An Earthquake-proof Analysis of a BWR Pressure Vessel using the Next-generation Computational Solid Mechanics Simulator

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We have been developing a next-generation computational solid mechanics simulation system based on the ADVENTURE, which is designed to be able to analyze a three dimensional Finite Element (FE) model with tens or hundreds of millions of Degrees Of Freedom (DOFs), to achieve the implementation of a virtual demonstration test on the Earth Simulator (ES). Main FE analysis process of the system was ported to the vector-parallel supercompuer. For a post process of a huge scale analysis, we developed visualization systems, which are able to work on PC clusters and the ES. As an application of our system, a Boiling Water Reactor (BWR) pressure vessel with 204 million DOFs mesh, whose model is provided in cooperation with industries, was performed. In this report, we present an outline of our visualization systems, and computational performances in solving and visualizing the implicit elastodynamic analysis of the BWR are shown. Consequently, it successfully solved one time step in about 2 minutes on 2,048 Arithmetic Processors (APs) and generated 100 image data in about 7.5 minutes on 32 APs.

Keywords: CAE system, parallel finite element analysis, balancing domain decomposition, off-line visualization, virtual demonstration test

1. Introduction

The ADVENTURE system [1] is an advanced general purpose computational mechanics system, and designed to be able to analyze a three dimensional FE (Finite Element) model of arbitrary shape with tens or hundreds of millions of DOFs (Degrees Of Freedom) mesh. Module based architecture of the system with standardized I/O format and libraries are developed and employed to attain flexibility, portability, extensibility and maintainability of the whole system. The one of main process modules for solid analysis, named ADVENTURE_Solid, is based on the hierarchical domain decomposition parallel algorithm [2] and employs the balancing domain decomposition [3, 4] as a solution technique for linearized equations.

In our project, the ADVENTURE system has been ported to the ES (Earth Simulator). Especially, ADVENTURE_Solid is vectorized well, and then it shows good performances of vectorization and parallelization. Using our system, as an example to realize the virtual demonstration test, a BWR (Boiling Water Reactor) pressure vessel consisting of many local features, whose DOFs amount to 204 million, is performed. The BWR is analyzed for an earthquake-proof design. For the post process of such a huge scale 3-D (three dimensional) structural analysis, we developed two visualization systems, i.e. one is for server-side off-line rendering and the other is for client-side interactive walkthrough.

In this report, at first, the BWR pressure vessel model is shown, next, an outline of our visualization systems is presented, and computational performances in solving and visualizing the implicit elastodynamic analysis of the BWR are shown.

2. The BWR pressure vessel model

As an example to realize the virtual demonstration test, this study subjects to an earthquake-proof analysis of the BWR pressure vessel of a nuclear power plant. The CAD (Computer Aided Design) data of the BWR is provided in cooperation with industries, and it is almost fully modeled with internal substructures, e.g. a core shroud, fuels, control rod guide tubes, and control rod drive mechanism housings. The tetrahedral solid element is used as the FE mesh, then detailed information of mesh is shown in Table 1 and mesh-es of some parts are shown in Figs. 1–2. In the structural analysis using quadratic mesh, the total DOFs of a problem amount to about 204 million.

The BWR consists of eleven materials, whose physical quantities are not uniform in value, e.g. the maximum ratio of Young's modulus is more than 400. For the elastodynamic analysis, the damping is taken into consideration. All material properties of the BWR are analyzed in comparison with results of the FE analysis in this study and the lumped mass-spring analysis in cooperators.

3. Visualization of a huge scale 3-D structural analysis

We developed two visualization systems for a huge scale 3-D structural analysis. One is for a server-side off-line rendering and the other is for a client-side interactive walk-through. Both of them support a scalar contour and deformation plots on the surface boundary of an analysis model. To use any of our visualization systems, a user has to follow these steps below.

1) Extract the surface patch from the FE mesh of a given analysis model. The surface patch is a collection of all the element faces only on the surface boundary of the mesh.
2) Decompose the surface patch into a subgroup. It can be automatically performed by a domain decomposer of the ADVENTURE, named ADVENTURE_Metis, with the mesh and other analysis condition information.
3) After a FE analysis, extract only calculated physical quantities on the surface patch from the analysis result files. Usually it reduces the file size about one tenth.

4a) To perform a server-side off-line visualization, run our off-line rendering system on the ES as a batch job or a command issued from TSS environment.

4b) To perform a client-side interactive visualization, transfer the domain-decomposed surface patch and its associated analysis result data through the Internet into a client PC terminal, and visualize them interactively using our walkthrough visualization system.

Table 1 The mesh information of the BWR pressure vessel model.

Number of elements (tetrahedron)	39,746,750
Number of nodes	67,910,224
(vertices/middles)	10,225,478 / 57,684,746
Total DOFs	203,730,672
Number of surface patches	15,424,402
Number of surface vertices	7,711,567
Edge length (Max./Min./Ave.)	115.65 / 1.45 / 28.77
Element height (Max./Min./Ave.)	72.60 / 0.31 / 15.15

The server-side off-line visualization system is mainly used if we need to check the status of the current analysis job as soon as possible. In case of using the client-side interactive system, we have to wait long until all the analysis result files are transferred into our client PC terminal in our laboratories through the Internet. To implement the off-line visualization system on the ES, it is vectorized and parallelized [5]. It renders surface contour and deformation plots of a 3-D structural analysis from user-specified set of viewing and visualization configurations. The main portion of the process is polygon rendering. We developed a vectorization algorithm for the polygon rendering. MPI-based parallelization is also performed using sort-last image superposition scheme.

The client-side walkthrough visualization system is used

Fig. 1 The FE mesh around of a shroud inside of the BWR pressure vessel.

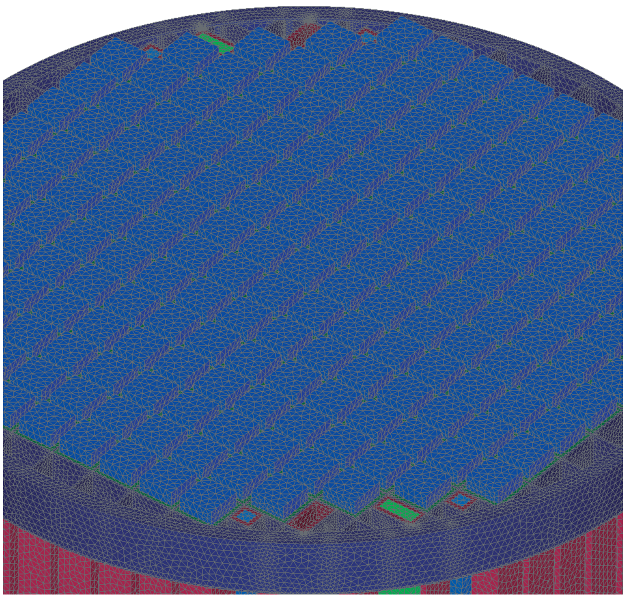

Fig. 2 The FE mesh upper side of fuels inside of the BWR pressure vessel.

for detailed investigation of the analysis results. If the 3-D structural model has a complicated geometry with many local features such as holes, nozzles, pipes and other support structures, immersive visualization of a visual data-mining style is beneficial. The system runs on a graphics cluster, which is a cluster of PCs with a graphics hardware device on each PC. A user can dive into the 3-D complicated structural model and walk around the model for deformation modes, stress concentrations and other interesting phenomena. To accelerate the rendering speed and maintain the interactive response while operating the system, we applied various kinds of walkthrough techniques, such as view frustum culling and occlusion culling, as well as fog and LOD (Level Of Detail) to visualization of a surface contour and deformation plot. To shrink the HDD read time in rendering an animation scene, the PC cluster is used to distribute the I/O workload.

4. Numerical Experiments

In this section, seismic response analysis of the BWR pressure vessel model with 204 million DOFs mesh is demonstrated. As boundary conditions for a transient analysis, earthquake-induced acceleration and load are applied to a bottom plane of its skirt portion, stabilizers, and control rod drive mechanism housing. The Rayleigh type damping is applied. The Newmark's beta method is used as a direct time integration scheme, and time increment is 0.01 seconds. As solver conditions for one time step, the convergence criteria of an iterative linear system solver is 1.0e-3.

Table 2 shows the computational performances of one batch job of dynamic analysis using 256 nodes, i.e. 2,048 APs (Arithmetic Processors). Our system is succeeded in solving 40 time steps of dynamic problem in about 45 minutes with about 18.9 % of peak FLOPS performance and about 97.9 % of vector operation performance.

Table 2 Computational performances of one batch job of elastodynamic analysis of the BWR pressure vessel with 204 million DOFs mesh on 2,048 APs.

Number of nodes (APs)	256 (2,048)
Batch job info	
Time (sec.)	2,727
GFLOPS	3,096
Memory (GByte)	3,934
Ave.V.Op.Ratio (%)	97.93
Solver info	
Number of time steps	40
Ave. iteration	156
Ave. Time (sec.)	67.5

Next, visualization examples are shown. As shown in Table 1, the BWR has about 15.4 million triangles on the surface boundary of the FE mesh. Using our server-side off-line visualization system, the visualization of 100 images of analysis results data is successfully performed in about 7.5 minutes using 32 APs. Figs. 3–5 show a deformation and equivalent stress contour plots of elastodynamic analysis results of the BWR pressure vessel model.

For the future work, as an earthquake-proof analysis, the seismic response problem of the BWR pressure vessel model is continuously analyzed.

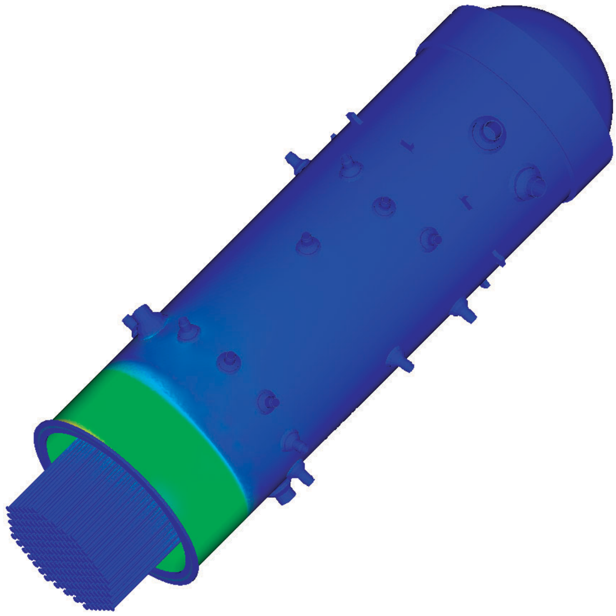

Fig. 3 Deformation and equivalent stress contour plots of the BWR pressure vessel model.

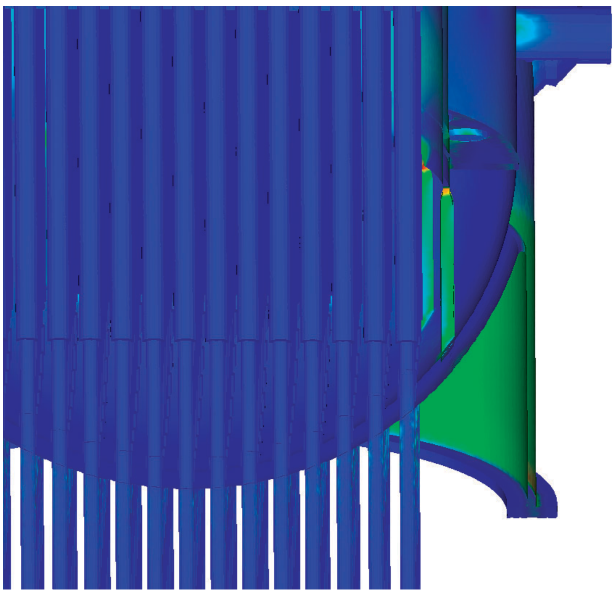

Fig. 4 Deformation and equivalent stress contour plots of the cross section around a skirt portion of the BWR pressure vessel model.

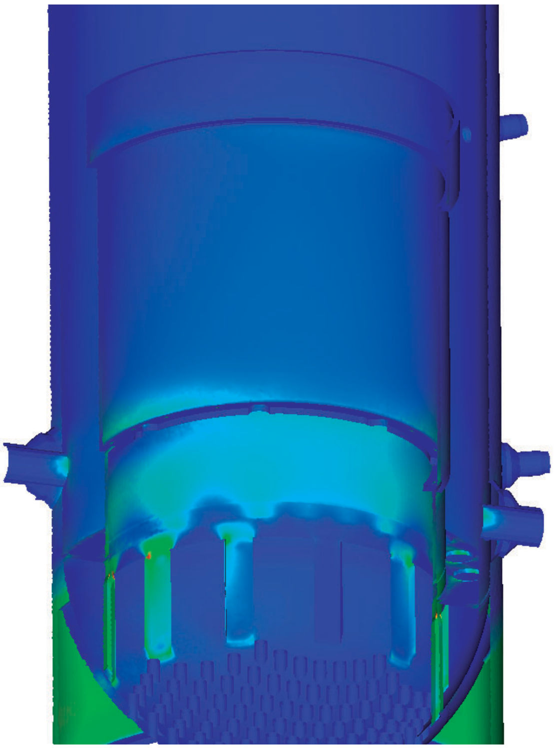

Fig. 5 Deformation and equivalent stress contour plots of the cross section of the BWR pressure vessel model excluding some structures, such as a fuel and a control rod driving mechanism.

Acknowledgements

The authors would like to thank Tokyo Electric Power Co. and Hitachi Ltd. for providing a model data of the BWR reactor pressure vessel. This work is performed as a part of the ADVENTURE project and the authors also would like to thank all the members of the ADVENTURE project.

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次世代計算固体力学シミュレータを用いた
BWR型圧力容器の耐震性能解析

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本プロジェクトでは、1千万から1億自由度級の大規模メッシュを用いた人工物や自然物の丸ごと詳細解析を可能とする汎用計算力学システムADVENTUREを地球シミュレータに移植し、バーチャル実証試験を実践するための次世代計算固体力学シミュレータの開発を行っている。ADVENTUREの主要並列ソルバの1つである構造解析モジュールADVENTURE_Solidでは、階層型領域分割法に基づく並列負荷分散と高速安定な線形ソルバであるBDD法を採用し、それらのアルゴリズムを地球シミュレータ向けに移植することで高いベクトル性能並びに並列性能が得られている。本システムを用いて、バーチャル実証試験を実現するために、産業界から提供を受けたBWR型原子炉圧力容器問題の解析を進めてきている。これまで、約2億自由度規模の非構造メッシュによるモデル化を行い、陰的動弾性問題の1時間ステップを約6分で解析に成功してきた。また、解析後処理として、数億自由度規模問題解析結果の3次元可視化を実現するために、計算サーバ上におけるオフライン可視化技術、並びにクライアントPC上におけるウォークスルー可視化技術の開発を行った。本報告書では、バーチャル実証試験の実例として、BWR型原子炉圧力容器の約2億自由度規模モデルを用いた耐震性能解析を行い、陰的動弾性解析の実行例、並びに地球シミュレータの演算プロセッサを用いたオフライン可視化例について、そのパフォーマンスを示す。結果として、BWR型原子炉圧力容器モデルに対して、地球シミュレータ2,048プロセッサを用いて陰的動弾性解析40時間ステップを約45分で成功し、地球シミュレータ32プロセッサを用いて可視化結果として100枚の画像ファイルの生成を約7.5分で成功した。今後継続して解析を進めることで、バーチャル実証試験の実現を目指す。

キーワード：CAE system, parallel finite element analysis, balancing domain decomposition, off-line visualization, virtual demonstration test