Investigations on interactive failure mechanism of a laminated composite using synchrotron radiation computed tomography and finite element analysis

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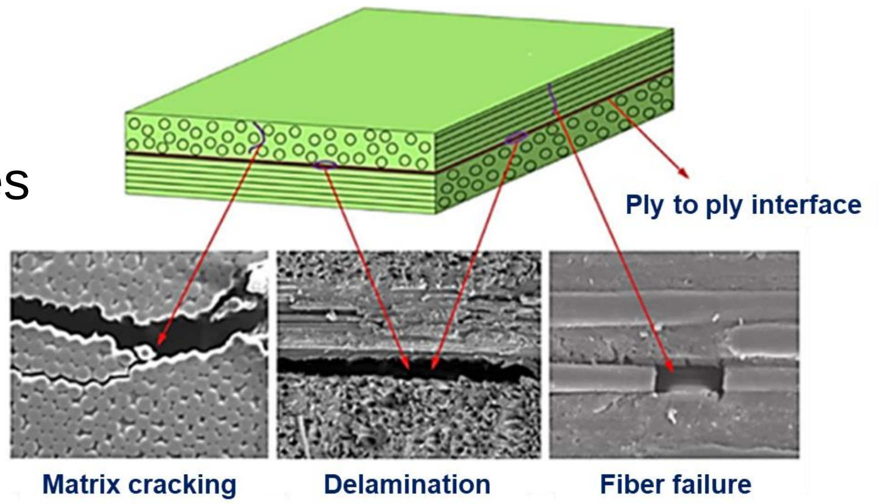
ICCM 23
INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS
BELFAST 2023
30 JULY – 4 AUGUST

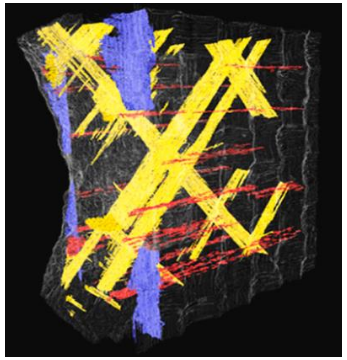
The ICC, Belfast
Northern Ireland
30th July – 4th August 2023

Motivation and Purpose

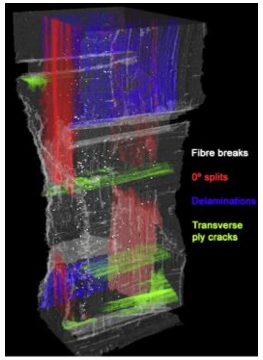
- **Motivation**
  - Complex failure mechanism of laminated composite
    - Anisotropy, heterogeneity, multi-scale, interactive failure modes
    - Internal damage progression
  - Understanding of failure mechanism
    - Optimal design of laminated composite
    - Validation of numerical model



- **Trends and Limitations**
  - Time-lapse high-resolution X-ray CT imaging
    - 3D visualization and history of multiscale cracks
    - Limited to the pre-peak zone



Ni et al. Compos. B. Eng, (2021)

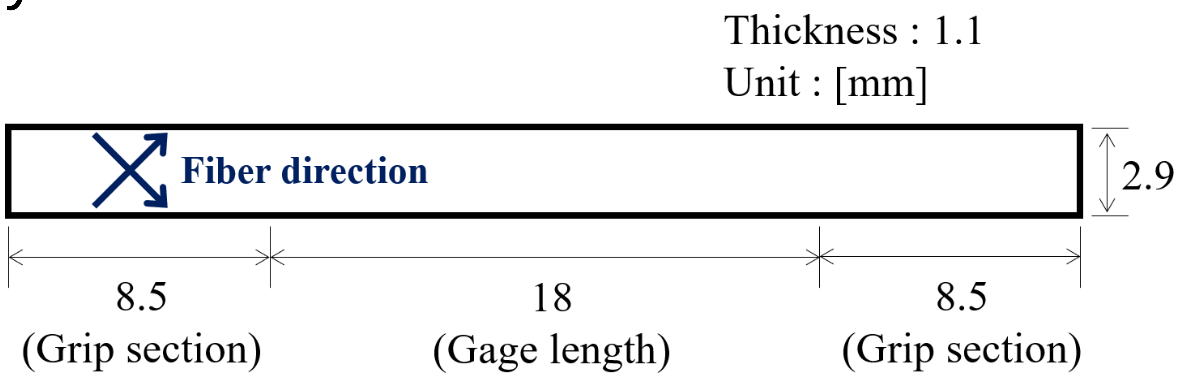


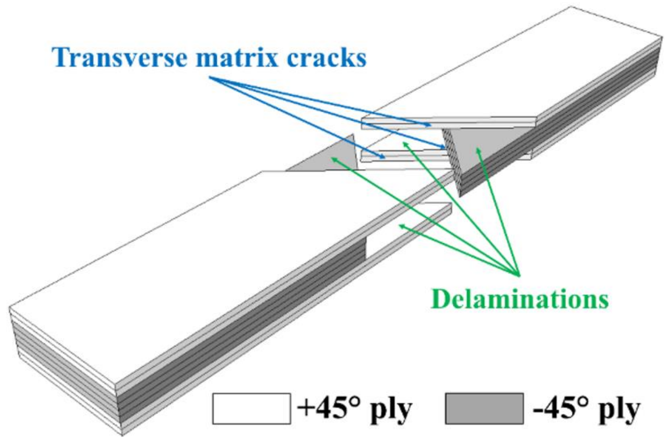
Scott et al. Compos Sci Technol, (2011)

- **Objectives**
  - Experimental investigations of interactive failure mechanisms in a cross-ply laminated composite while the materials form maximum load point
  - Finite element analysis for supplementing the experimental observation

Materials and Specimens

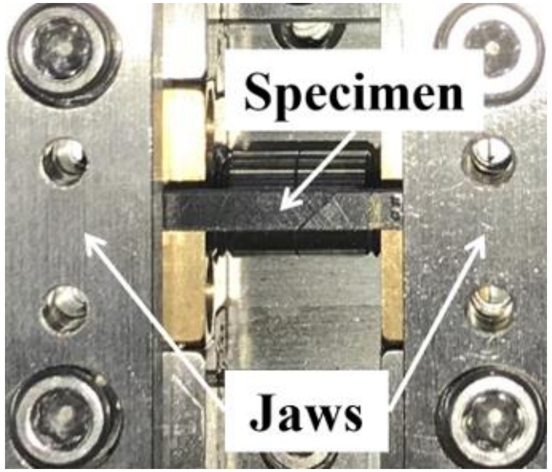
- [Carbon fiber / Epoxy] laminated composite
  - Autoclave process using UD carbon fiber-reinforced epoxy prepreg
    - UIN150/H15 prepreg (SK chemicals, South Korea)
    - Fiber volume fraction ~ 57%
- $[+45_2/-45_2]_s$ off-axis tensile specimen
  - Cut using a water jet
  - Focus on the interaction of matrix crack and delamination
  - Standard test specimen for in-plane shear response (ASTM D3518)
  - Dimensions based on a miniature tensile loading machine and inspection system

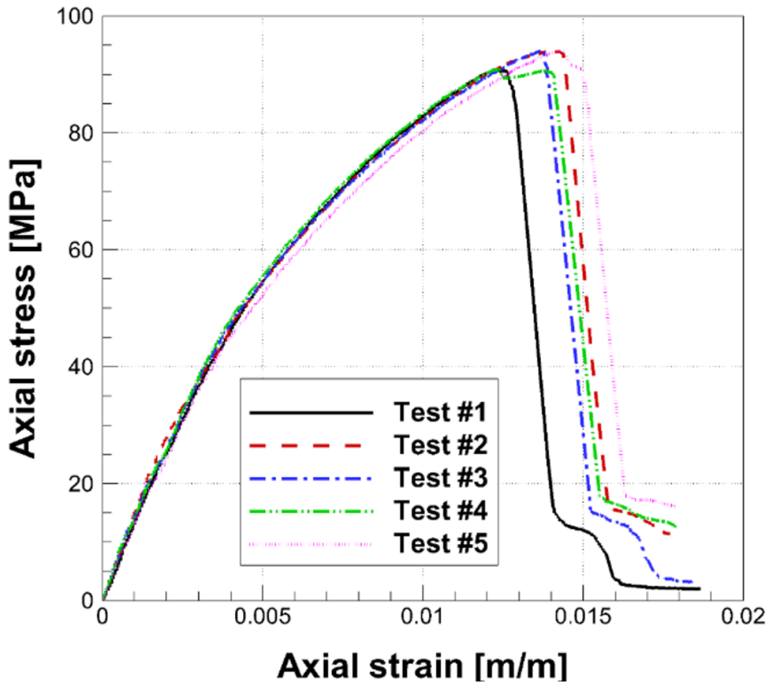




Tensile Behavior

- Response of the $[+45_2/-45_2]_s$ sample under tensile loading
  - Miniature loading stage (MT 2000, Deben Ltd, UK)
    - Maximum capacity of 2 kN
    - Displacement-controlled loading rate : 0.1 mm/min
    - Force data : Load cell
    - Displacement data : Linear extensometer
  - Residual load-carrying capabilities after the significant load drop
  - Peak stress: 92.74 ($\pm$ 1.53) MPa
  - Strain at peak: 1.339 ($\pm$ 0.091)

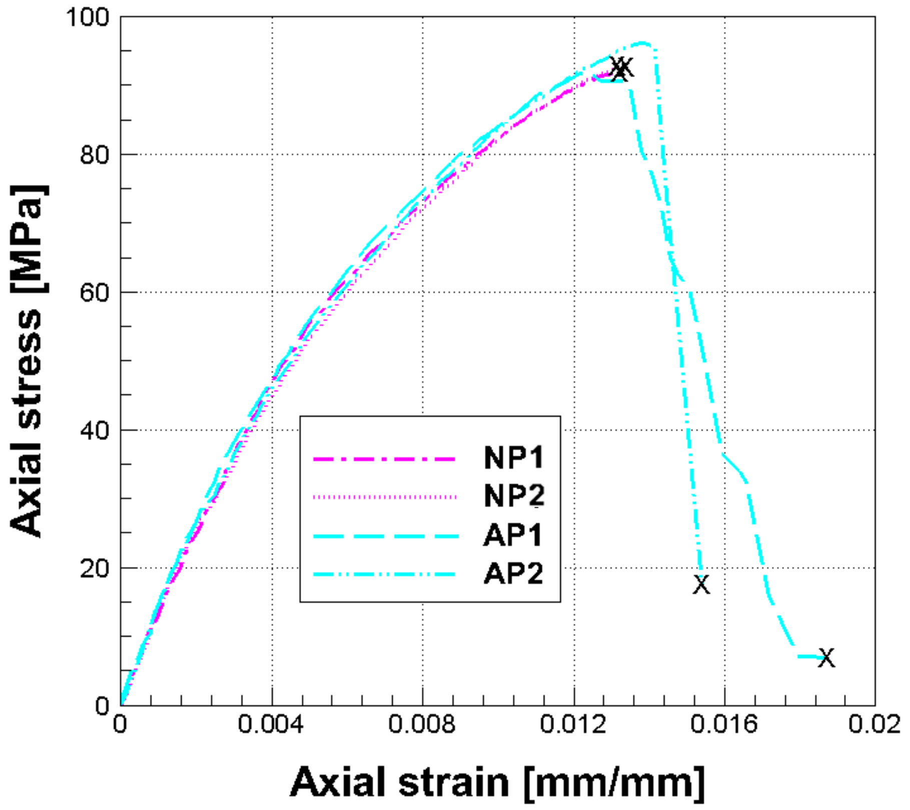




Preparation of Specimen for CT Imaging

- Interrupted specimens for the non-destructive X-ray inspection
  - Tensile tests were manually interrupted near the peak stress
    - As soon as the real-time force measurement began to decrease
  - Unstable specimens were stopped either near the peak stress (NP) or after-peak stress (AP)
  - Ex-situ observation using SRCT
    - Dye penetrant

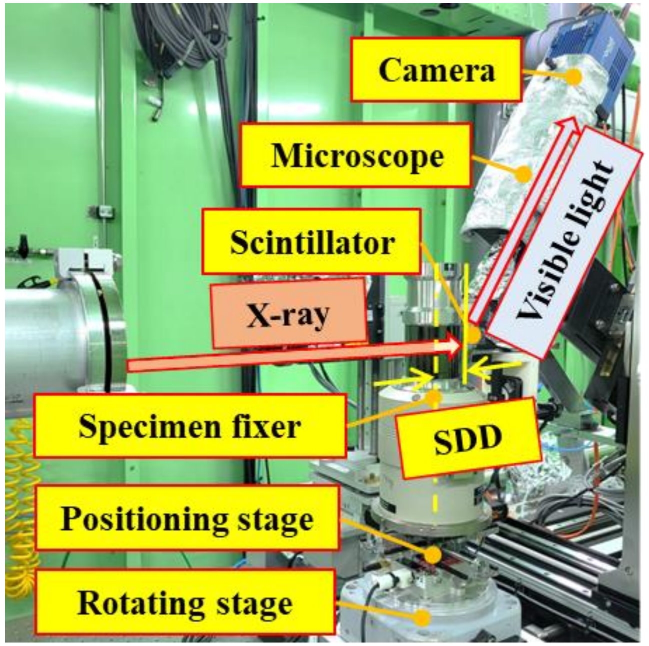
Specimen	Peak stress (and strain)	Interruption stress (and strain)	Dyeing
NP1	92.04 (1.317)	91.84 (1.322)	Dyed
NP2	92.71 (1.328)	92.60 (1.339)	Dyed
AP1	91.93 (1.228)	6.927 (1.872)	Undyed
AP2	96.16 (1.378)	17.59 (1.539)	Dyed



SRCT Setup for Crack Visualization

- Two different settings according to dye usage
  - Dyed setting for observation the cracks hidden inside the samples
    - ZnI_2-based dye solution penetrates and deposits on crack surfaces
  - Undyed setting for distinguish the carbon fibers from the epoxy matrix
  - Key parameters : Beam voltage, Sample-to-detector distance (SDD)

	Dyed	Undyed
Beam voltage	35.5 keV	25 keV
Beam current	250 mA	
Monochromator	DMM	DCM
Exposure time	50 ms	500 ms
SDD	100 mm	45 mm
FOV size	3.3×2.8 mm^2	4.16×3.51 mm^2
(Pixel size)	(1.3 µm)	(1.625 µm)
Scintillator	100 µm thick $CdWO_4$	

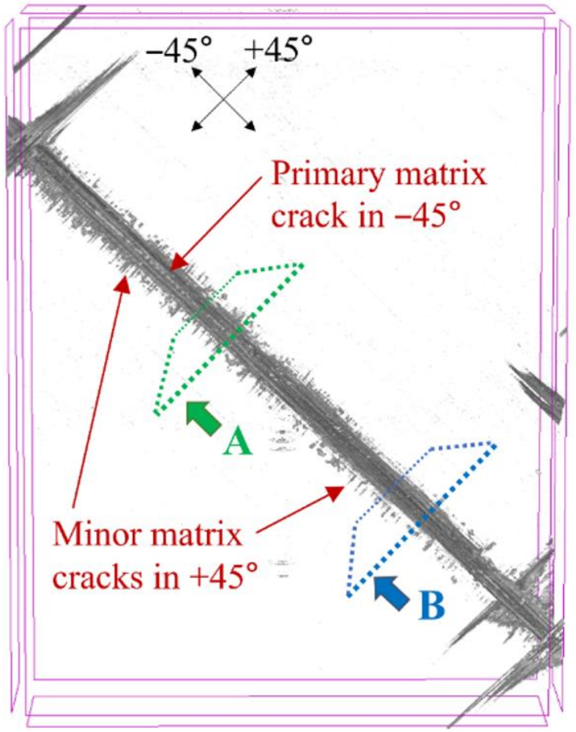


6C beamline at Pohang Accelerator Laboratory (PAL)

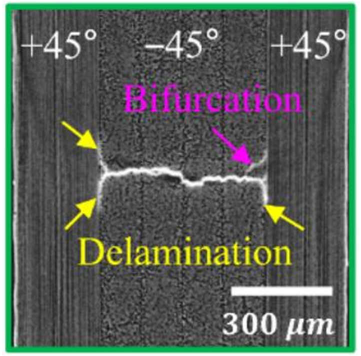
- Reconstruction
  - 3,000 projection images during 180° rotation
    - Reconstruct 2,160 tomograms using Octopus (XRE, Gent, Belgium)

Damage Pattern with SRCT

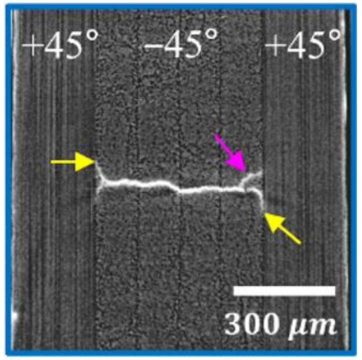
- Unique failure pattern
  - A single fully-developed matrix crack in either outside +45° or inside −45° layers → “Primary crack”
  - Multiple immature cracks in the other orientation layers
  - **NP1**, AP1 : Primary crack was found in the inside −45° layer



Front view



View A

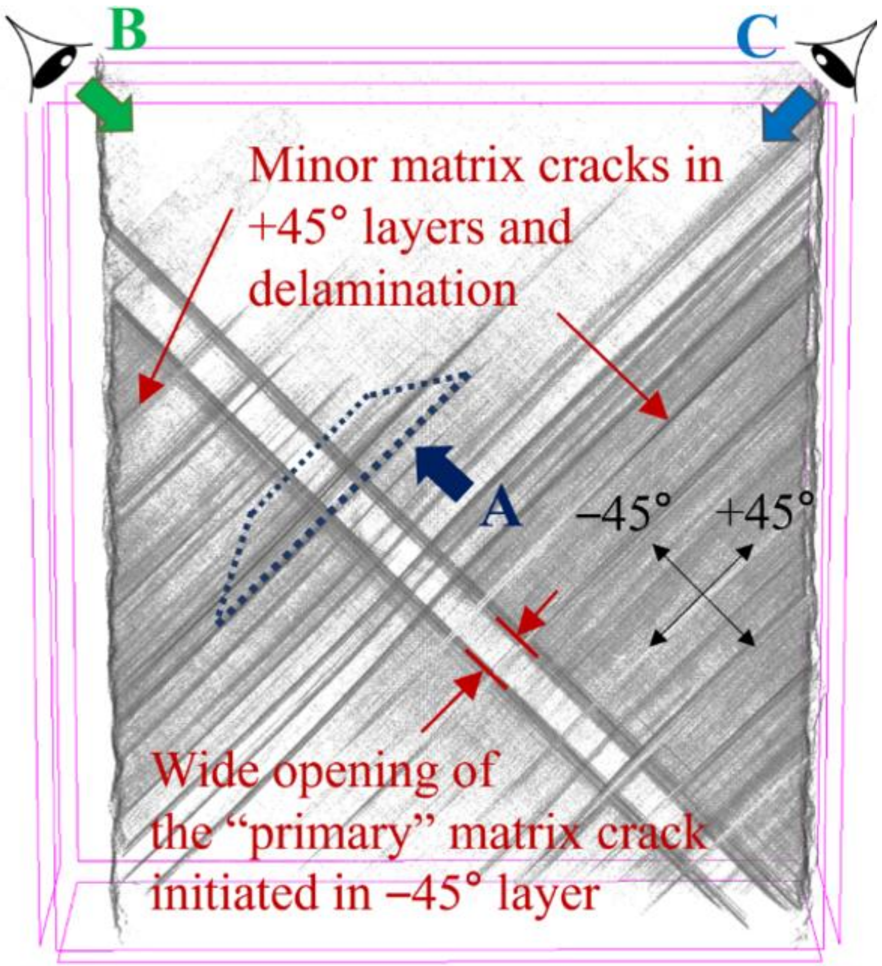


View B

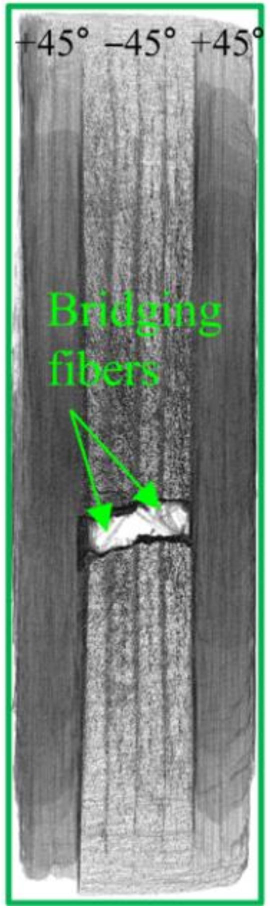
- ✓ Initiation of the delamination failure
  - From the edges of the primary crack in the −45° layers
  - Release of accumulating strain energy by turning the crack paths through the interfaces
  - Bifurcation occurred near the interfaces
  - ➢ Delamination was transitioned from the matrix crack
- ✓ Minor matrix cracks in +45° layers
  - Branch off from the primary crack band

Damage Pattern with SRCT

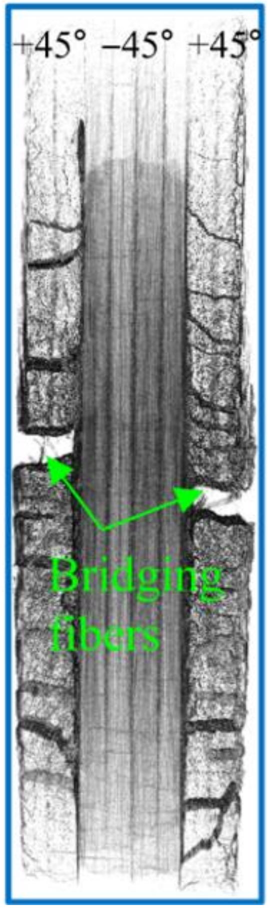
- Unique failure pattern
  - NP1, **AP1** : Primary crack was found in the inside –45° layer



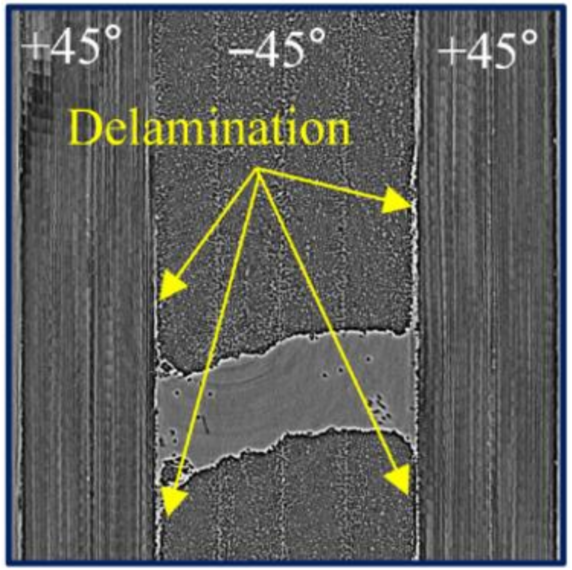
Front view



View B



View C

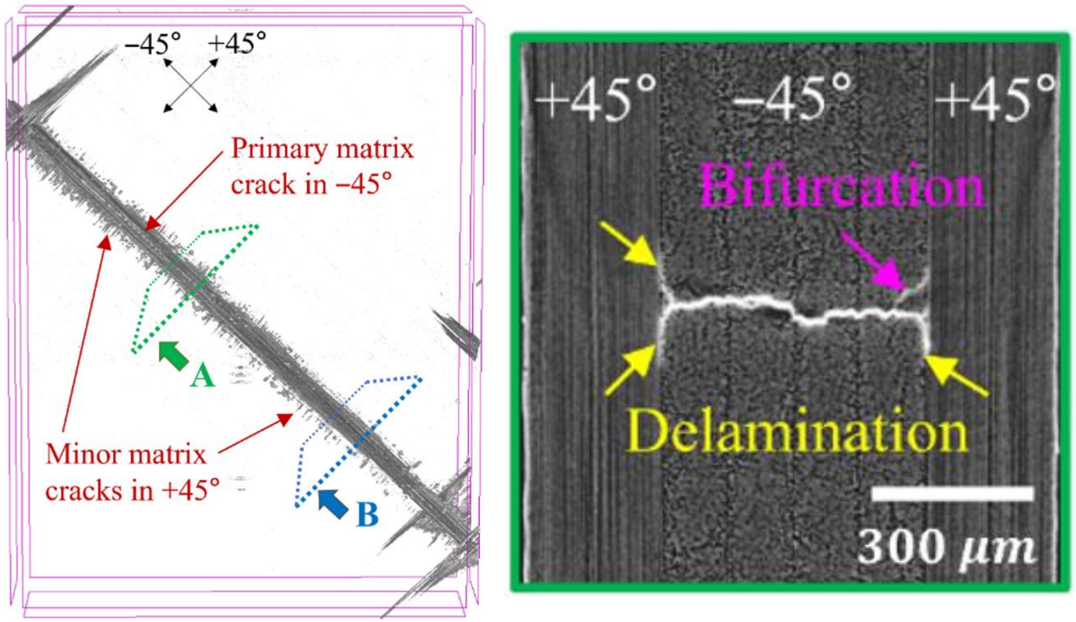


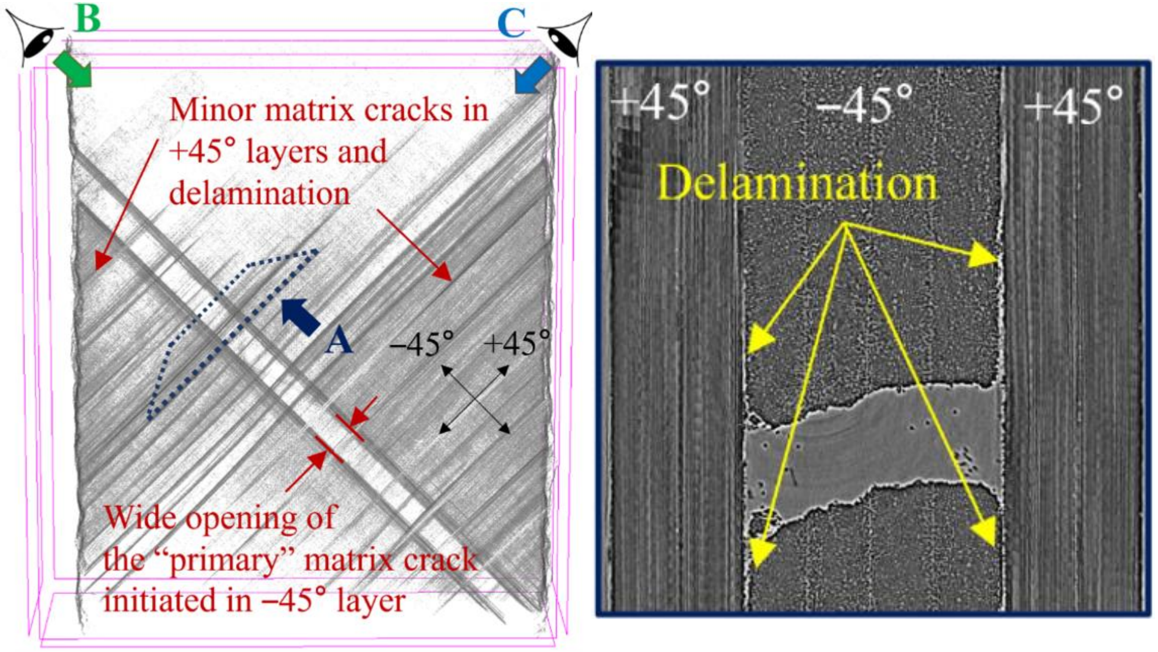
View A

- ✓ Opening of the primary crack in –45° layer
- ✓ Break into two pieces of +45° layers
- ✓ Widely observed delamination

Summary of Damage Pattern in NP1 and AP1

- Unique failure pattern



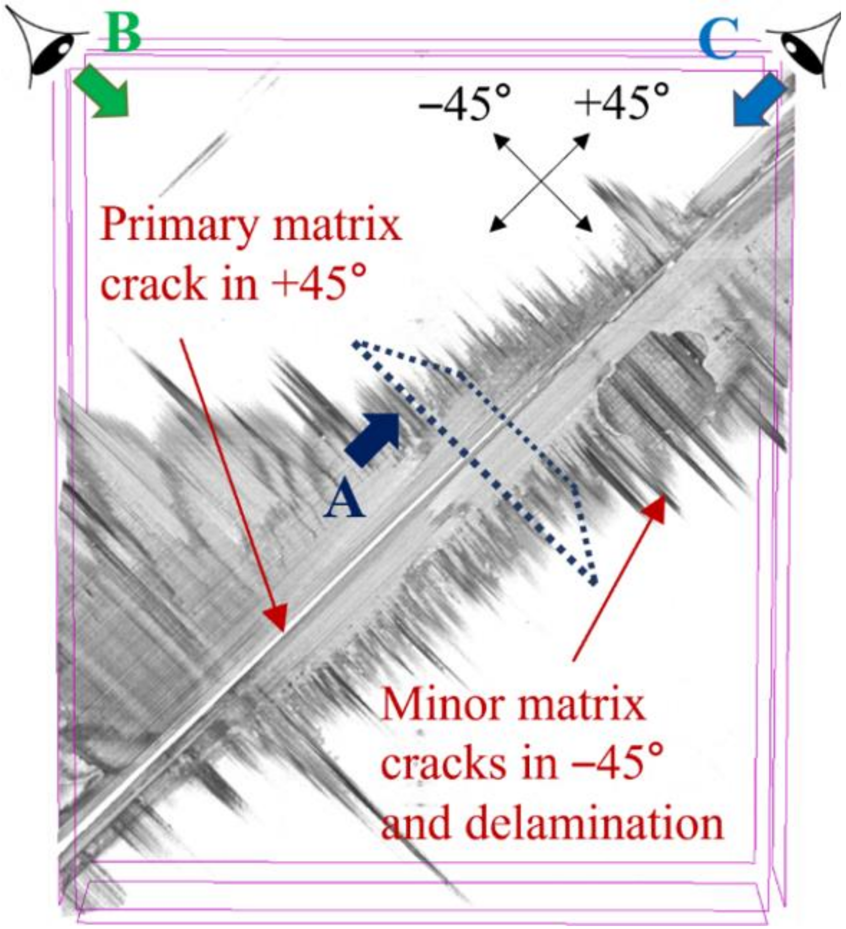


✓ Sequential and interacting failure process between the matrix crack and delamination

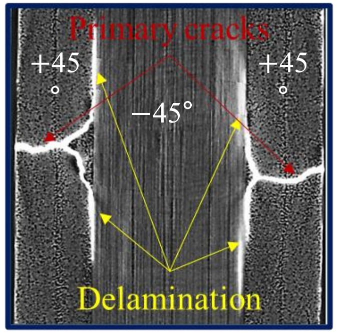
- Initiation of delamination from the internal primary crack
- Load transfer to the outside +45° layers → Initiation of multiple matrix cracks
- Growth of the +45° cracks in the transverse direction → Additional delamination
- One of the transverse cracks in each of the +45° layers further grew into a "primary crack" → Separation into two parts

Damage Pattern with SRCT

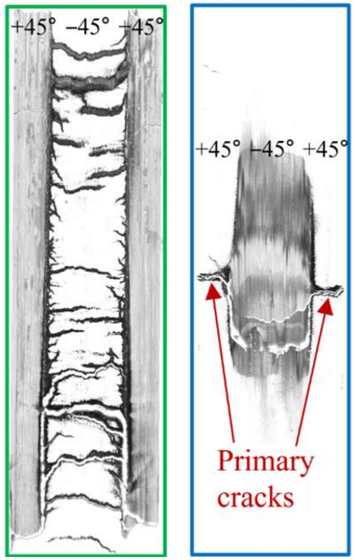
- Unique failure pattern
  - **NP2**, AP2 : Primary crack was found in the inside +45° layer



Front view



View A

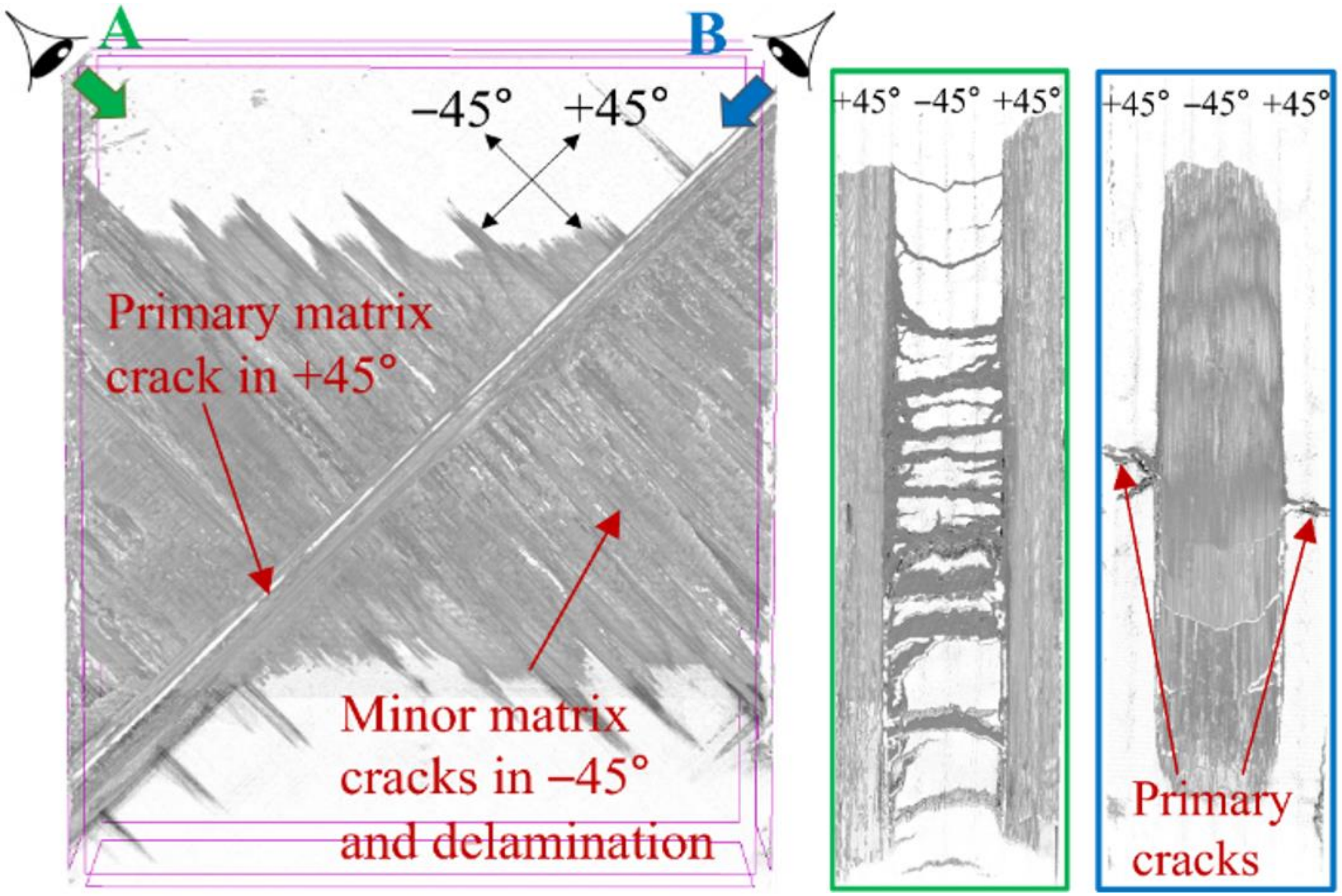


View B View C

- ✓ Similar but opposite failure process
  - Only one primary crack in each of the +45° layers
  - Multiple immature cracks in the −45° layers
- ✓ Interactive failure process
  - ① Primary cracks in the +45° layers
  - ② Initiation of delamination
  - ③ Load transfer to the −45° layers
  - ④ Multiple cracks in the −45° layers
  - ⑤ Growing of the multiple cracks in the thickness direction and fiber direction
  - ⑥ Additional delamination

Damage Pattern with SRCT

- Unique failure pattern
  - –NP2, **AP2** : Primary matrix crack was found in the inside +45° layer



Front view

View A

View B

✓ Can be considered the next stage of the NP2 specimen

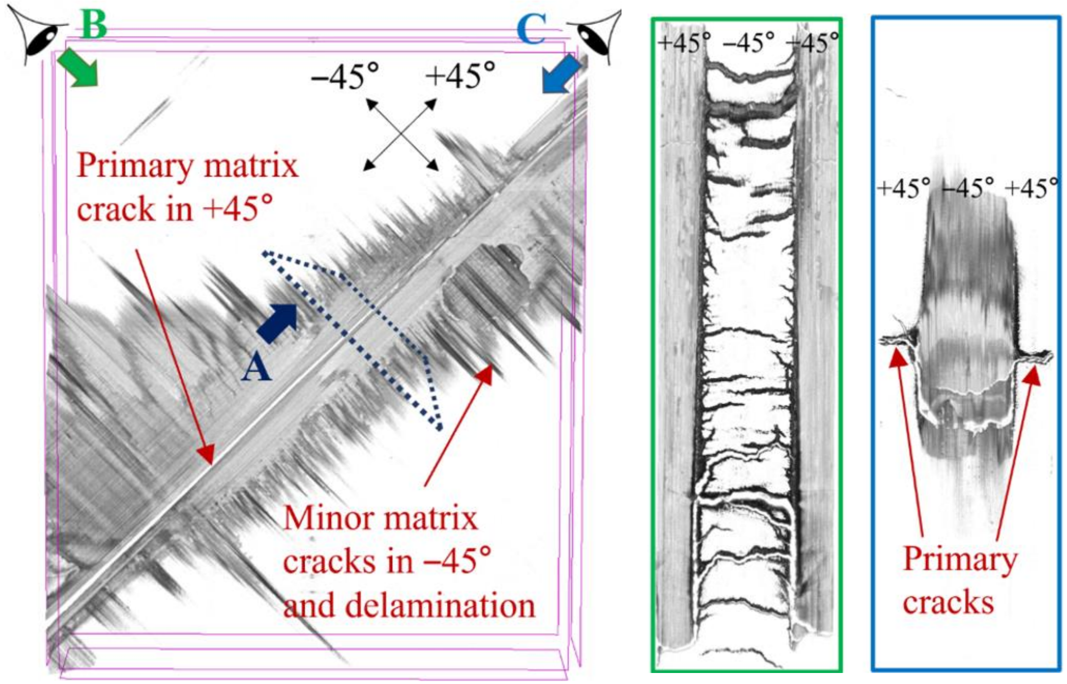
- Growing of the multiple cracks in the –45° layers
- Expansion of interfacial failure

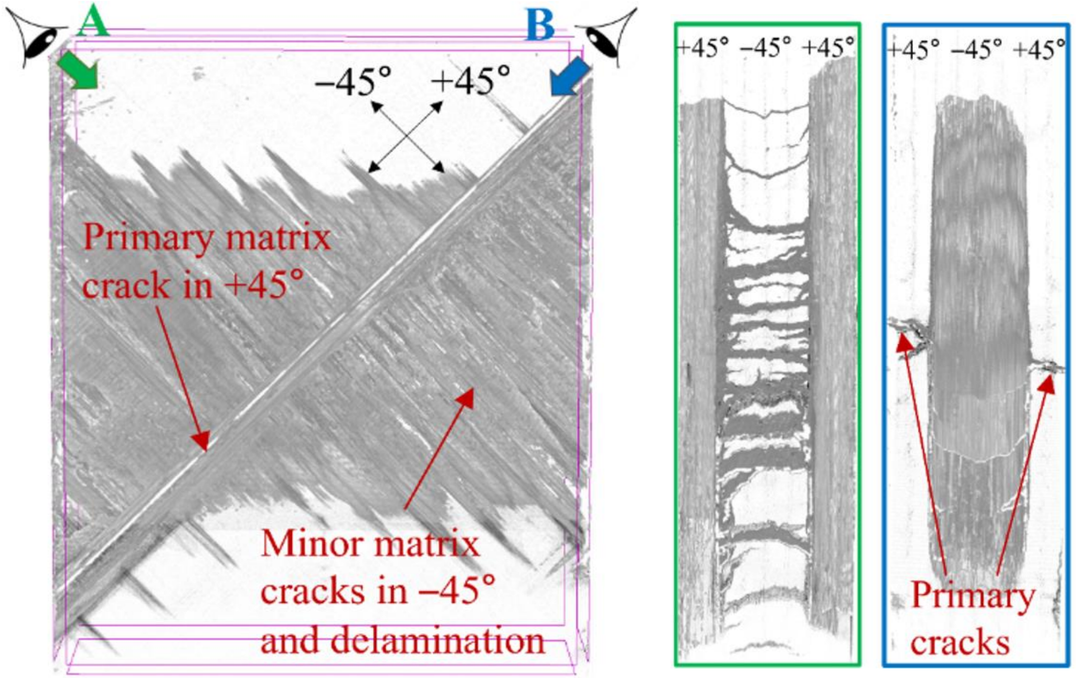
✓ No separation after load-drop

- No primary cracks in the -45° layers
- Not sufficiently developed delamination

Summary of Damage Pattern in NP2 and AP2

- Unique failure pattern



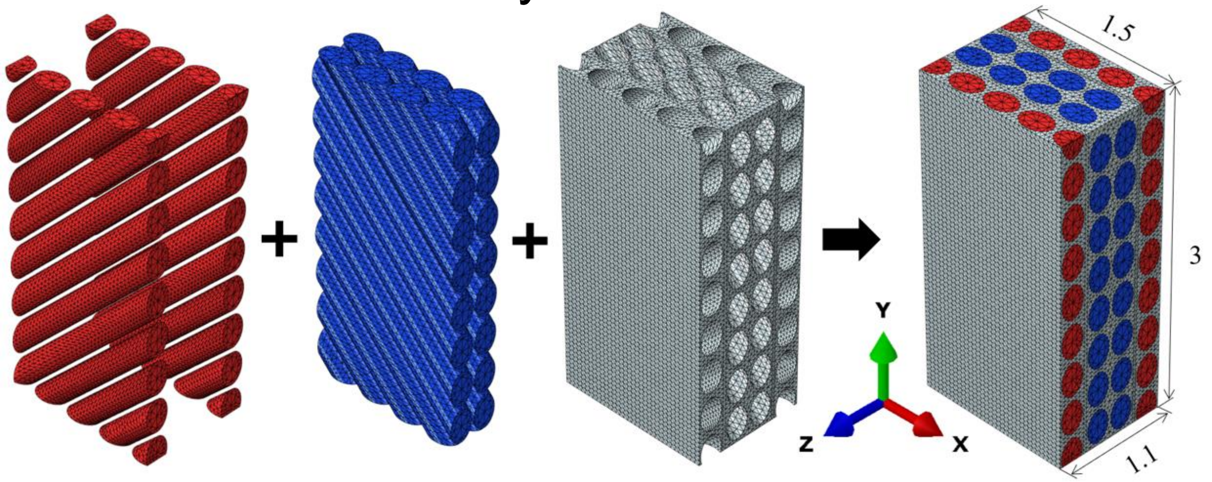


✓ Sequential and interacting failure process between the matrix crack and delamination

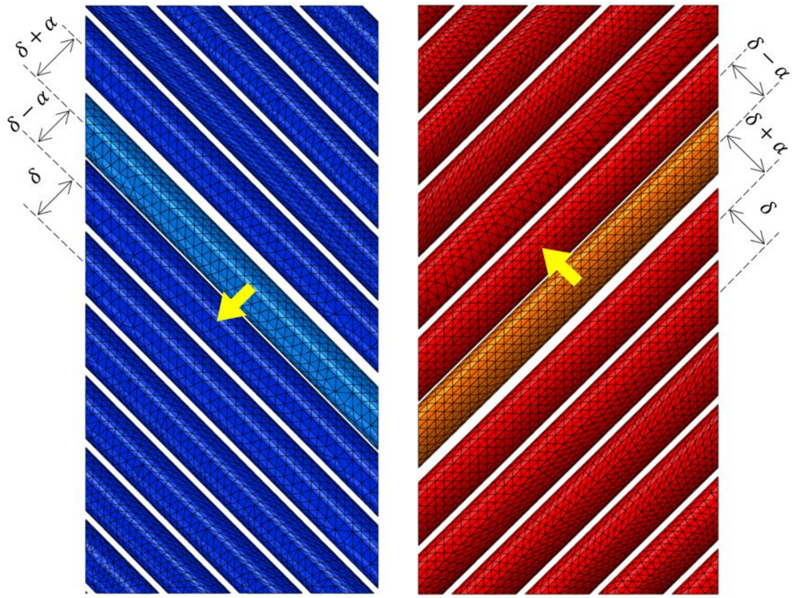
- Initiation of delamination from the external primary crack
- Load transfer to the inside −45° layers → Initiation of multiple matrix cracks
- Growth of the −45° cracks in the transverse direction → Additional delamination
- One of the transverse cracks in the −45° layer further grew into a "primary crack" → Separation into two parts

Finite Element Analysis

- Heterogeneous model configuration
  - Consider fiber-level fracture behavior with computational efficiency
    - Diameter of scaled-up fibers : 0.22 mm
    - Thickness of interface : 0.03 mm
    - Fiber volume fraction : 57.1 %
    - 337,746 Quadratic tetrahedral elements
  - Fiber shift : Artificial stress concentration between a fiber pair
    - Fiber shift in the −45° layer : “Model M”
    - Fiber shift in the +45° layer : “Model P”



+45° fibers −45° fibers In situ matrix



Model M Model P

Material Model and Input Parameters

- Material models
  - Fiber : Transversely isotropic & Linear elastic

*E_{11}	**$E_{22} = E_{33}$	***$G_{12} = G_{13}$	**G_{23}	**$\nu_{12} = \nu_{13}$	**ν_{23}	*ρ
290 GPa	19 GPa	18.1 GPa	7 GPa	0.2	0.2	1.81 g/cm^3

  - In situ matrix : Isotropic & Elasto-plastic & Post-peak strain softening
    - Johnson-Cook plasticity and damage model (available in ABAQUS)
    - Assumption: Damage initiation is independent of triaxiality, strain rate, and temperature

E	ν	σ_Y	$\bar{\epsilon}_D^{pl}$	G_c	ρ
3.354 GPa	0.33	39.97 MPa	0.03	0.169 N/mm	1.2 g/cm^3

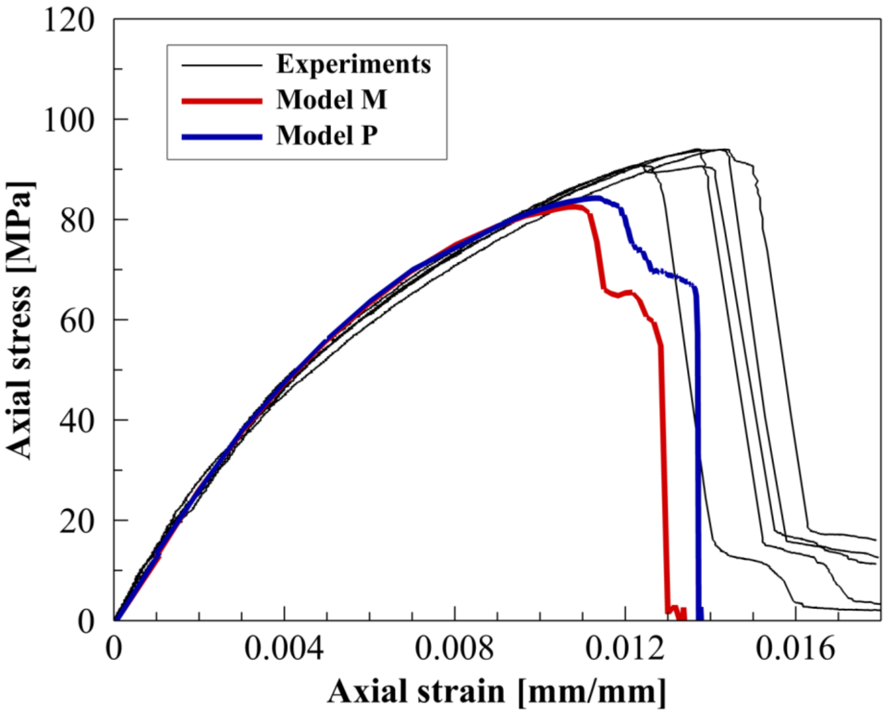
    - Modulus (E), Nonlinear behavior : Inverse-analysis approach[1]
    - Yield strength (σ_Y) : Where the secant stiffness is equal to 99% of the initial stiffness
    - Critical equivalent plastic strain ($\bar{\epsilon}_D^{pl}$) : Virtual V-notched shear test
    - Damage evolution energy (G_c) : Mode I fracture energy[2]

* Toray, T800H Technical Data sheet, (2018)
** Kaddour et al, J. Compos. Mater., (2013)
*** Kumar, Znt. SAMPE Symp. and Exhib., (1990)

[1] Ng et al. Compos Sci Technol, (2010)
[2] Jo et al. Compos. A. Appl. Sci. Manuf, (2020)

FEA result – Global Responses

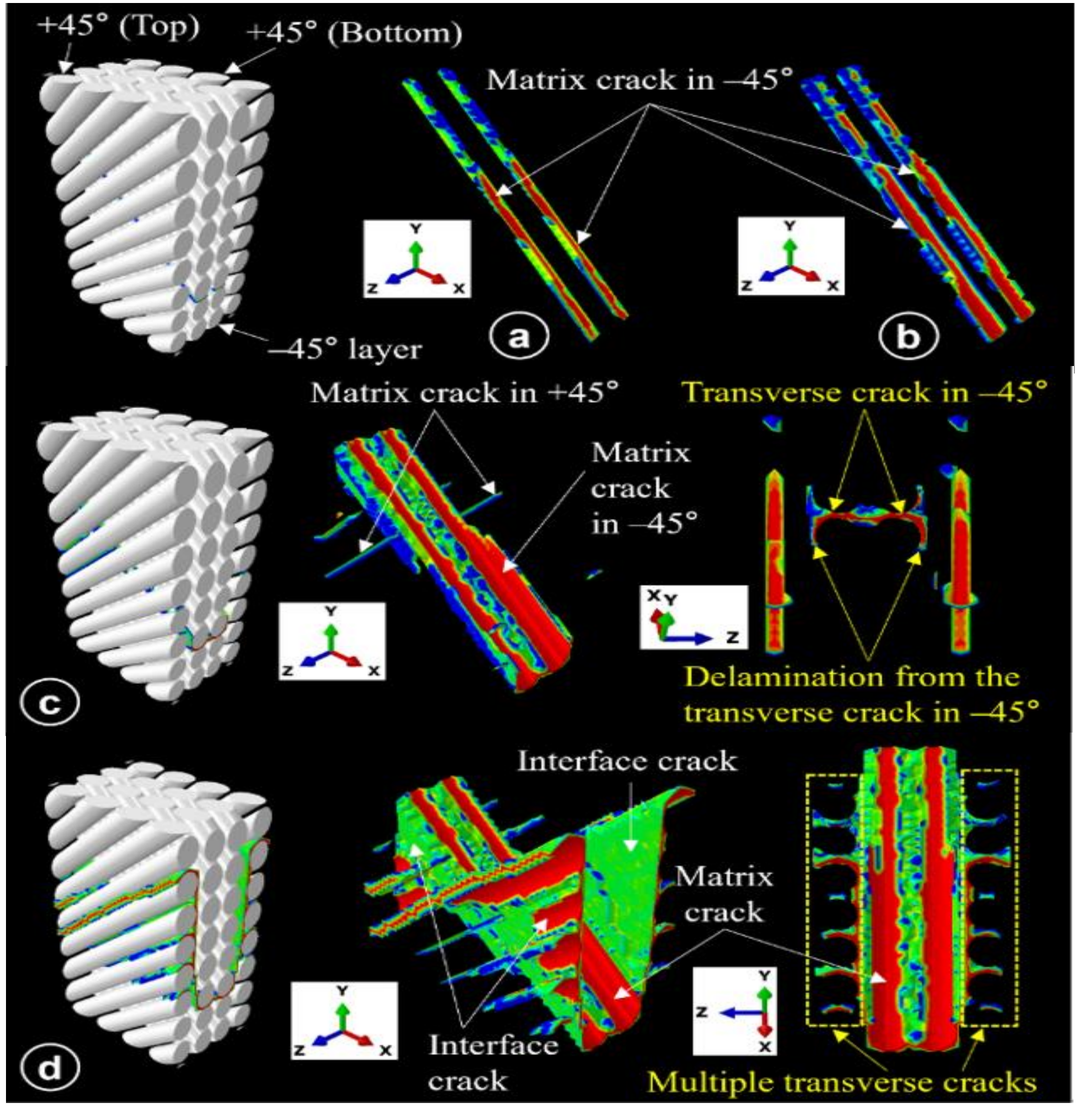
- Global responses
  - Successfully reproduction in the pre-peak region
    - Validation of modeling scheme to represent the effective properties of the laminated composite
  - Earlier break than the experimental measurements
    - Simplification of the real microstructure → Nonuniform stress distribution

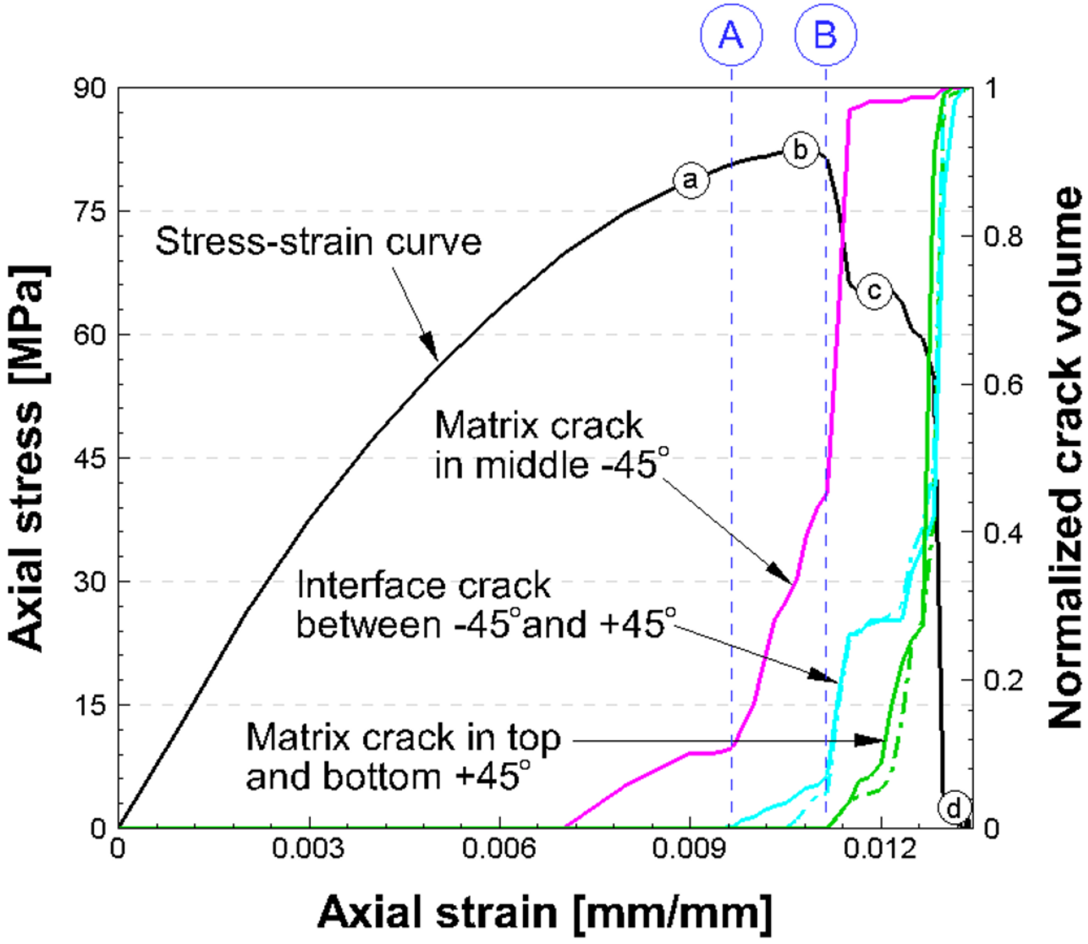


- Damage analysis
  - Initiation of "primary crack" between the shifted fiber-pair
  - Matrix failure index: Scalar stiffness degradation variable (SDEG)
    - "0" before the equivalent plastic strain of an element reaches $\bar{\epsilon}_D^{pl}$
    - "1" when fracture energy is entirely released

FEA result – Damage Pattern

- Model M (Fiber shift in -45° layer)



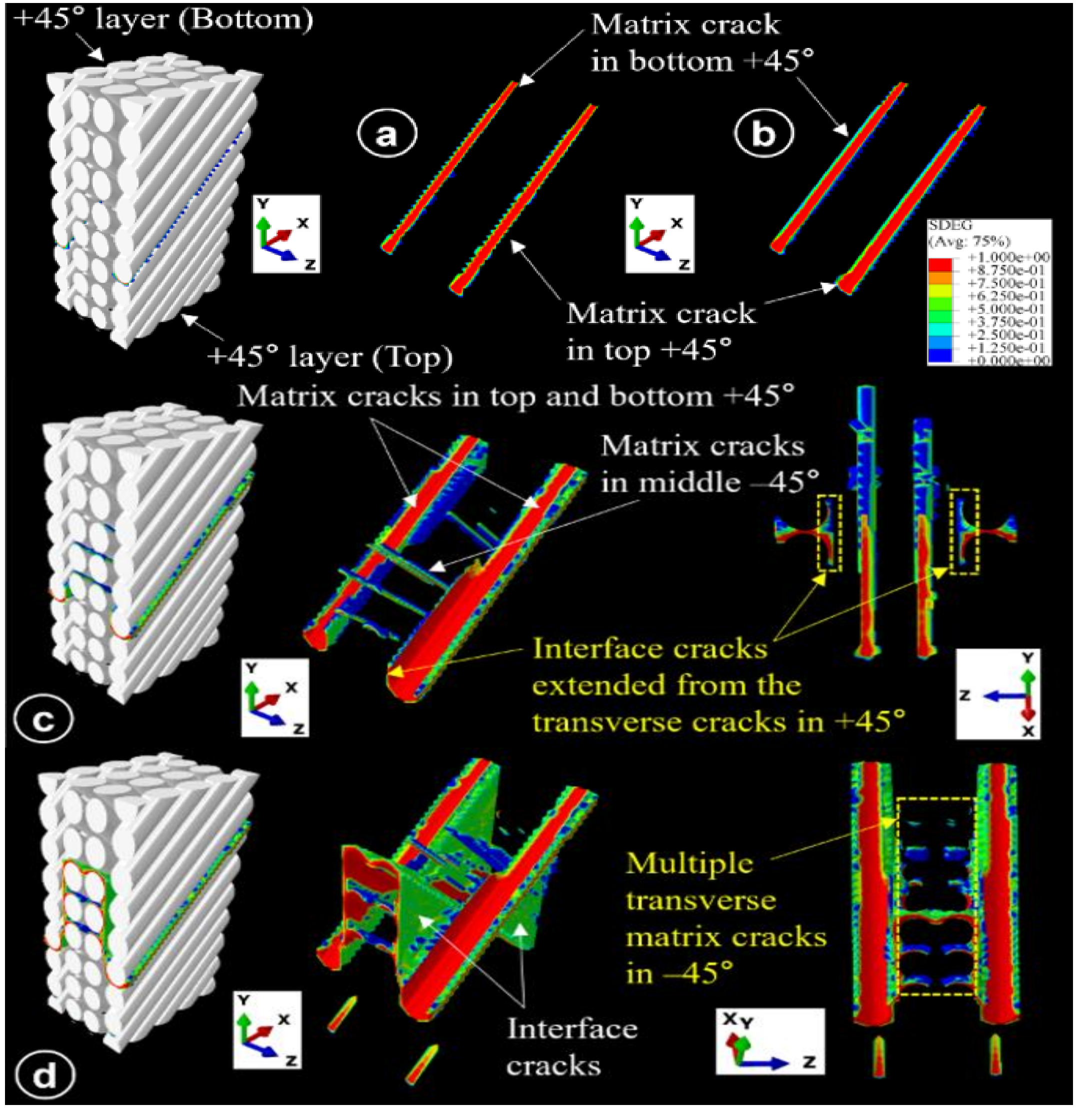


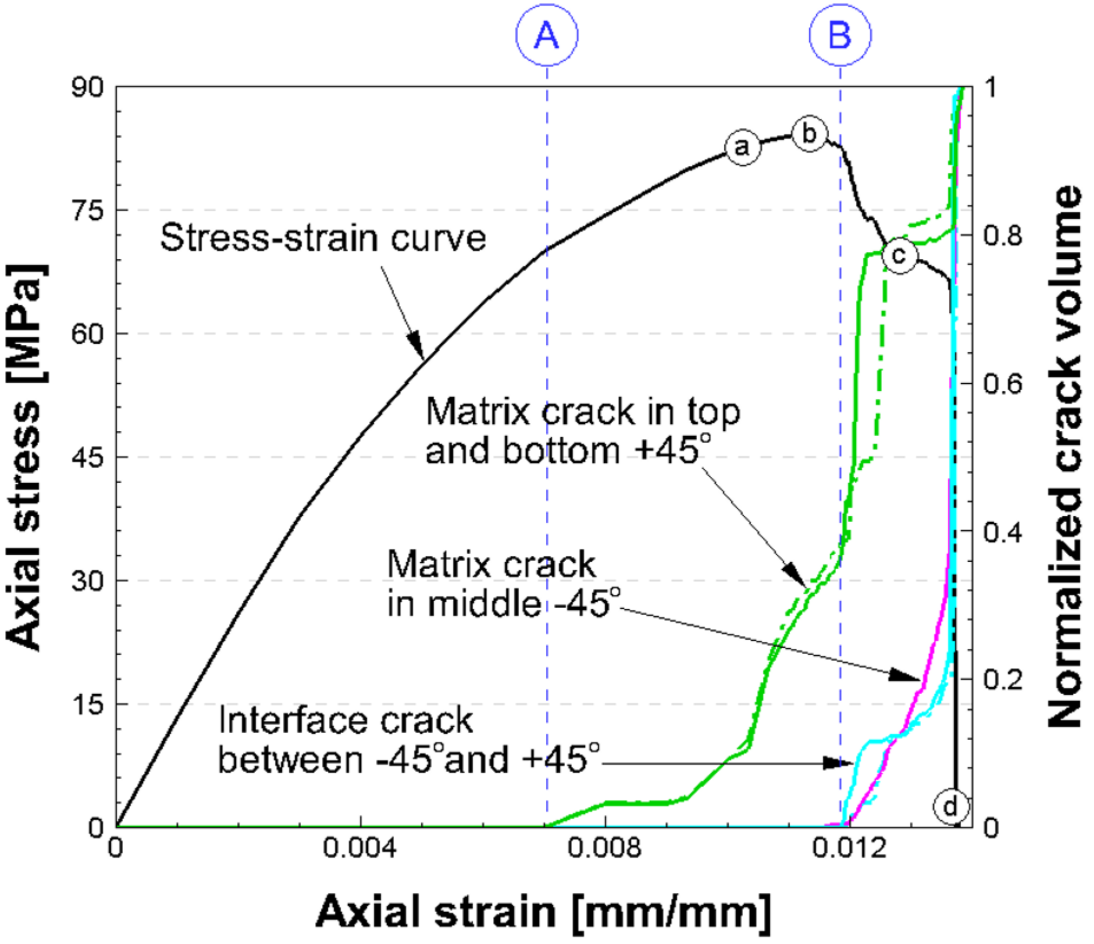
Ⓐ : Initiation point of the delamination
Ⓑ : Just after the peak stress

Note) Visualizing the elements with SDEG being greater than 0.8

FEA result – Damage Pattern

- Model P (Fiber shift in +45° layer)

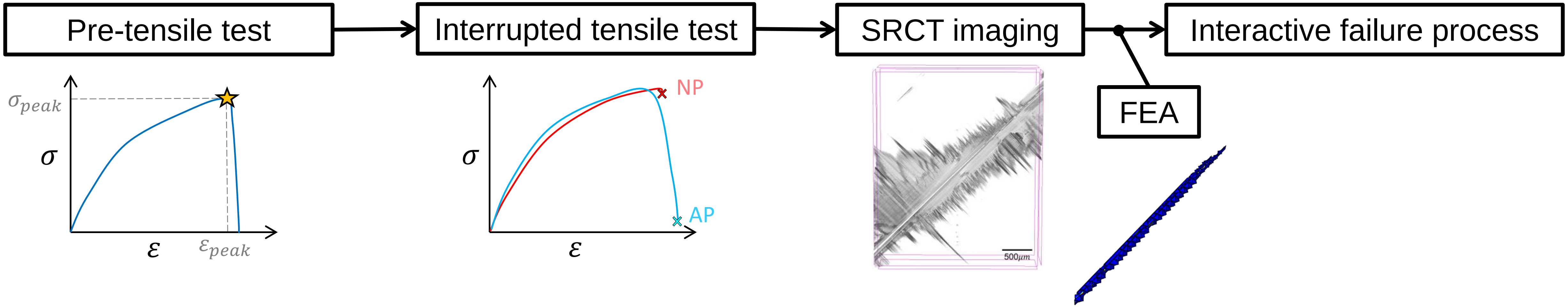




Ⓐ : Initiation point of the matrix cracks in the +45° layers
Ⓑ : Initiation point in the delamination and −45° layers

Note) Visualizing the elements with SDEG being greater than 0.8

Conclusion



- Interactive failure process during the rapid loss of load-bearing capacity
  ① A single fully-developed matrix crack (primary crack) in either +45° or −45° layers
  ② Delamination initiated from the primary cracks
  ③ Multiple immature cracks in the other orientation layers
  ④ Growth of delamination due to the multiple cracks
  ⑤ One of the multiple cracks grows into fully-developed matrix crack
  ⑥ Separation into two parts

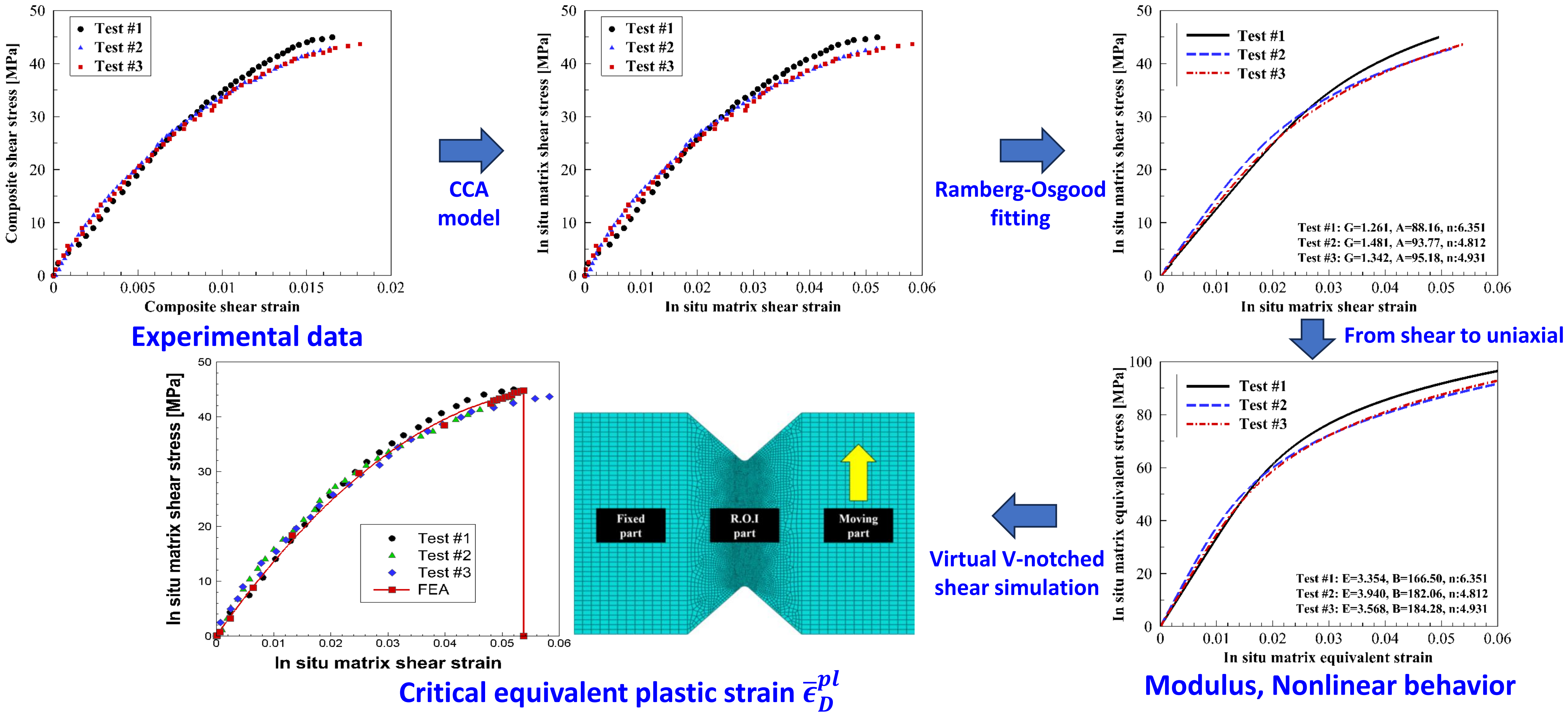
➢ Shear strength determining mechanism

Questions and Comments

Thank you for your attention

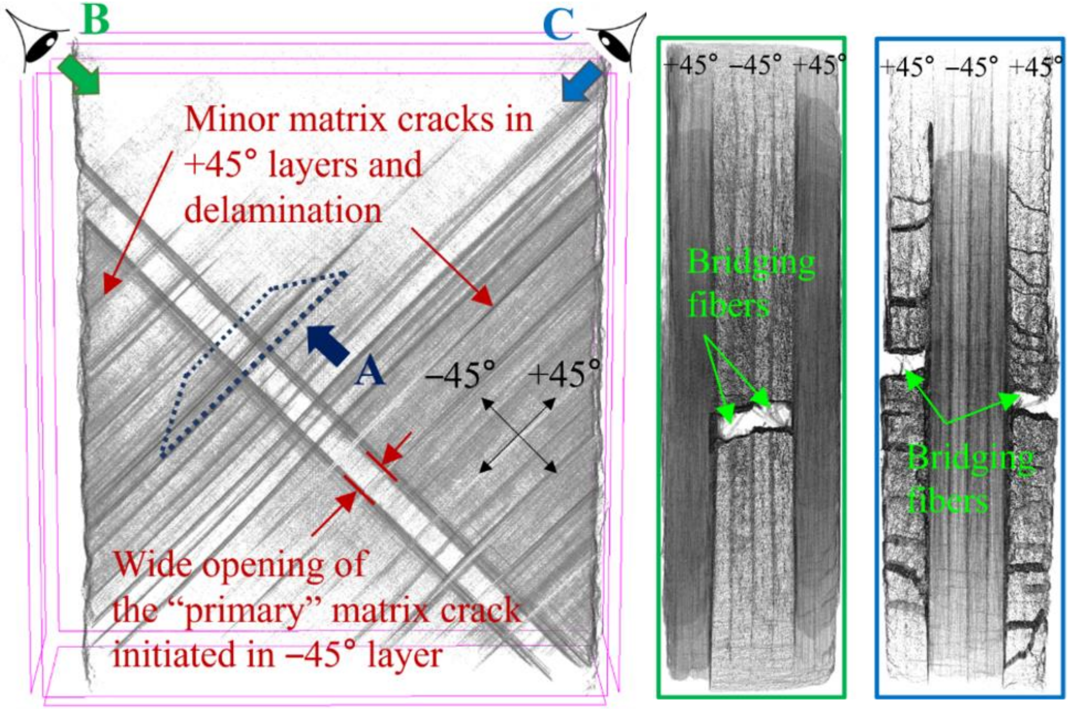
Appendix

- Input parameters for the matrix material



Appendix

- Bridging fibers in the AP1



Front view

View B

View C