Journal of the Korean Nuclear Society
Volume 30, Number 3, pp.212~221, June 1998

Structural Integrity of PWR Fuel Assembly for Earthquake

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(Received July 18, 1997)

Abstract

In the present study, a method for the dynamic analysis of a reactor core is developed. Peak responses for the motions induced from earthquake are obtained for a core model. The dynamic responses such as fuel assembly shear force, bending moment, axial force and displacement, and spacer grid impact loads are investigated. Prediction of fuel assembly stress during an earthquake requires development of a fuel assembly stress analysis model capable of interfacing with the models and results discussed in the dynamic analysis of a reactor core. This analysis uses beam characteristics which describe the overall fuel assembly response. The stress analysis method and its application for the case of an increased seismic level are also presented.

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 (FAP) and a core support plate (CSP) at the top and bottom ends, respectively, immersed in coolant with very narrow spacings between adjacent assemblies. Thus, in an earthquake event, their vibratory motions as a whole cluster may have a complicated nature including non-linearity due to the effect of collisions between assemblies and dynamic interactions through 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. The procedure for core analysis is described briefly in the following. As the first step, reactor vessel (RV) motion is obtained from the reactor coolant system (RCS) analysis in which a very simplified model of the reactor vessel internals and core is used. Subsequently, the reactor vessel motion is used as an input to a coupled model of the reactor vessel internals and core. In this model, only a lumped model of the core is used with a purpose to include interaction effects between the response of the fuel assemblies, core plates and core shroud. Motions of core plates and core shroud from the coupled internals and core analysis are input to the detailed core model in which each fuel assembly is modeled individually. In the last step, the deflected shapes of the fuel assembly and

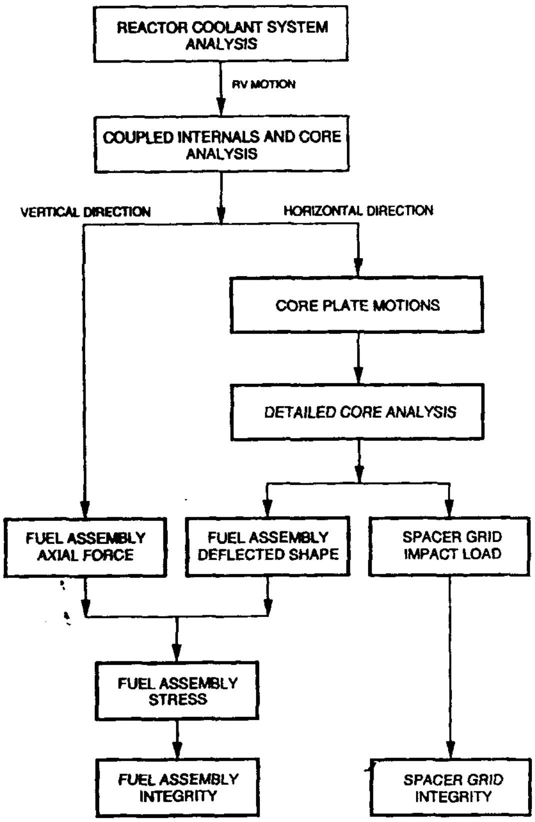

Fig. 1. Analysis Procedure for Fuel Assembly Seismic Design

spacer grid impact loads from the detailed core analysis are used to assure the structural integrity. Fig. 1 illustrates the overall design analysis flow.

For the purpose of assessing seismic safety of the reactor core, the dynamic response of the fuel assemblies should be evaluated with a sufficient accuracy, which requires a well validated large scale analysis methodology or experiment. In this context, various experimental efforts have been made to understand dynamic characteristics of a reactor core [1, 2]. But practically it is almost impossible to get the response by experiment because of difficulties of experimental setup or economical reasons. It necessitates the analytical study for the vibration characteristics of a fuel assembly.

In the present study, a method for the dynamic analysis of a reactor core is developed. A core model is set up to reflect the placement of the fuel assemblies within the core shroud. Peak responses are obtained for each model 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 investigated. Also, the sensitivity responses are obtained for the earthquake motions and the fuel assembly non-linear response characteristics are discussed.

Prediction of fuel assembly stress during an earthquake requires development of a fuel assembly stress analysis model capable of interfacing with the models and results discussed in the dynamic analysis of a reactor core, which obtains vertical and horizontal loads and the deflected shape based on a fuel assembly model as an equivalent beam. This analysis uses beam characteristics which describe the overall fuel assembly response. The stress analysis method and its application are also presented in this study.

2. Analysis

2.1. Dynamic Response Calculation

The horizontal core model is developed for the time history analysis for the seismic excitations, and dynamic response is determined using the core plate motions from the coupled internals and core analysis [3]. The vertical response is obtained in the coupled internals and core model and therefore separate analysis is not required [4].

The input excitations to the core model consist of the translational and angular 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.

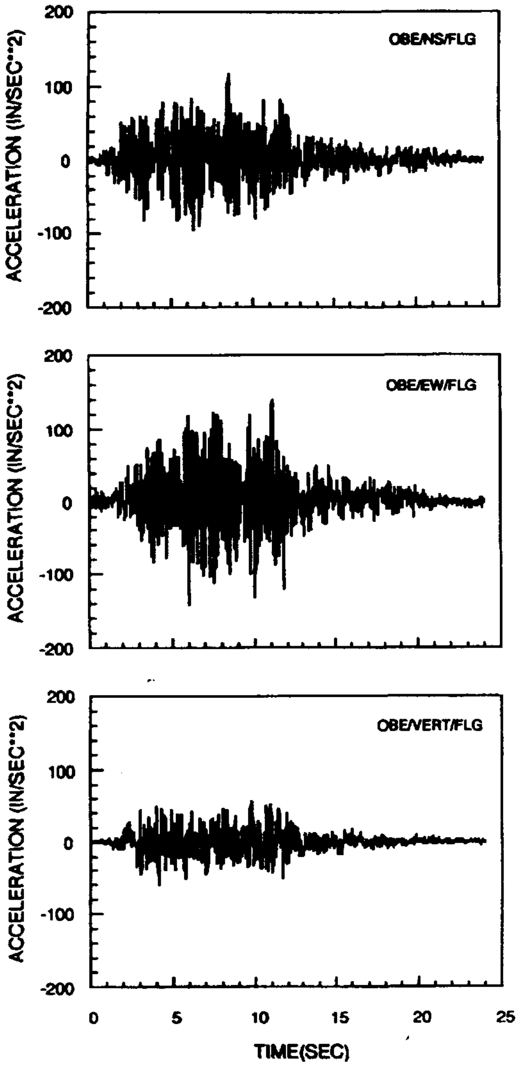

Fig. 2. Acceleration Time History of RV Flange for OBE.

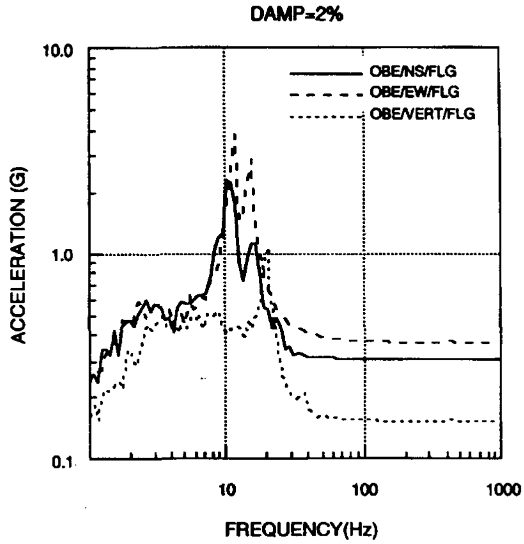

Fig. 3. Response Spectra of RV Flange for OBE.

Therefore, only the translational motion 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.

The reactor vessel motions of Ulchin nuclear power plant units 3 and 4 in Korea (UCN 3 and 4) as shown in Figs. 2 and 3 are used to excite the coupled internals and core model. The analysis of the coupled internals and core model generates the core plate motions which are amplified by a factor of more than 3 from the reactor vessel motions. The zero period accelerations (ZPAs) of FAP in the east-west direction are 1.401g and 3.201g for an operating basis earthquake (OBE) and a safe shutdown earthquake (SSE), respectively, and the corresponding values for CSP are 0.475g and 1.298g (Table 1). The ZPA ratios of OBE to SSE for FAP are 62.7 % and 43.8 % in the north-south and east-west directions, respectively.

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 SSE were considered to be 0.3g and 0.2g for the horizontal and vertical directions, respectively. Since the RV motions for the increased seismic level are not

Table 1. ZPA (g) Values of Input Motions for RCS, RVI and Core Analysis.

Earthquake	Direction[1]	DBE[2]	RCS	RV		CORE[3]	
			basemat	flange	snubber	FAP (UEF)	CSP (LEF)
OBE	N-S	0.1	0.119	0.301	0.135	0.960	0.366
	E-W	0.1	0.119	0.367	0.216	1.401	0.475
	Vert.	0.067	0.099	0.152	-	0.215	0.207
SSE	N-S	0.2	0.238	0.510	0.266	1.532	1.720
	E-W	0.2	0.238	0.604	0.375	3.201	1.298
	Vert.	0.133	0.197	0.288	-	0.390	0.377
SSE-0.3g	N-S	0.3	-	0.765	0.399	3.794	1.939
	E-W	0.3	-	0.906	0.563	5.122	5.590
Vert.	0.200	-	0.432	-	0.585	0.565	
Ratio (%)							
OBE/SSE	N-S	50.0	50.0	59.1	50.8	62.7	21.3
	E-W	50.0	50.0	60.8	57.7	43.8	36.6
	Vert.	50.0	50.0	52.7	-	55.1	54.9
OBE/SSE-0.3g	N-S	33.3	-	39.3	33.8	23.3	18.9
	E-W	33.3	-	40.5	38.4	27.4	8.5
	Vert.	33.3	-	35.1	-	36.8	36.6

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

2 DBE = Design basis earthquake.

3 For horizontal direction ZPAs of FAP and CSP are tabulated and for vertical direction ZPAs of upper end fitting (UEF) and lower end fitting (LEF) are tabulated.

Table 2. Amplification Factor of ZPA Values for AE, RCS and RVI Analysis

Earthquake	Dir.	AE	RCS	RVI
		DBE→RCS basemat	RCS basemat→RV flg.	RVflg.→core plt.[1]
OBE	N-S	1.2	2.5	3.2
	E-W	1.2	3.1	3.8
	Vert.	1.5	1.5	1.4
SSE	N-S	1.2	2.1	3.4
	E-W	1.2	2.5	5.3
	Vert.	1.5	1.5	1.4
SSE-0.3g	N-S	-	-	5.0
	E-W	-	-	6.2
	Vert.	-	-	1.4

1 For vertical direction, end fittings of fuel assembly are used.

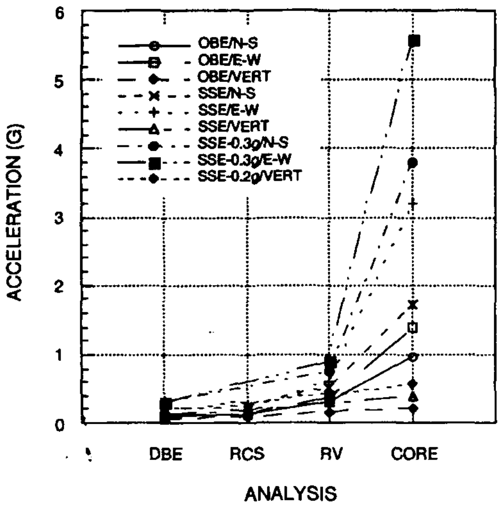

Fig. 4. Zero Period Accelerations of Input Motion

available from RCS analysis at this time, SSE RV motions of UCN 3 and 4 are increased by 50 % to generate 0.3g and 0.2g motions for the horizontal and vertical directions, respectively [5]. The response motions from the coupled internals and core are used for the 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 (Table 2 and Fig. 4). They are more severely amplified comparing with SSE (0.2g) and OBE cases. Fig. 5 shows the response spectra of the fuel alignment plate and the core support plate for a horizontal direction, and end fittings for a vertical direction.

The responses of the fuel assemblies to the

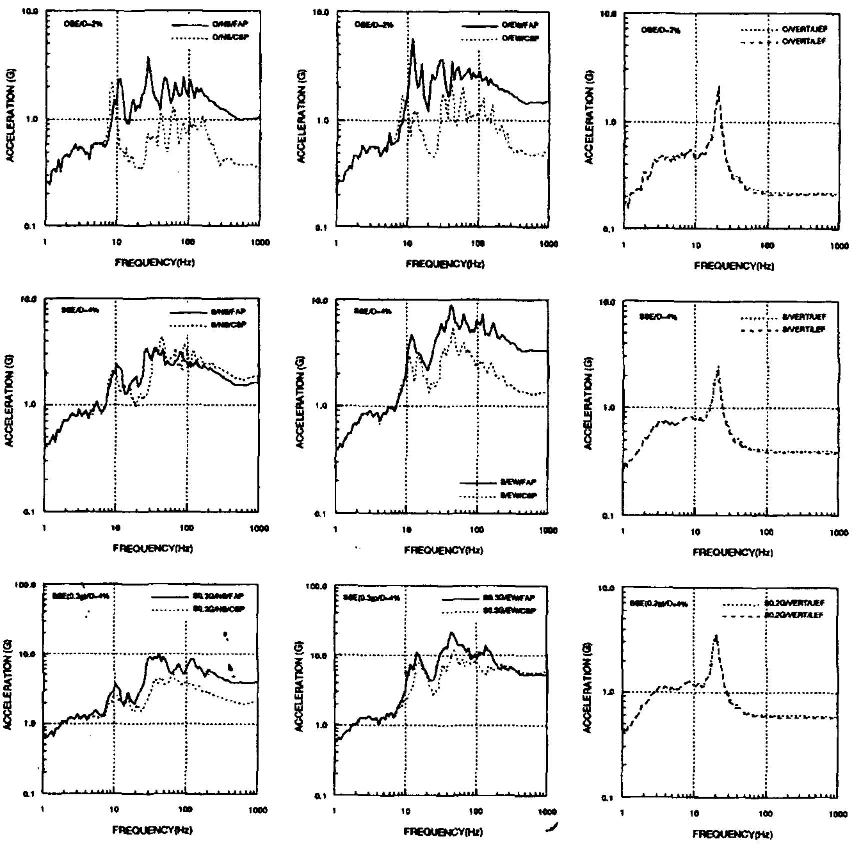

Fig. 5. Response Spectra of Fuel Assembly

excitations were obtained using the integration of equations of motion by the Runge-Kutta-Gill method for first-order differential equations [6]. The integration time step was determined based on the impact pulse which is typically estimated to be 10 milliseconds for the seismic excitation. The number of steps per pulse will be $(10 \times 10^{-3})/(2 \times 10^{-4}) = 50$ for the constant time step of 2×10^{-4} second, which is large enough for this kind of analysis. In this case, the maximum frequency range encompassed is $[2\pi(20)(2 \times 10^{-4})]^{-1} = 39.8$ Hz because time step is almost equal to (1/20)× (minimum period). The 39.8 Hz is wide enough to cover the fuel assembly frequencies because fuel assembly responds to the seismic excitation by moving back and forth approximately at the first mode frequency of 1 Hz [3].

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 them. 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.

Considering the general configuration which an element assumes under an arbitrary state of load (*P*), linear displacement (v) is allowed between the ends as well as independent angular rotation of each end (θ_1, θ_2). Guide tube or fuel rod may be treated as simple circular cross section beams sharing a common deflected shape within a given

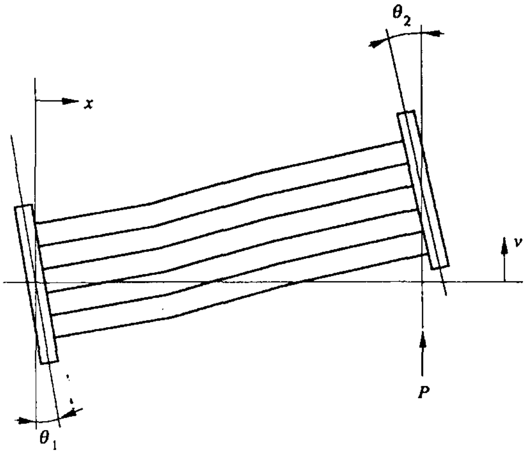

Fig. 6. Typical Element Under Load.

element. The differential equation governing flexure of one guide tube or fuel rod is [7] :

$$\frac{d^3 v}{dx^3} = -\frac{p}{EI} \quad (1)$$

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

$$v(0) = v_1, \frac{dv}{dx}(0) = \tan\theta_1, \frac{dv}{dx}(L) = \tan\theta_2 \quad (2)$$

where θ_1 and θ_2 are shown in Fig. 6.

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

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

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

$$\frac{d^2 v}{dx^2} = \frac{M}{EI} = -\frac{p}{EI}x + \left(\frac{\tan\theta_2 - \tan\theta_1}{L} + \frac{pL}{2EI}\right) \quad (5)$$

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

$$v_2 - v_1 = \frac{pL^3}{12EI} + \left(\frac{\theta_2 + \theta_1}{2}\right)L \quad (6)$$

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

$$p = \frac{12EI}{L^3}\left[v_2 - v_1 - \frac{(\theta_2 + \theta_1)L}{2}\right] \quad (7)$$

and equation (5) becomes for small θ

$$M = \frac{p}{2}(L - 2x) + \frac{(\theta_2 - \theta_1)}{L}EI \quad (8)$$

Therefore, the moment at x = L is calculated as

$$M = \frac{2EI}{L}\left[(2\theta_2 + \theta_1) - \frac{3}{L}(v_2 - v_1)\right] \quad (9)$$

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 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 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 [3]. 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 [8].

The spacer grid impact loads and the fuel assembly responses are shown in Table 3. 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 %.

Table 3. Horizontal Response Summary of Fuel Assembly

Component	Response						Ratio(%)			
	OBE		SSE		SSE-0.3g		OBE/SSE		OBE/SSE(0.3g)	
	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W
Spacer grid impact (lbs)[1]										
One-sided	1455	1275	2606	2801	3696	4307	55.8	45.5	39.4	29.6
Through-grid	948	894	209	1771	2214	2644	45.3	50.5	42.8	33.8
Fuel assembly										
Deflection (inch)	1.210	1.160	1.505	1.596	1.706	1.993	80.4	72.7	70.9	58.2
Shear (lbs)	164	199	298	394	417	483	55.0	50.5	39.3	41.2
Moment (lb-inch)	3566	3923	5934	7560	8378	9715	60.1	51.9	42.6	40.4

[1] Allowables of one-sided and through-grid impacts for UCN 3&4 fuel assembly are 4413 and 3396 lbs, respectively.

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 (Table 4). 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 required data for stress calculation of the fuel assembly is a deflected shape which represents the most severe conditions. The selection of cases of interest is identified in the following. Each fuel assembly member in the detailed core model will, at some time during the earthquake history, experience a maximum shear. The deflected shape of that assembly at that time is recorded. This is repeated for each

Table 4. Vertical Response Summary of Fuel Assembly

Axial force (lbs)	OBE	SSE	SSE-0.3g
Fuel rods	278.5	506.2	758.8
UEF	1.1	2.3	3.4
LEF	306.8	556.5	835.0
Guide tubes	24.9	45.2	67.8
Ratio (%)		**OBE/SSE**	**OBE/SSE(0.3g)**
Fuel rods		55.0	36.7
UEF		47.8	32.4
LEF		55.1	36.7
Guide tubes		55.1	36.7

Table 5. Summary of Stress Intensities for Guide Tube

Component	OBE		SSE		SSE-0.3g	
	N-S	E-W	N-S	E-W	N-S	E-W
Stress Intensity (ksi)[1]						
Maximum total	17.2	16.5	22.7	26.8	32.6	37.2
Maximum primary membrane	4.0	3.8	5.1	5.7	6.6	8.1

[1] Allowables of membrane and total stress intensities for SSE are 44.7 and 61.9 ksi, respectively.

Table 6. Summary of Stress Intensities for Guide Tube

Component	OBE		SSE		SSE-0.3g	
	N-S	E-W	N-S	E-W	N-S	E-W
Stress Intensity (ksi)[1]						
Maximum total	15.3	15.3	18.0	18.5	20.5	21.9
Maximum primary membrane	15.3	15.3	15.3	15.3	15.3	15.3

[1] Allowables of membrane and total stress intensities for SSE are 21.7 and 31.8 ksi, respectively.

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

member in the model. Similar sets of deflected shapes are recorded for times when, at each node in the fuel assembly, the members adjacent to the node experience a maximum moment, and for times when each node experiences a maximum displacement measured relative to the fuel alignment plate. For the fuel assembly model with eleven members (12 nodes), a total of thirty-three fuel assembly deflected shapes would be compiled that encompass the more severe stress conditions.

The guide tube and the fuel rod stress intensities are summarized in Tables 5 and 6, respectively. 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 method for the dynamic analysis of a reactor core is developed to get peak responses for the motions induced from earthquake. A core model is set up to reflect the placement of the fuel assemblies within the core shroud. The dynamic responses such as fuel assembly shear force, bending moment, axial force and displacement, and spacer grid impact loads are investigated. From the response comparisons between OBE and SSE, the fuel assembly non-linear characteristics 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. The 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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