Effects of mode mixity on microscopic damage process of adhesively bonded CFRP joints

Sota Oshima, Tokyo Metropolitan University, Japan
Tomoisa Mikami, Tokyo University of Agriculture and Technology Japan
Akinori Yoshimura, Nagoya University, Japan
Yoshiyasu Hirano, Japan Aerospace Exploration Agency (JAXA), Japan
Toshio Ogasawara, Tokyo University of Agriculture and Technology, Japan

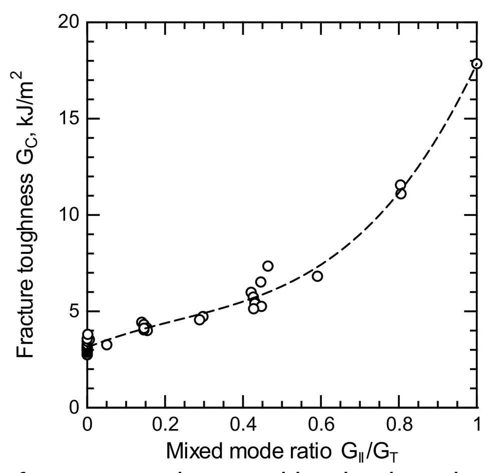
TOKYO METROPOLITAN UNIVERSITY

1. Background

Mixed-mode loading in adhesively bonded joints

- Realistic loading condition in practical applications
- Fracture toughness increases with an increase in mode II component for ductile adhesive
- Relation between stress-triaxiality-dependent properties of polymers and formation of process zone under mixed mode loading is still unclear

→ Linking adhesive properties to fracture process is required



Change in fracture toughness with mixed-mode ratio
Adapted from D Álvareza, et al., Eng Frac Mech 203 (2018), 224–239

2. Objectives

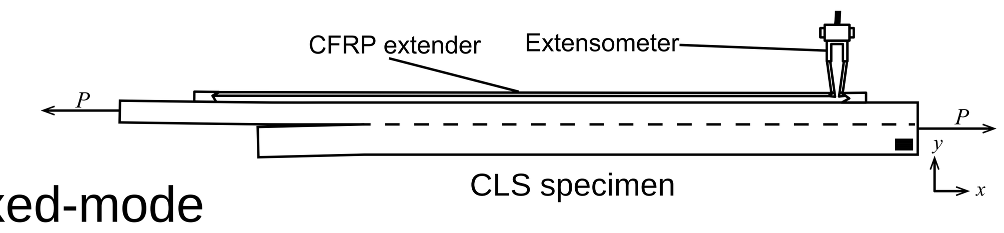
To clarify the effects of mode mixity on microscopic damage mechanisms

- Formation of the process zone until the crack initiation was investigated
- Microscopic damage was characterized by high-resolution in situ observation
- Finite element analysis was performed to obtain stress field around crack tip

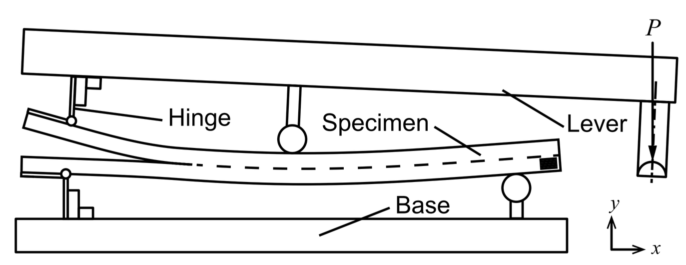
3. Methods

Materials and specimen

- Cracked lap shear (CLS) and mixed-mode bending (MMB) specimens were used
- Mixed-mode ratios $G_{II}/(G_I + G_{II})$ (= G_{II}/G_T) were set to 0.25, 0.5, and 0.81
- Unidirectional CFRP laminates were used for adherends (T800S/2592. Toray Industries Inc.)
- Laminates were bonded with rubber-modified epoxy adhesive films (NB102, Newport)



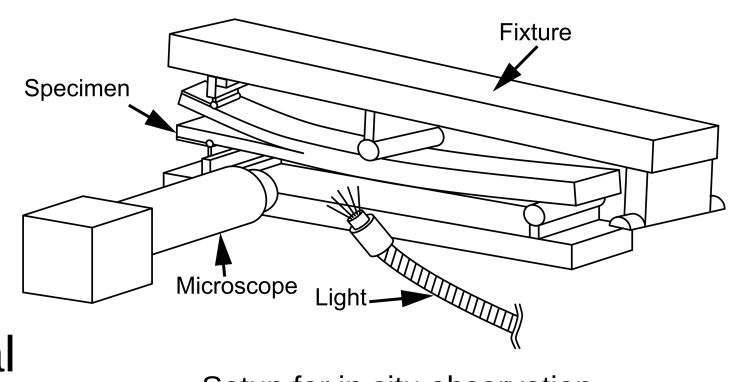
CLS specimen



MMB specimen

In situ observation

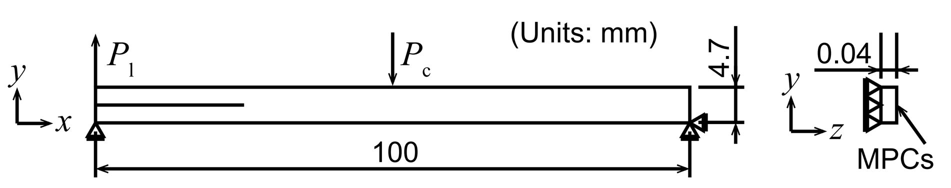
- In situ observation was performed using optical microscope
- Damage and failure processes were sequentially captured
- Plastic zone size was estimated using digital image correlation method by analyzing residual shear strain



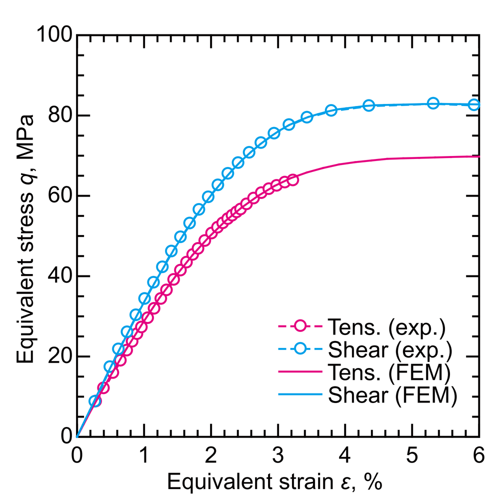
Setup for in situ observation

Finite element (FE) analysis

- FE analysis was conducted to obtain stress field around crack tip
- Adhesive properties depending on stress triaxiality were obtained from tensile and shear tests of bulk adhesive
- Drucker-Prager yielding criterion was used to simulate stress-triaxiality-dependent mechanical properties
- Two-dimensional plane strain analysis was conducted
- Abaqus/standard 2019 was used
- Temperature change from glass transition temperature to room temperature was applied first, then mechanical loading corresponding to mixed-mode tests were applied



FE model and boundary conditions



Stress–strain curves depending on stress triaxiality

Pure mode I and mode II tests

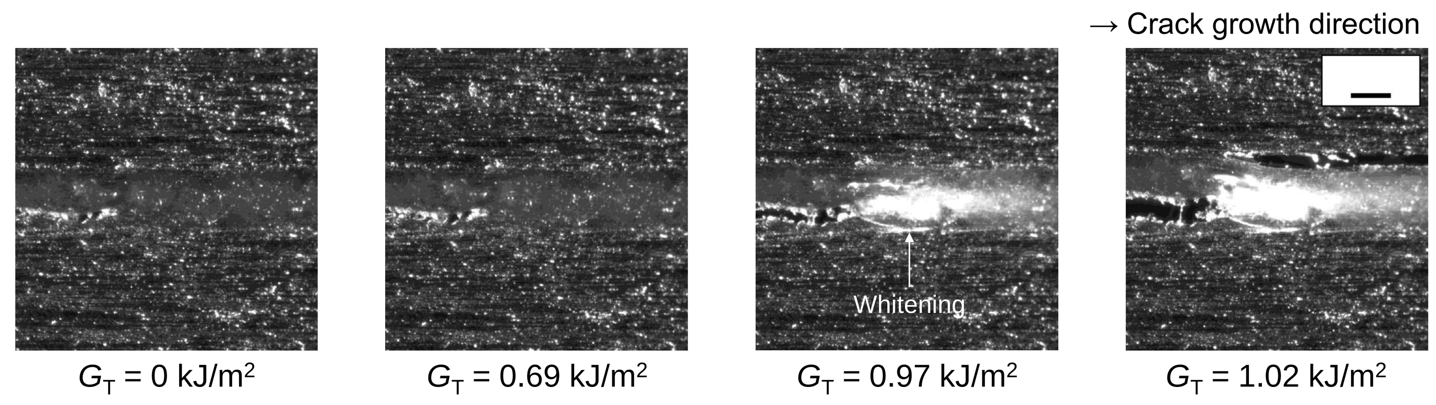
- Present results were compared with pure mode I and mode II tests
- Results were taken from our previous study

S Oshima, et al., Compos Struct 227 (2019), 111330

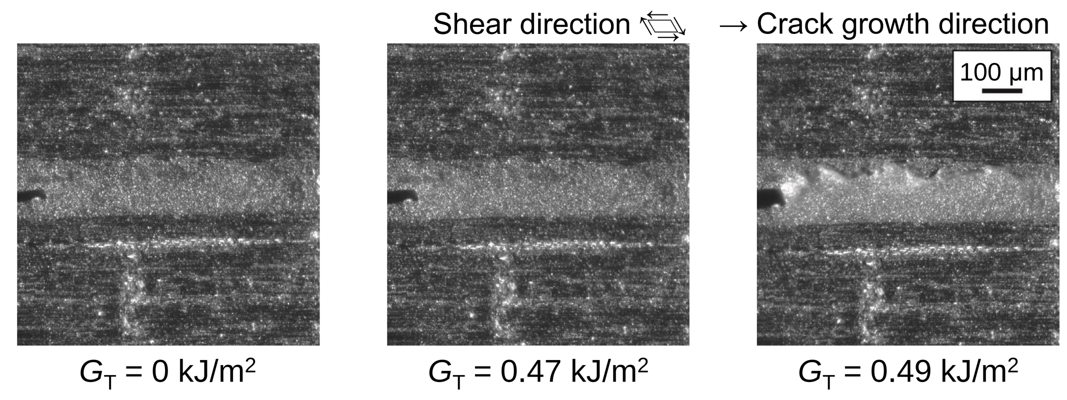
4. Results

Microscopic failure morphology

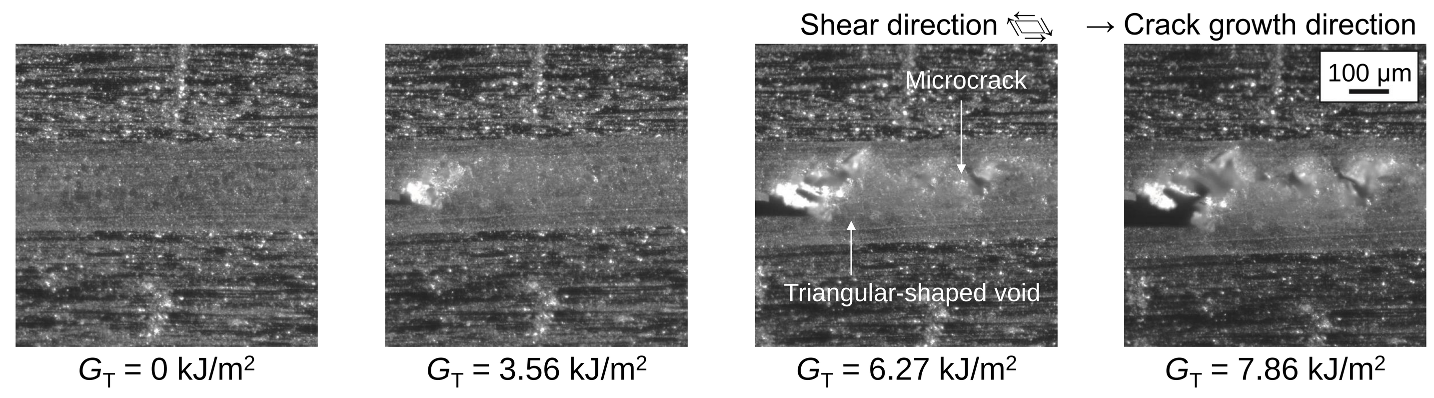
- Whitening of adhesive resin was observed under pure mode I loading because of cavitation from rubber particle for modification
- Brittle failure was observed for G_{II}/G_T = 0.25
- Ductile tearing was observed for G_{II}/G_T = 0.5 and more



Failure morphology under pure mode I loading (G_{II}/G_T = 0)



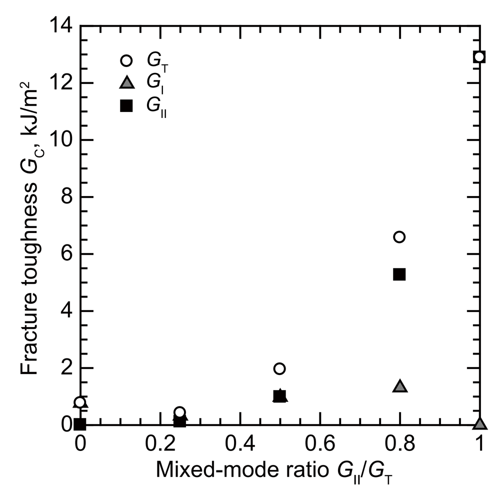
Failure morphology under mixed-mode loading (G_{II}/G_T = 0.25)



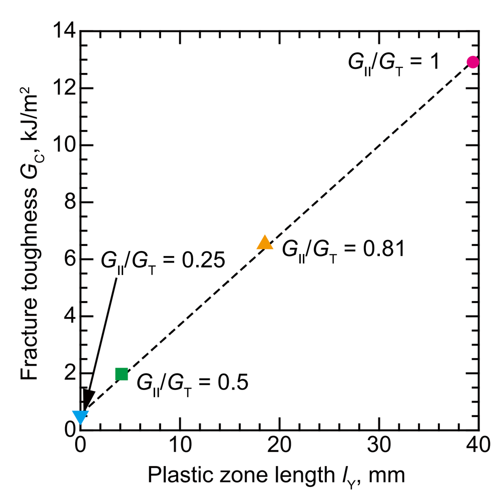
Failure morphology under mixed-mode loading (G_{II}/G_T = 0.81)

Fracture toughness and plastic zone size

- Lowest fracture toughness was obtained with G_{II}/G_T = 0.25
- Toughening under mode I was caused by cavitation of epoxy resin
- Toughening under mode II was caused by plastic dissipation because plastic zone length increased with an increase in mode II



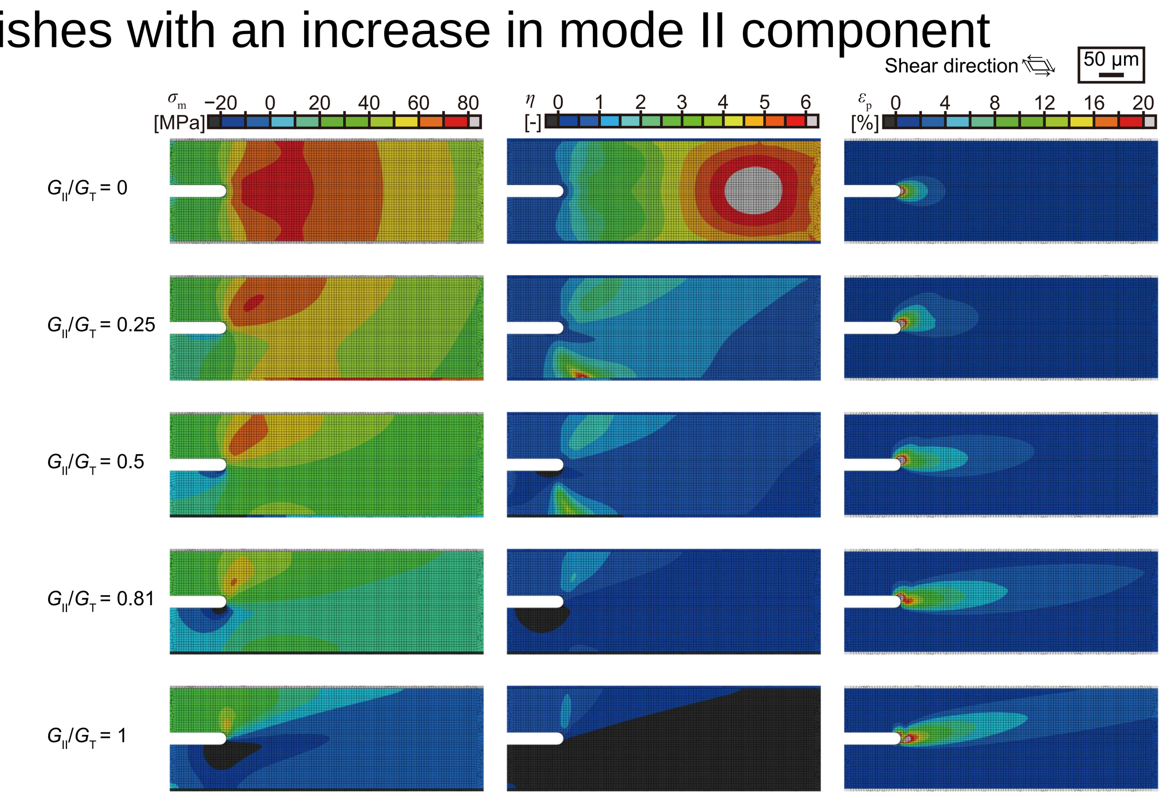
Fracture toughness with different mixed-mode ratios



Relation between fracture toughness and plastic zone length

FE results

- High stress and stress triaxiality are induced under pure mode I loading resulting in cavitation of epoxy resin
- Ductility of epoxy resin increases because stress triaxiality diminishes with an increase in mode II component



Hydrostatic stress, stress triaxiality, and equivalent plastic strain obtained by FE analysis.

6. Conclusion

The effects of mode mixity on microscopic damage process in adhesively bonded CFRP joints were studied by in situ observation. The microscopic failure process well reflects the deformation and failure behavior of epoxy resin depending on stress triaxiality.

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