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Numerical Study on Effect of Fiber Waviness on Mechanical Properties of Unidirectional Composite Laminates

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Outline

1. Introduction
2. Numerical modelling
3. Results & Discussion
4. Application
5. Summary & Future work

1. Introduction

CFRTP (Carbon Fiber Reinforced Thermoplastics)

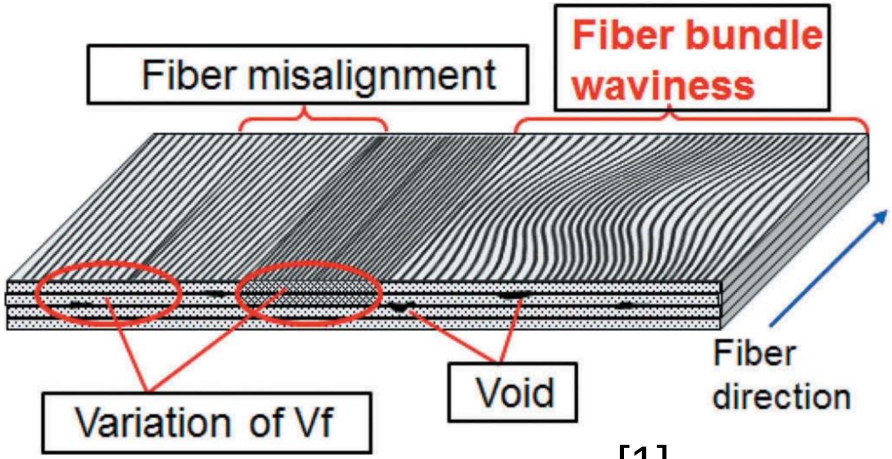
- High productivity and high recyclability
- Various manufacturing defects

→ ・Unpredictability due to the complex molding behavior of the resin
 ・In particular, the effect of **fiber waviness** on the strength is unexplained

High safety rate

↕

High specific stiffness & strength
(Superiority of CFRP)



[1]

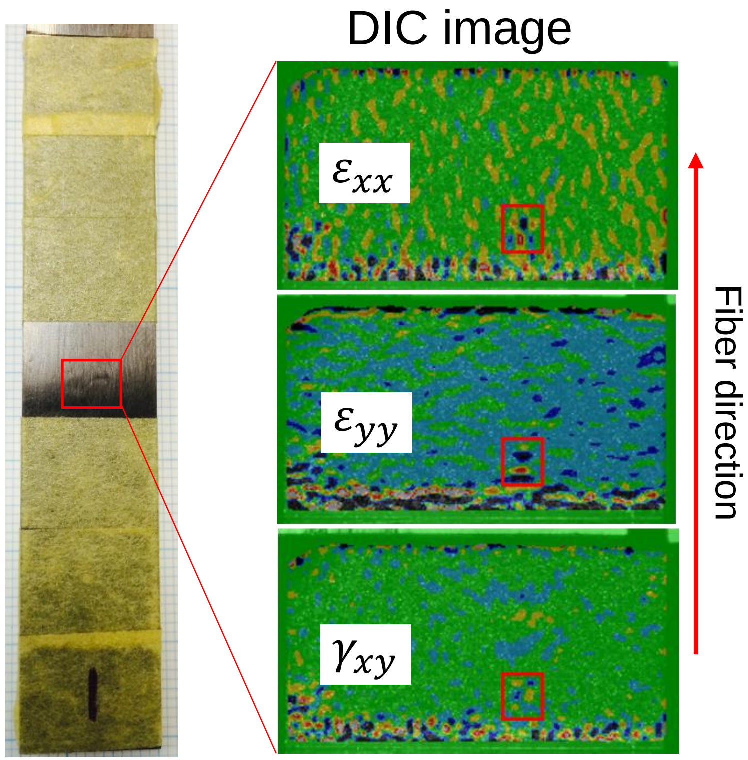
➡ Requirement for understanding the effect of fiber waviness on composites strength

[1] Yokozeki et al, ADVANCED COMPOSITE MATERIAL, 2020.

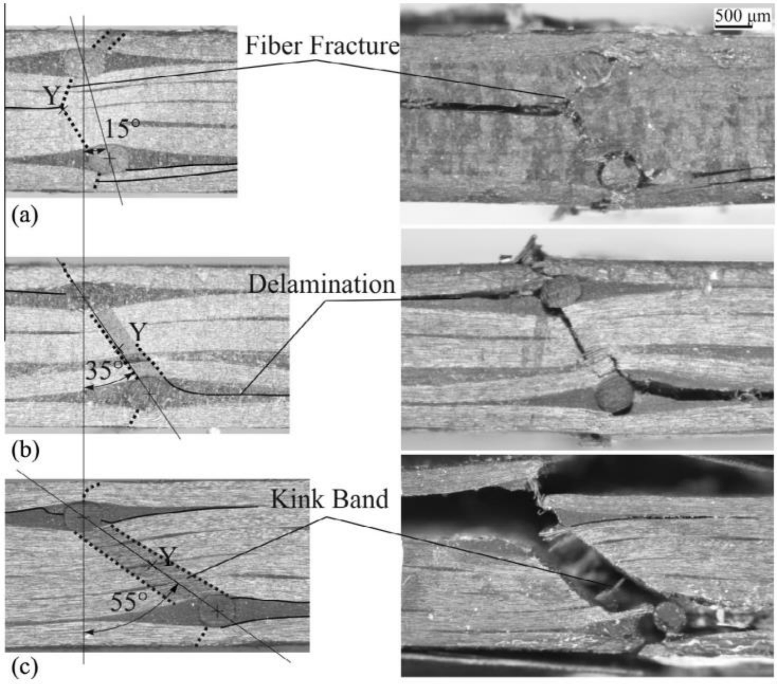
1. Introduction

Fiber waviness

- Inhomogeneous stress/strain field
- Various fracture modes



[2]



[3]

➡ Development of numerical scheme which takes into account the complicated fracture behavior of composites

[2] Akakabe, The University of Tokyo (Unpublished master thesis) , 2016.
[3] Hörrmann et al, International Journal of Fatigue, 2016.

1. Introduction

Objectives

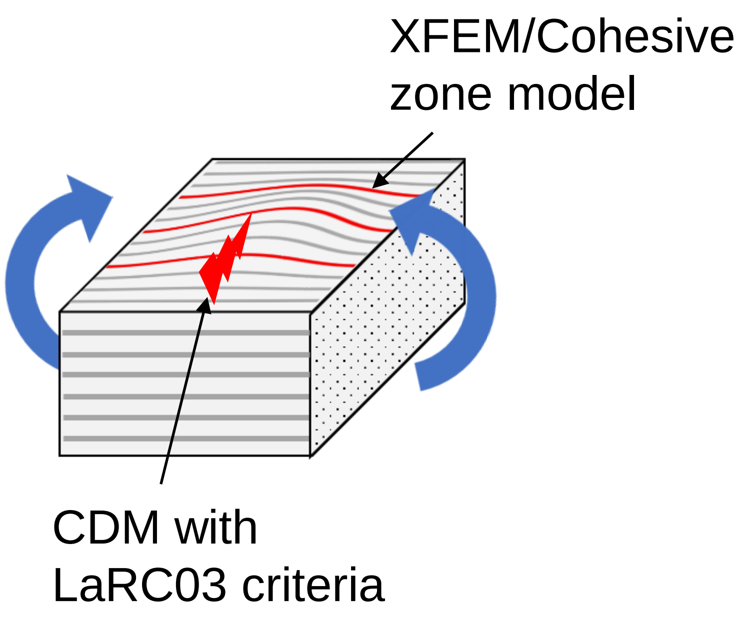
Investigation of the effect of fiber waviness on composite strength

Various modes of fracture around the fiber waviness

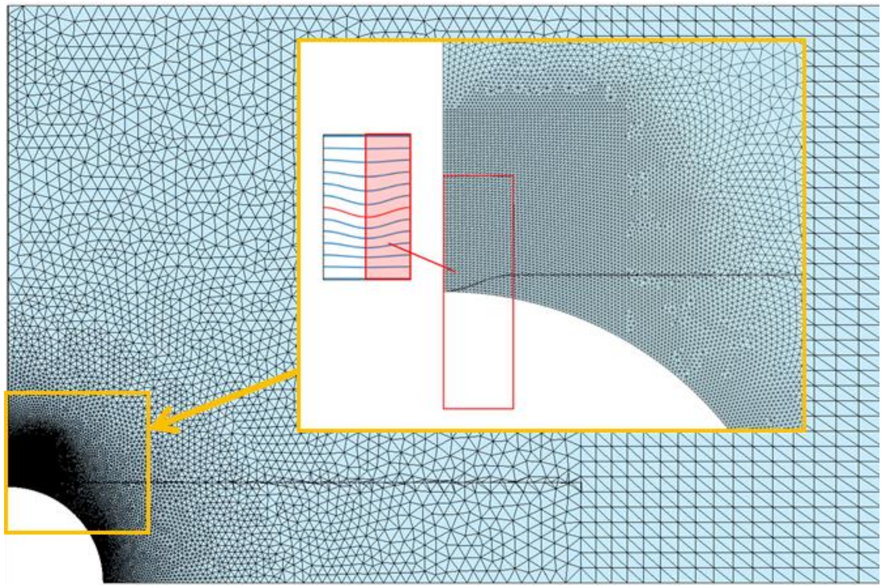
ex) Fiber kinking, Transverse crack growth along the fiber waviness

Contents

- Longitudinal compression of fiber waviness region

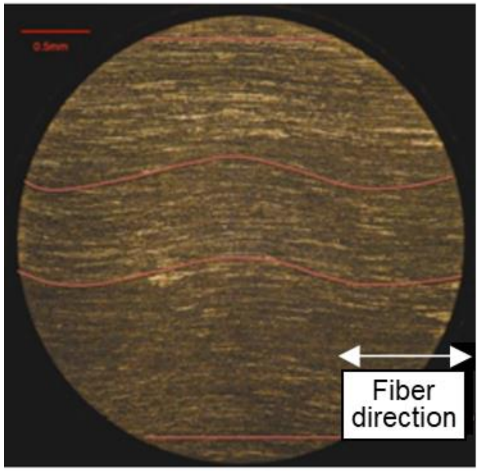


- Open hole compression (OHC)

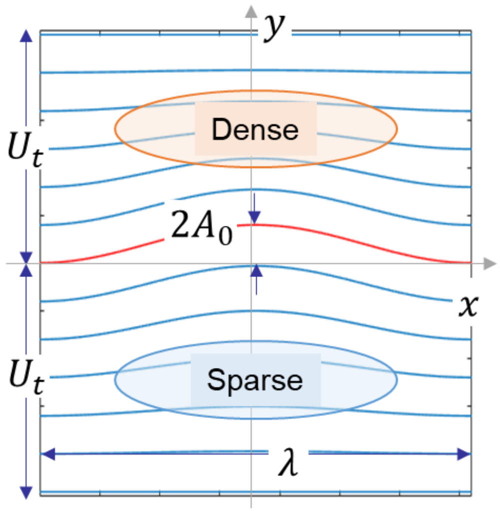


2. Numerical modelling

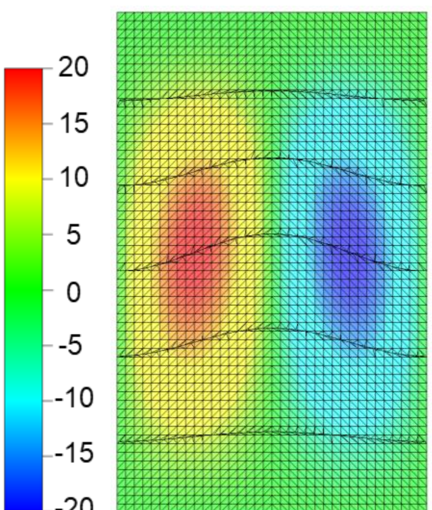
Fiber waviness modelling



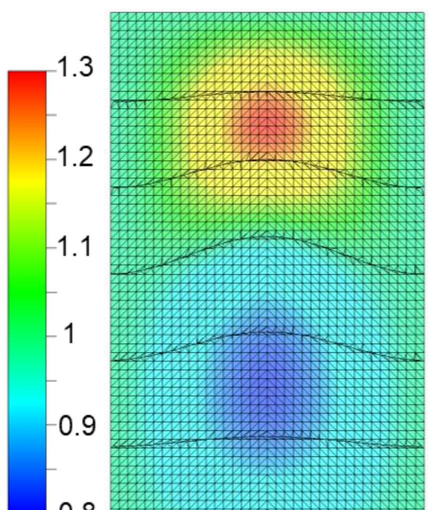
Optical image[1]



Geometry



$\theta \ (w = 0.06)$



$v_f / \bar{v}_f \ (w = 0.06)$

- Geometry → fitting a sine curve

$$Y(x, y) = A_0 \cos^2\left(\frac{\pi y}{2U_t}\right) \cos\left(\frac{2\pi x}{\lambda}\right)$$

  - ✓ Misalignment angle θ

$$\theta = \tan^{-1} \frac{\partial Y(x, y)}{\partial x}$$

  - ✓ Fiber volume fraction v_f

$$v_f = \left(1 + \frac{\partial Y(x, y)}{\partial y}\right)^{-1} \bar{v}_f$$

- Elements homogenization
  - ✓ Material properties
    Coordinate transformation: θ
    Rule of mixture: v_f

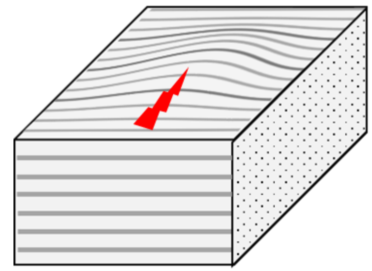
- Metric in this work
  → Severity of fiber waviness

$$w = A_0^{max} / \lambda$$

[1] Yokozeki et al, ADVANCED COMPOSITE MATERIAL, 2020.

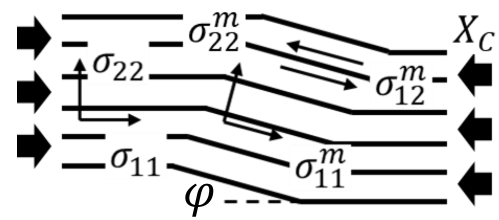
2. Numerical modelling

Fiber compressive failure



- **Failure Criteria: LaRC03 criteria** [4]

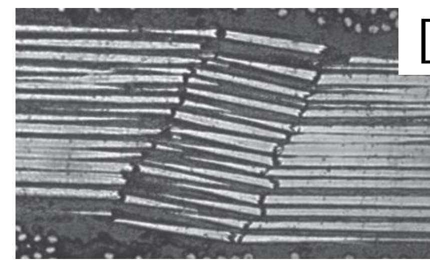
$$FI_F = \frac{|\sigma_{12}^m| + \langle \eta^L \sigma_{22}^m \rangle}{S_L} \geq 1, \qquad \left(\eta^L = -\frac{S_L \cos(2\alpha_0)}{Y_C \cos^2 \alpha_0} \right)$$



✓ Kink bands failure, typical failure mode for composite material under compression, is modeled

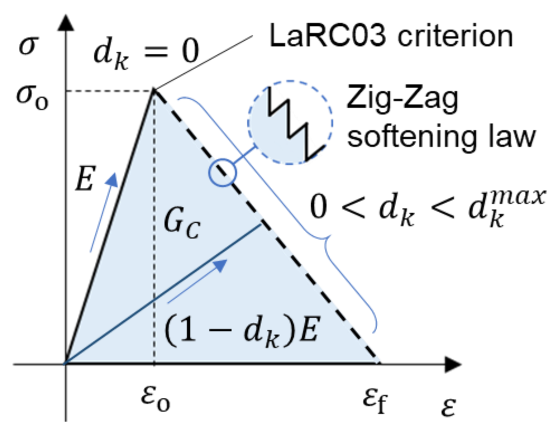
✓ Initial misalignment angle φ_0 in LaRC03 is used for misalignment angle in non-waviness elements

$$\varphi_0 = \left(1 - \frac{X_C}{G_{12}}\right) \tan^{-1}\left(1 - \sqrt{1 - 4\left(\frac{S_L}{X_C} + \eta^L\right)\frac{S_L}{X_C}} \Big/ 2\left(\frac{S_L}{X_C} + \eta^L\right)\right)$$


[6]

- **Model: Continuum Damage Mechanics (CDM) model** [5]

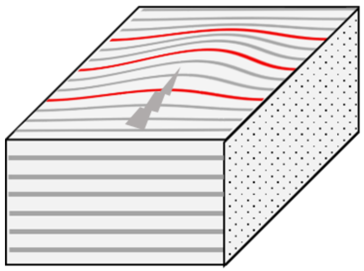
✓ Stiffness reduction along with energy-based propagation model is employed



[4] C.G. Davila et al., NASA / TM-2003- 212663, 2003.
[5] Z.P. Bazant and B.H. Oh, Matériaux et construction, 1983.
[6] S.T.Pinho et al., Journal of Composite Materials, 2012.

2. Numerical modelling

Transverse crack



- **eXtended Finite Element Method (XFEM)** [7,8]

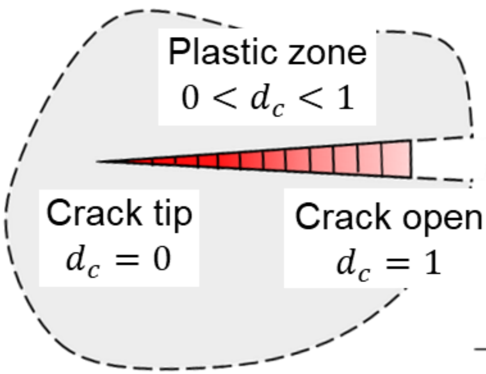
$$\boldsymbol{u}^h(\boldsymbol{x}) = \sum_I N_I(\boldsymbol{x})\boldsymbol{u}_I + \boxed{\sum_I N_I(\boldsymbol{x})g(\boldsymbol{x})\boldsymbol{a}_I}.$$

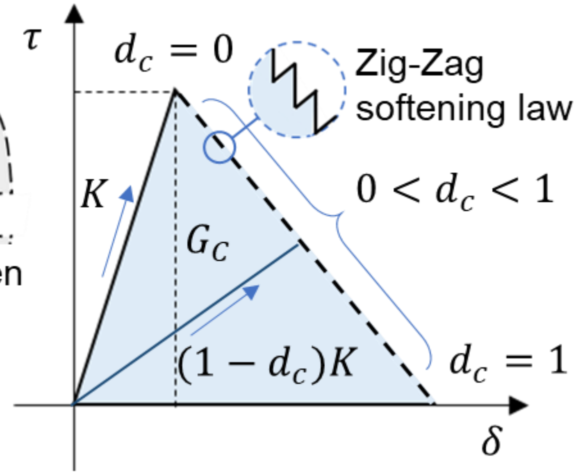
Enrichment for XFEM

$N_I(\boldsymbol{x})$: nodal shape function, $\boldsymbol{u}_I$: nodal displacement

- ✓ Cracks can be modeled independently from elements
- ✓ Discontinuity of displacement by cracks is modeled by enriching additional dofs $\boldsymbol{a}_I$ to nodes and discontinuous function $g(\boldsymbol{x})$ for interpolation

- **Cohesive Zone Model (CZM)** [9]
  - ✓ Combining with XFEM, plasticity around the crack tip is modeled with damage variable d_C
  - ✓ Onset: Quadratic stress criterion
  - ✓ Propagation: Energy criterion

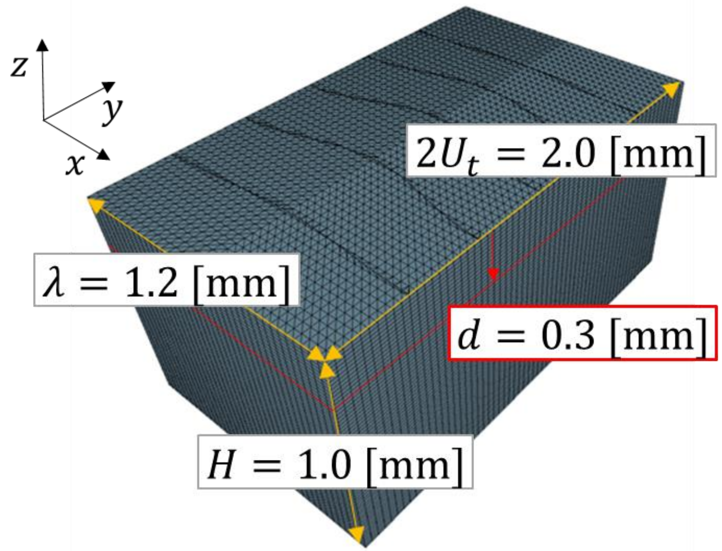




[7] T. Belytschko et al., International Journal for Numerical Methods in Engineering, 1999.
[8] N. Moes et al., International Journal for Numerical Methods in Engineering, 1999.
[9] P. Camanho et al., NASA/TM-2002-211737, 2002.

3. Validation

Simulation model



- ✓ Each element is cut in $1/30$ [mm] size in xy-plane, and $1/60$ [mm] size in z-direction
- ✓ Amplitude A_0 decreases linearly and 5 cracks are set in xy-plane from the upper surface to a depth of $d = 0.3$ [mm]
- ✓ Macroscopic curvature K is applied with periodic boundary condition [10], and macroscopic bending moment M is calculated
- ✓ Inter-lamina delamination was modeled with CZM

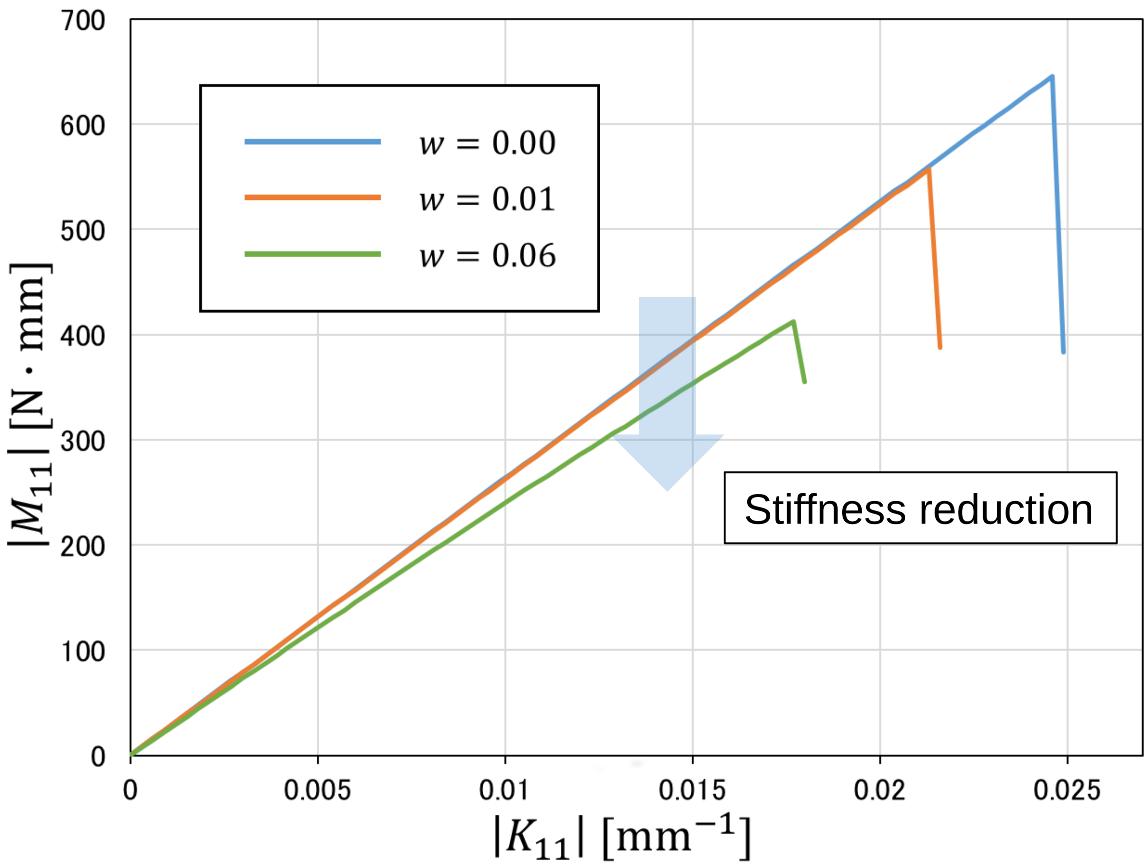
➢ Material properties (MCP1223) [1]

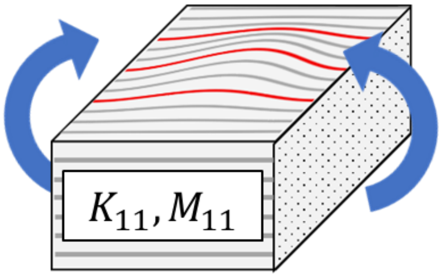
Average fiber fraction $\bar{v}_f$	0.65	
Fiber properties		
Longitudinal Young's modulus E^f_{11}	240	GPa
Transverse Young's modulus E^f_{22}	18.6	GPa
Poisson's ratio ν^f_{12}, ν^f_{23}	0.29	
Shear modulus G^f_{12}	100	GPa
Matrix properties		
Young's modulus E^m	4.5	Gpa
Poisson's ratio ν^m	0.3	
Shear modulus G^m	1.73	Gpa
Failure properties		
Longitudinal compressive strength X_C	1530	Mpa
Transverse compressive strength Y_C	280	Mpa
Transverse tensile strength Y_T	91	Mpa
Longitudinal shear strength S_L	80	MPa

[1] Yokozeki et al, ADVANCED COMPOSITE MATERIAL, 2020.
[10] K. Yoshida et al., Advanced Composite Materials, 2017.

3. Validation

Results

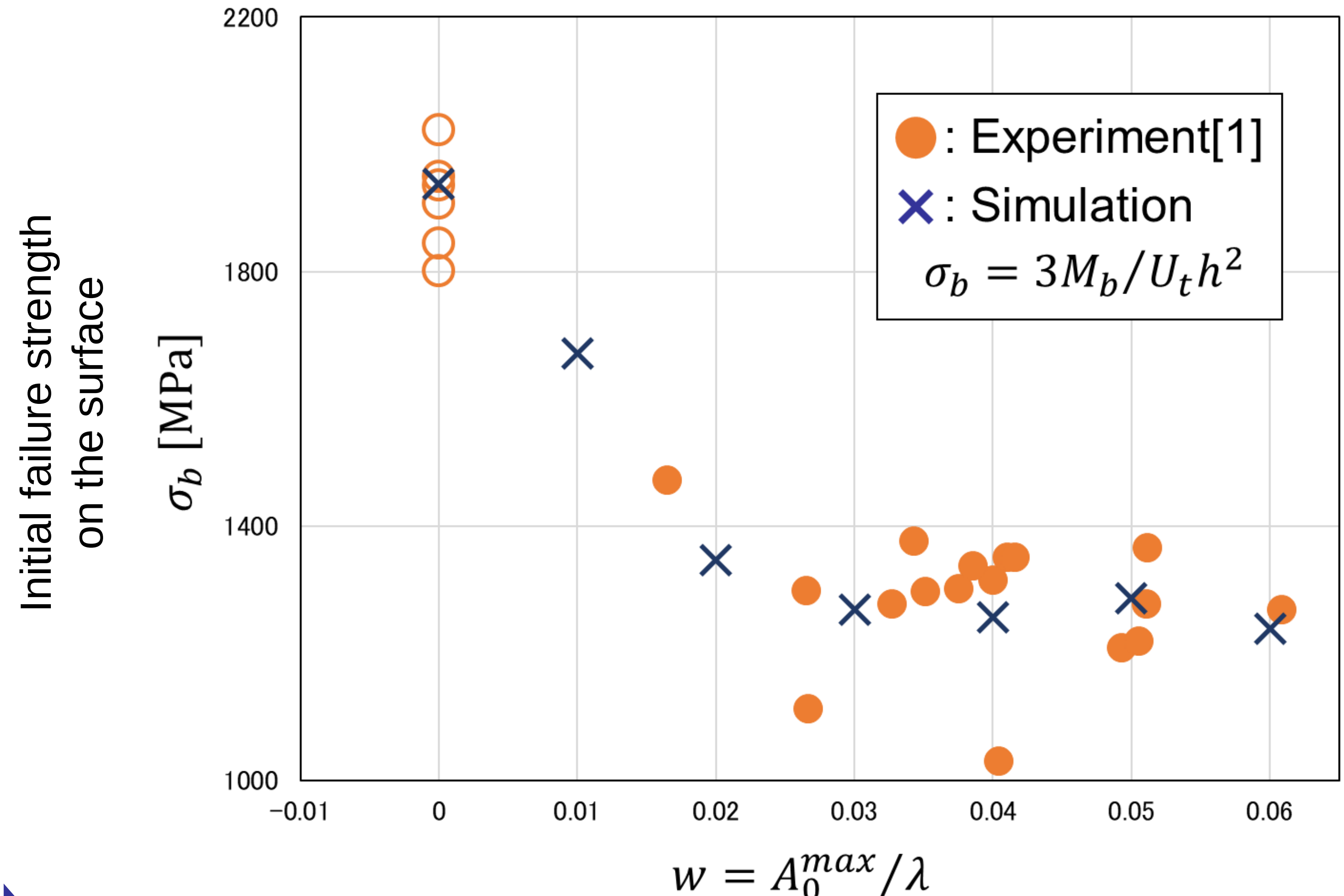




The strengths decrease with an increase in fiber waviness severity w

3. Validation

Comparison with experimental data: Yokozeki[1]

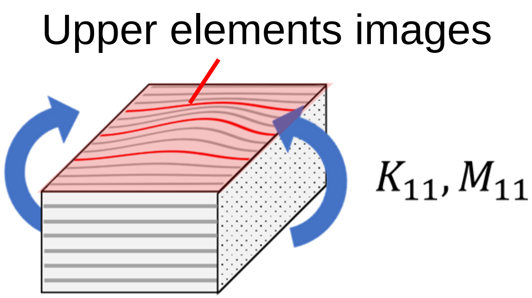


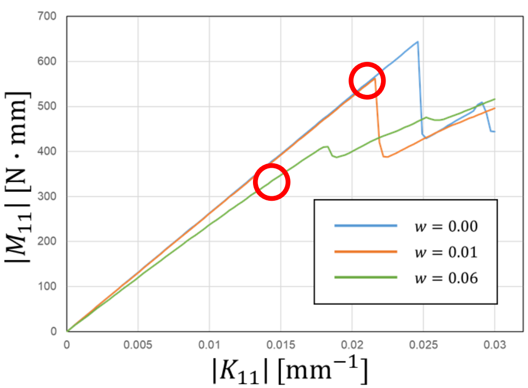
Numerical scheme in this work is validated with experimental data

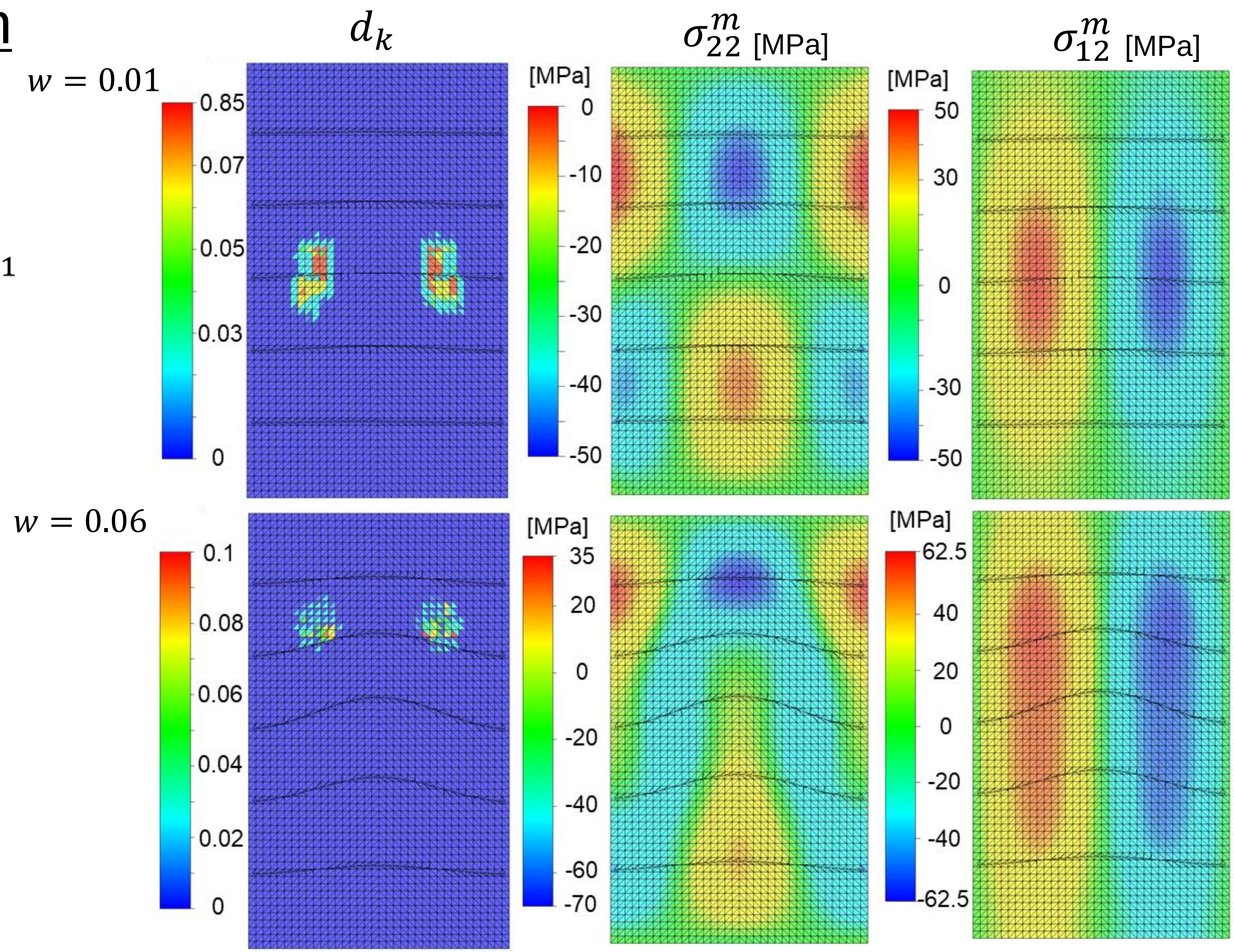
[1] Yokozeki et al, ADVANCED COMPOSITE MATERIAL, 2020.

3. Validation

Damage initiation





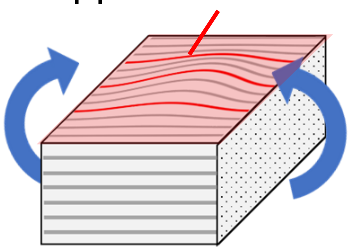


➡ Fiber kinking damage was initiated at the location of high shear stress caused by the fiber waviness

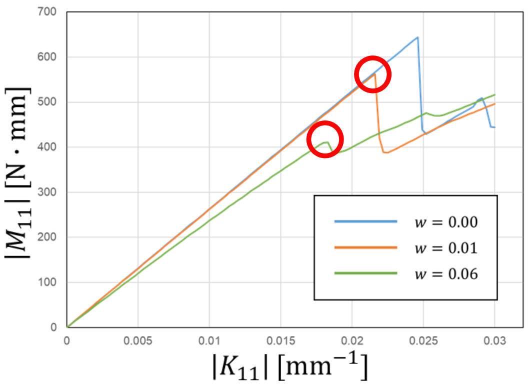
3. Validation

Failure initiation

Upper elements images



K_{11}, M_{11}

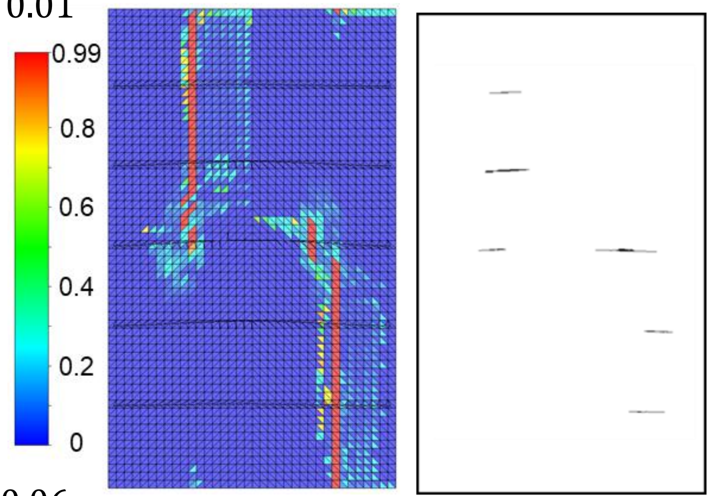


d_k

Crack propagation

Failure character

$w = 0.01$



- ✓ Predominant mode
  → Fiber failure
- ✓ Immediate propagation

  Damage initiation

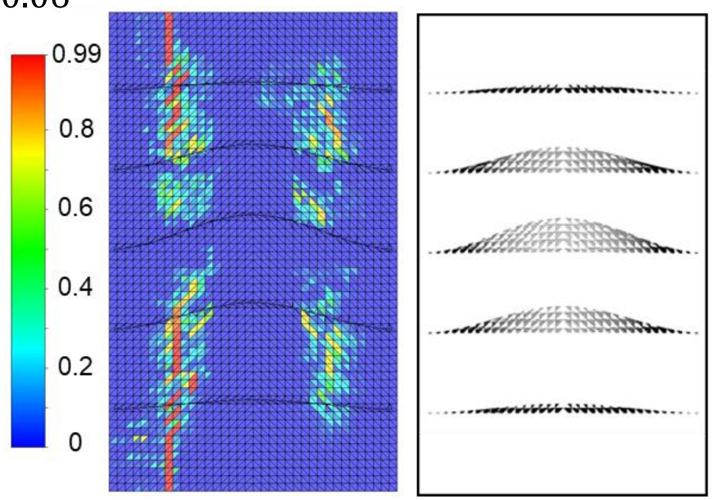
  $K_{11} = 0.0207$ [mm^{-1}]

  ↓

  Failure initiation

  $K_{11} = 0.0216$ [mm^{-1}]

$w = 0.06$



- ✓ Predominant mode
  → Transverse crack
- ✓ Asymptotic propagation

  Damage initiation

  $K_{11} = 0.0129$ [mm^{-1}]

  ↓

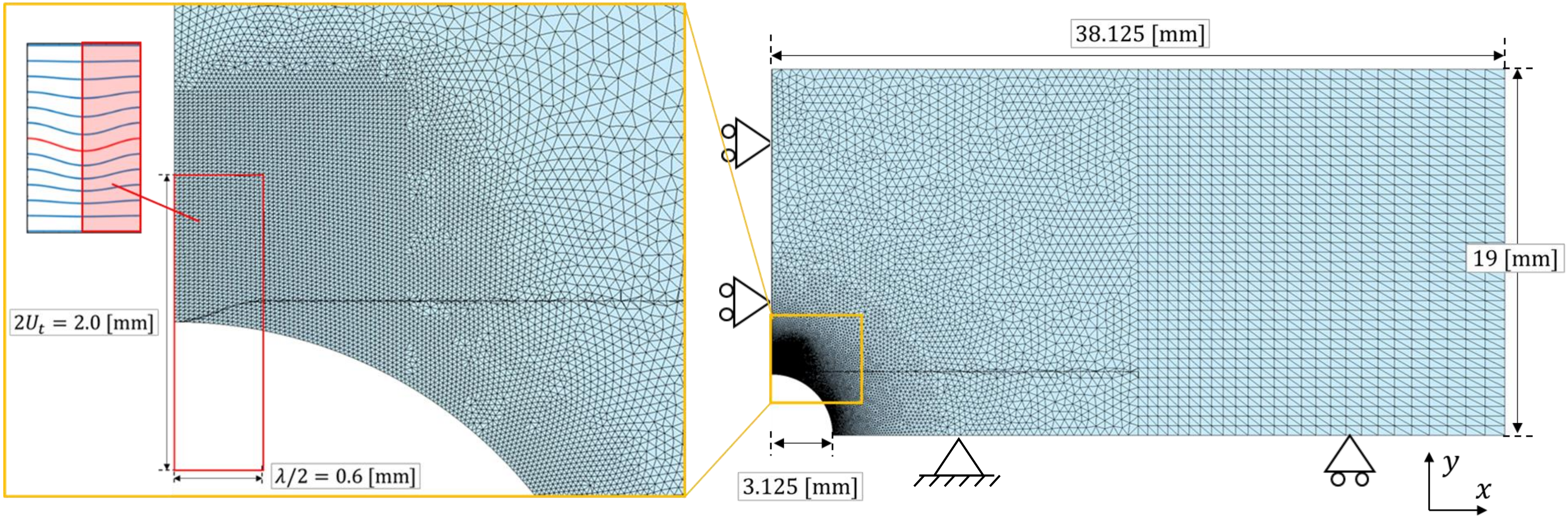
  Failure initiation

  $K_{11} = 0.0186$ [mm^{-1}]

4. Application (OHC test)

Simulation model

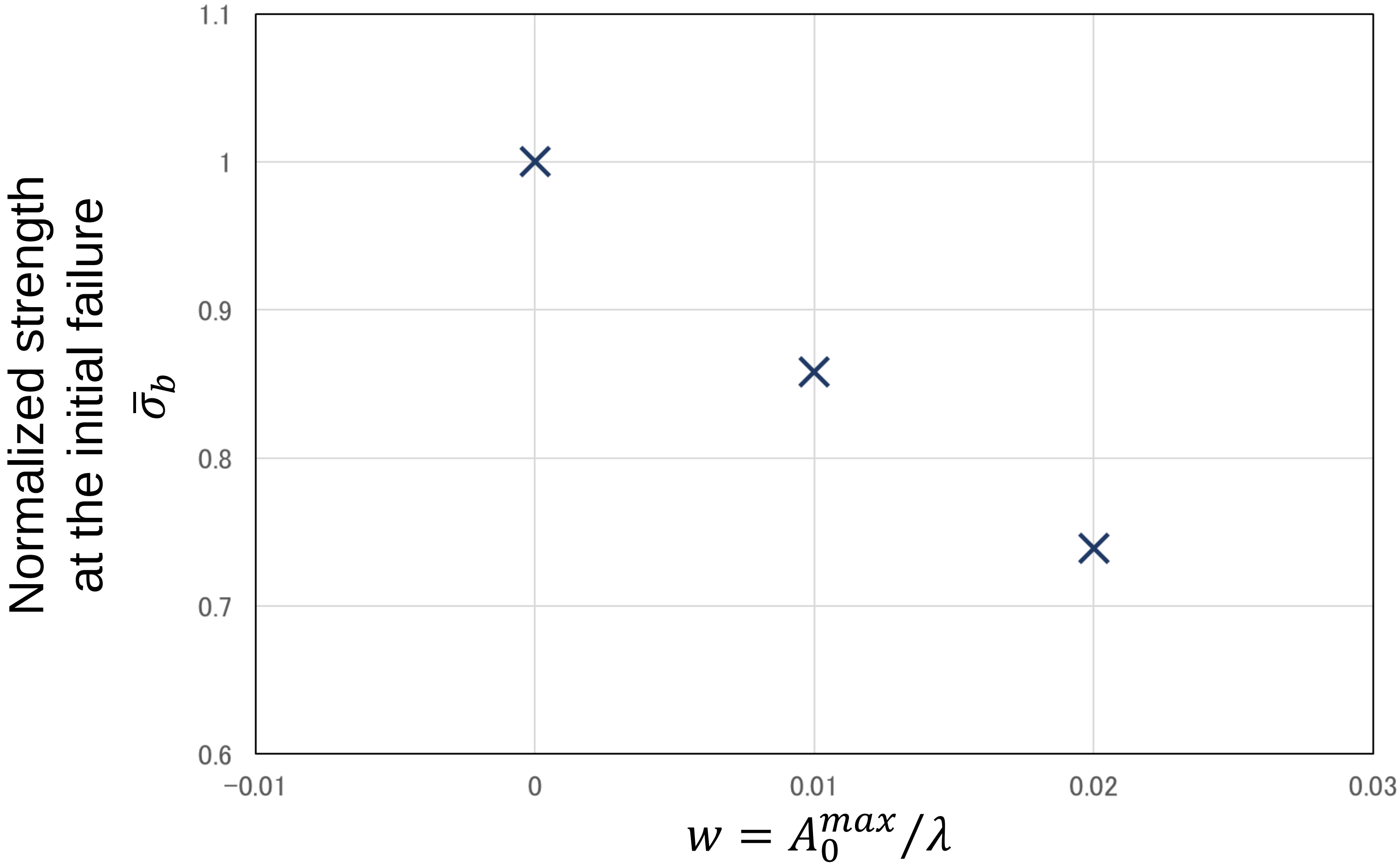
- ✓ ASTM D6484
- ✓ Each layer thickness: 1.25 [mm]
- ✓ Laminate configuration: $[0°, 90°, 90°, 0°]$



➡ Small scale waviness ($w = 0.00, 0.01, 0.02$) was simulated

4. Application (OHC test)

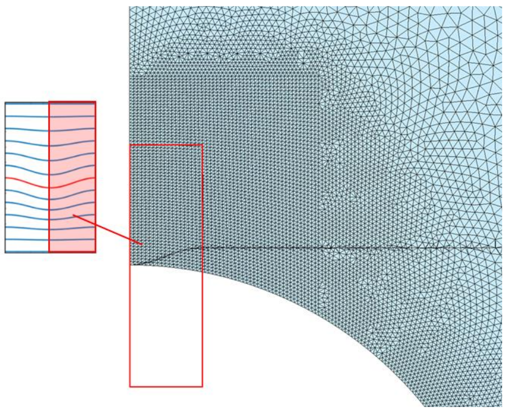
Results



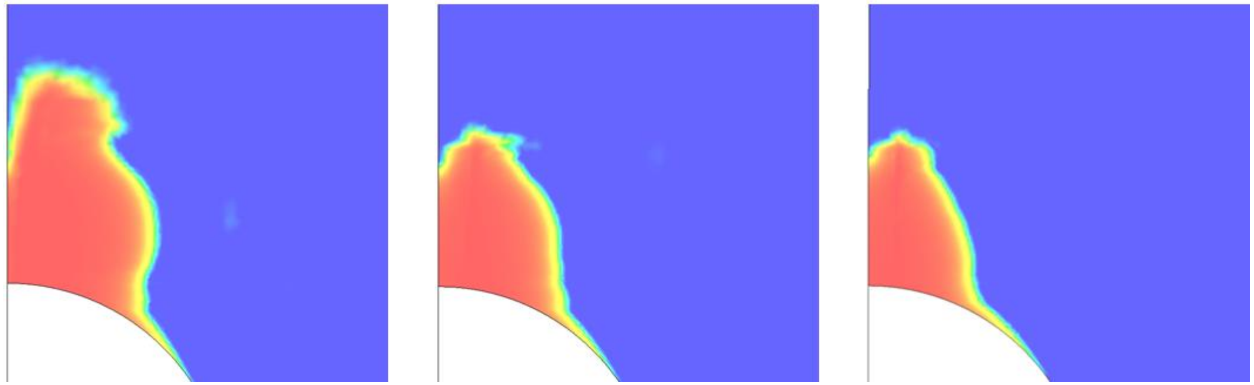
➡ The strengths decrease with an increase in fiber waviness severity w

4. Application (OHC test)

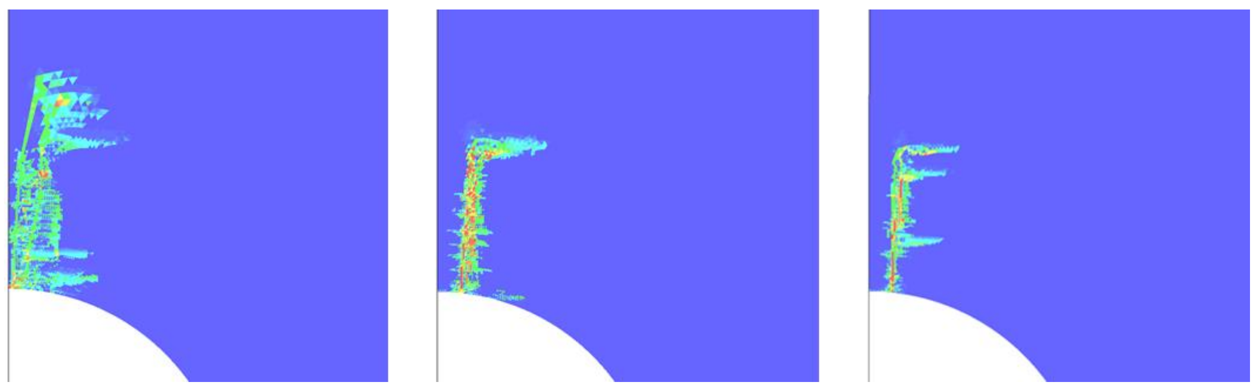
Discussion



Delamination



Kink bands



$w = 0.00$ $w = 0.01$ $w = 0.02$

- ✓ No significant effect on the transverse crack formation
- ✓ The predominant failure mode shift from delamination to kink bands, as the fiber waviness increases

4. Summary & Future work

Summary

- A numerical scheme for the prediction of types of strength of composite laminates with fiber waviness is developed.
- Fiber waviness region simulation
  - ✓ Even under longitudinal compression, transverse cracks become predominant more than fiber kinking in the case of large fiber waviness
- OHC simulation
  - ✓ For the small-scale fiber waviness, the predominant failure mode shift from inter-lamina delamination to kink bands as the severity increases

Future work

- Application of the proposed scheme to the prediction of open-hole compressive strengths of laminates with the larger fiber waviness
- Evaluation of coupling with other process-induced defects

Reference

[1] Yokozeki et al, ADVANCED COMPOSITE MATERIAL, 2020.
[2] Akakabe, University of Tokyo (Unpublished master thesis) , 2016.
[3] Hörrmann et al, International Journal of Fatigue, 2016.
[4] C.G. Davila et al., NASA / TM-2003- 212663, 2003.
[5] Z.P. Bazant and B.H. Oh, Matériaux et construction, 1983.
[6] S.T.Pinho et al., Journal of Composite Materials, 2012.
[7] T. Belytschko et al., International Journal for Numerical Methods in Engineering, 1999.
[8] N. Moes et al., International Journal for Numerical Methods in Engineering, 1999.
[9] P. Camanho et al., NASA/TM-2002-211737, 2002.
[10] K. Yoshida et al., Advanced Composite Materials, 2017.