A Virtual Demonstration Test of a BWR Pressure Vessel using the Next-generation Computational Solid Mechanics Simulator

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We have been developing an advanced general purpose computational mechanics system, named ADVENTURE, which is designed to be able to analyze a three dimensional finite element model of arbitrary shape with a 10-100 million degrees of freedom (DOF) 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 and employs the balancing domain decomposition as a solution technique for linearized equations. The ADVENTURE_Solid has been successfully implemented on the Earth Simulator consisting of 256 nodes, i.e. 2,048 arithmetic processors (APs), then applied for an elastostatic analysis of a historical building pantheon model of 140 million DOF mesh with 3.88 TFLOPS, which is 24.26% of the peak performance, and an elastodynamic analysis of a nuclear pressure vessel model of 100 million DOF mesh. In this report, as an application of the virtual demonstration test, a boiling water reactor (BWR) pressure vessel, which is modeled with 204 million DOF mesh, was analyzed. Consequently, it succeeds in solving one unsteady step of implicit elastodynamic problem in about 6.4 minutes on the 2,048 APs.

Keywords: CAE System, Parallel Finite Element Analysis, Hierarchical Domain Decomposition Method, Balancing Domain Decomposition, Virtual Demonstration Test

1. ADVENTURE system

The ADVENTURE system[1)] has employed a hierarchical domain decomposition based massively parallel algorithm as one of the major solution algorithms in order to efficiently handle a huge scale finite element model with 10-100 million degrees of freedom (DOF). We have been developing several kinds of main processes for implicit elastic-plastic analysis, rigid-plastic analysis, impact-contact analysis, thermal conductive analysis, thermal-fluid analysis and electromagnetic analysis. Especially, the implicit elastic-plastic analysis module, named ADVENTURE_Solid, is improved to apply to massively parallel processors (MPP) with over 1,000 processors and huge scale problems with over 100 million DOF. One of the key technologies implemented in the ADVENTURE_Solid is the hierarchical domain decomposition method[2, 3)] (HDDM), whose force equivalence and continuity conditions among subdomains are satisfied through iterative methods such as the preconditioned conjugate gradient method. As a preconditioner, the balancing domain decomposition[4, 5)] (BDD) is employed. Moreover, as an improving for large scale analysis on MPP, an incomplete balancing domain decomposition method, named IBDD-DIAG method, has been developed[6)] and then successfully applied for an elastostatic analysis of a nuclear pressure vessel model with 100 million DOF mesh on the Earth Simulator consisting of 2,048 arithmetic processors (APs)[7)]. Furthermore, we have succeeded in solving an implicit dynamic elastic analysis of a nuclear pressure vessel model with 100 million DOF mesh, and a static elastic analysis of a historical building pantheon model with 140 million DOF mesh[8)].

2. BWR pressure vessel model with 204 million DOF mesh

As an example to realize the virtual demonstration test, this study subjects to the seismic response analysis of the boiling water reactor (BWR) pressure vessel of the nuclear power plant. The BWR pressure vessel is almost fully modeled with internal substructures, for example a core shroud, a fuel, a control rod guide tube, and a control rod drive mechanism housing. Fig. 1 shows external appearance of the BWR pressure vessel model, and Fig. 2 does a cross section. Each color in Figs.1-2 means computer aided design (CAD) data of parts. The finite element mesh is used the tetrahedral solid element, then detailed information of mesh is shown in Table 1 and meshes of some parts are shown in Figs. 3-4. In the structural analysis using quadratic mesh, the total degrees of freedom of a problem amount to about 204 million. Moreover, as shown in Table 1, the mesh has irregularity and there is a large difference between a fine part and a coarse part. As the result, the BWR pressure vessel model seems to be ill-conditioned problem, which suffers from a bad convergence property. For solving such problems, a special method with a high convergence rate is indispensable, IBDD-DIAG method in ADVENTURE_Solid is so effective[7].

3. Numerical Experiments

In this section, seismic response analysis of the BWR pressure vessel model is demonstrated. As boundary conditions for a quasi static analysis, a bottom plane of its skirt portion is fixed, and body force by its own weight is taken to horizontal direction. On the other hand, as boundary conditions for a dynamic analysis, earthquake-induced accelera-

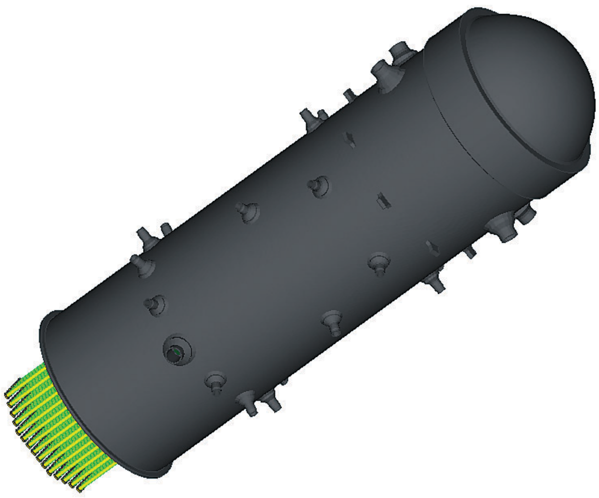

Fig. 1 The external appearance of the BWR pressure vessel model.

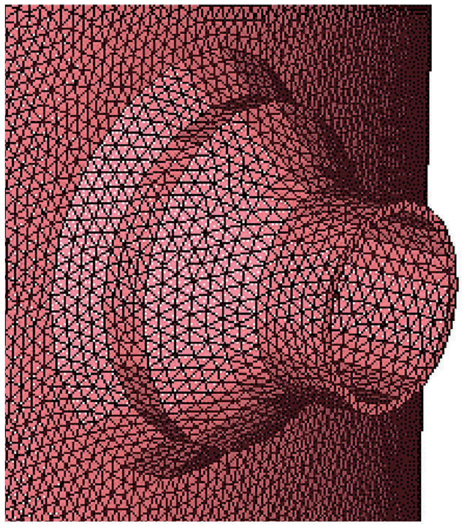

Fig. 3 The mesh around of a nozzle.

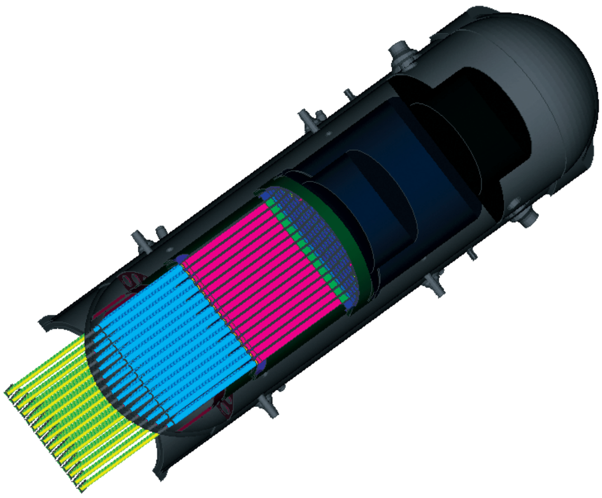

Fig. 2 The cross section of the BWR pressure vessel model.

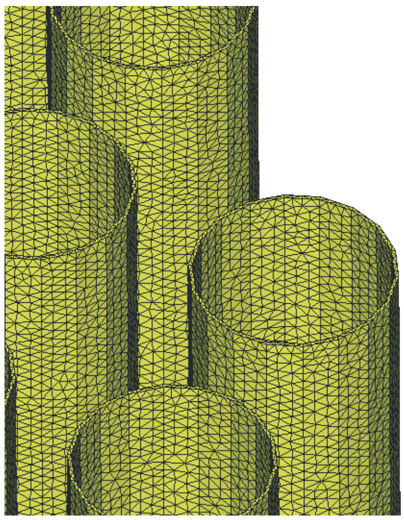

Fig. 4 The mesh around of a control rod guide tube.

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

Elements	Nodes		Edge length			Element height		
	Vertex	Middle	Maximum	Minimum	Average	Maximum	Minimum	Average
39,746,750	10,225,478	57,684,746	115.647	1.454	28.772	72.600	0.310	15.152

Table 2 Computational performances of the BWR pressure vessel model with single material properties using 1,024 APs.

Analysis type	Iterations	Time [sec.]	Memory [MB]	TFLOPS	V.OP.RATIO [%]
Static*	4,650	7,976	1,923	2.21	98.31
Dynamic**	391	773	1,945	2.06	98.44

*Static elastic analysis
**Implicit dynamic elastic analysis

Table 3 Computational performances of one unsteady step of elastodynamic analysis of the BWR pressure vessel model with multi-material properties.

# APs	Iterations	Time [sec.]	Memory [GB]	TFLOPS	V.OP.RATIO [%]
2,048	318	383	3,202	3.47	98.09

tion and load are applied to a bottom plane of its skirt portion, stabilizers, and control rod drive mechanism housing. Besides, the damping is not considered. At first analysis, the model is regarded as single material. Table 2 shows the computational performances of static or dynamic elastic analysis on the 1,024 APs. Fig. 5 plots convergence histories of relative residual norm by IBDD-DIAG method. Our system is succeeded in solving static problem in about 133 minutes and dynamic problem in about 13 minutes, which are with over 25% of peak FLOPS performance and over 98.3% of vector operation performance. In general, the dynamic problem is easy to solve owing to mass term compared with the static problem. As the result, the present system is possible to analyze the BWR pressure vessel model with very complex shape and about 204 million DOF mesh.

Next, for more realistic demonstration, the model is regarded as multi-materials. The number of materials is eleven, and the maximum ratio of Young's modulus is over 400 times. Table 3 shows the computational performances of one unsteady step of dynamic elastic analysis on the 2,048 APs. Fig. 6 plots convergence history of relative residual norm by IBDD-DIAG method. Our system is successfully to analyze in about 6.4 minutes. Moreover, since IBDD-DIAG method shows efficiently performance for multi-material problems[9], the multi-material problem is converged with 318 iterations almost same as the single material problem. Consequently, the present system is possible to realize the virtual demonstration test for the seismic response problem of BWR pressure vessel.

For the future work, the seismic response problem of the BWR pressure vessel model is continuously analyzed.

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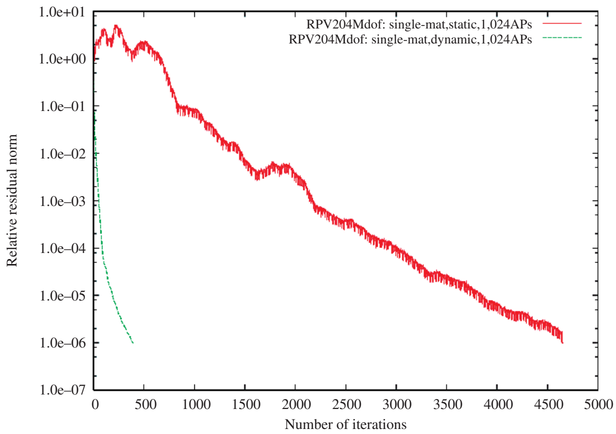

Fig. 5 Comparison with static and dynamic analysis of the BWR pressure vessel model with single material properties using 1,024 APs.

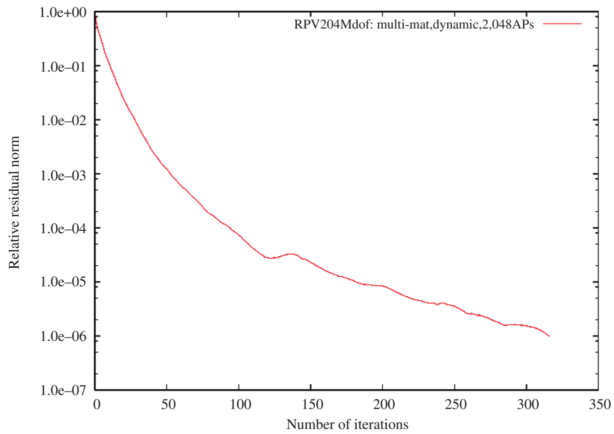

Fig. 6 Convergence history of residual norm of the BWR pressure vessel model with multi material properties using 2,048 APs.

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次世代固体力学シミュレータによるBWR型圧力容器のバーチャル実証試験

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既に多くの超並列計算機やPCクラスタ上において実績を示している、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導入することで、数億自由度規模の有限要素メッシュを用いた非定常非線形解析を実用時間で可能とする技術の確立を目的としている。本システムでは、超大規模解析における優れた実行性能、拡張性・保守性・開放性に重点を置き、モジュール型システムアーキテクチャを採用することで、各モジュールが独立したプログラムとして単独でも、また標準化されたI/Oを介して他のモジュールと協調しても稼動することを実現している。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を行い、さらに高速安定な線形ソルバとしてBDD法を採用している。これまで、地球シミュレータ256ノード(2,048プロセッサ)上において、1.4億自由度規模の非構造メッシュを用いた古代建築物パンテオンモデルの静弾性解析に成功し、実行性能24.26% (3.88TFLOPS)を示し、また1億自由度規模の原子炉圧力容器モデルの陰的動弾性解析に成功してきた。本報告書では、バーチャル実証試験の実例として、沸騰水型原子炉圧力容器を約2億自由度規模メッシュを用いてモデル化を行い、解析を行った。結果として、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1時間ステップを約6.4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が実現される。

キーワード：CAE System, Parallel Finite Element Analysis, Hierarchical Domain Decomposition Method, Balancing Domain Decomposition, Virtual Demonstration Test