Structural Integrity Evaluation of HANARO's Fuel Basket with 5 Tubes

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ABSTRACT

The objective of this paper is to perform a seismic analysis and a structural integrity evaluation of a HANARO new fuel basket with 5 tubes and its supporting box beam in water. For this purpose, ANSYS finite element models of the HANARO's fuel basket with 5 tubes and the box beam were developed for the in-air and submerged conditions, and their dynamic characteristics were analyzed. The seismic response spectrum analyses of the new fuel basket with 5 tubes and the box beam structure under the design floor response spectrum of OBE and SSE loads were performed. The analysis results show that the stress values of the new fuel basket with 5 tubes and the box beam for the seismic loads are within the ASME Code limits. It is also confirmed that the fatigue usage factor is much less than 1.0. Therefore no damage to the structural integrity of the HANARO new fuel basket with 5 tubes is expected. Finally, the fuel basket was successfully installed on the box beam and is being used successfully for a fuel handling purpose.

KEY WORDS: HANARO, fuel basket, 5 tubes, structural integrity, modal analysis, seismic response analysis

1. INTRODUCTION

HANARO(Hi-flux Advanced Neutron Application Reactor), an open-tank-in-pool type reactor with a thermal power of 30MW, has several irradiation holes(CT, IR, and OR) in the core region. The HANARO supports an active nuclear power development program in Korea as well as supplying an intensive neutron source for research and development of nuclear applications. These irradiation holes are being utilized for the production of radioisotopes and for the irradiation of capsules that contain nuclear fuel or other materials for R&D needs [1].

Fig. 1 and Fig. 2 show some of the structures installed at the reactor pool. The hexagonal fuel assemblies and the circular fuel assemblies are loaded in the reactor core.
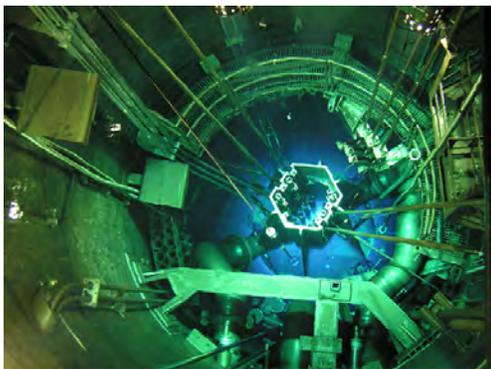

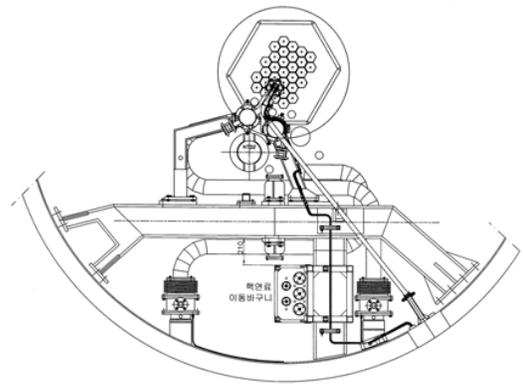**Fig. 1 Plain View of the HANARO Pool**   **Fig. 2 Installation Concept of the Fuel Basket**

HANARO's fuel basket is a structure to store the fuel assemblies temporarily and carry them when withdrawing, storing, and checking them out. As the existing fuel basket interferes with the FTL(Fuel Test Loop) IPS(In-Pile Section) and some supporting structures, a new fuel basket with 5 tubes has been newly designed. The fuel basket material is stainless steel and it contains 2 18-element fuel assemblies and 3 36-element fuel assemblies. Supporting box beam had already been installed at the reactor pool wall and the fuel basket was placed on the supporting box beam

The objective of this paper is to perform a seismic analysis and a structural integrity evaluation of a HANARO fuel basket with 5 tubes and its supporting box beam in water. Two ANSYS finite element models of the HANARO fuel basket with 5 tubes and the supporting box beam were developed for the in-air and submerged conditions, and their dynamic characteristics were analyzed with reference to a previous technical report [2]. The seismic response spectrum analyses under the design floor response spectrum of OBE and SSE loads were performed [3].

2. MODELING OF THE FUEL BASKET WITH 5 TUBES AND THE BOX BEAM

Fig.3 represents the 3-D finite element model of the fuel basket with 5 tubes and the supporting box beam used in the analysis. The supporting box beam structures are composed of a main beam frame and wall mounting plates. And the fuel basket is composed of 4 parts – a main frame assembly, a fuel tube guide assembly, a fuel tube, and top and bottom plates. It is placed on the supporting box beam at a distance of 210mm from the main box beam as shown in Fig. 2.

Because these structures are submerged in water, the "hydrodynamic mass" effect should be taken into account. For the supporting box beam, the hydrodynamic masses are calculated by considering the mass of the water surrounding the box beam. 240kg and 623kg are applied in the x and y directions, respectively, and 658kg is considered in the z direction. 27kg, 29kg, and 29kg are considered for the fuel basket in the x, y and z directions, respectively.

These masses are input as lumped masses into the finite element model by using element MASS21 of the ANSYS computer program. Two 3D finite element models are developed. The total number of elements is 23808, and the total number of nodes is 35700.
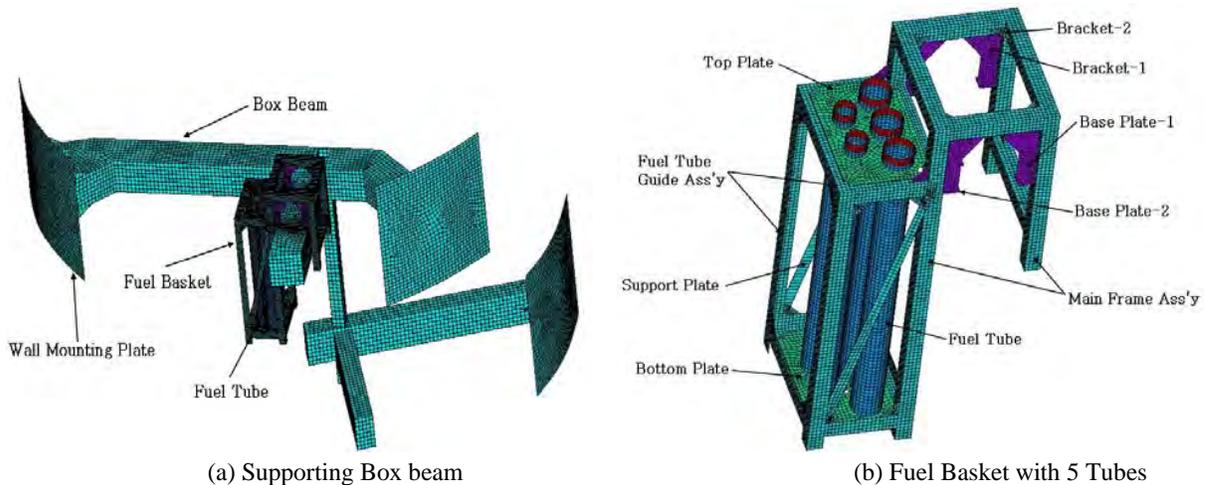

(a) Supporting Box beam   (b) Fuel Basket with 5 Tubes

Fig. 3 ANSYS finite element model of the fuel basket with 5 tubes and its supporting box beam

Table 1 summarizes the material properties of the fuel basket and its supporting box beam. The fuel basket is made of stainless steel 304(S.S304) and the supporting box beam is made of stainless steel 316L(S.S316L). The values for the design stress intensity, allowable stresses, material properties, and design fatigue curve are referred to from ASME Appendix I [4].

3. MODAL ANALYSIS

In order to investigate the dynamic characteristics of the fuel basket and the supporting box beam, modal analyses are performed for the in-air and submerged conditions. The eigenvalue and eigenvector are extracted using the Block Lanczos method. Since the fuel basket with 5 tubes is placed on the box beam structure, boundary conditions between the fuel basket and the box beam are applied in accordance with ASME Section NOG-4000 [5]. The natural frequencies for the in-air and

submerged conditions are listed in Table 2. These results show that the submerged mode is decreased by 20%~36% when compared with the in-air mode. This is caused by the hydrodynamic mass effect. These natural frequencies are higher than a strong seismic energy band, 3 - 10 Hz, thus it is predicted that the fuel basket with 5 tubes and the supporting box beam will not be seriously excited by an earthquake. Fig. 4 represents the fundamental mode shapes of the fuel basket with 5 tubes and the supporting box beam.

Table 1 Material properties of the fuel basket with 5 tubes and its supporting box beam

	Supporting box beam	Fuel basket
Material	S.S 316L	S.S 304
Reference temperature(℃)	100	100
Young's modulus(GPa)	193	193
Density(kg/m^3)	7990	7913
Poisson's ratio	0.28	0.27
Ultimate strength, S_u (MPa)	482.6	473.0
Yield strength, S_y (MPa)	172.4	163.4
Design Stress Intensity Sm (MPa)	115.2	118.8

Table 2 Natural frequencies of the fuel basket with 5 tubes and its supporting box beam (Hz)

Mode	Box Beam		Fuel Basket		Assembly Model	
	In Air	In water	In Air	In water	In Air	In water
1	105.1	84.0	22.0	14.1	26.4	17.3
2	146.3	137.5	31.8	21.0	37.7	27.8
3	216.7	167.0	38.3	28.9	38.3	29.3
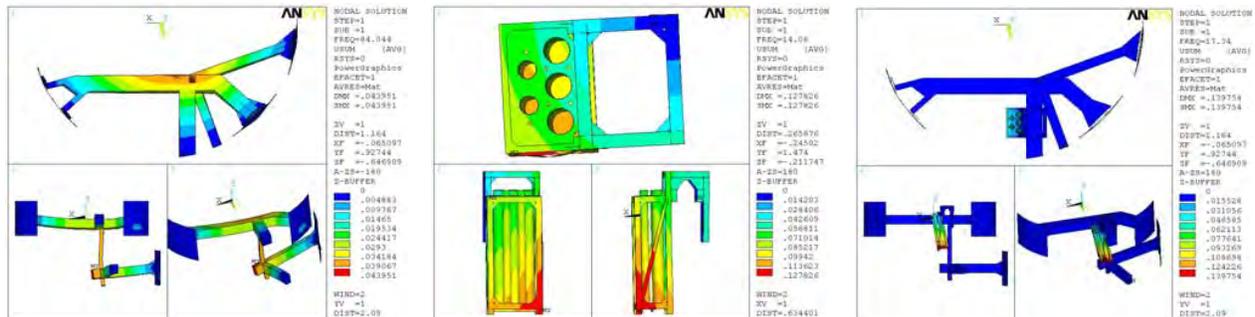
(a) Box beam (84.0Hz)　　　　(b) Fuel basket with 5 tubes (14.1Hz)　　　　(c) Assembly model (17.3Hz)

Fig. 4 Natural frequencies and mode shapes in water

4. SEISMIC RESPONSE ANALYSIS

     The fuel basket with 5 tubes is classified as a non-nuclear safety (NNS), seismic category II, and quality class T. For a conservative assessment of the structural integrity of the fuel basket with 5 tubes, a seismic response analysis according to a seismic category I structure is performed. The 3-D finite element models of the new fuel basket with 5 tubes are developed by utilizing the ANSYS program [6].Then, a seismic response analysis of the developed 3-D models is carried out.

4.1. Load combination and Seismic Loads

According to the ASME code(Section III, NF) [7], three load combinations as shown in Table 3 are used as the seismic load inputs for the seismic analysis. Dead load is a total weight of all the elements for the fuel basket with 5 tubes and the supporting box beam.

Table 3 Seismic loading conditions used for the seismic analysis of the fuel basket and its supporting box beam

Service Level	Load combination
Level A	Dead load
Level B	Dead load + OBE
Level D	Dead load + SSE

     The enveloped floor response spectrum for OBE and SSE are used as the seismic loads as shown in Fig 5. A 4% damping is considered for the horizontal and vertical floor response spectrum, SSE. Also a 2% damping is considered for the horizontal and vertical floor response spectrum, OBE. These enveloped curves are intended to be the most conservative for each direction.
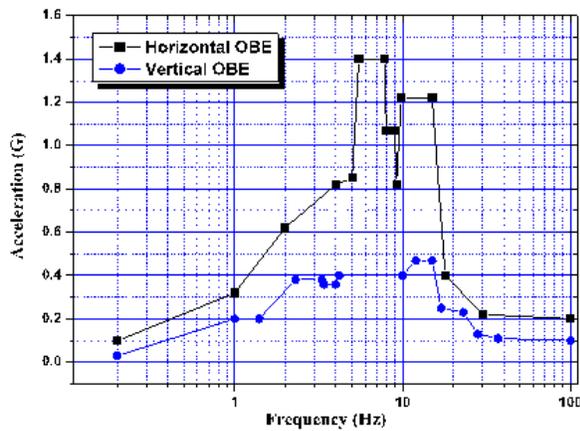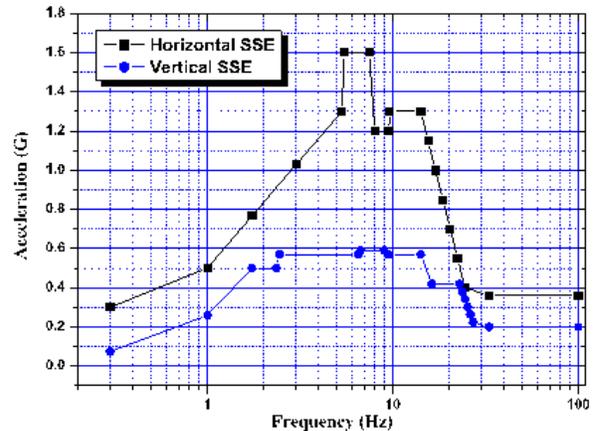
(a) OBE, 2%   (b) SSE, 4%

Fig. 5 Floor response spectrum (FRS) for OBE and SSE

4.2. Evaluation of a Structural Integrity

For estimating the structural integrity of shell-type components, membrane stress and bending stress are calculated across a solid section under consideration in accordance with ASME, NF-3200 [7] and Appendix F [8]. For an evaluation of the structural integrity of the beam elements, in accordance with ASME, NF-3322, the conditions below are applied.

For the estimation of the structural integrity of the beam elements of the pool-cover, in accordance with ASME Section III, NF-3322, following conditions are applied.

(a) Allowable stress(F_t: tensile, F_v: shear, F_a: compression, F_b: bending)

$$F_t = 0.6S_y \tag{1}$$
$$F_v = 0.4S_y \tag{2}$$
$$F_a = S_y\,(0.47\text{-}kl/r/444), \qquad kl/r < 120 \tag{3}$$
$$F_{b,major} = F_{b,minor} = 0.66S_y \tag{4}$$

(b) Combined stress ratio

$$(f_a/\,F_a)+(f_{bx}/\,F_{bx}) +(f_{by}/\,F_{by}) < 1.0, \quad f_a/\,F_a < 0.15, \tag{5}$$

where f_a denotes the calculated compression stress. f_{bx} and f_{by} denote the calculated bending stress in the x and y directions respectively.

According to ASME, NF-3324.6 [7], the following equations are applied for an estimation of the structural integrity of the anchor bolts that fix the supporting box beam to the inner wall of the pool.

(a) Allowable stress(F_{tb}: tensile, F_{vb}: shear)

$$F_{tb} = S_u\,/3.33 \tag{6}$$
$$F_{vb} = 0.62S_u\,/5 \tag{7}$$

(b) Combined stress ratio

$$(f_{tb}/F_{tb})^2+(f_{vb}/F_{vb})^2 < 1.0, \tag{8}$$

where f_{tb} denotes the calculated tensile stress, and f_{vb} denotes the calculated shear stress of a bolt.

4.3. Seismic Analysis Results

200 modes are considered for the modal response combination to take into account a modal effective mass of 90% of the model, and the square root of the sum of the squares (SRSS) method is used to combine the total response in each direction. Table 4 summarizes the maximum stress intensities obtained from the seismic response analysis. The maximum displacements are also shown in Table 5. And Fig. 6 shows the stress intensity distribution of the fuel basket in water.

The results show that the maximum stress values in the structure excluding the welding and bolting areas are much lower than the allowable limit values. Thus, we can confirm that no damage to the structural integrity of the fuel basket with 5 tubes and its supporting box beam is expected in the reactor pool.

Table 4 Maximum stress intensities of the assembly model

Component	Maximum stress intensity, P_m+P_b (MPa)			Materials	Allowable Values 1.0S1, 1.33S1, 2.4S1 (S1=1.5S)
	Service level A	Service level B	Service level D		
Box Beam	5.3	13.4	20.8	S.S 316L	172.8, 229.8, 414.7
Fuel Basket	15.3	39.6	61.9	S.S 304	178.2, 237.0, 427.6

Table 5 Maximum displacements of the assembly model (unit=m)

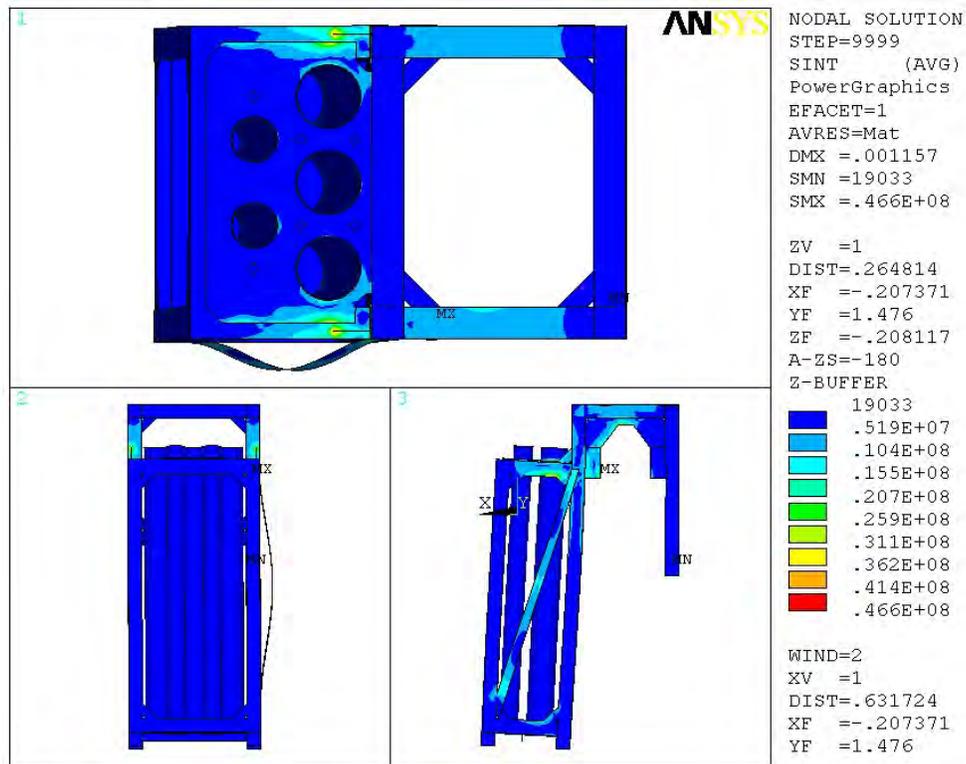| Component	Service level A	Service level B	Service level D	Materials
Box Beam	3.34e-5	3.95e-5	4.5e-5	S.S 316L
Fuel Basket	0.16e-3	0.78e-3	1.32e-3	S.S 304

Fig. 6 Stress intensity distribution of the fuel basket in water for SSE

5. The structural integrity of the welded joints and the bolted joints

The supporting box beam structure installed at the inner wall of the reactor pool supports the fuel basket with 5 tubes. They have several rectangular cross sections and are connected by a bolting and welding. To evaluate the structural integrity of these connections, we calculated the reaction forces and moments at the region of the connection points, and then we evaluated the stresses of the bolted joints and welded joints. These stresses were all within the allowable stress limits.

The fuel basket is composed of some L-shape cross section frames, plates and tube beams. They are all connected by a welding. The maximum stress intensity of the welded joints of the fuel basket is 132.9 MPa. This value is less than the allowable stress, so we can confirm its structural integrity.

6. FATIGUE ANALYSIS

A fatigue analysis of the fuel basket with 5 tubes and its supporting box beam is performed to investigate the possibility of a fatigue failure due to seismic loads. For a conservative prediction of a fatigue failure, a peak stress intensity is calculated by a multiplication of the maximum stress intensity due to seismic loads and a stress concentration factor. After calculating the peak stress intensity, its allowable operating cycles is obtained from the S-N curve of ASME, Appendix Fig. I-9.2.1 [4]. The predicted number of operating cycles (n) of the design life time is calculated as 2800, which is the expected value of a maximum stress loading due to five OBE and one SSE seismic loadings. Then, the fatigue usage factor is calculated as a ratio of the operating cycles to the allowable operating cycles. Table 6 summarizes the fatigue analysis results.

The fatigue analysis results show that the fatigue usage factor of the fuel basket with 5 tubes is 0.0028. Since the fatigue usage factor is less than 1.0, we can confirm that the possibility of a fatigue failure for the fuel basket with 5 tubes subjected to seismic loads is negligible during the design life of HANARO.

Table 6 Fatigue usage factor of the fuel basket with 5 tubes

Maximum stress intensity (S_{max})	Stress concentration factor	Peak stress intensity (S_p)	Operating cycle (n)	Allowable operating cycle (N)	Fatigue usage factor (n/N)
132.9MPa	2	265.8MPa	2800	100,000	0.028

6. CONCLUSIONS

The HANARO's fuel basket with 5 tubes has been newly designed. The structural integrity of a fuel basket with 5 tubes and its supporting box beam under seismic loads has been investigated. For this purpose, 3D finite element models were developed. Then, a modal analysis, a seismic response analysis, and a fatigue analysis were carried out by utilizing the ANSYS program. The modal analysis results show that the fundamental vibration modes are higher than a strong seismic energy band. It is predicted that the fuel basket with 5 tubes and its supporting box beam will not be seriously excited by an earthquake.

The seismic analysis results show that the maximum stresses due to the seismic loads are within the allowable stresses of the ASME code. In addition, the fatigue analysis demonstrates that the possibility for a fatigue failure for the fuel basket with 5 tubes and its supporting box beam is negligible, because the cumulative fatigue usage factor is much less than 1.0. No damage to the structural integrity of the fuel basket is expected when it is installed on the box beam structure in water. Finally, the fuel basket with 5 tubes was successfully installed at the box beam and is being used successfully for a fuel handling purpose.

ACKNOWLEDGEMENTS

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