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Seismic shaking table requirements and consideration of fluid-structure interaction effect in seismic response analysis model for in-reactor fuel assembly under severe earthquake accident

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1. Introduction

Structural integrity of nuclear fuel assembly must be justified for lateral loads from any dynamic event, especially in severe earthquake accident condition. The justification is performed via time history analysis with simplified dynamic model using a group of fuel assembly in the core. Key check points in this analysis might be the integrity of intermediate spacer grids when impacting fuels into core shroud plate or into neighboring fuel assembly. Thus, dynamic displacement and impact force at grid elevations are the important structural parameters to be traced out during the analysis and the simulation testing.

KAERI have a plan to develop dynamic analysis model and to setup test infrastructure for full scale and several fuel assembly rows seismic simulation testing. This paper briefly discuss on the reference earthquake accident scenario, shaking table requirements for full-scale seismic simulation testing, virtual testing issues before the hardware setup, and modelling issue related to fluid-structure interaction effect in accident core analysis.

2. Representative Seismic Accident Scenario and Dynamic Load Profile

Reactor accident at Fukushima Daiichi in Japan, following the Richter magnitude 9.0 Tohoku-oki earthquake and subsequent tsunami, is the most representative example for severe earthquake accident. In that accident, three reactor were in operation and shut down promptly in response to the earthquake; however when, about 40 min later, the tsunami inundated site electrical power, resulting in station blackout and loss of reactor coolant. Japanese operator TEPCO summarized that there was a nearly immediate loss of core cooling in unit 1 and almost all of fuel assembly melted and accumulated in the bottom of reactor vessel. Partial melting of the cores in unit 2 and 3, damaging one third of the fuel assemblies in each, occurred over the following days. Reaction of the zirconium alloy fuel cladding with water at high temperature generate hydrogen gas that accumulated and exploded in four of the units. Sea water was injected into reactor core and sprayed onto fuel storage pools to cool them[1]. Concern about fuel integrity is limited to the before the core melt down. There wasn't recorded dynamic loads to the core when occurring tsunami and during the following events such as explosion and water injection, except for the earthquake data, but virtual dynamic loads can be assumed from the accident simulation based on the numerical model of the reactor core. Those can be combination of the event signal, similar to earthquake time history, to integrate other form of dynamic events, based on the reference accident scenario. Each events has specific form of signal profile, duration, and peak magnitude. For instance, maximum ground acceleration from severe earthquake over the magnitude 9 can be estimated about 1 g and its recorded profile can be obtained from the online database [2].

3. Shaking Table Requirements

Reference seismic accident should be simulated using mockup fuel assembly and shaking table with desired excitation profile and fine precision of control.

Shaking table has various requirement as followings: total weight of the specimen is 3000 kg, including two specimen assembly, coolant water and the housing. Peak acceleration is 1g with full payload, except table weight. Rated capacity for the reference earthquake profile can be determined by the full pay load and peak acceleration. Hydraulic actuation system with biaxial excitation capability is preferred to electromagnetic one. Maximum stroke should be over 200 mm to compare previous test data and maximum velocity reaches up to +/- 1m/s. Operating frequency range should be up to 50 Hz to cover 5th natural frequency of fuel assembly and deliver high earthquake energy concentrated in the low frequency range. Fixture design should consider overturning moment from the horizontal movement of the tall and heavy specimen. Mass center of the specimen is 2.5m from the top surface of the table. Physical dimension of the shaking table is confined to 3m x 3m x 2.5m, according to the accommodation space in the laboratory. Furthermore, adaptive controllability to compensate time delay and backlash from the hydraulic actuation should be required. Control speed and linearity is also important. Support bearing system for biaxial actuation and high acceleration testing with full pay load should be guarantee to realize the ideal test condition. And, the specimen-table (test rig) interaction problem should be checked. Actuator should be properly designed to get enough axial and lateral stiffness for a long time operation. Affordable price, maintenance and future usage plan are important factors to select actuation system as well [3,4].

4. Virtual Testing Issue

Dynamic simulation testing can suffer from external disturbance or interaction with test hardware that leads to control instability, resulting in damaging test system. As well as, dynamic coupling between specimen and test rigs such as table, fixture, and actuator, can change ideal test condition and affect controllability of the system. Virtual testing consists in building software model representing physical behaviors of all subsystem that can influence on the performance of integrated test system [5]. A test can be simulated before it take place and a series of valuable conclusion can be extracted beforehand. This is an essential step, we believe, for selecting hardware and requirements.

5. Consideration of fluid-structure interaction effect in seismic response analysis

Dynamic response of fuel assembly can be significantly affected by added hydrodynamic mass and additional damping from the fluid and flow inside operating reactor core. Added mass or hydrodynamic virtual mass from surrounding fluid medium can be theoretically estimated by the potential flow theory. Solving Laplace equation in terms of velocity potential can leads to calculate mass components in the mass matrix of simplified fuel FE model. Previous study [6, 7] on this issue showed that in case of seismic accident, predominant coupling via inertia force term is between fuel assembly and core shroud and the coupling value is independent of position of fuel assembly.

Additional damping from the fluid and the flow inside reactor core are originated from fluid drag and flow lift force, respectively. Lift force from axial flow can increase fuel assembly damping by twice compared to still fluid damping from the loop testing [8,9]. In practice, fuel assembly damping should be measured by mockup loop testing and referred to published data in the literature.

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