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Investigation of Rack Motion for Seismic Safety Evaluation of a Spent Fuel Pool

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1. Introduction

The accurate assessment of the major equipment including the spent fuel storage rack and pool in the nuclear power plant is getting more important and its high resistance against the earthquake is in demand also, with the occurrence of major earthquakes in recent years [1,2]. Spent fuel storage rack is equipment temporarily storing spent fuel assemblies, which are removed from the nuclear reactor before they are moved to the dry cask storage. The rack is not fixed but is free standing on the bottom plane of the pool. The rack can slide on the pool floor as well as tilt in case that a strong motion including the earthquake is applied to the pool. The rack potentially impacts the adjacent racks, pool walls, and/or pool floor. Therefore, investigation of the motion of the rack is very critical in seismic assessment of the spent fuel pool.

The free-standing rack is submerged in the coolant. The rack is accelerated, in case of a postulated strong motion such as the earthquake, not only by the motion of the pool because of the earthquake, but also by the hydrodynamic fluid-structure interaction (FSI) which is induced by the coolant surrounding the rack [2–6]. Adequate assumption and formulation for FSI are very critical for the accurate seismic assessment of the spent fuel storage rack and pool. Hydrodynamic effects of the fluid on the submerged object have been classified into fluid inertia effects, sloshing effect, fluid elasticity effect, and damping effect [6]. The inertia effect of the coolant is considered while the others are generally ignored in seismic assessment of the spent fuel pool [7,8]. However, the rationale of the hypothesis or assumption is not clear.

In this study, we investigated the convective effect (or sloshing effect) and impulsive effect (or inertia effect) of the coolant in the spent fuel pool on the storage rack using computational fluid dynamics (CFD) analysis. Then, mechanical behaviors of the racks in the spent fuel pool were investigated and the rack, which showed the highest acceleration, was predicted using finite element (FE) analysis.

2. Materials and Methods

A simple two-dimensional CFD model representing a spent fuel pool of a nuclear power plant in Korea (Fig. 1). Pressures at 38 points and drag forces on six plates were predicted during the vibration of a spent fuel pool with a 40 mm of amplitude and 10 Hz of frequency. The pool was vibrated for 10 seconds. The pressures and forces were predicted at every 0.001 seconds. The predicted data were analyzed using the Fast Fourier Transform.

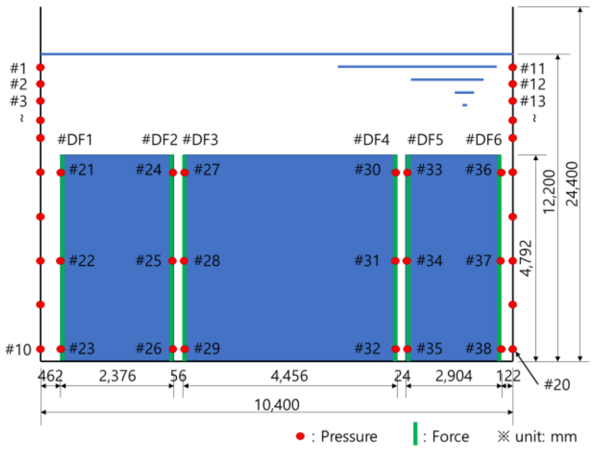


Fig. 1 Two-dimensional pool and rack for investigating the convective and impulsive effect of the coolant during seismic safety analysis

An FE model of the simple rack, which is developed for experiments, was developed using beam and warping elements (Fig. 2). Thus, the geometries of cross-sectional planes of the rack were developed using warping elements. The developed FE model was verified by comparing the natural frequencies of two FE models with beam and solid elements.

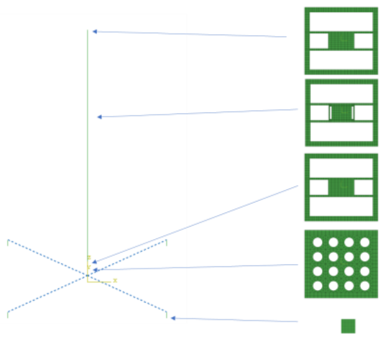


Fig. 2 Development of a finite element model of a simple rack using beam and warping elements

FE models of twelve racks were developed using beam and warping elements (Fig. 3). Among racks and spent fuel pool, contact conditions using gap elements were applied. Moreover, added masses to consider hydrodynamic effects were calculated using equations introduced in the previously published studies.

Seismic evaluation using FE analysis was performed under artificially generated time history ground acceleration data based on the R.G. 1.60 spectrum[9]. The maximum value of ground acceleration was set at 0.3 g.

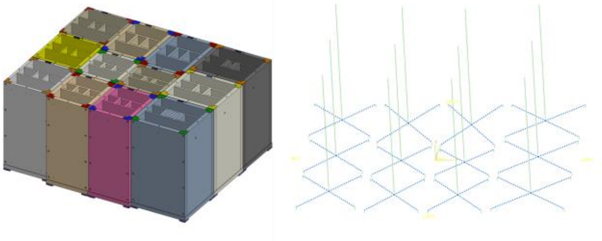
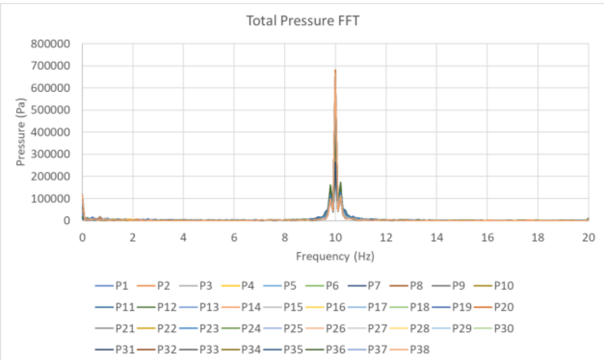


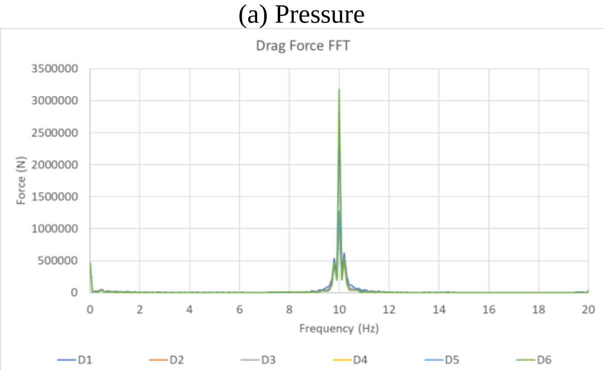
Fig. 3 Finite element models to analyze mechanical behaviors of racks using solid and beam elements

3. Results

The FFT results of the predicted pressures and drag forces showed that peak amplitude showed at only 10 Hz which is an applied frequency of the vibration (Fig. 4).



(a) Pressure



(b) Drag force

Fig. 4 FFT results of the predicted (a) pressures and (b) drag forces

The natural frequencies of the first three modes of FE models using beam and solid elements were compared. Two models showed similar natural frequencies in 10 % differences (Table 1). Thus, the result showed the development FE model is validated.

Table 1 Comparison of the natural frequencies of two FE models

Mode	Solid (A)	Beam (B)	(B)/(A)	Shape
1	2030	2232	110%	Torsion
2	2837	3012	106%	Bending
3	3060	3129	102%	Bending

While racks of A1, A2, C1, D1, E1, and G moved with the pool, thus the racks showed the same acceleration with the pool's acceleration (Fig. 5). Collison between other racks and pool and among the racks were expected. C2 rack showed a higher peak acceleration than others.

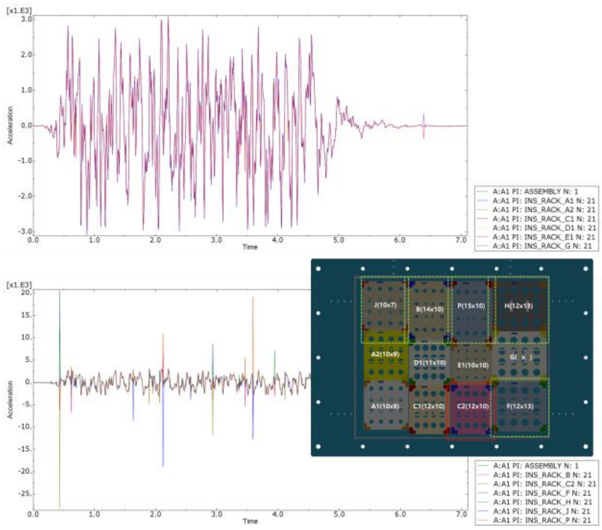


Fig. 5 Changes in acceleration during vibration of a spent fuel pool

4. Discussion

Because changes in both pressures and drag forces on the walls of racks and a spent fuel pool showed only one frequency the same with the frequency of the applied vibration, we could conclude that only impulsive effect was affected mechanical behaviors of the racks in the spent fuel pool. Therefore, the assumption that only added mass to apply the impulsive effect of the coolant is used for FSI while the convective effect is neglected in the seismic evaluation is proper.

Beam elements are generally used for the development of FE models of racks to reduce computational time for FE analysis. The use of mass-beam elements is very common for development. In this study, beam-warping elements were used. In our opinion, it is useful to reduce the time for the development of the FE model of the racks.

A seismic evaluation was performed using FE analysis. While the racks inside moved with the pool, racks beside the wall of the pool showed collision among racks and pool. Gaps between racks and pool walls were greater than those between racks. Thus, racks beside the wall could move more freely and have lesser FSI effects than those located inside.

5. Discussion

The results of this study provide a rationale to support the assumption that only added mass to apply the impulsive effect of the coolant is used for FSI while the convective effect is neglected in the seismic evaluation. Generally, an FE model of a rack with beam-mass elements is used. However, this study showed that an FE model of a rack with beam-warping elements is also useful. Moreover, the model with beam-warping elements is helpful to reduce the time to develop an FE model of a rack. The results of this study could help to progress the methods for seismic evaluation of a spent fuel pool.

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