HPCI magazine
富岳百景
FUGAKU HYAKKEI

Advancing Nuclear Safety with Computational Science

The reactor building of a nuclear power plant has a complex structure consisting of the building itself and major pressure boundary equipment, such as reactor pressure vessel (RPV), primary containment vessel (PCV), suppression chamber, vent pipes, etc. In order to evaluate structural integrity such as seismic resistance, it is important to consider the coupled effects of buildings and equipment; therefore, analyses of the entire structure are required. Dr. Miyamura is continually researching simulations that utilize computational capabilities in large-scale analyses that pursue accuracy down to the smallest detail, with the aim of helping to ensure safety.

Tomoshi Miyamura
Associate Professor,
Department of Computer Science, College of Engineering,
Nihon University

Fukushima Daiichi Nuclear Power Station Unit 1 Seismic Analysis Project

The importance of seismic design for the safe operation of nuclear power plants goes without saying, but this was reaffirmed by the magnitude 6.8 Niigata-ken Chuetsu-Oki Earthquake. At Tokyo Electric Power Company (TEPCO)'s Kashiwazaki-Kariwa Nuclear Power Station, located approximately 16 km from the epicenter, shaking equivalent to a seismic intensity of 7 was recorded, resulting in damage. While little damage was observed to safety-critical equipment and structures, the plant was shut down for an extended period for post-earthquake safety inspections and earthquake countermeasures. This prompted the launch of a project to use observed seismic waves from the earthquake to simulate the reactor's seismic response in detail.

As the results of this analysis project were being compiled, "the 2011 off the Pacific coast of Tohoku Earthquake" with magnitude 9.0 occurred on March 11, 2011. Shortly after the accident, a research project on seismic simulations for Unit 1 of TEPCO's Fukushima Daiichi Nuclear Power Station (hereafter referred to as 1F1) was launched, and Dr. Miyamura has been a key member since its inception. The computing platform has transitioned from the K computer to the supercomputer Fugaku, and advanced analysis continues.

The input seismic waves were created based on the time history of east-west and north-south translational acceleration observed in the basement of 1F1 during the 2011 off the Pacific coast of Tohoku Earthquake. "The seismometer on the second floor was out of service, so some of the information was missing. Therefore, we created input seismic motion, including rotational components, based on the results of a simulation using a simple ground model," Dr. Miyamura explains.

The analysis code Dr. Miyamura uses for this research is "ADVENTURE_Solid3FS," which he himself contributed to developing. This code performs calculations using the finite element method, which can accurately analyze how forces are transmitted through objects and structures with complex geometries. This code targets large-scale structural analysis based on parallel processing and tuned up for Fugaku, and is an extended version of an open source version in the large-scale computational mechanics system for design, "ADVENTURE."

Pursuing Precision with the Finite Element Method

Nuclear power plants are composed of structures with complex geometries. To simulate the internal forces (stresses) and deformations, it is necessary to solve problems that use the structure's geometry as a boundary condition. Unlike simulations of relatively simple geometries, such as seismic wave propagation within the Earth's crust or atmospheric flow in meteorology, analytical models cannot be created using uniform, orthogonal grids (structured grids). Therefore, analytical models (called meshes, or unstructured grids, as opposed to structured grids) are created by dividing complexly shaped regions using finite elements such as tetrahedrons and hexahedrons. Because the finite element method can accurately model complex geometries, it can provide reliable solutions in detail, from the boundary to the interior.

Modeling first requires 3D CAD*1 model data that represents the complex geometry. Unfortunately, for 1F1, only paper drawings existed, and it took an enormous amount of time to manually create a 3D CAD model from those drawings (Fig. 1).

Creating a mesh using tetrahedral elements for a defined shape can be done completely automatically, but time-consuming work is required to properly connect the meshes created for each part (Figs. 2 and 3). "To improve accuracy, we had to make the elements as small and finely divided as possible, which meant the data became huge, and handling it was difficult," Dr. Miyamura recalls.

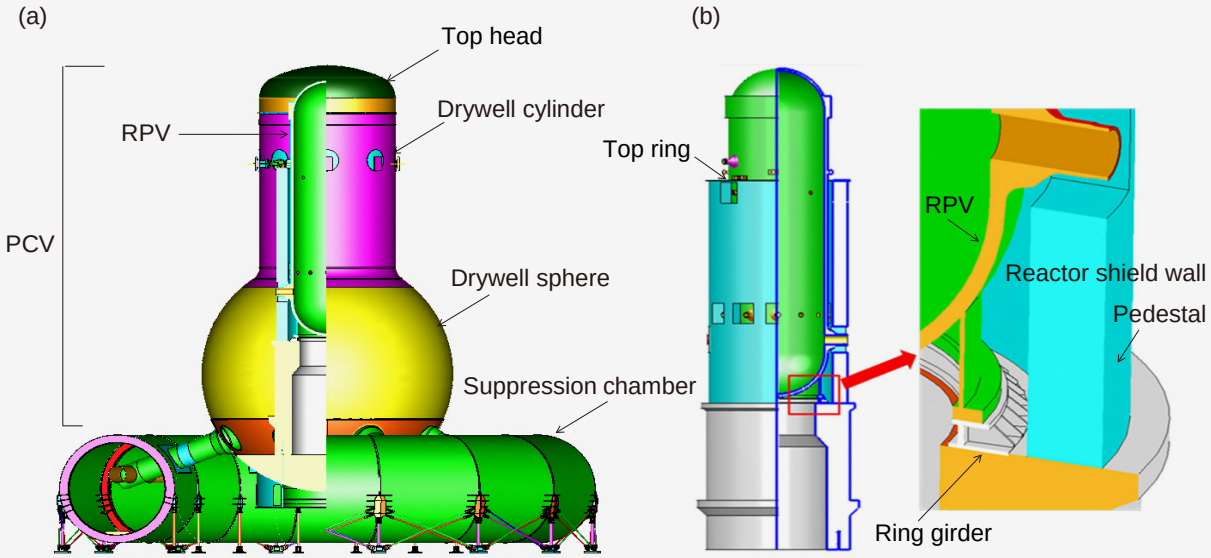


Fig. 1 : CAD model of Fukushima Daiichi Nuclear Power Station Unit 1 (1F1)

(a) The overall view of the pressure boundary equipment. (b) An enlarged view of the RPV and its cross section inside.

This realistic model was created after consultation with TEPCO and manufacturers and subsequently reviewed by nuclear experts.

Fig.1- Fig. 3 : Reprinted from Shinobu Yoshimura, Tomoshi Miyamura et al., “Seismic Response Analysis of Unit 1 of Fukushima-Daiichi Nuclear Power Plant During the 2011 off the Pacific Coast of Tohoku Earthquake Using Three-Dimensional Finite Element Method (1st Report: Development of Analysis Method, Model Construction and Verification of Analysis Performance),” Transactions of the Atomic Energy Society of Japan (2019) https://doi.org/10.3327/taesj.J18.001 with permission from the Atomic Energy Society of Japan.

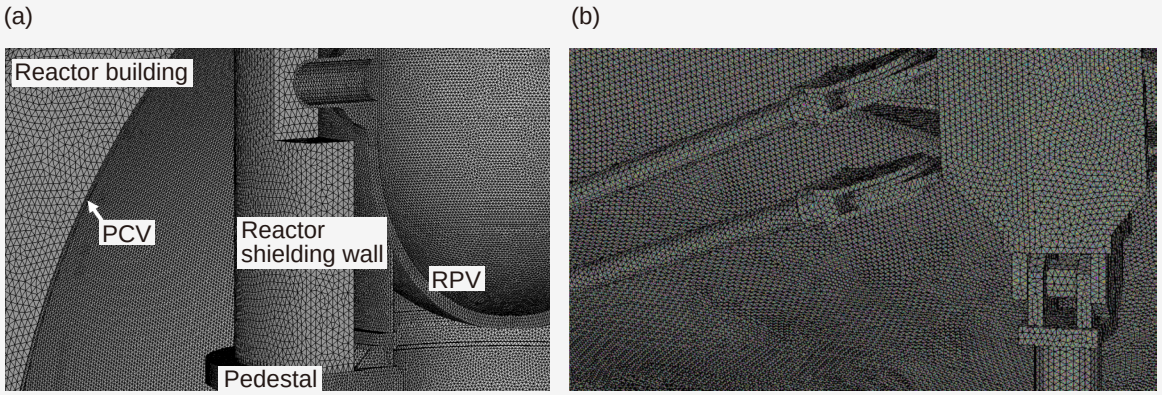


Fig. 2 : Enlarged view of the mesh used in the simulation

(a) Cross-section of the mesh of the lower part of the RPV and the nearby shielding wall, PCV, and reactor building shown in Fig. 1. The RPV and PCV are thin-walled structures, while the building is significantly thicker. To ensure analytical accuracy for thin structures, the shells of the vessels must be divided into about four layers in the thickness direction. Therefore, the RPV and PCV are divided into a finer mesh than the building.

(b) The mesh of the part that supports the suppression chamber shown in Fig. 1. The support pillars, the reinforcing members, called braces, that connect to them at an angle, and the pins at their attachment points are also discretized into fine elements using tetrahedral elements.

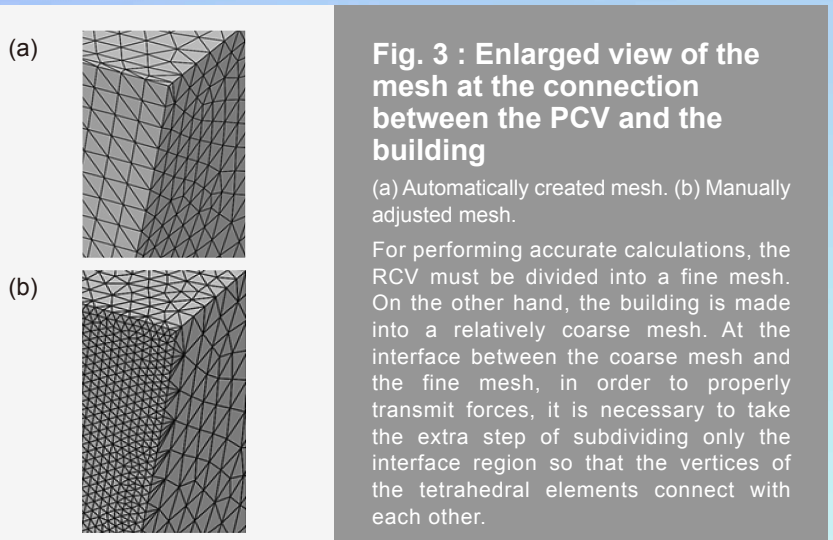


Fig. 3 : Enlarged view of the mesh at the connection between the PCV and the building

(a) Automatically created mesh. (b) Manually adjusted mesh.

For performing accurate calculations, the RCV must be divided into a fine mesh. On the other hand, the building is made into a relatively coarse mesh. At the interface between the coarse mesh and the fine mesh, in order to properly transmit forces, it is necessary to take the extra step of subdividing only the interface region so that the vertices of the tetrahedral elements connect with each other.

Development of ADVENTURE_Solid3FS to Maximize Fugaku's Computational Performance

The ADVENTURE system was developed as a "large-scale computational mechanics system for design" for performing various simulations on large-scale computers. ADVENTURE_Solid, which performs structural analysis based on the finite element method, is one of its modules. Its development began in 1997 as ADVENTURE Project*2, one of the Japan Society for the Promotion of Science's Research for the Future Program, and has continued through various projects since then. Researchers from many universities and companies have been involved in its development. Dr. Miyamura has been one of the core development members since its inception.

A procedure with high computational cost in ADVENTURE_Solid is a solution procedure of a system of linear equations with unknowns three times as many as the number of mesh vertices at each time step. This procedure is conducted repeatedly in the analysis. The 1F1 linear element model solves equations with approximately 200 million unknowns, while the quadratic element model*3 solves equations with approximately 1.5 billion unknowns using a method called an iterative method (or solver)*4. For thin-walled structures such as the pressure vessel in 1F1, the convergence of the iterative method (the number of iterations required to converge until the error becomes small) deteriorates, so ADVENTURE_Solid implements a powerful pre-processing method to improve convergence.

To fully utilize the performance of large-scale parallel computers with many processors in this calculation, it is important to divide the calculations according to the parallel computer's characteristics and assign them to each processor so that efficient parallel calculation is performed. "In the case of weather simulations, for example, the geometry of the analysis domain is simple, so it can be modeled using a 'structured grid' with a cubic grid, which makes it easy to maximize the performance of a parallel computer. However, the finite element method uses 'unstructured grids' such as tetrahedrons and hexahedrons, making it difficult to achieve high performance. Furthermore, the more effective the preprocessing method for the iterative solution of simultaneous linear equations, the more difficult it becomes to achieve parallel calculation. ADVENTURE_Solid employs various techniques to achieve both high parallel performance and good convergence of the iterative solution, even for analysis objects with complex geometries," Dr. Miyamura explains. As a result, ADVENTURE_Solid has been implemented on parallel computers such as PC clusters*5, the Earth Simulator (at JAMSTEC), the K computer, and Fugaku, and has been widely utilized. There is also commercial software that has been developed based on the ADVENTURE system, which is used in a variety of industries, including automotive, electronics, energy, and precision machinery manufacturing, and is highly regarded for its superior performance.

For analyses on Fugaku, it was necessary to develop

ADVENTURE_Solid3FS, a version of the existing ADVENTURE_Solid that was further tuned for Fugaku. Because Fugaku offers more computational nodes and cores than previous supercomputers, the previous method of dividing calculations did not efficiently utilize the cores. Dr. Miyamura therefore reviewed how the divided calculations were allocated to the computational cores, including the preprocessing portion of the iterative solution, and developed a new algorithm. "ADVENTURE_Solid3FS delivers high computational performance for a simulation code that handles unstructured grids. Furthermore, the iterative method for a system of linear equations converges extremely quickly, regardless of the analysis target. As a result, ADVENTURE_Solid3FS is a code that boasts unparalleled speed. Moreover, it has a wide range of functions that allow it to simulate a variety of targets," Dr. Miyamura says proudly.

Dr. Miyamura has also made repeated improvements to his data output method. The 1F1 analysis involved 6,500 time steps (equal to 65 seconds), and each time step generated numerous calculation results, making it difficult to output and save all of the calculation results. Therefore, Dr. Miyamura even visualized the calculation results using offline visualization technology*6 on Fugaku, generating multiple high-resolution images for each time step and then deleting the output data of results.

Nonlinear Analysis Realized by Fugaku

When Dr. Miyamura first began simulating 1F1, he used the K computer, which began operation in 2012, to perform linear analysis, treating materials as elastic bodies and assuming no cracks in concrete. Based on the simulation results, he was able to calculate floor response spectra at 690 points. Floor response spectra indicate the frequency at which a structure responds to earthquake acceleration, revealing its susceptibility to shaking.

Based on the results of the linear analysis performed by the K computer, Dr. Miyamura conducted a nonlinear analysis on Fugaku, incorporating plastic deformation and concrete cracking. Plastic deformation is deformation that does not return to its original shape even after the load is removed. For example,

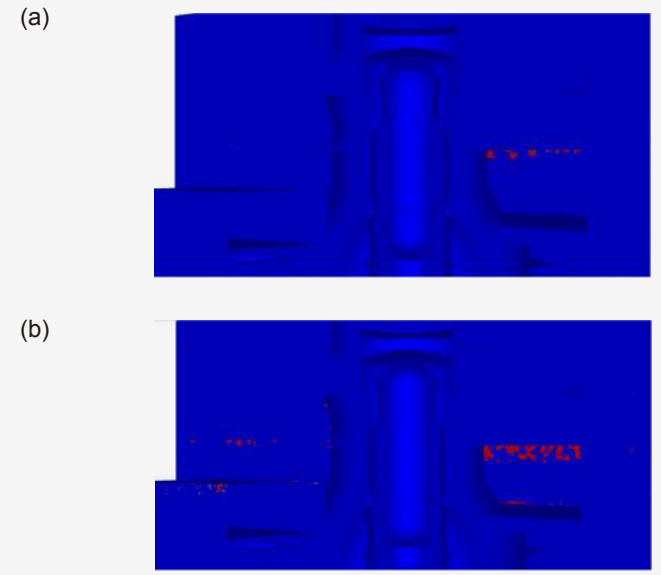


Fig. 4 : Concrete damage

(a) Simulation result using only tensile crack model. (b) Simulation result using both tensile crack model and elastic-plastic damage model.

Red indicates cracks. The analysis was performed using seismic motion with an amplitude 1.2 times that of the actual 2011 off the Pacific coast of Tohoku Earthquake.

Fig. 4 - Fig. 6 : Reprinted from Tomoshi Miyamura et al., "Nonlinear Seismic Response Analysis of a Nuclear Power Plant Using High-Fidelity Finite Element Model on Supercomputer Fugaku," Proceedings of the 38th Computational Mechanics Conference, The Japan Society of Mechanical Engineers (JSME) [No. 25-50] with permission from JSME.

crushed pipes and cracked concrete do not return to their original shape. This behavior represents the nonlinear characteristics of materials. While linear analysis requires solving a large system of linear equations once per time step, nonlinear analysis requires solving them multiple times, resulting in a significant increase in computational effort. Therefore, while the K computer was able to perform linear analysis, nonlinear analysis could only be performed in very short periods of time (a small number of time steps). However, Fugaku is capable of this. By leveraging the computational power of Fugaku, Dr. Miyamura now performs more realistic simulations (Figs. 4, 5, and 6).

The red areas in Fig. 4 show cracks in the concrete. (a) is the analysis result that only considers cracks that break when pulled (tensile crack model), while (b) also considers plastic deformation and the resulting crushing using an elastic-plastic damage model. Fig. 5 shows the history of the displacement (amount of movement from the original position) of the upper part of the reactor pressure vessel due to shaking. The blue line is for the tensile crack model only, while the red line takes into account both the tensile crack model and the elastic-plastic damage model. It was found that the response differs between the two due to the nonlinearity of the material model. The distribution of equivalent stress throughout the analysis model was also simulated (Fig. 6). It was found that significant stresses are concentrated in red areas, so in the future we plan to analyze their relationship to the crack initiation area. Furthermore, as computations can currently only be performed for approximately 4.5 seconds, we plan to perform computations for a longer period of time."

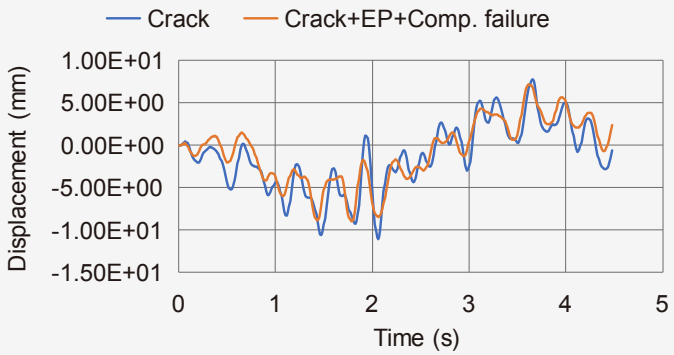


Fig. 5 : History of displacement of the upper part of the RPV

The horizontal axis is time. The vertical axis is displacement (distance moved from the original position). The analysis was performed using seismic motion with an amplitude 1.2 times that of the actual 2011 off the Pacific coast of Tohoku Earthquake.

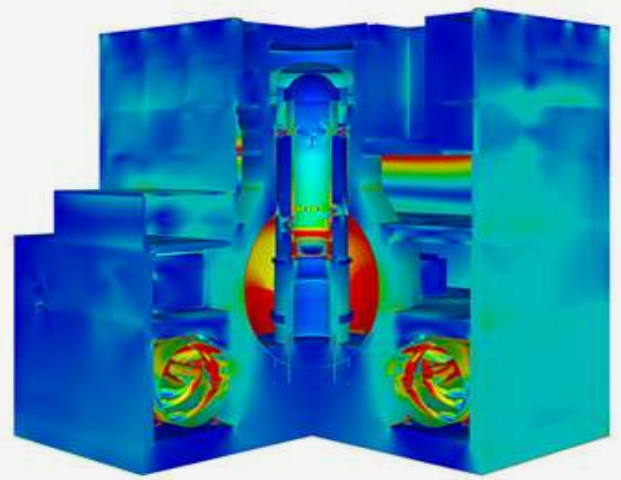


Fig. 6 : Distribution of equivalent stress throughout the analysis model of the reactor building

A scene from a simulation movie for 1.5 seconds (3 to 4.5 seconds in Fig. 5) (Here, the analysis was performed using seismic motion with an amplitude 1.2 times that of the actual 2011 off the Pacific coast of Tohoku Earthquake. Also, deformation is magnified 100 times to make it easier to see.)

Future Challenges Include Enhancing the Accuracy of Simulations and Analyzing the Response of Reactor Equipment and Piping

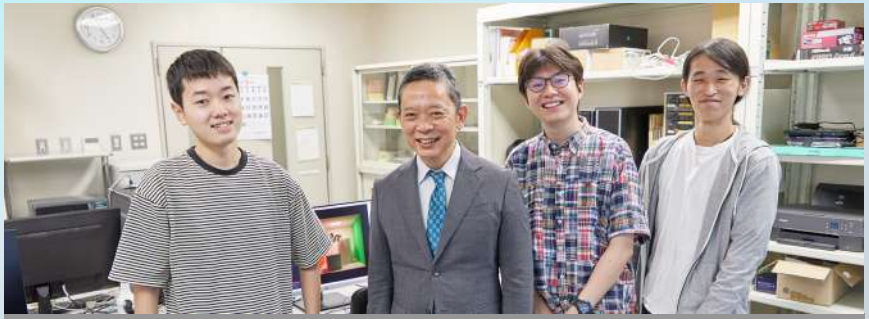
This study demonstrated that Fugaku allows simulations that take into account highly nonlinear phenomena such as cracking. However, consideration of the ground, improved accuracy of material models for concrete and other materials, and modeling of the water inside the reactor are still necessary, as well as simulations for various input seismic motions. Cracks in the concrete parts of the building are important when considering radiation shielding. Furthermore, the scope of analysis must be expanded beyond 1F1 to other nuclear power plants. "We are currently creating a mesh for a nuclear power plant with a new type of small modular reactors, and a prototype of the mesh has already been completed," Dr. Miyamura explains.

Nuclear power plants have various components and piping attached to their structures. Damage to these pieces of equipment during an earthquake poses a significant risk, therefore Dr. Miyamura believes that the results of this study should be utilized in future simulations.

"We performed a nonlinear analysis that accounted for cracks, and confirmed that the shaking of the pressure vessel changed. By using a floor response spectrum that reflects these results, we will be able to more realistically evaluate the shaking of equipment and piping inside the reactor, such as control rods."

One analysis method would be to incorporate the equipment into this model, but as the equipment is much lighter than the main body, this would not change the nature of the shaking of the main body. It may be better to analyze each piece separately.

"By attempting various simulations, we can become aware of hidden risks and reduce the occurrence of events beyond the design assumptions," Dr. Miyamura says, emphasizing the importance of continuing to conduct research on simulations aimed at improving the safety of nuclear power plants.



Dr. Miyamura and lab members.

*1 Software used to define 3D geometric models instead of 2D drawings.
*2 "ADVENTURE Project" https://adventure.sys.t.u-tokyo.ac.jp/
*3 A linear element model has nodes at the vertices of tetrahedrons. A quadratic element model also has nodes at the midpoints of edges, allowing for a more accurate representation of deformation than linear elements, but at the expense of increased computational cost.
*4 A method for solving large-scale systems of linear equations. Starting from an appropriate initial value, iterative calculations are performed to approach the solution. Here, the preconditioned conjugate gradient method is used as the iterative solution method. On the other hand, the nonlinear analysis described below uses an iterative solution method called the Newton-Raphson method. During the iterations, it is necessary to solve a system of linear equations of the same dimensions as the linear analysis multiple times. In other words, since there are double iterations of the Newton-Raphson method and the conjugate gradient method, the amount of calculations is many times greater than that of linear analysis.
*5 A system in which multiple general-purpose personal computers are connected via a network and operate as a single parallel computer.
*6 LexADV_WOVis https://adventure.sys.t.u-tokyo.ac.jp/lexadv/WOVis.html
This code was used with functions added for 1F1 analysis.

About the Researcher

Tomoshi Miyamura
Associate Professor, Department of Computer Science,
College of Engineering, Nihon University

Dr. Miyamura has been involved in research on large-scale parallel nonlinear analysis since the launch of the ADVENTURE Project about 30 years ago.

He says that the damage and accident at the TEPCO's Fukushima Daiichi Nuclear Power Station caused by the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011, was an unforgettable event. "I was shocked when the Fukushima accident occurred just as I was participating in the K computer projects on nuclear power plant seismic resistance, and on earthquakes and tsunamis." He says he reconfirmed his resolve that he would contribute to society through research on seismic analysis of nuclear power plants, utilizing his expertise in computational mechanics and high-performance computing. Since immediately after the disaster, he has spent much time discussing this research with students in his lab.

Dr. Miyamura hopes to continue teaching and conducting research while keeping his heart focused on Koriyama City, Fukushima Prefecture, where the university campus is located.

Interview date: September 19, 2025

Associated Research Projects:

Multi-purpose simulations of nuclear power plants using a full-scale 3D FEM model on Fugaku (hp230061)
Dynamic and nonlinear simulations of nuclear power plants using a full-scale 3D FEM model for evaluation of seismic / structural integrity performances (hp240138)
Principal Investigator: Tomoshi Miyamura, Nihon University

HPCI magazine
富岳百景
FUGAKU HYAKKEI

Registered Institution for Facilities Use Promotion /
The Representative for HPCI Operation
Research Organization
for Information Science and Technology
1-5-2, Minatojimaminami-machi, Chuo-ku, Kobe, Hyogo, 650-0047 JAPAN
Tel: +81-78-599-9511

HPCI Portal site
https://www.hpci-office.jp/en

HPCI PR site
https://fugaku100kei.jp/e/

Issued: December 2025