In situ mechanical testing of composite materials using 3D X-ray tomography

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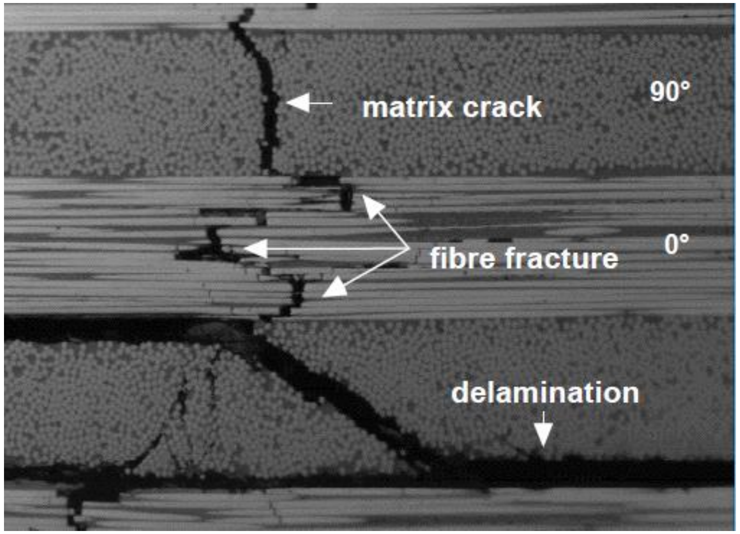
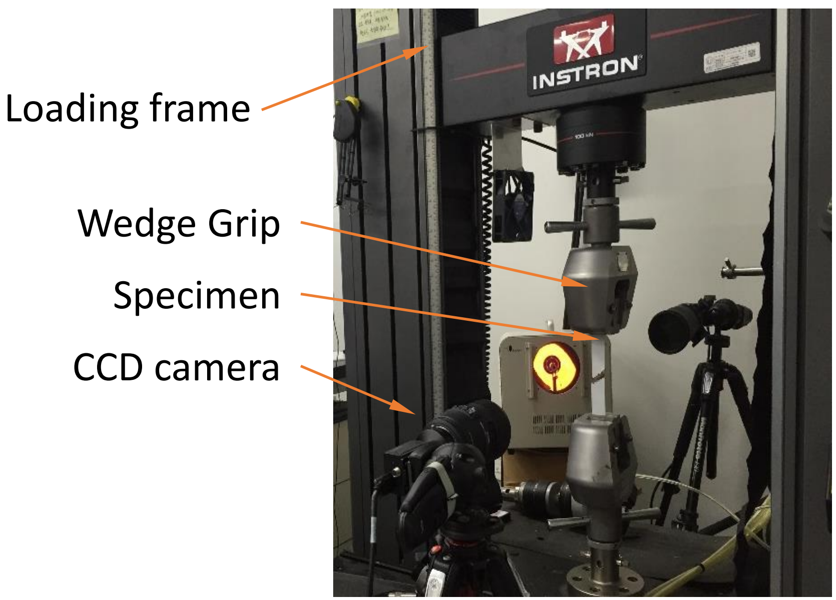
Introduction

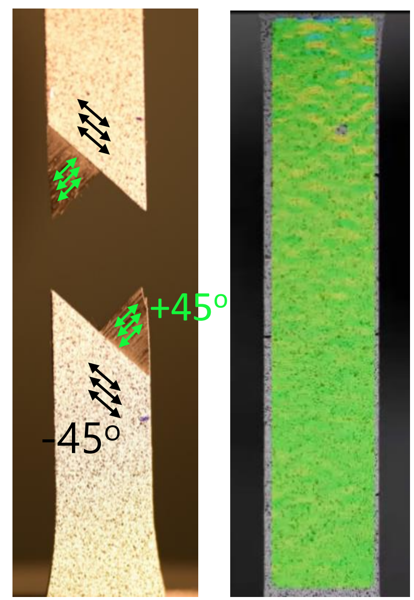
- **Many researches on failure behavior of composite materials**
  - Hard to predict failure behavior of composite materials
  - Complex interaction of multiple failure modes, including matrix microcracking, intra-laminar cracking, inter-laminar delamination and fiber rupture
- **Experiments are still the major tool for characterizing the damage and failure characteristics of composite materials**
  - Various tests are required to fully understand the basic mechanical response of composite materials
  - Mechanisms of interactive failure modes is still difficult to be identified by conventional testing methods



Motivation for advanced *in situ* testing method

- **No testing method for investigating crack initiation and propagation under the surface of composite materials**
  - Optical Microscope and Scanning Electron Microscope are limited to the surface
- **Issues with current Digital Image Correlation(DIC) technique**
  - Visualization of real time displacement (or strain) fields obtained from surface
  - DIC gives much more information and new insights
  - Limited to the surface where speckle patterns are applied



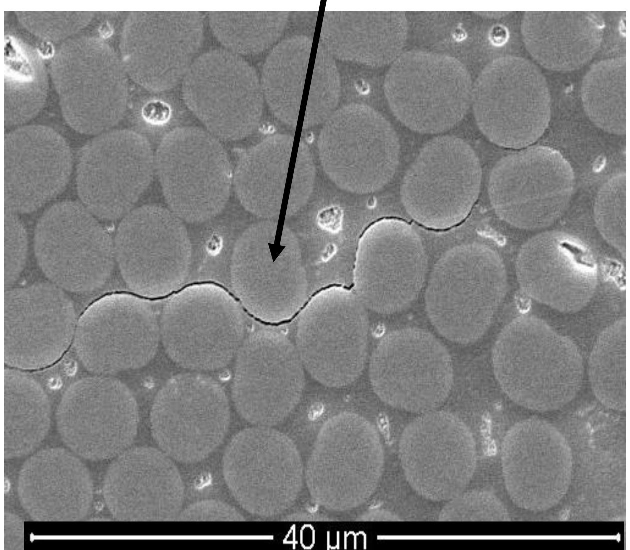


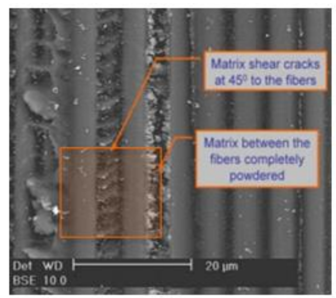
Real time strain fields with DIC analysis

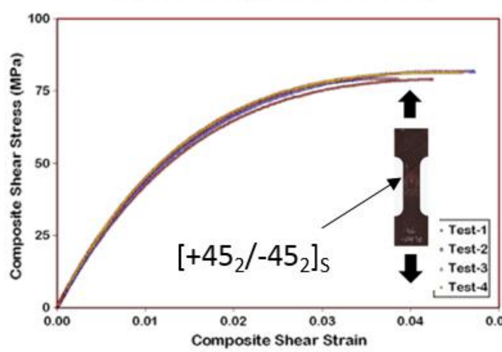
Importance of investigating micro-damage

- **The first failure mode in composite materials**
  - Microcrack is a local failure which occurs at fiber/matrix scale
  - Accumulation and/or growth of microcracks result in degradation of mechanical performance and other failure modes such as delamination
- **Need for in situ mechanical testing**
  - Micro-damage cannot be detected by conventional experimental techniques
  - Few attempts to study detailed initiation and propagation process of micro-damage

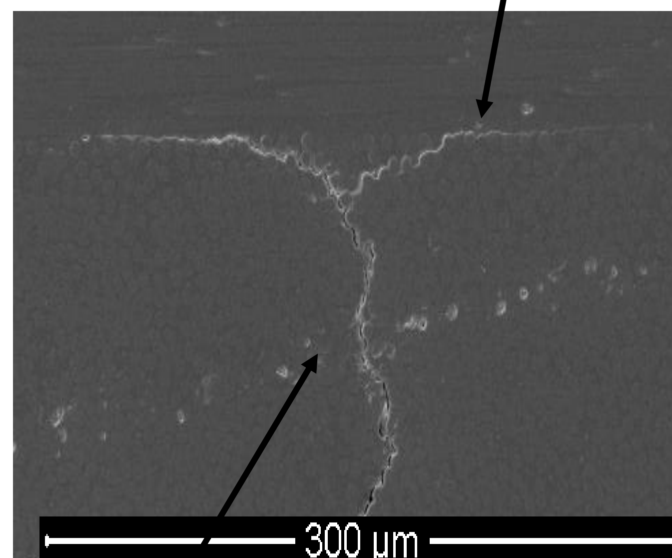
Microcrack







Delamination



Matrix transverse cracking

- ***In situ* mechanical testing with 3D X-ray computed tomography**
  - The interior structures of composite materials can be investigated
  - Micro-scale resolution for microcraks
  - Evolution of microcrack density can be measured
  - Complex and interacting failure modes of composite materials are observed

X-ray CT	Synchrotron
Beam geometry	Parallel beam
Total power	3.9 kW
Resolution	0.9μm (0.45μm)
FOV*	3.6 mm X 2.4 mm (1.8mm X 1.2mm)

** FOV: Field of view*

Pohang Accelerator Laboratory (PAL)

Synchrotron rotation stage

Overview of the in situ mechanical loading device

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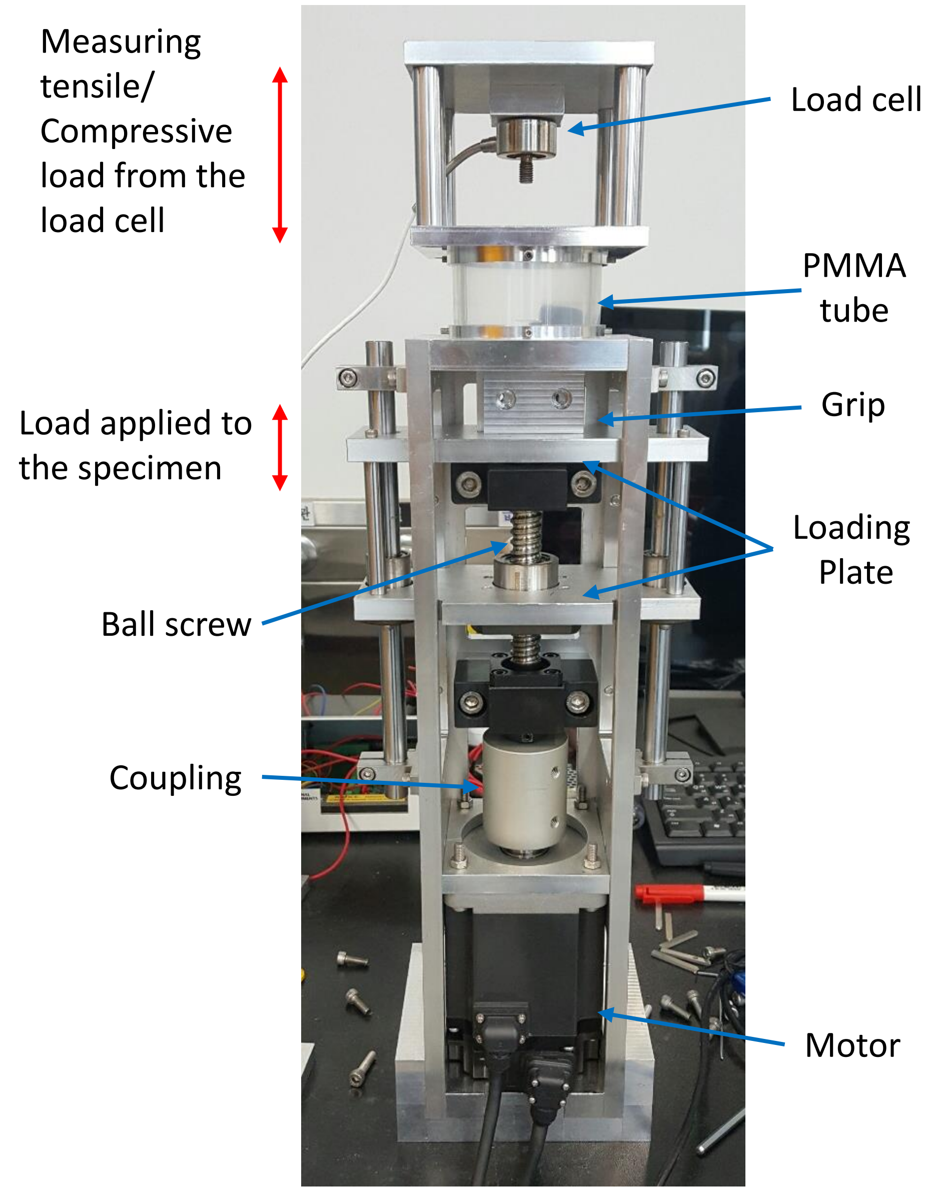
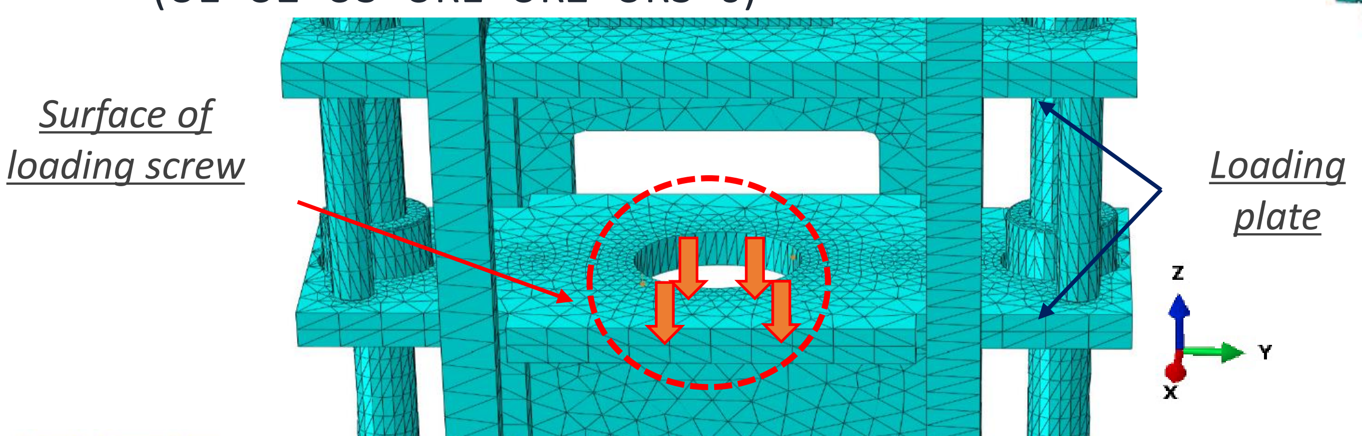
- **Purpose**
  - Obtain 3D tomography images of composite specimens during mechanical testing
- **Features of the in situ mechanical loading device**
  - Mounted onto the X-ray synchrotron stage
  - PMMA tube for the penetration of the X-ray beam
  - Load cell for measuring load and stepper motor with displacement based PID control from encoder
- **Synchrotron positioning system**
  - Limitation on the weight, height and inertial moment in the in-plain directions



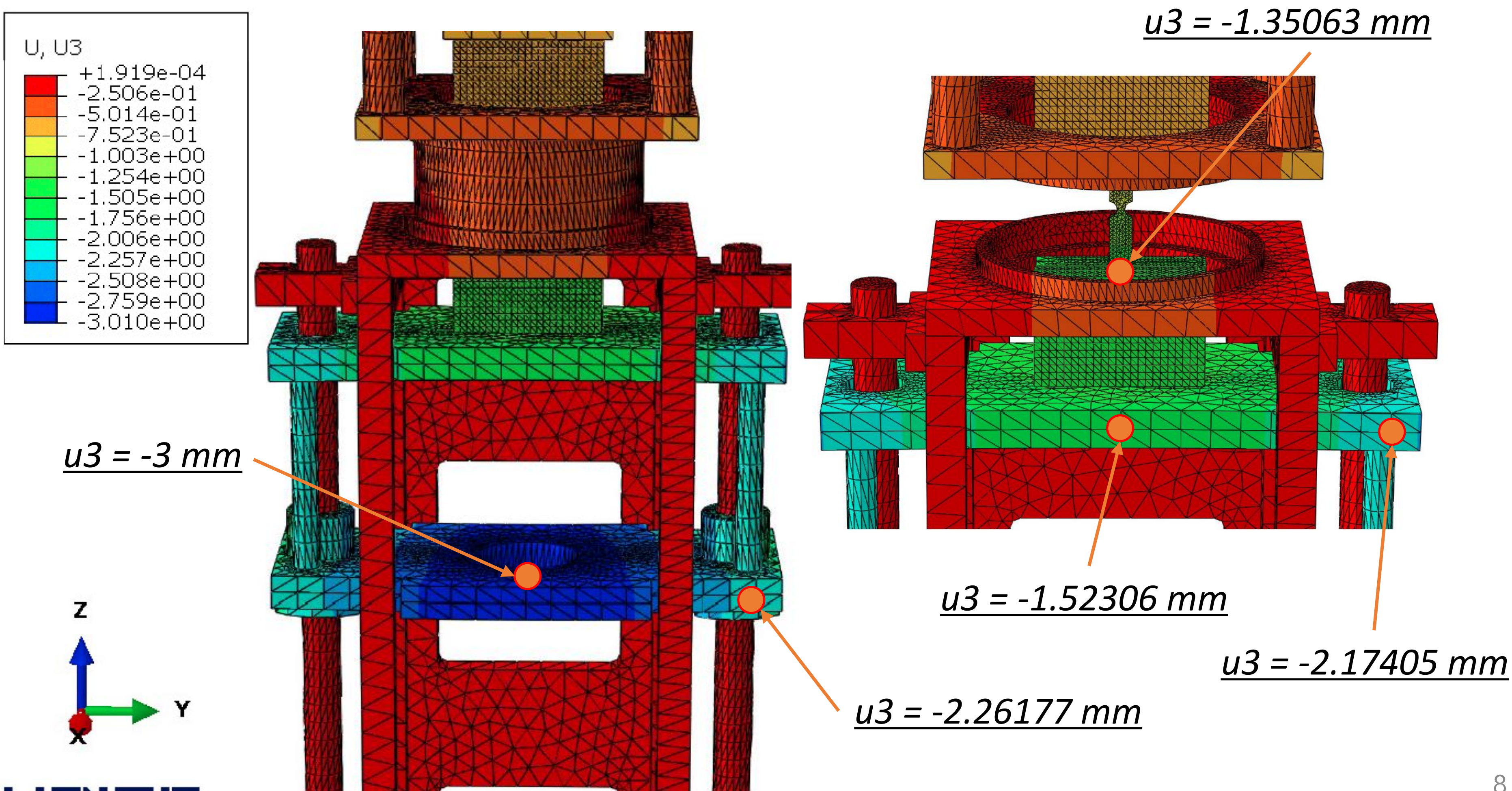
Micro loading device FEM test with ABAQUS

- **Stability analysis for loading device**
- **Modeling**
  - Many holes, bolts and threads are removed
  - Assume all the contact surfaces are bonded perfectly
  - Motor and loading screw are excluded in FEM analysis
- **Loading condition**
  - Load is applied in the surface of screw and loading plate by displacement control(U3 = -3 mm)
- **Boundary conditions**
  - Bottom surface are defined as encastre (U1=U2=U3=UR1=UR2=UR3=0)



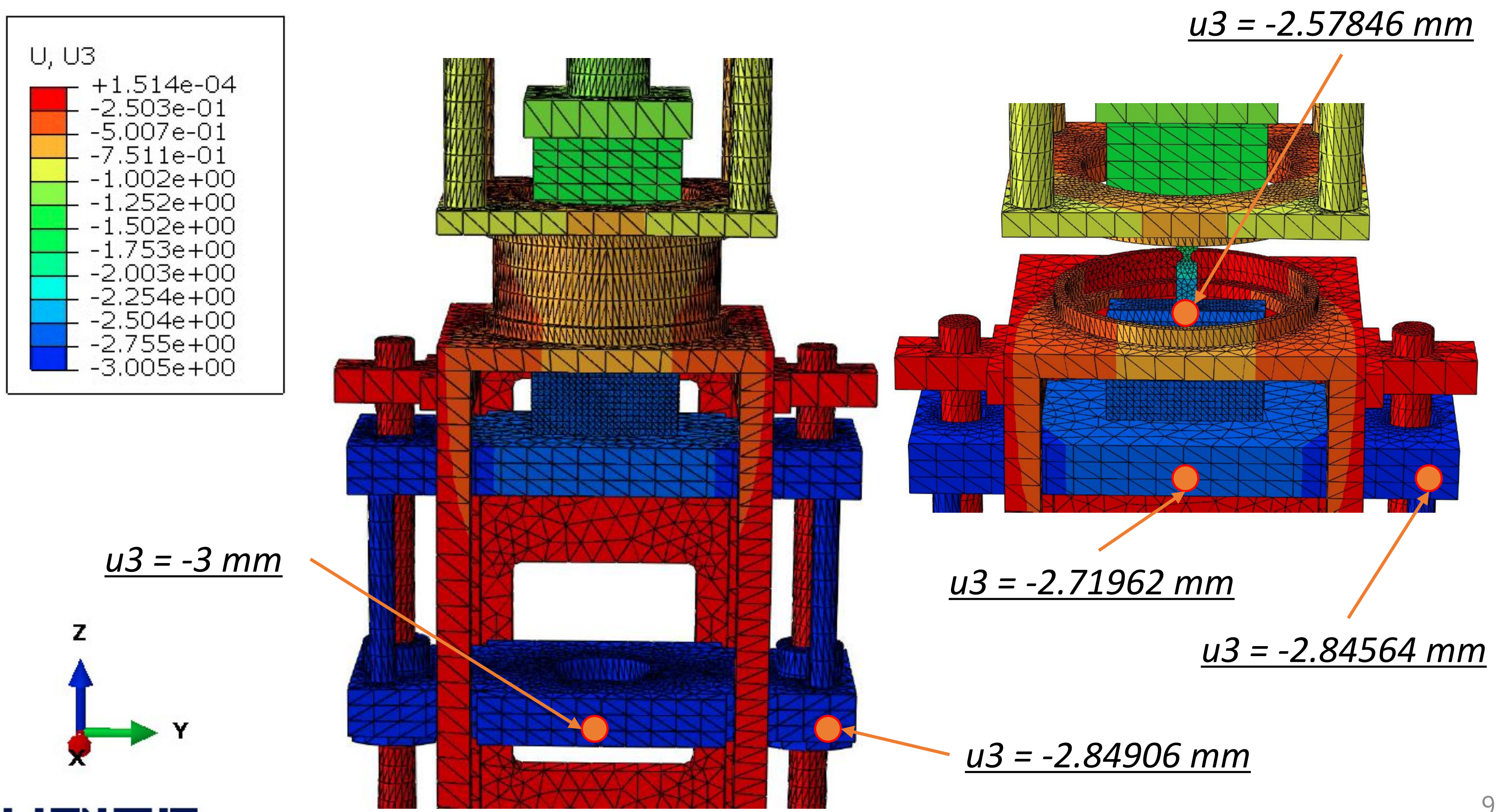
FEM analysis with initial design

- **Loading plate made of Al was resulted in compliance issues**
  - Due to the weight limitation of synchrotron stage, the first model was made of Al
  - As the displacement was applied to the loading plate, Al loading plate was bended



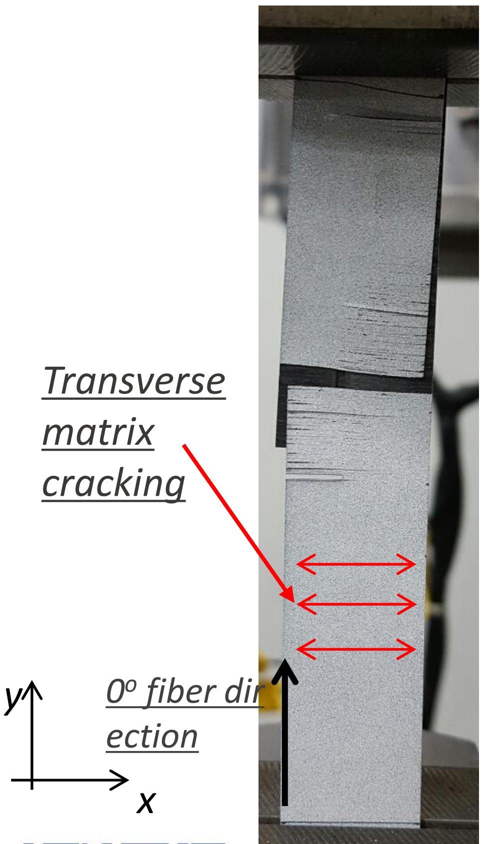
Revised loading device based on FEA result

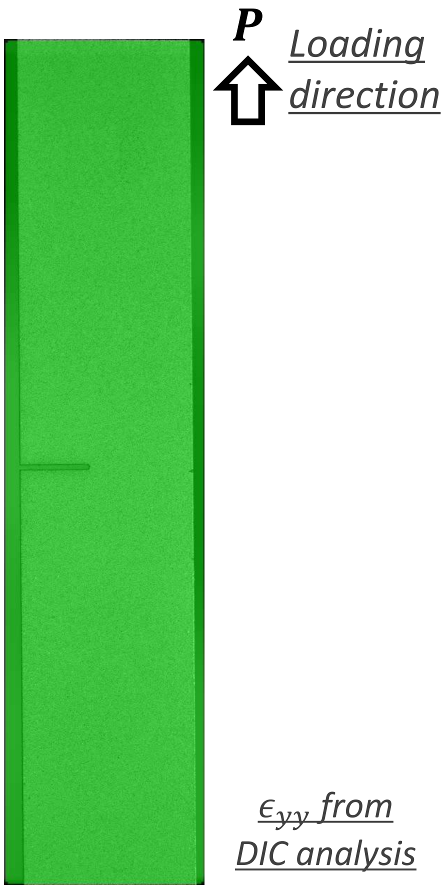
- **The loading plate material and thickness of the loading plate are changed**
  - The material was changed aluminum to steel (SUS304)
  - The thickness of the loading plate was changed from 10mm to 15mm

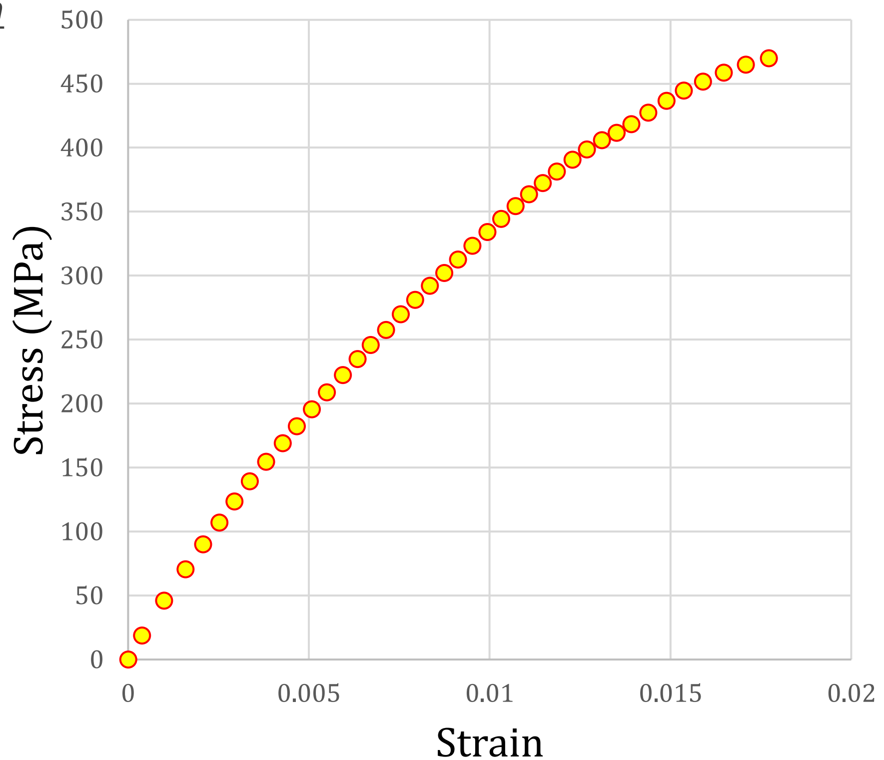


$[90_2/0_2]_S$ SENT Tests with DIC

- **Single Edge Notched Tension test with unidirectional $[90_2/0_2]_S$ specimens**
  - This is the best specimen configuration to observe interactive multiple failure modes
  - First failure mode is the transvers matrix crack on the 90 degree plies
  - Delamination is followed after the transverse matrix cracks on the 90 degree plies
  - 0 degree fiber directional failure

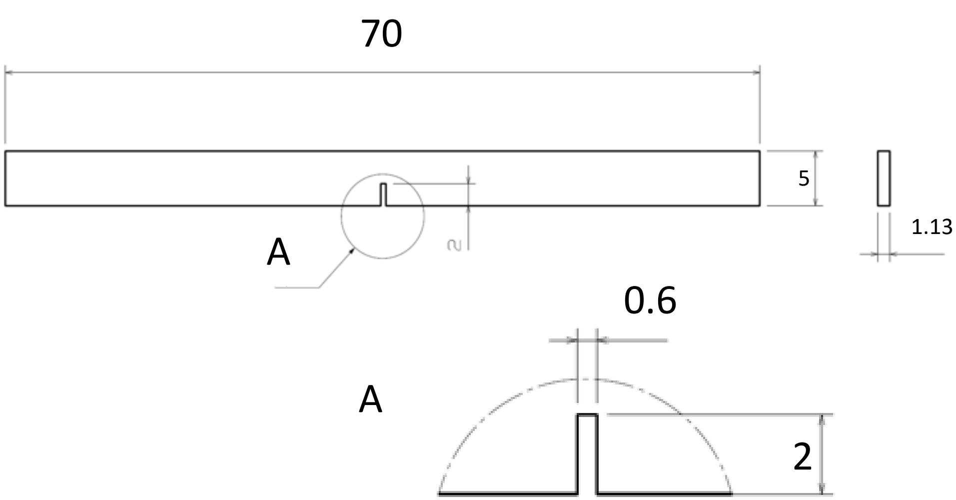




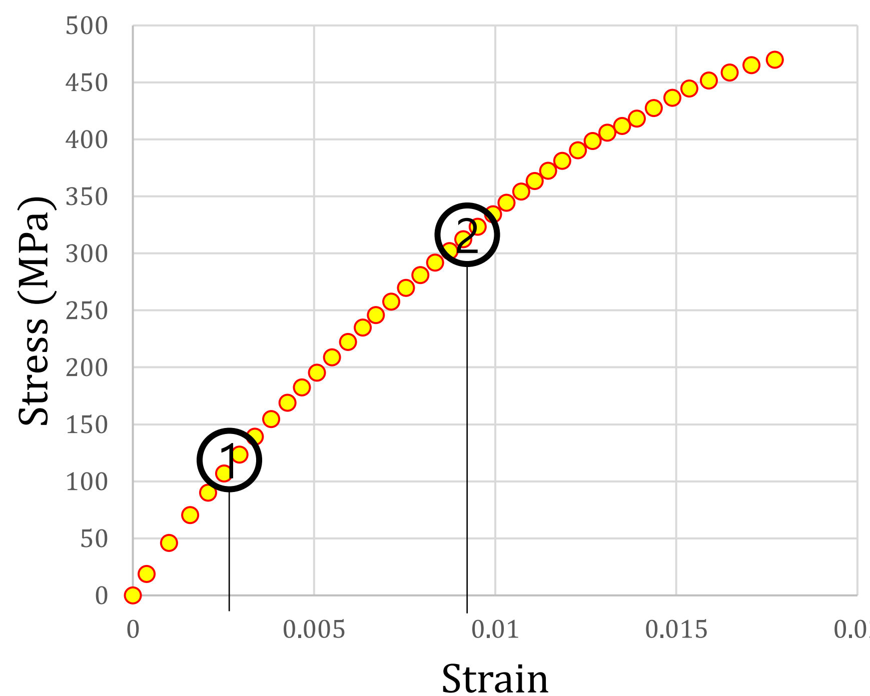


In situ test plan using SENT

- ***In situ* tension test with SENT $[90_2/0_2]_s$ specimen**
  - Single-edge notched specimens were manufactured from UD fiber reinforced laminated composite plate (for initial crack propagation in the filed of view)
  - Tensile test was performed in the Synchrotron, scanning images for tomography
  - Two loading steps were carried out at 30% and 70% of the ultimate tensile strength (σ_f)

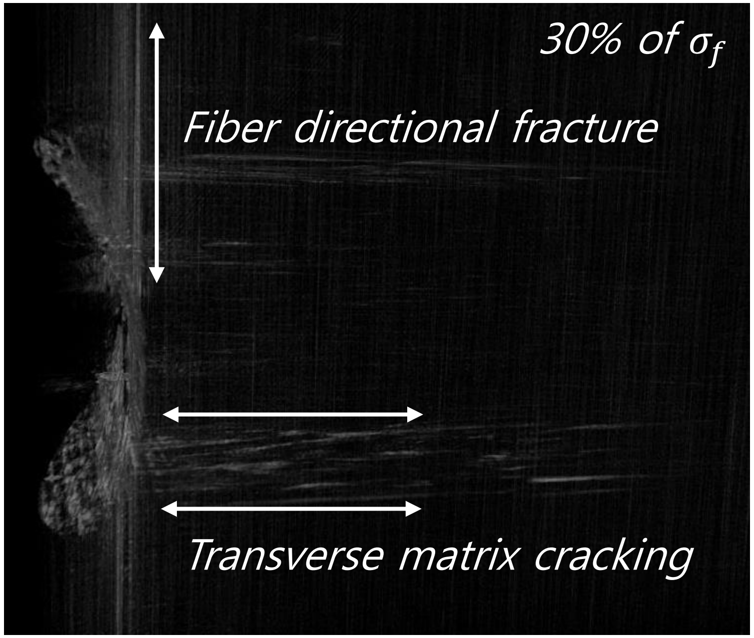


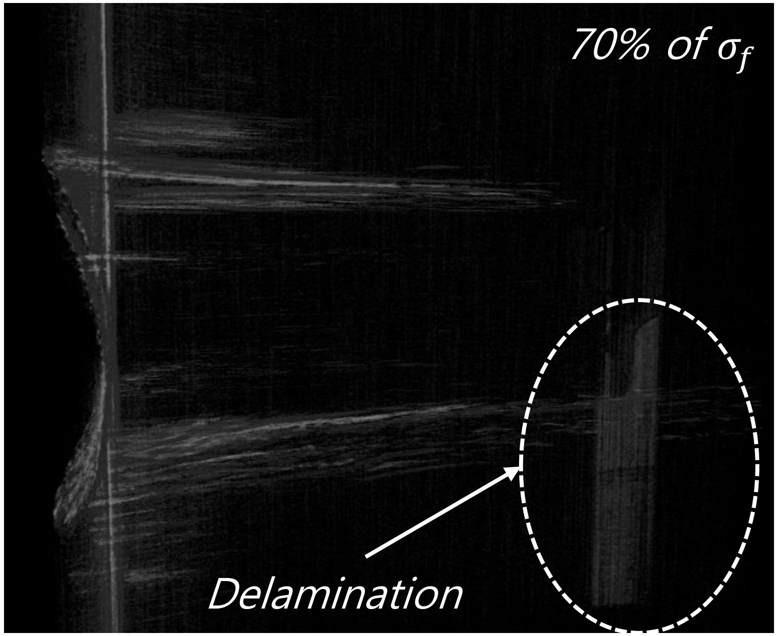
Specimen dimension (mm)



Loading steps in stress-strain curve

- **3D tomography of loaded $[90_2/0_2]_S$ specimen**
  - Transverse matrix cracking initiated in 90 degree plies from the initial notched edge
  - The transverse matrix cracks were deeper and longer as the loading increased
  - Delamination at the interfaces were initiated





Conclusion

- **In situ mechanical testing has been performed using a synchrotron X-ray beam.**
- **Special loading device has been designed and manufactured for the in situ mechanical testing at PAL.**
  - Fully automated loading control with a PID encoder.
  - Finite element analysis is performed to resolve the compliance issue.
- **Fully 3D computed tomography technique gives more information and insight**
  - Novel experiment method has a potential for enhancing understanding of composite materials
- **Quantification of 3D CT images will help investigation for complex failure modes of composite materials**
  - Fully 3D analysis will be done in the future
  - Investigation of crack density and energy release rate
  - Digital Volume Correlation algorithm development

Q & A