Fuel Assembly Design for High Seismic Sites

Hyeong Koo Kim[1], Jin Gon Chung[1], Chong Chul Lee[1], M. Arthur Johnson[2]

1) Department of Fuel Mechanical Design, KEPCO Nuclear Fuel Co. Technical Center, Daejeon, Korea
2) Westinghouse Electric Company LLC, USA

ABSTRACT

Fuel assembly spacer grids must maintain the fuel rods in a coolable array during and following an earthquake when they will be subject to impact loads. This can be a challenging requirement at a high seismic site. If a preliminary core seismic analysis indicates that the spacer grid impact loads exceed the strength of the spacer grids, design modification of the fuel assembly may be necessary. Modifying the fuel assembly design requires an understanding of the effects of individual design parameters on the dynamic behavior of the fuel assembly. With this understanding, the necessary design modifications can be determined. In this study, dominant parameters affecting the integrity of a fuel assembly have been examined to determine appropriate design parameters for application to a fuel assembly subject to high seismic loads. Based on these parametric studies, guidelines for fuel assembly design under high seismic loads are provided.

INTRODUCTION

Considerable research has been carried out with regard to the integrity of fuel assemblies under severe accident conditions like Safe Shutdown Earthquake (SSE) and Loss of Coolant Accident (LOCA) [1, 2, 3]. The basic functional requirement of a PWR fuel assembly, which must be satisfied during an SSE, is that the structural components of the fuel assembly maintain the fuel rods in a coolable geometry as well as assuring control rod insertability. This can be a challenging requirement at a high seismic site. If a preliminary core seismic analysis indicates that the spacer grid impact loads exceed the strength of the spacer grids, design modification of the fuel assembly may be necessary. Modifying the fuel assembly design requires an understanding of the effects of individual design parameters on the dynamic behavior of the fuel assembly. Seismic analysis parametric studies provide a way of obtaining the necessary understanding. The main parameters affecting fuel assembly response in a reactor core are the following: spacer grid impact stiffness, strength and coefficient of restitution, number and location of spacer grids, fuel assembly natural frequency, fuel assembly damping, gaps between fuel assemblies and between the peripheral assemblies and the core shroud, and the seismic excitation.

In this study, dominant parameters affecting the dynamic behavior of fuel assemblies have been examined to determine appropriate design parameters for application to a fuel assembly subject to high seismic loads. These parametric studies utilize a fuel assembly model and a detailed core model representing a row of 17 fuel assemblies across the core.

FUEL ASSEMBLY MODEL

The PWR fuel assembly considered in this paper consists of 236 fuel rods arranged in a 16x16 lattice, 5 guide tubes, 11 fuel rod spacer grids and upper and lower end fittings as shown in Fig.1. The guide tubes, spacer grids, and end fittings form the structural frame of the assembly. The fuel assembly model is developed to describe the axial and lateral static as well as dynamic characteristics of the fuel assembly using design drawings and test data from full-scale static and dynamic tests. The fuel assembly model used in this study is a uniform beam with torsional springs at each end to account for reactor end conditions, which are neither fixed nor pinned. The mass of the assembly is concentrated at mass points located coincident with the spacer grids, which has been shown to provide good agreement with test data. The normalized deflection shape of this model can be expressed analytically in terms of two non-dimensional parameters, $K_U\, L/EI$ and $K_L\, L/EI$, where:

K_U = torsional spring at upper end of fuel assembly
K_L = torsional spring at lower end of fuel assembly
EI = beam bending stiffness
L = length of fuel assembly.

The values of these two non-dimensional parameters which minimize the difference between the test deflection shape and that of the model provide the best possible agreement between the lateral deflection shape of the model and the tested fuel assembly. Fuel assembly natural frequency and critical damping ratio data from the forced vibration tests are used in the fuel assembly model. The fuel assembly model has been benchmarked against actual fuel assembly tests as explained in a previous paper [4].

DETAILED CORE MODEL

The major purpose for developing horizontal core models is to analyze the integrity of fuel assemblies, which may contact the core shroud, and other fuel assemblies during severe accidents like seismic and LOCA. The model represents a row of fuel across the core. This model incorporates several simplifying assumptions. The primary one is that the motion of the core is planar in response to seismic excitation [1]. 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 [5].

The fuel assemblies are separated by gaps. One major nonlinear aspect of fuel assembly response is the contact phenomena between fuel assemblies and/or between peripheral fuel assembly and the core shroud during a seismic event. Nonlinear springs are used to model the impacting of one fuel assembly with an adjacent fuel assembly or the core shroud. Each spacer grid is characterized by the two nonlinear springs which represent the dual load paths associated with both one-sided and through-grid impacts. The spacer grid impact spring representation is shown in Fig.2. The one-sided grid stiffness values are derived from a simulation of pluck impact tests. The through-grid stiffness values are based on static through-grid load-deflection tests. A typical detailed core model with 17 fuel assemblies is shown in Fig.3.

PARAMETRIC ANALYSIS

Fuel Assembly Natural Frequency

The effect of changes in the natural frequency of the fuel assembly on peak spacer grid impact loads was investigated using two fuel assembly models with different natural frequencies. The normalized natural frequencies of the fuel assembly models considered in this study were 1.0 and 1.23 as listed in Table 1.

The results do not indicate strong sensitivity to changes in fuel assembly natural frequency. Comparing the peak impact force from analyses using these two models, increasing the natural frequency of the fuel by 23% resulted in a decrease in peak impact load of 8%. From this study, increasing the natural frequency of the fuel assembly results in a decrease in impact force.

As described above, the deflection shape of this model during the seismic analysis is controlled by two non-dimensional parameters, $K_U\,L/EI$ and $K_L\,L/EI$. The effect of these non-dimensional parameters on fuel assembly response has been investigated with two models as shown in Table 2. The values of these non-dimensional parameters are very different but the natural frequencies of the fuel assemblies are approximately the same. In Case 2 the model approaches a fixed support condition while in Case 1 the boundary conditions approach a simple support. The results, as shown in Table 2, indicate that the change in the non-dimensional parameters had little affect on the spacer grid impact loads. However, the peak bending moment of Case 2 was significantly larger than that of Case 1. Since the maximum bending moment usually occurs at the end of the fuel assembly, this was due to the increased stiffness of the torsional springs.

Fuel Assembly Damping

Results from six core analyses with different fuel assembly damping values are shown in Table 3. For Study I, the fuel assembly critical damping ratios in Case 1 are approximately twice those in Case 2. Comparing Cases 2 and 3, the first mode critical damping ratios are the same while the third mode value for Case 3 is about twice that of Case 2. The results for Cases 1 and 2 show that higher damping ratios caused a decrease in spacer grid impact loads. The one-sided grid impact loads showed the largest difference, about 16%. For Cases 2 and 3, increased third mode damping caused a decrease in most maximum spacer grid impact loads. For example, the maximum one-sided impact load decreased 6%. However, the maximum through grid impact load increased slightly.

Study II of Table 3 provides the results of another damping study. For this study, the Case 2 damping ratios were twice those of Case 1 while those of Case 3 were three times those of Case 1. Increasing the damping values reduced the peak spacer grid impact loads by 15% and 19% for Cases 2 and 3, respectively.

Coefficient of Restitution of Fuel Assembly

Coefficient of restitution (COR) is classically defined for the impact of two objects as the ratio of the rebound velocity divided by the impact velocity. Thus the more energy which is dissipated during the impact, the smaller the value of COR. The COR values for spacer grids have been calculated from one-sided drop impact tests in which drop height, impact velocity, rebound velocity and impact force data were recorded. In the study shown in Table 4, Cases 1-3 examine the effect of changes in the COR. Decreasing the COR by 30% resulted in the peak spacer grid impact load decreasing by 28%. And decreasing the COR by 50% decreased the peak impact load by 35%.

Spacer Grid Stiffness

To investigate the effect of changes in spacer grid impact stiffness on peak spacer grid impact loads, both the one-sided and through-grid stiffness of the spacer grids located at the center of the fuel assembly were varied. Normalized spacer grid stiffness values and the corresponding resultant peak impact loads are shown in Table 5. This study showed that increasing the impact stiffness of the central spacer grids increases the maximum impact loads on these spacer grids and reduces the impact loads on the spacer grids that are away from the center grids.

It is possible to estimate the change in impact load due to a change in spacer grid impact stiffness by assuming that the strain energy absorbed in the grid impact spring is constant. The maximum strain energy absorbed by the grid during an impact is equal to the following:

$$E = \frac{1}{2}\frac{F^2}{K}, \qquad (1)$$

where E = strain energy, F = maximum impact force, and K= grid impact stiffness.

For this approximate method, it is assumed that the impact energy remains constant, that is, the impact energy is independent of the spacer grid stiffness. Therefore, the ratio of peak impact force can be calculated from the spacer grid impact stiffness values by the following equation:

$$F_2/F_1 = \sqrt{(K_2/K_1)} \qquad (2)$$

As evident from Table 5, estimates made using this equation agree well with the actual values calculated in the analyses using the detailed core model. For example, the grid impact stiffness value for Case 2 was 26% greater than that of Case 1. Equation 2 would estimate an increase in the peak one-sided impact force of 12% while the analyses found the increase to be 11%.

Core Gaps

The study listed in Table 6 examines the effect of changes in the gap between the peripheral assemblies and the core shroud and between fuel assemblies on the response of the fuel assemblies. In the study three sets of core gap values were considered. For a 17 row core model, the total core gap is equal to the peripheral gap times 2 plus the interior gap times 16. The total core gaps and the results for the three cases considered in this study are listed in the Table 6.

The results show that increasing the core gaps (within the range of reasonable core gaps) increases the spacer grid impact loads.

RESULTS AND DISCUSSIONS

Core seismic analysis parametric studies have been performed with variations in five dominant fuel assembly dynamic response parameters; natural frequency, critical damping ratio, spacer grid impact coefficient of restitution, spacer grid impact stiffness and core gap size. These studies examined the effect of these parameters on spacer grid impact loads. Based on these results, fuel assemblies for high seismic sites should be designed to maximize the fuel assembly natural frequency, critical damping ratios and energy dissipation due to grid impacts and minimize the spacer grid stiffness and core gaps. The first three parameters are difficult to control during the design phase, making it important that the testing done to measure these parameters be performed carefully to obtain the most realistic values.

The last two parameters, spacer grid impact stiffness and core gap size, are the easiest to control during the design process. These parameters provide a method for maintaining the distribution of maximum spacer grid impact loads along the length of a fuel assembly within acceptable limits. For example, five different grid stiffness patterns and one different set of core gaps (see Table 7) have been investigated to determine if the peak impact load pattern along the length of the assembly could be made more uniform by appropriate combination of spacer grid stiffness and core gaps. That is, reduce the peak loads in the center and increase those away from the center. The resulting maximum one-sided impact loads along the length of the assembly are plotted in Figure 4. The plot shows that it is possible to reduce the peak grid impact load by careful placement of stiffer grids and by controlling the core gaps. In this example, the peak grid load in Case 5 is about 15% less than that in Case 1 and about 37% less than that in Case 6.

CONCLUSIONS

A series of parametric studies have been performed to examine the effect of the fuel assembly model parameters on spacer grid impact loads during a seismic core analysis. The study shows that most dominant parameters affecting the spacer grid impact loads are spacer grid impact stiffness, core gaps and critical damping ratios. By controlling these parameters carefully, the maximum impact loads acting on the spacer grids can be controlled. In actual practice, a fuel assembly for a high seismic site has been designed based on the results of the present parametric studies by positioning four high stiffness (and high strength) grids at the center of the assembly and six less stiff spacer grids away from the center.

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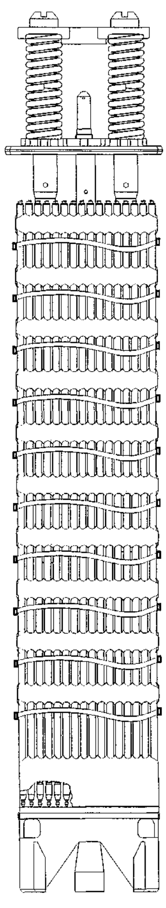

Fig. 1 Fuel Assembly

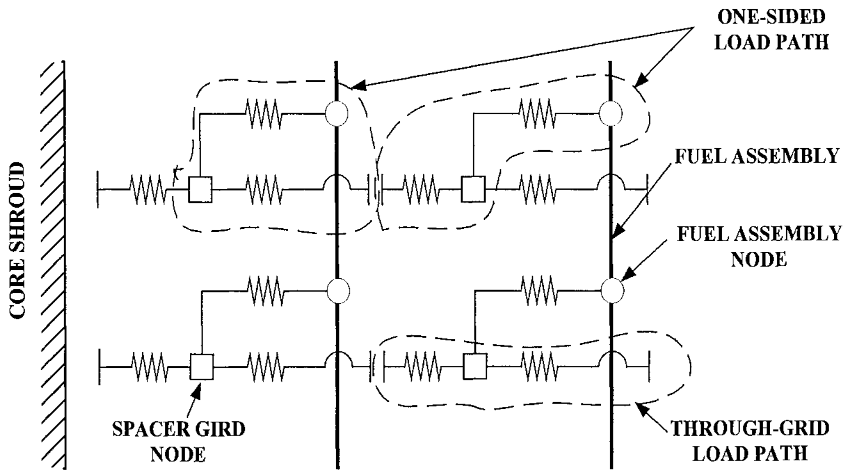

Fig. 2 Typical Spacer Grid Spring Model

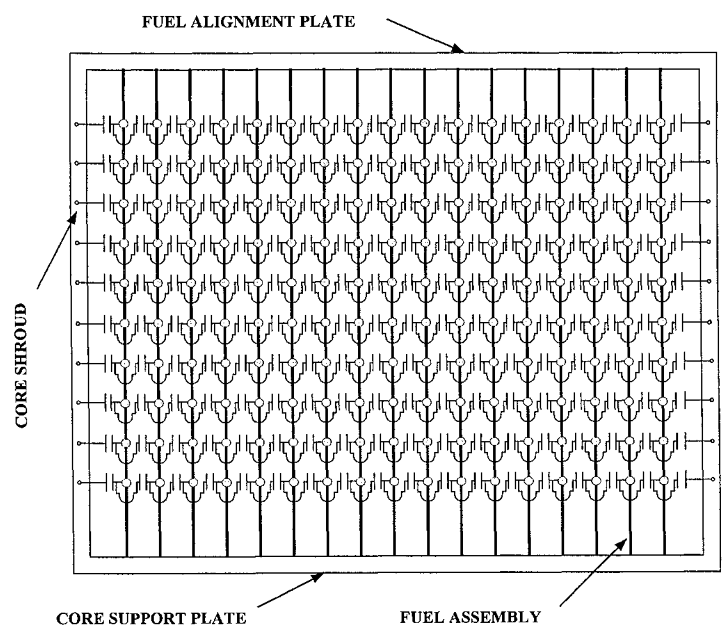

Fig. 3 Typical Detailed Horizontal Core Model

Table 1. Natural Frequency versus Corresponding Maximum Impact Load

	Case 1	Case 2
Normalized Natural Frequency	1.00	1.23
Ratio of One-sided Impact Load	1.00	0.92

Table 2. Normalized Non-dimensional Spring Parameter versus Corresponding Maximum Impact Load

	Case 1	Case 2
Normalized $K_U\ L/EI$ Normalized $K_L\ L/EI$	1.00 1.00	7.50 7.50
Ratio of One-sided Impact Load	1.00	0.99
Ratio of Through-grid Impact Load	1.00	1.03
Ratio of Max Bending Moment	1.00	1.33

Table 3. Normalized Damping value versus Corresponding Maximum Impact Load (I)

	Study I			Study II		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Normalized Critical Damping Ratios 1st Mode 3rd Mode	 1.00 1.00	 0.47 0.64	 0.47 1.32	 1.00 1.00	 2.00 2.00	 3.00 3.00
One-sided Impact Load (lbs)	1.00	1.16	1.10	1.00	0.85	0.81
Through-grid Impact Load (lbs)	1.00	1.060	1.064	N/A	N/A	N/A

Table 4. Normalized Coefficient of Restitution versus Corresponding Maximum Impact Load

	Case 1	Case 2	Case 3
Normalized COR	1.00	0.7	0.5
Ratio of One-sided Impact Load	1.00	0.72	0.65

Table 5. Normalized Spacer Grid Stiffness versus Corresponding Maximum Impact Load

	Case 1	Case 2	Case 3
Normalized One-sided Stiffness	1.00	1.26	1.75
Normalized Through-grid Stiffness	1.00	1.26	1.75
Ratio of One-sided Impact Load	1.00	1.11	1.32
Ratio of Through-grid Impact Load	1.00	1.05	1.14
Ratio of Estimated One-sided Impact Load	1.00	1.12	1.32

Table 6. Normalized Core Gap versus Corresponding Maximum Impact Load

	Case 1	Case 2	Case 3
Normalized Core Gap (CS-FA/FA-FA)*)	1.00/ 1.00	1.04/ 1.19	1.06/ 1.29
Normalized Total Core Gap	1.00	1.16	1.24
Normalized One-sided Impact Load	1.00	1.11	1.15

*) CS-FA: Core Shroud to Fuel Assembly
FA-FA: Fuel Assembly to Fuel Assembly

Table 7. Combination of Various Spacer Grids with Different Stiffness*) and Core Gaps **)

Grid	Case1	Case2	Case3	Case4	Case5	Case6
9	A,F	A,F	E,F	A,F	A,F	A,F
8	A,F	A,F	D,F	C,F	C,G	A,F
7	A,F	D,F	C,F	C,F	C,H	C,F
6	A,F	A,F	B,F	A,F	A,F	A,F
5	A,F	A,F	A,F	A,F	A,F	C,F
4	A,F	A,F	B,F	A,F	A,F	A,F
3	A,F	D,F	C,F	C,F	C,H	C,F
2	A,F	A,F	D,F	C,F	C,G	A,F
1	A,F	A,F	E,F	A,F	A,F	A,F

*) Normalized Stiffness of Spacer Grids
A : 1.00 B : 1.38 C : 1.74 D : 2.30 E : 3.45

**) Normalized Core Gaps (CS-FA/FA-FA)
F : 1.00/1.00 G : 0.69/0.43 H : 0.83/0.65

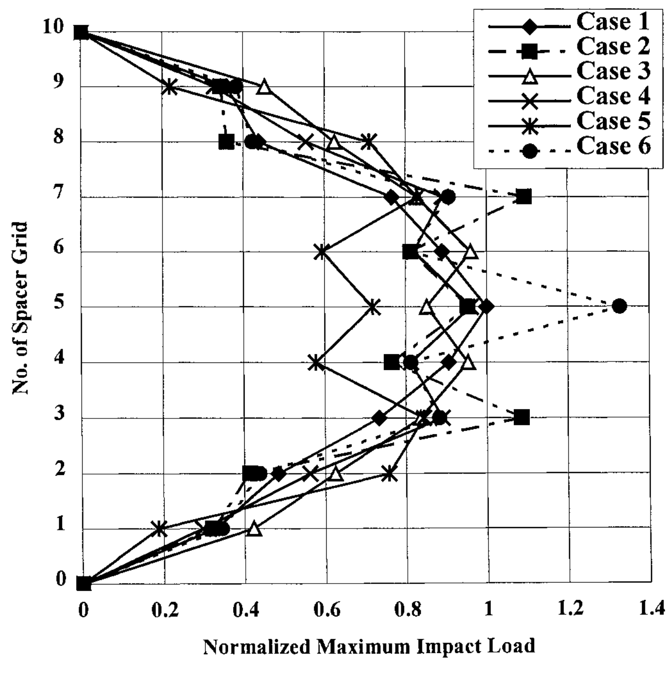

Fig.4 Spacer Grid Impact Load Distribution along Fuel Assembly