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

Nonlinear dynamic response of whole pool multiple spent fuel racks subject to three-dimensional excitations

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ABSTRACT: The seismic evaluation of submerged free standing spent fuel storage racks is more complicated than most other nuclear structural systems. When subject to three dimensional (3-D) floor seismic excitations the dynamic responses of racks in a pool are hydrodynamiclly coupled with each other, with the fuel assemblies stored inside the racks, and with the pool walls through the accelerated surrounding water in gaps. The motion behavior of the racks is significantly different from that observed using a 3-D single rack model. Few seismic analyses using 3-D whole pool multiple rack models are available in literature. In this paper an analysis was done for twelve racks using potential theory for the fluid-structure interaction, and using a 3-D whole pool multi-rack finite element model developed herein. The analysis includes the potential nonlinear dynamic behavior of the impact of fuel-rack, rack-rack, and rack-pool wall, the tilting or uplift and the frictional sliding of rack supports, and the impact of the rack supports to the pool floor.

1 INTRODUCTION

The U. S. Nuclear Regulatory Commission (USNRC, 1979, 1981) has issued the licensing criteria and requirements for spent fuel storage rack activities onsite. Seismic evaluation is one of the most important and complicated regulatory requirements. Because of the fluid-structure interaction effects and the highly nonlinear nature of the potential impact of fuel-rack, rack-rack, and rack-pool wall, and the frictional motion of free standing rack supports against the pool floor in seismic events, the evaluation of submerged free standing spent fuel racks for earthquake loading is more complicated than for most other nuclear structural systems (DeGrassi, 1992). Rack sizes and adjacent gap dimensions are key factors to determine the hydrodynamic effects (Fritz, 1972; Dong, 1978) and are usually unsymmetrical in practice. Thus the dynamic behaviors of racks are different from rack to rack and should be analyzed using a whole pool multi-rack model since all fuel assemblies, racks, and pool walls are hydrodynamically coupled.

Most references available are about analyses using 3-D single rack models or 2-D multiple rack models as summarized by DeGrassi (1992). However, few analyses and results using a 3-D whole pool multiple rack model have been reported. Singh and Soler (1991) reported briefly a 3-D whole pool multiple rack analysis they performed using the component element method.

In this paper the modeling and analysis of a 3-D whole pool multi-rack model developed for an independent seismic evaluation of twelve racks in a storage pool for a typical PWR nuclear power plant are summarized.

2 3-D WHOLE POOL MULTI-RACK MODEL

Figure 1 presents the layout of nine new racks referred to as N1 through N9 and three existing racks as E1 through E3. Figure 2 shows a typical welded honeycomb stainless steel rack module with 12x13 cells, in which the standard 17x17 fuel assemblies are stored. Every new rack has four support legs, while each existing rack has seven. The 3-D whole pool multi-rack finite element model developed (Figure 3) consists of twelve 3-D single rack stick models and can effectively simulate the physical responses of all the racks.

The typical 3-D single rack model for the new racks (Figure 4) consists of a total of 38 elements (including 20 material nonlinear truss-gap impact elements and 4 geometrical nonlinear contact-friction elements) with 96 DOF and 9 1-D rigid links. There are only two lumped rack and fuel masses specified at the rack top and bottom. Assuming all the fuel assemblies moving in phase, the fuel-rack impact in the four horizontal directions is simulated using eight impact elements and eight 1-D rigid links. A 1-D rigid link vertically connecting the rack and the fuel bundle at the rack bottom is defined assuming they remain in contact on a frictionless surface. Four 3-D contact-friction elements are defined to represent the support leg and pool floor interfaces. The potential impact between the four supporting legs and the pool floor is modeled using four impact elements. In addition, eight impact elements are included to represent the potential impact between the rack and the adjacent racks or pool walls. Each existing rack stick model developed has a total of 49 elements (including 23 impact and 7 contact-friction elements), 138 DOF, and 9 1-D rigid links. In summery the 3-D whole pool multi-rack model consists of 407 elements (including 184 impact and 57 contact-friction elements), 1296 DOF, and 108 1-D rigid links. All the new and existing rack modules, surrounding water, and pool walls are hydrodynamically coupled in the model.

The fluid-structure interaction can be rationally taken into account using the added hydrodynamic mass concept based on potential theory (Fritz, 1972; Dong, 1978; DeGrassi, 1992; USNRC, 1979, 1981). This approach allows use of available structural analysis finite element codes and the stick model. The hydrodynamic mass M_{Hx} for two submerged rectangular cylinders with non-uniform gaps filled with water as shown in Figure 5 due to relative motion in the X direction was derived based on the work by Scavuzzo (1979), Pop (1990), and Singh (1990) as:

$$M_{Hx}=2\rho hC^2(C/3g_1+C/3g_3+B/g_2+B/g_4) \tag{2.1}$$

in which, ρ is water mass density, h is the cylinder height, C and B are the nominal dimensions, and g_1, g_2, g_3 and g_4 are the gap sizes. The hydrodynamic coupling between any two solid masses, Mass 1 representing a fuel bundle and Mass 2 a rack, is then described as "adding" forces by

$$\begin{vmatrix} F_{X1} \\ F_{X2} \end{vmatrix} = \begin{vmatrix} M_1+M_2+M_{HX} & -(M_1+M_{HX}) \\ -(M_1+M_{HX}) & M_{HX} \end{vmatrix} \begin{vmatrix} \ddot{X}_1 \\ \ddot{X}_2 \end{vmatrix} \tag{2.2}$$

where, F_{X1} and F_{X2} are the adding forces acted on Mass 1 and Mass 2 separately. M_1 and M_2 are the water masses displaced by Mass 2 and enclosed by Mass 1 in the absence of Mass 2, respectively. $\ddot{X}_1$ and $\ddot{X}_2$ are the absolute accelerations of Mass 1 and Mass 2.

The mass matrix in Equation (2.2) is easy to calculate and add to the structural finite element model. An in-phase motion of the racks may be conservatively assumed (DeGrassi, 1992; Pop, 1990). The effect of the variation of the gap sizes on the hydrodynamic mass during a seismic event is not large until the gap on one side becomes very small (Singh, 1990). Zhao (1995) gave the detailed modeling and associated impact stiffness analyses.

3 3-D NONLINEAR DYNAMIC TIME HISTORY ANALYSIS

The static Coulomb friction coefficient of 0.2 (USNRC, 1979, 1981) was found to be the upper bound to describe the sliding friction resistance in the 3-D single rack model analyses (Zhao, 1995) and, therefore, was used herein. Rayleigh damping (Clough and Penzien, 1975) used in the analysis was determined using the prescribed critical viscous damping of 3% in a frequency range of 5Hz to 25Hz. The prescribed uncorrelated 3-D floor seismic time histories of a safe shutdown earthquake (SSE) event with peak floor horizontal accelerations of 0.2g were applied simultaneously plus the rack deadweight. A time step of 0.0015 seconds was determined to achieve a good convergence. The general purpose nonlinear finite element code SOLVIA (1992) used for the nonlinear 3-D dynamic analysis has been commercial for six years and was developed from the well-known ADINA code.

4 RESULTS AND DISCUSSIONS

Typical response results obtained (Figures 6 and 7) indicate that the rack motion is governed by the sliding because the displacements at the rack top and bottom are almost identical (Figure 6). No tilting or uplift occurs since the contact gaps at the support interfaces are always closed. The rack displacements are less than the surrounding gap dimensions and, therefore, no rack-rack or rack-pool wall impact occurs for all the 12 racks. Rack N4 exhibits the largest displacement of 0.01 m in the E-W direction (Figure 7). One explanation may be that Rack N4 is one of the largest (12x13) modules with larger inertia and hence larger displacement than other smaller modules. Another reason may be due to the smaller adjacent gaps (Table 1) and the larger hydrodynamic effects on its motion than other 12x13 modules. Further, for Rack N4 itself a larger hydrodynamic mass was computed in the E-W direction than in the N-S direction. Even though Rack N5 has smaller gaps than Racks N4 and N7 (Table 1), it exhibits smaller displacement responses than Racks N4 and N7 because the adjacent racks are smaller and the hydrodynamic coupling effects are weaker. The fuel-rack impact happens only at a few instants with a maximum of 3990 Newtons per cell with Rack N4 in the East direction (Figure 7). Of the three existing racks, Rack E2, with the strongest hydrodynamic effects, exhibits the largest displacements which are about 3.5 times lower than those of Rack N4. No fuel-rack impact is found with the existing racks. This study indicates that the stronger the hydrodynamic coupling effects with a rack in a particular direction, the higher its dynamic responses in the same direction.

One of the important findings through this study is that the displacements at the top of Rack N7 are about 2.8 (in the N-S direction) to 3.2 (in the E-W direction) times those determined in the 3-D single rack model analyses with the same excitations and friction coefficient of 0.2 (Zhao, 1995), which means that the 3-D single rack model may under predict the responses by about three times those observed using the whole pool multi-rack model. A whole pool multi-rack model is recommended for a layout design of racks.

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Table 1 Dimensions of Racks and Adjacent Gaps (1.0 inch = 2.54 cm)

Dimension (inch)	Rack Module I.D.											
	N1	N2	N3	N4	N5	N6	N7	N8	N9	E1	E2	E3
2B	110.59	110.59	110.59	109.34	109.34	109.34	109.59	109.59	109.59	111.50	111.50	111.50
2C	119.51	109.34	119.51	119.51	109.34	119.51	119.51	109.34	119.51	111.66	111.10	114.10
g_1	2.99	2.99	2.99	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00
g_2	2.70	0.50	0.50	2.70	0.50	0.50	2.70	0.50	0.50	2.70	1.60	1.60
g_3	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	2.99	2.99	2.99
g_4	0.50	0.50	2.70	0.50	0.50	2.70	0.50	0.50	2.70	1.60	1.60	7.60

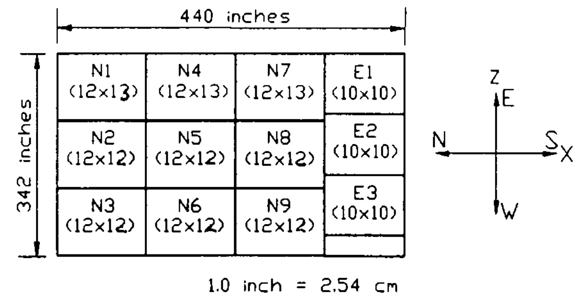


Figure 1 Rack Layout in a Storage Pool

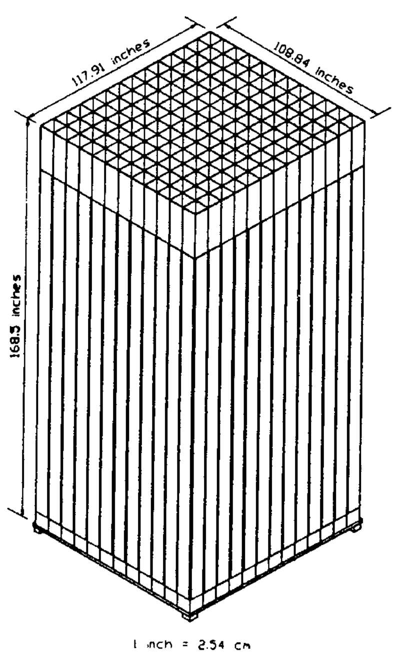


Figure 2 Typical 12x13 Cell Rack

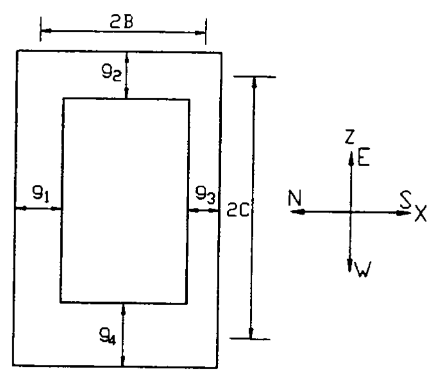


Figure 5 Cross Section Dimensions of Two Cylinders Coupled by Fluid

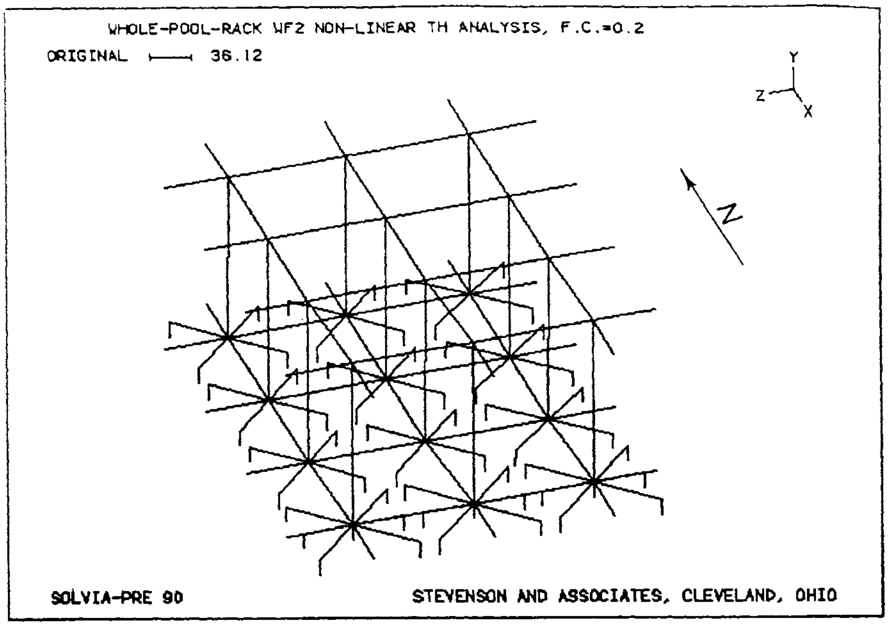


Figure 3 3-D Whole Pool Muilti-Rack Finite Element Model

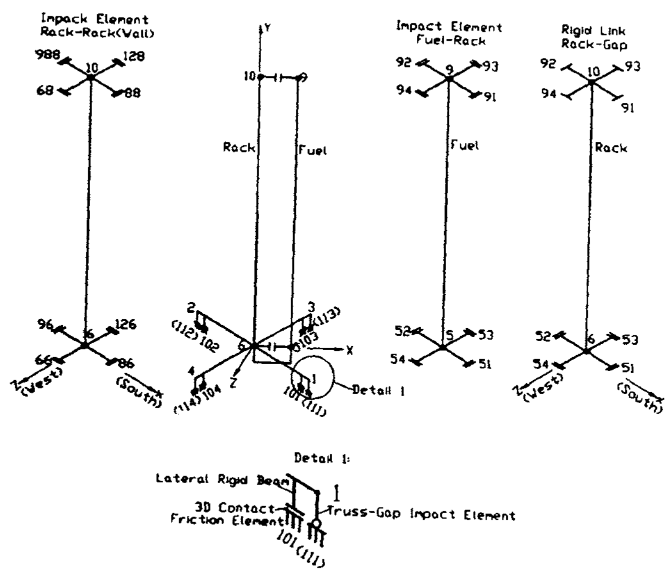
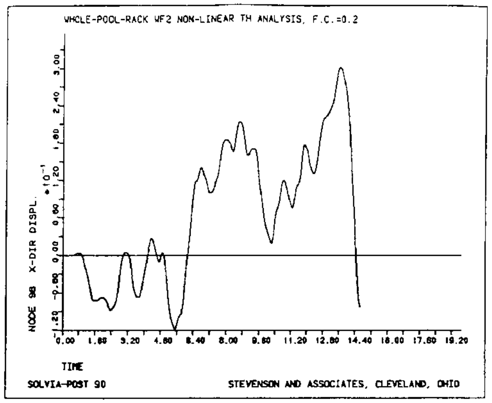
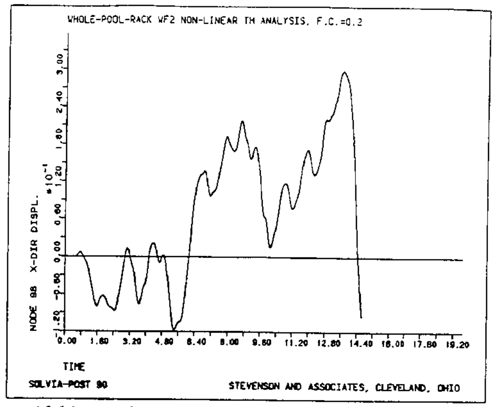


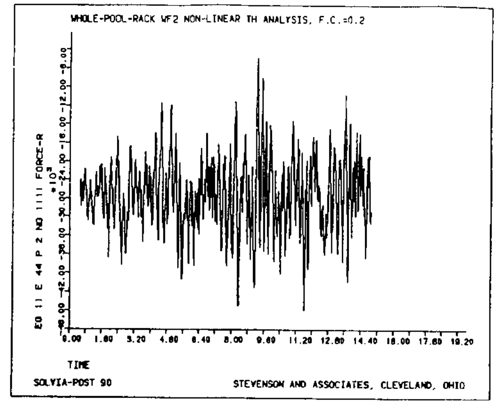
Figure 4 Typical Stick Finite Element Model of a New Rack in the Pool



(6-a) Rack Top Displacement in the N-S

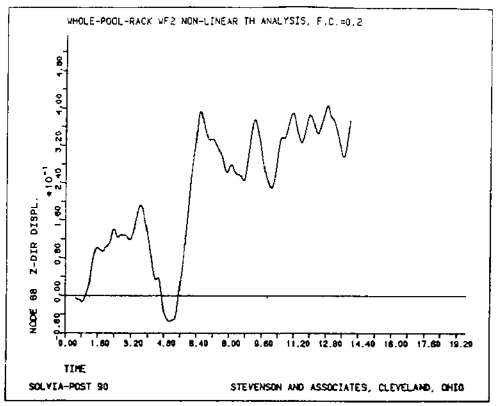


(6-b) Rack Bottom Displacement in the N-S

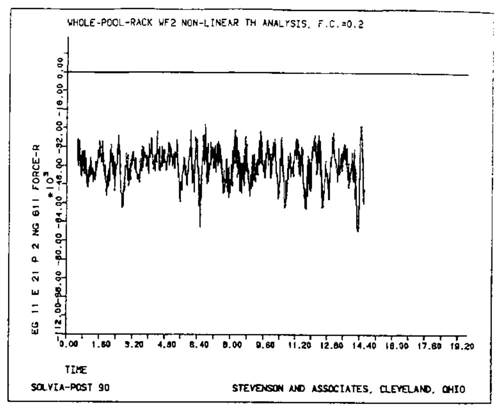


(6-c) Contact Force at Bottom of S-W Rack Support

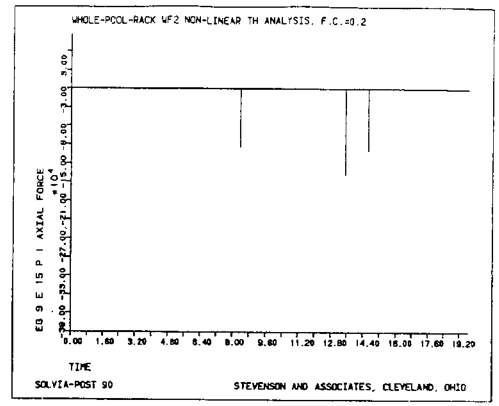
Figure 6 Typical Responses of Rack N7 (1.0 in = 2.54 cm, 1.0 lbf = 4.448 N)



(7-a) Rack Top Displacement at in the E-W



(7-b) Contact Force at Bottom of S-E Rack Support



(7-c) Fuel-Rack Impact at Top in East Direction

Figure 7 Typical Responses of Rack N4 (1.0 in = 2.54 cm, 1.0 lbf = 4.448 N)