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Fuel Assembly Model to Determine the Natural Frequency Lower Bound

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1. Introduction

Nuclear fuel suppliers have been licensed fuel assembly under the most conservative terms of the begin of life(BOL) condition, but safety problems have recently been raised for the end of life(EOL) condition. AREVA reported that the impact strength of the spacer grid is very low under the EOL condition[1]. The US Nuclear regulatory commission(NRC) issued an official document[2] detailing the changes in the fuel characteristics of the EOL condition and degradation of the spacer grid impact strength.

Fuel assembly is continuously exposed to the high-temperature in the reactor. In particular, the cell size of the spacer grid is increased due to the thermal expansion of the cladding tube, and maintained at a high temperature for a long time, resulting in permanent deformation. In addition, the effects of irradiation growth and stress relaxation by the neutrons cause a gap between the spacer grid and the fuel rod, thereby reducing the frictional force between the spacer grid and the fuel rod. Therefore, the stiffness of the fuel assembly is reduced because the rigidity of the fuel rod is not fully transferred to the fuel assembly because the spacer grid does not fully support the fuel rod. If the fuel assembly stiffness is reduced, it can easily deform even under low load conditions, and the seismic performance is degraded due to the reduced natural frequency.

In the paper, the skeleton model is used to simulate the characteristics of the EOL fuel assembly. By adding the weight of the fuel rods to the skeleton model, the EOL model is constructed assuming that the fuel rods had no effect on the rigidity of the fuel assembly. Those of the models are used to predict the natural frequency lower limit of fuel assembly.

2. Methods and Results

The skeleton assembly consists of top and bottom nozzle, guide tubes and spacer grids. In other words, it means a structure without fuel rods in the fuel assembly.

The fuel rod effects the mechanical properties of the fuel assembly by the frictional force with the spacer grid. Friction forces between the fuel rods and the spacer grids contribute to strengthening the structural rigidity of the fuel assembly. Therefore, it is understood that the skeleton assembly analysis model can be utilized irrespective of the life condition.

The skeleton assembly model ignoring damping can be written as Eq. (1).

$$[M_s]\{\ddot{u}_s\} + [K_s]\{u_s\} = \{F\} \tag{1}$$

Where,
$[M_s]$: Mass of skeleton
$[K_s]$: Stiffness of skeleton
$\{\ddot{u}_s\}$: Acceleration of skeleton
$\{u_s\}$: Displacement of skeleton
$\{F\}$: External force

In the case of fuel assembly under EOL condition, the size of the spacer grid cell is increased. If there is no friction between the fuel rod and spacer grid and only the inertia of the fuel rod works, the Eq. (1) is as follows.

$$[M_s + M_r]\{\ddot{u}_s\} + [K_s]\{u_s\} = \{F\} \tag{2}$$

Where,
$[M_r]$: Mass of fuel rod

Because the mass of fuel rods are added to the skeleton assembly model, the total natural frequency is greatly reduced. That is, the natural frequency ratio between the skeleton of the fuel assembly can be written as following.

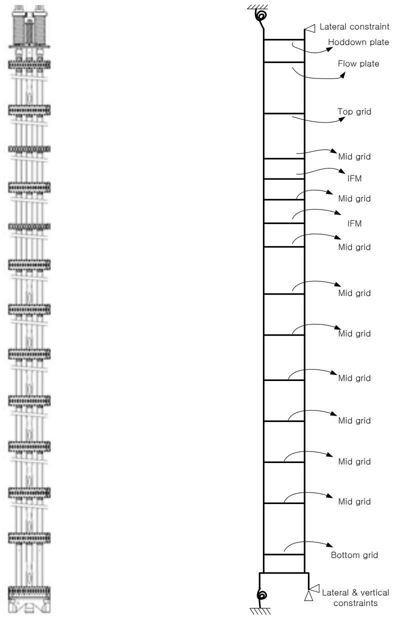
$$\frac{\lambda_i^s}{\lambda_i^{FA}} \approx (1+2\varepsilon)(1+\{\varphi\}_i^T[M_r]\{\varphi\}_i)\frac{\lambda_i^s}{\lambda_i^s(1+2\varepsilon)} \tag{3}$$

Where,
λ_i^s : Skeleton assembly model natural frequency of ith mode
λ_i^{FA} : Fuel assembly model natural frequency of ith mode
$\{\varphi\}_i$: ith mode shape
ε: Positive constant to consider mode change

It is assumed that the mode shape of fuel assembly model is slightly different from that of the skeleton assembly model. That is, ε means a positive number greater than 0 for considering the mode change amount. As a result, it can be seen that the larger the mass of the fuel rod from Eq. (3), the more the difference in the natural frequency ratio occurs. Therefore, the model considering only the mass of the fuel rods in the skeleton assembly model becomes the natural frequency lower bound of EOL fuel assembly model.

2.1 Skeleton assembly analytical model

In the skeleton assembly, four guide tubes are screwed to the top/bottom nozzle and welded to nine mid grids. Also, four guide tubes are connected to two IFM grids and top/bottom grid. Fig. 1 (a) is a representative configuration. Since slenderness ratio is very high, the dynamic and static characteristics of fuel assembly are similar to the behavior of the beam. Reflecting this characteristic of structure, the skeleton assembly is modeled as Fig. 1 (b).



(a) Skeleton configuration (b) 2D skeleton model
Fig.1 Skeleton configuration and analysis model

As shown in Fig. 1 (b), the analytical model consists of top/bottom nozzle, two guide tubes, nine mid grids, two IFM, and top/bottom grid. All components are modeled as beams. On the left side of top nozzle, a rotation spring was added to simulate incomplete constraint by the upper core plate. In addition, lateral constraint is given to the right of top/bottom nozzles, and axial movement is restricted by adding the vertical displacement boundary condition at the bottom nozzle. All analysis were performed with ANSYS R15. The skeleton analysis model was verified by comparing the results with the skeleton mechanical test results.

As shown in Fig. 2, the natural frequencies obtained from the skeleton test(cold, air) results was compared with the natural frequencies obtained from the skeleton analytical model. It can be confirmed that first and second mode, which greatly effects the behavior of the skeleton assembly, is very similar with skeleton test result.

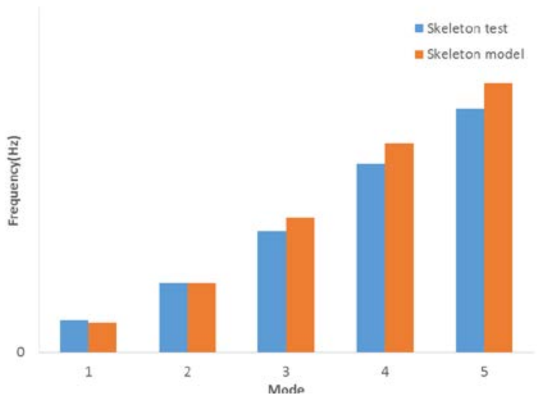


Fig.2 Comparison of natural frequency

2.2 Fuel assembly lower bound model

As mentioned before, to obtain the lower natural frequency bound of fuel assembly, the fuel rod weight was added to skeleton analytical model to construct fuel assembly lower bound model (FA lower bound model).

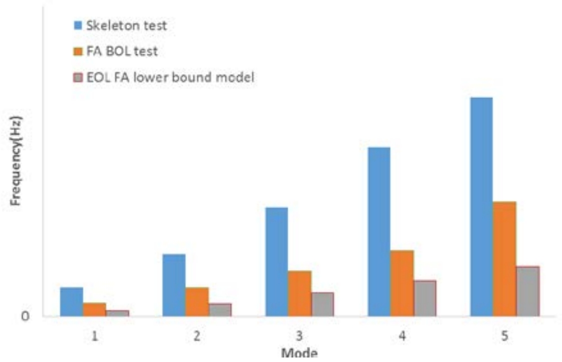


Fig. 3 Natural frequency of FA lower bound model

As shown in the Fig. 3, the natural frequencies from the skeleton test results, fuel assembly test results and FA lower bound model analysis results were compared.

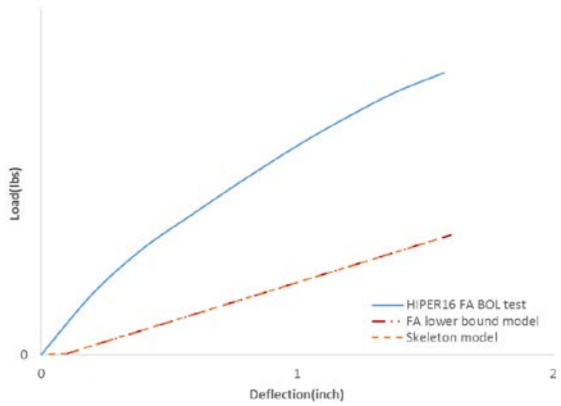


Fig.4 Load-deflection curve of Fuel assembly BOL test result and FA lower bound model analysis result

In the same manner as the method used for chapter 2.1, the 6^{th} mid grid was pulled about 1.5 inches to obtain corresponding displacement and reacting force. As mentioned above, since FA lower bound model is exactly equal to the skeleton model except the weight. Thus both have the same the bending stiffness. For this reason, bending stiffness of FA lower bound model is much smaller than fuel assembly BOL test results as shown in Fig. 4.

3. Conclusions

The spacer grid after irradiation has a gap between the spacer grid spring and fuel rod due to thermal expansion, irradiation growth by neutrons, and stress relaxation. As a results, the frictional forces between the spacer grids and fuel rods are reduced and the rigidity of fuel rod is not fully transferred to the fuel assembly because the spacer girds does not fully support fuel rods. A skeleton analysis model was used to simulate these characteristics.

In order to determine the natural frequency lower bound of fuel assembly under EOL condition, a new model to estimate the lower bound natural frequency of the EOL fuel assembly was constructed. It is confirmed that the lower bounds of the model provide reasonable natural frequency limits.

REFERENCES

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[2] NRC Information Notice 2012-09, Irradiation Effects on Fuel Assembly Spacer Grid Crush Strength, ML113470490, US-NRC, 2012