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The effect of seismic level increase on fuel assembly response

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ABSTRACT : To cover a range of the seismic condition of possible sites where the Korean next generation reactor may be constructed, the peak ground accelerations for the safe shutdown earthquake are considered to be 0.3g and 0.2g for the horizontal and vertical directions, respectively. For this increased seismic level, the dynamic responses such as fuel assembly shear force, bending moment and displacement, and spacer grid impact loads are calculated using the detailed core model. Also fuel assembly stress is predicted using the deflected shape based on a fuel assembly model as an equivalent beam to check the structural integrity of the fuel assembly for the increased seismic level.

1 INTRODUCTION

The reactor core of a pressurized water reactor is composed of several hundreds of assemblies of different kinds such as ordinary fuel assemblies and control element assemblies. They are rectangular beams supported by a fuel alignment plate and a core support plate at the top and bottom ends, respectively, immersed in coolant with very narrow spacings between adjacent assemblies. The vibratory motion of thewhole cluster in an earthquake event, may have a complicated nature including non-linearity due to the collision of assemblies with each other and dynamic interactions between fluid and solid structures which cause the fluid coupling forces.

Seismic safety qualification of the reactor core is one of the crucial issues in the seismic design of a pressurized water reactor, and it should be secured that the structural integrity of the fuel assemblies and the control rod insertion capabilities be maintained against the design seismic loads. To cover a range of the seismic condition of possible sites where the Korean next generation reactor may be constructed, a range of generic site conditions was selected for geologic and seismologic evaluation. The complete historic record of earthquakes in the region will be included in the site specific data. To envelop other Asian countries as well as the Korean peninsula, the peak ground accelerations for the safe shutdown earthquake (SSE) are considered to be 0.3g and 0.2g for the horizontal and vertical directions, respectively.

In the present study, a method for detailed dynamic analysis of a reactor core is developed. Detailed core model is set up to reflect the placement of the fuel assemblies within the core shroud. Peak horizontal responses are obtained for the motions induced from earthquake. The dynamic responses such as fuel assembly shear force, bending moment and displacement, and spacer grid impact loads are carefully investigated.

Also, in this study, fuel assembly stress during an earthquake is predicted using the results discussed in the detailed dynamic analysis of a reactor core, which gives vertical and horizontal loads and the deflected shape. The effect of an increased seismic level on the fuel assembly structural integrity is discussed.

2 ANALYSIS

2.1. Dynamic response calculation

A detailed horizontal core model is developed for the time history analysis for the seismic excitations, and the dynamic response is determined using the core plate motions from the coupled internals and core analysis. The vertical response is obtained in the coupled internals and core model and therefore separate analysis is not necessary [1].

The input excitations to the detailed core model consist of the translational and rotational motions of the core plates and the translational motion of the core shroud. The core shroud is so stiff comparing with fuel assembly that its local effect is negligible. Therefore, only the translational component of the core shroud is used. The input motions are obtained from a seismic analysis of a coupled internals and core model which has a much less detailed representation of the core.

Since the reactor vessel (RV) motions for the increased seismic level are not available from the reactor coolant system analysis at this time, SSE RV motions of the Ulchin nuclear power plant units 3 and 4 in Korea (UCN 3 and 4) are increased by 50 % to generate 0.3g and 0.2g motions for the horizontal and vertical directions, respectively [2]. The response motions from the coupled internals and core are used for the detailed core analysis. The core plate motions for a increased seismic level are amplified by 5.0 and 6.2

times from the reactor vessel motions in the north-south and east-west directions, respectively (Fig. 1). They are more severely amplified comparing with SSE (0.2g) and operating basis earthquake (OBE) cases.

The responses of the fuel assemblies to the excitations were obtained using the integration of equations of motion by the Runge-Kutta-Gill method for first-order differential equations. The integration time step was determined based on the impact pulse which is typically estimated to be 10 milliseconds for the seismic excitation.

2.2. Stress calculation

The fuel assembly axial and lateral internal support consists of five guide tubes (primary structural members) supported by spacer grids welded to the guide tubes. Because this configuration is complex it requires consideration of the distribution of shear forces and bending moments within the bundle in order to calculate guide tube and fuel rod stresses for a given loaded condition. The stress analysis is performed based on the premise that for lateral fuel assembly deflections and the resultant material strains, there is a direct correspondence between the deflected shape of the assembly and the strains in the assembly structure.

The differential equation governing flexure of one guide tube or fuel rod is [3] :

$$\frac{d^3v}{dx^3} = \frac{-p}{EI} \tag{1}$$

where v is the displacement of any point on the guide tube, x is the distance along the guide tube, E is the elastic modulus, I is the section moment of inertia and p is the load per guide tube or fuel rod. The appropriate boundary conditions are :

$$\begin{aligned} &v(0) = v_1 \\ &\frac{dv}{dx}(0) = \tan\theta_1 \\ &\frac{dv}{dx}(L) = \tan\theta_2 \end{aligned} \tag{2}$$

where θ_1 and θ_2 are independent angular rotations of each end. Guide tube or fuel rod may be treated as simple circular cross section beams sharing a common deflected shape within a given element.

Solving equation (1) for boundary conditions (2) gives the following solution

$$v=\frac{-p}{6EI}x^3+\left(\frac{\tan\theta_2-\tan\theta_1}{2L}+\frac{pL}{4EI}\right)x^2+\tan\theta_1 x+v_1 \tag{3}$$

$$\frac{d^2v}{dx^2}=\frac{M}{EI}=\frac{-p}{EI}x+\left(\frac{\tan\theta_2-\tan\theta_1}{L}+\frac{pL}{2EI}\right) \tag{4}$$

For the case with given θ_1, θ_2 and $v(L) = v_2$, equation (3) becomes for small θ

$$v_2-v_1=\frac{pL^3}{12EI}+\left(\frac{\theta_2+\theta_1}{2}\right)L \tag{5}$$

From this equation the net load applied to one guide tube or fuel rod is determined as ;

$$p=\frac{12EI}{L^3}\left[v_2-v_1-\frac{(\theta_2+\theta_1)L}{2}\right] \tag{6}$$

and equation (4) becomes for small θ

$$M=\frac{p}{2}(L-2x)+\frac{\theta_2-\theta_1}{L}EI \tag{7}$$

Therefore, the moment at $x = L$ is calculated as

$$M=\frac{2EI}{L}\left[(2\theta_2+\theta_1)-\frac{3}{L}(v_2-v_1)\right] \tag{8}$$

From this moment, the bending stress can be computed.

The total stress intensity due to dynamic loads will have stress contributions from the bending loads caused by overall deformation and axial loads induced by frictional restraint at the spacer grids.

3 RESULTS AND DISCUSSION

The result of the detailed core analysis consists of peak spacer grid impact loads, fuel assembly moments, shears and deflected shapes. The impact loads are used to evaluate the structural integrity of spacer grids. The deflected shapes which correspond to peak loading conditions - peak displacement, peak shear and peak moment - are used to calculate stresses using a detailed static model of the fuel assembly. The deflected shapes for earthquake excitation indicate that the fuel assemblies respond to the seismic excitation by moving back and forth across the core at approximately their first mode natural frequencies [4]. The maximum deflection which is found in the middle of the fuel assembly height should be small enough to guarantee a control element assembly insertion [5].

The spacer grid impact loads and the fuel assembly responses are shown in Table 1. The square root of the sum of the squares (SRSS) of one-sided impact are 1935 lbs and 3826 lbs for OBE and SSE, respectively. The OBE impact is almost half of SSE impact. For the through-grid impacts, the SRSS values are 1303 lbs and 2740 lbs for OBE and SSE, respectively. The ratio of OBE to SSE is 48 %. For the axial response of fuel assembly, the axial force of fuel rods is 278.5 lbs and 506.2 lbs for OBE and SSE, respectively. The response ratio of OBE/SSE ranges in 48 % to 55 % for the fuel rods, end fittings and guide tubes.

The 0.3g SRSS of spacer grid impacts are 5675 lbs and 3449 lbs for one-sided and through-grid impacts, respectively. This exceeds the allowables by 28.6 % and 1.6 % for one-sided and through-grid impacts, respectively, which indicates that the fuel assembly design need to be modified for the seismic level increase to 0.3g of SSE. For the axial response of the fuel assembly, the axial force of fuel rods is 758.8 lbs. The response ratio of OBE/SSE(0.3g) ranges in 32.4 % to 36.7 % for the fuel rods, end fittings and guide tubes. For both horizontal and vertical directions the response ratio is almost the same as the ratio of input motions, which means that the non-linearity of the fuel assembly response is not significant.

The guide tube and the fuel rod stress intensities are summarized in Table 2. For the fuel rod stress calculation the differential pressure which always exists during a plant operation is included. Most of the stress intensity for fuel rod came from the differential pressure load and the contribution of the earthquake excitation for a primary membrane component is almost negligible. The resulting stress intensity in each direction is combined by the square root-sum-squares method to give the total stress intensity and also the stress intensities from other loading conditions are considered to be compared with code allowables to verify the structural integrity.

4 CONCLUSIONS

A detailed dynamic analysis of a reactor core is performed to get peak responses of a fuel assembly for the motions induced from earthquake. The dynamic responses such as fuel assembly shear force, bending moment, axial force and displacement, and spacer grid impact loads are carefully investigated. From the response comparisons between OBE and SSE, the non-linear characteristics of the fuel assembly are found to be insignificant.

To assess a structural integrity of the fuel assembly for earthquake, fuel assembly stress during an earthquake is predicted using the deflected shape based on a fuel assembly model as an equivalent beam. This stress analysis method and its application for the case of an increased seismic level are also presented. The results showed that the present design of the guide tube and the fuel rod satisfies the allowables for the 0.3g ground motion, but the spacer grid does not and needs to be modified for the increased seismic level.

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Table 1 Responses of fuel assembly for earthquake excitations

Component	OBE			SSE			SSE-0.3g		
	N-S[1]	E-W	Vert	N-S	E-W	Vert	N-S	E-W	Vert
Spacer grid[2]									
One-sided impact (lbs)	1455	1275		2606	2801		3696	4307	
Through-grid impact (lbs)	948	894		2091	1771		2214	2644	
Fuel assembly									
Deflection (inch)	1.210	1.160		1.505	1.596		1.706	1.993	
Shear (lbs)	164	199		298	394		417	483	
Moment (lb-inch)	3566	3923		5934	7560		8378	9715	
Axial Force (lbs)									
@ Fuel rod			278.5			506.2			758.8
@ Guide tube			24.9			45.2			67.8

[1] N-S : north-south direction, E-W : east-west direction, Vert. : vertical direction.

[2] Allowables of one-sided and through-grid impacts are 4413 and 3396 lbs, respectively.

Table 2 Maximum stress intensities of fuel assembly for earthquake excitations

Component	OBE		SSE		SSE-0.3g		Allowable[1]
	N-S	E-W	N-S	E-W	N-S	E-W	
Guide tube							
Total	17.2	16.5	22.7	26.8	32.6	37.2	61.9
Primary membrane	4.0	3.8	5.1	5.7	6.6	8.1	44.7
Fuel rod[2]							
Total	15.3	15.3	18.0	18.5	20.5	21.9	31.8
Primary membrane	15.3	15.3	15.3	15.3	15.3	15.3	21.7

[1] Allowables are for the faulted conditions.

[2] Includes stress components due to fuel rod differential pressure.

[3] Unit = ksi.

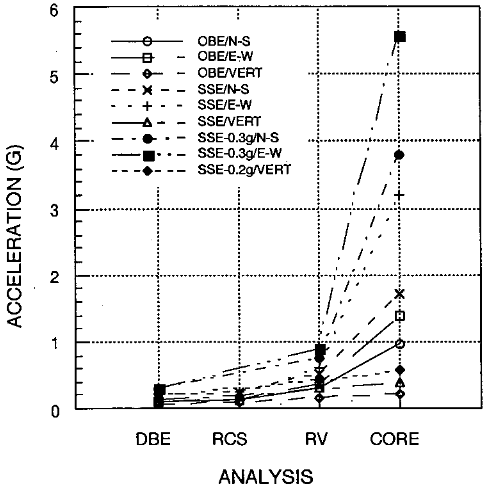

Figure 1 Zero period accelerations of input motion