NONLINEAR ANALYSIS OF SPENT FUEL STORAGE RACKS FOR KOREA MULTI-PURPOSE RESEARCH REACTOR (KMRR)

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ABSTRACT

This paper presents the analysis briefs to evaluate the structural adequacy of the KMRR spent fuel storage racks which stack modules in three layers. The seismic analysis models are idealized to consider the overall dynamic motions such as rocking, sliding and liftoff in the event of an postulated earthquake. The displacement time histories of the floor obtained from the floor response spectra in three orthogonal directions are simultaneously applied to the nonlinear seismic model of the structure with gap and friction elements.

1. INTRODUCTION

Structural analyses have been performed for the spent fuel storage modules and racks, which are initially designed by the Nuclear Power Department, Plant Division, Hyundai Heavy Industries Co., Ltd., to justify the structural adequacy for the proposed storage of fuel assemblies for the Korea Multi-purpose Research Reactor (KMRR) of Korea Atomic Energy Research Institute (KAERI). The technical specification for these modules and racks is issued as KOPEC Doc. No. KM-354-DT-P001[1].

In a departure from the design of spent fuel storage racks used in commercial nuclear power plants, the modules in which the fuel assemblies are stored are stacked in three layers in the KMRR spent fuel storage rack. Since the structural models employ the nonlinear gap and friction elements, the analysis models are idealized and simplified to make possible the nonlinear seismic analyses of these racks in consideration of the overall motion of the racks during the postulated seismic events.

In modelling the free standing racks, it is assumed that the friction coefficient between the rack feet and the pool floor may vary from 0.2 to 0.8 with a 95% confidence interval.

Since the racks can store a total of 18 modules in 3 layers a 6 modules apiece, it is assumed that the most critical loading condition is that all 18 modules are fully stored in rack.

The allowable stress criteria are applied in accordance with the ASME Boiler and Pressure Vessel Code, SecIII, Div I, Part NF[2].

2. STRUCTURAL DESCRIPTION

Three spent fuel racks, racks 1&2 and rack3, are stored in the KMRR spent fuel storage pool, and the empty space in the pool is used for loading of fuel into the shipping cask as shown in Fig. 1.

In order to store the fuel in as small an area as possible, the KMRR spent fuel storage rack is designed to stack the modules in the rack in three layers different from the conventional rack type. Four of 36-element fuel modules and two of
18-element fuel modules are stored in each layer of rack1 and rack2. Two of 18-element fuel modules and three of Triga fuel modules are stored in each layer of rack3.

Each rack sits on the pool floor liner. There are no bolted or welded connections between the rack and the pool structure, or between adjacent racks. Therefore, vertical loads are transmitted by bearing from the rack feet directly to the floor, and horizontal loads from the feet to the floor by friction only.

In these module designs, the lower plate is used to provide both vertical support and lateral bracing for the cell pipes, but the upper plate provides only lateral bracing for the cell pipes. A small gap exists between the cell pipe and the circular hole of upper plate to allow for thermal expansion of the cell pipe.

The three layers of modules stacked on the base support of the rack are restricted only in horizontal direction by the small pin joints. The spacing between the outer beams of the module and the inner bracing of the rack is 20mm.

A240 Type 304L stainless steel is used for all parts of modules and racks with the exception of the pins, bosses and bolts. Since the maximum pool water temperature is below 80 °C, it is used as a reference design temperature for the evaluation of material properties.

3 SEISMIC LOADING

The OBE and SSE acceleration time histories used for the seismic analysis of spent fuel storage racks are generated using the given OBE and SSE floor response spectrum. The duration of the time histories is 15 seconds.

The displacement time histories are generated by double integrating the acceleration time histories using PREP6 of ANSYS[3]. The displacement time histories in three orthogonal directions represent the translational motions of the ground and walls.

The displacement time histories of SSE are shown in Fig. 2.

Seismic loads for the OBE and the SSE are then simulated by applying these three components of displacement time histories to the ground nodes simultaneously.

4. MODEL DESCRIPTION

4.1 Idealization of Static and Dynamic Models

Only rack 1&2 is examined in the nonlinear seismic analysis, since rack 1&2 has a higher ratio of overturning moment to minimum rack base width which would be more conducive to sliding and rocking during an earthquake for low values of the friction coefficient. The rocking and sliding motions are apt to cause rack and module impacts. Considering that the applied loads for rack 1&2 are larger and the member sizes are very similar to those of the rack 3, rack 1&2 is judged to be the more critical rack with higher stress levels due to dead weight and seismic loadings.

Since the modules will be stacked up from the rack base by six(6) modules for each layer to have the lower center of gravity and the top module is expected to have the larger dislocation and impact toward the rack, the partially filled rack does not seem to be a worse case than the fully loaded rack. It is assumed that the most critical loading condition in connection with the distribution of mass in rack is that 18 modules are fully loaded and stored in the rack.

The ANSYS computer program is used to perform the rack seismic evaluation. ANSYS is a general purpose structural analysis program which has the capability to perform nonlinear time history analysis.

The nonlinear analysis capability is required for the following reasons:

1. The racks are not anchored to the stainless steel pool floor liner. Therefore, the rack may slide on the pool floor; one or more legs may momentarily lose contact with the liner; or the rack may experience a combination of sliding, rocking and liftoff conditions. In order to simulate these kinematic events, the rack seismic model is idealized with the use of the ANSYS three-dimensional interface element, which represents two surfaces which may maintain or break physical contact and may slide relative to each other. This element is capable of supporting only compression in the direction normal to the surface and shear in the tangential direction. Thus the sliding interface between the pool liner and rack feet, and the potential for rack rocking and
liftoff is modeled by implementation of the three dimensional interface element into the rack seismic model.

- The gap between the rack and the pool wall varies from 62.6mm to 122.6 mm, and the nominal gap between racks varies from 50mm to 62.6mm. The nominal gaps between the modules and the rack are 10mm. There is a average gap of 8.475mm between the outer wall of the fuel assembly and the inner wall of the cell pipe in the 36-element fuel module. In addition, there is a nominal gap of 2.4mm between the cell pipe and the upper reinforcing plate of the 36-element fuel module. In order to incorporate these gaps into the rack seismic model, the ANSYS combination element is used. This element is a combination of a friction element, spring and damper in parallel, coupled to a gap element in series. For application in this seismic model, the friction and damping capabilities of the element are removed.

Module-to-rack impact, rack-to-rack impact, and rack-to-wall impact, if they were to occur, would be modeled by these spring-gap combination elements which transfer compressive forces only.

Figure 3 shows the conceptual configuration of the simplified seismic model for the modules and rack. In the assembled seismic model, the most significant concept is the implementation of the combination and interface elements, which will be discussed in detail in Section 4.2 in terms of boundary conditions.

The stacked modules are idealized in two different ways: the simplified models and the lumped mass models. Only one group of actual module models is stacked on the rack base to evaluate member forces and nodal displacement of the 36-element modules due to the seismic loading. The rest of modules are idealized as lumped mass elements which are linked with simplified beam element.

In order to reduce the total degrees of freedom, the tube reinforcing plate is idealized as single cross beam which has the same physical properties as the plate. The base support plate is modeled in the same way as the tube reinforcing plate. In addition, the cell pipes are modeled by conservatively assuming that all 25 fuel assemblies in the cell pipes vibrate exactly in phase.

These cell pipes are idealized as one lumped beam of which sectional properties are 25 times the cross sectional area and moments of inertia of a single cell pipe.

The stiffness of the fuel assembly is not included in the calculation of the properties of the lumped beam. Only the mass of the fuel assembly is assumed to act as an inertia term in the cell pipe during seismic events and is distributed equally at both nodes of the lumped beam. Rattling of fuel assemblies in the cell pipes is considered separately in the detailed module stress analysis.

In order to avoid the complexity in the detailed analysis of the modules, the cell pipes are modeled by beam elements which are connected with the perforated plates by use of rigid links. Rigid links which couple the x and y translations are used in the upper reinforcing plate and rigid links which couple all degrees of freedom are used between the base support plate and the cell pipe.

The detailed strength evaluation of the cell pipe for impact forces due to rattling of the fuel assembly is performed by use of a separate model. Rattling of the fuel assembly inside the cell pipe is simulated by applying the displacement time history obtained from the rack seismic analysis.

4.2 Boundary Conditions

Figure 3 shows how the ANSYS combination (gap) and interface (friction/ liftoff) elements are implemented in the seismic model.

The rack feet are connected with the ground by the friction/liftoff element to transfer the compressive and frictional forces between the rack feet and the pool floor.

The gap elements model the gaps between the racks which are being modeled, and the other racks and walls. It is assumed to be the most conservative case that the adjacent racks oscillate 180 degrees out of phase relative to the rack being analyzed. Therefore, only one-half of the initial gap between the racks is applied to the seismic model. These gap elements in two horizontal directions are defined by corner nodes at the top and bottom of rack, and by ground nodes which are assumed to move with the pool floor and walls.

The gap elements for two horizontal directions are used to model the gaps between
the top corner nodes of each stacked module and the corner nodes at the connecting
top surface of the vertical columns and horizontal beams of the rack.

Since a module is stacked through the pins at the top corners of a lower module,
four nodes at the top of the lower module and at the bottom of the upper module are
connected by the combination elements which couple the horizontal displacements of
both modules.

The rest of the modules are idealized as lumped masses which are connected to
the rack by horizontal gap elements at the top mass and by the combination elements
at the bottom mass as defined in the stacked modules.

The gap between the upper reinforcing plate and the cell pipe is not defined by a
gap element on the assumption that the impact force generated within the very small
gap is negligible. Both elements are connected by coupling their nodal displacements
in the two horizontal directions.

In the detailed cell pipe analysis, it is assumed conservatively that the gap between
the fuel assembly and the cell pipe changes from a maximum of twice the nominal
gap to a theoretical zero gap.

4.3 Fluid Coupling Effects
The effects due to the submergence of the modules and rack in water have been
incorporated as follows[4].

Hydrodynamic masses of the structural members of modules and rack are added to
their masses. Assuming that each body moves in and is surrounded by an
unbounded fluid initially at rest, the hydrodynamic masses are calculated using the
formulae in UCRL-52342[5].

The water that is entrapped inside the fuel assemblies is added to the fuel
assembly masses.

The water which fills the gaps between the fuel assemblies and the cell pipes is
added to the masses of cell pipes.

Spent fuel racks used in commercial nuclear power plants normally have little or no
spacing between cell pipes. For this reason, hydrodynamic coupling is assumed to
occur between the racks and pool wall. However, the hydrodynamic coupling effects
between racks, rack and pool wall in this seismic analysis are not included, because
their spacings of the KMRR rack arrangement is larger than the upper limit of the
range of the coupling effect[5]. It leads to more conservative results.

In reality, the damping of the rack motion arises from material hysteresis, relative
intercomponent motion in structures, and fluid viscous effects. The maximum of 4%
structural damping imposed on the rack and module structures during seismic
simulations and material damping is due to material hysteresis and fluid damping due
to fluid viscosity are conservatively neglected. This is consistent with the existing
seismic basis for the plant[6].

5. STRUCTURAL ANALYSIS

5.1 Seismic Analysis
Two kinds of analyses have been performed to evaluate the structural responses of
the spent fuel storage rack during the seismic event. One is the response spectrum
analysis, and the other is the nonlinear time history analysis. The results of
response spectrum analysis cannot be exactly compared with those of time history
analysis because of the inclusion of nonlinearity of structural model. Nevertheless, the
response spectrum analysis has been carried out upon the Owner's request who
believes the results are very much conservative.

For response spectrum analysis, the largest acceleration value within the range of ±
15 percent variation of structural natural frequencies is chosen as input for the
acceleration response spectrum at elevation 72.3m. The applied modal damping ratios
are 4 percent for SSE and 2 percent for OBE, respectively[6]. The SRSS method is
used to sum the effects of direction and modes.

For nonlinear time history analysis of rack and modules, the acceleration time
histories for 15 seconds are developed using the acceleration response spectrum in
three orthogonal directions.

The acceleration time histories are converted to displacement time histories by
double integrations, using PREP6 of the ANSYS Code. The displacement time
histories are applied to pool floor and pool wall in three orthogonal directions
simultaneously. The structural damping effects are also included in this analysis.

The friction coefficients between pool base and rack feet are 0.2 and 0.8. Four
seismic cases are studied in accordance with the two cases of OBE and SSE and
two values of friction coefficients.

The detailed stress evaluation of modules is done using NISA II computer
program[7].

A proprietary program was developed to perform the Unity Check of rack and
module structures except for the base plate and tube reinforcing plate of the modules.
This program reads beam force histories of all elements from the ANSYS output file
and calculates the value of the maximum calculated/allowable stress ratio.

5.2 Fatigue Evaluation

In compliance with the Technical Specification[1], an analysis shall be performed to
consider the fatigue effects produced by 5 OBEs followed by the SSE and this also
may be performed by accounting for 2400 OBE stress cycles and 400 SSE stress
cycles.

However, the total number of stress cycle is much less than the minimum of
20,000 cycles so that NF-3330 of the ASME Code for high cycle fatigue design
cannot be used. Instead, the fatigue usage factors are calculated for critical members
and welds of racks and modules according to the allowable number of cycles defined
in Fig. I-9.2.1 of Section III of the ASME B & FV Code[2], based on the method
defined in NE-3221.5.

6. SUMMARY

Structural analyses have been successfully performed to evaluate the structural
adequacy of the spent fuel storage modules and racks which will be located in the
spent fuel storage pool of the Korea Atomic Energy Research Institute.

From the analysis result, though it is not presented here, rack 1&2 satisfy the
structural acceptance criteria of the ASME Code[2] and meet all the structural
requirements stated in the Owner’s Technical Specification[1] in the event of an OBE
or SSE, the design earthquake specified by KAERI.

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6. USAEC Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear
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Fig. 1 Spent Fuel Storage Pool Plan

Fig. 2 Displacement Time Histories of SSE

Fig. 3 Conceptual Configuration of Simplified Seismic Model