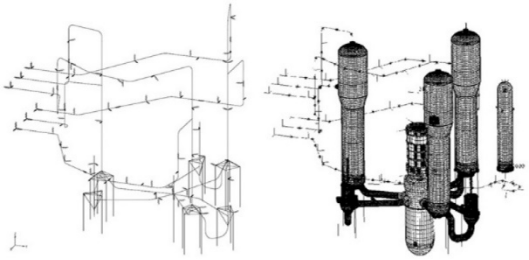
Advanced Structural Evaluation Process for Main Components of Reactor Coolant System Using Large-scale Structural Analysis Technology



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For main components such as reactor vessels and steam generators that constitute the reactor coolant system of a PWR (Pressurized Water Reactor) nuclear power plant, the evaluation of structural integrity against temperature and pressure transients during operation and against seismic loads using detailed analysis is required. Conventionally, we have performed this detailed structural analysis process using subdivided analysis models. In addition, with the recent evolution of structural analysis methodology, we are developing a method to develop a structural analysis process that seamlessly efficiently performs the structural analysis of the main components of a reactor coolant system (hereinafter referred to as seamless structural analysis process).

1. Introduction

A reactor coolant system consists of a reactor coolant loop in which reactor coolant pumps, steam generators located around a reactor vessel are connected by primary coolant piping. Inside the reactor vessel, there are fuel assemblies constituting the reactor core and the core support structures supporting them. Above the reactor vessel, there are control rod drive mechanisms for controlling the output of the reactor core. These components (hereinafter referred to as the main components) are required to maintain the pressure resistance function as a reactor coolant pressure boundary and the core support function against transient changes in the temperature and pressure of the reactor coolant and shaking at the time of an earthquake. Therefore, the pressure-resistant parts of the main components and the core support structures are evaluated in detail under various load conditions to verify their structural integrity.

2. Structural integrity evaluation of main components

The structural integrity evaluation of the main components is carried out to verify that the main components meet the prescribed structural integrity criteria. For that purpose, first the temperature and pressure conditions during operation and the loads acting on the components due to an earthquake are obtained by load analysis, and then the stress generated in each part is calculated by stress analysis that locally simulates that part. An overview of the structural calculation process is shown in **Figure 1**.

Load analysis models for calculating loads acting on each part include an overall model for obtaining loads acting on the main parts of the main components and multiple detailed component models for obtaining loads acting inside each main component in detail. Those models are constructed so that the vibration characteristics and the response of the components can be evaluated appropriately or conservatively by representing the stiffness and mass of each part with beam elements, spring elements and mass elements. **Figure 2** gives an example of load analysis models. The element properties of the load analysis model can be obtained by manual calculation using theoretical formulas and finite element (hereinafter, FE) analysis that locally simulates a

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structure. For example, a part that can be treated as a simple cylinder, such as the primary coolant pipe or the cylindrical part of a reactor vessel, is simulated by a simple beam element or pipe element, and the element properties calculated based on the dimensions and material properties (second moment of inertia, etc.) are input. On the other hand, a part with complicated shapes, such as inlet/outlet nozzles of a reactor vessel, is simulated by a spring element that simulates local stiffness calculated by FE analysis that locally simulates the actual shape. Using these load analysis models constructed in the procedure described above, seismic response analysis is performed using the analysis conditions and analysis methods specified in the Technical Code for Seismic Design of Nuclear Power Plants[1] to calculate loads acting on each part. The validity of this load analysis method has been verified by comparing the results of excitation tests using reduced-scale models of actual components with the evaluation results of analysis in Seismic Proving Tests on Reliability for Large Components conducted from the 1980s to the early 1990s.

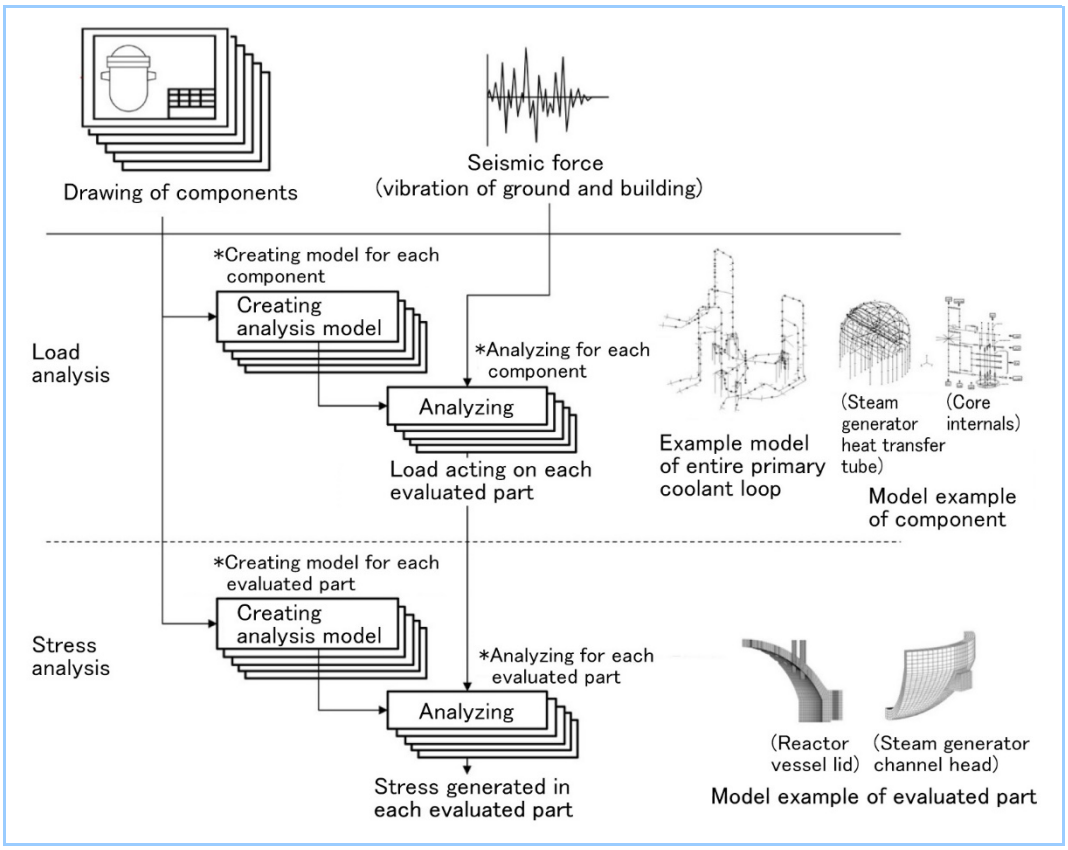

Figure 1 Schematic flow of current evaluation process

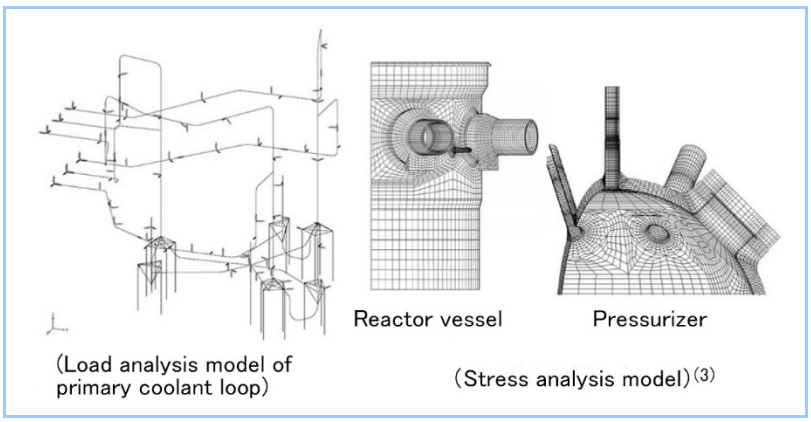

Figure 2 Example of analysis models

Next, the stress generated by each load is calculated by stress analysis. For the stress analysis, stress analysis models which are obtained by three-dimensional-solid modeling or axisymmetric-element modeling of the actual shape are used. Figure 2 presents an example of the stress analysis models[2].

For the stress obtained by the structural calculation process that coordinates the load analysis and stress analysis, stress evaluation is performed according to the procedure and criteria specified in Rules on Design and Construction[3]. This evaluation can reasonably and conservatively evaluate the structural integrity of the main components, so at many nuclear power plants in Japan, from the time of their construction to the present, it has been used for stress and seismic evaluation reports of construction approval applications submitted to the national government and the latest evaluation of structural integrity against aging, long-term operation, and so on. As such, it also contributes to the reliability of the main components.

3. Development of seamless structural analysis process

In recent years, with the improvement of computer technology and the popularization of 3D CAD tools, large-scale structural analysis using three-dimensional FE analysis models has become commonplace. Based on these trends, we are developing a structural analysis process that simulates the main components, such as the reactor vessel, steam generators, and so on, using a single analysis model that seamlessly calculates from load analysis to stress analysis[4]. By putting this method into practical use, it is made possible to obtain the stress generated in a target part without transferring the result of the load analysis to the stress analysis and performing the stress analysis for each part. As a result, the time from determining the component shape and the load conditions to obtaining the stress calculation result can be shortened, so it is expected that a quick response to changes in design conditions and component specifications will be made possible.

3.1 Analysis procedure in seamless structural analysis process

Figure 3 illustrates the schematic flow of the seamless structural analysis process. The structural analysis procedure using this process is described below.

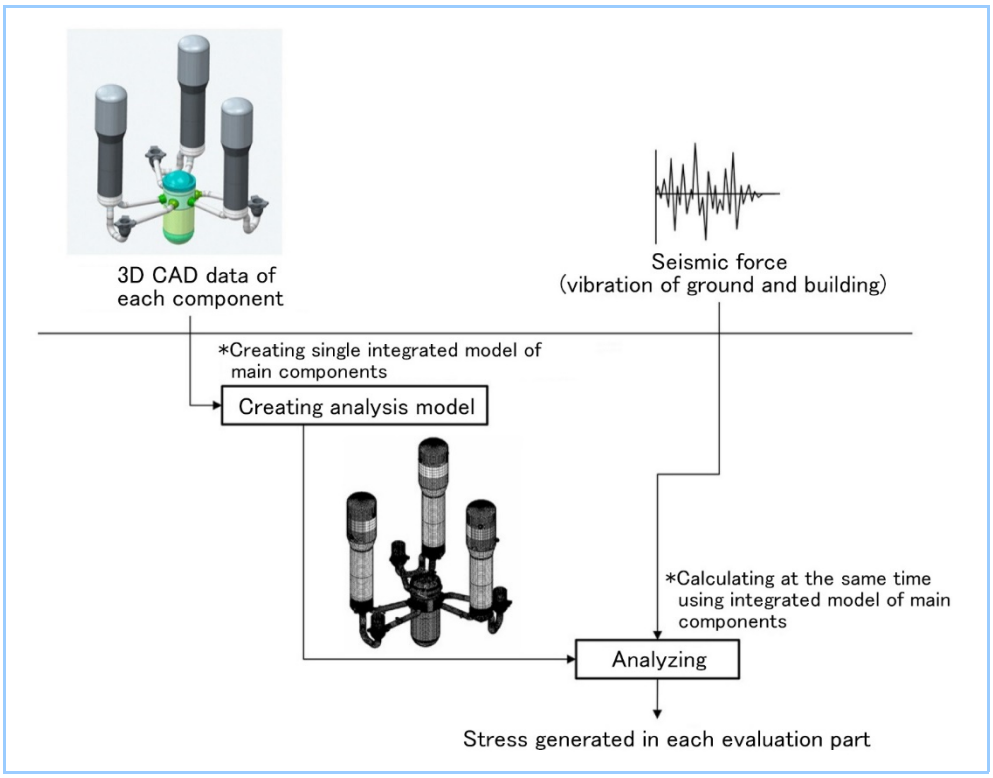

Figure 3 Schematic flow of seamless structural analysis process

3.1.1 Creation of analysis model

First, a three-dimensional FE analysis model is created by performing mesh division with three-dimensional solid elements (hexahedron or tetrahedron) using the three-dimensional shape information of the main components input from the 3D CAD data. The mesh size is basically fine enough so that the stress distribution inside the material and the peak stress on the surface can be understood in detail. However, in the case of parts in which it is clear that no significant stress is generated, the mesh size should be coarser within a range that does not affect the rigidity and vibration characteristics of the model so as not to increase the number of

elements and nodes of the entire model too much. The elements used are hexahedral elements for parts with a simple shape such as cylindrical parts, and tetrahedral elements for parts with a complicated shape such as nozzles, parts with discontinuities in shape, etc.

3.1.2 Analysis

Next, object load conditions such as the seismic forces, the temperature and so on and appropriate boundary conditions are set, and the analysis is performed.

(1) Static analysis

The stress caused by static load conditions (internal pressure, own weight, and so on) is calculated by static structural analysis.

(2) Dynamic analysis

The stress in each part generated by seismic motion is calculated by the time history response analysis in which the time history seismic wave is input and the response at each time is calculated. The time history response analysis includes a direct integration method that can solve even a non-linear problem and a modal method that uses a linear model and can be performed at high speed. The latter model is applied because the analytical models of the main components consist only of linear elements. As a result of a benchmark comparison of the calculation speed using a same model, the modal method was confirmed to be about 40 times faster than the direct integration method.

(3) Thermal stress analysis

The temperature distribution is calculated for the temperature transient using unsteady heat transfer analysis, and the stress is calculated for each time point during the transient using the static structural analysis with the temperature distribution calculated as an input.

3.1.3 Stress evaluation

The obtained analysis are moved to post-process, and the stress evaluation is performed according to the stress evaluation process based on Rules on Design and Construction[3].

3.2 Example of analysis result of seamless structural analysis process

Figure 4 is an example of a created FE analysis model for the main components using the seamless structural analysis process. A general-purpose structural analysis program, ANSYS, which has been used for the approval and licensing of nuclear power plants, was applied, and the computer used was a general-purpose analysis workstation (CPU: Intel Xeon Gold 6244 [3.6 Hz, 8 cores] x 2) with relatively high computing performance and ease of operation based on the results of benchmark calculations in various computing environments, including a cluster system in which multiple computers are parallelized. The mesh sizes of the created analysis model were set so that the stress distribution inside the material and the peak stress on the material surface could be calculated to the same level of accuracy as the current stress analysis model.

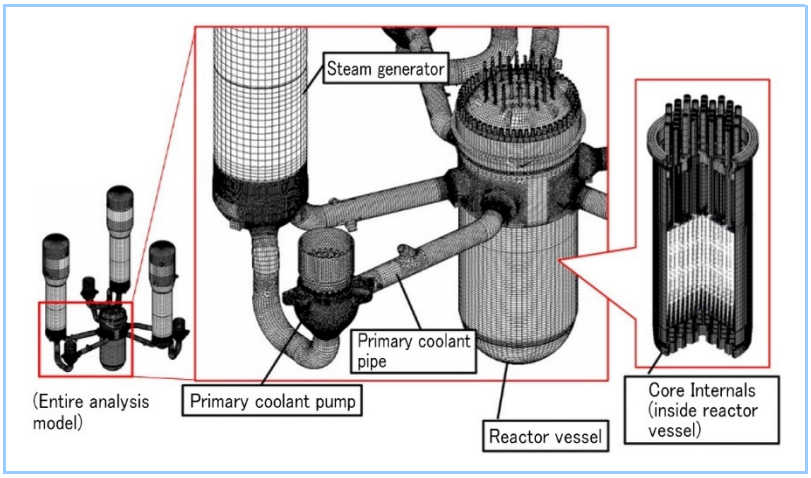

Figure 4 Example of creating analysis model

In order to verify that this model is an appropriate analysis model from the perspective of seismic evaluation, a parameter study with different mesh sizes was performed to understand the changes in the natural frequency of a typical vibration mode, and the natural frequency was compared with that of the current load analysis model. **Figure 5** depicts the result schematically.

Even when the average mesh size was expanded to about double, the natural frequency of the typical mode experienced no significant change and was similar to that of the current model, which has been verified that the mesh size is appropriate. **Figure 6** gives a stress contour diagram at the time of an earthquake as an example of the calculation result. The generated stress has been verified to be almost the same as that of the current method.

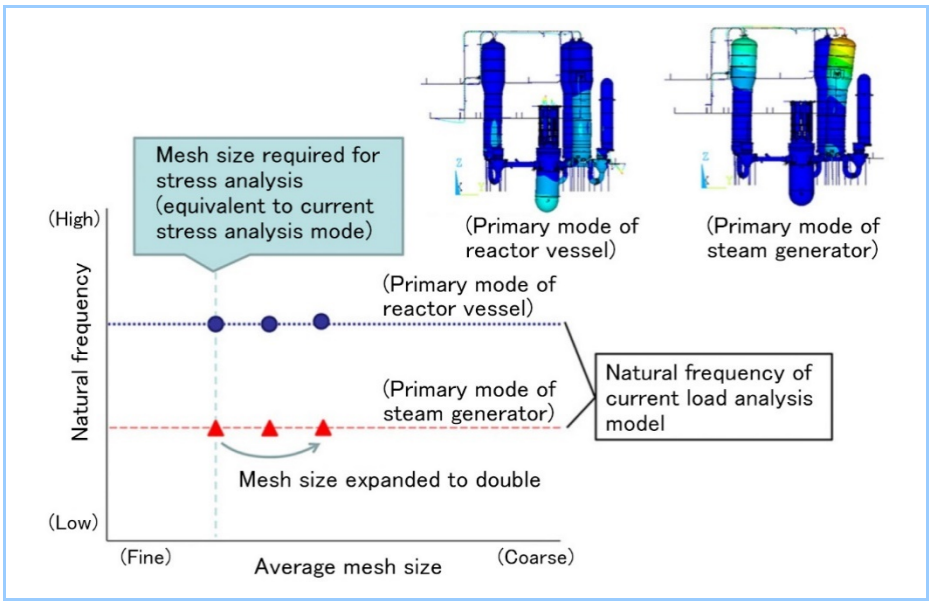

Figure 5 Result of validity verification of mesh size based on comparison of natural frequencies

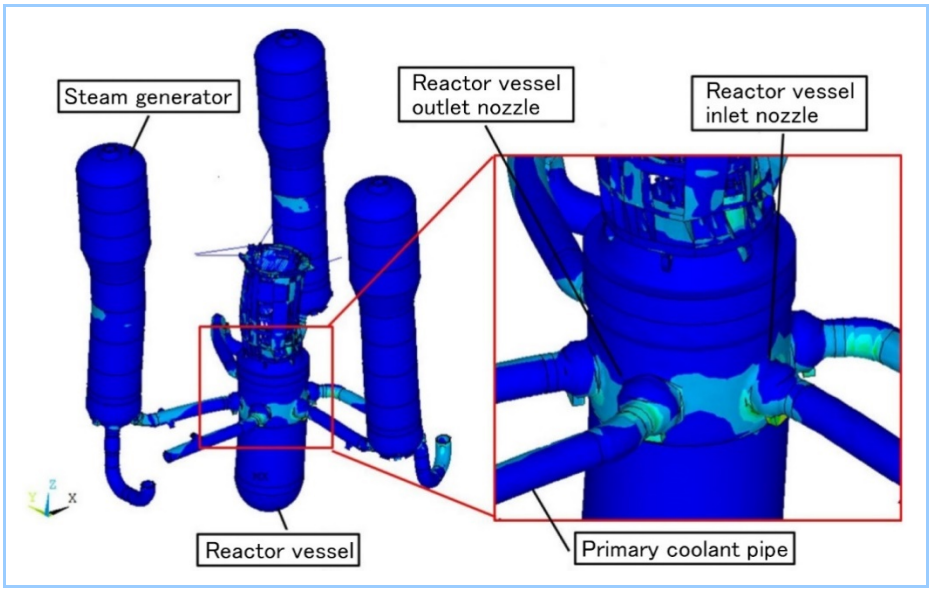

Figure 6 Example of analysis result

With dynamic analysis which is the highest calculation load and takes time for calculation, the calculation for a 10,000-step seismic wave using a model with the aforementioned mesh size necessary for stress analysis (about 3.3 million elements and about 5.5 million nodes) was completed in 3.5 hours. This result has brought that the structural analysis of the main components of a reactor coolant system can be calculated in a practical amount of time by using large-scale structural analysis technology.

4. Conclusion

For the main components of reactor coolant systems, a structural analysis process has been used in which the loads acting on the component are obtained by load analysis and the result is input for stress analysis for each part in order to verify the integrity against transient changes in the temperature and pressure of the reactor coolant and shaking at the time of an earthquake. This structural analysis process even conforms to the latest codes and has been widely used for structural

integrity evaluation of the main components of many nuclear power plants in Japan from the time of their construction to the present, contributing to ensuring reliability.

Against the background of the evolution of analysis methodology, we have developed a seamless structural analysis process that simulates the main components of a reactor coolant system with a single seamless FE analysis model and performs structural analysis using this model. Research on this seamless structural analysis process started in fiscal 2017. In this research, a modeling method for simulating the entire reactor coolant system with three-dimensional solid elements and a calculation method, computer specifications, and other factors that can be used for large-scale structural analysis have been examined. At the same time, an FE analysis model of the actual equipment was created and trial analysis was performed using the created model, and it was verified that the stress at the time of an earthquake, as well as the thermal stress, can be calculated. This eliminates the need to transfer loads from load analysis to stress analysis and simplifies the structural analysis process, and the iteration time accompanying design condition changes and design optimization can be shortened. As such, it is expected that development periods can be shortened. In addition, new applications, such as real-time monitoring of the component status based on the operation history (temperature, pressure, and so on), are also anticipated. In the future, in order to ensure the reliability of the new seamless structural analysis process, we will evaluate and verify the validity using the results of excitation tests, and so on conducted in the past.

References

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