible for a rather high flexural stiffness whereas the base plate exhibits openings for water circulation and thus appears to be more easily deformed. The analysis of the deformation behaviour of a module therefore leads to a simplified model of the structure consisting in a vertical beam characterized by

- a rotational stiffness at the bottom end that is considered to be pinned to the pool floor,
- a flexural stiffness which is retained also its effect is rather small compared to the overall rotation of the structure.

The five modules in the row that is to be studied are also characterized by their mass per unit length thus allowing partially loaded modules to be analysed. However, this partial load is considered homogeneously distributed in the beam, obviously a simplifying assumption.

It is then necessary to introduce the fluid-structure interaction. Hydrodynamic effects between immersed objects may be suitably represented by an added mass matrix [Fritz, 1972, Levy and Wilkinson, 1975, Wu et al, 1977, Scavuzzo et al, 1979], the terms of which are to be determined. This is done with a second finite element analysis conducted on an equivalent thermal problem. A 2-dimensional model representing a horizontal cross section plane of the central part of the pool containing the row of modules is used as fluid-structure interaction is assumed to be depth-independent (see Fig. 3). Solid boundaries represent pool walls or modules in adjacent rows. All solid surfaces are assumed to be undeformable. The dynamic problem consists in accelerating one of the immersed object in order to obtain the pressure resulting on other surfaces. Its resolution yields a row (or column) of the symmetrical added mass matrix and thus, accelerating each solid in turn gives the entire matrix. This is replaced by an equivalent thermal problem that is governed by other variables but identical equations. In brief, linear thermal sources are placed on each solid boundary in turn (positive on one side, negative on the other) and the problem is solved for temperature on other surfaces.

Fig. 3 2-dimensional Finite Element Model for Hydrodynamic Coupling Determination.
The symmetrical added mass matrix, obtained for a height equal to 1.11 m, is the following (10*3 kg):

\[
\begin{array}{ccccccc}
332 & -62 & -60 & -61 & -61 & -62 & \text{sum per row} \\
-62 & 60 & -3 & 0 & 0 & 0 & \text{actual} \quad 27.11 \\
-60 & -3 & 63 & -3 & 0 & 0 & \text{theoretical} \quad 27.04 \\
-61 & 0 & -3 & 63 & -3 & 0 & -4.38 \\
-61 & 0 & 0 & -3 & 63 & -3 & -4.42 \\
-62 & 0 & 0 & 0 & -3 & 61 & -4.43 \\
\text{total sum} & \rightarrow & 5.02 & 4.90 \\
\end{array}
\]

The first row (or column) corresponds to the pool wall whereas rows (or columns) 2 to 6 correspond to modules 1 to 5.

A check on consistency is easily performed since the theoretical sum of the terms in line 1 is pool water capacity, those in lines 2 to 6 are module displaced water masses and that of all terms is water mass around modules.

The above values of added masses are quite important, thus indicating strong fluid-structure coupling. A nearly rigid motion of the entire row may therefore be anticipated.

RESULTS

At this point, the study makes use of the final 2-dimensional finite element model, representing a row of five modules immersed in water and consisting in five vertical beams pinned to the pool floor and four horizontal 6-nodes elements connecting each beam to the others and to the pool wall (see Fig. 4).

![Diagram of 2-dimensional Finite Element Model of Row of Modules]

Fig. 4 2-dimensional Finite Element Model of Row of Modules.
These four elements are there to simulate water coupling between the various solids and, therefore, as explained previously, are characterized by full mass matrices and empty stiffness matrices. In the first analysis, even numbered modules are considered as half loaded and therefore, bear smaller weights than the others.

The modal analysis is carried out and all the vibration modes are computed. In the seismic domain, i.e. for frequencies below 33 Hz, only five modes are present. They all correspond to horizontal displacements of all nodes. They are found in the range 4.7 to 5.1 Hz, well below frequencies that would prevail in the absence of water (respectively, 11.1 and 12.9 Hz, for fully or half loaded modules).

For each of the first five modes, all nodes of a given individual module deviate in the same direction; yet, it is only in the fifth that all five modules exhibit complete in-phase motion. In fact, the maximum displacement of each mode corresponds each time to a different module. With this direct relationship between mode and module motion, the first three modes, closely clustered, correspond to odd numbered modules that have a larger mass than the remaining two.

The fifth mode exhibits the greatest modal participation factor: those of modes 1 and 3 are roughly three times smaller, those of modes 2 and 4, roughly fifty times smaller. As all five frequencies are close, effective modal masses vary approximately as the square of the modal participation factors.

The sum of the first five effective modal masses accounts for less than 6% of the total mass of the system but for 90% of the unsupported mass. Important coupling masses are responsible for the large difference between the two concepts and the two criteria. Although sufficient for most practical purposes, it is generally not true that the sum of effective modal masses converges towards the total mass of a system and the difference turns out to be especially important in the case under consideration. As far as seismic behaviour is concerned, the correct convergence criterion is that which refers to the unsupported mass.

The spectral response of the system is then obtained taking into consideration all significant modes (accounting for 99.9% of the unsupported mass). The structure is assumed to be excited by the horizontal acceleration spectrum in the row direction. This spectrum is roughly characterized by a value of 1.0 g at 5 Hz, a peak value of 1.75 g between 8 and 14 Hz, and a zero period acceleration of .55 g.

To sum up the contributions of the various modes the grouping method is used [USNRC, 1976] and, actually, the first five modes fall into a single group. The spectral quantities (displacements, forces...) are shown to be very similar to that of pure mode 5, thus indicating that the overall motion cannot depart much from the in-phase motion corresponding to the principal mode. The water coupling limits the maximum displacement which is found to be equal to 3.4 mm at the top of the central module. This is much smaller than the initial clearance between two adjacent modules and in fact, even if the modules were to vibrate out of phase, they would not interfere with each other.

Study of reaction forces and moments shows that sliding or tilting of the modules cannot entirely be ignored, although the model used does not take these phenomena into consideration. However, as they would be initiated with a frequency close to that of mode 5, it can be inferred that these phenomena have only limited amplitudes. Therefore, the previous conclusion, stating that two modules never touch, holds true. It can also be shown that the same conclusion is reached for a row of fully loaded modules.
CONCLUSION

This paper presents a simple approach to the determination of the overall seismic behaviour of a spent fuel storage rack immersed in water. It is shown that, when clearance between module and pool walls is reduced, the fluid introduces an important coupling effect between modules which otherwise are entirely independent. For FRAMATOME type N325 storage rack, in case of horizontal safe shutdown earthquake, five modules, whether fully or partially loaded, aligned on the pool floor in the seismic direction, are shown to vibrate essentially in phase and with very limited amplitude. Therefore, the possibility of two modules impacting each other is ruled out.

REFERENCES