Development of the Next-generation Computational Solid Mechanics Simulator for a Virtual Demonstration Test

Project Representative
Ryuji SHIOYA Faculty of Engineering, Kyushu University

Authors
Ryuji SHIOYA Faculty of Engineering, Kyushu University
Masao OGINO Faculty of Engineering, Kyushu University
Hiroshi KAWAI Faculty of Science and Technology, Keio University

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), and applied for an elastostatic analysis of a nuclear pressure vessel model of 100 million DOF mesh with 5.08 TFLOPS, which is 31.75 % of the peak performance. In this report, the parallel performance of the solid analysis module, which is programmed by the flat MPI parallelization, is investigated. Furthermore, the solid module is demonstrated an implicit dynamic elastic analysis of a model of 100 million DOF mesh on the 256 nodes (2,048 APs), and succeeded in solving 5 unsteady steps in about 2.4 minutes. Besides, it succeeds in solving an elastostatic problem of a historical building pantheon model of 140 million DOF mesh in about 10 minutes on the 256 nodes (2,048 APs).

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

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 successfully to analyze a simplified pressure vessel model with 100 million DOF mesh[2]. One of the key technologies implemented in the ADVENTURE_Solid is the hierarchical domain decomposition method[3] (HDDM), whose force equivalence and continuity conditions among subdomains are satisfied through iterative methods such as the preconditioned conjugate gradient method. Especially in the ADVENTURE_Solid, the balancing domain decomposition[4, 5] (BDD) is employed as a preconditioner. 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].

2. Parallel performance of the ADVENTURE_Solid

For getting high performance of parallel efficiency on the Earth Simulator, it is expected to be programmed by the hybrid parallelization. Considering to maintain the portability of the ADVENTURE system and difficulty in programming of the BDD with hybrid style, however, the ADVENTURE_Solid is programmed by flat MPI parallelization. This section describes parallel performances of the IBDD-DIAG method. As shown in Fig. 1, an elastostatic stress analysis for a precise model of an advanced boiling water reactor (ABWR) vessel with a 35 million DOF unstructured

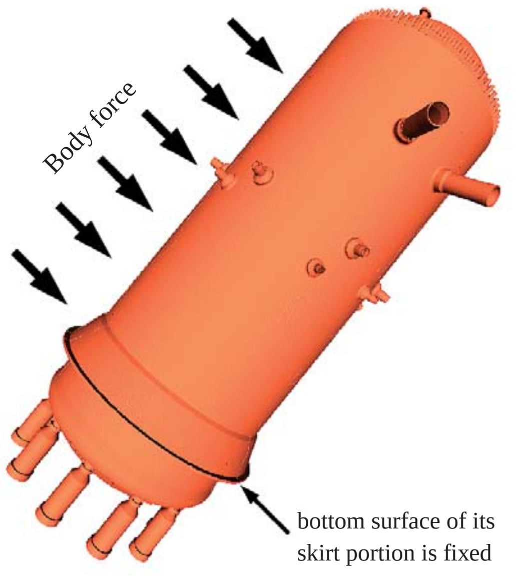

Fig. 1 The analysis conditions for elastostatic analysis of the ABWR model

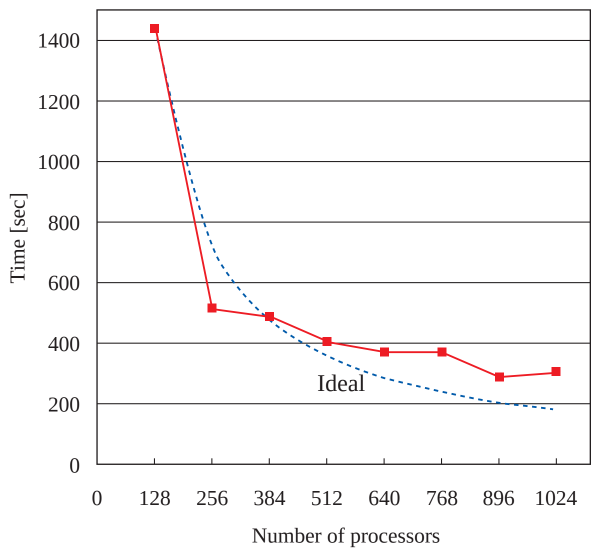

Fig. 2 Scalability in total computation time of elastostatic analysis of the ABWR model on the Earth Simulator

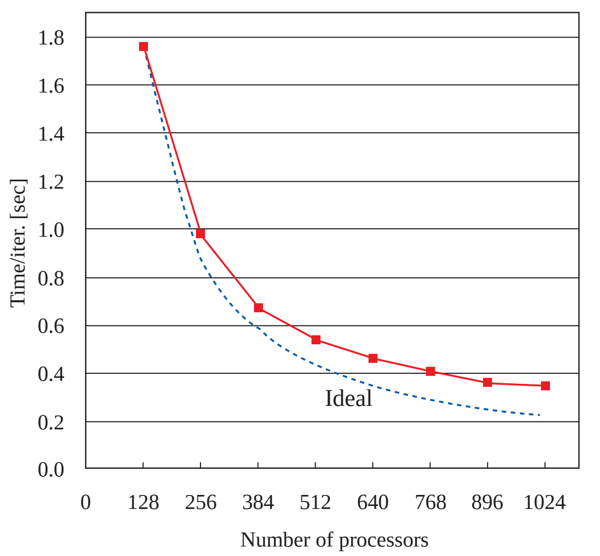

Fig. 3 Scalability in total computation time per iteration of elastostatic analysis of the ABWR model on the Earth Simulator

mesh is performed. We evaluated the practicality of parallel computing, varying the number of processors employed. The results are shown in Fig. 2 and Fig. 3. As shown in Fig. 2, parallel efficiency over the whole calculation using 1,024 APs was estimated as about 53%, referring the value for using 128 APs. The system showed good performances of parallel efficiency, while these performances showed a little unstableness compared as an ideal one. This is attributed due to the fact that convergences feature of the IBDD-DIAG method of the ADVENTURE_Solid depends on the number of processors employed. For instance, the 128 PEs case and 1,024 PEs case require 739 and 830 iteration counts, respectively. On the other hand, parallel efficiency for one iterative calculation showed a stable performance compared as an ideal one and was estimated as about 58% from Fig. 3. It is judged from such high parallel efficiency that the present system is sufficiently parallelized.

3. Seismic response analysis of a pressure vessel model 100 million DOF mesh

This system has been applied for a seismic response analysis of the ABWR model with 35 million DOF mesh (Fig. 1), and succeeded in solving 300 unsteady steps in about 4.3 hours using 1,024 APs. In this section, the system is demonstrated for a seismic response analysis of a simplified pressure vessel model with 100 million DOF mesh on the 2,048 APs. Fig. 4 illustrates analysis conditions. As boundary conditions, a bottom plane of its skirt portion is fixed. As a seismic load, the acceleration history of 1,940 Elcentro earthquake ground motion is taken to a body force direction in Fig. 4, whose data is provided by the Building Center of Japan8). Table 1 shows the calculation performances. This

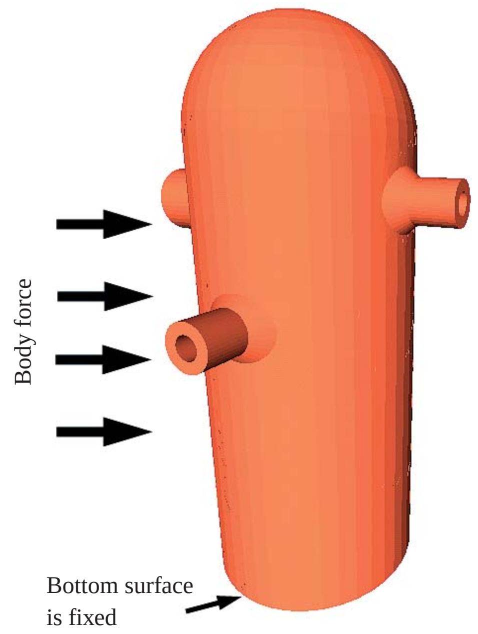

Fig. 4 The analysis conditions for dynamic elastic analysis of a pressure vessel model with 100 million DOF

Table 1 Calculation performances of dynamic elastic analysis of a pressure vessel model with 100 million DOF

Time steps (elapsed time)	Time (sec)	TFLOPS	(to peak %)	V.OP. RATIO (%)
1-5 (0.1sec)	141.7	3.64	(22.8)	97.9

problem is easy to solve owing to simple shape compared with the ABWR model, but, on the other hand, the performance of computational time is expected to be practical use. Consequently, the present system is possible to analyze of seismic response problem with 100 million DOF mesh.

4. Elastostatic analysis of pantheon model with 140 million DOF mesh

This system is applied to a historical building pantheon model with 140 million DOF mesh on the 2,048 APs. Fig. 5 illustrates a tetrahedral mesh of a pantheon model, furthermore, each finite element of a model is subdivided into 64 elements. As the result, a pantheon is modeled with 140 million DOF mesh. As boundary conditions, a bottom plane is fixed and own weight is taken as a body force. Fig. 6 and Fig. 7 shows the calculated stress distribution. Table 2 shows the calculation performances with 2,048 APs. The present system with the IBDD-DIAG method is successfully to analyze with good performances in FLOPS and vectorization, which are 24.26% of peak performance and 98.6% of vector operation, respectively. As the result, it makes little difference of performances between the analysis case of 100 million DOF model and the analysis case of 140 million DOF model. Consequently, the present system with the IBDD-DIAG method gives effective solution for huge scale analysis such as over 100 million DOF.

References

1) http://adventure.q.t.u-tokyo.ac.jp/
2) G. Yagawa and R. Shioya, "Parallel finite elements on a massively parallel computer with domain decomposition", Computing Systems in Engineering, 4, pp.495-503, 1994.
3) R. Shioya and G. Yagawa, "Parallel finite elements of ten-million DOFs based on domain decomposition method", WCCM IV, Computational Mechanics -New Trends and Applications-VII, 11, pp.1-12, Buenos Aires, Argentina, June 1998.
4) J. Mandel, "Balancing domain decomposition", Communications on Numerical Methods in Engineering, 9, pp.233-241, 1993.

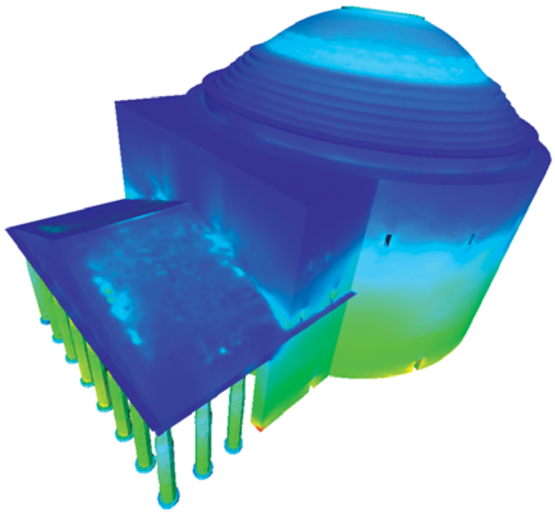

Fig. 6 Stress distribution of a pantheon model

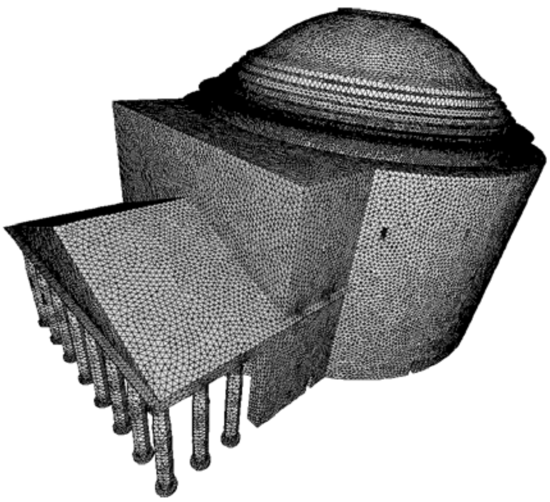

Fig. 5 A historical building pantheon model

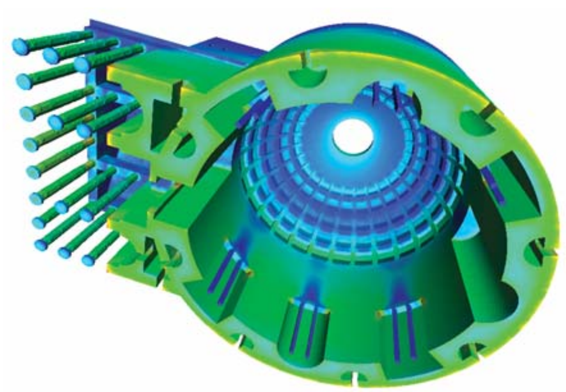

Fig. 7 Stress distribution of a pantheon model (bottom)

Table 2 Calculation performances of elastostatic analysis of a pantheon model with 100 million DOF

# APs	Iterations	Time (sec)	Memory (TB)	TFLOPS	(to peak %)	V.OP. RATIO (%)
2,048	373	577.0	3.05	3.88	(24.26)	98.6

5) R. Shioya, M. Ogino, H. Kanayama, and D. Tagami, "Large scale finite element analysis with a balancing domain decomposition method", Key Engineering Materials, Vols.243-244, pp.21-26, 2003.
6) M.Ogino, R.Shioya, H.Kanayama, and A.M.M. Mukaddes, "Incomplete balancing domain decomposition for large scale thermal-solid coupling problems", Proceedings CD-ROM of the WCCM VI in conjunction with APCOM'04, M-64_OginoM.pdf, pp.1-8, Beijing, China, Sept. 2004.
7) M.Ogino, R.Shioya, H.Kawai, and S.Yoshimura, "Seismic response analysis of nuclear pressure vessel model with ADVENTRUE system on the Earth Simulator", Journal of The Earth Simulator, Vol.2, pp.41-54, March 2005.
8) http://www.bcj.or.jp/

次世代固体力学のためのバーチャル実証試験

プロジェクト責任者
塩谷　隆二　　九州大学大学院 工学研究院

著者
塩谷　隆二　　九州大学大学院 工学研究院
荻野　正雄　　九州大学大学院 工学研究院
河合　浩志　　慶応義塾大学 理工学部

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、1億自由度規模の非構造メッシュを用いた簡易原子炉圧力容器モデルの静応力解析に成功し、実行性能31.75%(5.08 TFLOPS)を示してきた。本報告書では、MPIフラット型並列で実装されているADVENTURE_Solidの地球シミュレータ上における並列効率について調査を行った。また、1億自由度規模モデルの陰解法に基づく動的応力解析(5ステップ)を約2.4分で成功し、大規模自由度メッシュを用いた非定常解析の可能性を示した。さらに、1億4千万自由度規模メッシュを用いた古代建築物パンテオンモデルの静応力解析を行い、256ノード(2,048プロセッサ)上において約10分で成功した。

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