Development of the Next-generation Computational Fracture Mechanics Simulator for Constructing Safe and Sustainable Society

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The authors have been developing a crack propagation analysis system that can deal with arbitrary shaped cracks in three-dimensional solids. The system is consisting of mesh generation software, a large-scale finite element analysis program and a fracture mechanics module. To evaluate the stress intensity factors, Virtual Crack Closure-Integral Method (VCCM) for the quadratic tetrahedral finite element is adopted and is included in the fracture mechanics module. The rate and direction of crack propagation are predicted by using appropriate formulae based on the stress intensity factors. Combined with ADVENTURE system, a large-scale fully automatic fracture analysis can be performed on Earth Simulator 2.

Keywords: fracture mechanics, crack propagation analysis, finite element method, domain decomposition method, aging structure

1. Introduction

For the realization of sustainable society in the 21 century, structural integrity assessments for gradually aging social infrastructures are increasingly gaining their importance. Fracture mechanics simulation will be one of the key numerical methodologies for the structural integrity assessments. However, three-dimensional crack analyses for realistic highly complex structures have not widely been used so far, because of many obstacles such as the lack of computational power. The authors have been developing an open-source CAE system, ADVENTURE [1]. It is based on the hierarchical domain decomposition method (HDDM) with the balancing domain decomposition (BDD) pre-conditioner [2] [3]. A general-purpose structural analysis solver, ADVENTURE Solid, is one of the solver modules of the ADVENTURE system. On the other hand, the authors have been developing a fracture mechanics analysis system that can deal with arbitrary shaped cracks in three-dimensional structures. The system consists of mesh generation software, a finite element analysis program and a fracture mechanics module. In our system, a Virtual Crack Closure-Integral Method (VCCM) for the quadratic tetrahedral finite elements [4] is adopted to evaluate the stress intensity factors. This system can perform the three-dimensional fracture analyses. Fatigue and SCC (stress corrosion cracking) crack propagation analyses with more than one cracks of arbitrary complicated shapes and orientations. The rate and direction of crack propagation are predicted by using appropriate formulae based on the stress intensity factors.

In this year, we developed a fracture mechanics analysis system with ADVENTURE and VCCM for large scale and complex-shape crack models with over 100 million DOFs tetrahedral mesh on Earth Simulator2.

2. Overview of VCCM

VCCM for the quadratic tetrahedral elements that is proposed by Okada et al. [4] is adopted for the computations of the stress intensity factors. In this section, a very brief summary of the VCCM is presented. The readers are referred to Okada et al. [4] for the full details of the VCCM. In the VCCM, the energy release rate is expressed by energy which is required to virtually close a finite element face which is adjacent to the crack front. the is able to evaluate the energy release rate G_I from nodal displacement and reaction force nearby crack front calculated by structural analysis.

$$G_I(S_1) = \frac{2\delta \overline{W}_I(S_1)}{3S_1} \tag{1}$$

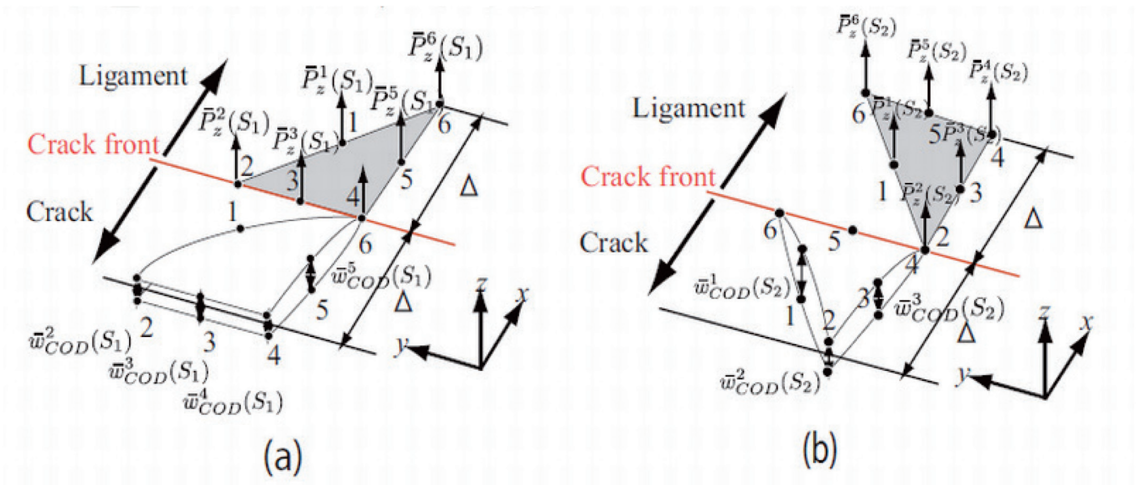

Fig. 1 VCCM calculation [(a) for area S1, (b) for area S2].

$$G_I(S_2) = \frac{2\delta \overline{W}_I(S_2)}{S_2} \tag{2}$$

where G_I is the mode I energy release rate, S_1 and S_2 are the areas of element faces whose vertex node and edge are on the crack front, respectively. S_1 and S_2 are illustrated in Fig. 1 (a) and (b). $\delta\overline{W}_I(S_1)$ and $\delta\overline{W}_I(S_2)$ are the energies that are required to virtually close the faces S_1 and S_2. $\delta\overline{W}_I(S_1)$ and $\delta\overline{W}_I(S_2)$ can be computed by using the nodal crack opening displacements $\overline{w}^I_{COD}$ and the nodal forces $\overline{P}^I_Z$ arising from the cohesive stress on the element faces at the ligament side. $\overline{w}^I_{COD}$ and $\overline{P}^I_Z$ are schematically presented in Fig. 1. The energies $\delta\overline{W}_I(S_1)$ and $\delta\overline{W}_I(S_2)$ are expressed by:

$$\delta\overline{W}_I(S_1) = \frac{1}{2}\sum_{I=1}^{5} \overline{P}^I_Z(S_1)\overline{w}^I_{COD}(S_1) \tag{3}$$

$$\delta\overline{W}_I(S_2) = \frac{1}{2}\sum_{I=1}^{3} \overline{P}^I_Z(S_2)\overline{w}^I_{COD}(S_2) \tag{4}$$

The stress intensity factor is computed from the energy release rate. The stress intensity factor K_I is expressed, by:

$$K_I = \sqrt{E'G_I} \tag{5}$$

where $E' = E$ or $E' = E/(1-\nu^2)$ for the plane stress or the plane strain conditions. E and ν are the Young's modulus and the Poisson's ratio, respectively.

3. Numerical Analysis

In this section, a case study is demonstrated. The analysis model is a notched round bar with 3 inclined cracks (Fig. 2). Mesh of this model consists of 128,875,945 nodes and 95,663,296 elements. In FE analysis, calculation time and memory usage of solver depend on domain decomposition parameter and preconditioner. Based on our experience of analysis using Earth Simulator2 [5], we adopt about 12,000 DOF per domain for domain decomposition parameter and apply incomplete BDD-diag preconditioner on the Earth Simulator2.

Calculation result is as follows (Fig. 3). In calculation on ES2, we used 64 PEs and mesh decomposed to 512 parts/32,768

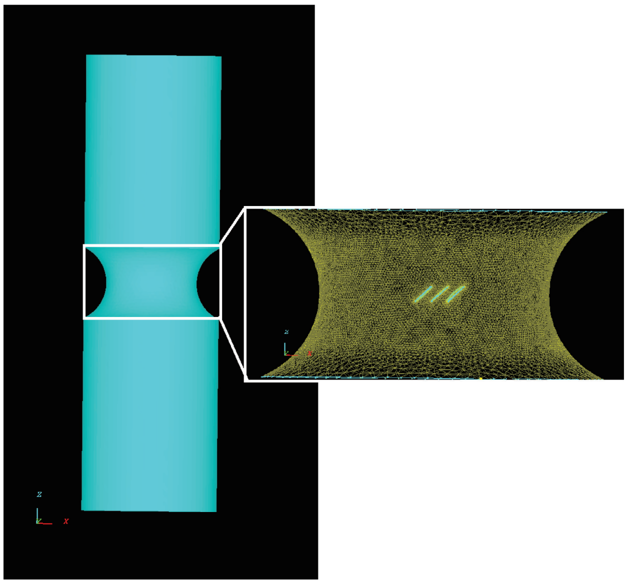

Fig. 2 CAD view of analysis model.

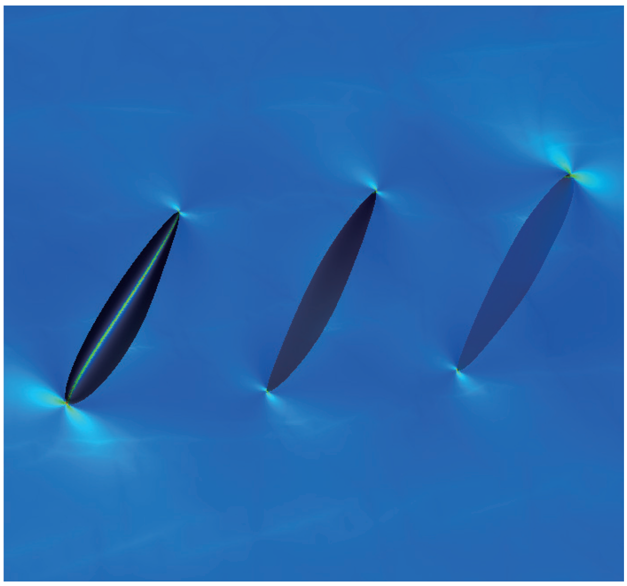

Fig. 3 Contour plot of Mises stress near by cracks.

subdomains and achieved 1717.3 sec. as calculation time and 2204.8 GFLOPS.

Finally, we evaluate the stress intensity factors. The results are presented in Figs. 4, 5 and 6 for the left side, center and right side cracks, respectively.

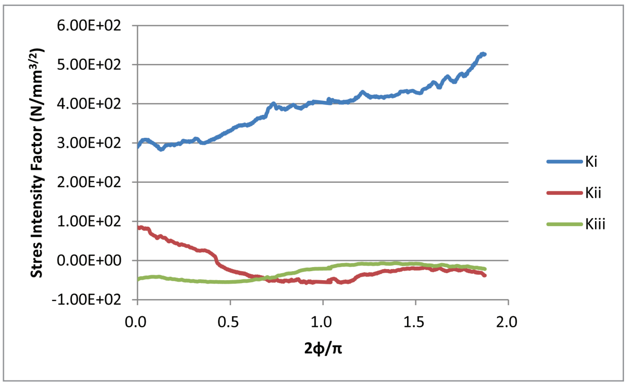

Fig. 4 Stress intensity factors of left crack.

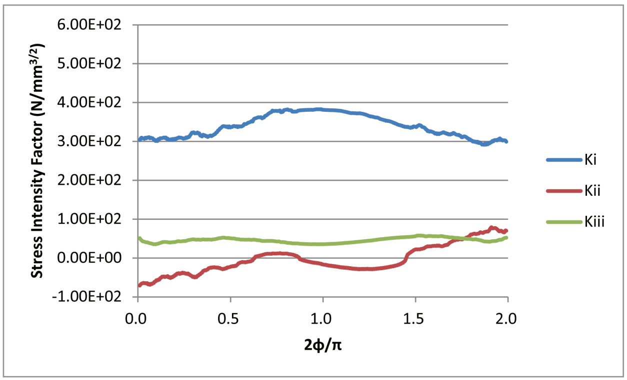

Fig. 5 Stress intensity factors of center crack.

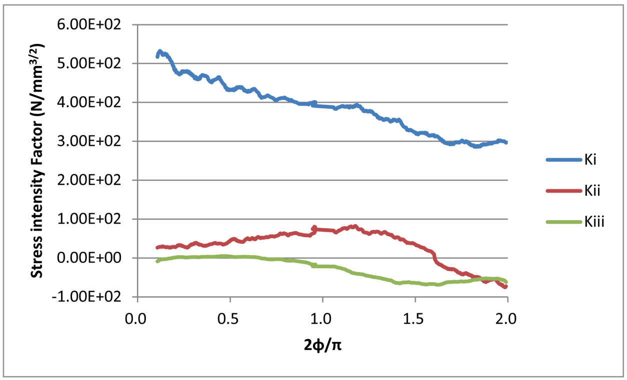

Fig. 6 Stress intensity factors of right crack.

4. Conclusions

We have developed an analysis system which can perform large scale fracture analyses on ES2. The quadratic tetrahedral finite element is adopted so that we can make use of automatic mesh generation methodologies. Therefore, our system is very advantageous over the conventional fracture analysis procedures that commonly adopt the hexahedral finite elements. It is noted that the mesh generation processes cannot be fully automated when we use the hexahedral elements.

We will continue present development and ultra-realistic large scale fracture mechanics analysis for the structural integrity assessments for aging structures will be possible in near future.

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安全・安心な持続可能社会のための
次世代計算破壊力学シミュレータの開発

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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 をもちいて、実用大規模構造材料・機器の直接破壊シミュレータを ES2 上で開発し、低炭素社会構築のカギを握る小型高圧水素貯蔵タンクの超精密破壊解析や、安全・安心社会の基盤である経年化した社会的インフラストラクチャーの超精密破壊解析を通して本技術の確立を目指すことにより、21 世紀の持続可能社会の構築に寄与することを目的としている。

破壊力学パラメータの評価手法として、岡田らが開発を進めている四面体要素を用いた VCCM を用いることで、任意複雑形状モデルに複数のき裂が存在するような問題においても十分な精度を保証している。

今年度は、昨年度までの成果を基に、複数のき裂を持つ試験片の約 4 億自由度メッシュの有限要素解析を行い、その結果からき裂ごとに応力拡大係数を求めることに成功した。メッシュ生成には岡田・河合らが開発してきた CAD モデルから生成したメッシュの任意位置にき裂を挿入する手法を用い、さらに昨年度開発した要素細分割による大規模メッシュ生成プログラムを併用することで、4 億自由度のメッシュの生成に成功した。地球シミュレータ上での有限要素解析を行う際には、昨年度のパラメータチューニングの成果から最適な領域分割パラメータ及び前処理手法の選択を行い、2.2 Tflops（ピーク性能比約 4.2%）、1 回の静解析を 28.6 分での解析に成功した。また、計算結果からき裂周辺の変位を抽出し、そこから VCCM を用いてき裂ごとの応力拡大件数を計算した。

キーワード : fracture mechanics, crack propagation analysis, finite element method, domain decomposition method, aging structure