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Three-Dimensional Seismic Analysis for Spent Fuel Storage Rack

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Abstract

Time history analysis is usually performed to characterize the nonlinear seismic behavior of a spent fuel storage rack(SFSR). In the past, the seismic analyses of the SFSR were performed with two-dimensional planar models, which could not account for torsional response and simultaneous multi-directional seismic input. In this study, three-dimensional seismic analysis methodology is developed for the single SFSR using the ANSYS code. The 3D- Model can be used to determine the nonlinear behavior of the rack, i.e., sliding, uplifting, and impact evaluation between the fuel assembly and rack, and rack and the pool wall,

This paper also reviews the 3-D modeling of the SFSR and the adequacy of the ANSYS for the seismic analysis. AS a result of the adquacy study, the method of ANSYS transient analysis with acceleration time history is suitable for the seismic analysis of highly nonlinear structure such as an SFSR but it isn't appropriate to use displacement time history of seismic input.

1. Introduction

A free standing spent fuel storage rack(SFSR) is submerged in water in a spent fuel storage pool of a nuclear power plant. The seismic analysis of the free standing SFSR requires careful considerations of several nonlinear phenomena. During an earthquake, the fuel assembly can rattle inside its storage cell. An SFSR module can slid on the pool floor and potentially impact the adjacent module or pool wall. Also, the SFSR can tilt and/or lift off at one or more support pads with resulting in pool floor impact. The submergence of the SFSR in water further complicates the problem causing the considerations of hydrodynamic coupling effects. Fuel rack vendors have developed their own analysis methods to predict the nonlinear seismic responses. In developing the dynamic models, most vendors used simple beam models of a fuel rack which have appropriate stiffness and mass distribution and the seismic analysis of most fuel rack systems has been performed with a two-dimensional model[1,2]. However, the analysis procedures, modeling techniques and basic assumptions vary significantly among the different vendors[1,2]. In recent years, a few studies have performed to demonstrate seismic adequacy of the SFSR by performing three- dimensional time history analysis with simultaneous application of three orthogonal components of seismic motion.

In Younggwang 3&4 and Ulchin 3&4, two-dimensional time history analysis was applied to the SFSR seismic analysis using the CESHOCK code[3]. The 2-D planar model could not account for torsional response and simultaneous multi-directional seismic input. The torsional effect can be significant when a rack tilts and/or lifts off with only one support pad remaining in contact with the floor. Unless the three directional seismic components are applied simultaneously, nonlinear phenomena such as sliding may not be accurately predicted[1].

In this paper, three-dimensional seismic analysis methodology is developed for the single SFSR using the ANSYS code[4].

2. Three-Dimensional Single Fuel Rack Model

Figure 1 shows a typical 12X10 cell SFSR module designed for Younggwang 3&4 and Ulchin 3&4. In the two-dimensional seismic analysis, two kinds of 2-D models for east-west and north-south planes were separately used to consider the three- dimensional seismic effects.

To develop the three-dimensional SFSR model of Figure 2, two kinds of 2-D rack models were combined to a single 3-D beam, and a horizontal X-shape base beam was attached on the rack base which supported at the four corners by friction and vertical gap elements that can slid or lift off the pool floor. The rack structure is represented as a simple vertical array of massless beams and lumped masses which duplicate the weights, natural frequencies, and mode shapes. Lumped mass nodes are located at the same fuel assembly spacer grid elevations.

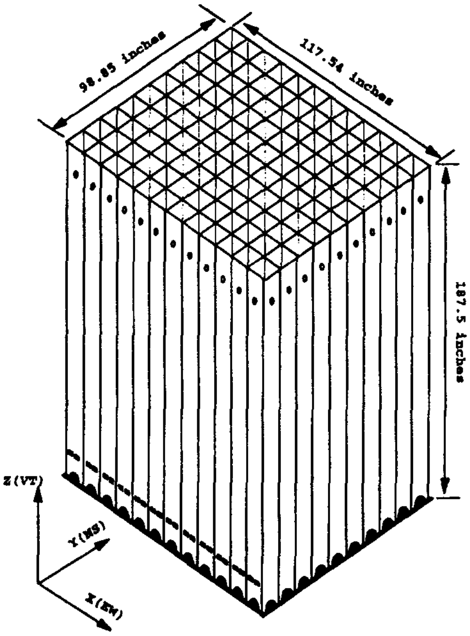


Fig. 1. Typical 12×10 Cells SFSR

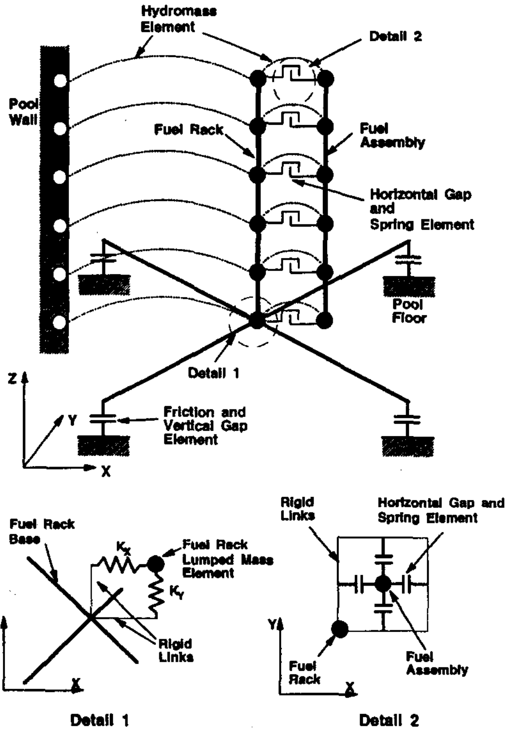


Fig. 2. Three-dimensional Dynamic Model for SFSR

To make a simplified mathematical beam model which has equivalent natural frequencies and mode shapes, the first mode shape of the rack module with the natural frequency (rad/sec) is assumed as Figure 3. To determine the mechanical properties for simplified rack model, single mass and spring element and uniformally mass distributed cantilever beam element are combined and the horizontal base spring constant(K) and vertical beam stiffness(EI) is calculated as followings:[5]

$$F_i = \frac{\omega^2 w_i \delta_i}{g}$$

$$F = \sum_{i=1}^{n} F_i = M\delta_1\omega^2 = K\delta_1$$

$$K = M\omega^2$$

where

$$M = \sum_{i=1}^{n} mi$$

F : horizontal spring support force due to beam motion

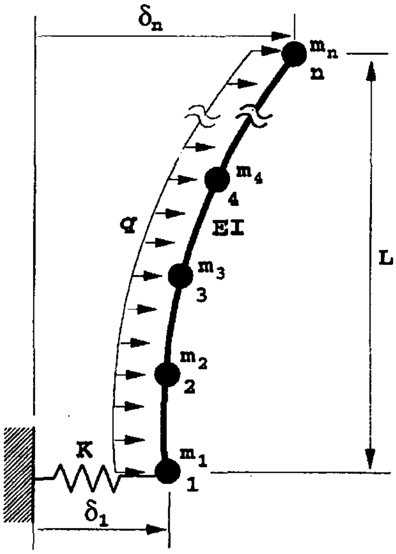


Fig. 3. Conceptual 1^{st} Mode Shape for Simplified Rack

δ_1 : averaged horizontal rack base displacement representing concave rack mode shape.
ω : fundamental frequency
w_i : nodal weight on node i
g : gravitational acceleration
K : spring constant for base spring
m_i : nodal mass on node i

$$EI = \frac{qL^4}{8(\delta_n - \delta_1)}$$

$$q = \frac{F}{L} = \frac{M}{L}\delta_1\omega^2$$

where

q : uniformally distributed load on simplified beam model
L : length of beam model
δ_n : nodal displacement on node n

The first and the second modes for the 3-D rack model showed typical beam modes with 6.93Hz and 9.24Hz of natural frequencies. Two kinds of 2-D Ulichin 3&4 CESHOCK models also showed 6.99Hz and 9.35Hz of natural frequencies and the 3-D rack model also showed closely equivalent mode shape to that of the 2-D model.

The fuel assembly is also modeled to a stick model, on the base of experimental data, which have duplicated weight and natural frequencies[6]. Four horizontal gap and spring elements are used to model the impacting of the fuel assembly against the rack cell at lumped mass locations. Four geometrical friction and vertical gap elements are defined to simulate the motion behavior of vertical contacting and horizontal friction sliding at the support leg and pool floor.

The model used to evaluate the hydrodynamic coupling effects for the rack to the pool and the fuel to the rack assembly is as described by Fritz[7], for the rigid coaxial cylinders with annular space filled with fluid. The fluid reaction forces on the inner cylinder, Fi , and the outer cylinder, Fo, can be written for each horizontal direction as followings:

$$F_i = -M_H \ddot{X}_i + (M_1 + M_H)\ \ddot{X}_O$$
$$Fo = (M_1 + M_H)\ \ddot{X}_i - (M_1 + M_2 + M_H)\ \ddot{X}_O$$

where

$\ddot{X}_i$: absolute acceleration for the inner cylinder
$\ddot{X}_O$: absolute acceleration for the outer cylinder
M_1 : mass of water displaced by inner cylinder
M_2 : mass of water displaced by outer cylinder
M_H: hydromass mass of vibrating fluid

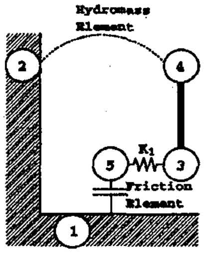
Hydrodynamic mass M_H for any two submerged rectangular cylinder with non-uniform gaps filled with water due to horizontal relative motion is calculated using ADDMASS[8]. ANNULUS[9] is also used to consider various boundary conditions associated with the fixity of the cylinder and the fluid flow in the axial direction.

3. Adequacy of ANSYS for Dynamic Analysis

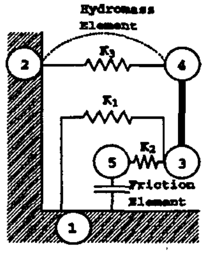
ANSYS is a general purpose structural analysis program which has the capability to perform nonlinear time history analysis. But the transient dynamic analysis using ANSYS with displacement time history showed overly conservative results[10] and that is not recommended[4].

For selecting better analysis method, analyses by ANSYS with displacement time history, ANSYS with acceleration time history, and CESHOCK with acceleration time history are carried out as a benchmark test for the seismic analysis of the SFSR. To compare the sliding behaviors for the SFSR, empty SFSR is considered as a simple rigid block and modeled to CASE-I and CASE-II in Figure 4. The Case-I and Case-II models represent one-dimensional single rigid block which has the same mass, hydromass and friction coefficient as those of an empty SFSR. Comparing Case-I with Case-II, springs K_1 and K_2 are attached to Case-II which transfer load interaction between the pool and the block. The Case-III is an empty SFSR model excluding fuel assembly model in Figure 2.

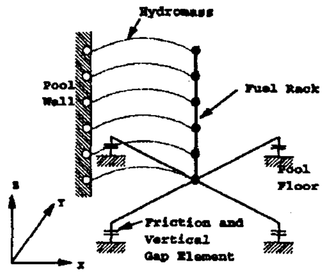
To study the ANSYS reliability for the nonlinear time history analysis, the hypothetical time history data in Figure 5 are used in this benchmark test. Figure 6 shows the result of time history analysis for Case-I, Case-II and Case-III. The result of Case-



(a) Case-I



(B) Case-II



(C) Case-III

Fig. 4. Benchmark Test Model for the Sliding Response of ANSYS

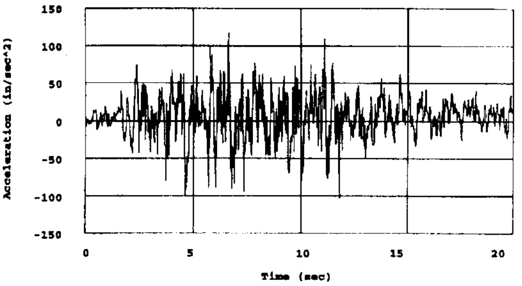
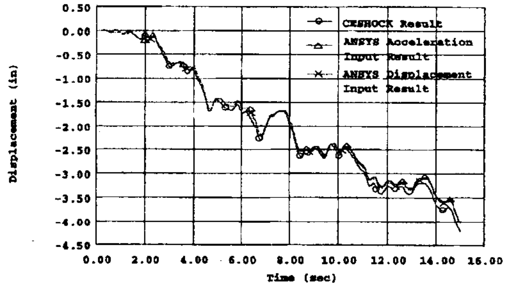
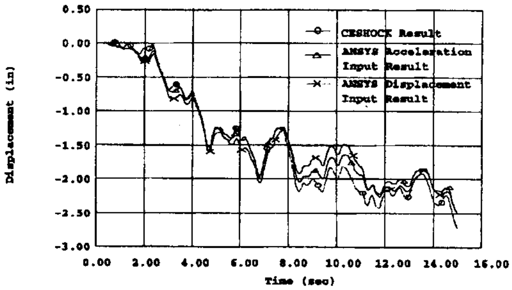


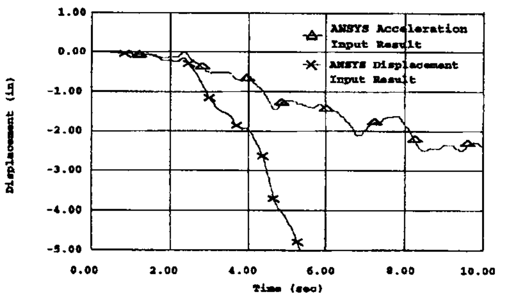
Fig. 5. Time History Data for ANSYS Benchmark Test



(A) Sliding Displacement for Case-I



(B) Sliding Displacement for Case-II



(C) Sliding Displacement for Case-III

Fig. 6. Benchmark Test Results

I shows that all three sliding responses nearly coincide. Comparing Case-I and Case-II with Case-III, the ANSYS analysis result with acceleration time history showed similar sliding behaviors but the results of ANSYS with displacement time history show big deviation of sliding response.

Therefore, the results of ANSYS transient analysis results with displacement time histories could not be reliable on the highly nonlinear model, and it is recommended to use the option of acceleration time history.

4. Three-dimensional Seismic Analysis for the Single SFSR

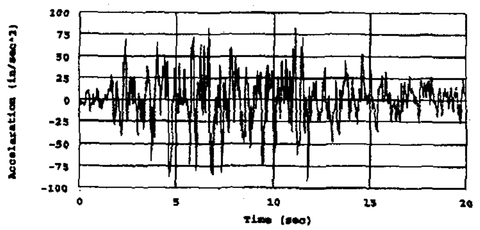
4.1. Seismic Loading

The baseline corrected safety shutdown earthquake of Ulchin 3&4 for the fuel building is used for the seismic analysis of the SFSR. Three components of acceleration time histories are simultaneously applied to Figure 2 of the 3-D SFSR model. Three components of acceleration and displacement time histories are shown in Figure 7.

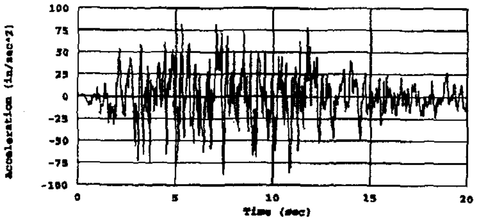
4.2. Assumptions

Fluid Effects : Inertial effects of water on the vibrating structures are considered, while fluid damping and sloshing effects are generally ignored. Hydrodynamic mass coupling elements in the finite element stick model (Figure 2) are used between fuel assembly and rack cell nodes, and between fuel rack and pool wall nodes.

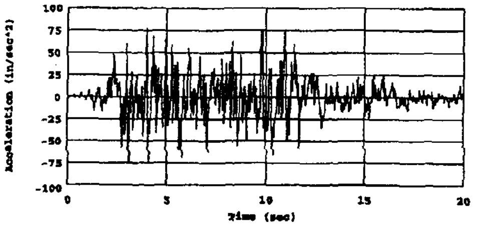
Gaps : Compression-only springs are used to model the gap interface between the fuel and the rack cell and between rack support leg and pool floor locations.



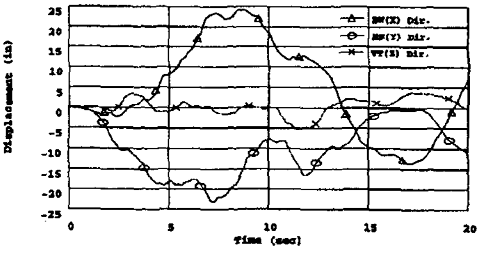
(A) EW(X) Acceleration



(B) NS(Y) Acceleration



(C) VT(Z) Acceleration



(D) EW, NS and VT Displacement

Fig. 7. Three-directional Seismic Data for SFSR Seismic Analysis

Friction : Coulomb friction elements are used between the rack support leg and pool floor nodes and between fuel assembly and rack interface nodes. These elements behave like stiff spring until the force reaches a limiting value equal to the specified friction coefficient times the normal force.

Fuel Assembly Representation : Composite structural properties of all fuel assemblies in a rack are represented by a single stick model as shown in Figure 2. It is usually assumed that all fuel assemblies in a rack module will move in phase.

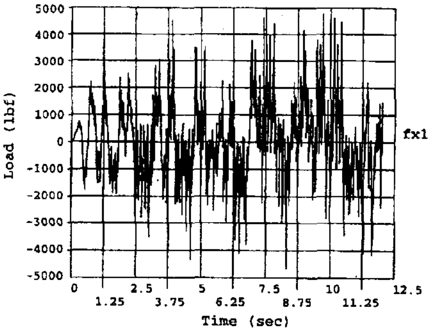
4.3. Results

Three components of seismic loads on a SFSR support leg, impact load between the rack and the fuel assembly, and horizontal sliding displacement at rack bottom are shown in Figures 8-10. Three component loads for rack support leg and rack sliding displacement show the representative three- dimensional behavior of the SFSR, the vertical seismic load on the rack support leg varied due to vertical seismic load and rack lift off, and reasonable impact motions are showed in the gap elements between rack cell and fuel assembly nodes.

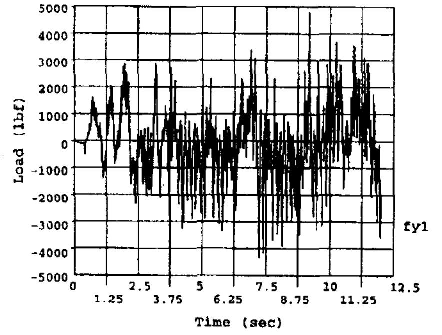
The 3-D model used in this study could analyse the important characteristics of the seismic response of the SFSR in comparing with the previous two-dimensional model, that is, the model developed for this analysis simultaneously monitored three components of seismic loading, sliding, uplifting, and impact between the fuel and the rack and between the rack and pool bottom.

5. Conclusions

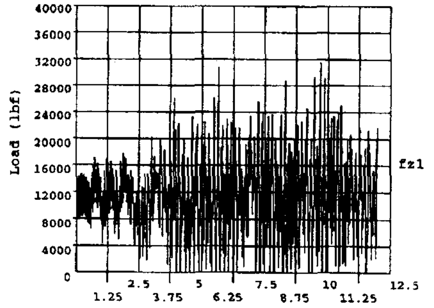
Three-dimensional seismic analysis method for a single SFSR has been developed using ANSYS with acceleration time histories. The 3-D SFSR model created in this paper can be used to determine the nonlinear and three-



(A) EW(X) Horizontal Load for Rack Base



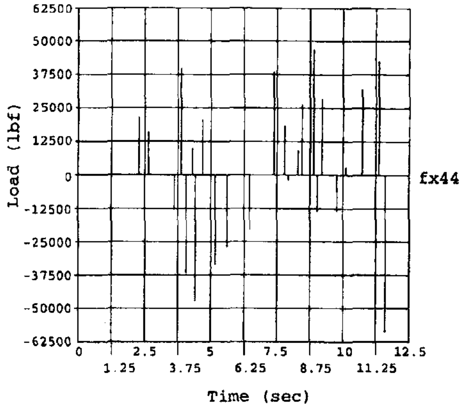
(B) NS(Y) Horizontal Load for Rack Base



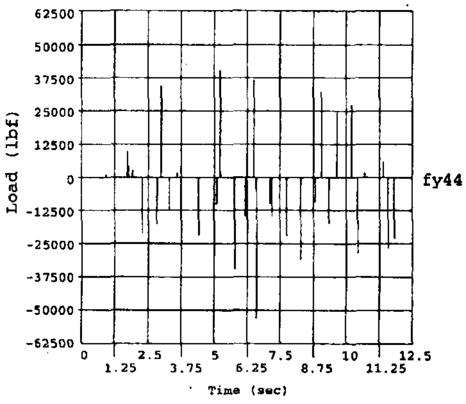
(C) VT(Z) Vertical Load for Rack Base

Fig. 8. Seismic Loads for Rack Support Leg

dimensional response of the rack, i.e., sliding, uplifting and impact between a fuel and a rack, and a rack and pool floor. These seismic responses are used to evaluate the structural integrity of the racks and fuel assembly.



(A) EW(X) Impact Load



(B) NS(Y) Impact Load

Fig. 9. Impact Loads Between Rack and Fuel Assembly

The method of ANSYS transient analysis with displacement time history can not be reliable on the highly nonlinear model, but it is suitable to use the option of acceleration time history.

The ANSYS transient analysis option with acceleration time history accepts only single acceleration on one axis of global cartesian coordinates, therefore this method can not be applied to the multi-node seismic input system. Further investigation on the multi-rack interaction, model sensitivity, and scale model test will provide greater confidence in the proposed method.

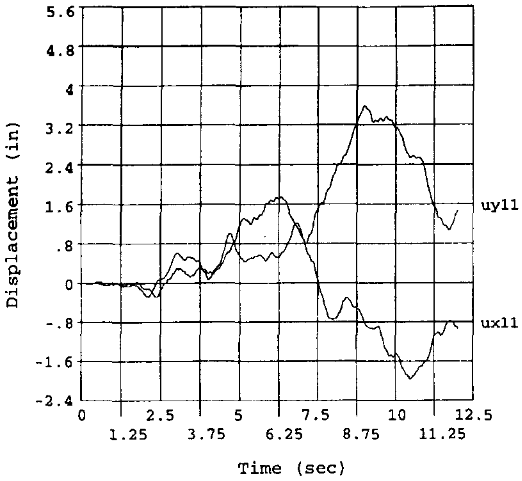


Fig. 10. Horizontal Sliding Displacement on Rack Bottom

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