Progressive Damage Analysis of 3D Woven Composites Based on Decoupled Multi-scale Method

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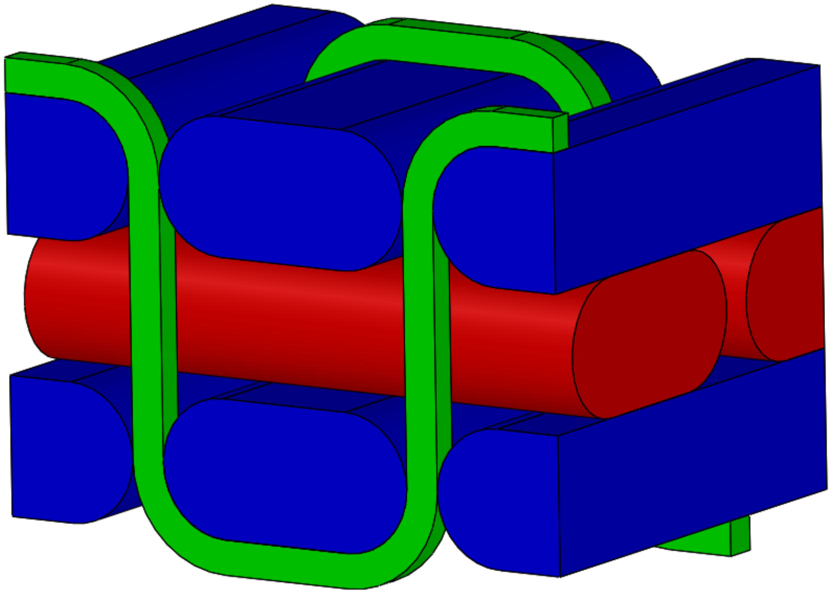
Introduction

☐ 3D woven CFRP

- Three-dimensionally oriented fiber bundles
- Higher impact resistance than UD-CFRP laminates
  ⇒ Applied in aerospace industry



3D woven CFRP model

Challenges

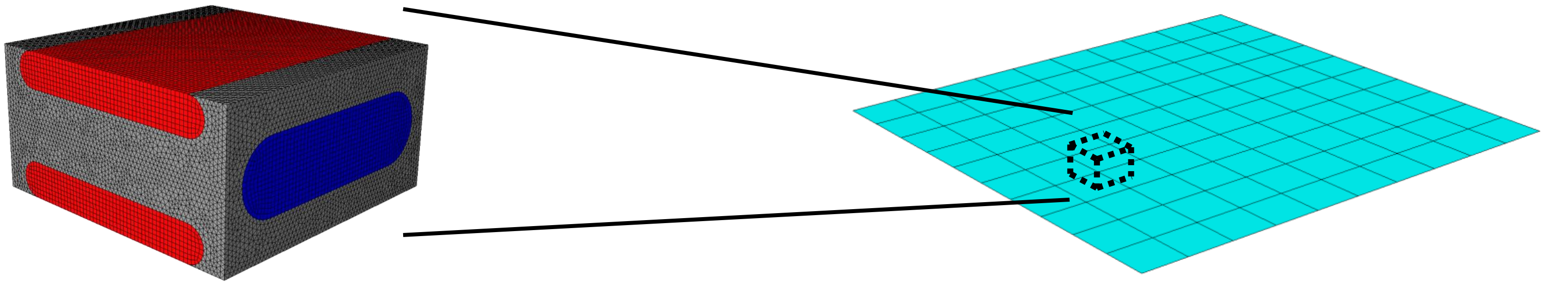
- Prediction of damage behavior with consideration of complex structure
- Reduction of the number of component tests

Efficient numerical method for simulating damage propagation behavior of 3D woven CFRP components is demanded.

Introduction

☐ Strength prediction using conventional homogenization method

- Assuming that microscopic structure is set up periodically
- Adopted only for uniform deformation in macroscopic scale



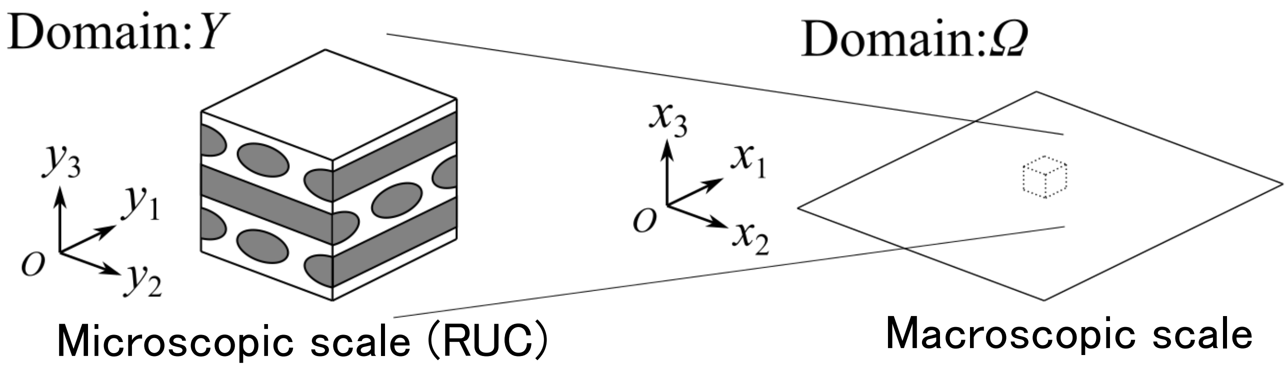
Microscopic scale
(RUC : Representative Unit Cell)

Macroscopic scale
(CFRP plate)

Objective

- Proposing simulation method of **progressive damage of 3D woven composites**
- Adopting proposed method to **macroscopic non-uniform deformation**

Multi-scale analysis



- **Two scale analyses** for woven structure

$$\boldsymbol{\varepsilon} = \tilde{\boldsymbol{\varepsilon}} + \boldsymbol{\varepsilon}^{(\mathrm{per})} \qquad \tilde{\boldsymbol{\sigma}}(\boldsymbol{x}) = \frac{1}{|Y|}\int_Y \boldsymbol{\sigma} dy$$

Microscopic variables

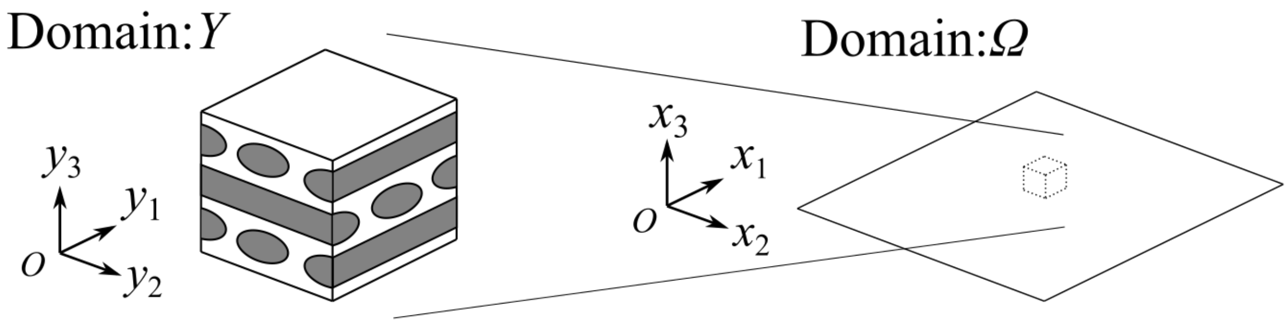
Macroscopic variables

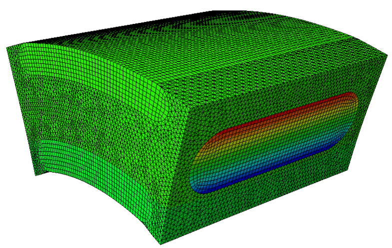
☐ Micro-macro coupled method : Conventional

- Both of two scale analyses must be carried out **alternately.**
- Microscopic analysis is carried out at **every integration points** of macroscopic model.

High calculation cost ⇒ Unrealistic for progressive damage simulation

Decoupled multi-scale method





Microscopic
analysis result

Identification

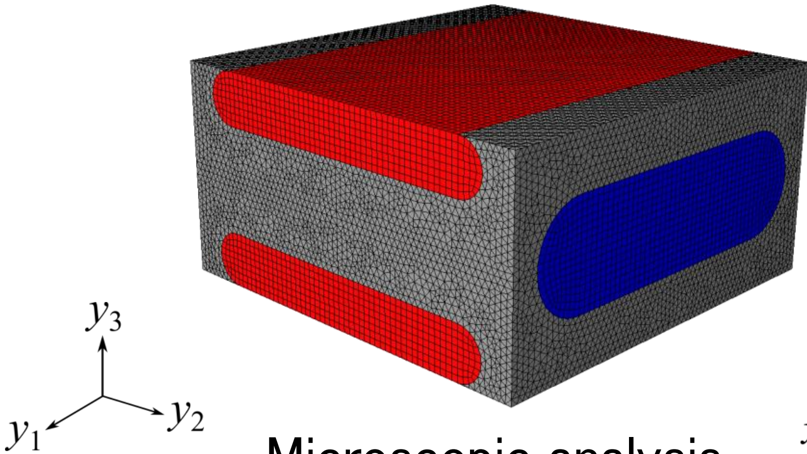
$$\boxed{\begin{aligned} \boldsymbol{N} &= \boldsymbol{A}\boldsymbol{E}^{\mathbf{macro}} \\ \boldsymbol{A} &= \boldsymbol{f}(\boldsymbol{D}) \end{aligned}}$$

Macroscopic
constitutive law

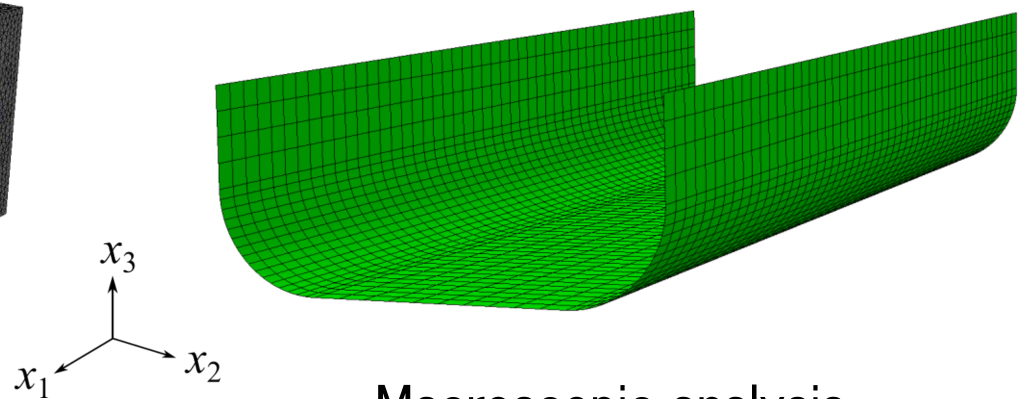
- Identifying macroscopic constitutive law by microscopic analysis
  ⇒ Non-simultaneous analyses
- Lower calculation costs than previous method

Effective method for damage simulation of woven composites.

Decoupled multi-scale analysis



Microscopic analysis
(RUC of woven CFRP)



Macroscopic analysis
(U-shaped beam structure)

□Microscopic scale

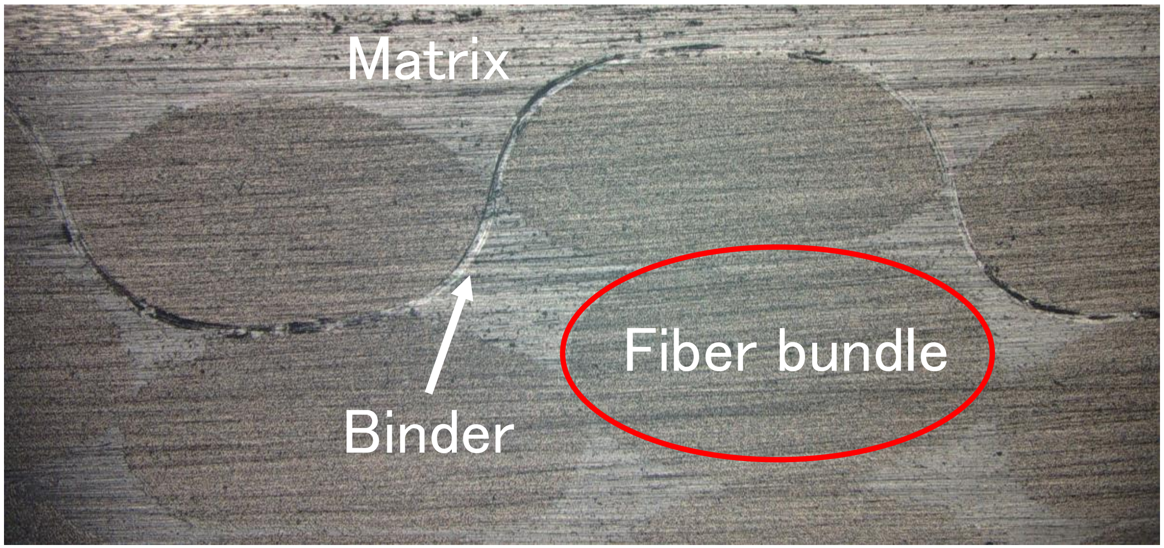
- Woven structure
- Damages modeling
- Analysis

□Macroscopic scale

- Identifying constitutive law
- Analysis
- Validating the proposed method

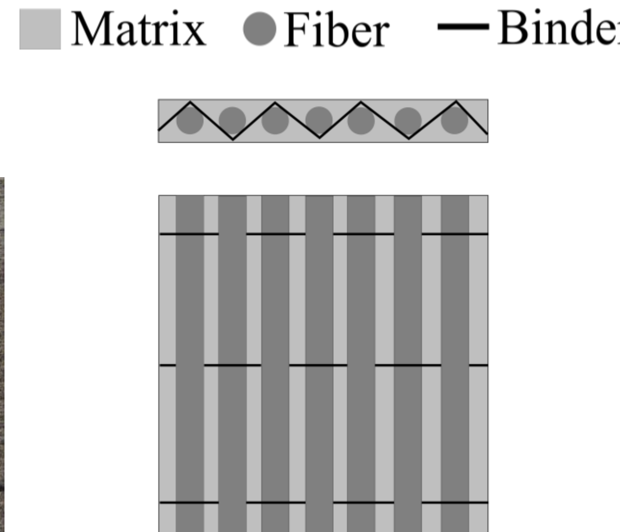
Bamboo weave

□ Textile composites used in this study



Cross section of Bamboo woven CFRP (90deg layer)

- Fiber is oriented in one direction.
- Nylon binders are woven orthogonally.

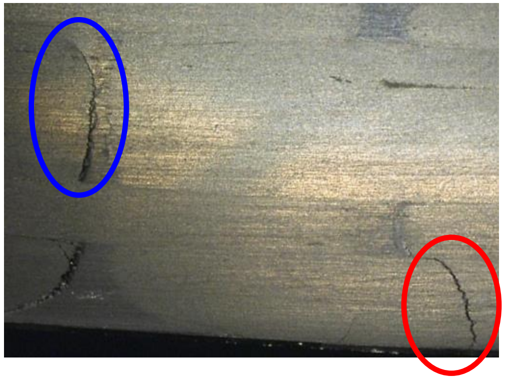


Schematic

Specimen

Microscopic damage modeling

Considering transverse crack and interface debonding
as typical damages of woven structure



① Transverse crack

Modeled by continuum damage mechanics (**CDM**) model

□ Constitutive law

$$\boxed{\boldsymbol{\sigma} = \boldsymbol{C}\boldsymbol{\varepsilon},\ \boldsymbol{C} = \boldsymbol{f}(d_2)}$$

Expressing stiffness degradation by
Transverse damage variable $\boldsymbol{d_2}$

□ Damage evolution law

$\boldsymbol{d_2} = \boldsymbol{g}(\boldsymbol{y_{d_2}})$ ⇒Identified by experiment

$$e = \frac{1}{2}\boldsymbol{\sigma} : \boldsymbol{\varepsilon}$$

$y_{d_2} = -\dfrac{\partial e}{\partial d_2}$ ⇒calculated by strain

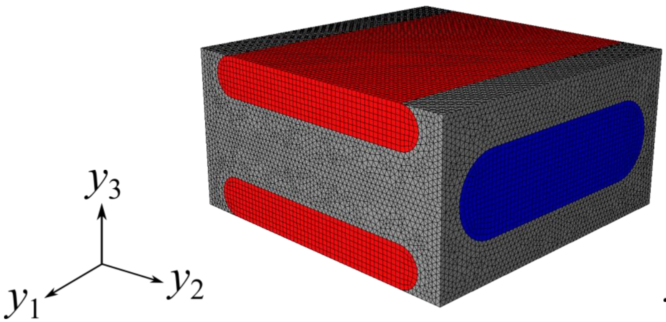
$\boldsymbol{C}$	: Stiffness tensor
d_2	: Transverse damage variable Undamaged → 0 Completely damaged → 1
e	: Helmholtz free energy per unit area
y_{d_2}	: Damage conjugate variable

② Interface debonding

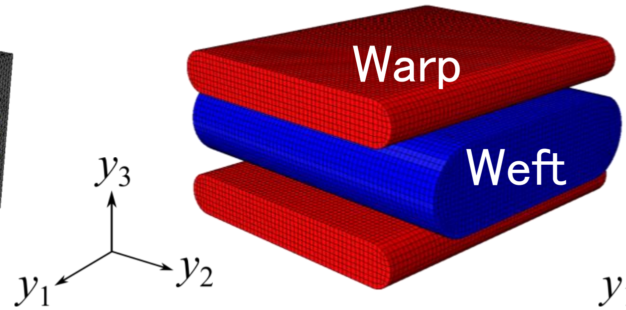
Modeled by cohesive zone model (**CZM**)

Microscopic analysis model

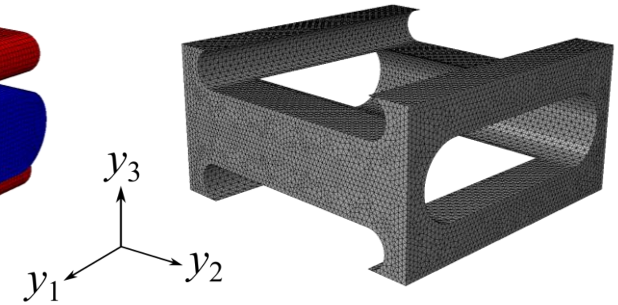
Carried out by
Abaqus/Standard 2018



RUC of bamboo weave



Fiber bundles



Resin

Nodes : 148,153, Elements : 242,392
Fiber bundles : hexa element (C3D8), Resin : tetra element (C3D4)
y_1 6.12 mm $\times$ y_2 6.12 mm $\times$ y_3 3.12 mm

Bamboo weave CFRP laminate $[0_3/90_3]_S$ is modeled. (Nylon binders are not considered)

□ Conditions

y_1, y_2 tensile, $y_1 y_2$ shear
y_1, y_2 bending, $y_1 y_2$ torsion

- **Periodical boundary conditions** are given, using Key-DOF method.
- **Macroscopic unit strain** and **curvature** are forced.

Parameters of fiber bundle

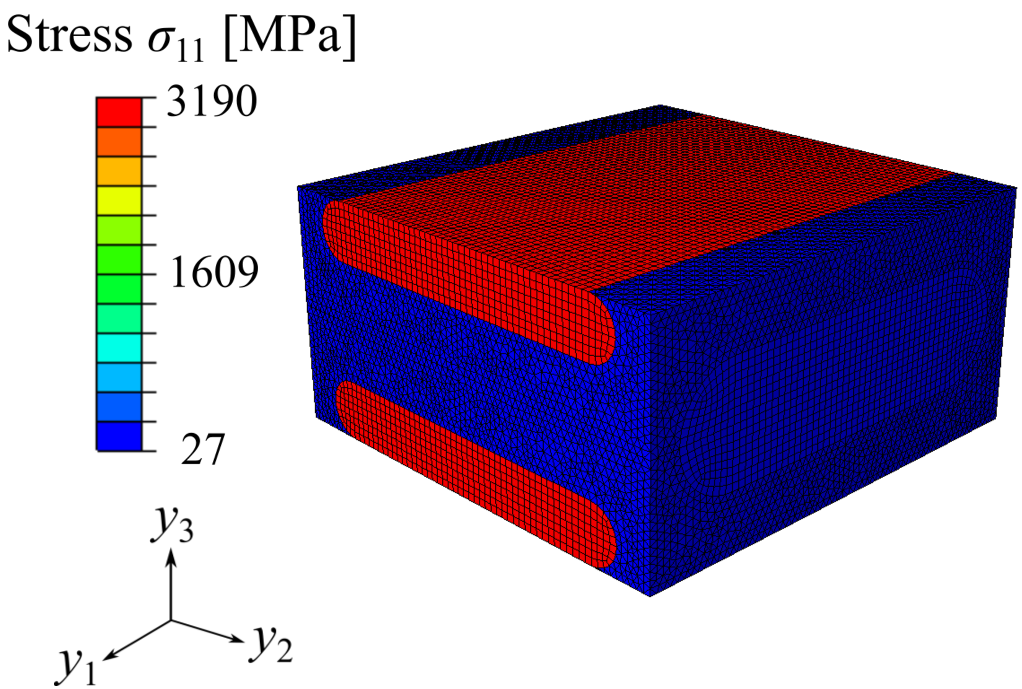
$E_L = 152.9\text{GPa}$	$E_T = 9.7\text{GPa}$
$\nu_{LT} = 0.373$	$\nu_{TT} = 0.450$
$G_{LT} = 4.5\text{GPa}$	

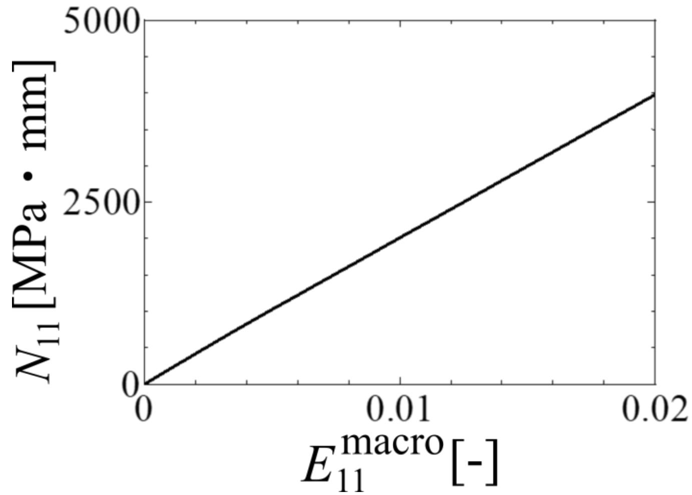
Parameters of resin

$E = 3.1\text{GPa}$	$\nu = 0.438$

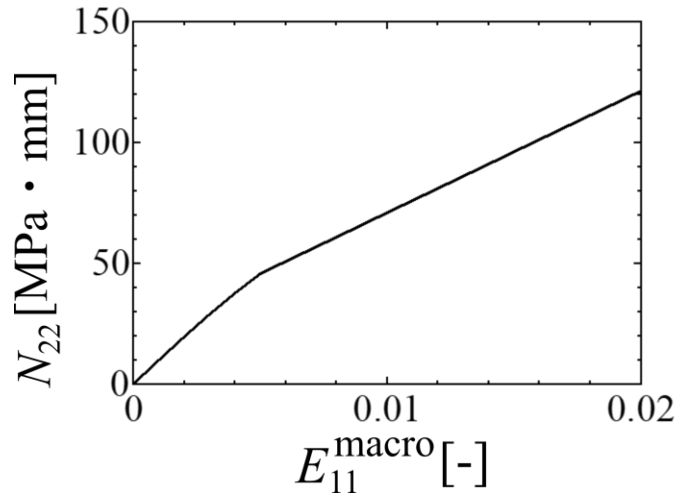
Microscopic analysis

y_1 tensile





Relationship between N_{11} and E_{11}^{macro}

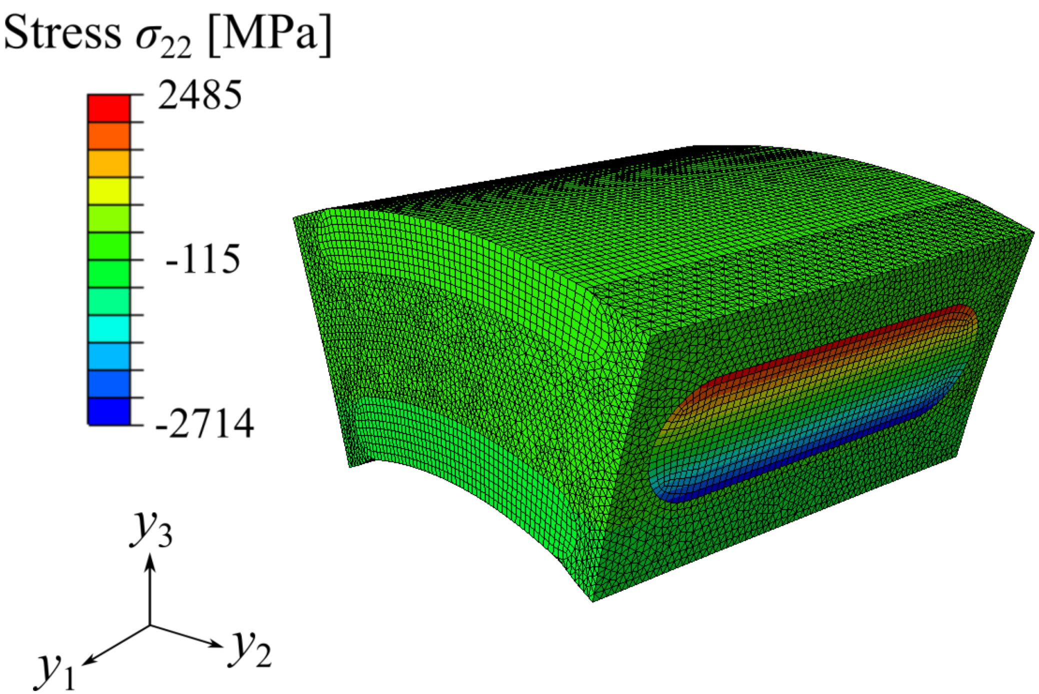


Relationship between N_{22} and E_{11}^{macro}

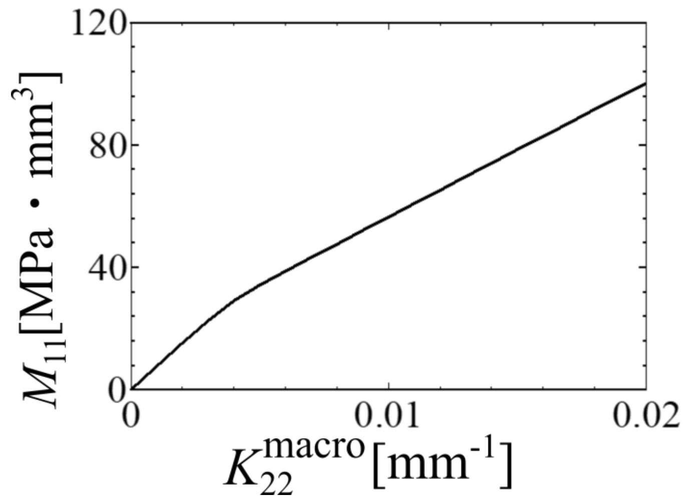
- Stress resultant N_{11} increases linearly and warp fiber bundles are under stress σ_{11}.
- N_{22} increases non-linearly due to transverse damage of weft fiber bundle.

Microscopic analysis

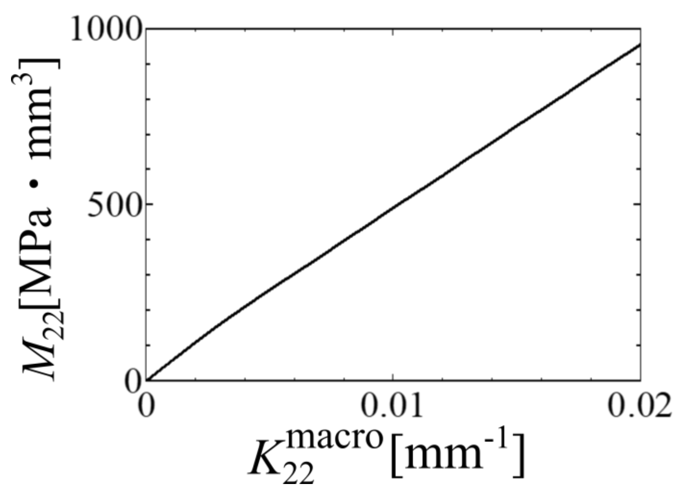
y_2 bending



- Moment resultant M_{22} increases linearly and weft fiber bundle is under stress σ_{22}.
- M_{11} increases non-linearly due to transverse damage of warp fiber bundles.

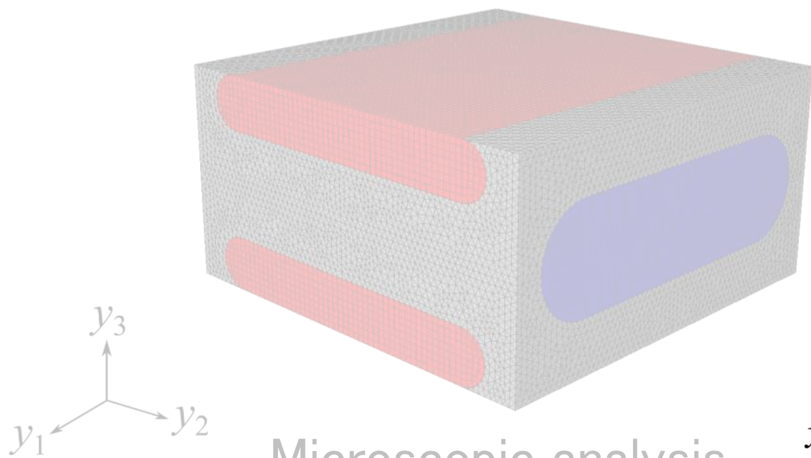


Relationship between M_{11} and K_{22}^{macro}

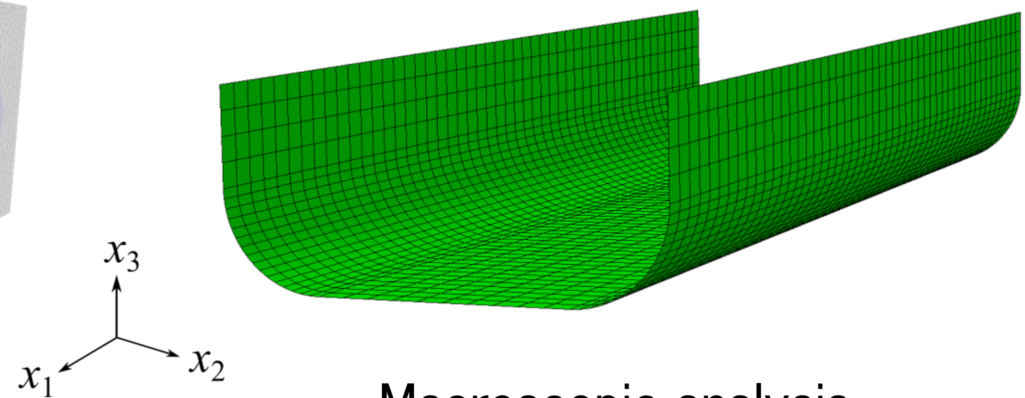


Relationship between M_{22} and K_{22}^{macro}

Decoupled multi-scale analysis



Microscopic analysis
(RUC of woven CFRP)



Macroscopic analysis
(U-shaped beam structure)

□Microscopic scale

- Woven structure
- Damages modeling
- Analysis

□Macroscopic scale

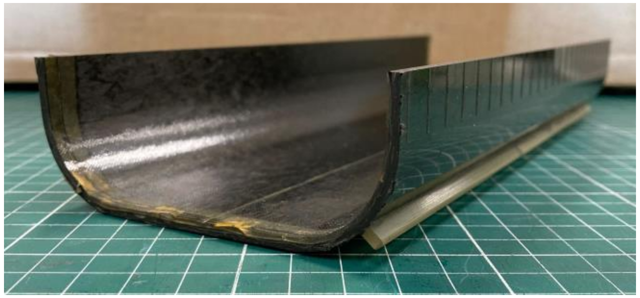
- Identifying constitutive law
- Analysis
- Validating the proposed method

Macroscopic constitutive law

☐ Constitutive law

Relationship between
stress resultant and unit strain

$$\boxed{\boldsymbol{N} = \boldsymbol{A}\boldsymbol{E}^{\mathrm{macro}},\ \boldsymbol{A} = \boldsymbol{f}(\boldsymbol{D})}$$



U–shaped specimen

- Damage is modeled by CDM model.
  - **Warp fiber bundle direction** at microscopic model ⇒ $\boldsymbol{D}_1$
  - **Weft fiber bundle direction** at microscopic model ⇒ $\boldsymbol{D}_2$

☐ Damage evolution law

$\boldsymbol{D} = f(\boldsymbol{Y}_{\boldsymbol{D}})$ ⇒ Identified by microscopic analysis

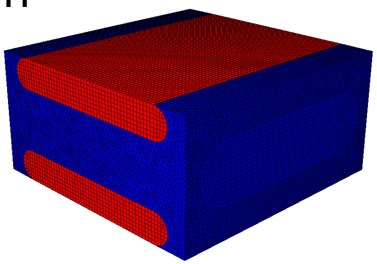
$$e = \frac{1}{2}\boldsymbol{N}:\boldsymbol{E}^{\mathbf{macro}} + \frac{1}{2}\boldsymbol{M}:\boldsymbol{K}^{\mathbf{macro}}$$

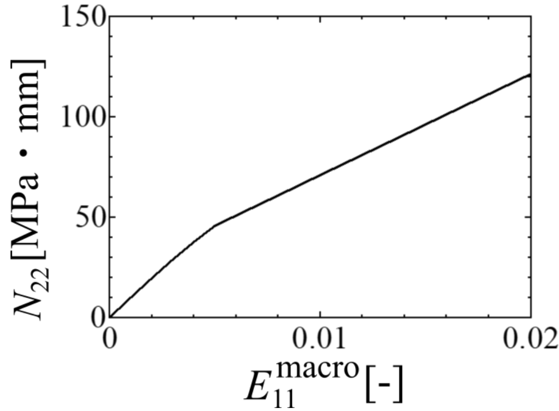
$\boldsymbol{Y}_{\boldsymbol{D}} = -\dfrac{\partial e}{\partial \boldsymbol{D}}$ ⇒ Calculated by strain and curvature

$\boldsymbol{A}$	: In–plane stiffness matrix
$\boldsymbol{D}$	: Macroscopic damage variables Undamaged → 0 Completely damaged → 1
e	: Helmholtz free energy per unit area
$\boldsymbol{Y}_{\boldsymbol{D}}$	: Damage conjugate variables

Identifying constitutive law

- Damage variables $\boldsymbol{D}$
  ⇒Obtained from Stiffness degradation of microscopic analysis
- Damage conjugate variables $\boldsymbol{Y_D}$
  ⇒Calculated by macroscopic strain and curvature

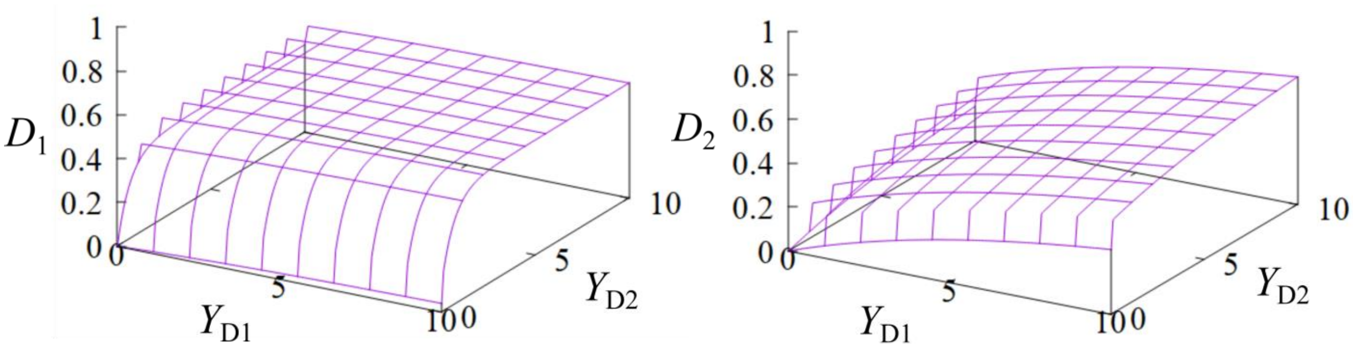




Stiffness degradation of microscopic analysis

☐ Damage evolution law

$$D = a_1[1 - \exp(-b_1 Y_{D1})] + a_2[1 - \exp(-b_2 Y_{D2})] + a_3[1 - \exp(-b_3 Y_{D1} Y_{D2})]$$



Relationship between $\boldsymbol{D}$ and $\boldsymbol{Y_D}$

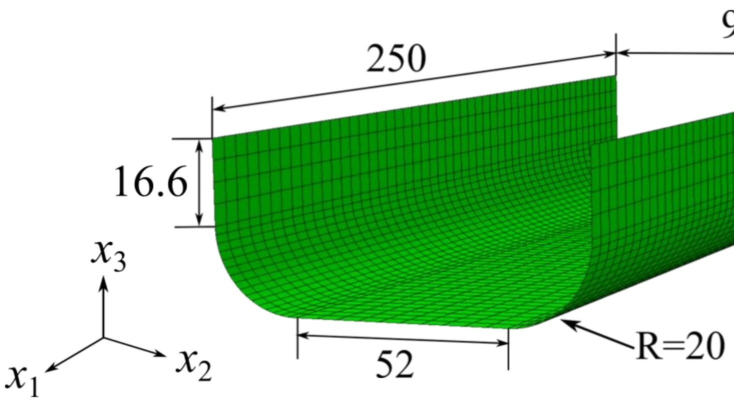
Fitting parameters

D_1		D_2	
a_1	0.05	a_1	0.40
b_1	0.151	b_1	0.133
a_2	0.40	a_2	0.20
b_2	1.501	b_2	0.156
a_3	0.0866	a_3	0.128
b_3	10381	b_3	4453.8

Macroscopic analysis can be carried out separately from microscopic analysis.

U-shaped flexural analysis

☐ Analysis model

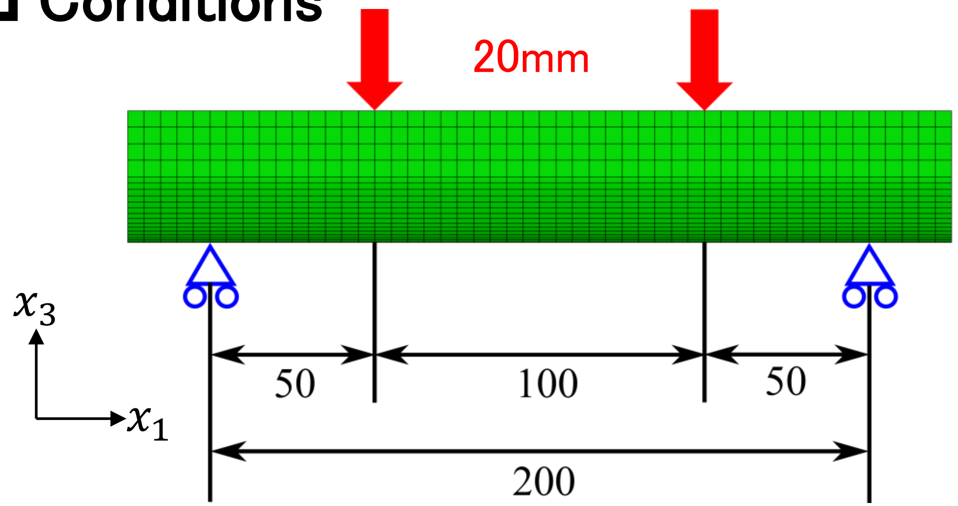


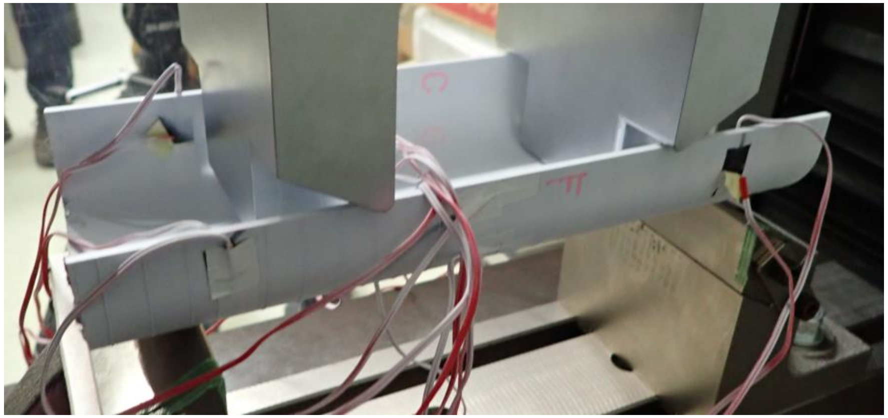
Nodes : 7701, Elements : 2500
Second order shell elements (S8R)

- x_1 direction ⇔ Warp direction of microscopic model

Four-point bending analysis is carried out to investigate **the initial damage occurrence location and damage process.**

☐ Conditions

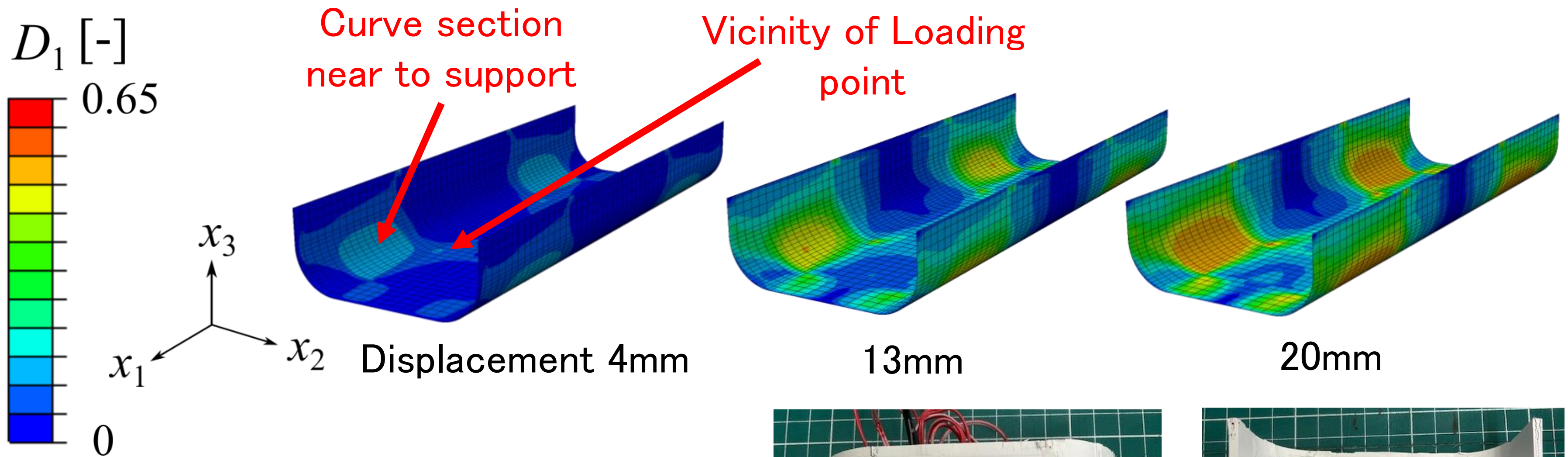




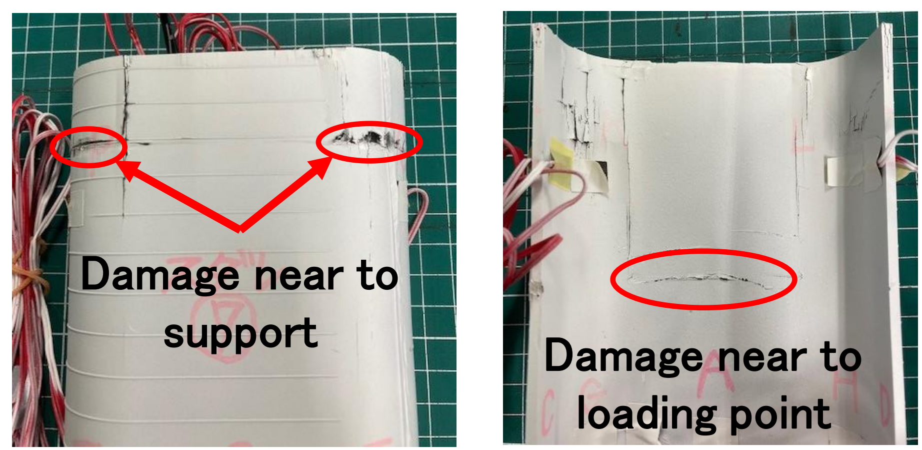
Four-point bending test

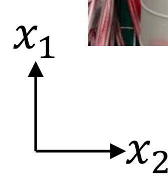
Investigating initial damage location

☐ Results (Warp direction damage variable D_1 distribution)



- Damage occurs <u>near to support and near to load point</u> in analysis.
- Damage are observed <u>near to support and near to load point</u> in experiment.

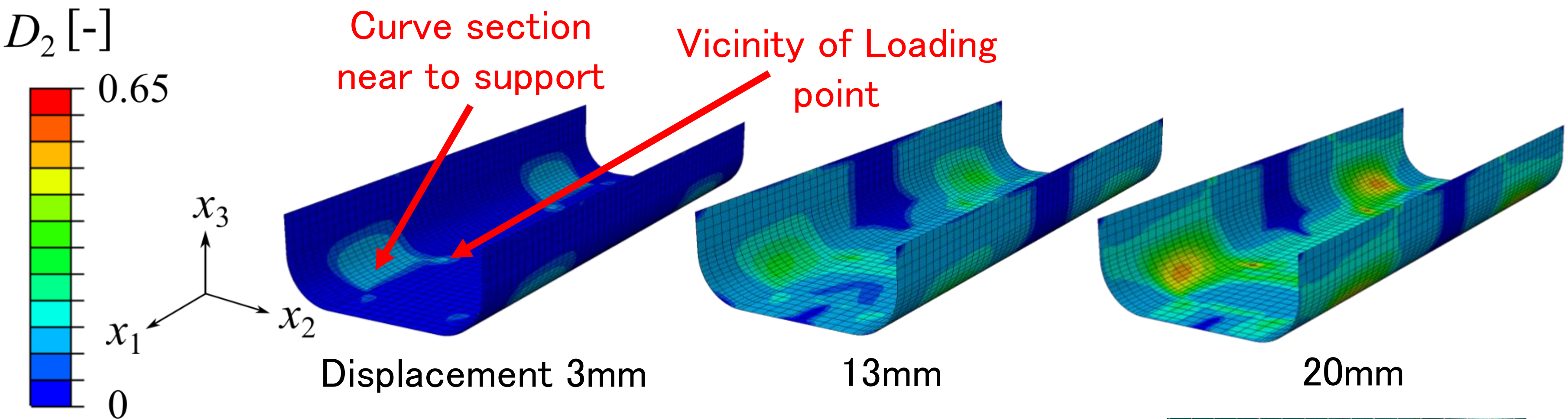




Damage observation
(Left : outside, Right : inside)

Investigating initial damage location

☐ Results (Weft direction damage variable D_2 distribution)



- Damage occurs <u>near to support and near to load point</u> in analysis.
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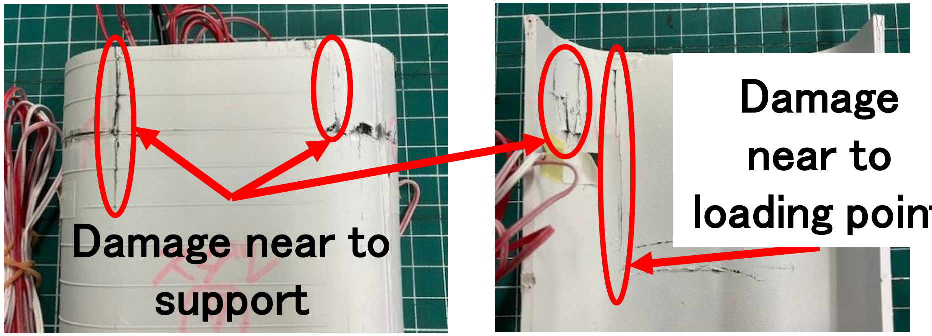

Proposed method can predict the initial damage location of U-shaped specimen.

Conclusion

Decoupled multi-scale damage analysis method for textile composite has been proposed.

- **Transverse crack and interface debonding** were modeled as typical damages of woven structure and macroscopic constitutive law was identified by microscopic analysis.

- **U-shaped beam structure** was chosen as macroscopic structure, and damage propagation was modeled by CDM model.

- **Four-point bending** analysis was carried out to investigate initial damage occurrence location and flexural test was also carried out for validating the proposed method.

The proposed method effectively simulated the initial damage occurrence location of macroscopic complex structure.