Nonlinear analyses of spent-fuel racks for consolidated fuel loading

A.F.Kabir, L.E.Malik & S.Bolourchi
URS/John A.Blume & Associates, San Francisco, Calif., USA
P.C.Godha
Northeast Utilities Service Company, Hartford, USA

1 INTRODUCTION

Storage racks for spent-fuel assemblies in nuclear power plants are designed to withstand various combinations of loads generated by gravity, seismic, thermal, and accidental fuel drops. Due to the need for storing increased amounts of spent fuel in the existing fuel pools, many nuclear power utilities are evaluating existing fuel racks to safely carry the additional loads. The current study presents the seismic analyses of existing fuel racks of Northeast Utility Company's Millstone Unit Number 1 (BWR Mark I) nuclear plant to accommodate a 2:1 fuel consolidation. This objective requires rigorous nonlinear analyses to establish the full available capacities of the racks and thereby avoid expensive modifications or minimize any needed upgrades.

2 DESCRIPTION OF FUEL RACKS

The fuel racks are typically 46 in. by 72 in. by 176 in. high, made of stainless steel, with a honeycombed cellular cross-section. The cells are slender tubes, 6.5 in. by 6.5 in. in cross-section, which are welded together. Fuel rods are to be consolidated into canisters and placed inside the rack cells. The fuel pool contains 32 racks organized into six "super modules" (Figure 1). Each super module contains 6 or 4 racks welded together by tie plates. The super module support legs are free-standing on the fuel pool floor, and the entire super module assembly is laterally braced 9 in. above the base against the pool walls.

Several complex phenomena may take place when the fuel racks are subjected to vibratory ground motions during an earthquake. The fuel canisters are free-standing inside the rack cells with a 0.125-in. gap. They may sway and impact against the cell walls producing locally concentrated impact forces. The super modules are only 1 in. apart at the top in the north-south direction and may impact against each other. Furthermore, the super module legs may slide and/or uplift. The entire super module assemblies are submerged under borated water, and the water dynamically couples the responses between the fuel canisters and the rack cells, between the super modules themselves, and between the super modules and the adjacent pool walls.

The hydrodynamic effects are very important, as studies (Dong, 1978; Fritz, 1972) have shown that they tend to make different components to move in phase and thus reduce potential impact between them. The fuel pool slab, on which the six super modules are placed, is flexible in the vertical direction and has different vertical motions at different locations, thus subjecting the racks to different support excitations.

3 MATHEMATICAL MODELS

Two mathematical models are developed to obtain seismic responses of the fuel racks. A nonlinear 3-D model is developed to obtain global responses of the super modules. A detailed linear 3-D finite element model of a fuel rack is developed to obtain detailed seismic stresses and forces in various members for structural evaluations. The general purpose finite element computer program ADINA (1984) is used for model development and analysis.

The 3-D nonlinear global model (Figure 2) is developed to account for global aspects of the super module behavior in the fuel pool, such as hydrodynamic coupling and possible impact between modules. Since consideration of full 3-D models of all the six super modules is computationally expensive, only super module 1 (the heaviest super module) is modeled as three-dimensional. The adjacent super modules 5 and 2 are modeled in 2-D to interact with super module 1 for east-west motion. Similarly, a 2-D rpresentation of module 3 is obtained for interaction in the north-south direction. Coupled mass matrices between the adjacent super modules and between super modules at the perimeter and the fuel pool walls represent the hydrodynamic coupling. Nonlinear gap elements are provided between the super modules to monitor possible impact.

The stiffness properties of fuel racks and fuel canisters in a super module is represented by vertical beams. Eccentricities between fuel mass and the center of stiffness is considered for possible torsional effects. The gap closing and possible impact between the fuel canisters and the racks are monitored by nonlinear gap elements. The hydrodynamic coupling is modeled by providing coupled mass matrices, similar to those derived by Soler et al (1982), between the fuel canister and the rack mass nodes.

The interface between the support legs and fuel pool slab are modeled by three-dimensional contact-friction elements to account for possible sliding and/or uplift. Seismic lateral restraints at the base of the modules are modeled as nonlinear compression only members.

The detailed linear finite element rack model utilized plane stress and prismatic beam elements. Figure 3 is a schematic representation of this model.

4 ANALYSIS PROCEDURE

The nonlinear 3-D model is used to obtain global responses, such as super module acceleration, displacement, shear forces and overturning moments, uplift and impact of the rack legs on the pool slab, forces due to impact of fuel canisters against rack cells, and reaction forces in the lateral seismic restraints. The model is subjected to three components of seismic displacement time history at the pool slab location. Multiple support excitation procedure is used to consider the varying vertical motion under the four super modules.

The linear 3-D model is used to obtain detailed stress results in the various components of a single fuel rack for rack evaluation. The maximum force patterns on the super module 1 are proportionately applied at different nodes of the linear rack model as a static load to obtain detailed stresses for rack component evaluation.

5 DISCUSSION OF RESULTS

Figure 4 presents the axial force responses in leg 3 (extreme west side) of super module 1. The leg force can be compressive only as it uplifts when subjected to tension. The response plot indicates that the super module rocks with the legs at the edges uplifted alternately quite a few times due to seismic motion. The impact of the legs on the pool slabs when they fall back after each uplift produces high compressive forces in the legs. These are represented by the sharp peaks after each time the axial force becomes zero (denoting uplift). Figure 4 also indicates that the average compressive force in leg 3 is about 120 kips, which is the reaction in the leg due to static dead load only. The reaction increases by a factor of 4 due to impact after uplift.

Figure 5 presents the relative displacement between the fuel canisters and fuel racks. Since these are separated by a gap of 0.125 in., a displacement of 0.125 in. indicates the canisters are pressing against the fuel rack causing impact forces.

Figure 6 presents the axial forces in lateral seismic restraints for super module 1 at the south side of the pool. These restraints take compressive forces only when the rack modules press against them. Zero forces indicate that the super module is disengaged from the restraint and is pressing against the other side. The figure presents the time periods when the module 1 is pressing against the lateral restraint and is disengaged. The sharp peaks at the start of each engagement indicate the impact of the super module againast the lateral restraint.

The responses from the 3-D nonlinear model indicate super module leg uplift from and impact on the pool slab, pressing and disengagement of super modules against lateral restraints, and impact of fuel canisters on the fuel rack cell walls. These nonlinear effects cause high impact forces which are to be considered in fuel rack and pool floor evaluation.

6 SUMMARY AND CONCLUSIONS

The 3-D nonlinear model of four neighboring super modules captures the significant seismic responses of the fuel racks as configured in the Millstone 1 Fuel Pool. The model allows consideration of interaction between the super modules by hydrodynamic mass coupling as well as monitoring possible impact between the super modules. The variation in vertical seismic input to the super modules due to pool slab flexibility is accounted for by using a multiple-support-excitation procedure. The responses show significant nonlinear effects, such as super module leg uplift due to rocking, impact of super modules against lateral seismic restraints, and impact between the fuel canisters and rack cell walls. These nonlinear effects cause high impact forces which are to be considered in fuel rack and pool floor evaluation.

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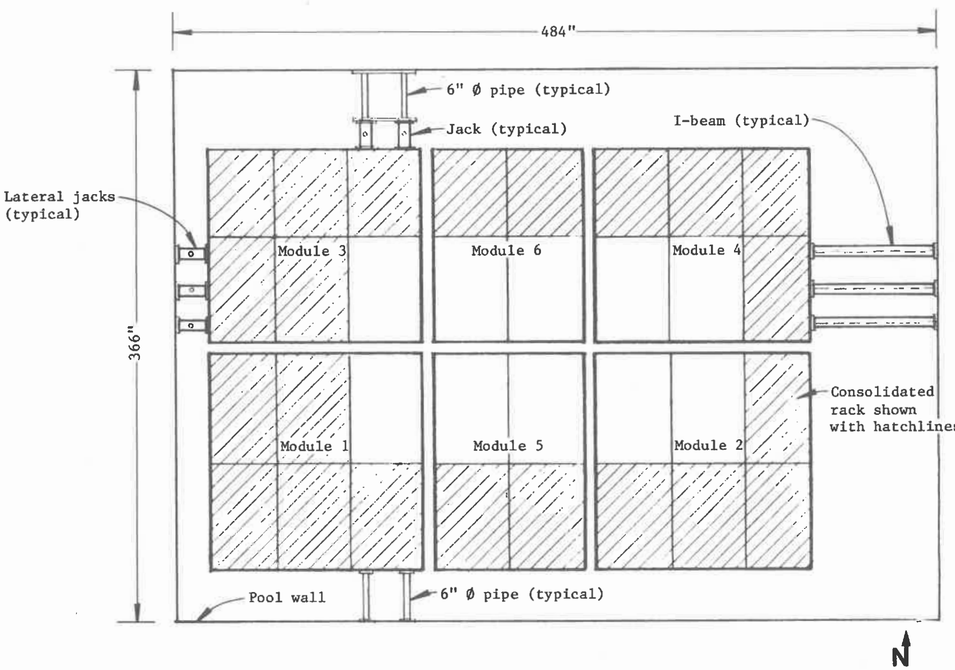


Figure 1 Fuel Pool Plan Showing Fuel Racks

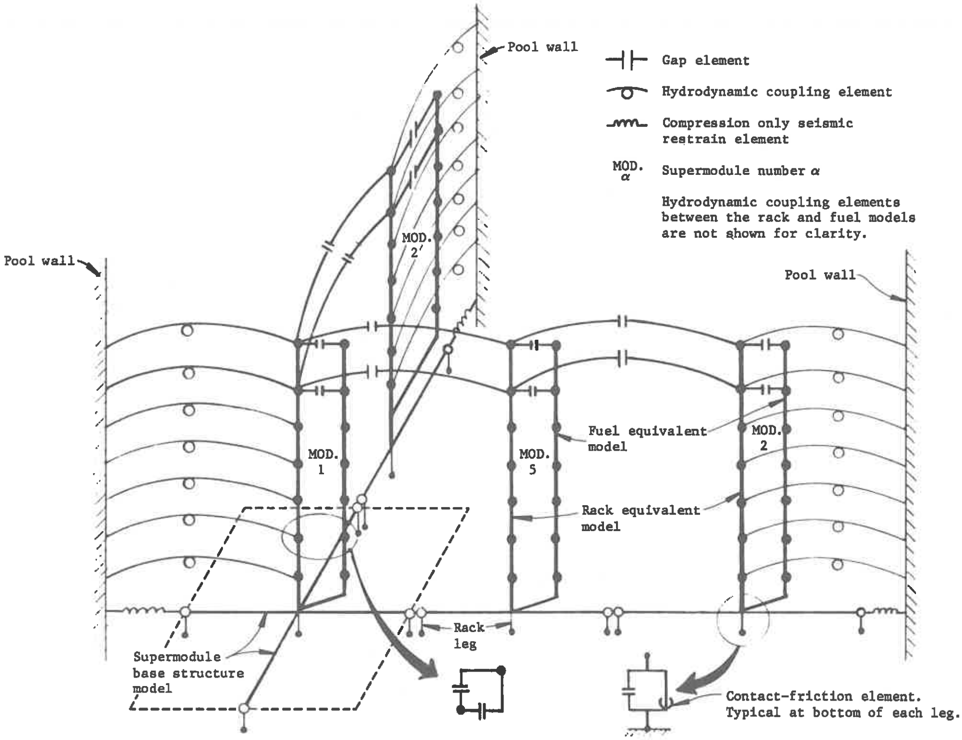
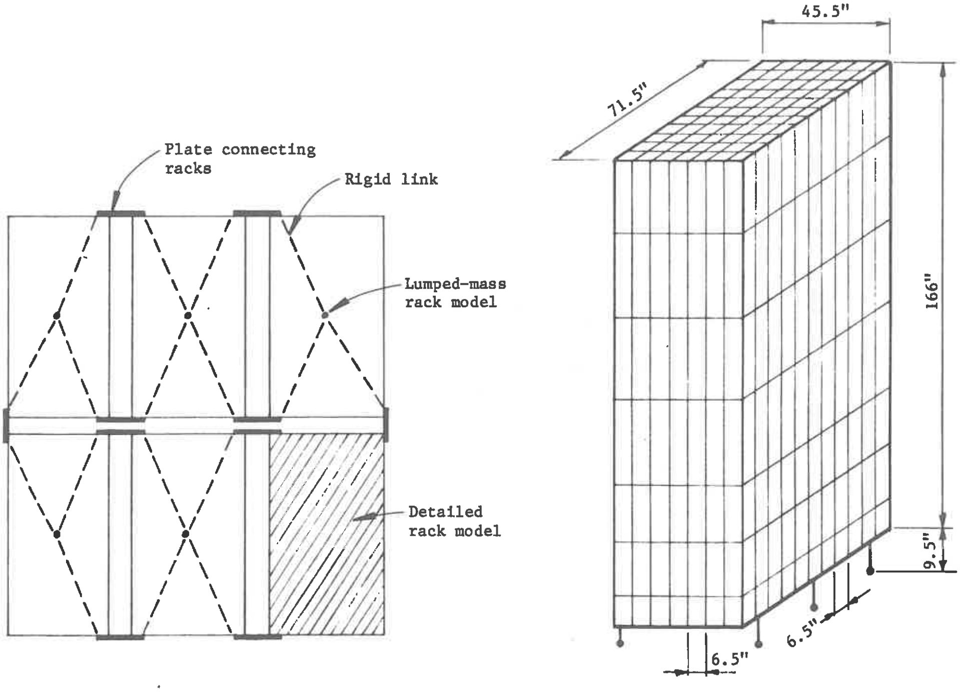


Figure 2 Schematic Representation of Nonlinear Seismic 3-D Global Model



a. Plan of Supermodule 1

b. Detailed Rack Model

Figure 3 Detailed Linear 3-D Model

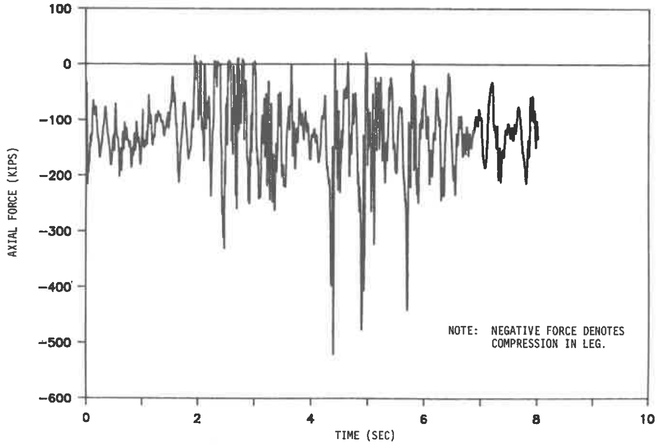


FIGURE 4 AXIAL FORCE IN LEG 3 OF SUPERMODULE 1

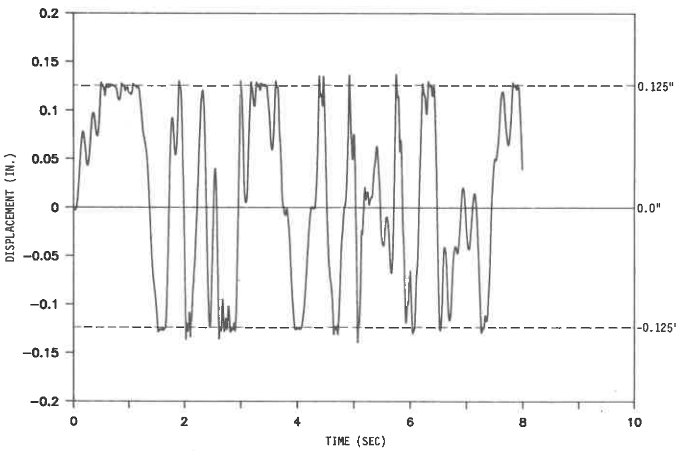


FIGURE 5 EAST-WEST DISPLACEMENT OF FUEL CANISTER RELATIVE TO FUEL RACK (TOP ELEVATION, SUPERMODULE 1)

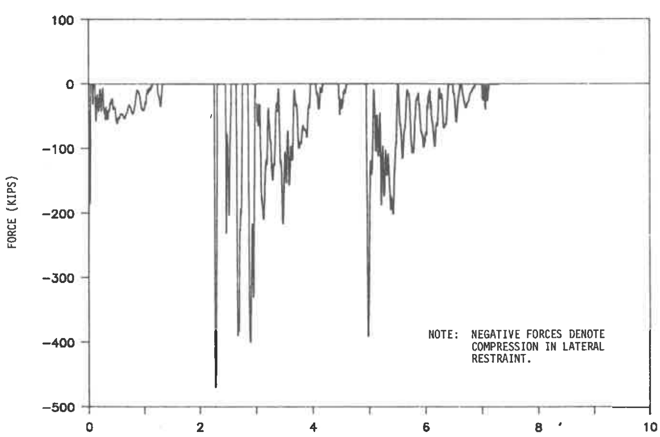


FIGURE 6 AXIAL FORCE IN SEISMIC LATERAL RESTRAINTS (SUPERMODULE 1 TO POOL SOUTH WALL)