Structural Analysis of PWR Fuel Assemblies in LOCA and Seismic Conditions

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ABSTRACT

The purpose of this paper is a general presentation of the analyses performed by FRAGEMA to evaluate the efforts applied on the structure of the fuel assembly in accidental conditions.

In the accidental analyses, the vertical effect (LOCA) and lateral effect (LOCA and SEISM) are investigated separately.

That leads to the development of a vertical model of the assembly and a lateral model representing a row of 15 assemblies located on a symmetry axis of the core reactor.

The characteristics of the models are deduced from the results of various mechanical tests on fuel assembly prototype.

Typical results of LOCA and SEISM analyses are presented.

The paper presents also the results of sensibility analyses performed to evaluate the incidence on the fuel assembly behaviour of parameters such as gap between assemblies and vibrationnal properties of the fuel assemblies (frequency), and dynamic grids properties.
I INTRODUCTION

To get a sufficient safety level, the effects of hypothetical accidents have to be considered in the reactor design verification. For the PWR Fuel assemblies structure, the LOCA (Loss-of-Coolant Accident) is limiting. Furthermore, its effects are combined with those resulting from a safe shutdown earthquake (SSE).

Obtention of the corresponding efforts on the Fuel assembly requires a lot of analyses which are shown in the figure 1. The steps noted 1 and 2 generate the loading on the reactor system. The step 3 corresponds to dynamic non-linear analyses of the reactor system, which includes the vessel, the internals equipments and the core. The step 4 represents the final detailed analyses of the Fuel assembly structure behaviour.

For these analyses, the input data (obtained from the step 3) are:
- the impact forces applied at the bottom of the fuel assembly, when the vertical effects are evaluated;
- the displacements and velocities of the core plates and barrel (surrounding internals structure) when the transverse effects are analyzed.

The main parameters which are obtained through this step 4 are:
- the maximum compressive vertical forces applied on the various parts of the fuel assembly structure,
- the maximum horizontal impact forces on the spacer grid of the fuel assembly,
- the maximum lateral deflection of the fuel assembly.

The axial and lateral effects are separately computed. For each type of analysis, an associated fuel element model has been developed (axial and lateral models).

With these models, the designer performs the following type of evaluations:
- analysis of a fuel assembly axial drop,
- analysis of the transverse behaviour of a fifteen assemblies row under loading time history.

The present paper gives a detailed presentation of these models and some results obtained in typical analyses.

2 AXIAL ANALYSIS

2.1 Fuel axial modelisation

The finite element model is a lumped mass model with one dimensional spring and sliding elements (friction). The friction between the Fuel rods and the spacer grid is simulated by the sliding elements. The thimbles (structure supporting the Fuel rods) and the Fuel rods are represented by spring elements. This model is shown in figure 2.

The spring element characteristics are directly determined from geometric and materials considerations, except for the nozzles (end structural parts) whose stiffness has been got from compressive tests.
The sliding element characteristics are deduced from measurements on production assembly (drag force measurements).

Validation of the model is based on a comparison between the analytical results and those obtained during compressive static tests and axial impact tests (drop test) performed on fuel assembly prototypes.

Under static compression, the following parameters are evaluated: distribution of the compressive force on the thimbles and the Fuel rods, characteristics load-deflection at various elevations. The damping involved in the model is adjusted until a good agreement between analysis and impact test is obtained as to the impact force, the impact duration, the rebound amount (rebounds number). In this case, the stiffness of the struck load has been considered.

2.2 Typical results and sensitivity analyses

The fuel assembly is then extrapolated for hot (operating) conditions and used to determine the thimble stress in the various spans between grids as a function of the accidental impact force at the bottom end of the fuel assembly. Figure 3 shows the results so obtained in the lower two spans. Since the friction force between grids and fuel rod is modified under irradiation sensitivity analysis has been performed. It can be seen in figure 4 that the most severe effects are obtained on a fresh fuel assembly, when the friction effects are stronger.

The influence of the amount of damping in the various model elements have been investigated too. From figure 4 it is concluded that uncertainties in the damping data have a low effect on the fuel assembly response.

3 LATERAL ANALYSIS

3.1 Fuel lateral modelisation

The lateral modelisation of the Fuel assembly is shown in figure 5. This elementary model is repeated 15 times to obtain the fuel assemblies row model. To limit the computer time in the final accidental analysis, the number of degrees of freedom in the elementary model has been minimized.

This model consists of beam (and rotary springs) having the free vibrational characteristics of the fuel assembly and a set of one dimensional dynamic element (spring, dash-pot and gap) which are acting when the assembly impacts occur at the grid level.

The characteristics of these various elements are adjusted by referring to the results of an extensive test program including the following measurements:

- grid static stiffness,
- grid behaviour under lateral impact,
- fuel assembly transverse stiffness,
- vibrational features of the fuel assembly (natural frequencies, mode shapes, damping)
- assembly behaviour under lateral impact.
The results of the transverse stiffness test and of the free vibration test on the fuel assembly enable to fix the beams and rotary springs characteristics.

The comparison between analysis and test is illustrated by figure 6. Two types of elements are used to simulate the various impact conditions on the fuel assembly. When the grid impact compression is applied between the two opposite sides of the grid, the elements noted \( (K_e, C_e) \) : external grid characteristics in figure 5 are acting. Their characteristics are those obtained from the impacts tests on grids. When only a grid side is concerned by the impact, the other type of elements \( (K_i, C_i) \) : internal grid characteristics is also acting. Their characteristics are finally determined by comparison with the results of the fuel assembly lateral impact tests (see figure 7).

### 3.2 One row model

The model above determined is assembled to form a row of fifteen fuel assemblies (figure 8). In the LOCA analysis or the SEISM analysis this full model is loaded by input displacements and velocities at its boundary : lower and upper core plates and core barrel (at the grid levels). These input data come from the reactor system analyses. The time duration of the analyses is generally of 0.25 second for the LOCA and between 10 and 20 seconds for the SEISM.

Typical results for the LOCA analysis are shown in figure 9. This picture gives the displacements at center grid level for each of the fifteen fuel assemblies of the row. For such a loading impacts occur only near the core barrel and some fuel assemblies in the center of the row are never impacting.

Results shown in figure 10 and 11 are typical of a seismic analysis (corresponding time history given in figure 12). The total duration of the analysis is 15 seconds. Figure 9 shows the result for the first four seconds. Data reduction is presented in figure 13 : the impacts frequency versus the maximal impact force percentage is given for each fuel assembly.

### 3.3 Sensitivity analyses

Sensitivity analyses are performed on the LOCA nominal case above presented. The corresponding results of this reference analysis are shown in figure 14 : the distribution of impacts is given for each assembly.

The parameters deviations investigated are :
- gaps between fuel assembly grids,
- fuel assembly stiffness (beam inertia),
- grids characteristics.

The results of these analyses are illustrated by the figures 15 through 18.

From figure 19, it seems that the most sensitive parameter is the gap value between assemblies.

Even if the other parameters are largely modified (more than fifty percent) the spacer grid force change is less than fifteen percent.
FIGURE 1 - ACCIDENTAL ANALYSES SEQUENCE

FIGURE 2 - FUEL ASSEMBLY AXIAL MODEL

FIGURE 3 - FUEL ASSEMBLY STRESS UNDER AXIAL IMPACT

FIGURE 4 - AXIAL MODEL - INFLUENCE OF DAMPING INPUT DATA
**FIGURE 15** IMPACT FREQUENCY FOR LOCA GAPS INCREASE OF 42 %

**FIGURE 16** IMPACT FREQUENCY FOR LOCA GAPS DECREASE OF 42 %

**FIGURE 17** IMPACT FREQUENCY FOR LOCA BEAM INERTIA INCREASE OF 33 %

**FIGURE 18** IMPACT FREQUENCY FOR LOCA BEAM INERTIA DECREASE OF 42 %

**FIGURE 19** MAXIMAL IMPACT FORCE VARIATION VERSUS MODEL PARAMETERS DEVIATION FOR LOCA NOMINAL CASE