A Seismic Response Analysis of the BWR Pressure Vessel Model 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, which is called ADVENTURE_Solid and based on the hierarchical domain decomposition method and an IBDD-DIAG method, was ported to the vector-parallel supercompuer. Moreover, for a post process of a huge scale analysis, we developed a parallel off-line visualization system, which is able to implement on PC clusters and the ES. As an implementation of a virtual demonstration test using our system, a Boiling Water Reactor (BWR) pressure vessel of a nuclear power plant, whose model is provided in cooperation with industries, has been analyzed. The total DOFs of the BWR model amount about 204 million. In this report, we present an outline of our parallel off-line visualization system, and show computational performances of a seismic response analysis of the BWR model. Consequently, it successfully solved 1,000 time steps analysis of the BWR model with 204 million DOFs in about 26 hours on 2,048 arithmetic processors.

Keywords: CAE system, seismic response 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 an IBDD-DIAG method [3] as a solution technique for linear 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 [4]. Using our system, as an example to realize the virtual demonstration test, a BWR (Boiling Water Reactor) pressure vessel model consisting of many local features, whose DOFs amount to 204 million, is performed. The BWR model is analyzed for an earthquake-proof design. For the post process of such a huge scale 3-D (three dimensional) structural analysis, we developed a parallel off-line visualization system, which is a pure software-based polygon renderer to implement on the computational server.

In this report, the BWR model is shown, and then an outline of a parallel off-line visualization system is presented. Next, as an implementation of the virtual demonstration test, a seismic response analysis of the BWR model is demonstrated.

2. The BWR pressure vessel model

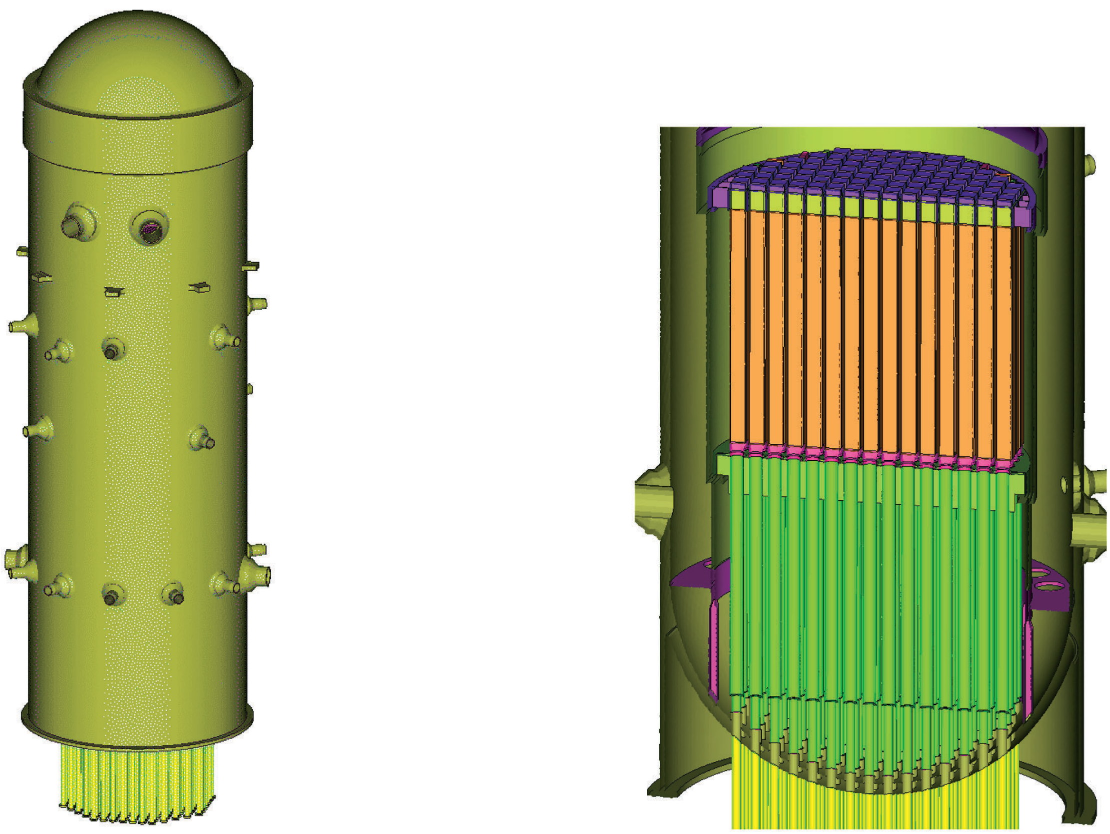
As an example to realize the virtual demonstration test, this study subjects to a seismic response analysis of the BWR pressure vessel of a nuclear power plant. The CAD (Computer Aided Design) data of the BWR is provided in cooperation with industries, and it is almost fully modeled with internal substructures,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

3. Parallel off-line visualization of a huge scale 3-D structural analysis

Using the ADVENTURE system on the ES, huge scale problems such the BWR pressure vessel model with 204 million DOFs can be solved. However, such huge scale analysis task produces gigantic analysis result data files, which may occupy a disk space size of terabytes order. Because of this size issue, it is difficult and time consuming for the simulation user to move those analysis result data files back to own workstation for visualization purposes. Actually, the size of analysis result data files of the BWR model, which includes a deformation vector and an equivalent stress defined on the node, become about 2.3 G bytes, therefore the total data file size of 1,000 time steps by a seismic response analysis assumedly amount 2.3 T bytes. To visualize such a huge scale 3-D structural analysis result data, we developed a parallel off-line visualization system of the polygon renderer [5, 6]. The keyword 'off-line rendering' that often used in the computer graphics field means non-interactive image generation.

Main characteristics of our off-line polygon rendering system are as follows.

a) perform on the computational server remotely
b) generate a final image data directly on the computational server
c) supports to render triangle polygons only
d) supports basically visualization functionalities, e.g. pan, zoom, rotate, lighting, shading, smooth/band contours,



(a) Overview (b) Cross section around a core shroud and fuels

Fig. 1 The BWR pressure vessel model with 204 million DOFs.

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

Number of elements (tetrahedron)	39,746,750
Number of nodes	67,910,224
Total DOFs	203,730,672
Number of surface patches	15,424,402
Number of surface vertices	7,711,567

and clipping planes

e) vectorize visualization procedures in triangle-wise or fragment-wise using the look-up table

Especially, a vectorization scheme using the look-up table is one of our originality. In the visualization procedures, a triangle defined in the world coordinate system is transformed into the screen coordinate system. Further, we transform the triangle in the screen coordinate system into a triangle coordinate system, shown in Fig. 2. With the triangle coordinate system, the triangle is redefined by two vertices v1 and v2, which are defined integer values tx1, ty1, tx2, and ty2. Next, we perform the scan conversion of a triangle in the triangle coordinate system, and then the triangle is decomposed into multiple fragments, shown in Fig. 3. Here, these fragments are the pixels composing the triangle. Usually, only a portion of the fragments, which pass depth test using a depth buffer, is reflected into the corresponding pixels in the screen image. After all, some visualization procedures are vectorized in fragment-wise when the fill patters are prepared for all the possible combinations of four integer values (tx1, ty1, tx2, ty2). It is called a 'look-up table' to store fill patters of triangles in a triangle coordinate system.

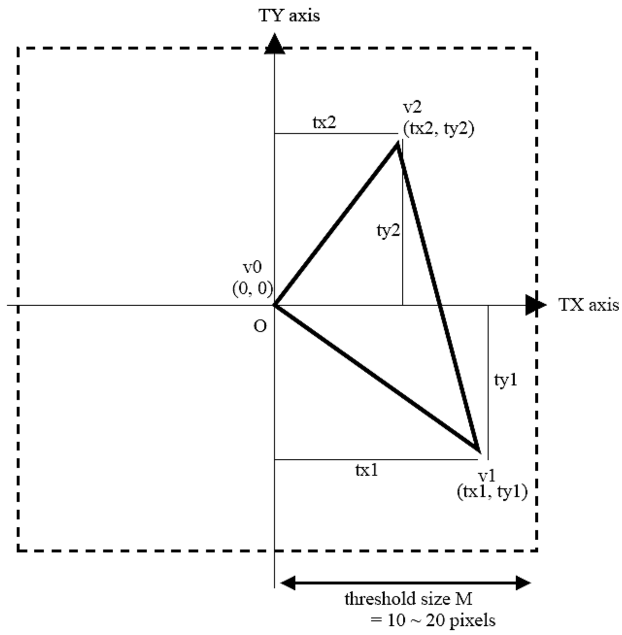


Fig. 2 Triangle coordinate system, which is a special system for assigning a triangle defined in the screen space.

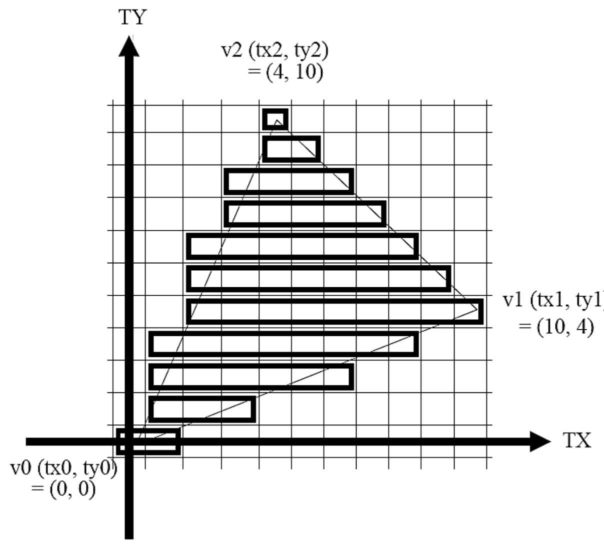


Fig. 3 Scan conversion of a triangle using a look-up table.

4. Numerical Experiments

In this section, a 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 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. The Rayleigh type damping is applied. Here, damping coefficients of the Rayleigh type are assumed using the eigenvalue data by the lumped mass-damping analysis in cooperators. The Newmark's beta method is used as a direct time integration scheme, and time increment width is 0.01 seconds. As solver conditions for one time step, the convergence criteria of an iterative linear system solver is 1.0e-3. This analysis is performed on 256 nodes, i.e. 2,048 APs (Arithmetic Processors).

Table 2 shows the computational performances in all. The 1,000 time steps problem was performed by 25 times batch job, and then successfully analyzed in about 26 hours. The computational performances of one batch job and one time step are shown in Table 3 and Table 4, respectively. Our system is succeeded in solving 40 time steps of the elastodynamic problem in about 45 minutes with about 18.9% of peak FLOPS performance and about 97.9% of vector operation performance.

Here, an executed batch job is finished in 45 minutes, however, the transmission of the analysis result data files of 92 G bytes from the ESC to our laboratory is expected to require 13 hours or more. Thus, an effective visualization system performed on the ES is indispensable. Using our parallel off-line visualization system, the visualization of 100 images of an analysis result data is successfully performed in about 7.5 minutes using 32 APs. Figure 4 shows the deformation configuration and the equivalent stress contour plots of the BWR model in one step of the seismic response analysis.

Table 2 Computation performances of a seismic response analysis of the BWR pressure vessel with 204 million DOFs mesh on 2,048 APs. In this unsteady analysis, the total number of time steps amount 1,000.

Number of executed batch jobs	25
Amount of analysis time (hr.)	26
Amount of output data (TB)	2.3

Table 3 Computation performances of one executed batch job in the seismic response analysis.

Number of time steps	40
Time (sec.)	2,727
GFLOPS	3,096
Memory (GB)	3,934
Ave. V.Op.Ratio (%)	97.93
Amount of output data (GB)	92

Table 4 Average computation performances of a linear solver for one time step of the seismic response analysis.

Number of iterations	156
Time (sec.)	67.5

5. Conclusions

A seismic response analysis of the BWR pressure vessel model with 204 million DOFs is performed on the ES consisting of 2,048 APs, and then successfully solved in about 26 hours. For the future work, to realize the virtual demonstration test, analysis conditions of the BWR model, e.g. material properties and boundary conditions, are improved using the analysis result data of this case, and then the seismic response problem is continuously analyzed.

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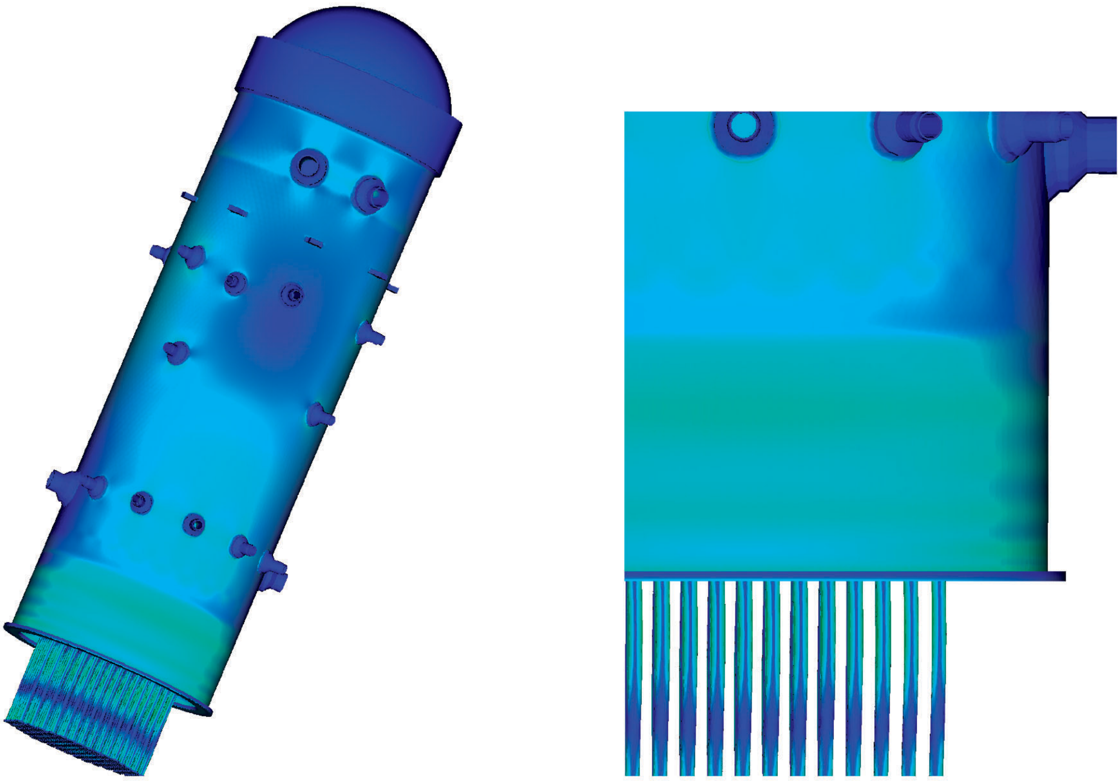

(a) Overview (b) Around a skirt portion

Fig. 4 Deformation and equivalent stress contour plots of the BWR pressure vessel model in one step of the seismic response analysis.

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次世代計算固体力学シミュレータを用いたBWR原子炉圧力容器の地震応答解析

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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IBDD-DIAG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及び並列性能が得られている。

本システムを用いたバーチャル実証試験として、産業界から提供を受けたBWR型原子炉圧力容器の地震応答解析を進めている。圧力容器に加えてコアシュラウドや燃料集合体、制御棒駆動機構ハウジングなどの内部構造物まで詳細にモデル化を行い、非構造メッシュを用いたモデル総自由度数は約2億となった。各構成部品の材料定数は、有限要素法による部品解析結果や、多質点系モデルによる全体解析結果などを活用することで推定した。地球シミュレータ256ノード(2,048プロセッサ)を用いることで、2億自由度規模BWR圧力容器モデルに対して設計用地震動を与えた陰的動弾性問題の1時間ステップを約67.5秒で解析に成功した。また、そのような大規模自由度モデルの3次元可視化を実現するために、ベクトル機向けの参照テーブルを用いた高速並列オフライン可視化技術の開発を合わせて行った。地球シミュレータ4ノード(32プロセッサ)を用いることで、BWRモデルの移動、回転、及び拡大縮小などを行った100枚の画像生成に約7.5分で成功した。本報告書では、2億自由度規模BWR型原子炉圧力容器モデルを用いた地震応答解析を継続して実施した結果を示す。結果として、地球シミュレータ2,048プロセッサを用いることで、継続時間10秒間つまり陰的動弾性解析1,000時間ステップを約26時間で成功した。今後は解析結果を分析し、より現実的な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