Transactions of the 13th International Conference on Structural Mechanics in Reactor Technology (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Tests and calculations on a scale one spent fuel storage rack

Moudrik, R.[1], Queval, J.C.[1], Gantenbein, F.[1], Champomier, F.[2], Trollat, C.[3]
1) CEA - CE/SACLAY, DRN/DMT/SEMT/EMSI, Gif-sur-Yvette Cedex, France
2) Framatome, Paris la Defense Cedex, France
3) EDF/SEPTEN, Villeurbanne Cedex, France

ABSTRACT: Several tests on a shaking table have been conducted on a scale one spent fuel storage rack in air, during which sliding and uplift have been measured. In parallel a finite element model has been developed to determine the behaviour of the rack.

1 INTRODUCTION

In a PWR reactor, spent fuels are stored in racks set in a pool. During an earthquake coupling between the racks and between racks and the pool by the fluid but also sliding and impacts occur. So it is necessary to study the racks behaviour in their environment and the effect of some parameters such as :

- fluid ;
- loading (number of fuel assemblies) ;
- gaps ;
- sliding coefficient between racks feet and the base of the pool.

For this purpose, EDF, FRAMATOME, and CEA have launched a large research program on several mock–ups (scale 1, scale ½ and scale ¼). This paper presents the first part of the research program devoted to the study of a scale one rack in air without assemblies, and for model validations.

2 PRESENTATION OF THE SCALE ONE FUEL STORAGE RACK

The tested rack is a P'4 storage rack built by SULZER. This rack (figure 1) consists in :

- 63 connected cells (9X7) ;
- a rectangular lower plate with 14 peripherical legs.

A cell consists in 2 concentric envelops with inside boral plates. The weight in air and without fuel assemblies is 16 tons. The principal dimensions of the rack are:

- height = 5,4 m
- width = 2,0 m
- length = 2,6 m

After a validation of this model on the eigen frequency analysis, it was applied to interpret the tests with acceleration levels such that only sliding occur.

3 TESTS

3.1 PROGRAM

Preliminary tests have been performed with a shaker to measure the eigen frequency of a single cell.

The seismic tests have been performed on a large biaxial 6m X 6m table at CEN Saclay and have been composed by:

- sine sweeps to measure the eigen frequencies of the rack ;
- seismic tests with increasing levels between 0,1 g and 0,6 g.

Two synthetic accelerograms have been calculated from the same floor response spectra.

The instrumention consisted in :

- horizontal and vertical accelerometers to measure frequencies and motions of the rack ;
- horizontal displacement sensors at the base to measure the rack sliding on the table ;
- vertical displacement sensors to measure the uplift of the rack.

3.2 RESULTS

Eigen frequencies

In air the first frequency of a single cell has been measured at 8,2 Hz. At low level excitation (0,1 g), the first frequencies of the rack are 18,8 Hz in the major axis (OX) and 17,8 Hz in the minor axis (OY).

The seismic tests show a non linear response of the rack. The frequencies decrease with the excitation level. For high excitation level (0.2g – 0.6g), the frequencies are 14 Hz and 11Hz.

Seismic test results

For the OX axis, during seismic tests, slidings have been observed. The sliding reached 50 mm peak to peak without uplift for 0.6 g on the table. During sliding phases, oscillations are measured with frequencies located in range 22 Hz – 25 Hz at the top of the rack. This frequency range corresponds to the free–free mode of the rack. These oscillations produce high level accelerations at the top of the rack.

For the other axis (OY), slidings and important uplift motions have been measured for table accelerations over 0.5 g. The vertical displacement reachs 24 mm and produce impacts between legs and table.

In function of the table acceleration, several parameters have been studied (figure 2) :

- the global sliding (figure 3);
- the maximum sliding (figure 4);
- the residual displacement (figure 5).

For the 2 directions, the sliding begins when the acceleration is over 0.27 g. The static friction coefficient value of the legs on the table is estimated at 0.26.

4 CALCULATION

4.1 LINEAR MODEL

A linear model of the rack has been developed. The model is presented in figure 6. It consists in a beam which represents the cells (section $S = \Sigma S_i$ and inertia $I = \Sigma I_i$). A mass was added at the base to represent the base plate and legs. The spacing of the legs to the rack centre is taken into account by a rotary spring : $K_\psi = \frac{ES_l}{L} \sum_{i=1}^{14} y_i^2$

where S_l and L are the section and the length of the leg, E is young's modulus and y_i is the spacing of the leg to the rack center axis.

To take into account links between cells, rotary stiffnesses are introduced between the beam nodes. These stiffness values are obtained in the same way than the previous equation.

As tests performed on a single cell showed that the link between the cell and the base plate is not a perfect clamping a rotary stiffness element is added between the beam modelling the cells and the one modelling the base plate and legs. This stiffness is obtained by adjustement on the cell tests.

The calculated frequency with this rack model is 37.6 Hz which is not in good agreement with test results. This discrepancy is related to the links between cell as it was supposed there is no rotation of the sections of the cells while a small vertical displacement between cells can occur.

A reduction coefficient has then been applied to the stiffness values of the links between cells so that calculated frequency agrees with test results at low excitation level (18.8 Hz).

For high excitation level reduction coefficients have been also be applied to the stiffness k_X of legs (see figure 1). After this correction, calculated and measured modal shapes are in good agreement and the frequency is in good agreement with seismic test results (14 Hz at 0.4 g).

These results show that it is very difficult to model :

- the links between cells ;
- the link due to the legs bolted in the base plate.

4.2 NONLINEAR MODEL

Base on the first model, a nonlinear model has been also developed to take into account the sliding during high level excitation. At the base, the boundary condition is modelled by the Coulomb model. According to this model, friction Coulomb force is applied to the contact point during sliding phase:

$$F_T = - \mu |F_N| \frac{U'_t}{|U'_t|}$$

in which μ is friction coulomb coefficient, F_N is the normal force, U_t and U'_t are relative displacement and relative velocity between the contact point and the base. During adherence phase, a stiffness spring K_T and a critical damping C_T are added, to the contact point in order to have velocity equal to zero. Friction force is then given by the equation following

$$F_T = - K_T\left(U_t - U_o\right) + Fg_o - C_T\ U'_t$$

in which U_0 and Fg_0 are the contact point relative position and friction force at the end of the previous sliding phase.

In this calculation, a modal superposition method is used and the equation of motion are integrated with an explicit time integration method. The calculated time history of the base relative displacement and top acceleration calculated and measured, for support acceleration 0,43g (earthquake #1), are in good agreement with test results (figures 7 and 8). The difference between calculated and measured maximum displacement is less than 4%. The calculated top acceleration spectra at the top of the rack (figure 9) shows that we obtain oscillations with a frequency at 22 Hz, like during seismic tests. These oscillations are generated at the top of the rack by the sliding and appear only during the sliding phases.

5 CONCLUSION

A scale one P'4 storage rack was tested on a large shaking table. Tests showed :

- The dynamic response of the rack is nonlinear. The first mode frequency decreases in function of the excitation level (18.8 Hz to 14 Hz).
- For a seismic excitation along the major axis, slidings appeared for table accelerations over 0.27 g. The sliding of the rack reached 50 mm peak to peak for 0,6 g on the table.
- During the sliding phases, oscillations are observed at the top of the rack. The frequency of these oscillations corresponds to the free–free mode frequency.
- For an excitation along the minor axis, slidings and uplift are measured. Rocking appeared for table accelerations over 0.5 g. The uplift reached 24 mm.

The nonlinear finite element model using the friction Coulomb force to model the sliding allowed to calculate with a good agreement the time history responses, the maximum acceleration and displacements for seismic tests with sliding and without uplift.

In addition, this nonlinear model will be modified to study the uplift of the rack. Test performed on a reduced scale mock–up will allow to study the effect of water and loading on the rack behaviour.

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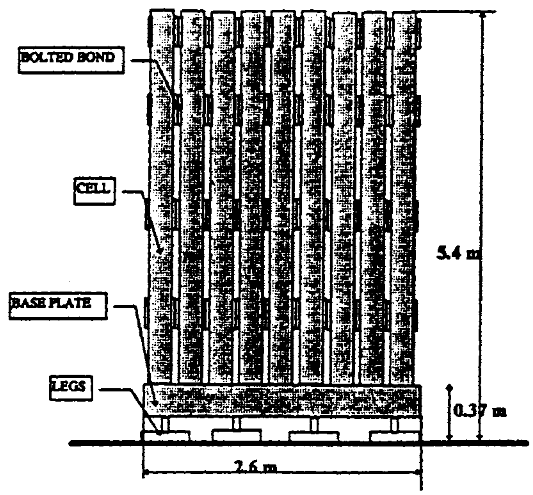

Figure 1: P'4 STORAGE RACK

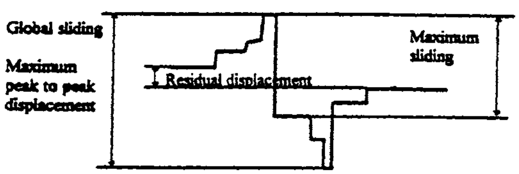

FIGURE 2 - Studied parameters for seismic tests

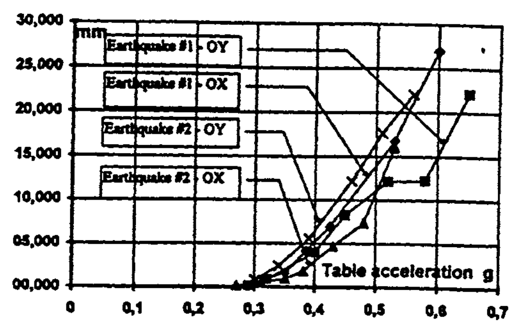

FIGURE 3 – Maximum sliding measured during all seismic tests

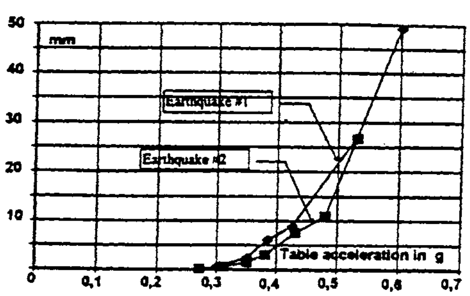

FIGURE 4 - Maximum peak to peak displacement

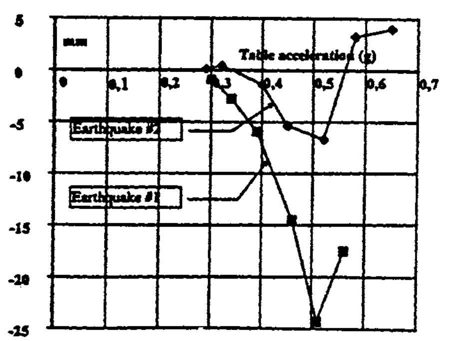

FIGURE 5 - Residual displacement (Excitation in OY)

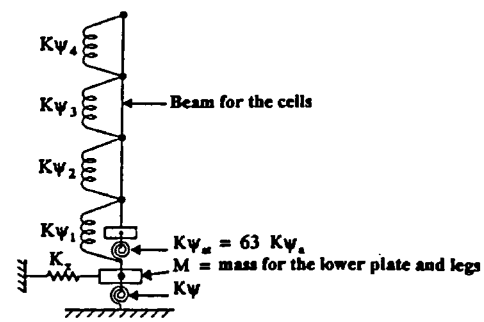

FIGURE 6: Linear rack model

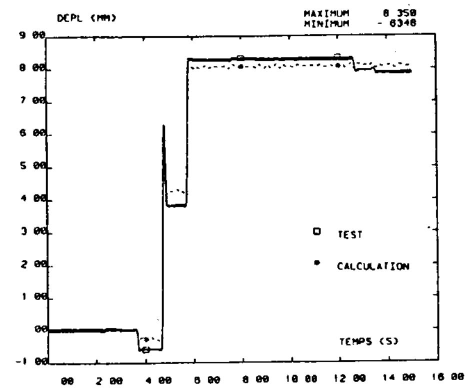

FIGURE 7: Relative base displacement

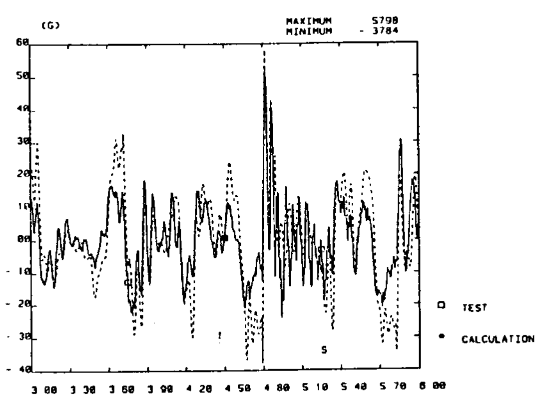

FIGURE 8: Top acceleration

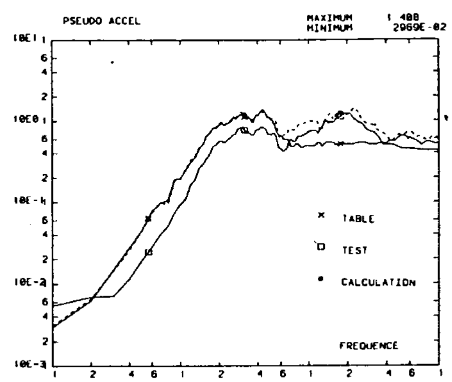

FIGURE 9: Top acceleration and table spectra