Development of Core Seismic Analysis Models for KNGR Fuel Assemblies Associated with 0.3 g Seismic Loads

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ABSTRACT

In order to evaluate the structural integrity of fuel assemblies associated with 0.3g seismic loads in the Korean Next Generation Reactor (KNGR), detailed fuel assembly model and core series models with 7 and 17 assemblies were developed with the MSC/NASTRAN code. The time histories considered in this analysis were generated based on 0.3g ground motion from a seismic analysis of the System 80+ reactor internals that is reference plant of the KNGR. The detailed fuel assembly model and core series models for the KNGR developed with the MSC/NASTRAN code have a good correlation with test results and in-reactor impact behavior of fuel assemblies under applied seismic loads. It is necessary to study further on the evaluation for the KNGR fuel assembly and the models using the site specific time histories. However, it is expected that the further evaluation and some modifications can be performed effectively with the aid of the models developed in this study.

1. INTRODUCTION

The basic functional requirement of a PWR fuel assembly which must be satisfied during Safe Shutdown Earthquake (SSE) is that the structural components of the fuel assembly must be capable of maintaining the fuel rods in a coolable geometry as well as assuring control rod insertability. During such event, significant reactor core displacements are produced by the earthquake ground accelerations transmitted to the reactor core boundary. The horizontal component of the displacement leads to fuel assembly lateral deflections and impacts at each spacer grid location, between fuel assemblies and/or between fuel assembly and core shroud.

One of the important requirements for the Korean Next Generation Reactor (KNGR) is a SSE having a peak ground acceleration of 0.3g in the horizontal direction for both rock and soil sites. This requirement can cause serious impacts on the fuel assembly structural integrity. Therefore, it is inevitable to evaluate whether the fuel assembly considered for the KNGR retains its integrity under such a high seismic load. An analysis was already performed to estimate the effects of increased seismic loads using the CESHOCK code which is special

code for ABB-CE plants and fuel and a time history which was just increased 0.2g motion by 50% to generate 0.3g seismic motion [1].

In this study, detailed fuel assembly model and core series models with 7 and 17 fuel assemblies will be developed with the MSC/NASTRAN code in order to evaluate the structural integrity of the fuel assemblies for the KNGR associated with 0.3 g seismic loads. The time histories used in this study are generated for both soil and rock conditions from the reactor internals model of System 80+ plant which is reference plant of the KNGR, because the site specific time histories for the KNGR were not available at this time.

With the developed models and the time histories, direct transient analyses will be performed for 15 seconds. Dynamic responses of the fuel assemblies under the applied seismic loads will be carefully investigated in order to evaluate not only the integrity of fuel assembly components but also the adequacy of the models developed in this study for the KNGR.

2. STRUCTURAL MODELS AND ANALYSES

2.1 Grid Cage Model

The grid cage model is developed from design drawings and static test results. Area, moments of inertia along with the cross section and length dimensions for each element in the model are determined from the design drawings. Element connectivity and nodalization is identified for the MSC/NASTRAN computer code input.

The MSC/NASTRAN model is refined based on full scale force vs. deflection test data by adding and adjusting rotational springs at each spacer grid location. The masses of the various grid cage components are determined from actual weight data calculated from the DOWSER code and distributed over the model. The schematic configuration of developed grid cage model is shown in Fig.1. This model consists of 188 nodal points, 174 bar elements, 15 masses, 14 rigid links, 11 linear springs, and 11 multi-point constraint equations.

2.2 Fuel Assembly Model

The fuel assembly model is developed from design drawings and test results such as static, modal, pluck and pluck impact tests. Area, moments of inertia along with various cross sections and length dimensions for each element in the model are also determined from the design drawings. This information is coupled with the grid cage model to develop the final model data to be used for the MSC/NASTRAN computer code input. The developed model is planar with each bar element representing the total mass and stiffness of a total row of fuel rods at a specified spacer grid cell location. The schematic configuration of developed fuel assembly model is shown in Fig.2. This model is consisted of 1092 nodal points, 974 bar elements, 15 masses, 25 rigid links, 99 linear springs, and 110 multi-point constraint equations.

2.3 Seismic Time Histories

Seismic wave is transferred from the free field to the reactor building that excites the

NSSS. The vessel motion is transmitted through its internal structure to the core support barrel and in turn to the core region. The seismic response at the core boundary used in evaluating fuel assembly structural integrity is in the form of velocity time histories. These velocity time histories were generated for both soil and rock conditions from the reactor internals model of System 80+ plant which is reference plant of the KNGR, because the site specific time histories for the KNGR were not available at this time. The typical plot of the time history and its response spectrum used in this study is shown in Fig.3 and Fig.4, respectively.

2.4 Horizontal Core Models (7 Assemblies, 17 Assemblies)

The major purpose for developing the core region horizontal models was to assess the condition of the fuel assemblies for the KNGR, contacting the core shroud and other fuel assemblies. In the KNGR core, all 241 fuel assemblies are aligned laterally such that the shortest row is made up of seven assemblies while the longest row consists of seventeen assemblies. In general, the highest fuel assembly LOCA response loads occur in the shortest row across the core, whereas the highest seismic loads occur in the longest row across the core. Therefore, two models, a 7 row and a 17 row, were developed. These row models incorporate several simplifying assumptions. The primary one is that the motion of the core is planar in response to seismic excitation and that this core response can be represented by a single row of fuel assemblies [2]. It is further assumed that the effect of torsional motion of the fuel assemblies, barrel shell displacements and gap tolerances are negligible when determining overall core region lateral response. A more complete listing of fuel system analysis assumptions is presented as part of a USNRC study [3]. The fuel assemblies are separated by gaps. One major nonlinear aspect of the core region is the contact phenomena between fuel assemblies and/or between peripheral fuel assembly and core shroud during a seismic event. These gaps are modeled with nonlinear elements.

Because the detailed fuel assembly model has a large number of degree of freedoms, it's nearly impossible to perform a direct transient analysis. Since all 7 or 17 fuel assemblies are identical, only one assembly needs to be modeled in detail. This detailed fuel assembly model is referred as the primary assembly. The remaining 6 or 16 fuel assemblies are referred to as image assemblies. Using the superelement capability of the MSC/NASTRAN, therefore, the detailed model is reduced to a smaller set of grid points called the residual structure [4]. The primary assembly is reduced to 15 grid points representing the center of each spacer grids, upper end fitting, and the lower end fitting, maintaining an accurate dynamic characteristics of the original detailed fuel assembly model using component mode synthesis method, which is a subset of the MSC/NASTRAN superelement capability. The sketch of 17 row model is shown in Fig. 5.

2.5 Direct Transient Analysis

The equation of motion of the reduced model is given by :

$$[M]\{\ddot{x}\} + [B]\{\dot{x}\} + [K]\{x\} = \{P(t)\} + \{P_n\}$$

,where

- [M] : Mass Matrix
- [B] : Damping Matrix
- [K] : Stiffness Matrix
- {x} : Displacement of a set of physical coordinates of the reduced model
- {P(t)} : Time Dependent Applied Force Vector
- {P_n} : Non-Linear Force Vector, function of {x} and { $\dot{x}$ }, used to model the gaps and the one-way impact damping.

The direct transient analysis capability of the MSC/NASTRAN, SOL109, is used to solve the equations of motion. The applied non-linear forces, P_n, are evaluated with this option as the variations from a linear response for the spacer grid elements. This solution technique eliminates the traditional approach of reformulating the stiffness matrix for each successive time step since it uses the modified Newmark-Beta direct integration procedure [4]. Analysis convergence and stability were checked by altering the time step of $\Delta t = 0.0001$ sec. $\pm 25\%$. The time step used for the transient analysis is 0.0001 second and the non-linear force was computed for every fifth time step. The total number of time steps for the each analysis is 150000 yielding the analysis duration of fifteen seconds.

3. RESULTS AND DISCUSSION

In order to verify that the detailed fuel assembly model has comparable characteristics with tested fuel assembly in both static and dynamic point of view, four kinds of analyses were carried out as follows:

- Load-Deflection Static Analysis
- Modal Analysis
- Pluck Test Simulation
- Pluck Impact Test Simulation

The characteristics and behavior of the developed models were carefully investigated with comparison of analysis results with the corresponding test results. The modal analysis result is shown in Fig.6. Fig.7 shows the simulation models of pluck impact tests and Fig.8 represents the comparison results of test and analysis results. As shown in the figures, the developed fuel assembly model has a good correlation with test results.

Impact loads, deflections, and component loads are determined from core region horizontal analyses. Spacer grid impact loads and fuel assembly deflections represent the primary horizontal analysis results. Typical analysis result showing a xy-plot of the non-linear force in the gap with highest load is shown in Fig.9. Maximum impact loads occurred on both sides of the core region. A peak load occurred at the spacer grid No. 5 and 6 near the center of the peripheral fuel assembly of left side due to impact at the core shroud. The maximum impact loads exceeded the maximum allowable strength of the spacer grid. This indicates that the fuel assembly considered for the KNGR at present needs to be modified for the increased seismic load of 0.3g for SSE.

4. CONCLUSIONS

Detailed fuel assembly model and core series models with 7 and 17 fuel assemblies were developed with the MSC/NASTRAN code to evaluate the structural integrity of the fuel assemblies for the KNGR associated with 0.3g seismic loads. The models have a good correlation with test results and in-reactor impact behavior of fuel assemblies under applied seismic loads.

The transient analysis results showed that the maximum impact loads exceeded the maximum allowable strength of the spacer grid. Therefore, the fuel assembly considered for the KNGR at present needs to be modified for the increased seismic load of 0.3g for SSE.

It is necessary to study further on the evaluation for the KNGR fuel assembly and the models using the site specific time histories. However, it is expected that the further evaluation and some modifications can be performed effectively with the aid of the models developed in this study.

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Fig.1 KNGR Grid Cage Model

Fig.2 KNGR Fuel Assembly Model

Fig. 3 Core Support Plate Horizontal Velocity Time History (Rock Site, SSE-Z)

Fig. 4 Core Support Plate Horizontal Response Spectrum
(Rock Site, SSE-Z, 4% Damping)

Fig. 5 KNGR Core Model (17 Fuel Assemblies)

Fig.6 Fuel Assembly Modal Analysis Results (In-Water)

Fig.7 Pluck Impact Simulation Models

Fig.8 Comparison of Single Grid Pluck Impact Test Data with Analysis Results

Fig.9 Spacer Grid Impact Load Time History (6th SG, Between FA and Shroud)