Nonlinear Analysis and Evaluation of a Reinforced Concrete Spent Fuel Storage Pool for Accidental Thermal Loads

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ABSTRACT

A feasibility study was conducted for addition of consolidated fuel racks to an existing reinforced concrete spent fuel storage pool of a Mark I BWR plant. Nonlinear analysis of a detailed three-dimensional model of the fuel pool, considering cracking in concrete under gravity and thermal load conditions, showed that the pool has reserve capacities to carry the additional loads.

1 INTRODUCTION

There is currently a great need to store increased amounts of spent fuel in existing fuel pools of nuclear power plants because of delays in establishment of a permanent storage site. Many nuclear power utilities are evaluating existing fuel pools to carry these additional loads. The current study presents the gravity and thermal load evaluation of a BWR Mark I fuel pool to accommodate 48% more fuel. This objective required rigorous nonlinear analysis of the fuel pool to establish the capacity of the pool without any undue conservatism, and, thereby avoid expensive modifications or minimize any needed upgrades.

2 DESCRIPTION OF THE FUEL POOL

The storage pool is a reinforced concrete rectangular structure 30 ft by 40 ft in plan and 40 ft high. It is located between elevations 70 ft to 110 ft above ground in the reactor building. The fuel pool has 5 ft thick walls and 5 ft thick base slab. The base slab is supported by thick perimeter walls and reactor wall. There is a 3/16 in. thick steel liner plate in the interior face of the fuel pool. The fuel pool is filled with water up to a height of 37 ft 9 in. from the bottom of the pool floor.

3 MATHEMATICAL MODEL

A three-dimensional finite element model of the fuel pool was developed to calculate stresses in the fuel pool walls and base slabs under gravity and

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thermal loads. The concrete slab and walls of the fuel pool were modeled with 8-node isoparametric solid elements. The fuel pool slab had five layers of solid elements across the depth to rigorously model the stress distribution due to bending of the slab. The top and bottom layers of the slab were modeled with 12-node isoparametric elements to facilitate placement of top and bottom steel reinforcement layers. The steel reinforcement layers in the slab and walls were modeled by two-dimensional isoparametric elements and truss elements. The steel liner plate inside the fuel pool was modeled with two-dimensional isoparametric elements. The model is presented in Figure 1 in schematic form.

A nonlinear concrete material model was prescribed for the 3-D solid elements. The model employed three basic features to describe the material behavior, namely, (1) a nonlinear stress-strain relationship including strain-softening to allow for the weakening of the concrete material under increasing compressive stresses, (2) failure envelopes that define cracking in tension and crushing in compression under multi-axial stress state, and, (3) a strategy to model the post-cracking and crushing behavior of the material. The numerical solution allowed for unloading and reloading of the material. Figure 2 presents the stress-strain law and the failure envelopes for the concrete model prescribed in the ADINA program (Bathe et al 1989) and used in the current analysis. The stress-strain law is presented in Figure 2a for the uniaxial stress condition for clarity. It shows that when the stress exceeds a prescribed tensile strength σ_t, the material will crack in a direction perpendicular to the stress direction and the stress will be reduced for tensile strains beyond this point. If the stress is compressive, it will follow the nonlinear compressive stress-strain law until it reaches the compressive strength, σ_c. The material becomes much softer at strains beyond this point and crushes at the ultimate strain, e_u. The stress is reduced to zero at strains beyond this point.

For multi-axial stress-state, the relationship of Figures 2b and 2c are used to determine the values of the parameters of the stress-strain law of Figure 2a, such as, tensile strength σ_t, compressive strength, σ_c, and crushing strain e_u etc. The failure envelope is based on the experimental work of Kupfer, et al. (1969). Elasto-plastic material model was used for steel reinforcement elements.

4 GRAVITY AND THERMAL LOAD ANALYSIS

The above-mentioned model was subjected to gravity loads (weight of the concrete structure, hydrostatic pressure on the pool floor and walls and fuel buoyant weight) and accidental thermal load in an incremental fashion and forces and moments were obtained in the structure for evaluation purposes. At each increment of the loading, iterations were performed to allow the load redistribution from cracking to equalize. A full Newton iterative solution scheme with line search option was adopted to obtain good convergent solutions.

The solution strategy involved application of gravity load first over several increments to allow any concrete cracking and load redistribution to develop. The concrete model allows cracking in any of the three orthogonal directions at an integration point in the 3-D solid element when the tensile stress in the particular direction exceeds the specified tensile strength. When a crack develops, the load capacity of the element at that integration point is reduced to zero in the direction perpendicular to the crack while retaining some shear capacity in the plane of the crack. The loads are then redistributed to other elements or rebars during the next load increment. If the crack closes (compressive strain across the crack face), the element strength in compression is reinstated, but the direction is remembered so that subsequent crack openings occur in the same direction under any tensile strain.

After the application of total gravity load, the nodal thermal loads, calculated in a steady state heat transfer analysis, were applied in increments with the gravity load maintained on the structure. These thermal loads were applied in increments to allow concrete cracking to develop.

5 DISCUSSION OF RESULTS

Under total gravity load, the pool floor deforms in a concave shape and produces tension in the bottom of mid span and at the top of the sides of the floor slab. This is illustrated in Figure 3 which shows the deformed pattern of the pool and the cracked pattern under gravity load. The pool floor slab indicates insignificant tensile cracking under gravity load.

As the thermal load is applied to the pool, the pool floor tries to expand and bend due to temperature gradient across the slab section. However, restraint to the expansion is provided by the pool end walls and the floor slab develops compression. In effect, because of the end walls, the thermal load acts as a prestressing mechanism for the floor. An examination of the deformed shape of the pool under gravity and thermal loadings, as presented in Figure 3, illustrates the additional bending induced in the floor and walls due to the thermal loads. Extensive cracking also occurs in the zones of higher tension.

This analysis shows the importance of three-dimensional effects for the load carrying capacity of the spent fuel pool. The back and interior walls constrain the pool floor so that thermal loads prestress the floor, thereby increasing its flexural capacity which is critical for carrying the additional fuel load. This effect could not have been captured from a conventional two-dimensional analysis.

6 CONCLUSIONS

The main conclusions of the study are:

(1) A rigorous nonlinear analyses, as conducted here, is essential to properly capture the stress in the different elements of the fuel pool.

(2) The three-dimensional model accounts for the constraining effects of the front and back walls on the flexural capacity of the pool floor slab, thereby helping it to carry additional fuel loads. A two-dimensional model cannot capture these important effects.

(3) The concrete nonlinear material model was numerically stable and was able to trace the progressive cracking through the structure at different increments of loading.

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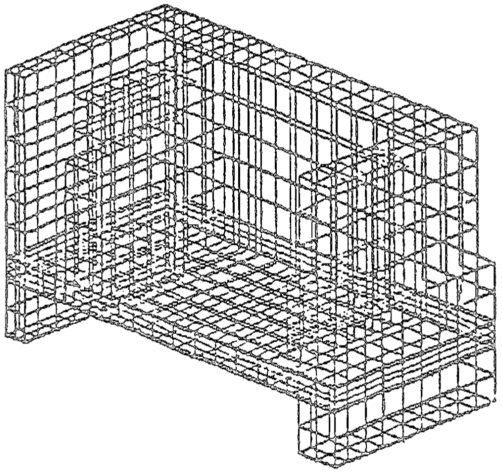
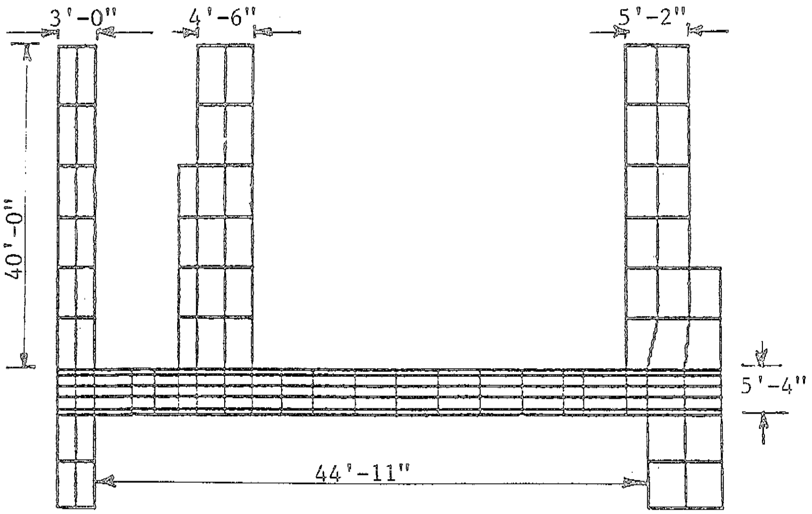
Kupfer, H., Hilsdorf, H.K., Rusch, R., 1969, J. Am. Concr. Inst. 66, 656-666, 1969.

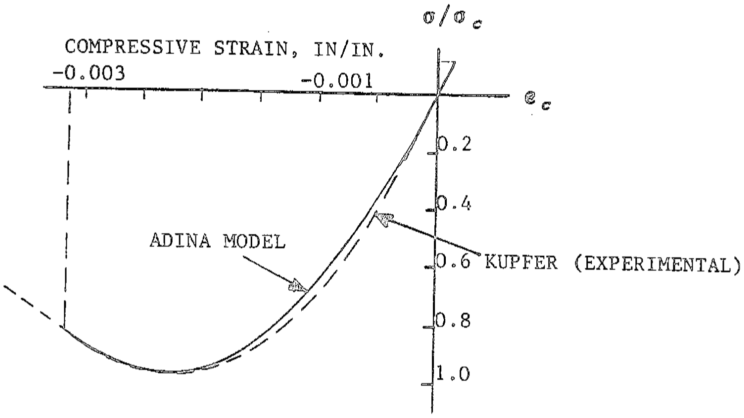


a. Three-Dimensional Schematic View

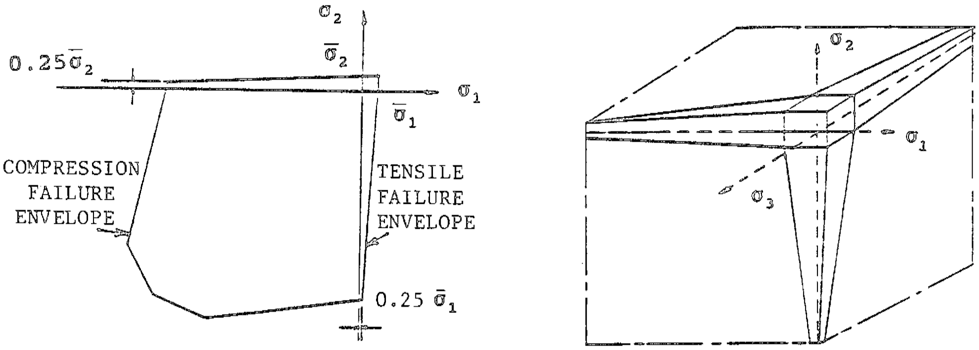


b. Mesh at Midspan

FIGURE 1 FINITE ELEMENT MESH FOR FUEL POOL MODEL



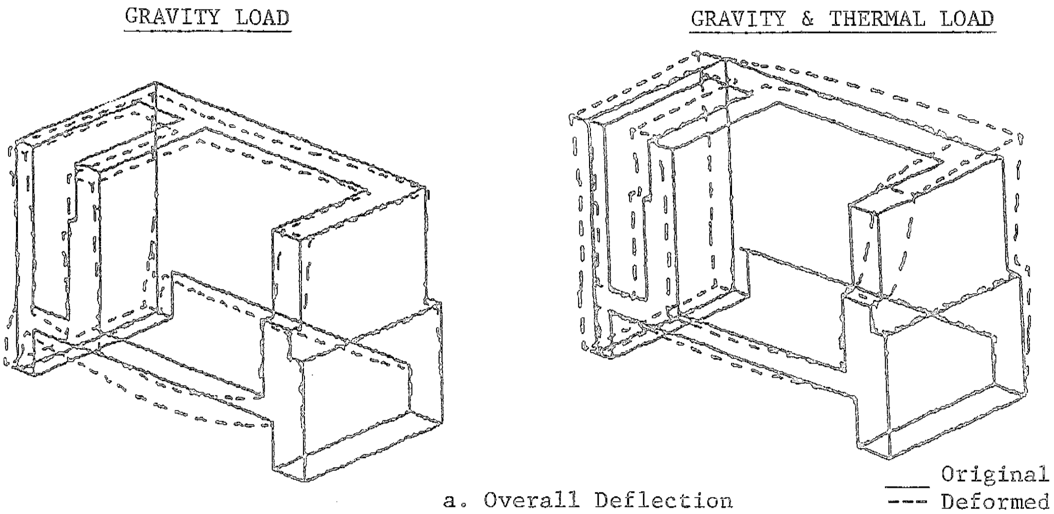
a. Nonlinear Uniaxial Stress-Strain Law for Concrete



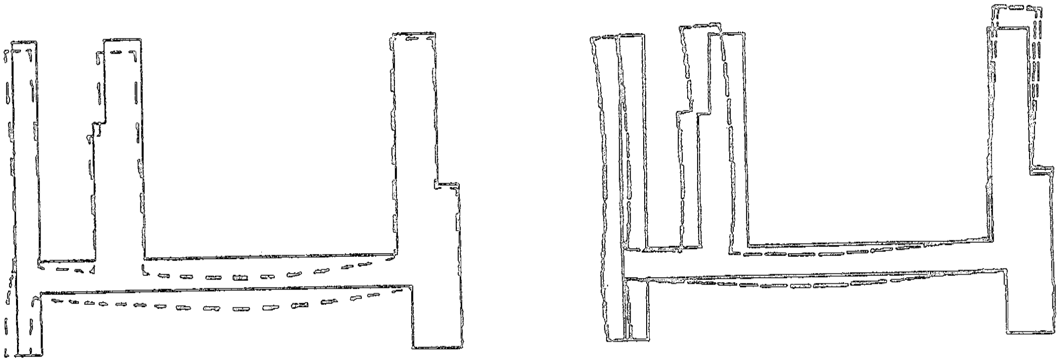
b. Triaxial Failure Envelopes Reduced to 2-D Conditions

c. Triaxial Tensile Failure Envelope

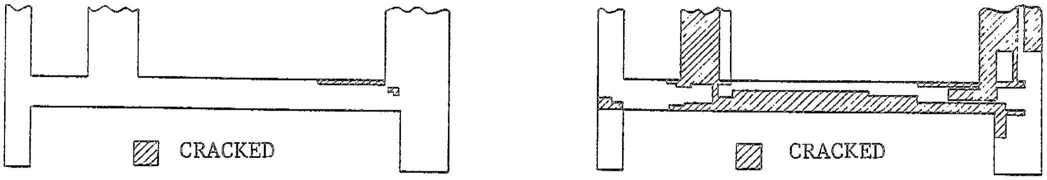
FIGURE 2 NONLINEAR 3-D MATERIAL MODEL OF CONCRETE USED IN THERMAL/DEAD LOAD ANALYSIS



a. Overall Deflection



b. Midspan Deflection



c. Crack Pattern

FIGURE 3 DEFLECTION AND CRACK PATTERNS IN THE FUEL POOL FOR GRAVITY AND THERMAL LOADS