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Seismic response analysis of FBR core by FINAS code

Morishita M.
Power Reactor and Nuclear Fuel Development Corporation, Japan

Abstract

This paper describes the benchmark analysis work done by PNC, under the framework of the IAEA Coordinated Research Program (CRP) on "Intercomparison of LMFR Seismic Analysis Codes". Three sets of seismic tests, namely, PEC mock-up, up to 19 elements, MONJU mock-up, 29 elements in a row and 37 elements in a matrix, and RAPSODIE mock-up, up to 291 elements, were used as benchmark problems.

A series of analysis corresponding to these data sets was made using FINAS code that has been developed by PNC. Although these experiments vary in size, number of subassemblies, core configuration (free-standing or restrained), and excitation conditions, the results by FINAS were found to be in good accordance with the experimental data with a reasonable accuracy. The present analysis method with FINAS, therefore, is judged to be capable for practical use.

Through the study, some issues were identified to be further investigated from the view point of core seismic methodology improvement.

1. INTRODUCTION

Fast reactor cores are composed of several hundred subassemblies of different kinds, such as fuel subassemblies and neutronic shield elements. The subassemblies are, from the structural point of view, self-standing beams supported by a core support structure (diagrid), immersed in liquid sodium with very narrow spacing between adjacent ones. Thus, during an earthquake event, their vibratory motion as a whole cluster may have a complicated and highly non-linear nature due to the shocks at pads and dynamic fluid-structure interaction.

Seismic safety qualification of the core is among the crucial issues in the seismic design of an LMFR. Control rod insertion capability should be maintained and structural integrity of the subassemblies be secured against the design seismic loads. Variation in reactivity during an earthquake should also be assessed. For these assessments, the dynamic response of the core should be evaluated with a sufficient accuracy, which requires a well-validated large scale non-linear dynamic analysis method.

With the recognition for the importance of LMFR core seismic analysis as a back ground, the coordinated research program (CRP) on 'Intercomparison of LMFR Seismic Analysis Codes' was organized by the IAEA/IWGFR as a part of its international collaboration program. An overview of the CRP is given in ref. [1]. Among the participants, CEA, ENEA, and PNC, have provided with their experimental data for the benchmark study.

CEA(France): RAPSODIE mock-up, up to 291 elements[2]
ENEA(Italy): PEC mock-up, up to 19 elements[3]
PNC(Japan): MONJU mock-up, 29 elements in a raw and 37 elements in a matrix[4]

This paper reviews the benchmark analysis done by PNC, and some discussions are given on the further study in this particular technical area.

2. METHOD OF ANALYSIS

FINAS is a general purpose structural analysis system based on the finite element method. It has been developed by PNC, with a purpose of supporting overall structural design and safety evaluation of LMFR components. Its analytical capability extends from static stress and dynamic to heat transfer analysis.

In the present analysis of seismic response of the core, a subassembly is represented by elastic beam elements and the shock is modeled by a series connection of a linear spring-dashpot and a gap element. In order to represent a lowered natural frequency due to the clearance between the spike and the diagrid, a linear spring element is inserted at the upper end of the spike. Fluid added mass is estimated by the virtual added mass method to take into account the effect of fluid-structure interaction between the core and the vessel. Rayleigh damping is used for the beam mode damping, and a damping coefficient is directly defined for the shock damping. The response calculation is performed by the direct time integration scheme (Newmark β) in which the time increment is mainly governed by the duration of shock force.

3. RESULTS OF ANALYSIS

Since RAPSODIE mock-up is the largest in the number of subassemblies and hence the most challenging problem for analysis, the results on RAPSODIE experiments are mainly reviewed. Prior to this, shock response analysis on MONJU subassembly collision tests are briefly reviewed.

3.1 Analysis on MONJU Experiment

Shock response test: A fuel subassembly which is supported at its entrance nozzle (spike) is subjected to an initial displacement at its top and released to collide with a heavy weight, either at its top or middle load pad. Shock force was measured by a load cell mounted on the weight.

Shock response analysis: Prior to the seismic response analysis, a series of free vibration analyses which corresponds to the shock response tests in air was performed with a single subassembly. In Fig. 1 shown are the time histories of shock force pulse accompanied by the local deformation behavior of the subassembly due to the shock at load pads. In the case of M.L.P., a fairly good agreement is seen between the analysis and the experiment on the first shock force both in term of its peak value and duration. The shock force reaches its peak at around 3 msec after the contact occurred, while the deformation of the subassembly is much slower. This suggests that the shock force is mainly governed by a local deformation of the load pad. In the case of the T.L.P., whose stiffness is much higher than that of the M.L.P., the duration of the shock force is very short and almost no deformation takes place in the subassembly during the shock. Although the analysis agrees with the experiment in terms of the duration, it gives about twice as high peak values as that of the experiment.

3.2 Analysis on RAPSODIE Experiment

Test in air: The analysis was made with a single row model (19 elements) in which each subassembly is allowed to vibrate in the direction of excitation only.

Fig. 2 is a comparison on the distribution of the maximum, minimum, and range of relative displacements at the top of the elements on the central row. Here, the range is a simple algebraic summation of the maximum and minimum displacements. It is seen from the figure that the present analysis gives a quite good result. Precisely comparing, the analysis result is slightly smaller than the experiment, and the difference is larger for the neutronic shield elements than for the fuel subassemblies.

In Fig. 3 and Fig. 4 compared are the displacement time histories and the response spectra of the central fuel assembly on the central row. Quite good agreements can be seen between the analysis and experiment both for the time history and the response spectra.

Test in water: On the test in water, a single row and a three dimensional half cluster models were both used for the analysis. The latter model, including 145 subassemblies, was a quite large scale and challenging as a non-linear time response analysis. Before the response analysis, a preliminary study was made on the effect of fluid-structure interaction. The reductions in natural frequency and apparent (effective) excitation level were quantified by the study and used in the response analyses.

Fig. 5 is a comparison of the maximum and minimum displacement distributions along the central row. While the single row model gives a good agreement with the experimental data, the results of half cluster model is somewhat larger than the others, especially in the minimum displacements. The reason for this unsymmetry in the half cluster analysis is presently unknown. The distribution of the maximum shock forces are shown in Fig. 6. The half cluster analysis gives quite larger values than the single row model, which is consistent with the displacement results.

In Fig. 7 and Fig. 8 compared are the displacement time histories and the response spectra of the central fuel assembly on the central row. As far as the time histories are concerned, there is a good similarity in their appearances. It is consistent that in the spectra there is a clear peak in 0.08 sec (12.5 Hz) which is a predominant component in the excitation spectra.

From these observations, the present analysis with the single row model is judged to be in good accordance with the experiment, while there is a room for refinement in the half cluster model.

4. ISSUES FOR FURTHER STUDY

As seen in the previous sections, the current codes can predict the dynamic and seismic response behavior of various core mock-ups within a practical accuracy. However, in pursuant of more realistic and reliable seismic qualification of fast reactor cores, there seems to be some issues left for further study.

Fluid-structure interaction: Fluid-structure interaction affects the seismic response of a core in two aspects; i.e., a reduction in the natural frequency and a reduction in the apparent excitation. A simplified virtual added mass approach is mostly used to take these effects into account in the analysis. However, there seems to be a limitation in this method in that a theoretical added mass value does not always lead to the experimentally observed reductions both in frequency and excitation consistently. In addition, there are two classes of fluid-structure interaction, e.g., core-vessel and inter-subassembly interactions. While the former can be expressed by the added mass approach, the latter requires a more sophisticated analytical measure like FE analysis.

Response to 2-D horizontal excitations: An actual earthquake motion in the horizontal direction is two dimensional in nature. Nevertheless, seismic studies on the core so far have focused on 1-D excitation and response, both experimentally and analytically. This can mainly be attributed to the limitation of seismic testing facilities and computational capabilities. To understand the real behavior of the core, however, it is encouraged to make a challenge to develop 2-D response analysis methodologies with experimental verifications. 2-D response of the core is important when reactivity variation during an earthquake is to be evaluated.

Response in a base isolated plant: Base isolation is a promising technology to enhance seismic safety of an LMFR. As its advantage is taken, the reactor block tends to be designed more flexible both for reduction of thermal stresses and construction cost. An attention should be paid in this case to avoid frequency tuning between the reactor vessel and the core. In addition, there is little knowledge on the core response to displacement dominant excitations which characterize the seismic isolation. Therefore, experimental and analytical verification of the core under seismic isolation environment is desired.

Response to vertical excitations: Although it is unusual, when a very high level of vertical excitation (diagrid response) is considered, up-lift, or floating, of subassemblies and consequent loss of core configuration may become a concern. From the safety point of view, it is needed to establish qualification methods for the vertical response of the core.

Effect of pin bundles and bowing: In almost seismic response analyses it is assumed subassemblies stand straight up at an even spacing, and that the effect of pin bundles on the flexural rigidity is negligible. In a high burn up core, there is a possibility that thermal and irradiation bowing of the subassemblies becomes significant and the pin bundles cannot be ignored due to the bundle duct interaction (BDI). These factors can be dealt with by the current analysis methods, and their effects on the seismic response may be studied.

5. CONCLUSIONS

As the final report on the Coordinated research Program on "Intercomparison of LMFR Seismic Analysis Codes", the analysis results by FINAS on the PEC, RAPSODIE, and MONJU core mock-up experiments. Although these experiments vary in size, number of subassemblies, core configuration (free-standing or restrained), and excitation conditions, the results by FINAS are in good accordance with the experimental data with a reasonable accuracy. The present analysis method with FINAS, therefore, is judged to be capable for practical use. However, there is still a room for improvement of analysis method, especially on large scale 3D problems.

Finally, some issues were identified to be further studied from the view point of core seismic methodology improvement.

6. RFERENCES

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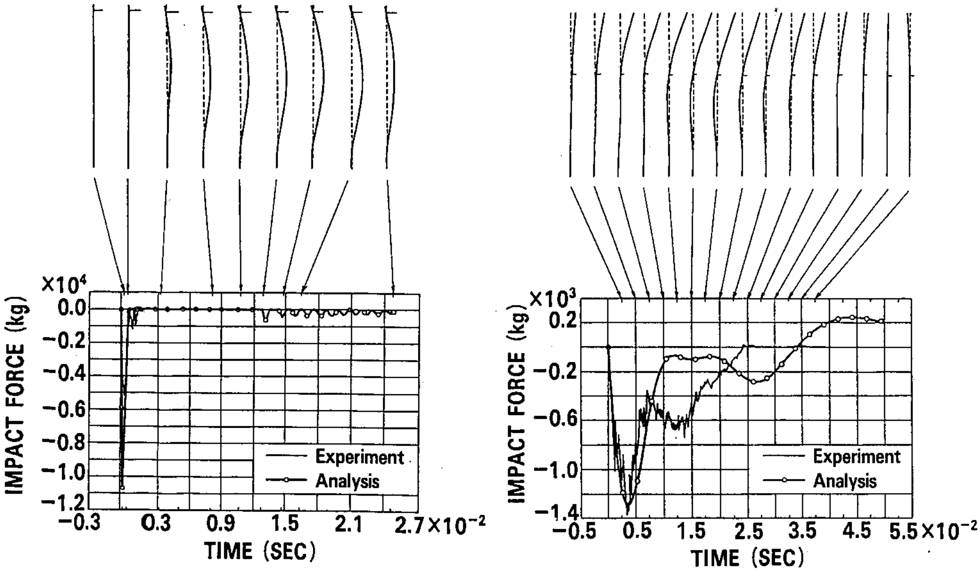


(a) (b)

Fig. 1 Shock Response Analysis of MONJU Single Subassembly
(a) Top Load Pad, (b) Middle Load Pad

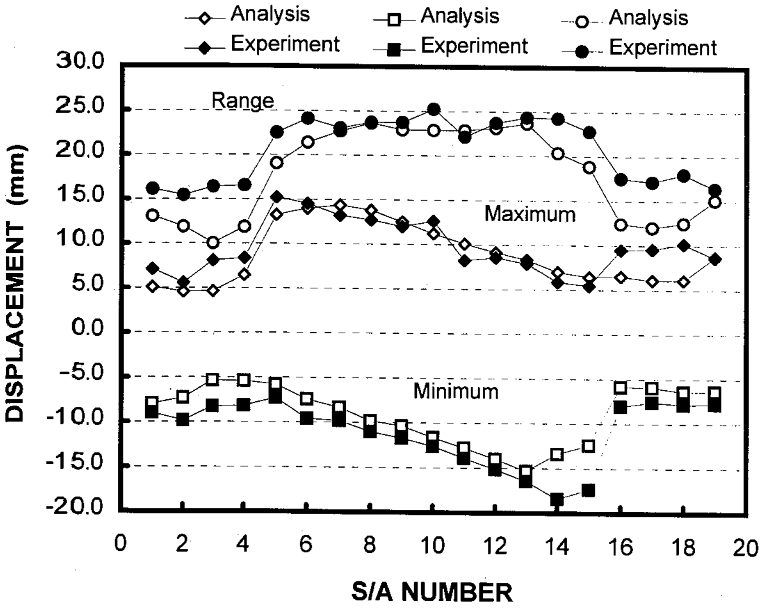


Fig. 2 Comparison of Maximum Displacement Distribution:
RAPSODIE In-air

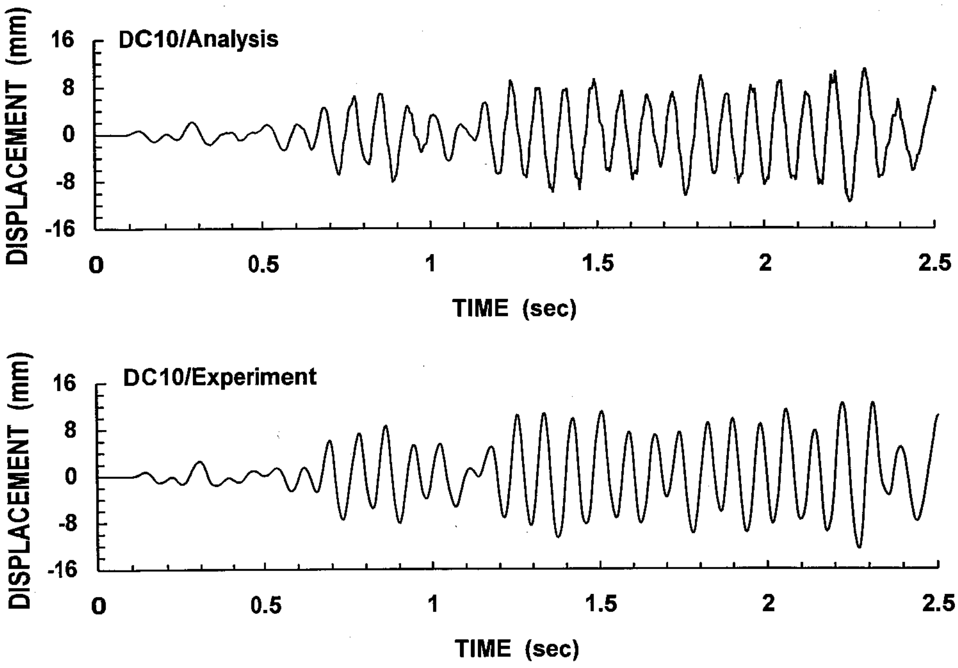


Fig. 3 Comparison of Displacement time Histories: RAPSODIE In-air

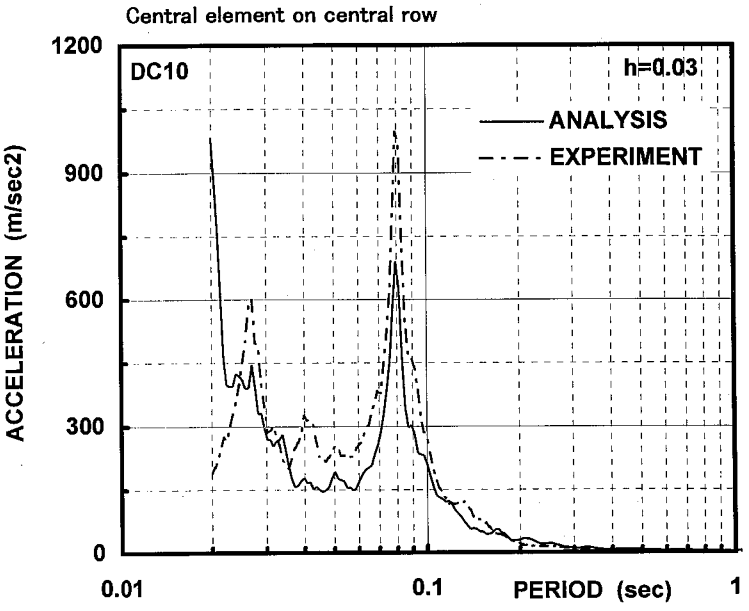

Central element on central row

Fig. 4 Comparison of Floor Response Spectra: RAPSODIE, In-air

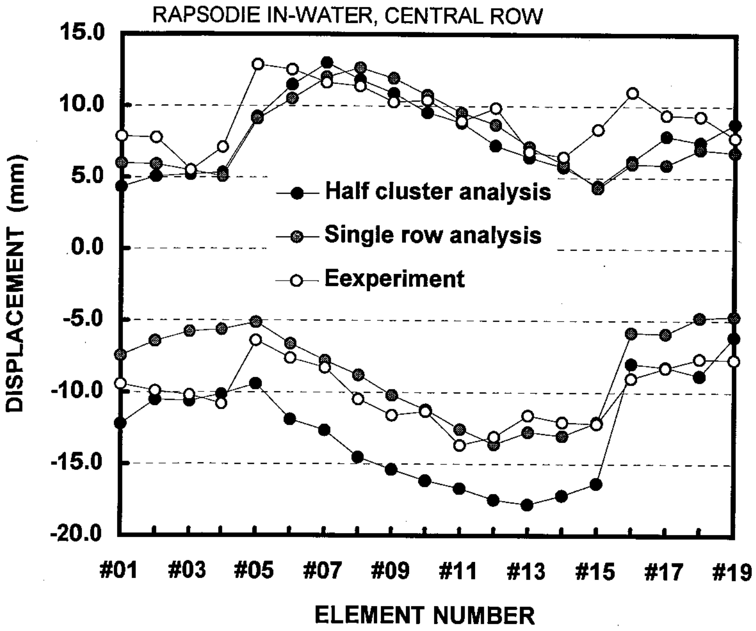


Fig. 5 Comparison of Maximum Displacement: RAPSODIE In-water

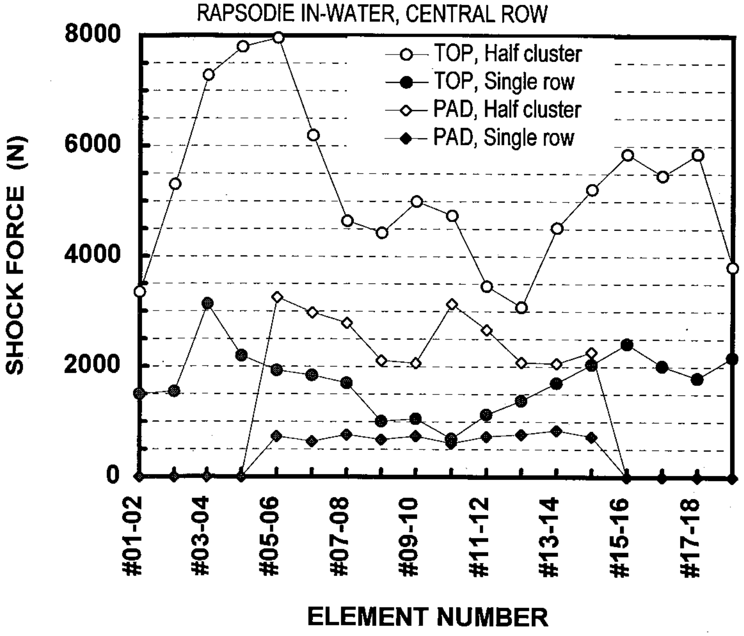
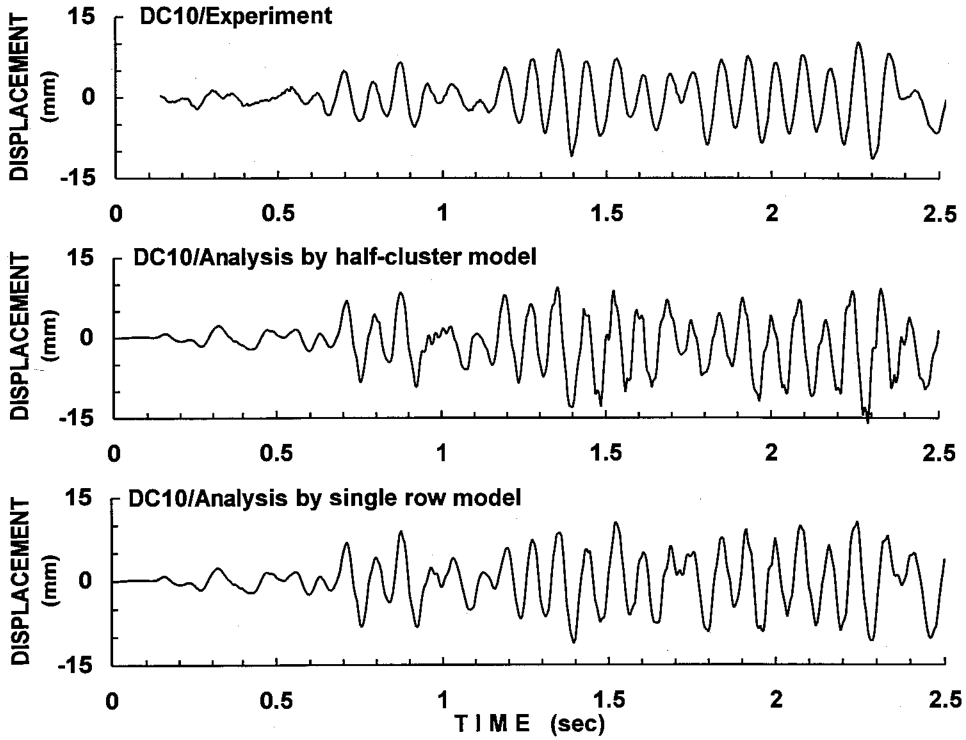


Fig. 6 Comparison of Maximum Shock Forces: RAPSODIE In-water

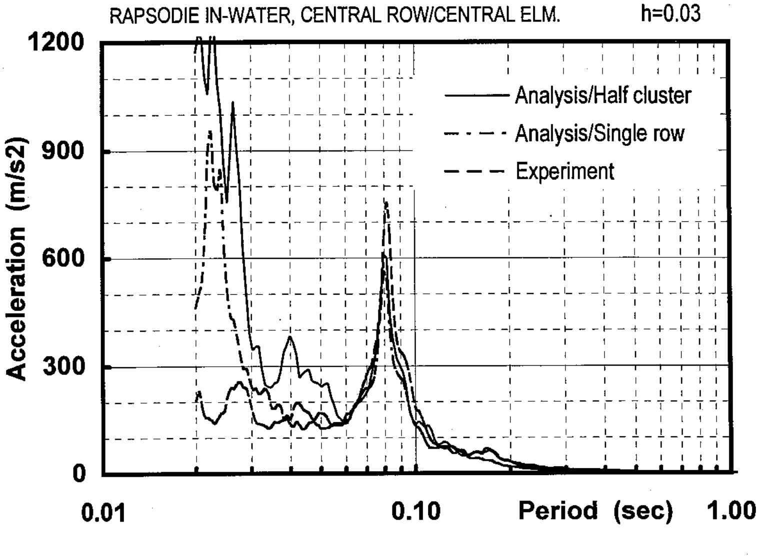


DC10/Experiment

DC10/Analysis by half-cluster model

DC10/Analysis by single row model

Fig. 7 Compariosn of Displacement Time Histories: RAPSODIE In-water



RAPSODIE IN-WATER, CENTRAL ROW/CENTRAL ELM. h=0.03

Fig. 8 Compariosn of Floor Response Spectra: RAPSODIE In-water