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Design and Material Issues for Fusion Systems
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SiC/SiC Creep Strength

- New FEM Analysis of Time-Dependent Crack Growth in SiC/SiC Composites -

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Fiber Bridging Zone in SiC/SiC Composites

SiC/SiC Composite

Pre-existing Cracks (or Pores)

caused by manufacturing methods (CVI, CVD, PIP)

&

Structural Materials

Various Loads are Applied

Fiber Bridging Zone

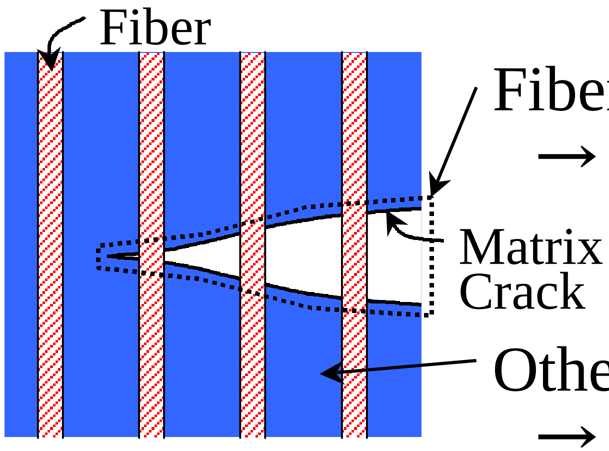
1) Matrix Cracking
2) Fiber Bridge Cracks
3) Fiber Creep

Methods of estimating the crack propagation in composites

previous methods … microscopic
new method … ***macroscopic***

crack growth → *determined by* ***the creep rate of bridging fibers***

Modeling in this study



Fiber Bridging Zone
→ Interface Elements
(Interface Potential $\phi \equiv \phi_f + \phi_m$)

Other Zone
→ Ordinary Elements

- One interface element was assumed to represent many fibers and matrices in bridging zone.
- Interface potential was defined as same as the simple rule of mixture.

Interface Element

Potential function

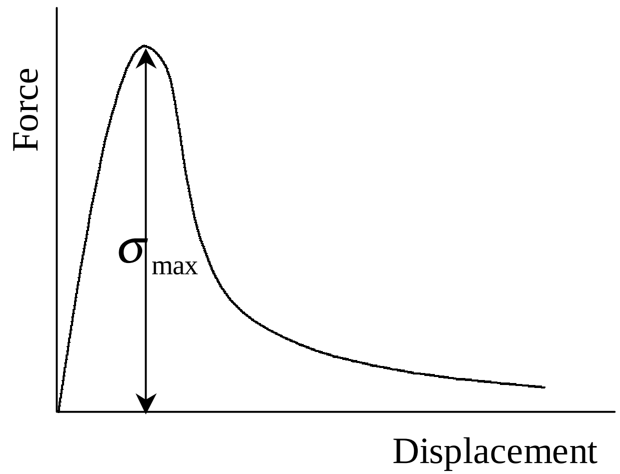
(Lennard-Jones type potential energy)

$$\phi = 2\gamma\left\{\left(\frac{r_0}{r_0+\delta}\right)^{2n} - 2\left(\frac{r_0}{r_0+\delta}\right)^{n}\right\}$$

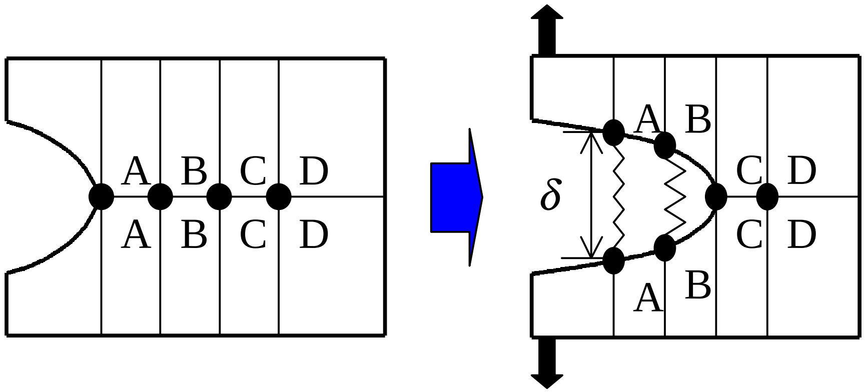
2γ :surface energy per unit area

δ :crack opening

n , r_0 :material constants



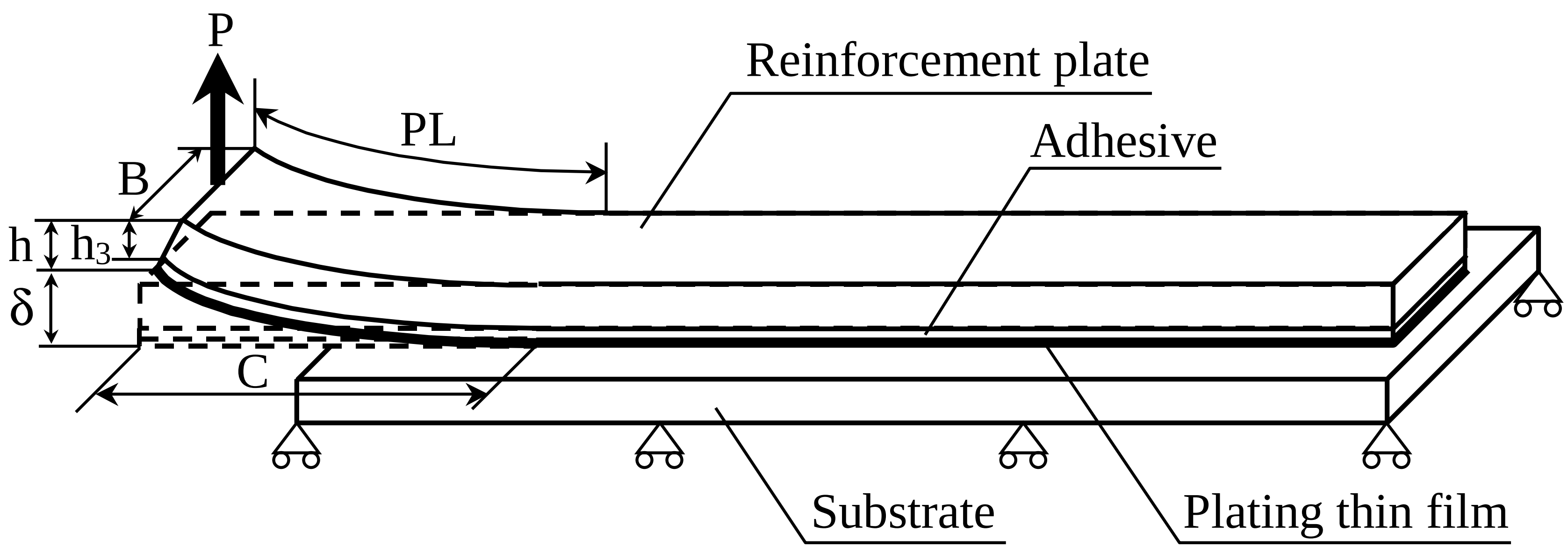
Relation between crack opening displacement and bonding stress



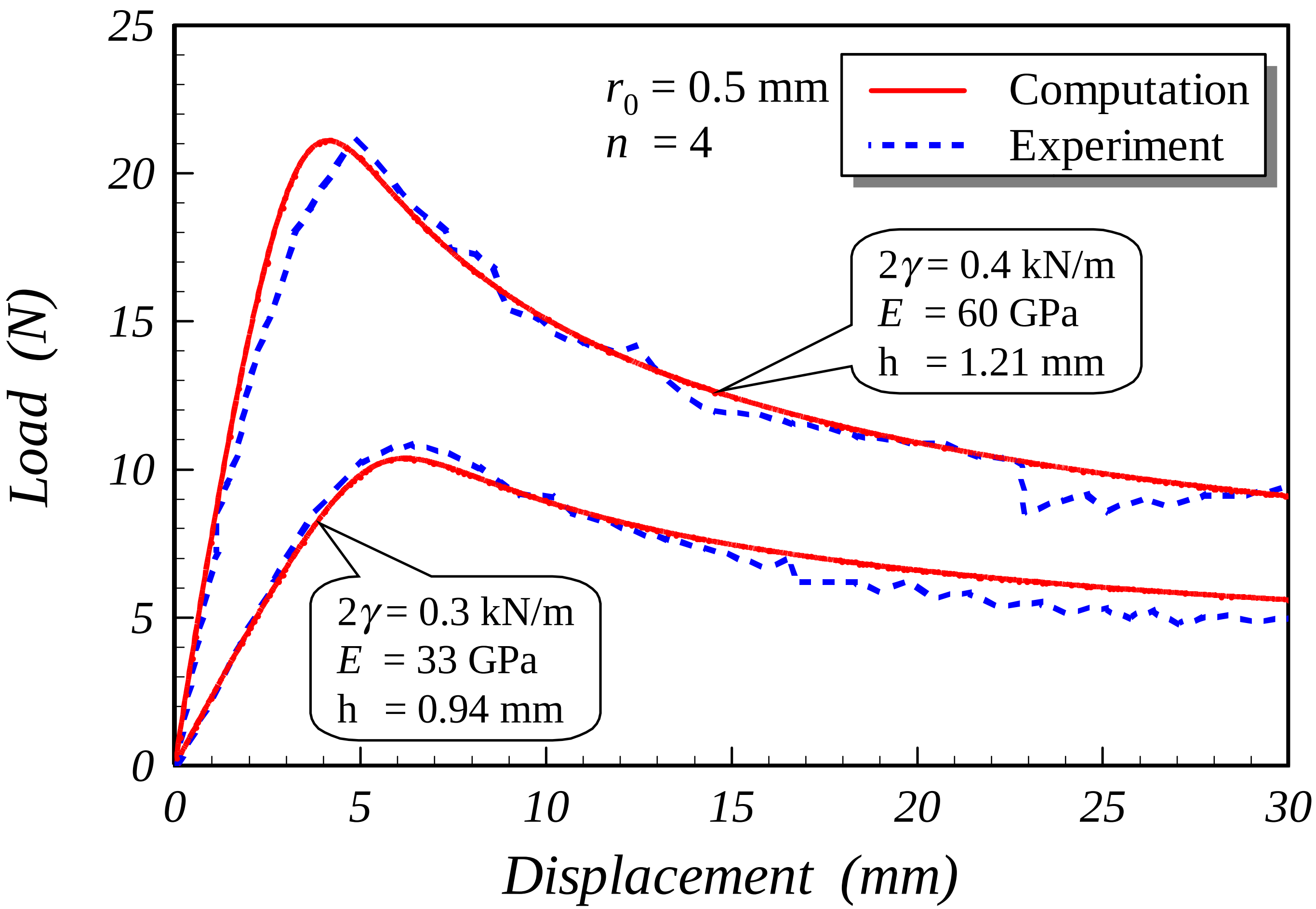
before crack propagation during crack propagation

・The fracture behavior can be regarded as the formation of a new surface, which is represented by interface element based on the interface potential energy.

Schematic Illustration of Peeling Test



Comparison between Experiment and Computation



- The computational results excellently agreed with the experimental results.

Interface Potential of Interface Element

Many Fibers and Matrices in Bridging Zone

↓

One Interface Element

Interface Potential

$$\phi \equiv \phi_f + \phi_m$$

$$\phi_f \equiv 2\gamma_f \cdot \left\{ \left(\frac{r_{f0}}{r_{f0} + \delta} \right)^{2n} - 2 \cdot \left(\frac{r_{f0}}{r_{f0} + \delta} \right)^{n} \right\}$$

$$\phi_m \equiv 2\gamma_m \cdot \left\{ \left(\frac{r_{m0}}{r_{m0} + \delta} \right)^{2n} - 2 \cdot \left(\frac{r_{m0}}{r_{m0} + \delta} \right)^{n} \right\}$$

← ***Time Dependency***

Objectives

To develop a new *Time-Dependent Interface Element*
for introducing the creep property of fibers
into the interface element

To apply the *Time-Dependent Interface Element*
for analyzing time-dependent crack growth
especially slow crack growth of SiC/SiC composite

Theory of Two Methods (General and New)

General

displacement increment of interface element

$$\Delta\delta = \Delta\delta^e + \Delta\delta^c$$

$\Delta\delta^e$: elastic displacement increment

$\Delta\delta^c$: creep displacement increment

assumption

$$\Delta\delta^c = A \cdot \sigma^m \cdot \Delta t \quad \text{(creep law)}$$

σ : stress

Δt : time increment

potential function

$$\phi_f(\delta^e) = 2\gamma_f \left\{ \left(\frac{r_{f0}}{r_{f0} + \delta^e} \right)^{2n} - 2\left(\frac{r_{f0}}{r_{f0} + \delta^e} \right)^{n} \right\}$$

New

assumption

increment of r_{f0}

$$\Delta r_{f0} = B \cdot \sigma^m \cdot \Delta t$$

σ : stress

Δt : time increment

initial value : r_{f0}

potential function

$$\phi_f(\delta, t) = 2\gamma_f \left\{ \left(\frac{r_{f0}(t)}{r_{f0}(t) + \delta} \right)^{2n} - 2\left(\frac{r_{f0}(t)}{r_{f0}(t) + \delta} \right)^{n} \right\}$$

Theory of New Method

potential function

$$\phi(\delta,t)=2\gamma_f\left\{\left(\frac{r_{f0}(t)}{r_{f0}(t)+\delta}\right)^{2n}-2\left(\frac{r_{f0}(t)}{r_{f0}(t)+\delta}\right)^{n}\right\}+2\gamma_m\left\{\left(\frac{r_{m0}}{r_{m0}+\delta}\right)^{2n}-2\left(\frac{r_{m0}}{r_{m0}+\delta}\right)^{n}\right\}$$

fiber ***matrix***

bonding stress

$$\frac{\partial\phi}{\partial\delta}=\frac{4\gamma_f\cdot n}{r_{f0}(t)}\left\{\left(\frac{r_{f0}(t)}{r_{f0}(t)+\delta}\right)^{n+1}-\left(\frac{r_{f0}(t)}{r_{f0}(t)+\delta}\right)^{2n+1}\right\}+\frac{4\gamma_m\cdot n}{r_{m0}}\left\{\left(\frac{r_{m0}}{r_{m0}+\delta}\right)^{n+1}-\left(\frac{r_{m0}}{r_{m0}+\delta}\right)^{2n+1}\right\}$$

assumption

* increment of r_{f0}

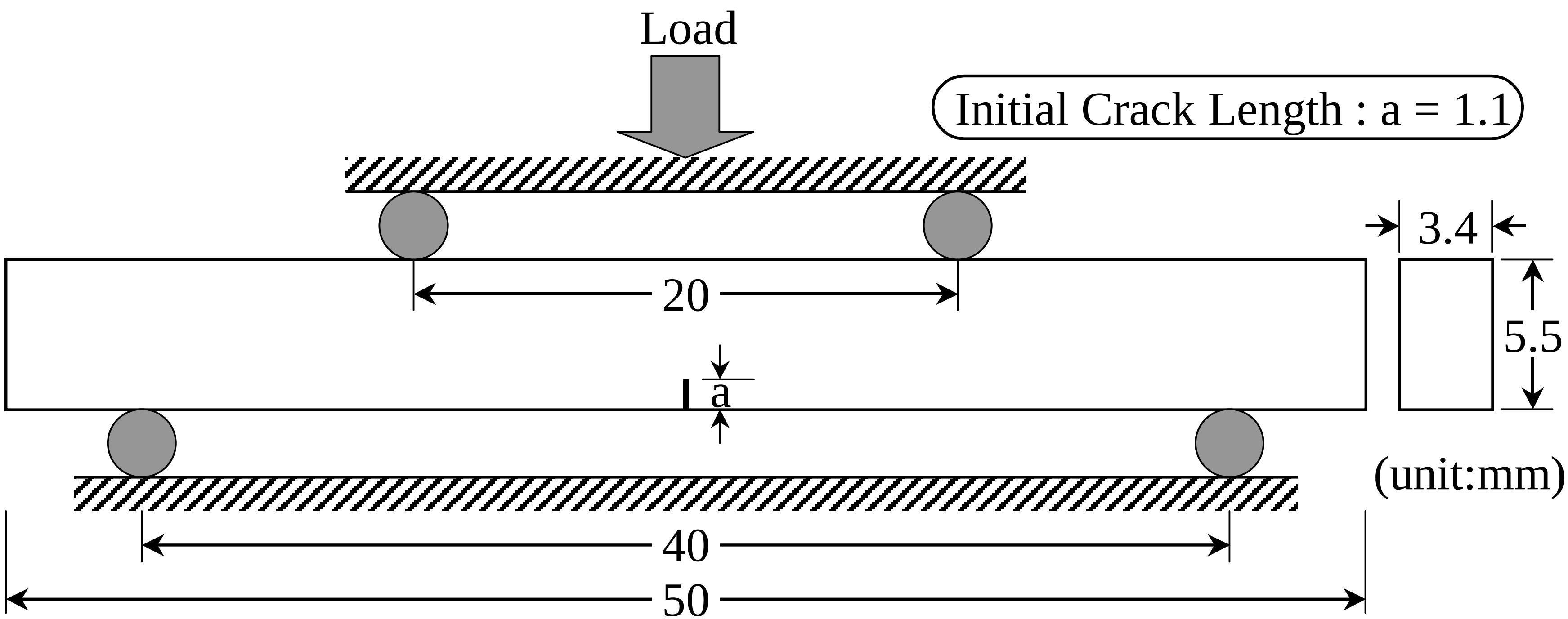
$$\Delta r_{f0}=B\cdot\sigma\cdot\Delta t$$

σ : stress

Δt : time increment

* initial value : r_{f0}

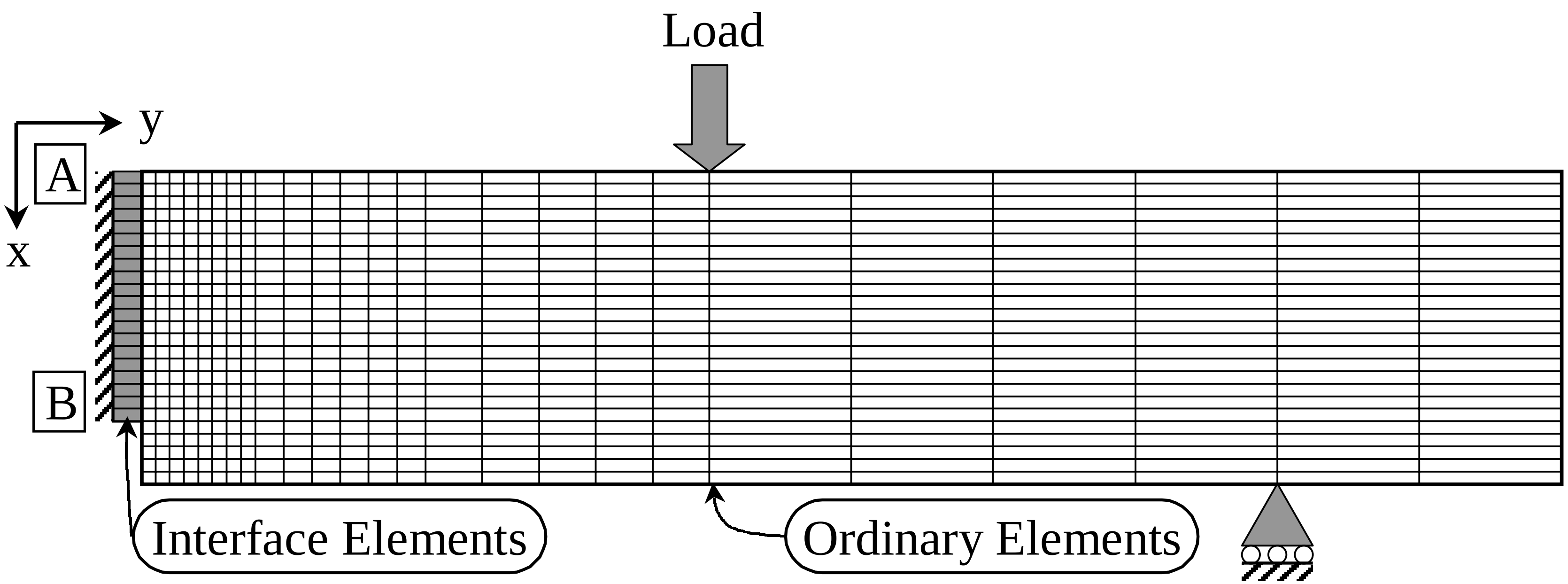
Schematic Illustration of Four-Point Bending Test



・The reinforcements of the composites were 2-dimensional, plain-weave Hi-Nicalon fiber mats, which were stacked in the direction of thickness, and the matrices were deposited by chemical vapor infiltration.

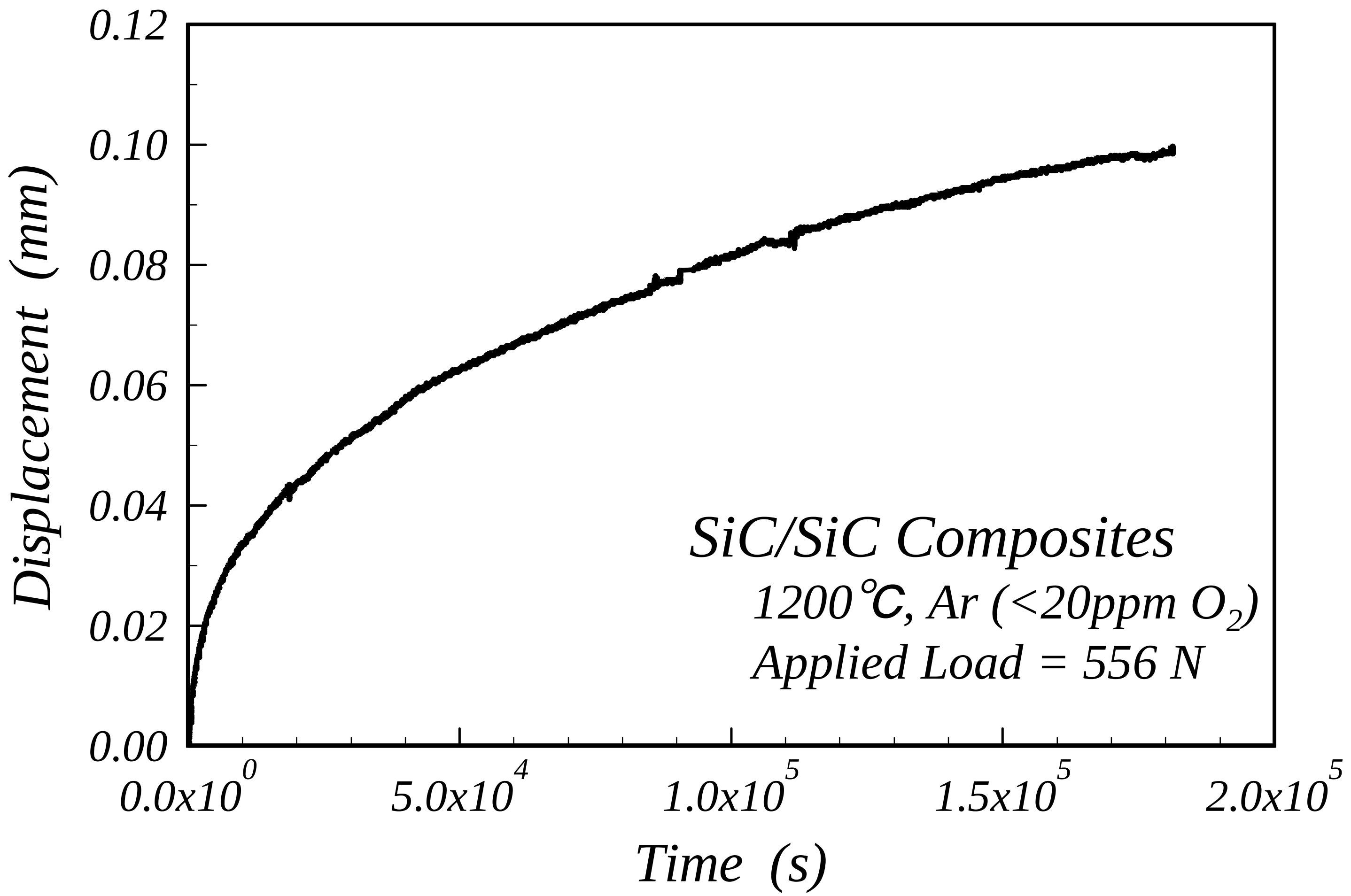
・The crack propagated from the tip of the notch in the direction, which is parallel to the applied load.

Model and Mesh Division for Analysis



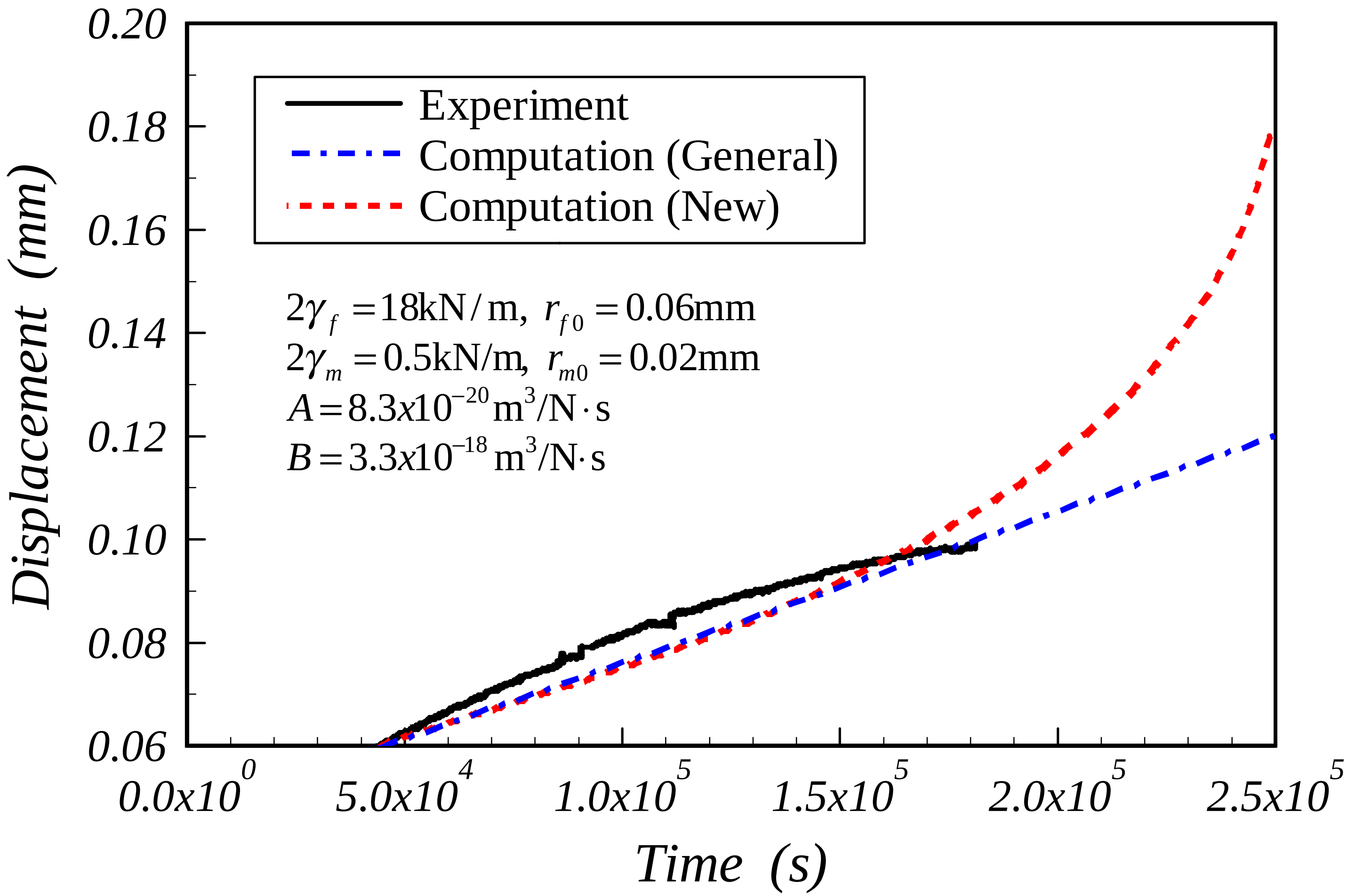
・Because of the symmetry of the problem, only the half of the specimen was used.
・The time dependent interface elements were arranged along the crack propagation path.
・Only the mode-I type crack propagation parallel to y-axis was taken into account according to the experimental results.

Displacement-Time Curve during Time-Dependent Crack Growth in SiC/SiC Composite



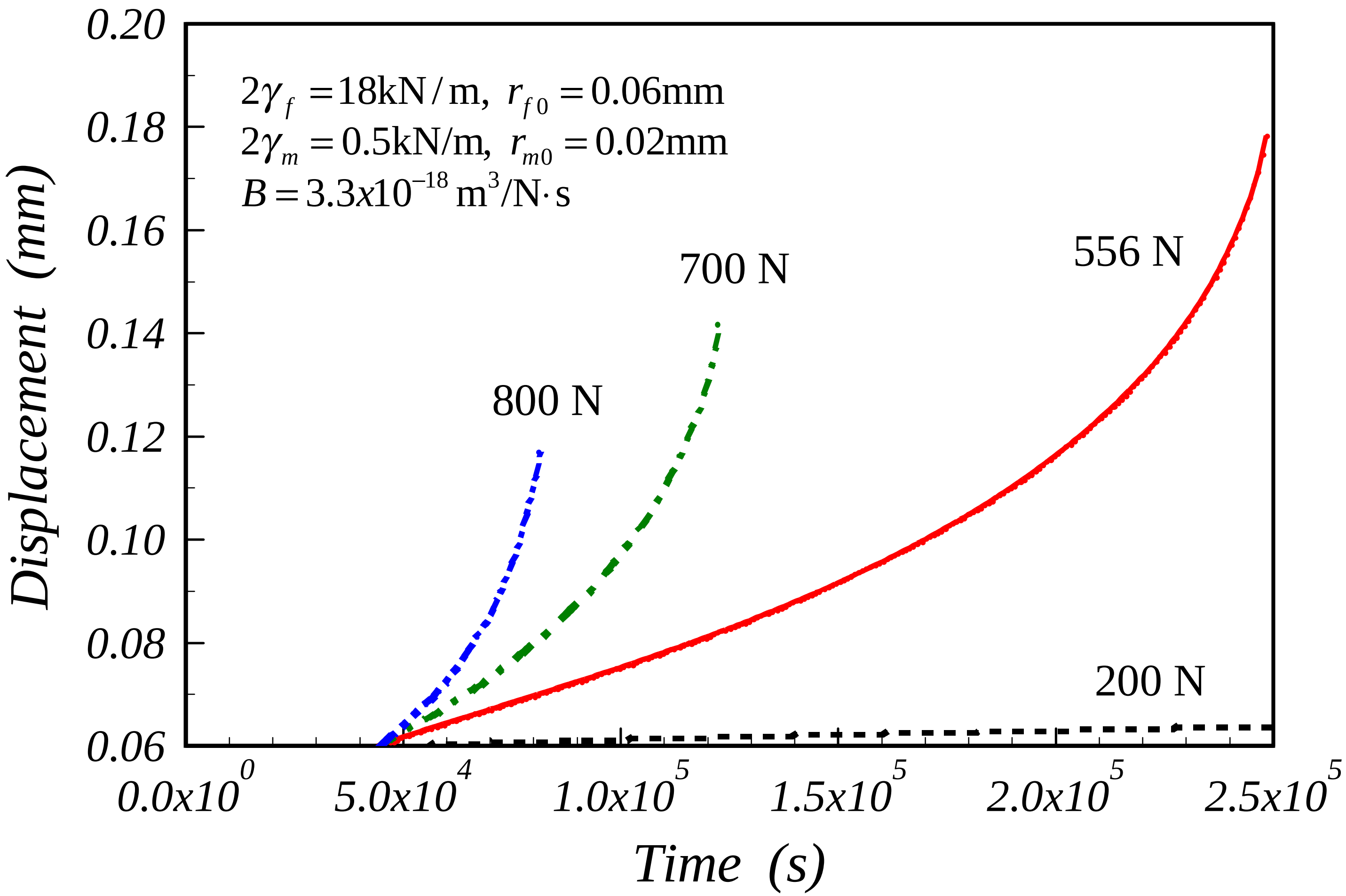
･The area in time-displacement curve, where the displacement was more than 0.06 mm, was compared with calculation results since the rate of change of the displacement, with respect to time, was minimal.

Comparison between Experiment and Computations in Time-Dependent Crack Growth



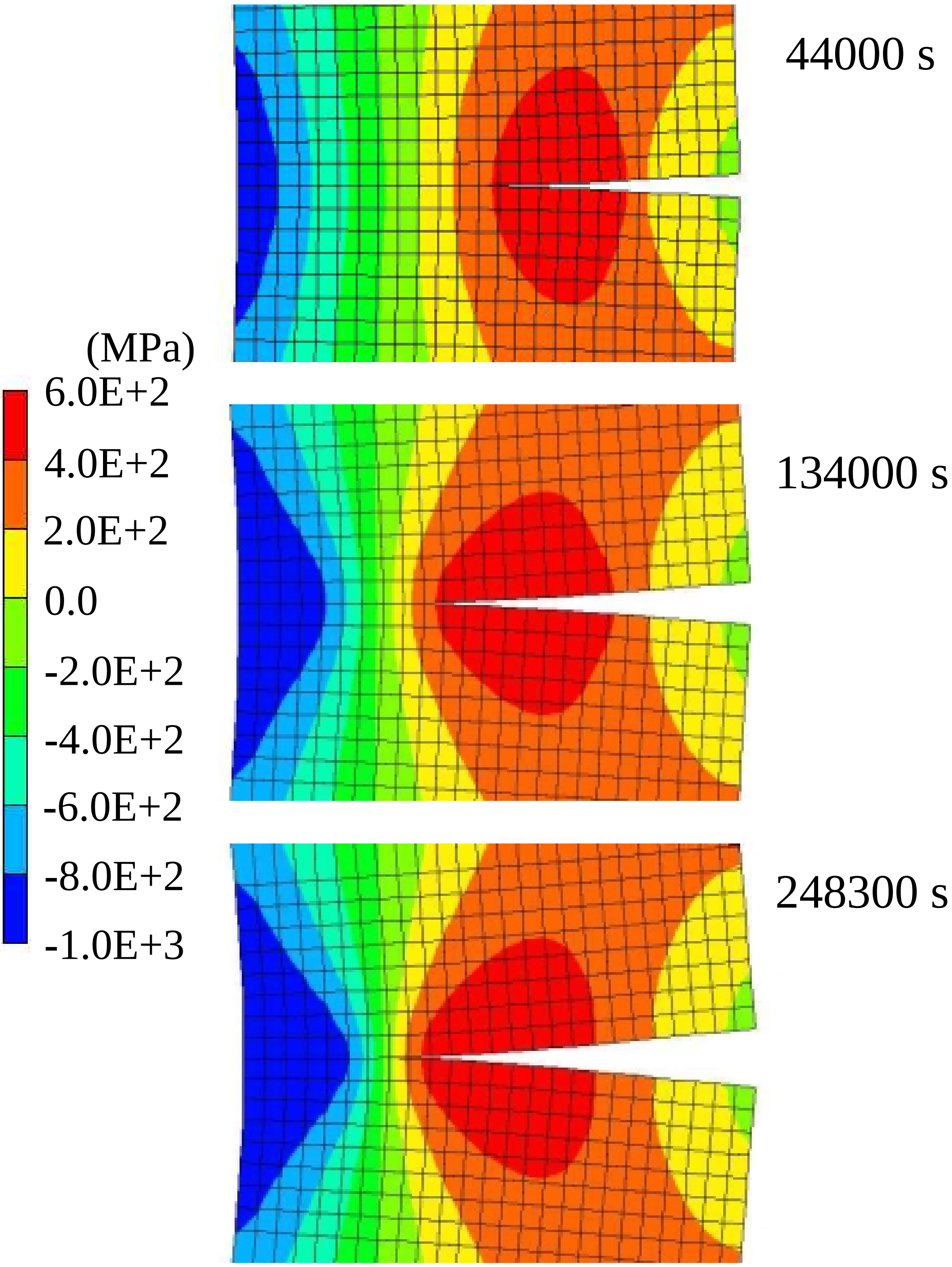
・Although both calculation results simulated the stage-II slow crack growth, the result using the new method represented not only the stage-II slow crack growth but also the stage-III crack growth.

Calculated Displacement-Time Curves under Various Applied Load



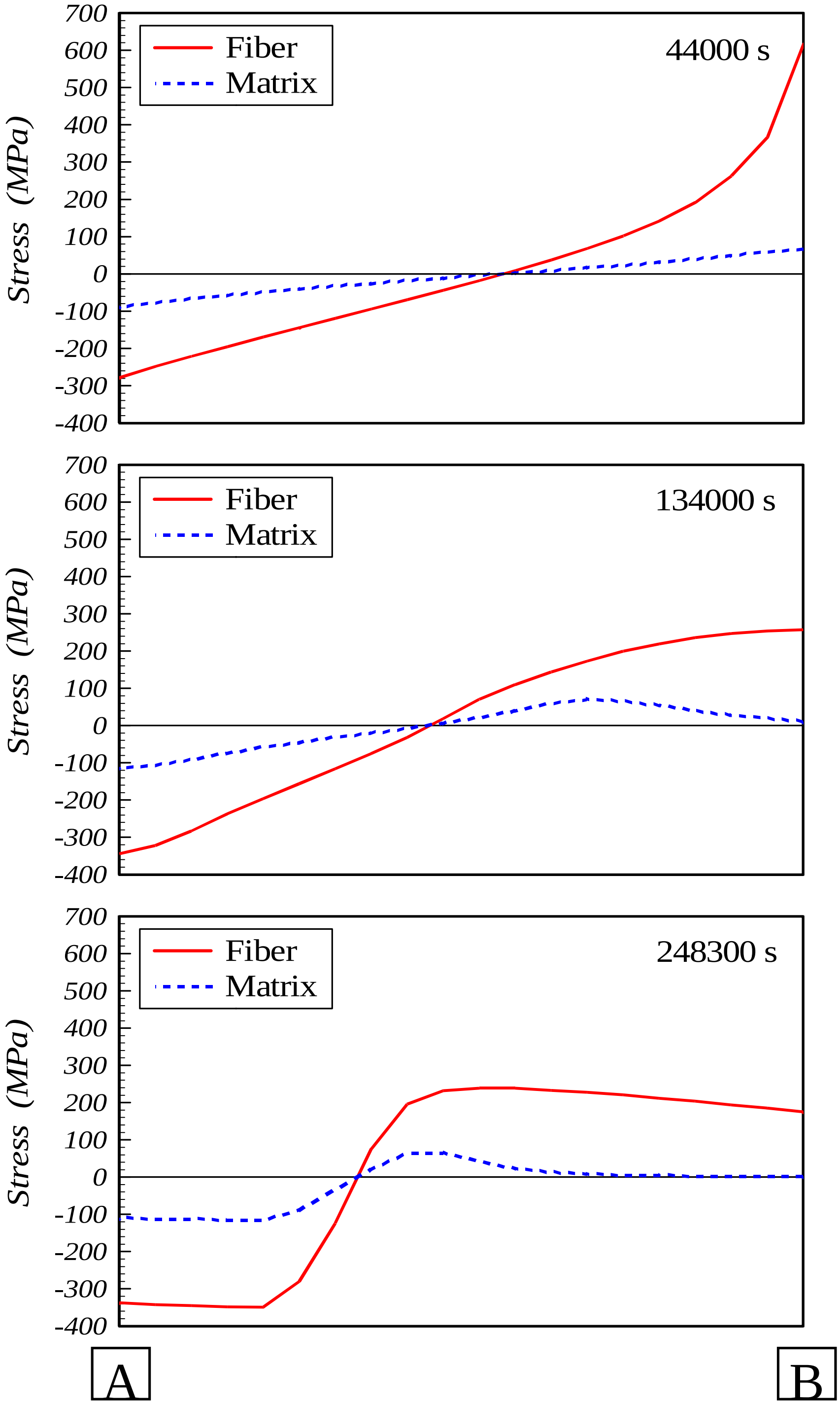
・The transition time from stage-II to stage III decreased with increasing applied load, similar to the general creep deformation. Therefore the new method is considered to be useful for analyzing such a creep behavior.

Deformations and Stress Distribution near Crack Path



・The crack propagation behavior was clearly demonstrated and the stress relaxation behavior at the crack tip was also calculated.

Stress Changes of Fiber and Matrix along Crack Path



・The stress of matrix became almost zero. On the other hand, the stress of fiber maintained around 200 MPa after the crack propagated since the fiber was assumed to continue to creep.

Conclusion

In order to analyze crack propagation behavior in SiC/SiC composite, a new computer simulation method using time dependent interface elements was developed and applied to time-dependent crack growth in SiC/SiC composites. The conclusions can be summarized as follows.

(1) The time-dependent crack growth in SiC/SiC composite was simulated by two methods, in which the creep property was introduced into the interface elements according to :

1) the general method of FEM analysis

2) a new method making the best use of the potential function.

In both cases, the stage-II slow crack growth of a general creep deformation was simulated.

(2) By using the new method, not only the stage-III crack growth but also transition phenomena from stage-II to stage-III could be simulated. So the new method is considered to have the potential capability to model all stages of time-dependent crack growth behavior in SiC/SiC composite.