A novel benchmark test for composites under complex loading sequences resulting in non-self-similar damage evolution

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Girona, 31st May 2023

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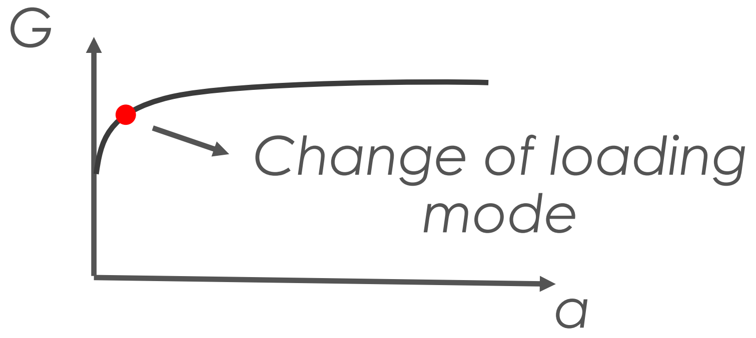
Introduction

Introduction

- *Characterization tests provide information about the fracture in composites*

- *But they are not representative of the in-service loading conditions of a structure:*

Simplified as a 2D problem



Do not consider a non-self similar damage evolution

Introduction

- *Predictive models should not be validated by characterization tests*
- *But larger structures are more complex and expensive to test*

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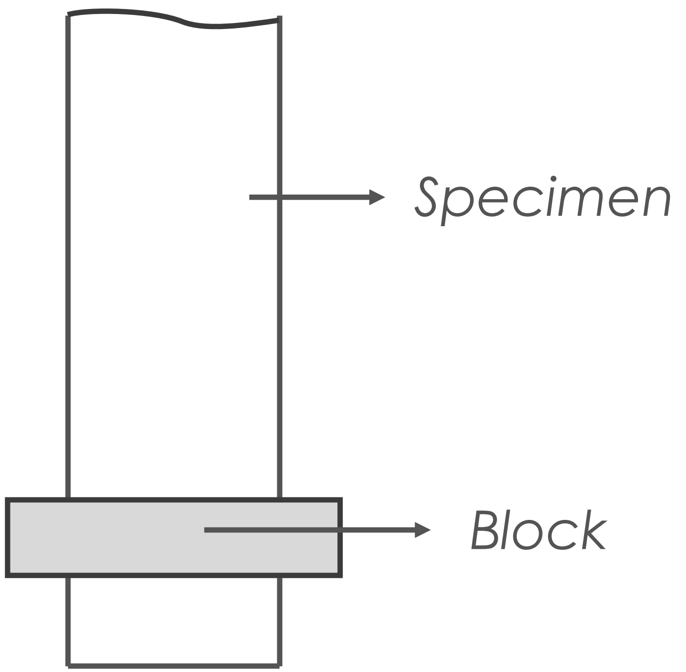
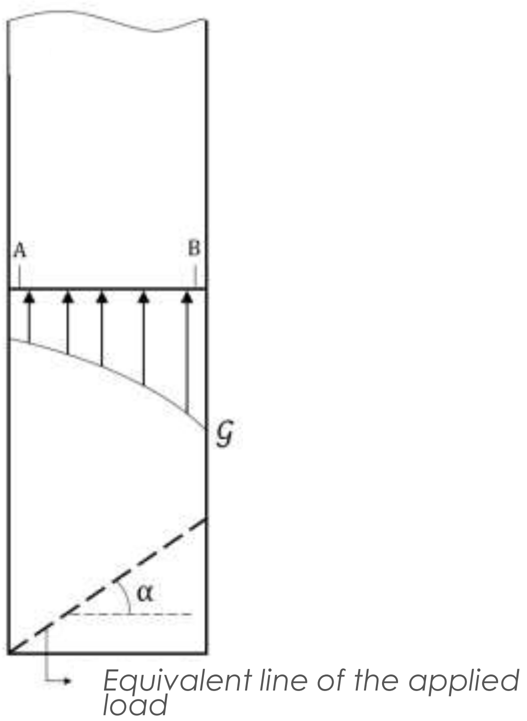
- *Development of a new validation test method:*
  - *Allows the combination of complex loading modes (I, II and III):*
    - *3D crack fronts*
    - *Switching between different loading modes*
  - *Test coupon as simple as a standardized specimen*

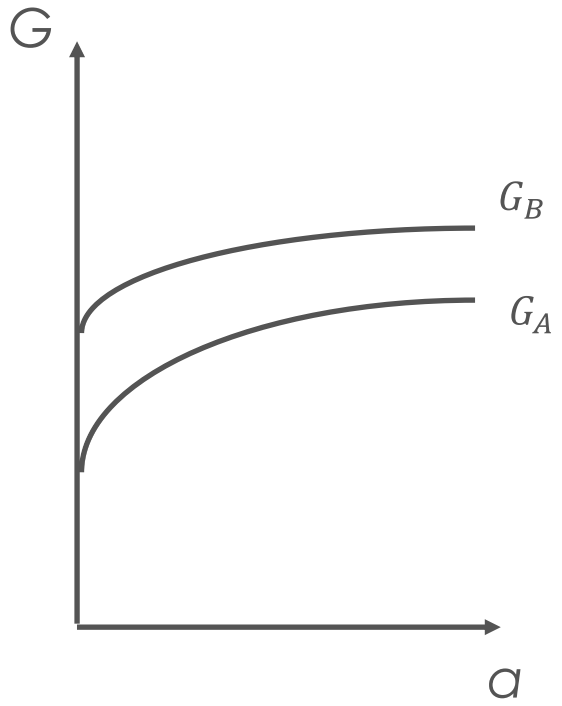
A novel test concept

Test concept

- By rotating the block, the R-curve evolves dissimilarly



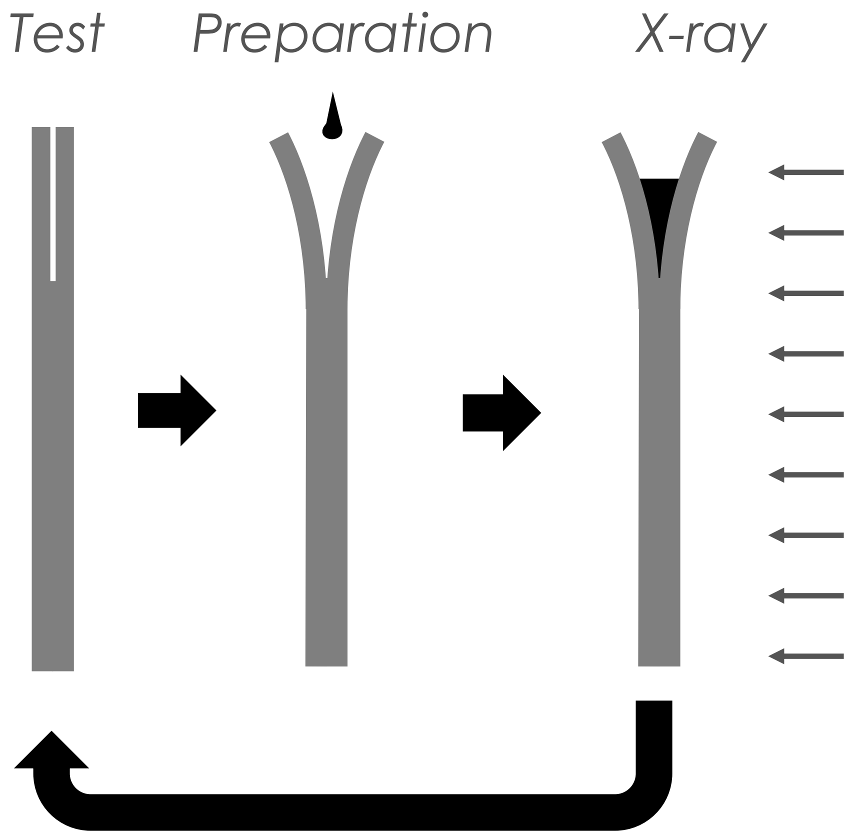




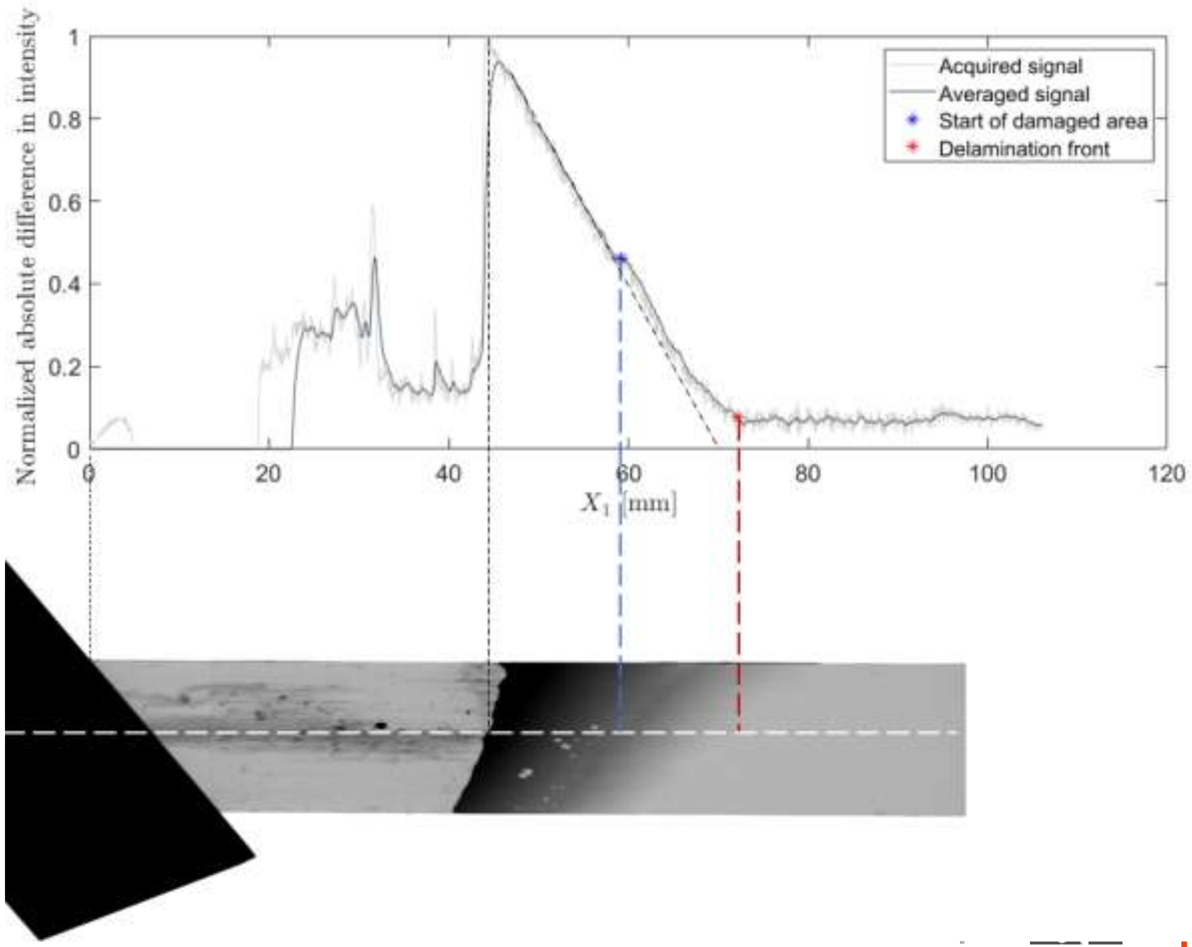
- We can rotate the loading blocks at different angles (α) sequentially achieving an ever-evolving non-self-similar delamination process

Monitoring of the delamination

- *The delamination front is monitored with X-ray*



- *An algorithm (low pass filter + moving linear regression) is used to identify the crack tip and detection of damage*



Case study

Material properties and specimen design

- *CFRP – AS4D/PEKK-FC, UD prepreg, ply thickness 0.138 mm*
- *Cured in autoclave (consolidation process)*
- *Specimen dimensions: 250mm x 25 mm x 4.2 mm*
- *Insert: 12.5μm polyimide film 60 mm*

Tijs et al. Characterization and analysis of the interlaminar behavior of thermoplastic composites considering fiber bridging and R-curve effects. Composites Part A (2022)

Loading sequence and test procedure (I)

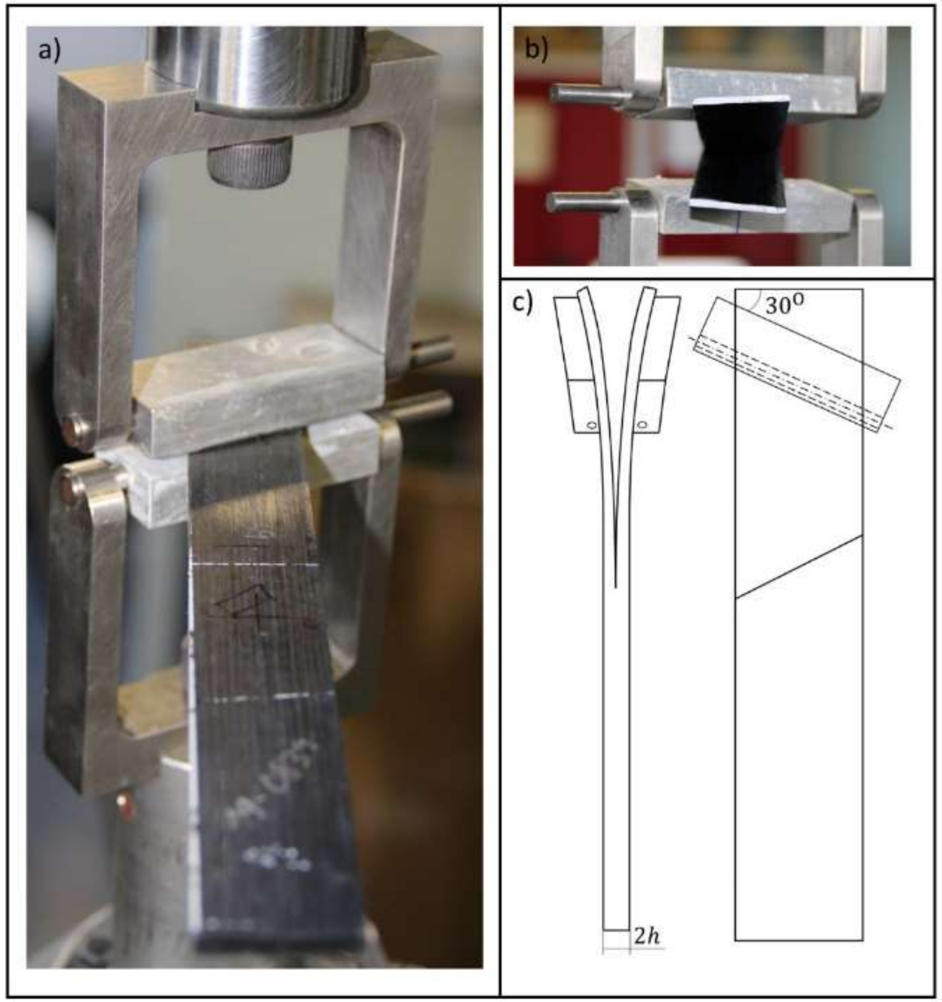
- Combination of:
  - Static and fatigue tests
  - Mode I and mode II loading

Step	Loading mode	Loading angle	Maximum displacement	Number of cycles
0	Mode I (DCB)	+0°	Precrack	-
1	Shear mode (ELS)	+30°	7 mm	12 000
2	Mode I (DCB)	-30°	5 mm	30 000
3	Mode I (DCB)	-30°	10 mm	-
4	Mode I (DCB)	-30°	10 mm	400 000

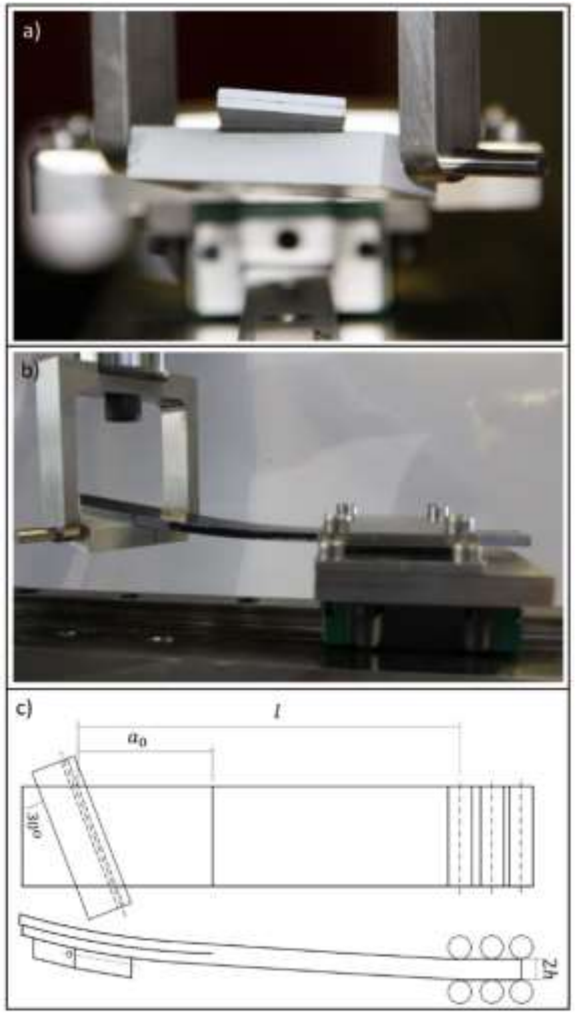
- Monitoring the delamination
- SEM of the fractured surfaces

Loading sequence and test procedure (II)

- DCB with inclined blocks



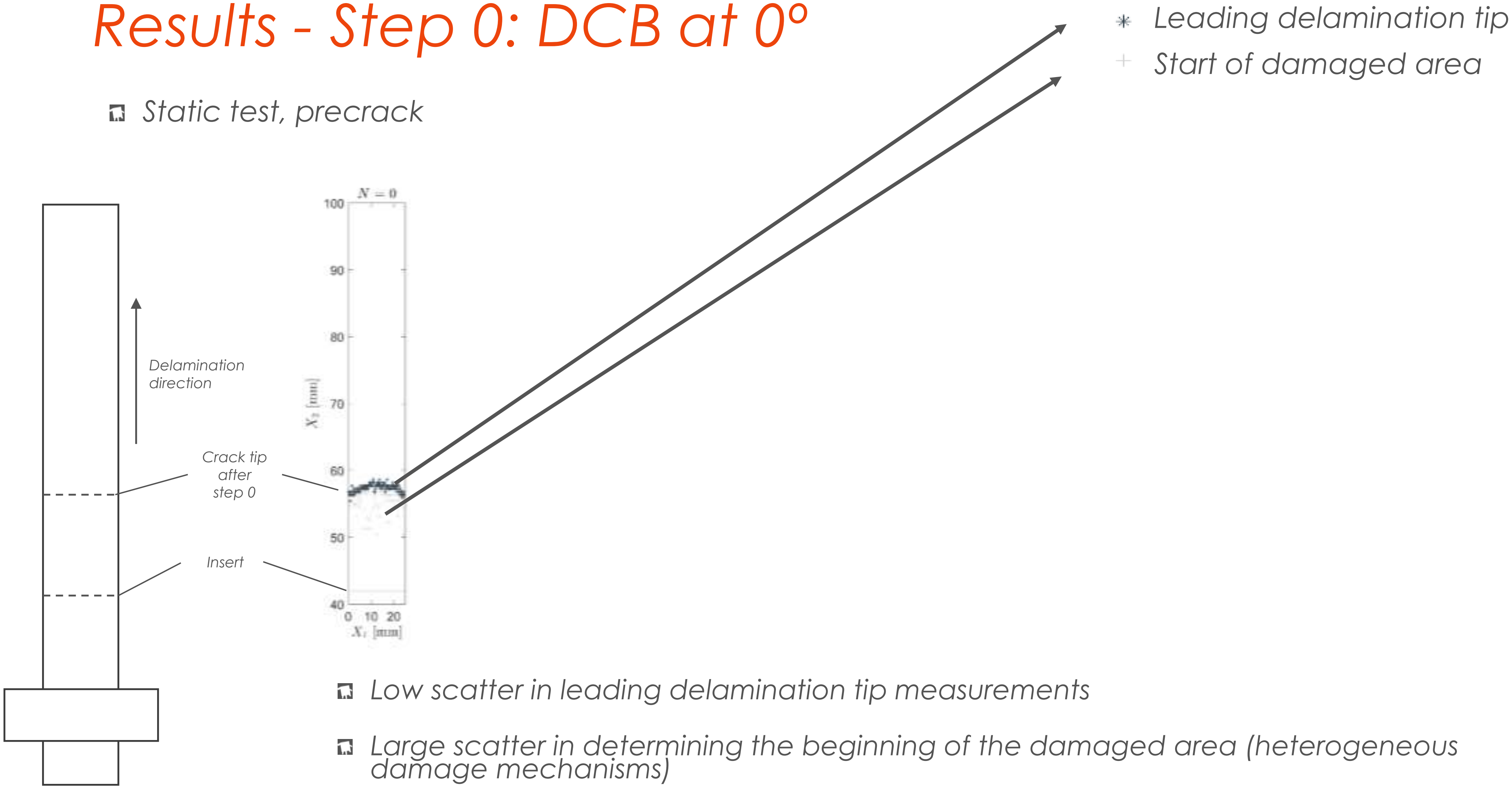
- ELS with inclined blocks



Results

Results - Step 0: DCB at 0º

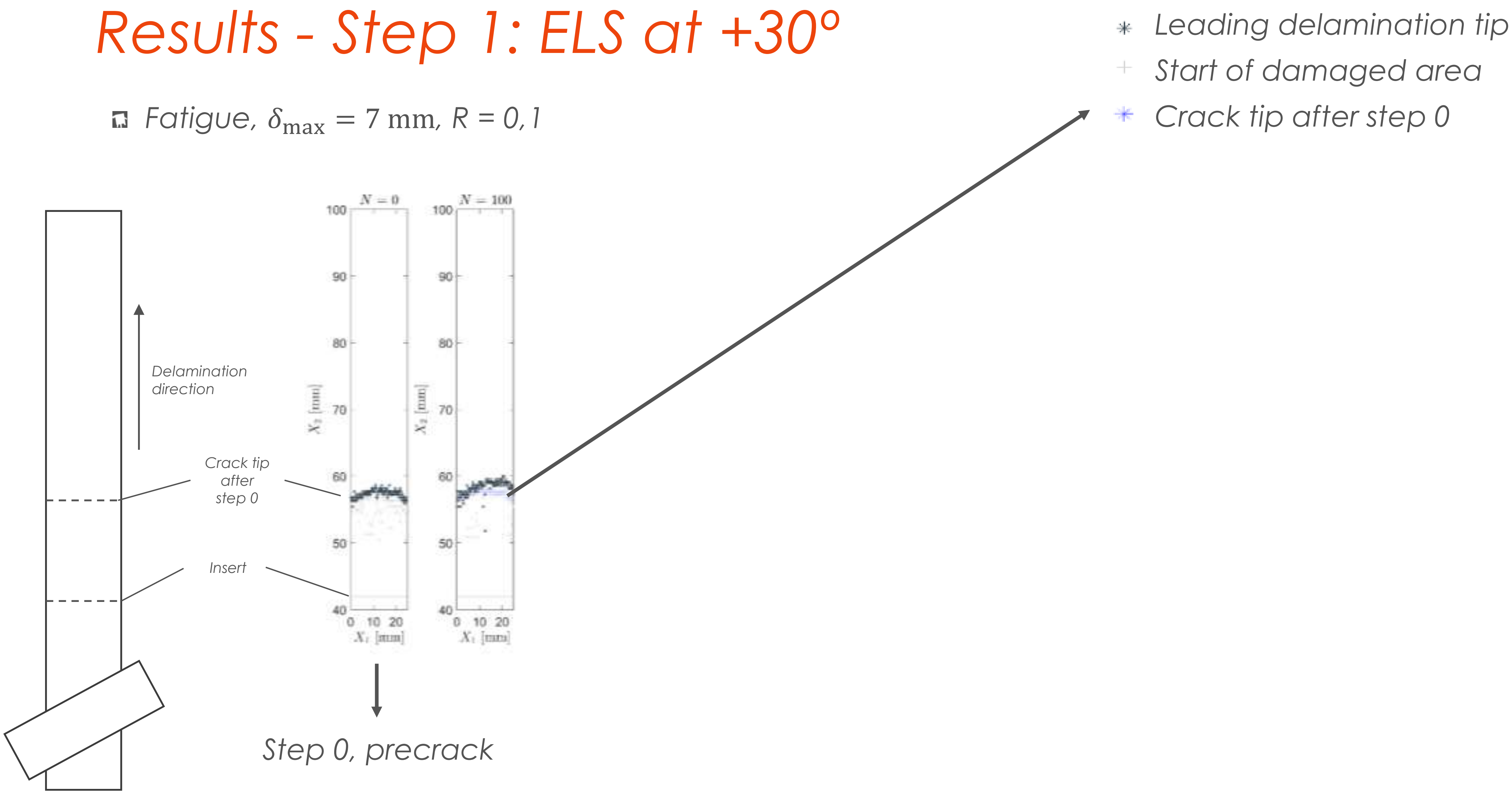
- Static test, precrack



- Low scatter in leading delamination tip measurements
- Large scatter in determining the beginning of the damaged area (heterogeneous damage mechanisms)

Results - Step 1: ELS at +30°

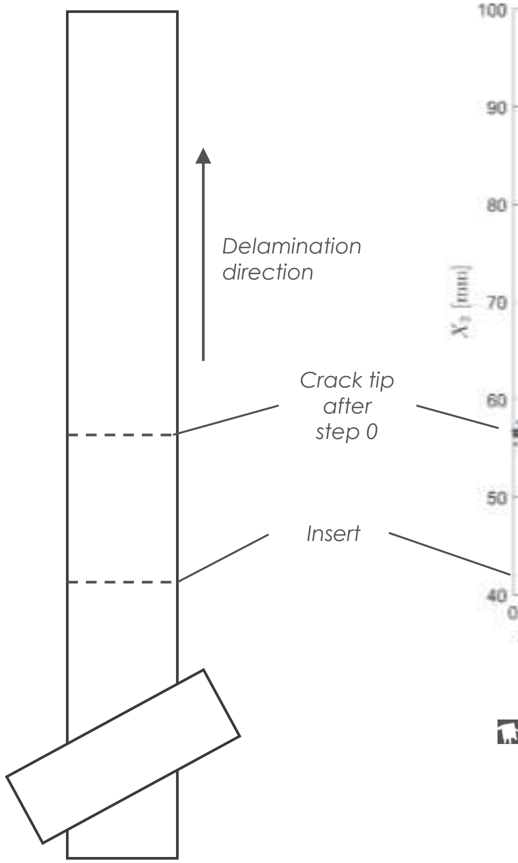
- Fatigue, $\delta_{max} = 7\ \mathrm{mm}$, $R = 0,1$

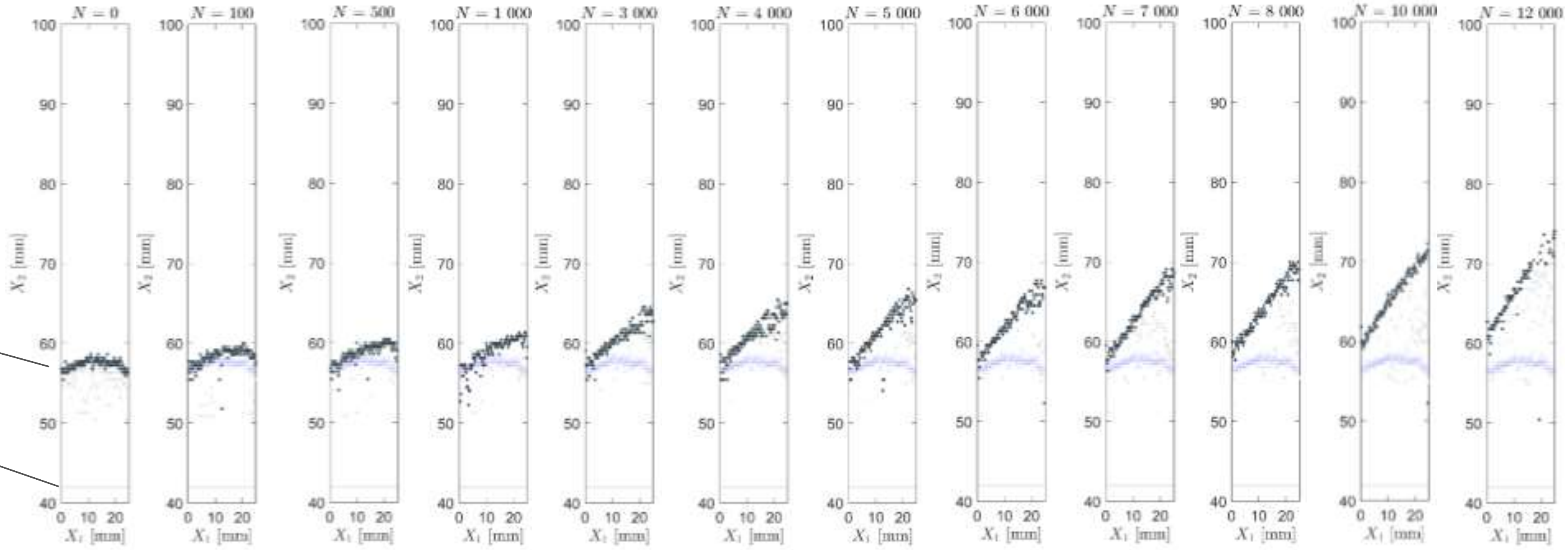


Results - Step 1: ELS at +30°

- *Fatigue,* $\delta_{max} = 7$ mm*,* $R = 0,1$

- *Leading delamination tip*
- *Start of damaged area*
- *Crack tip after step 0*

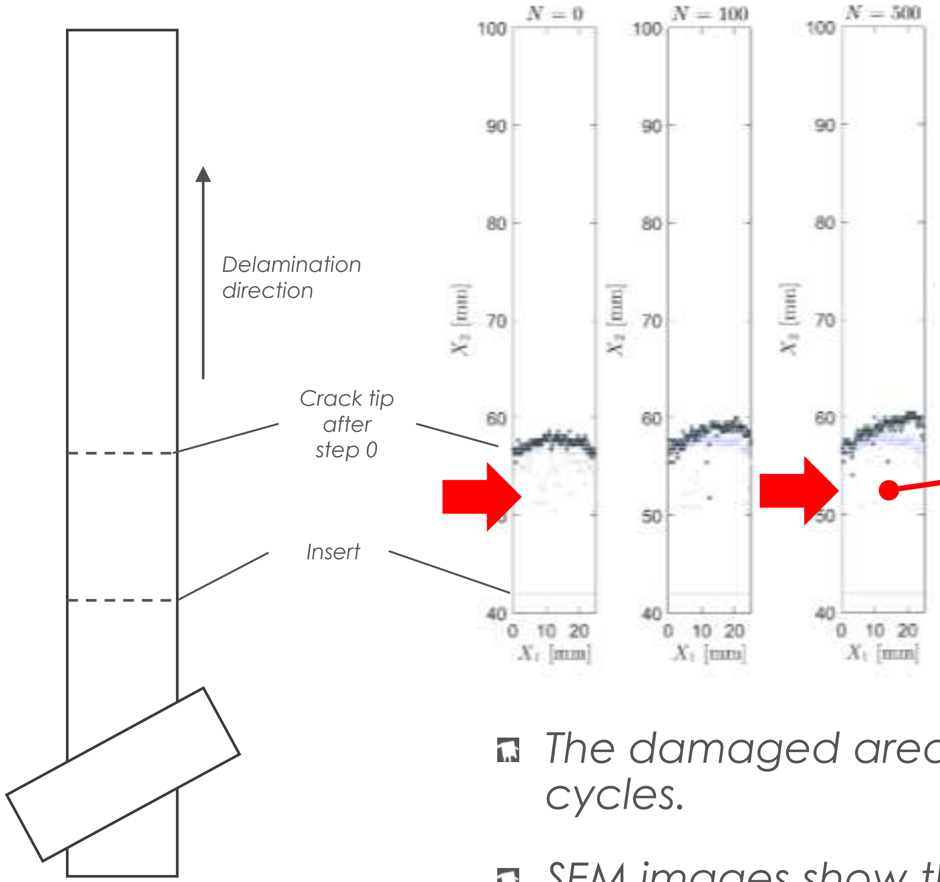


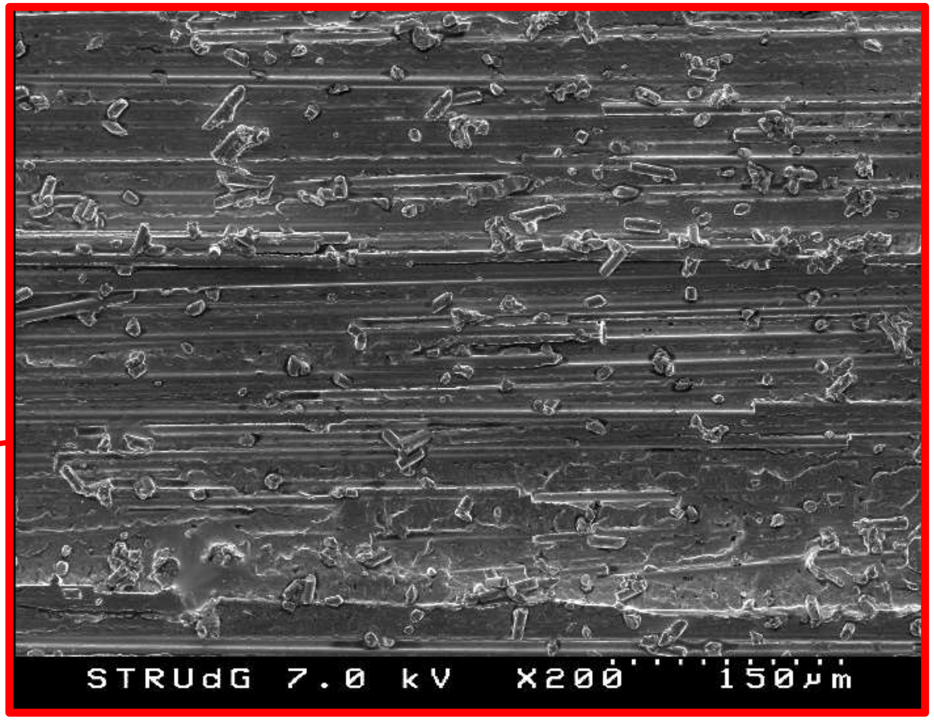


- *Inclined delamination tip following the inclination of the blocks but not with the same angle*

Results - Step 1: ELS at +30º

- Fatigue, $\delta_{max} = 7$ mm, $R = 0,1$



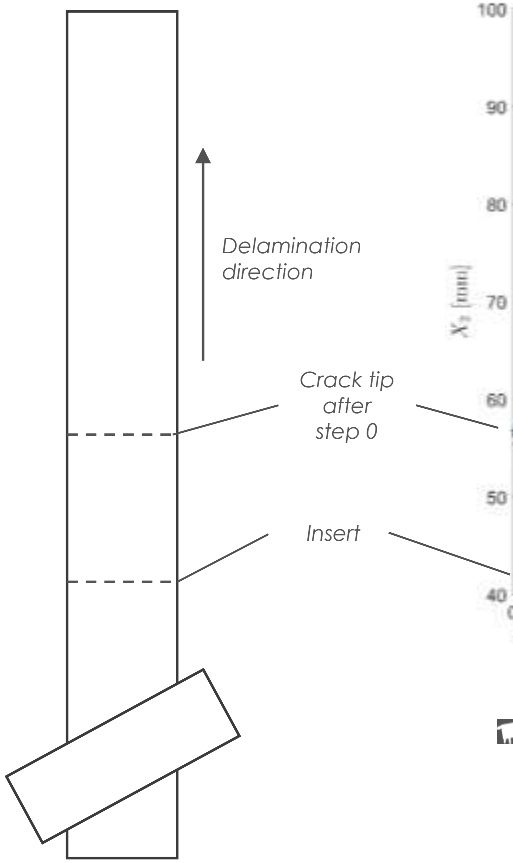


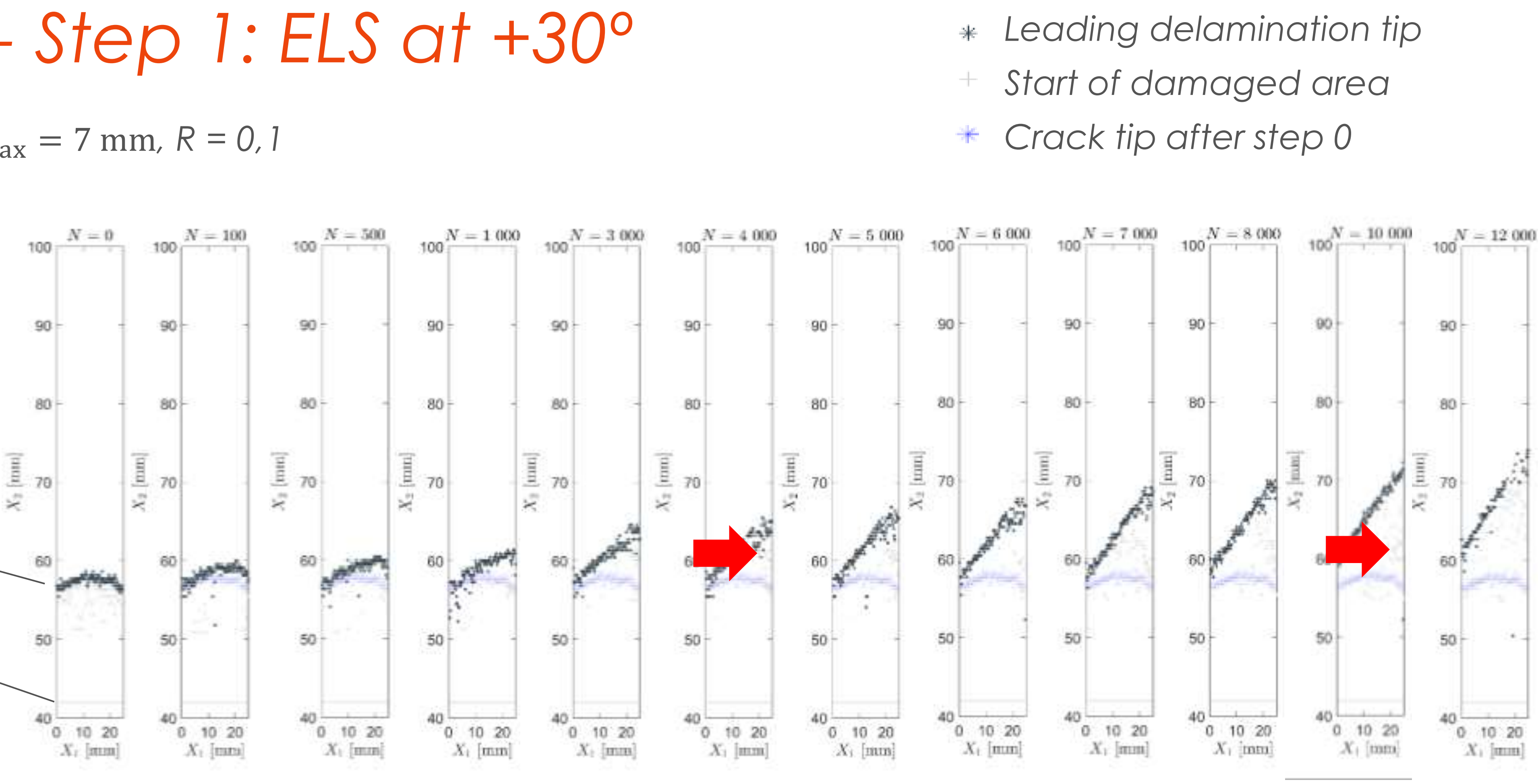
- Leading delamination tip
- Start of damaged area
- Crack tip after step 0

- The damaged area created by the Mode I pre-crack disappears after 500 cycles.
- SEM images show that fibres from fibre bridging are broken

Results - Step 1: ELS at +30°

- Fatigue, $\delta_{max} = 7$ mm, $R = 0,1$

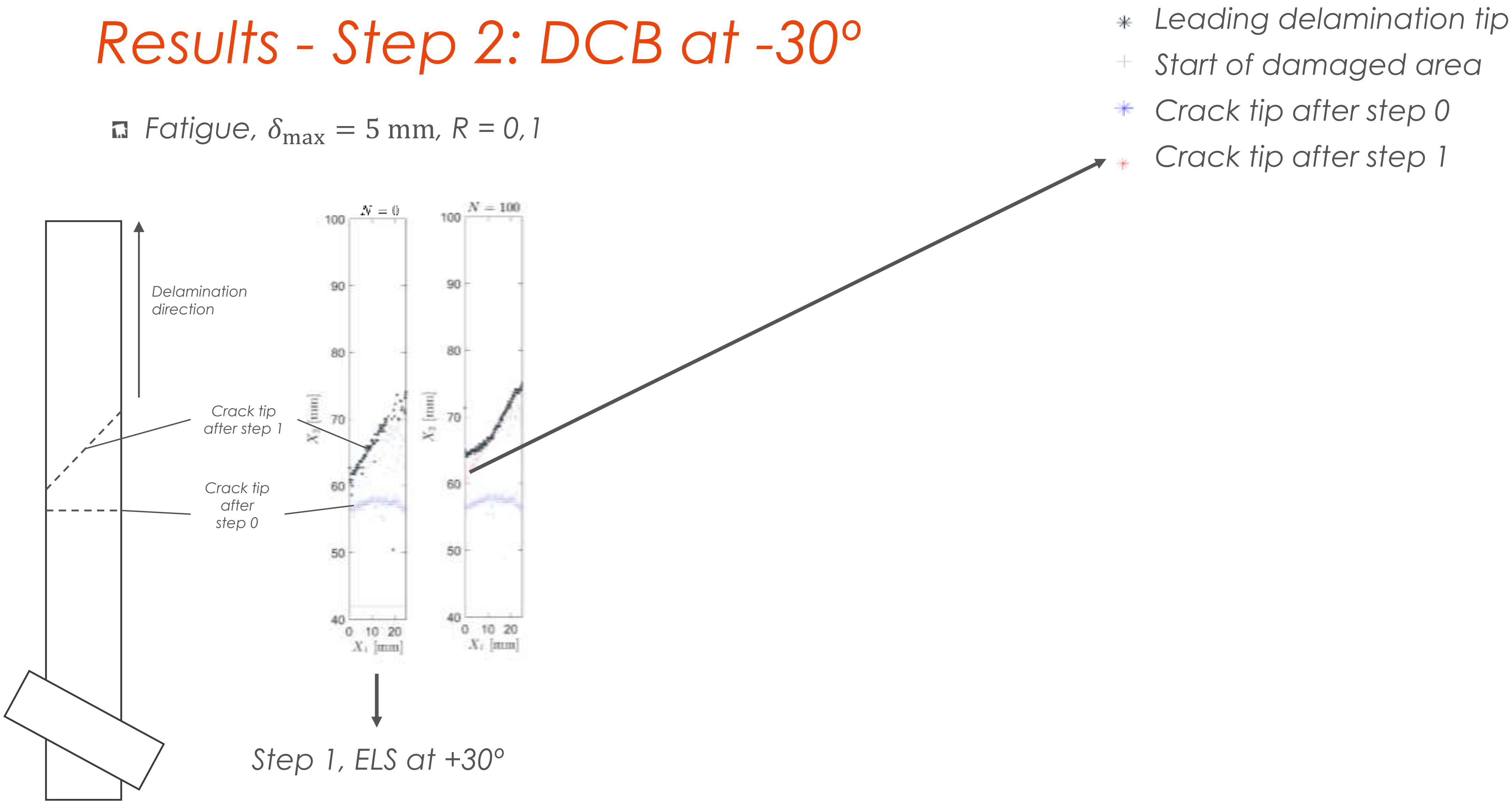




- The Mode II fatigue test creates a new damaged area

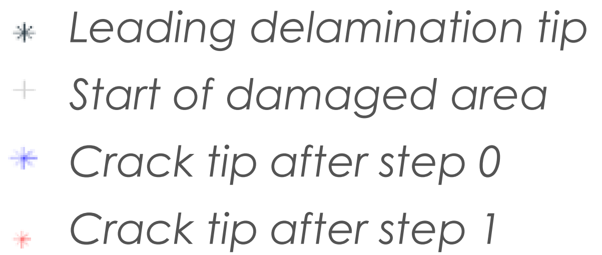
Results - Step 2: DCB at -30°

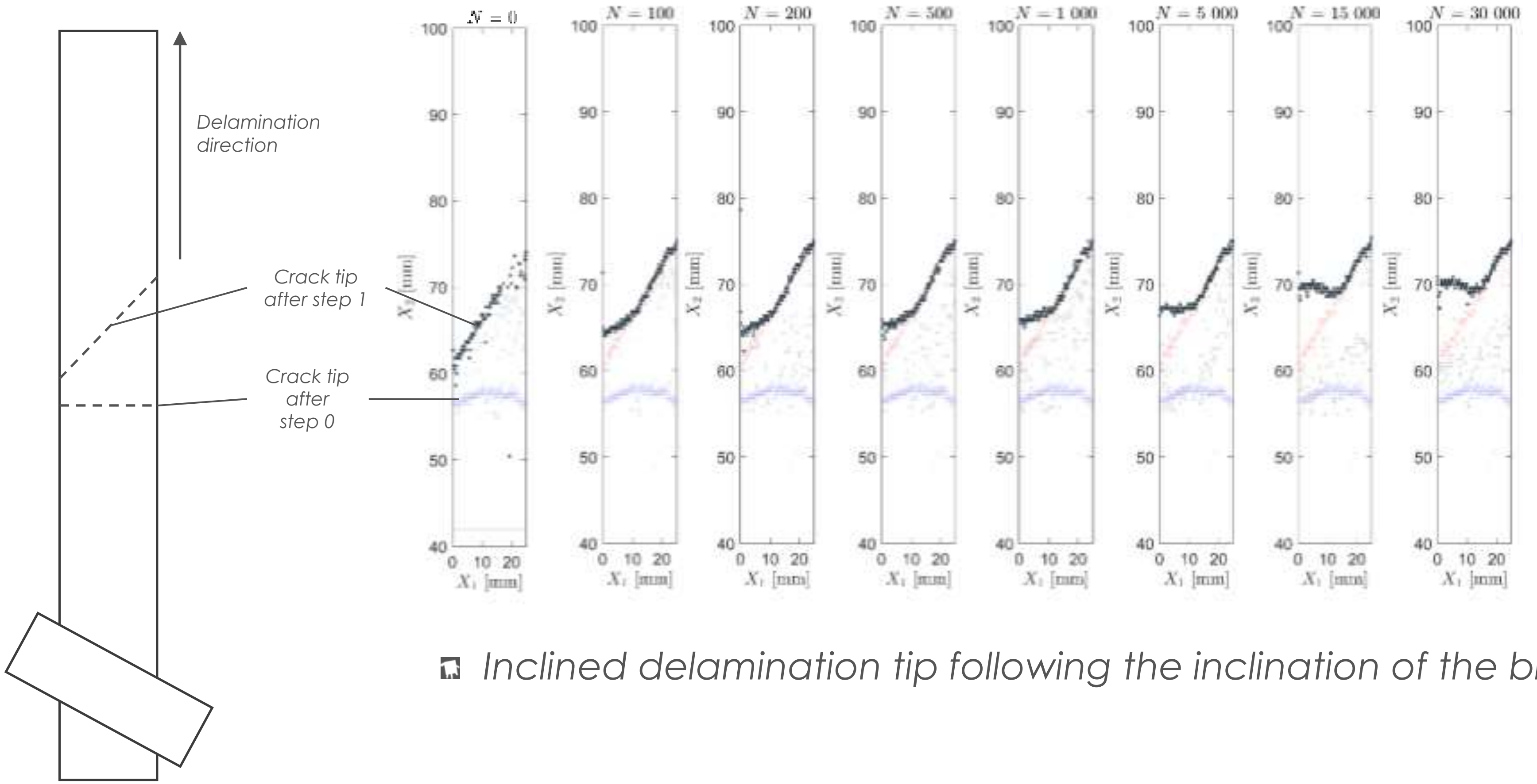
- *Fatigue*, $\delta_{max} = 5$ mm, $R = 0,1$



Results - Step 2: DCB at -30°

- Fatigue, $\delta_{max} = 5\ \mathrm{mm}$, $R = 0,1$



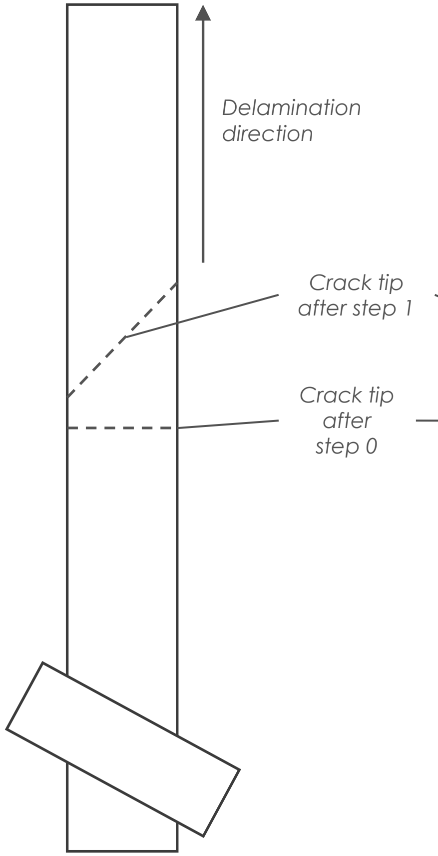


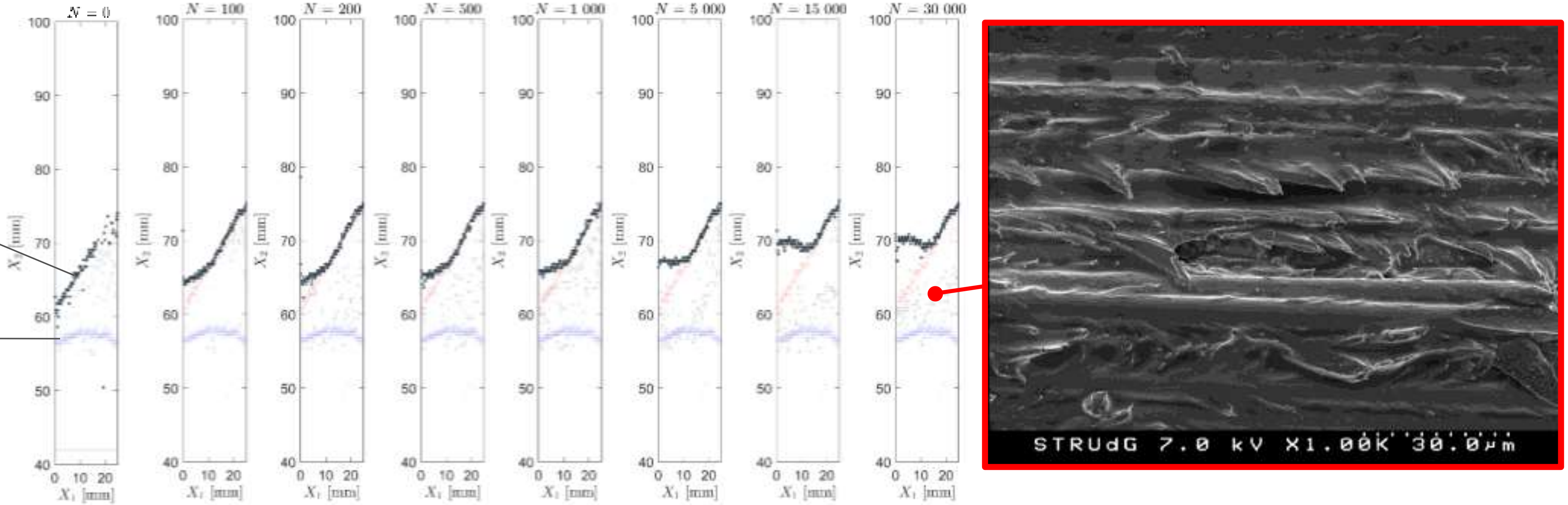
- Inclined delamination tip following the inclination of the blocks

Results - Step 2: DCB at -30°

- Fatigue, $\delta_{max} = 5$ mm, $R = 0,1$

- Leading delamination tip
- Start of damaged area
- Crack tip after step 0
- Crack tip after step 1



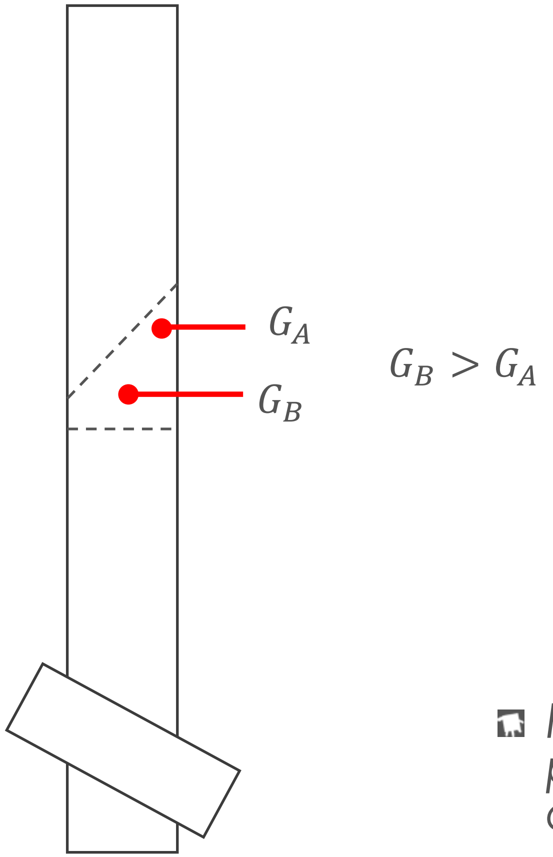


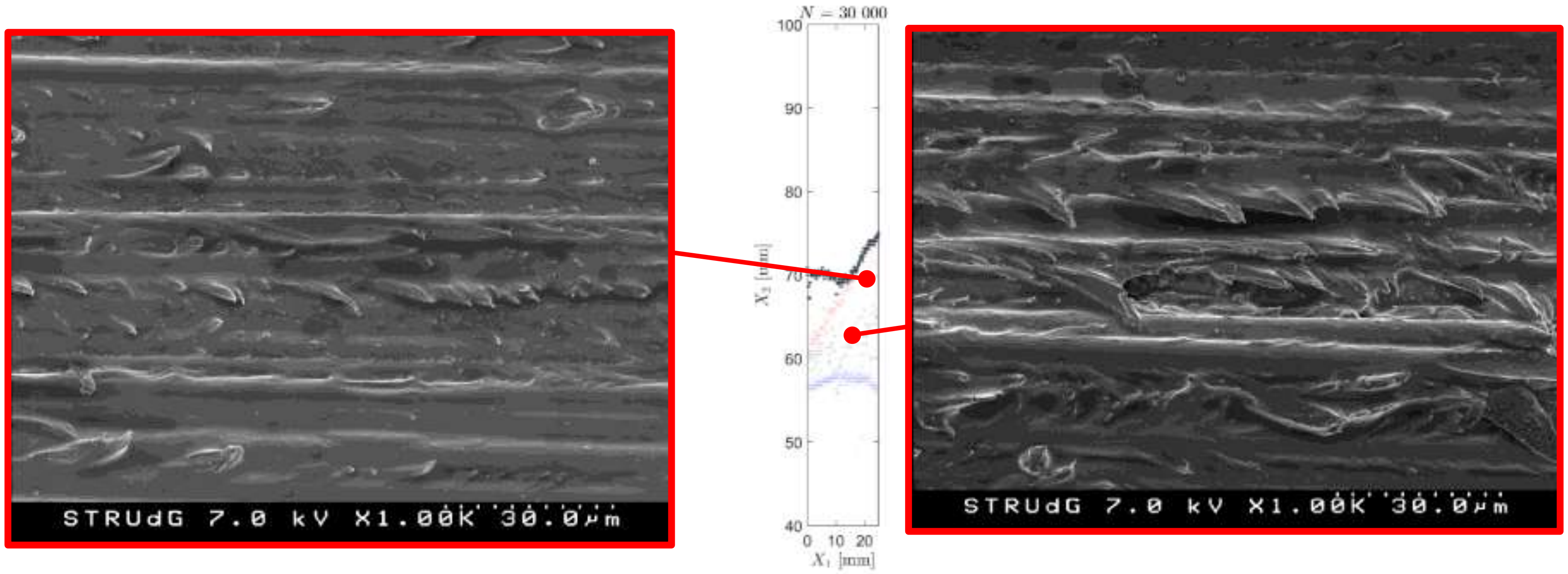
- The damaged area created by the Mode II fatigue tests does not disappear even after the application of Mode I loading

Results - Step 2: DCB at -30°

- Fatigue, $\delta_{\max} = 5$ mm, $R = 0,1$

- Leading delamination tip
- Start of damaged area
- Crack tip after step 0
- Crack tip after step 1

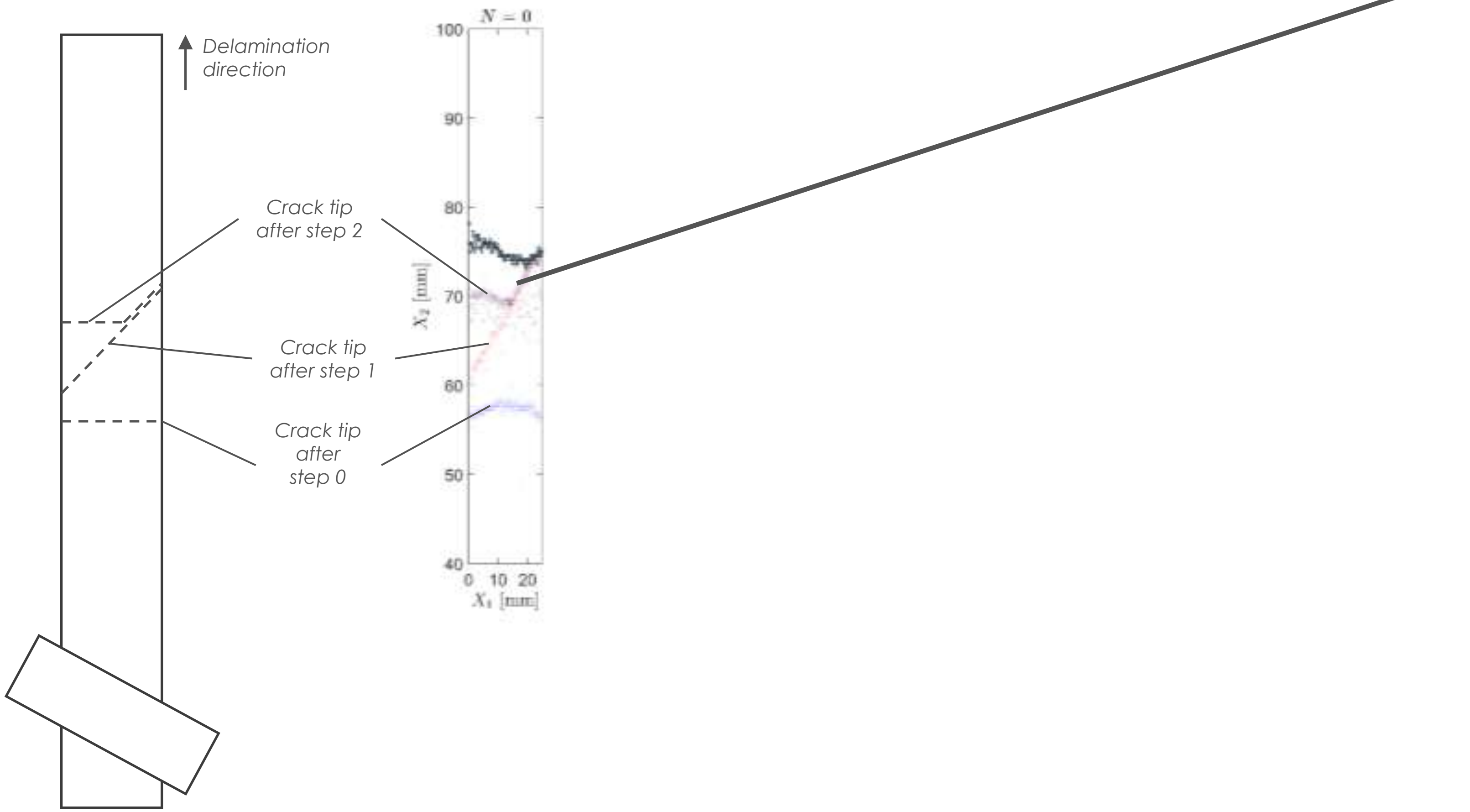


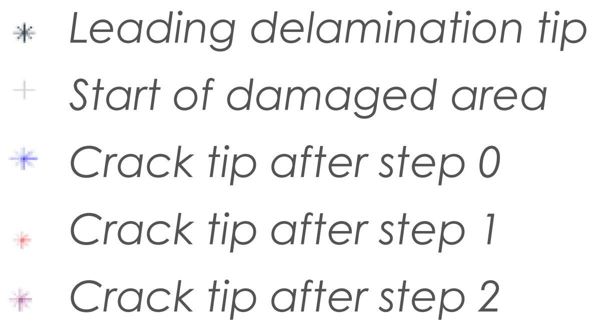


- Plastic deformation traces at shear mode fracture regions were more pronounced in regions where a higher strain energy release rate was applied

Results - Step 3: DCB at -30°

- Static, $\delta_{max} = 10\ \mathrm{mm}$

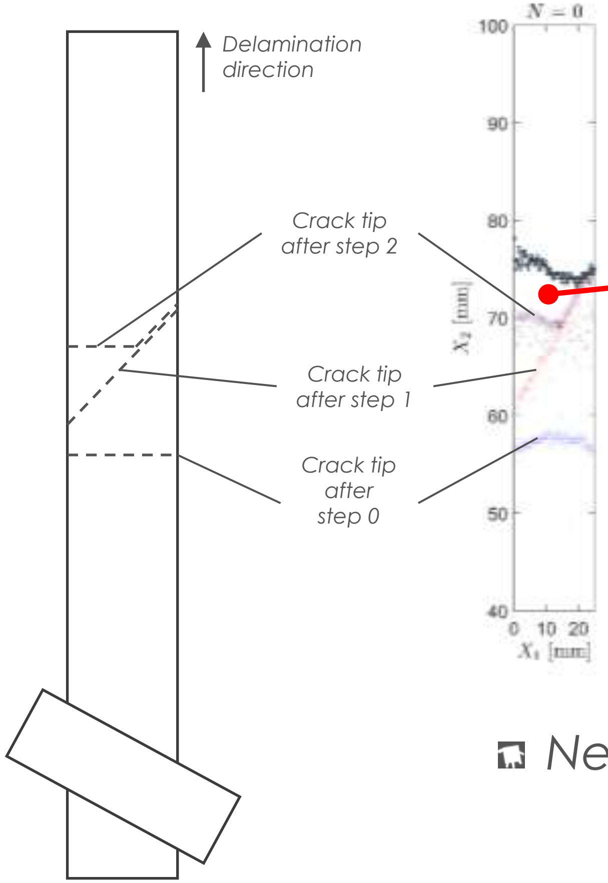


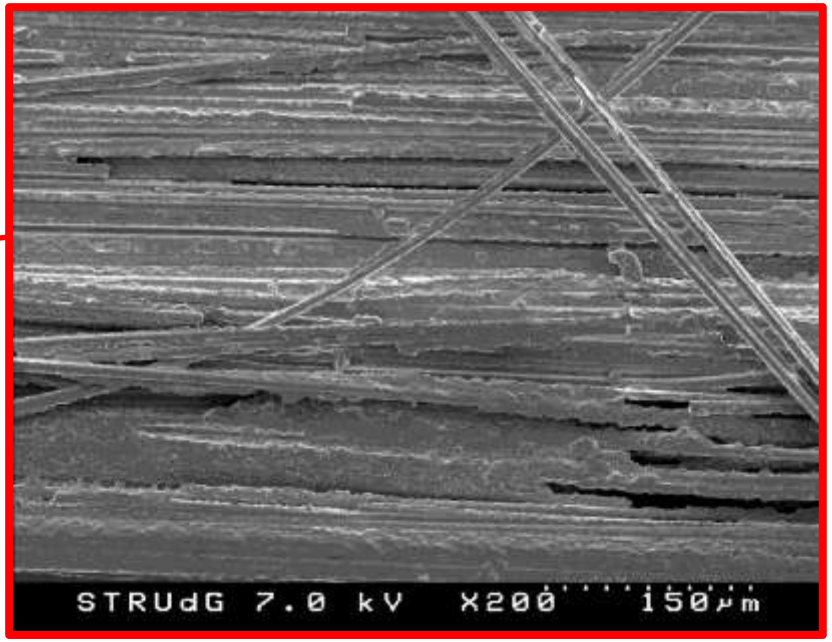


Results - Step 3: DCB at -30°

- Static, $\delta_{max} = 10$ mm

Leading delamination tip
Start of damaged area
Crack tip after step 0
Crack tip after step 1
Crack tip after step 2



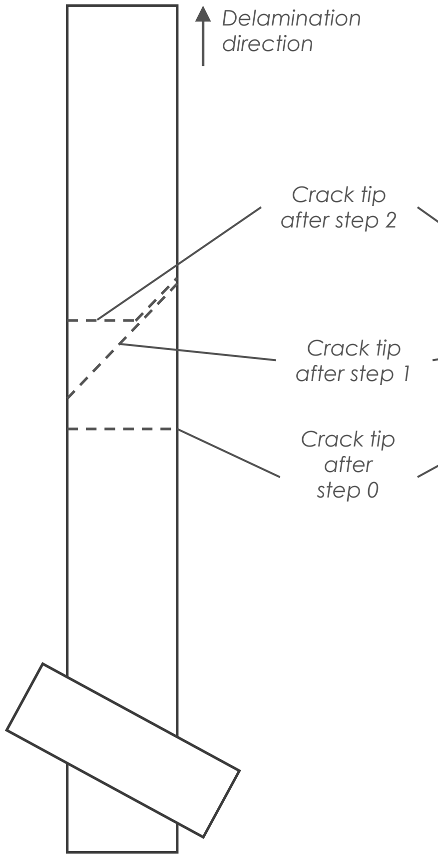


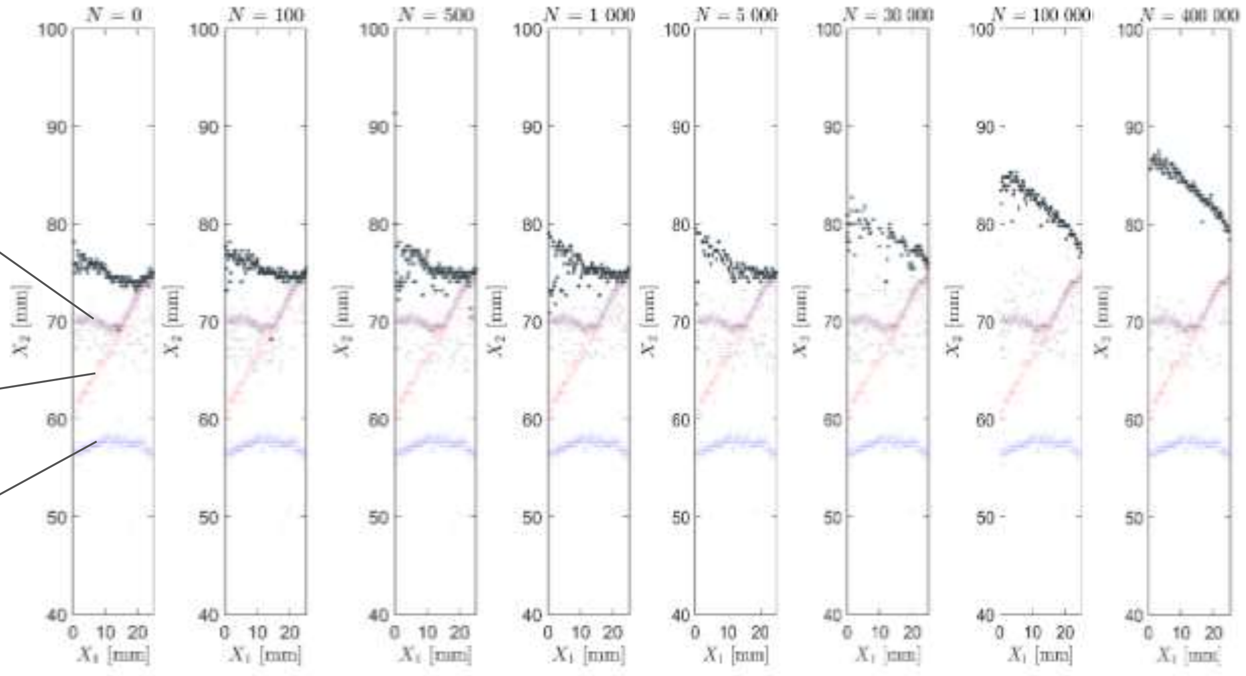
- New Mode I failure surface created (fiber bridging)

Results - Step 4: DCB at -30°

- Fatigue, $\delta_{max} = 10$ mm, $R = 0,1$

Leading delamination tip
Start of damaged area
Crack tip after step 0
Crack tip after step 1
Crack tip after step 2



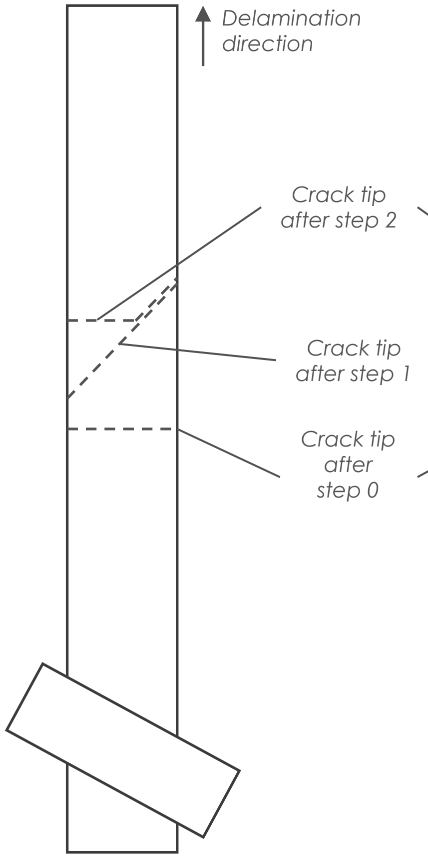


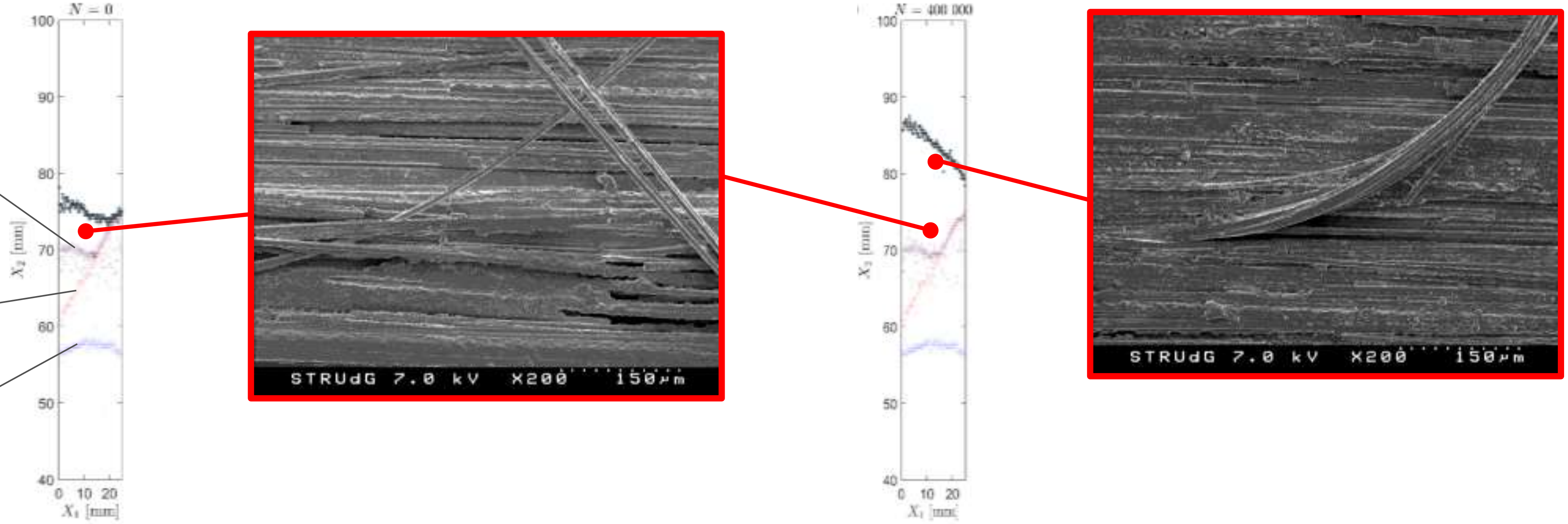
- Inclined delamination tip following the inclination of the blocks

Results - Step 4: DCB at -30°

- Fatigue, $\delta_{\max} = 5\ \mathrm{mm}$, $R = 0{,}1$

- Leading delamination tip
- Start of damaged area
- Crack tip after step 0
- Crack tip after step 1
- Crack tip after step 2



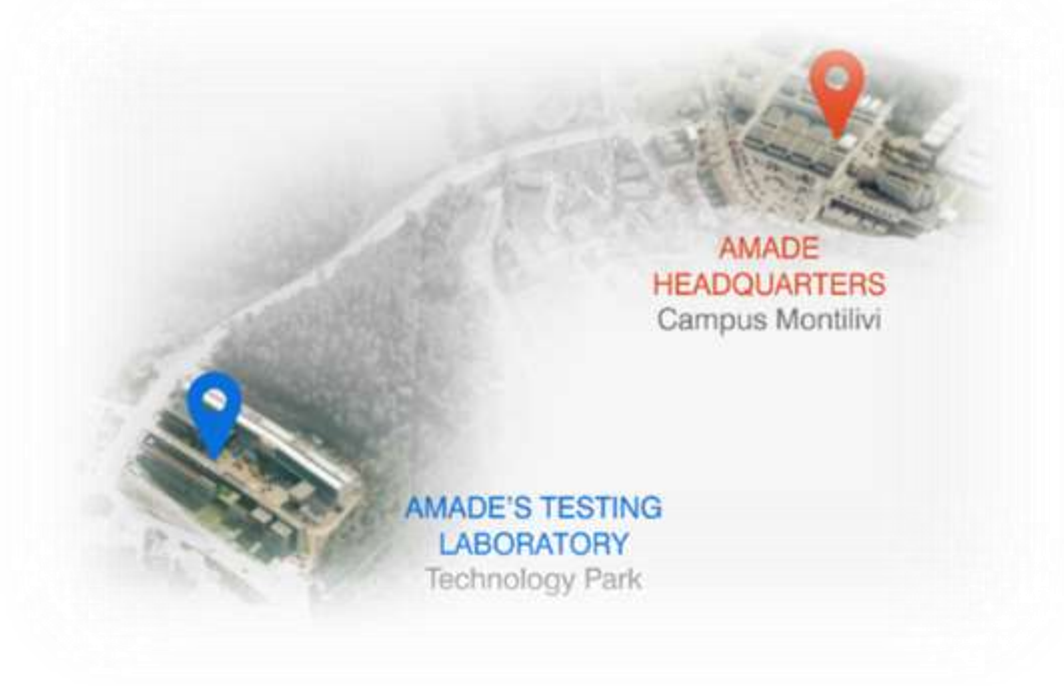


- Same fracture surface along the entire step.

Conclusions

Conclusions

- *A novel benchmark test for composite materials is presented where:*
  - *3D delamination fronts are obtained by rotating the loading blocks.*
  - *It allows testing any combination of loading conditions resulting in non-self-similar delamination process.*
- *A case study was provided with AS4D/PEKK-FC thermoplastic composite material, which is known to have a strong R-curve behavior:*
  - *The loading mode history must be considered in materials that exhibit R-curve effects to accurately model the delamination process*
  - *The loading severity must be considered when evaluating the mode history and the R-curve effects*



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