International Conference on Composite Materials 2023
Jul. 30 – Aug. 4, 2023, The ICC Belfast, Belfast, UK

Efficient Damage Simulation Method for Textile Composite Using Fiber-bundles / Matrix-resin Separated Model

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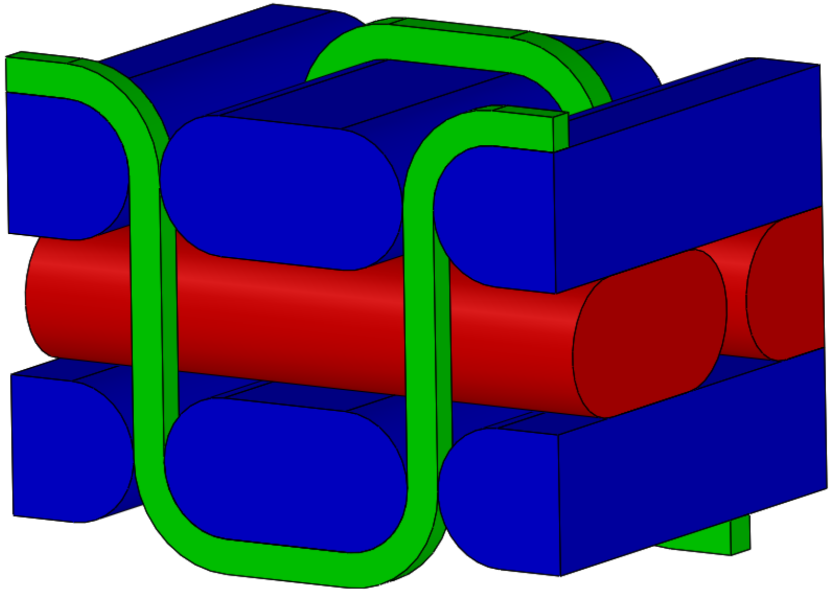
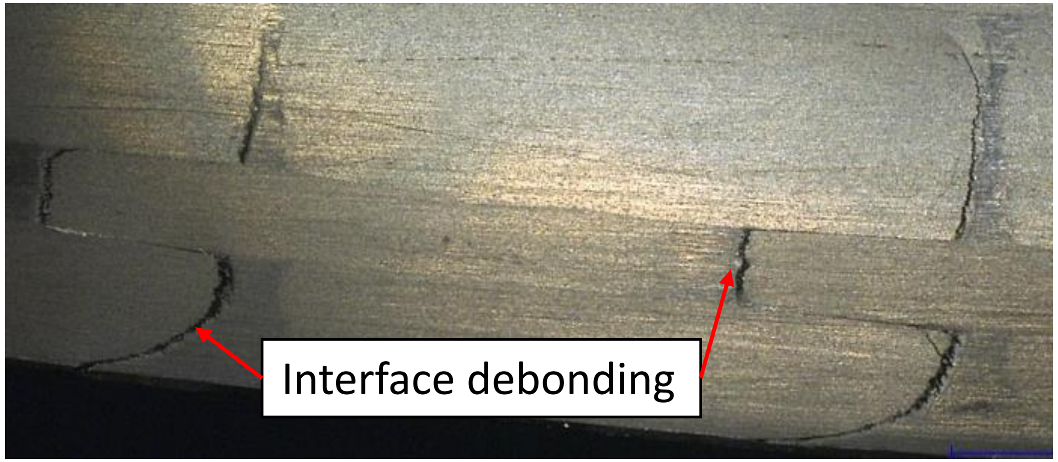
Background

<u>**Woven composites, Textile CFRP**</u>



Example of tow structure



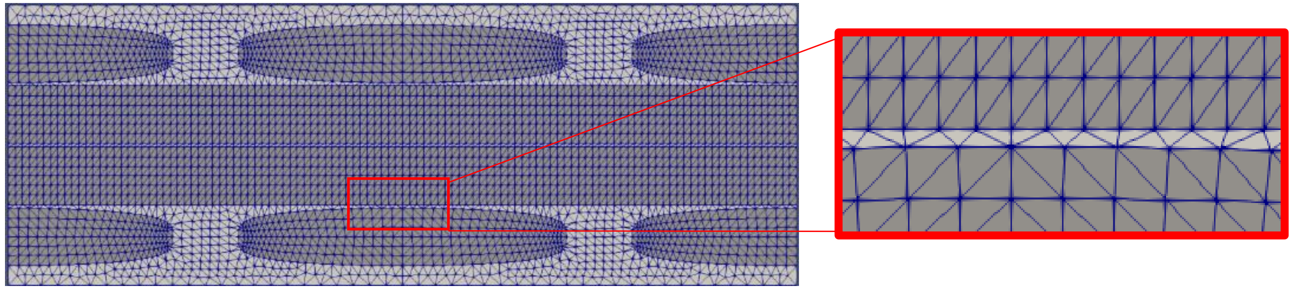
- ✓ Reinforced by mesoscopic carbon fiber tow structure
- ✓ **Higher strength and toughness in the out-of-plane direction**

- Complex geometry of meso-scale structure
- Complex damage process of textile composite
- **Analysis of damage evolution and its effect by using numerical simulation is necessary.**

⇨ **Progressive damage analysis based on finite element method**

Approach

Issues in the finite element analysis of textile composites

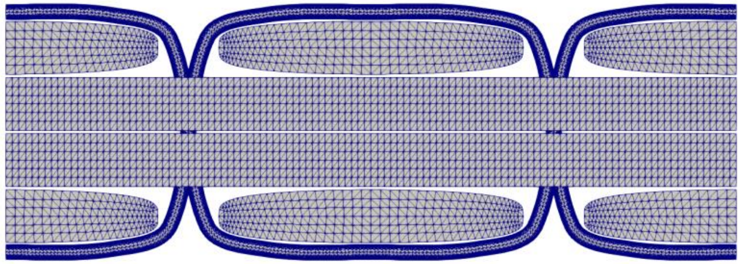


- **Huge effort** is needed for **mesh generation**.
- **Distorted elements** are often generated.

⇨ **Degraded calculation accuracy**
Increased calculation cost

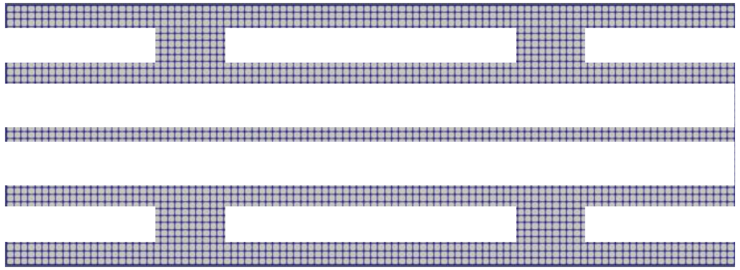
Separated mesh approach

Fiber bundle and matrix resin are *separately meshed*



Fiber bundle mesh

+



Matrix resin mesh

- ✓ **Less effort for mesh generation**
- ✓ **No distorted small resin elements**

Goal of this study

Propose a finite element modeling method for textile composite, in which **fiber bundle and matrix resin are *separately meshed***

Outline

1. Formulation
2. Validation
3. Progressive damage analysis of textile composite
4. Summary

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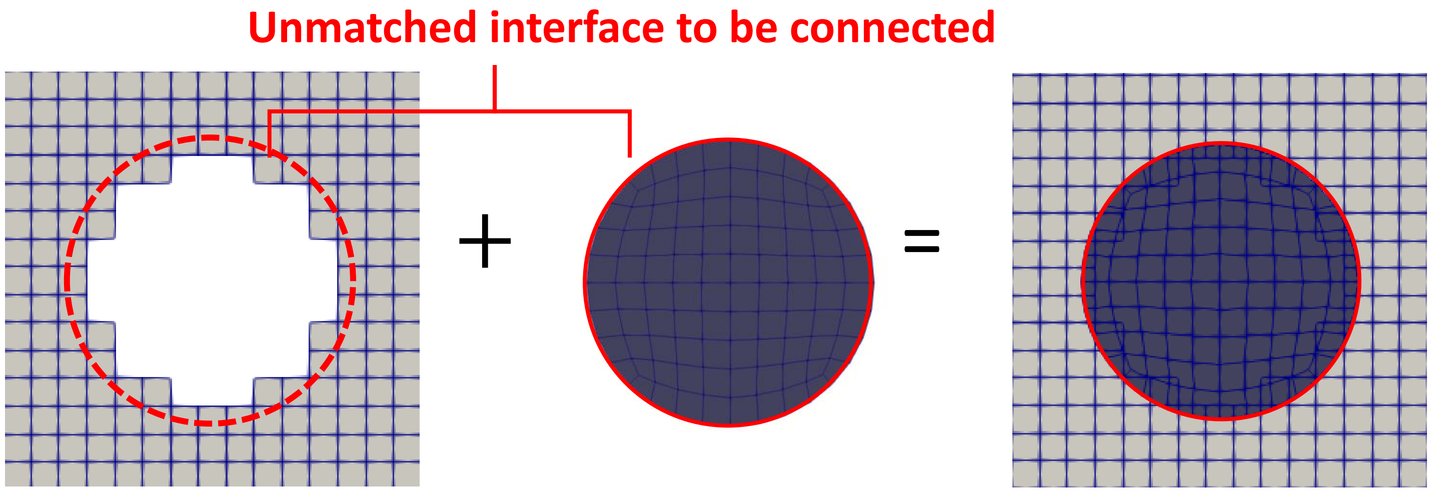
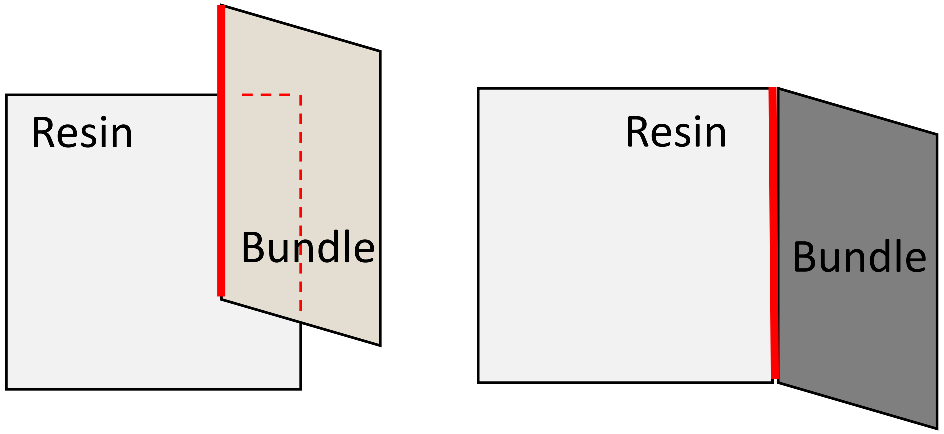
Connection between two separated subdomains

Overlap of domains



Matrix resin subdomain | Fiber bundle subdomain | Analytical domain

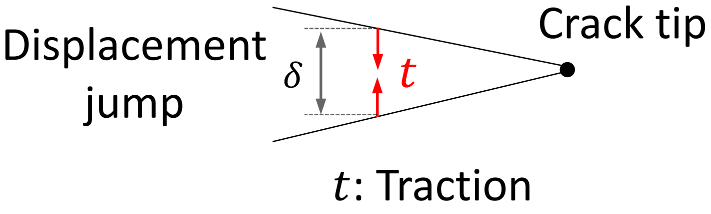


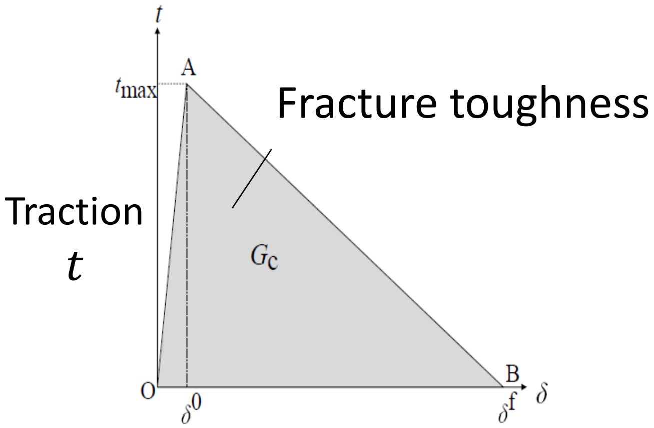
Proposed method | **Usual FEM**

Fiber bundle elements **partially overlap** matrix resin elements

- ✓ **Simple regular mesh** is used for resin subdomain. **No distorted element** exists.
- ✓ Mesh overlap is allowed.

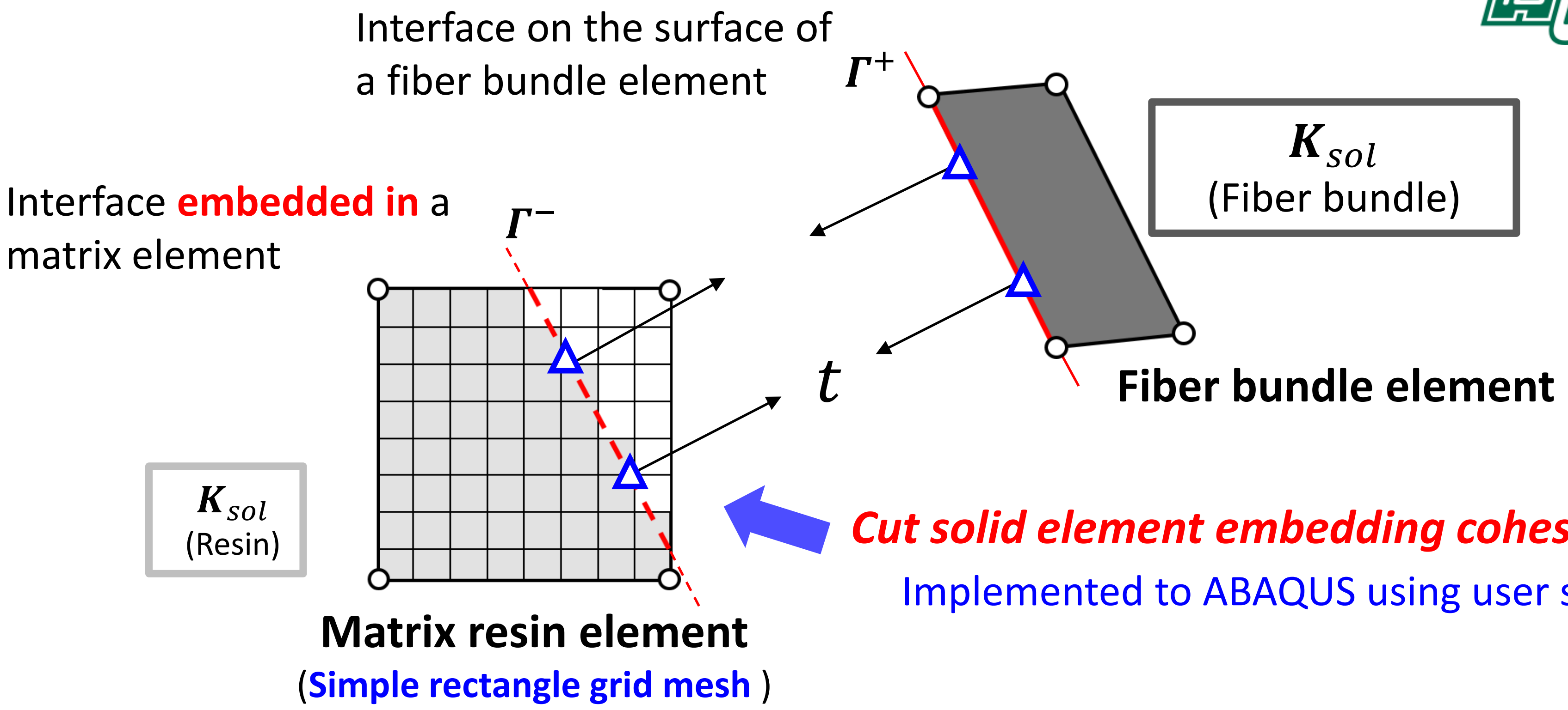
Bilinear cohesive zone model





- Fiber bundle elements and matrix resin elements are **connected by bilinear cohesive zone model**

Formulation



Cut solid element embedding cohesive zone model

Implemented to ABAQUS using user subroutine, UEL.

Procedure of user subroutine UEL

① Calculate stiffness matrix of cut resin element $\boldsymbol{K}_{sol}$

An element is divided into subcells, **the stiffnesses of non-overlapped subcells** are integrated.

② Calculate traction $\boldsymbol{t}$, and interface stiffness $\boldsymbol{K}_{coh}$ using separated bundle and resin meshes.

Displacement jump δ is calculated at **evaluation points (△) distributed on the interface**.

Rectangle grid mesh allows fast calculation

③ Total stiffness matrix $(\boldsymbol{K}_{sol} + \boldsymbol{K}_{coh})$ is calculated, and overall equation is solved by **ABAQUS**.

Outline

1. Formulation
2. **Validation**
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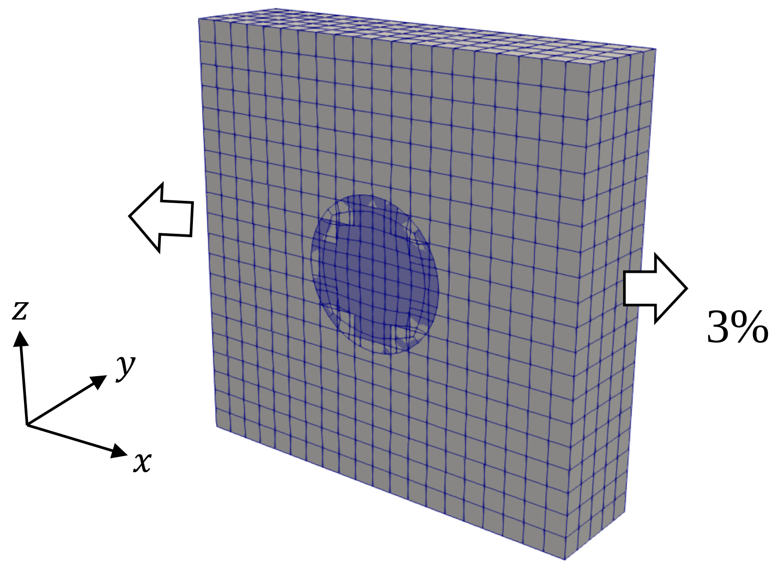
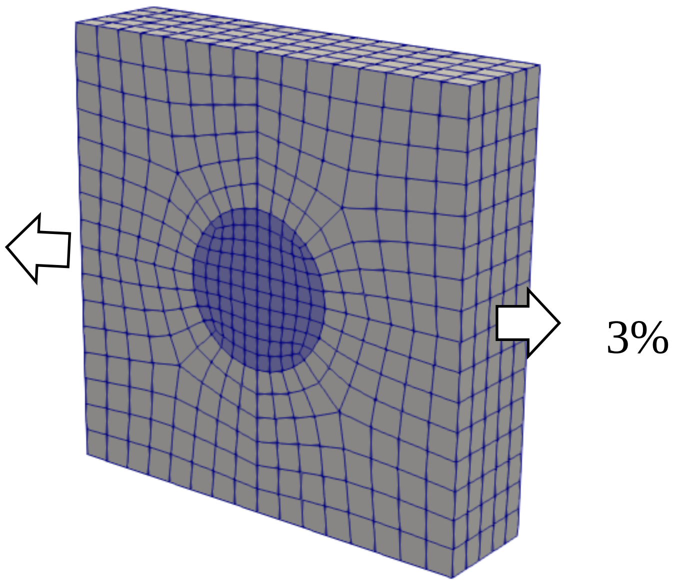
Validation

Simulation of cylindrical inclusion (carbon fiber) embedded in the matrix resin



Mesh used for proposed method



Mesh for reference calculation (Conventional method)

Elastic moduli of T700S

$E_L = 177.9$ GPa	$E_T = 26.1$ GPa
$\nu_{LT} = 0.27$	$G_{LT} = 23.9$ GPa
$\nu_{TT} = 0.77$	

Elastic moduli of epoxy matrix

$E = 2.86\ GPa$	$\nu = 0.36$

Parameters of cohesive region

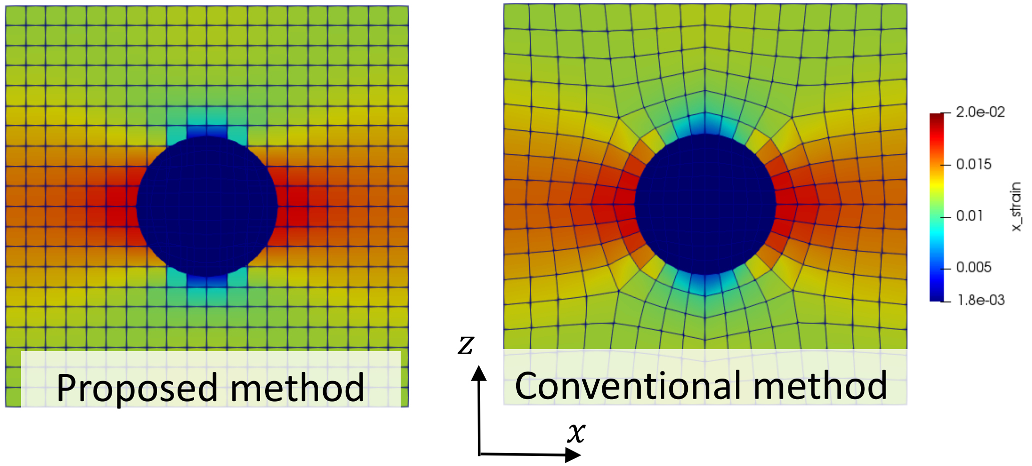
$$G_{\mathrm{IC}} = G_{\mathrm{IIC}} = 0.10\mathrm{k\,J/m^2}$$
$$K_{\mathrm{ini}} = 1.0 \times 10^7\ \mathrm{GPa/m}$$
$$t_{\mathrm{I}} = t_{\mathrm{II}} = 78.0\mathrm{MPa}$$

Boundary condition

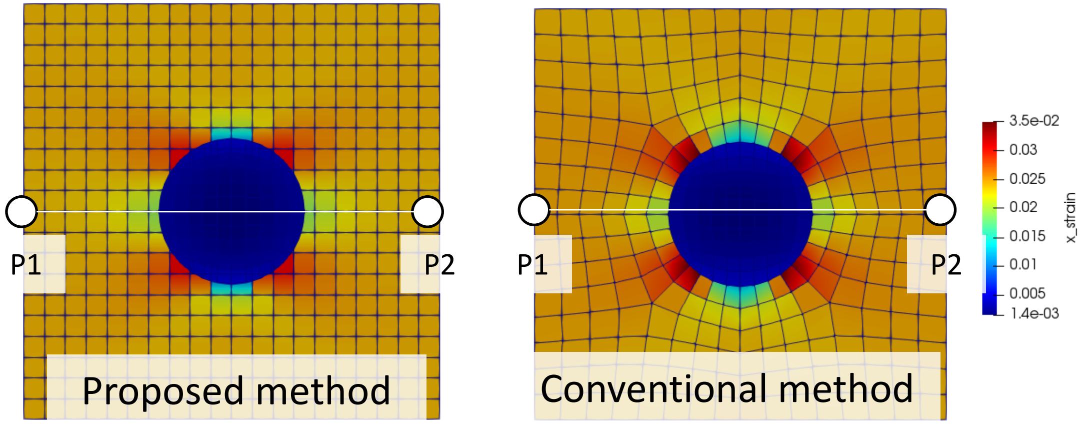
3% tensile strain is applied by displacement

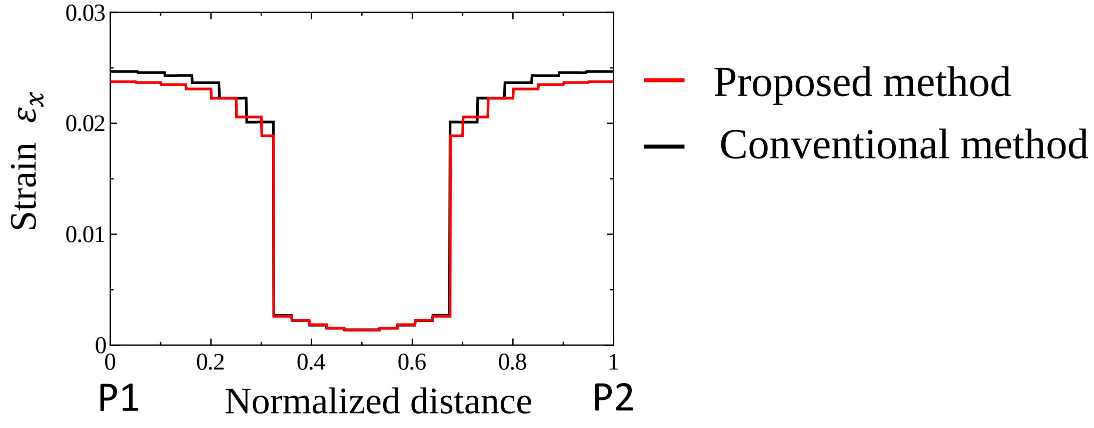
Validation results

Strain $\varepsilon_x^G = 1.2$ %

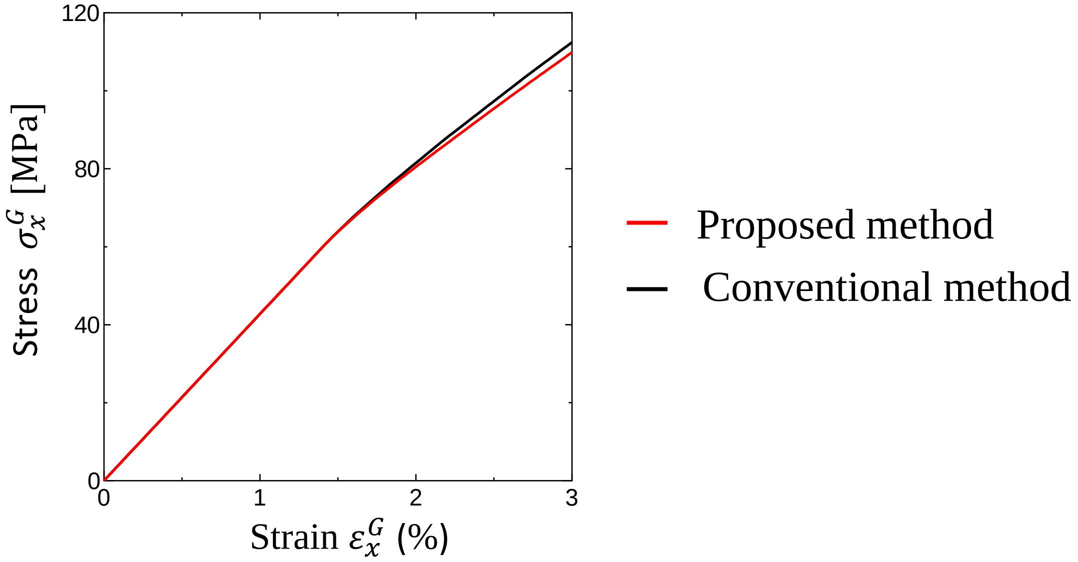


Strain $\varepsilon_x^G = 2.4$ %





Strain along the path P1-P2 ($\varepsilon_x^G = 2.4$ %)



Proposed method achieves precise simulation of damage propagation.

Outline

1. Formulation
2. Validation
3. **Progressive damage analysis of textile composite**
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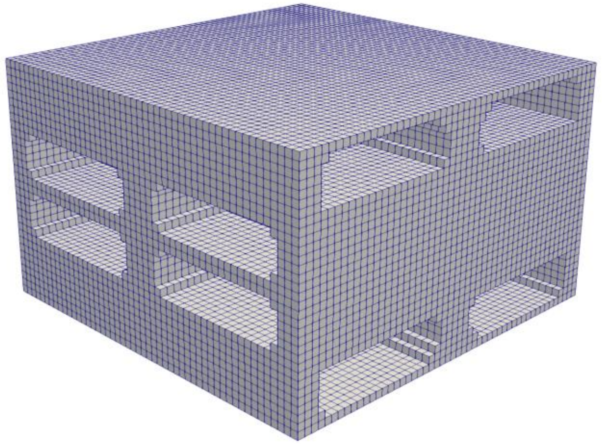
Simulation for textile composites

Mesh used for proposed method

Matrix resin mesh
(Cuboid grid mesh)



Fiber bundle mesh

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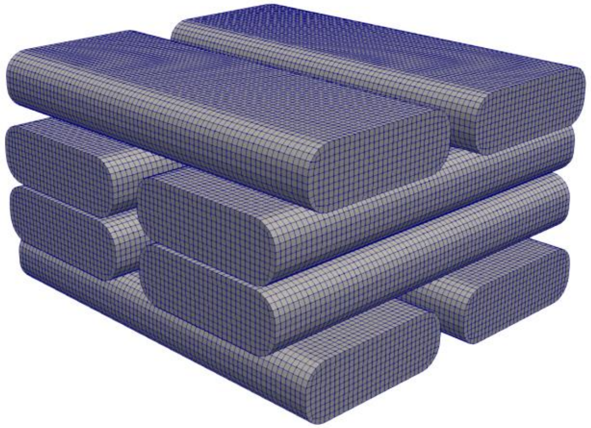
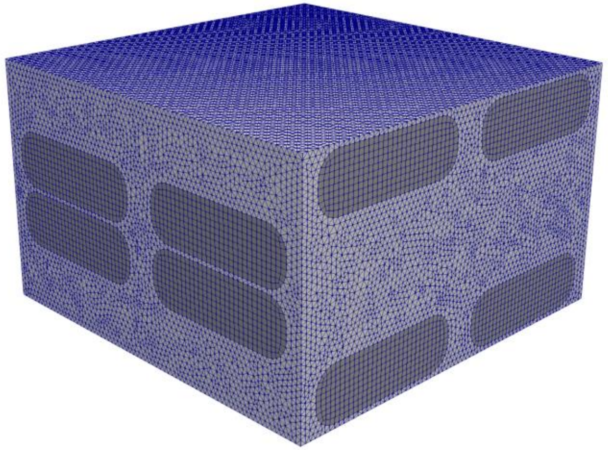


Mesh used for conventional method



- ✓ Tetrahedral elements are used for matrix region

Mesh generation procedure

① **Prepare fiber bundle mesh and simple cuboid grid mesh.**

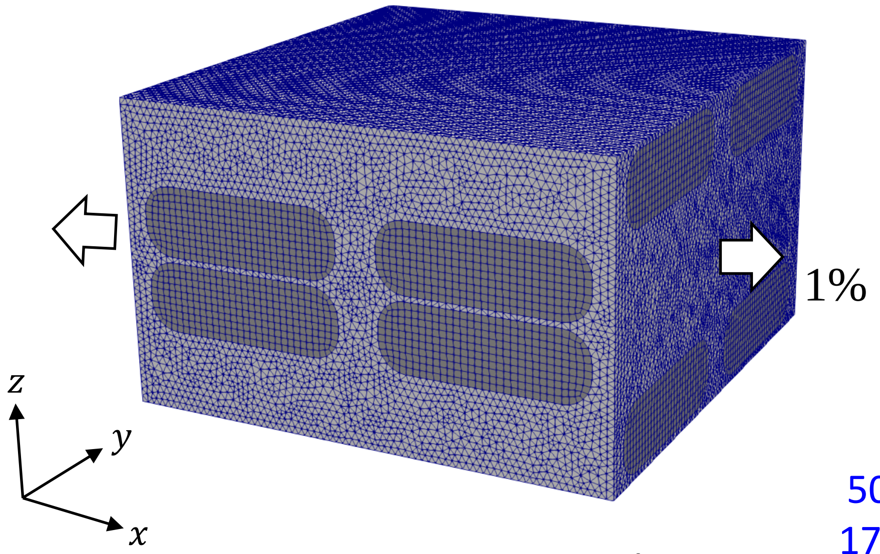
② **Bore the matrix mesh**
•Delete matrix elements fully overlapped by the fiber bundle elements

③ **Two meshes are connected by the proposed method**

Resin mesh generation is very easy and only takes short time.

Simulation for textile composites

Mesh for conventional method



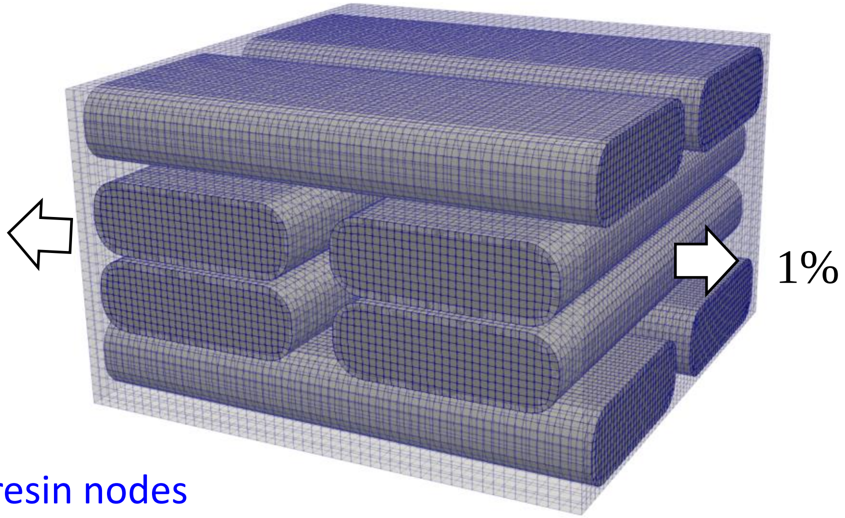
96,247 resin nodes

194,473 fiber bundle nodes

50% reduced resin nodes

17% reduced in full model

Mesh for proposed method



48,464 resin nodes

194,473 fiber bundle nodes

Elastic moduli of fiber bundle

$E_L = 143.9$ GPa	$E_T = 8.88$ GPa
$\nu_{LT} = 0.304$	$G_{LT} = 4.5$ GPa
$\nu_{TT} = 0.452$	

Elastic moduli of epoxy

$E = 3.10\ GPa$	$\nu = 0.438$

Parameters of cohesive zone model

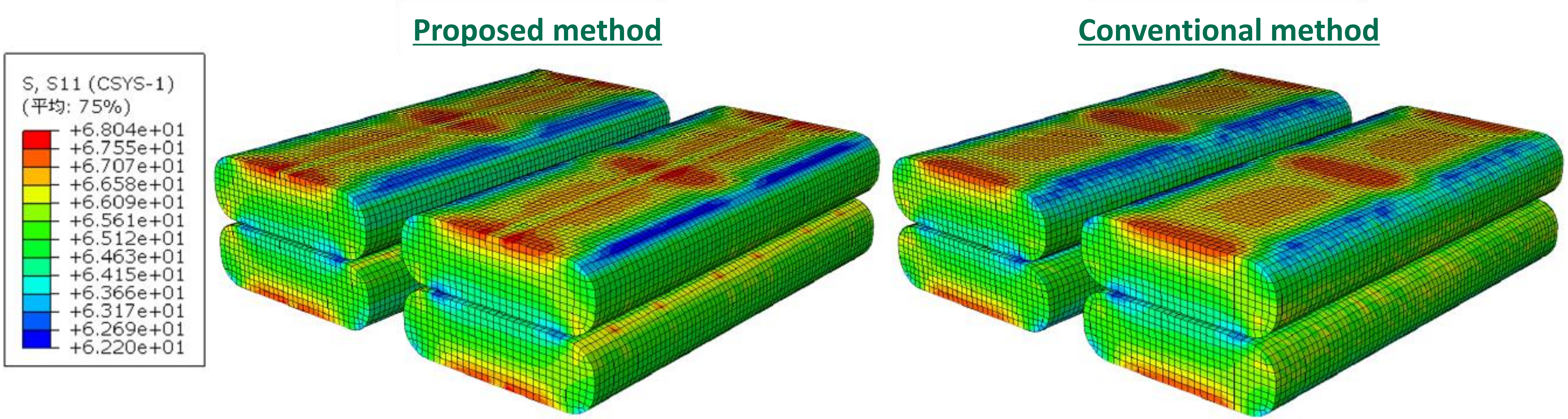
$G_{\mathrm{IC}} = 0.277\mathrm{kJ/m^2}$, $G_{\mathrm{IIC}} = 0.788\mathrm{kJ/m^2}$
$K_{\mathrm{ini}} = 8.0 \times 10^6\ \mathrm{GPa/m}$
$t_{\mathrm{I}} = 69.0\mathrm{MPa}$, $t_{\mathrm{II}} = 100.0\mathrm{MPa}$

Boundary condition

1% tensile strain is applied by displacement

Calculation results

σ_x distribution (central weft bundles) $\varepsilon_G = 0.60\%$

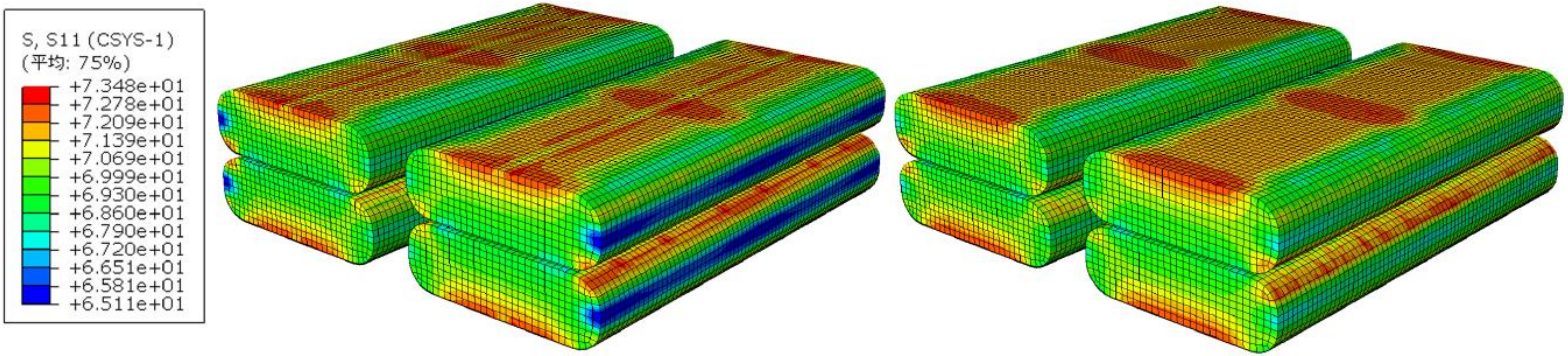


- ✓ **Overall stress distribution agrees well in both model**
- ✓ **Position and strain of occurrence of debonding agree well**
- ✓ **Delamination propagation behavior agrees well**

Calculation results

σ_x distribution (central weft bundles) $\varepsilon_G = 0.65\%$

Proposed method **Conventional method**

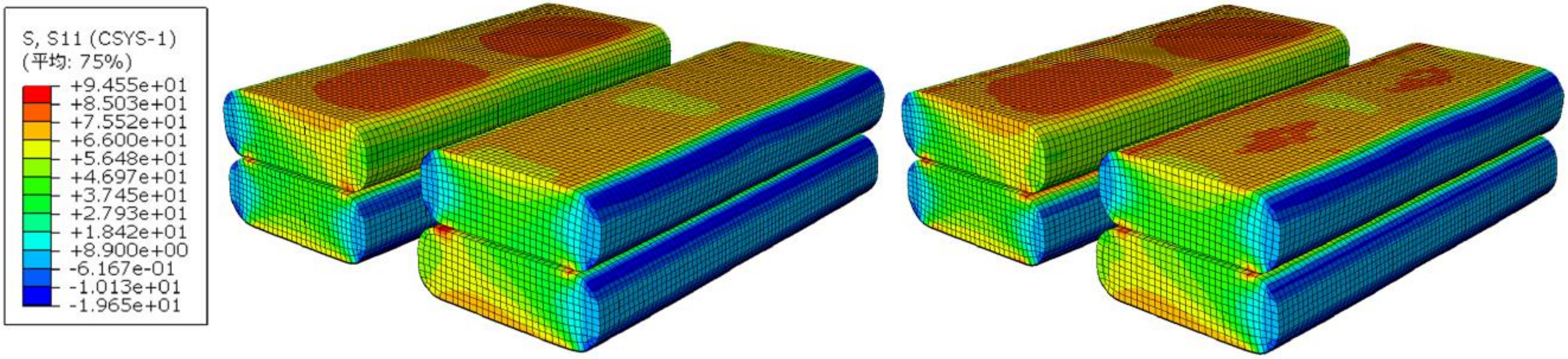


- ✓ **Overall stress distribution agrees well in both model**
- ✓ **Position and strain of occurrence of debonding agree well**
- ✓ **Delamination propagation behavior agrees well**

Calculation results

σ_x distribution (central weft bundles) $\varepsilon_G = 1.00\%$

Proposed method **Conventional method**



- ✓ **Overall stress distribution agrees well in both model**
- ✓ **Position and strain of occurrence of debonding agree well**
- ✓ **Delamination propagation behavior agrees well**

Summary

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- A new finite element modeling method for progressive damage analysis of textile composite was proposed, in which **fiber bundle and matrix resin are separately meshed**, and they are connected by using cohesive zone model.

- Validity of the proposed method was demonstrated by comparing the results to the conventional FEM results.

- **Mesh generation is very easy and takes short time**. Textile geometries can be modeled much smaller number of the nodes and elements.

- The proposed method can achieve precise damage progressive simulation of textile composites.