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MATERIALS ENGINEERING

Composite materials group

Dual-scale model for delamination of composites with different fiber orientations at interface

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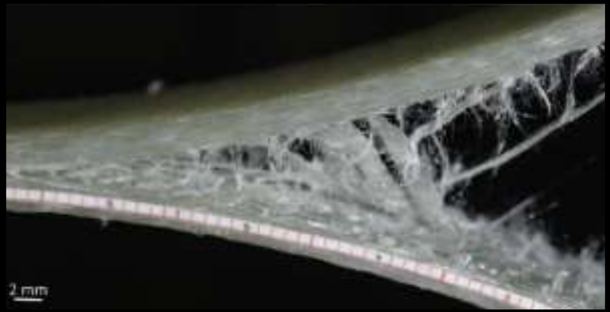
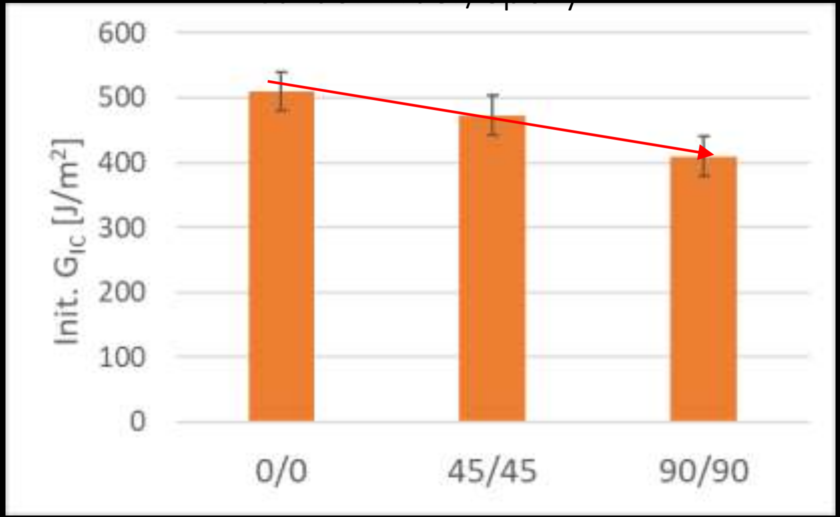
What’s the issue?

- **Inconsistency** in the literature on the influence of interface fiber orientation on fracture toughness (especially at initiation)

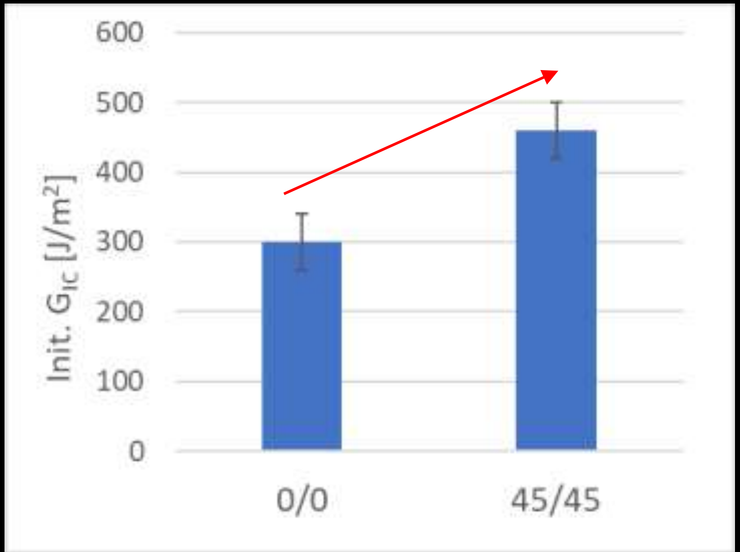
- Factors influencing the fracture toughness tests:
  - Unfavorable damage mechanisms
  - Specimen geometry (thickness, lay-up)
  - Accyracy of in-situ characterization techniques in real time measurement of delamination



Nikbakht and Hosseini-Toudeshky *Comp Part B* 113 (2016)



Chai *Composites* 15 (1984)



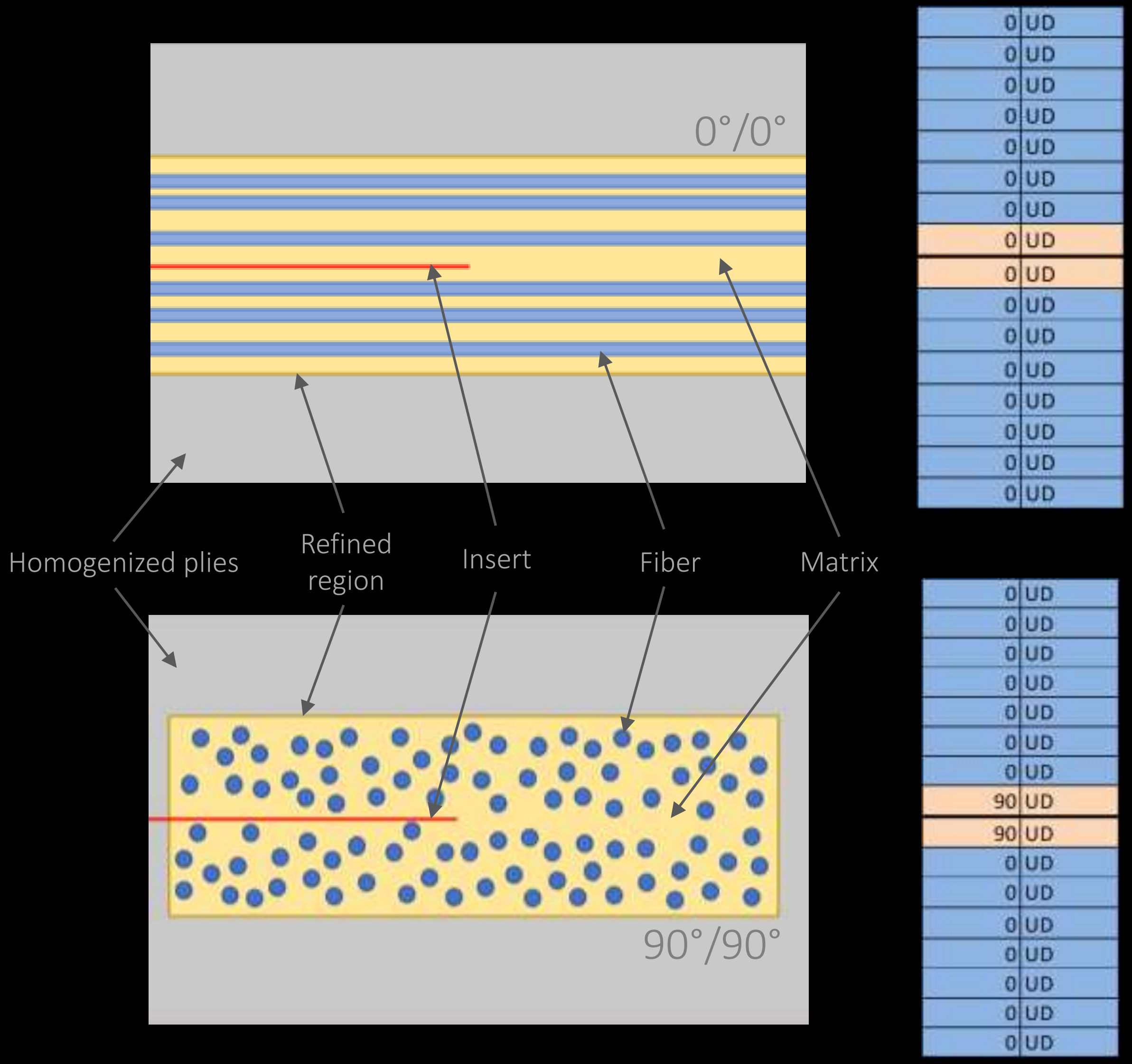
Rehan et al. *Comp Struct* 161 (2017)

Dual-scale model

To reduce computational cost:

- Around the crack tip → refined region with individual fibers modeled
- Remaining part of the specimen → plies with homogenized properties

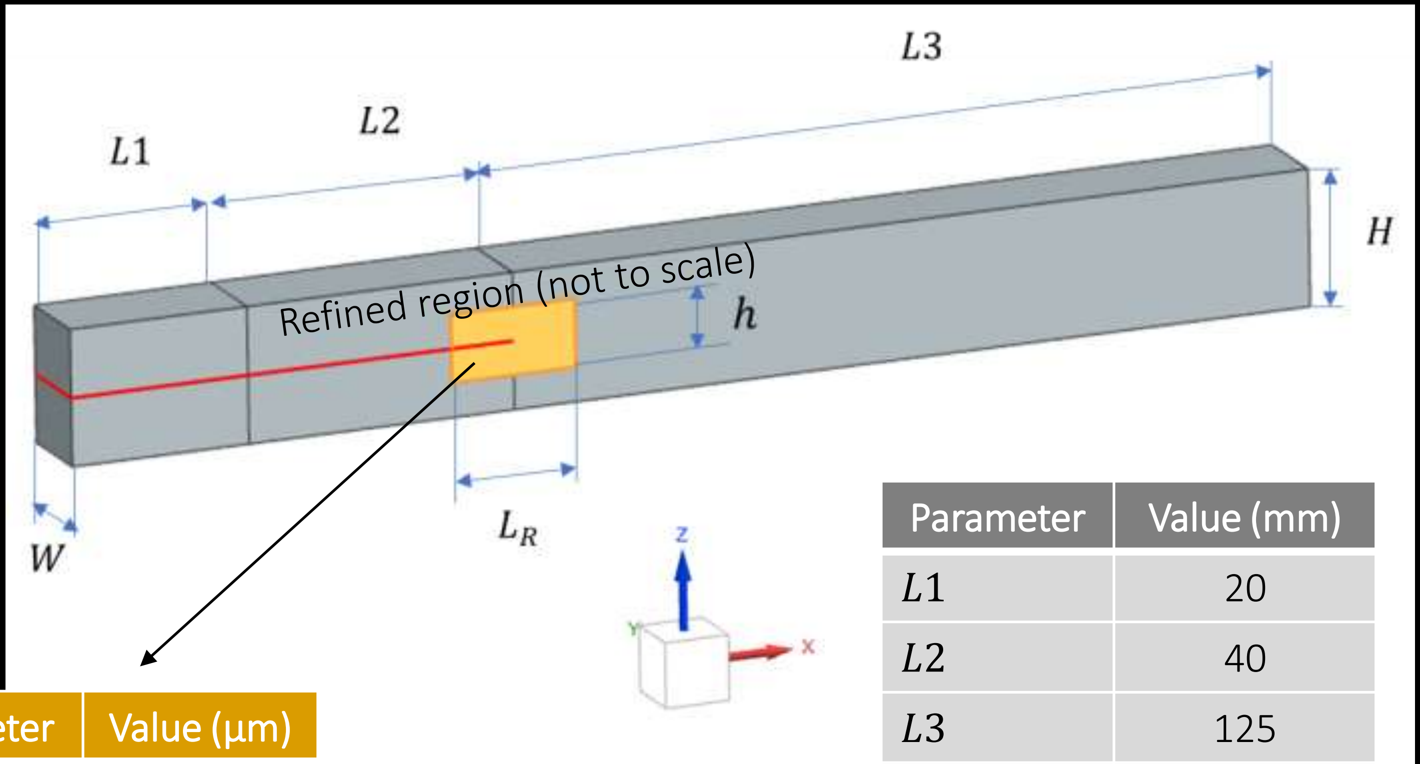
Two stacking sequences: different only at the delamination interface



CAD Geometry

Specimen width is reduced ~ 15 times compared to the ASTM standard to keep the model computationally manageable.

CAD design and FE modeling in
Simcenter 3D
Siemens Industry Software NV

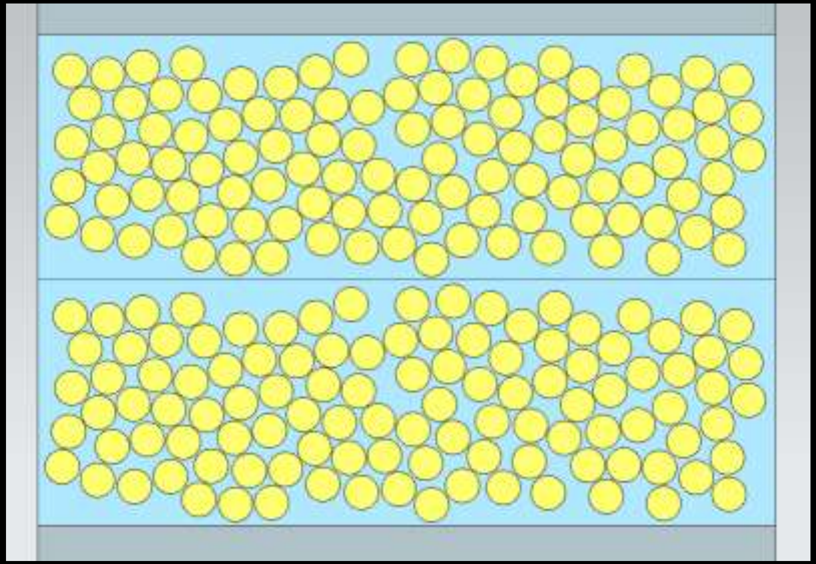


Parameter	Value (µm)
h	100
L_R	460

Parameter	Value (mm)
$L1$	20
$L2$	40
$L3$	125
L_{TOT}	185
H	3.62
W	150

Microstructure generation

- Random distribution of fibers with initial fiber V_f = 67% (using algorithm in Melro et al. *CSTE* 68 (2008))
- Final fiber V_f = 57%



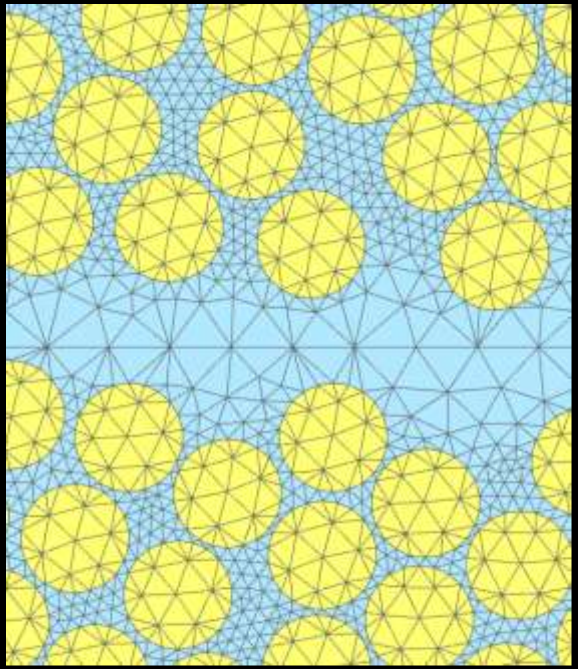
- Resin-rich region at the delamination plane that reflects ply interface in realty

- Element size:

  1 µm at fiber/matrix interface

  4 µm at edges

  Coarser mesh for homogenized plies



- 90°/90° ~ 0.8 million elements
- 0°/0° ~ 2.5 million elements

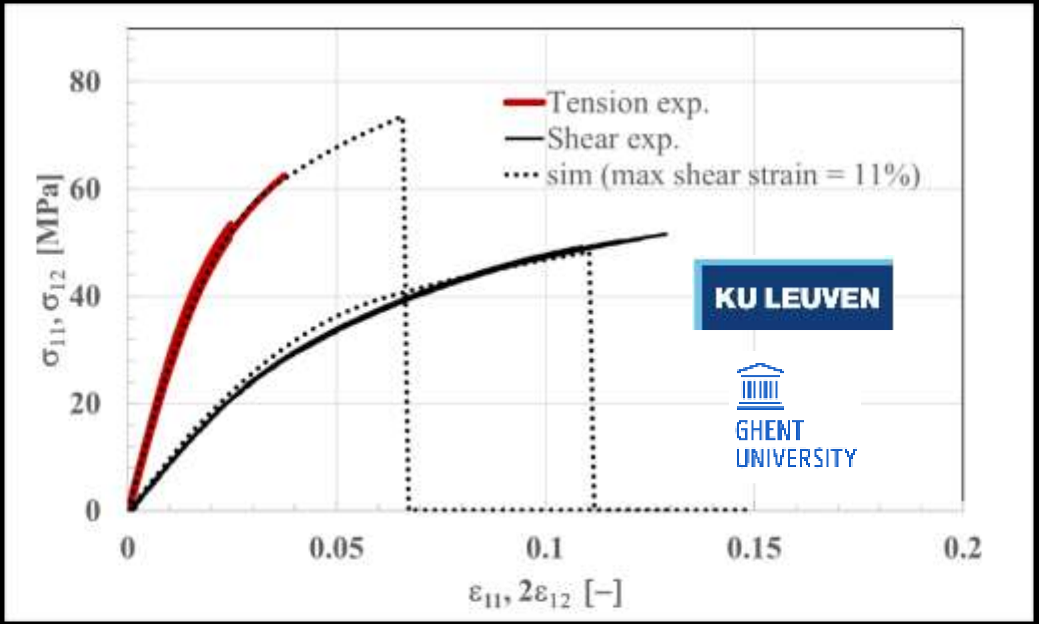
Material input properties

Carbon fibres
linear elastic – transversally isotropic (no damage)
Sevenois et al., CSTE 168 (2018)

Epoxy matrix
- elasto-plastic constitutive law – Raghava yield criteria
  Raghava and M.Caddell *Int J Mech Sci* 15 (1973)
- isotropic damage model available in Simcenter Samcef

Fiber/matrix interface
perfect bonding assumed to reduce computational cost

Homogenized plies
properties obtained from Chamis' formulae



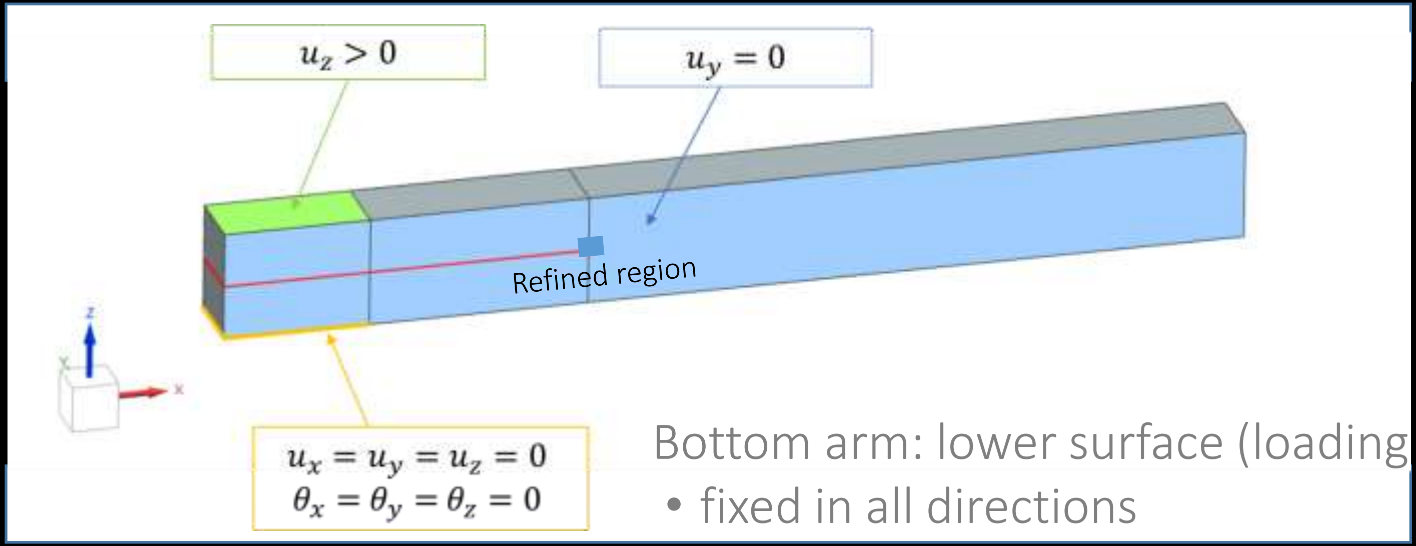
Input data	Value
Tension to compression	1.3
Limit of equivalent plastic strain	0.04

Matveeva et al. *Mater Sci & Eng* 406 (2018)

Boundary conditions

Top arm: upper surface (loading block)
- z displacement (1 – 1.8 mm)

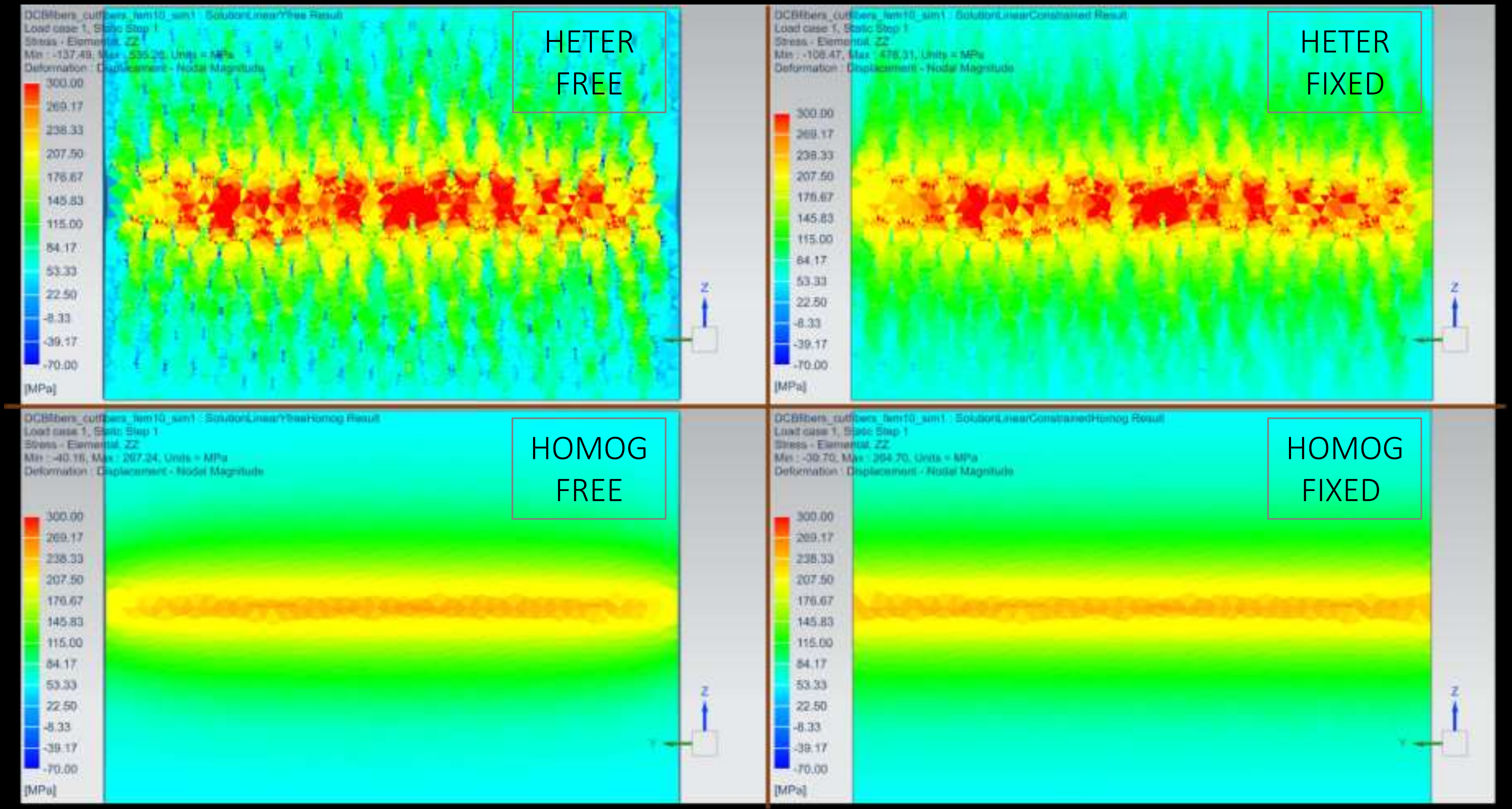
Side edges: two different (extreme) conditions
1. free edge: free in all directions
2. fixed edge: displacement in y direction is fixed



Bottom arm: lower surface (loading block)
- fixed in all directions

All other surfaces are left traction-free in all directions.

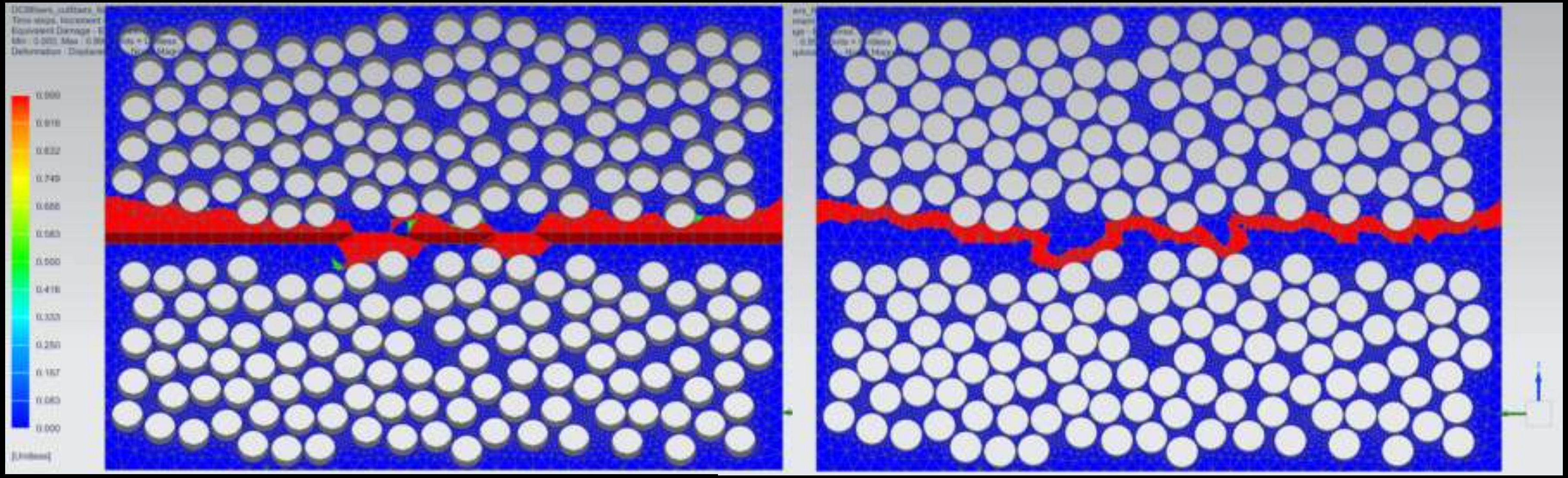
Stress heterogeneity – elastic analysis, 0°/0° interface



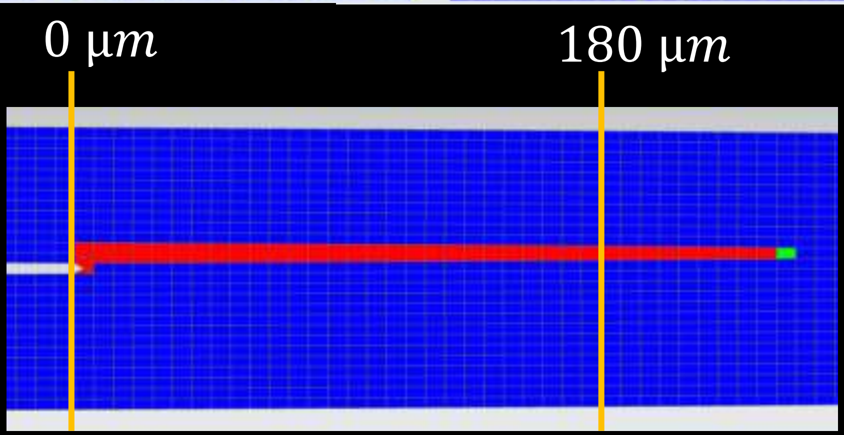
cross section view (σ_{zz})

Damage analysis 0°/0° – crack path

Only heterogenous model with fixed edges



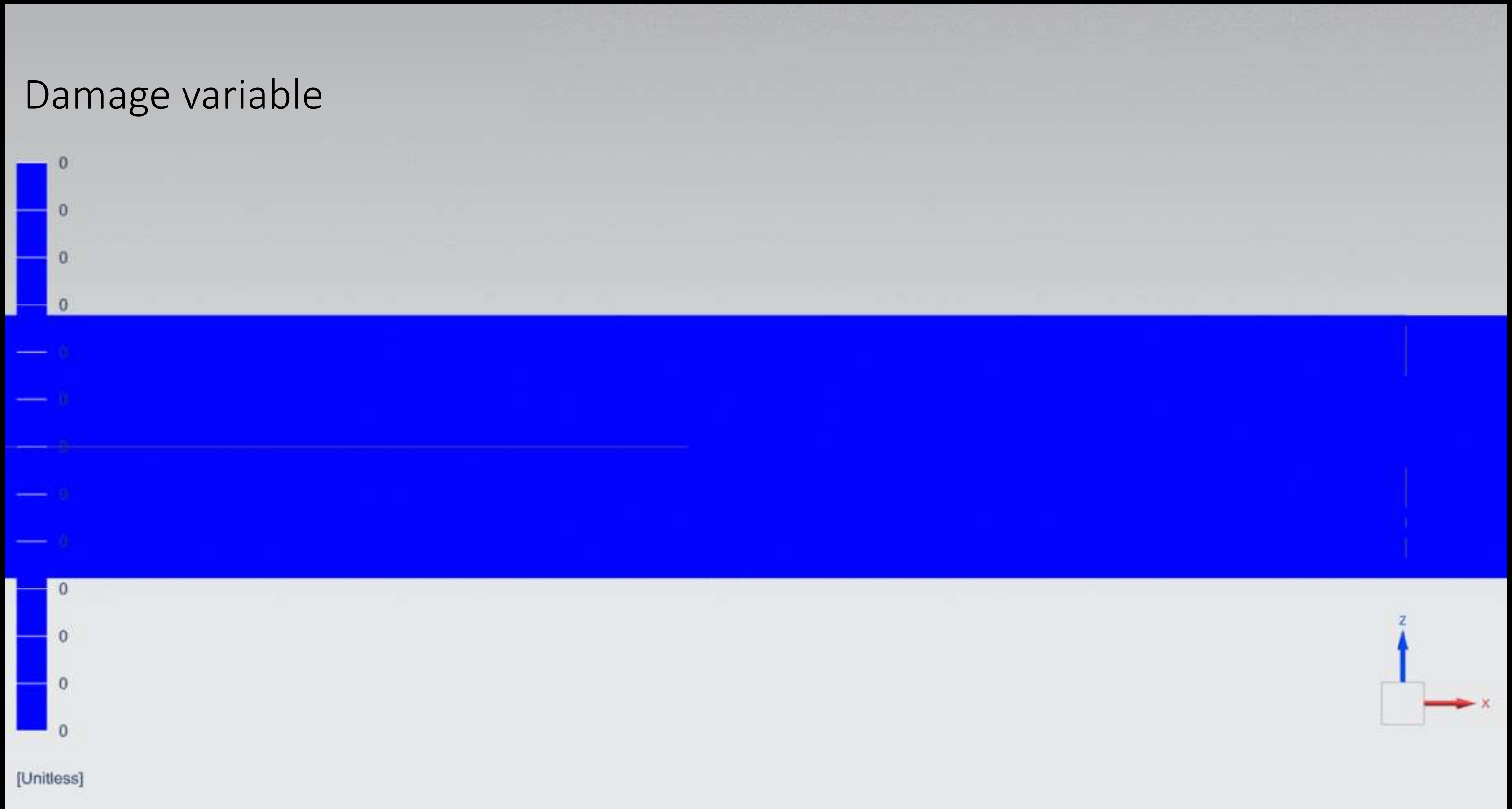
Cross-section view



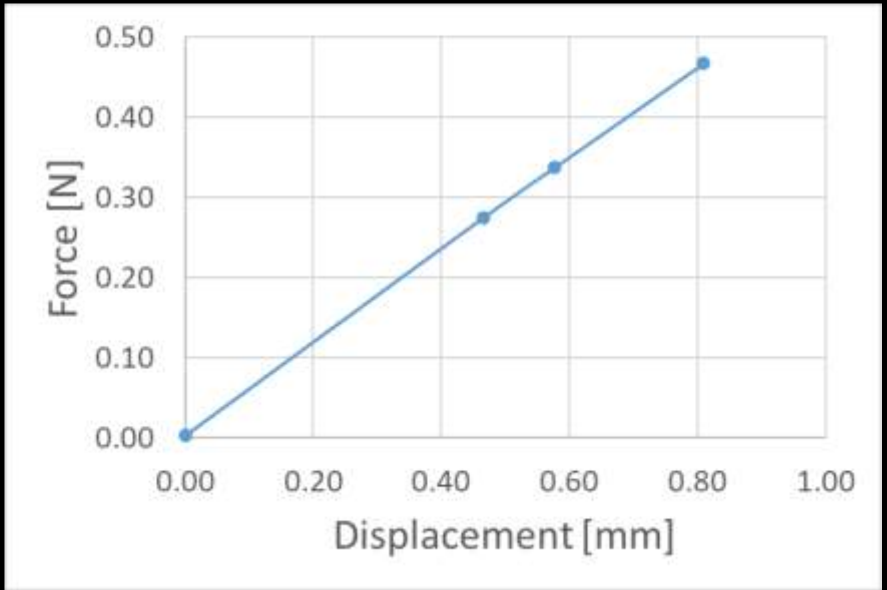
Crack tends to propagate in the interlaminar resin rich region

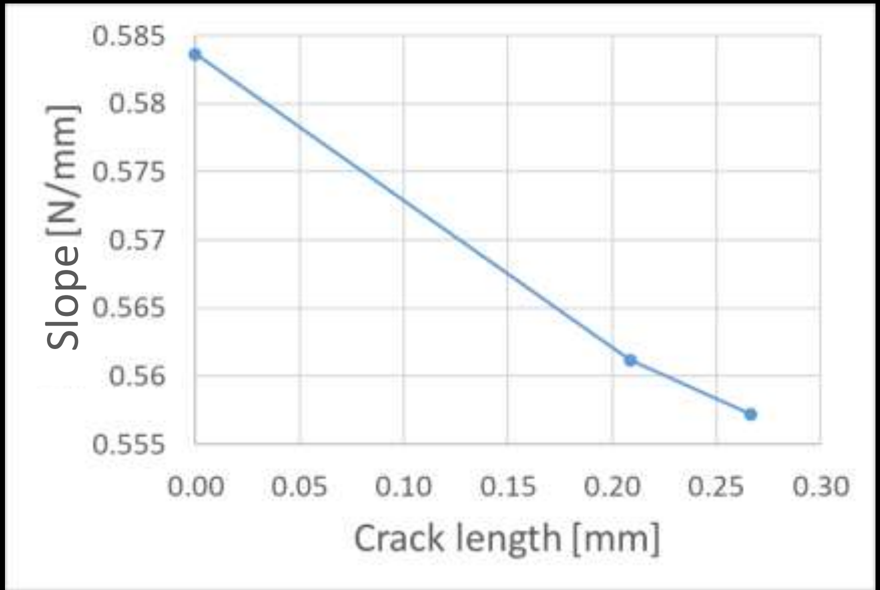
Side view

Damage analysis 0°/0° – crack path



Damage analysis 0°/0° – G_{Ic}





Crack length [mm]	G_{Ic} [J/m^2]
0.208	38.8
0.266	75.2

$$G_{Ic} = \frac{3\,P\,\delta}{2\,b\,(a + \Delta)}$$

- Small reduction in slope
- Lower G_{Ic} compared to experimental results (300-600 J/m^2)

G_{Ic} at macroscale and microscale

Microscale

- Modeled crack increment ~ 10 µm

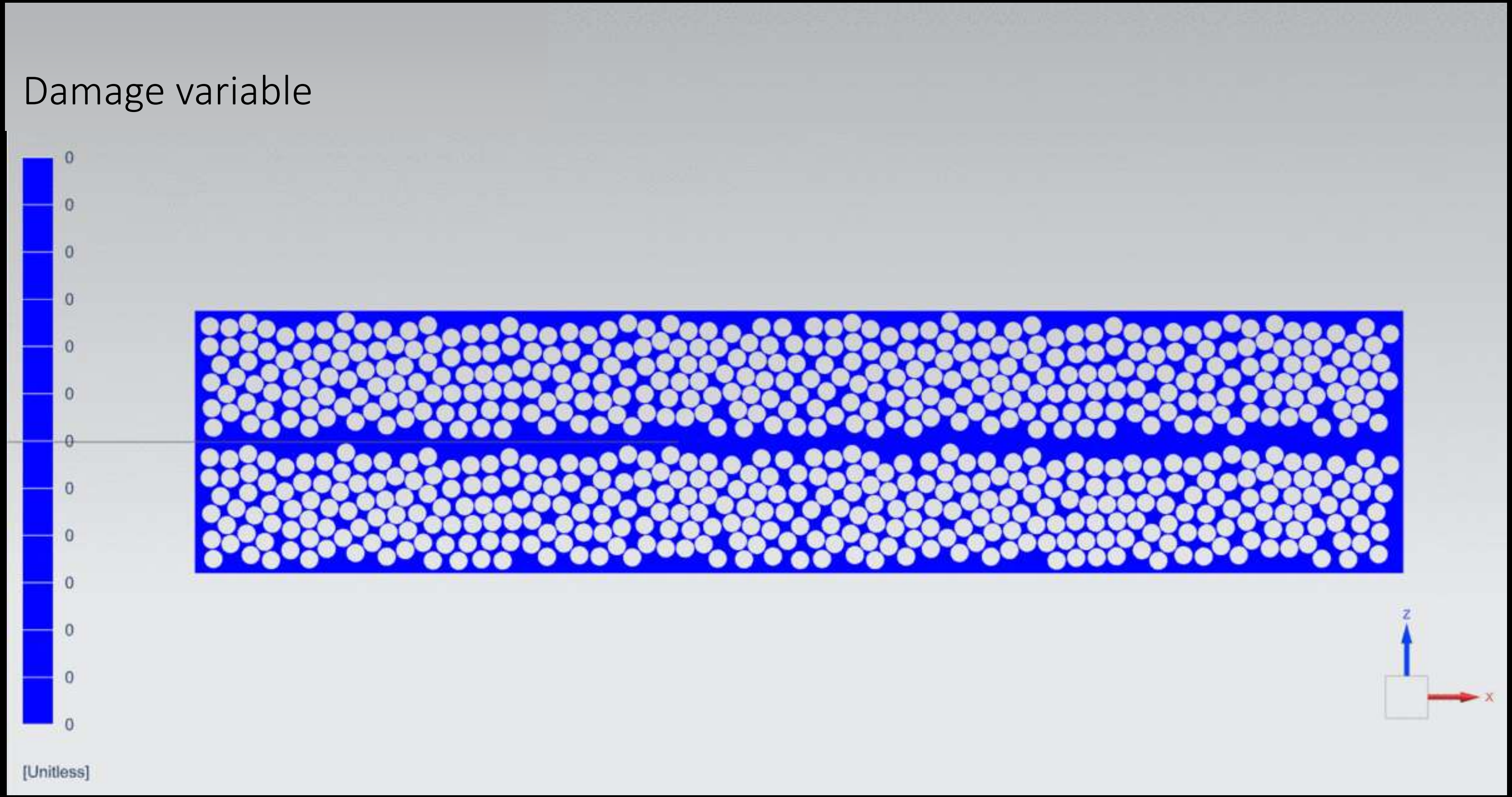
Macroscale

- Crack measurement precision ~ 1 mm
- Not accurate enough to detect the exact crack onset → higher G_{Ic}

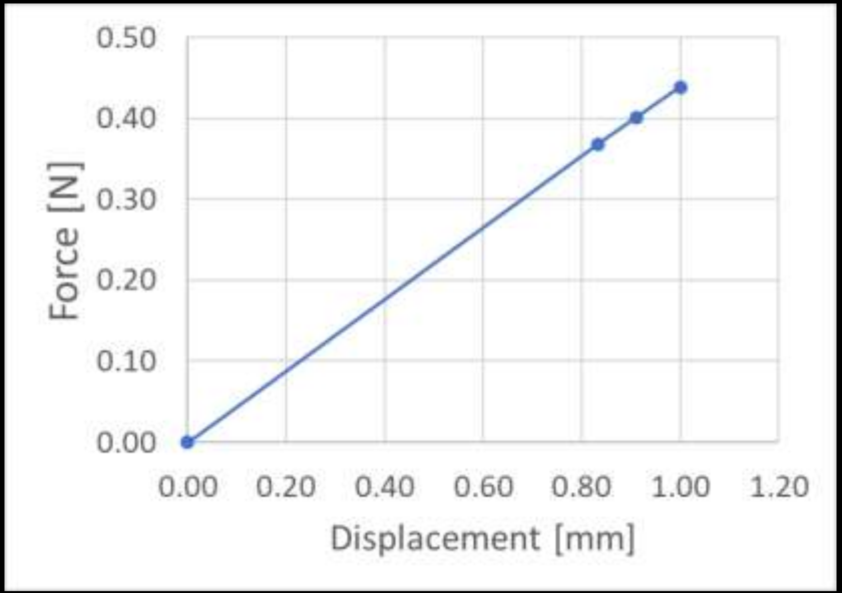
Questions

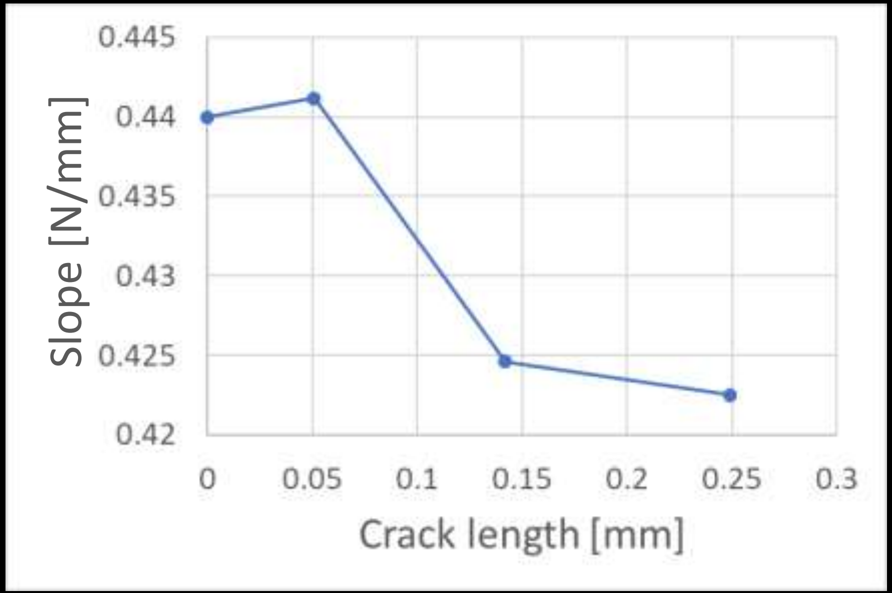
- Does what we measure in experiments really correspond to initiation G_{Ic}?
- Should a minimum crack length be reached to consider it for initiation G_{Ic}?

Damage analysis 90°/90° – crack path



Damage analysis 90°/90° – G_{Ic}

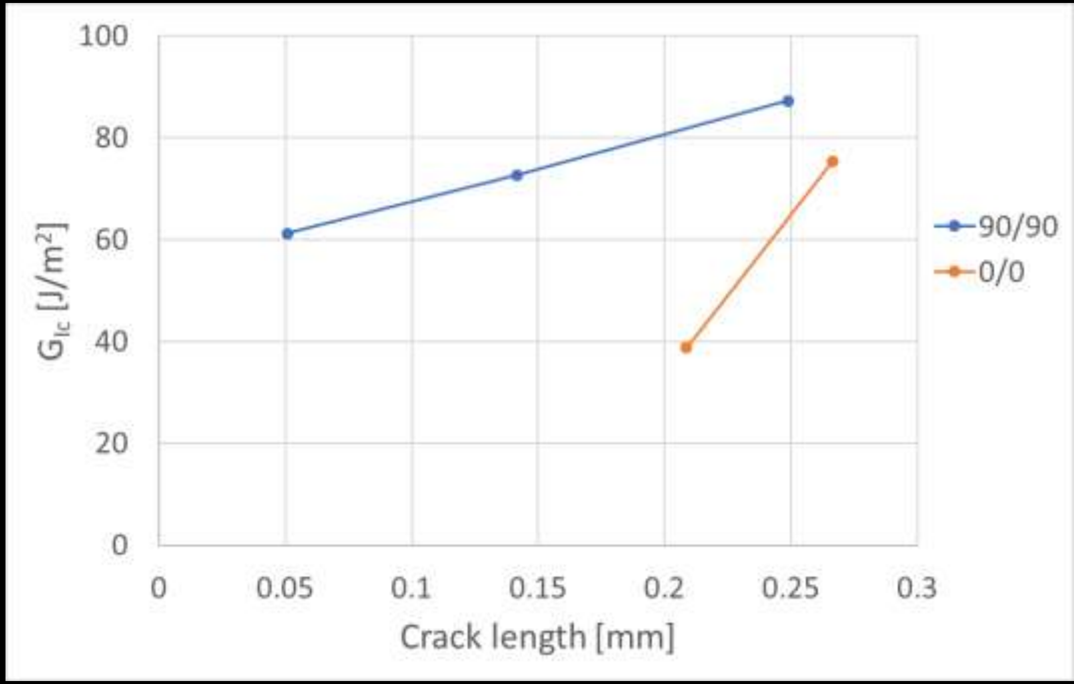




Crack length [mm]	G_{Ic} [J/m^2]
0.051	61.2
0.142	72.7
0.249	87.2

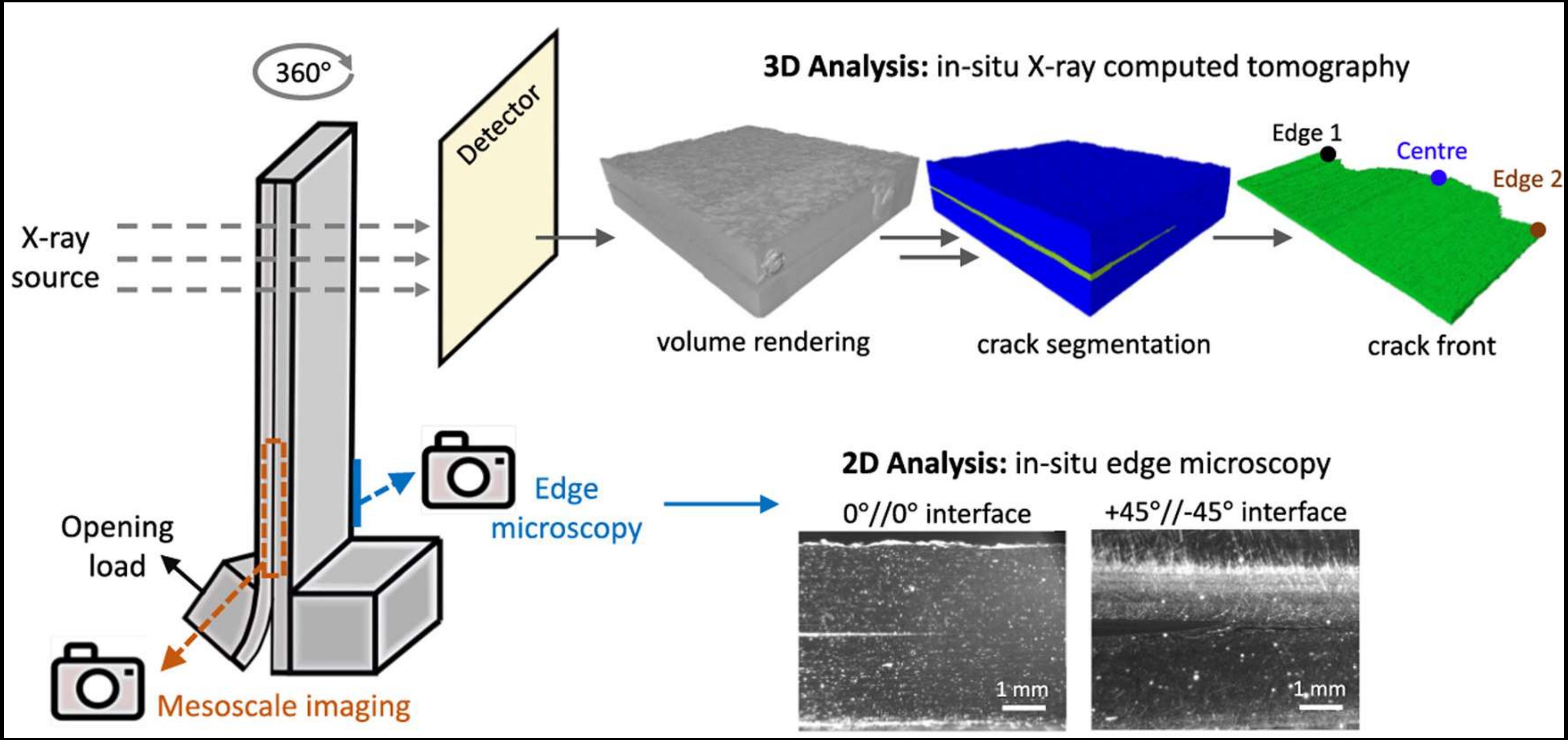
Again smaller G_{Ic} than the experimental values, but the same order of magnitude as that in a similar 2D modeling study Herraez et al. *Int J of Solids Struct* 134 (2018)

0°/0° vs 90°/90°



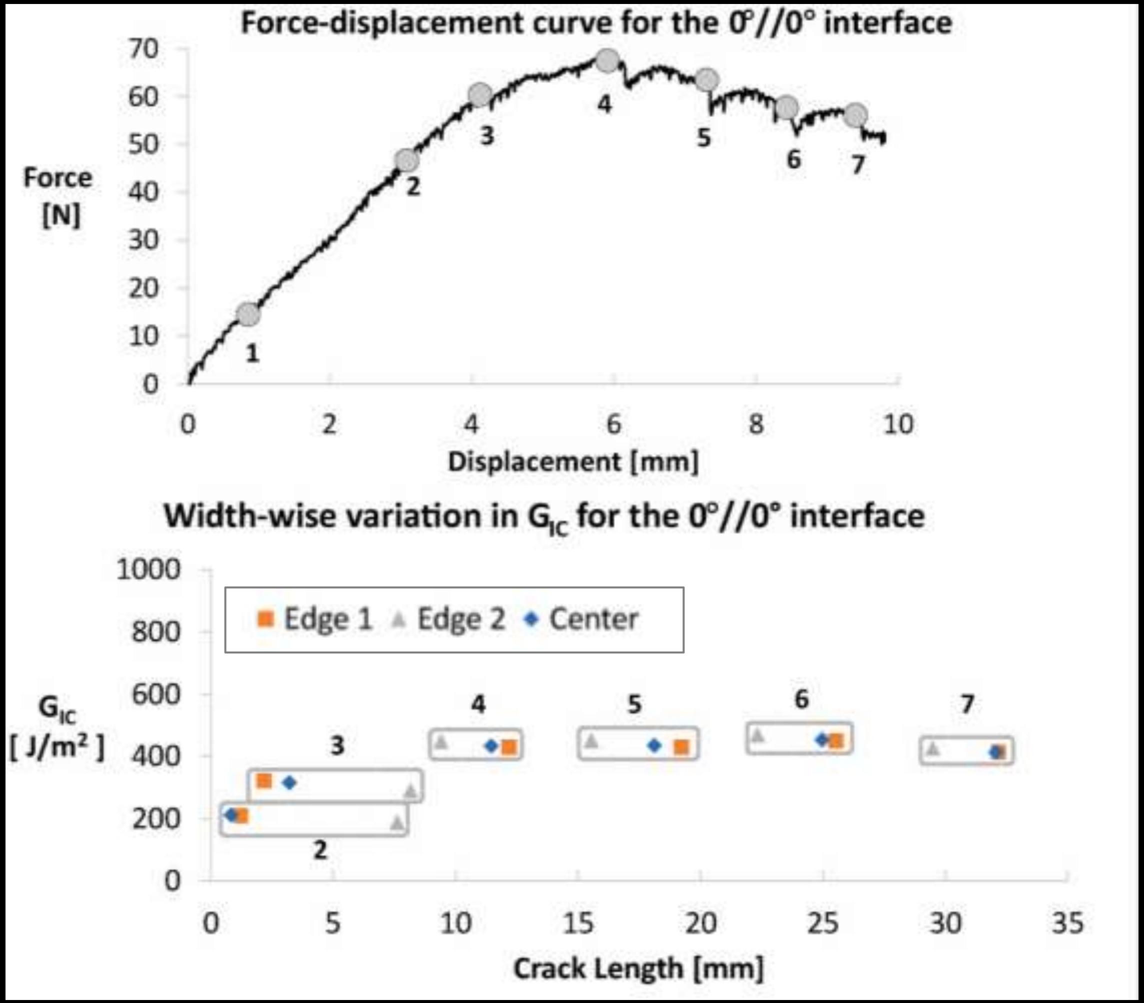
- 0°/0° crack propagates in the interlaminar resin rich region.
- 90°/90° crack migrates in the bottom ply among the fibers.

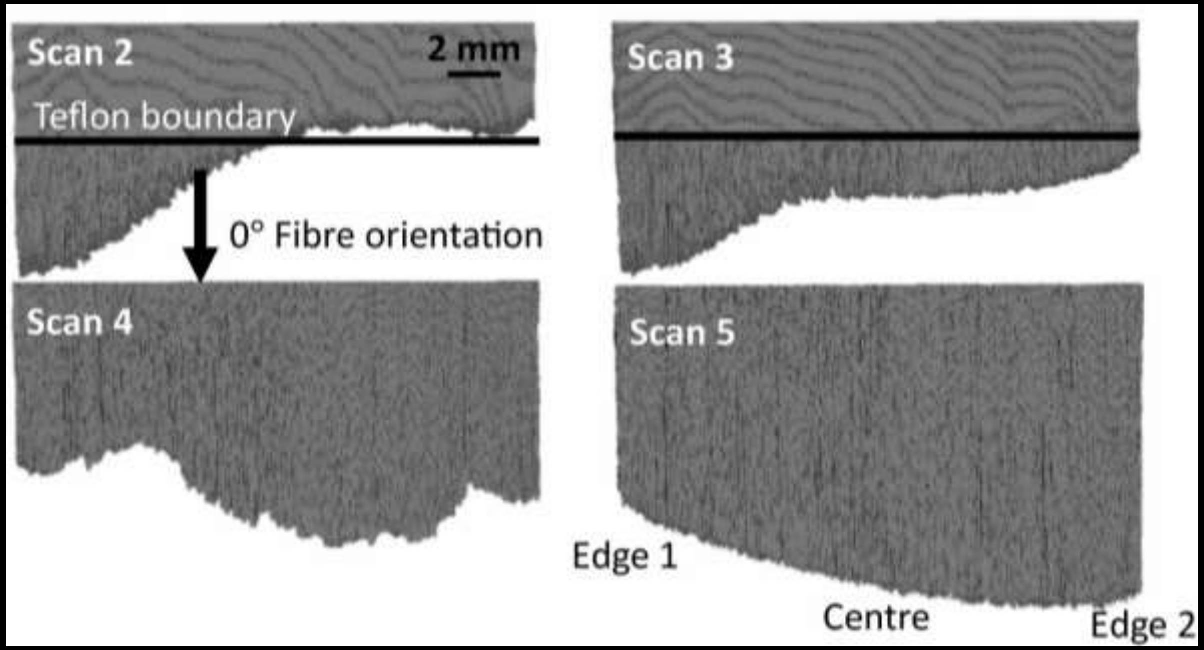
In-situ CT of a DCB test



Chatziathanasiou et al., Comp Part B 260 (2023)

In-situ CT results





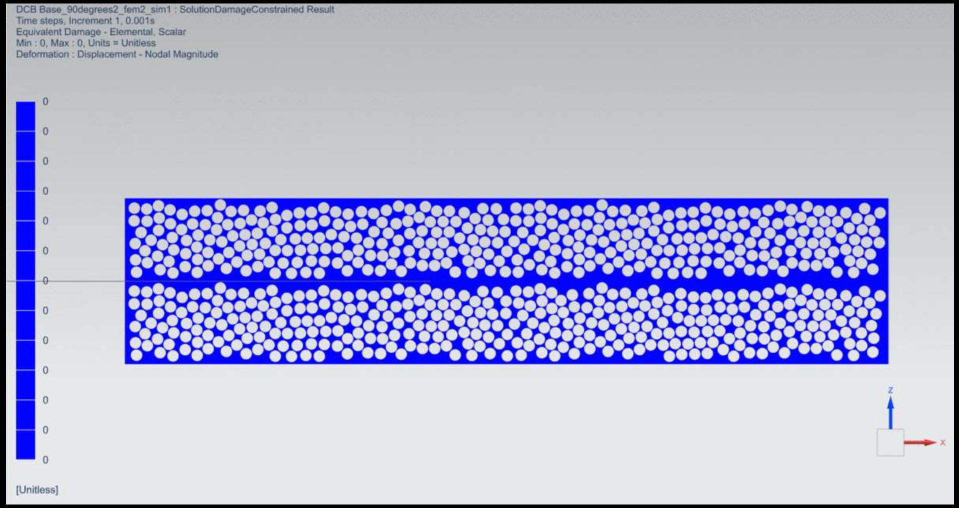
Chatziathanasiou T, Soete J, Vanhulst J, Carrella-Payan D, Gorbatikh L, Mehdikhani M. *In-situ X-ray computed tomography of mode I delamination in carbon-epoxy composites: The effect of the interface ply orientation*. Composites Part B: Engineering. 2023 Jul 1;260:110761.

Conclusions

- The model can be used as a preliminary tool to optimize the design of composites for delamination resistance.
- The edge effect seems to vanish not so far away from the free surfaces. Thus, the stress is recovered close to the edges even if the specimen width is very small.
- The stress concentrations in the heterogenous model are significant, thus it is vital to model the fibers explicitly.
- The estimated G_{IC} is lower than experimental values → attributed to incompetence of the edge measurement techniques in detecting the real initiation

Future steps

- Bringing the specimens dimension closer to the standard
- Including fiber/matrix debonding
- Experimental validation
- Investigating models with different fiber orientation at the interface
- Deriving a local cohesive law from the model



Funding and support

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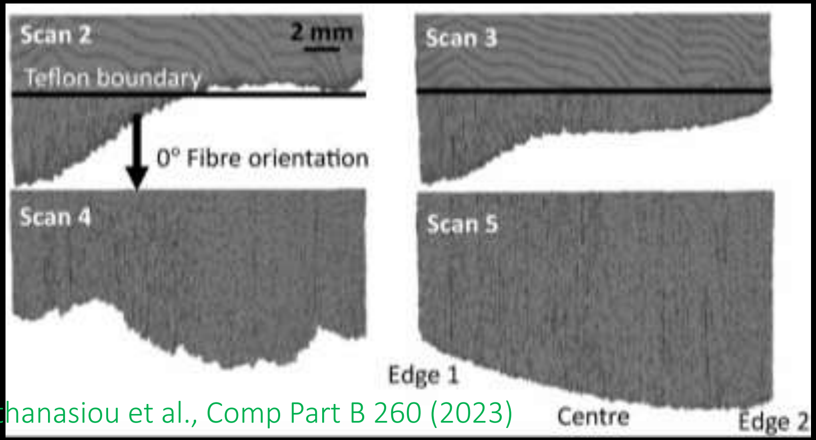
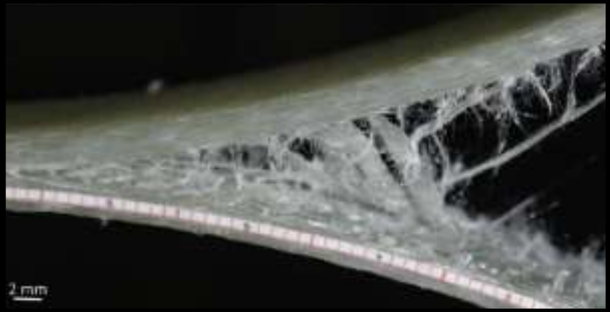
Thanks for your attention!

Undesired effects in DCB test



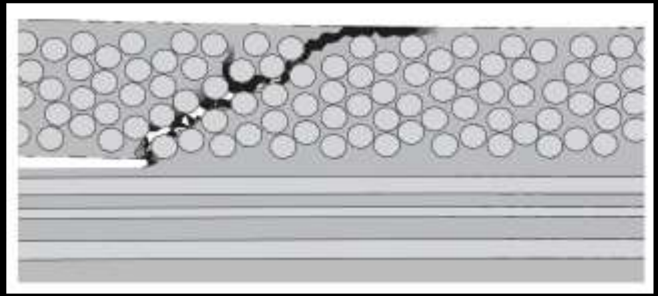
Chatziathanasiou et al., Comp Part B 260 (2023)

Curved crack front



Nikbakht and Hosseini-Toudeshky *Comp Part B* 113 (2016)

Fiber bridging

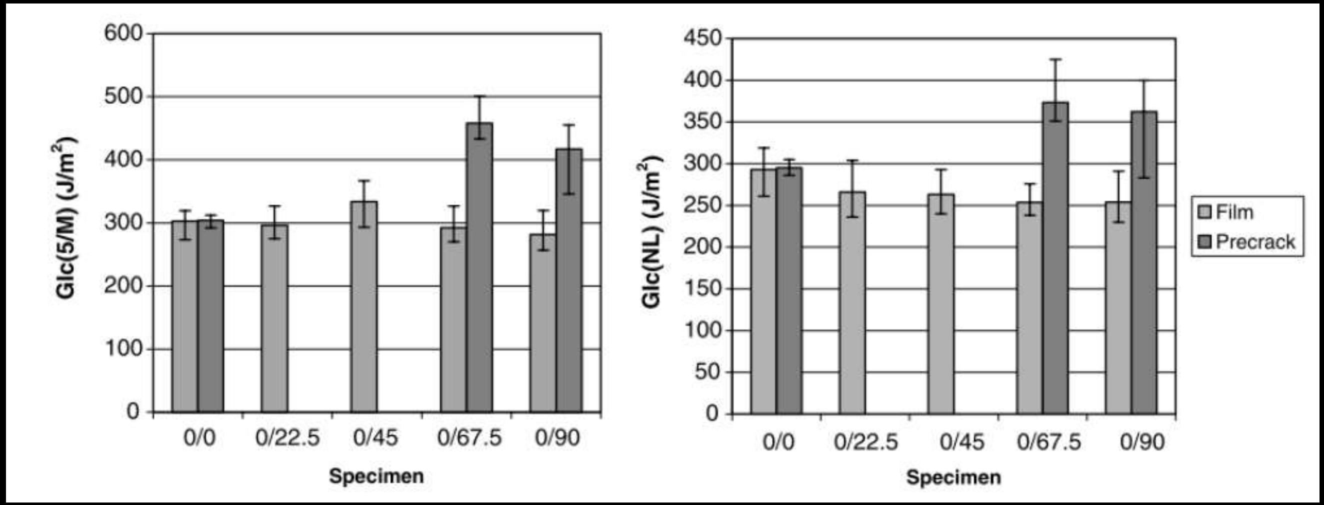


Varandas et al. *Comp Struct* 220 (2019)

Crack migration

A methodology to control/exclude these effects is needed to investigate the effect of fiber orientation on fracture toughness.

Method dependency



Pereira and de Morais *CSTE* 64 (2004)

What do we want to do?

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Goal → Understanding the effect of **interface fiber orientation** on fracture toughness using numerical simulations

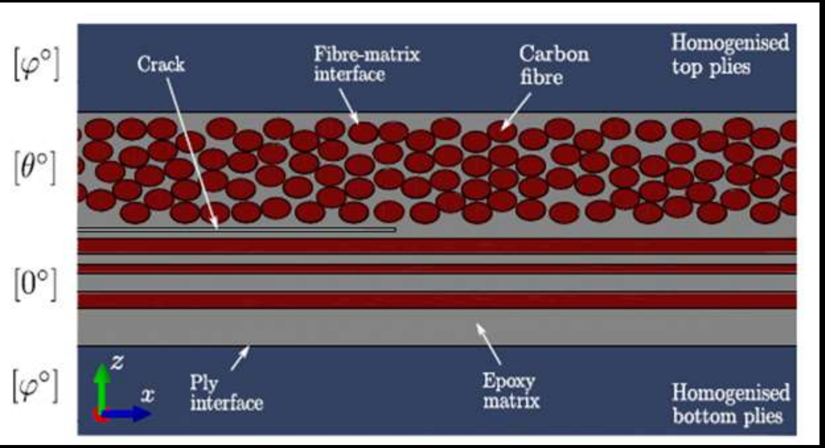
Objectives →
- Developing a methodology to account for the **micro-structural features**, yet **computationally manageable**
- Studying the effect of constituents on macroscale properties

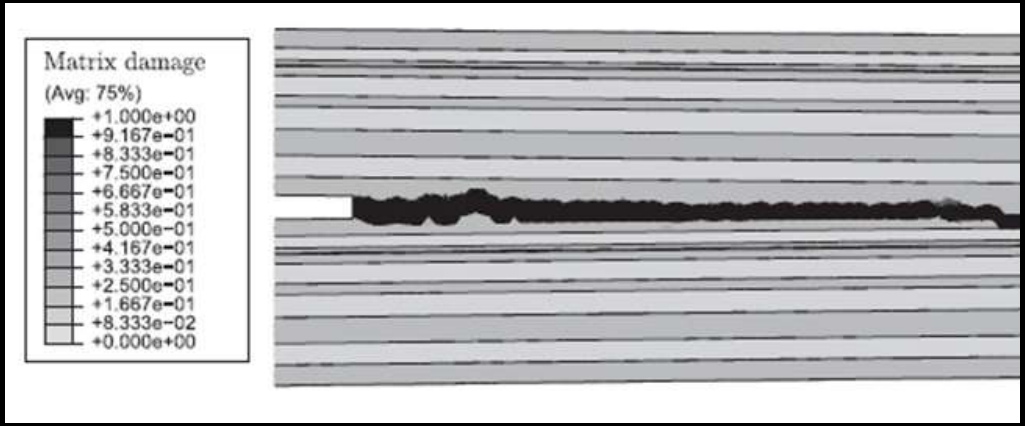
Procedure → Setting up a **dual-scale model** of a mini-DCB specimen with fibers and matrix explicitly modelled only in front of the insert tip (refined region)

Model found in the literature

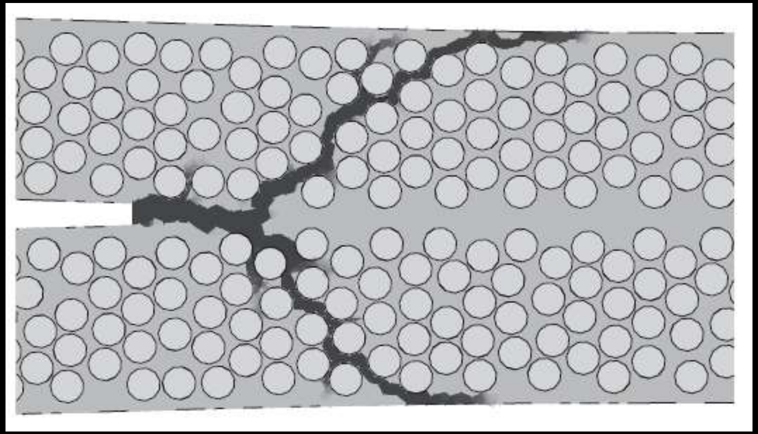
DCB specimen with RVE at the insert tip:

- Dimensions scaled down from standard
- No calculation of fracture toughness





0°/0° interface
crack propagated stably in the interlaminar region



90°/90° interface
sever crack migration at the start of propagation

Varandas et al. *Comp Struct* 220 (2019)

Modeling procedure

1. Optimization of dimensions of model and refined region
2. Generation of a random distribution of fibers for refined region
3. CAD design of specimen and embedding refined region
4. Creating compatible mesh between refined region and homogenized plies
5. Assignment of material properties for different parts
6. Definition of boundary conditions
7. Simulation with elastic and damage behavior

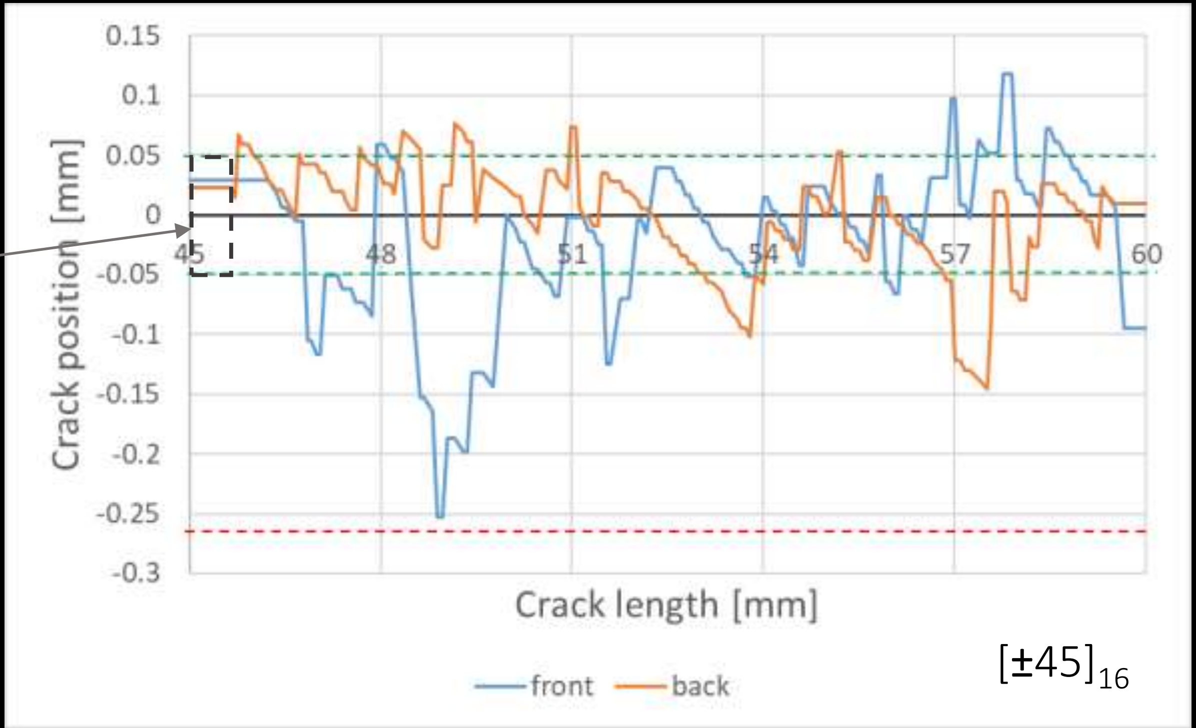
- Construction of geometry
- FE meshing and material properties
- Boundary conditions

(minimum) size of refined region

Based on on experimental results:

Crack propagates for at least 700 µm, before deviating more than 50 µm from the mid-plane

→ Thickness: 100 µm



Results from tests performed at Vrije Universiteit Brussel in M3 project (2014-2018)

Refined zone lies within the delamination process zone

→ Length → 280 µm from insert tip

Heterogeneity analysis – elastic regime

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Two different material properties for the refined region:

- Heterogenous properties: fiber and matrix assigned with their properties (dual-scale)
- Homogenized properties: homogenized properties assigned to all elements – same mesh as in the heterogeneous model (single scale)

Four models for elastic analysis

Heterogeneous model with free edges	Heterogeneous model with fixed edges
Homogenized model with free edges	Homogenized model with fixed edges

Stress profile at crack tip (0°/0° interface)

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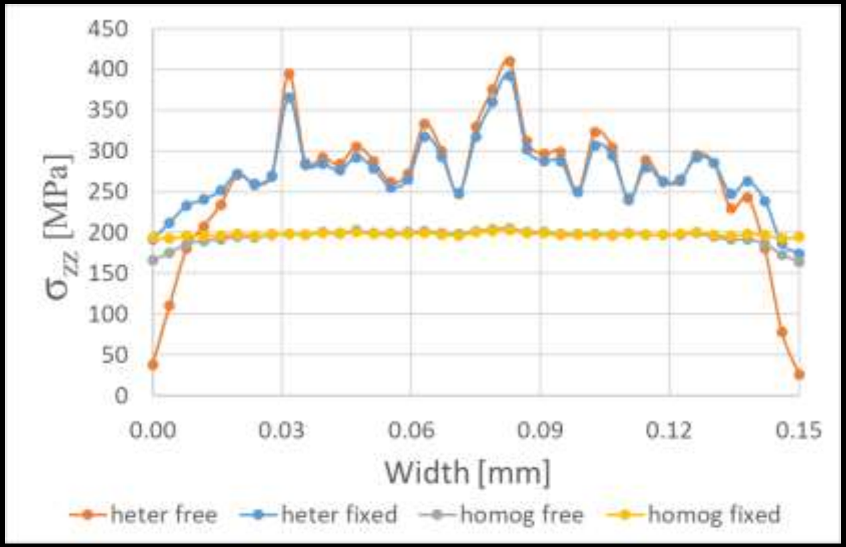
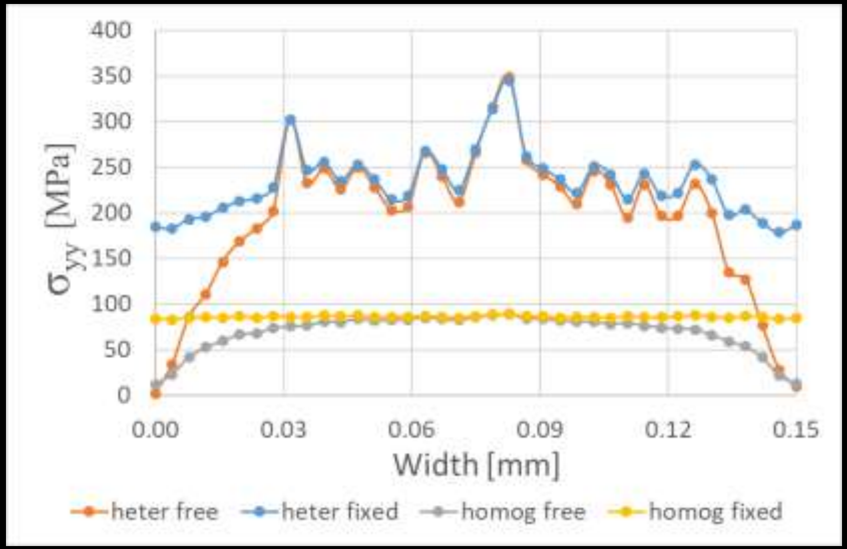
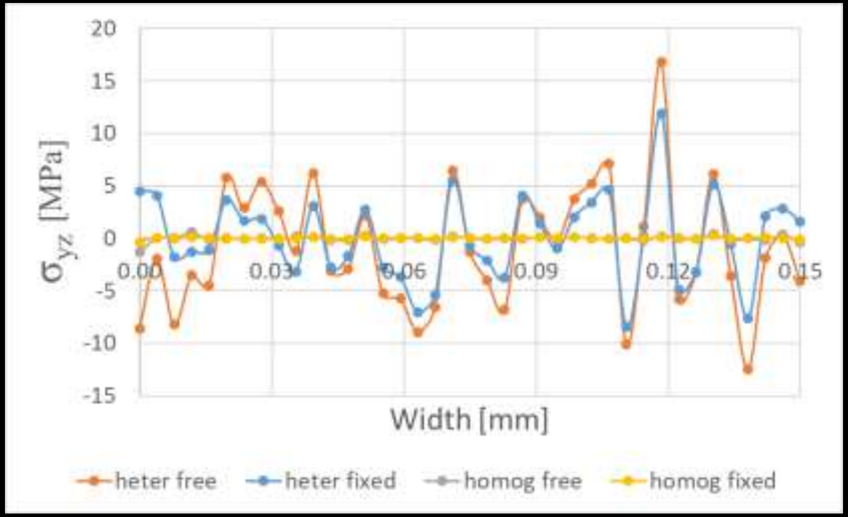
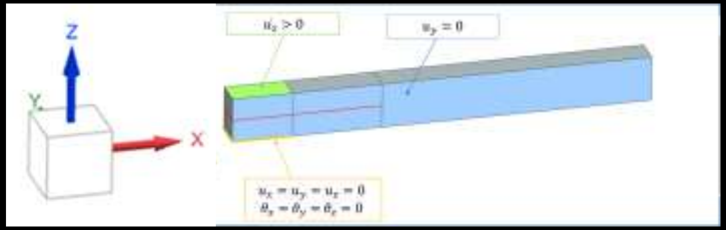






- Heterogenous models show stress variation.
- Free edge effect vanishes not so far from the free edges.
- σ_{yy} equal to zero at the free edges



Stress heterogeneity – elastic analysis, 90°/90° interface

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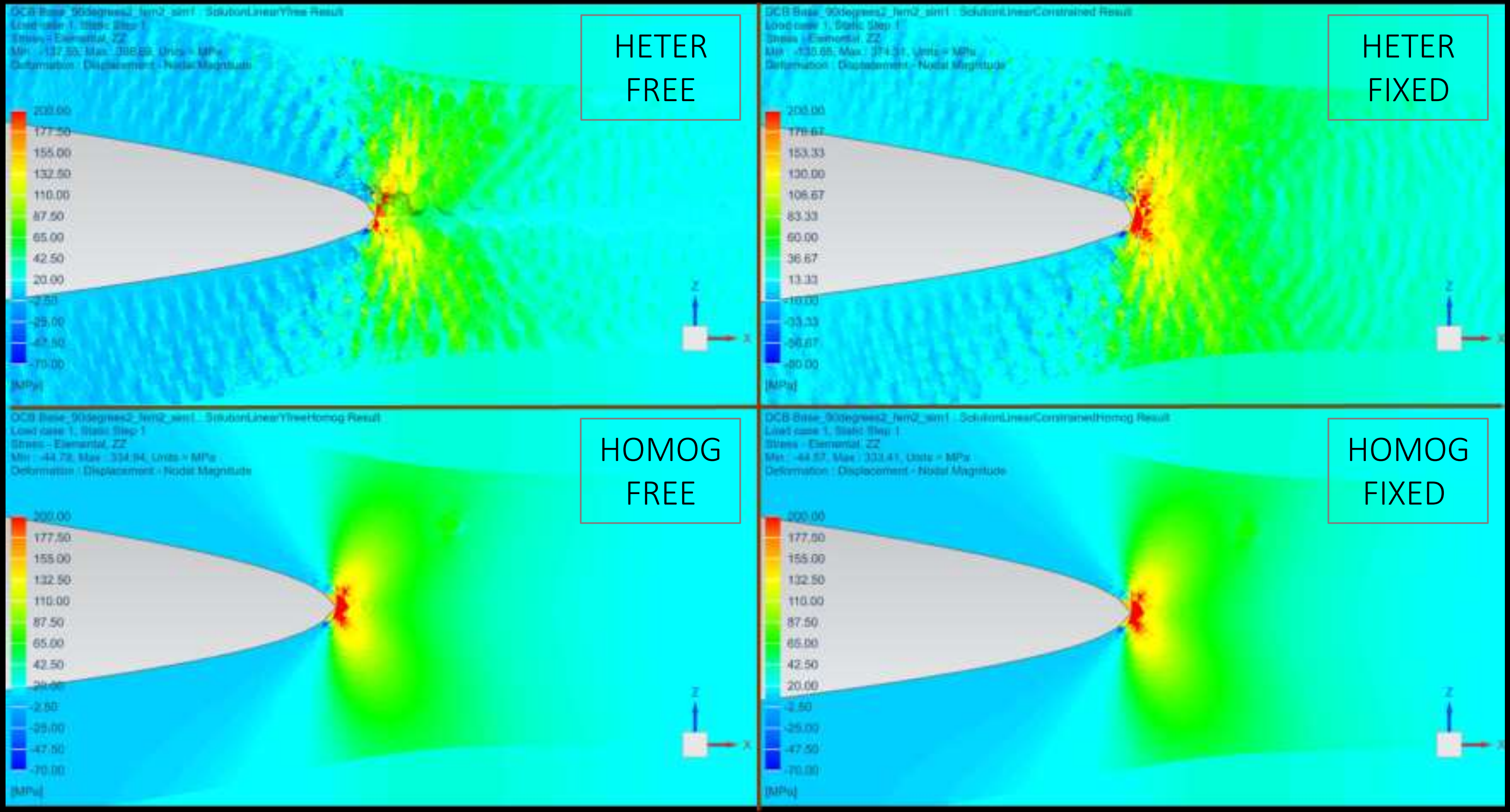

Side view (σ_{zz})

Stress profile at insert tip (90°/90° interface)

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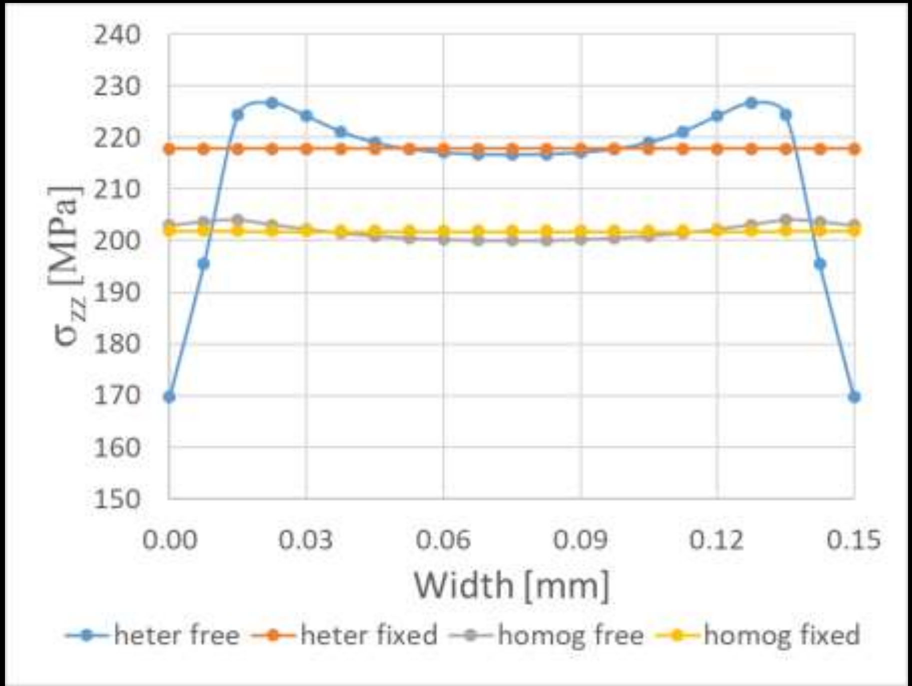

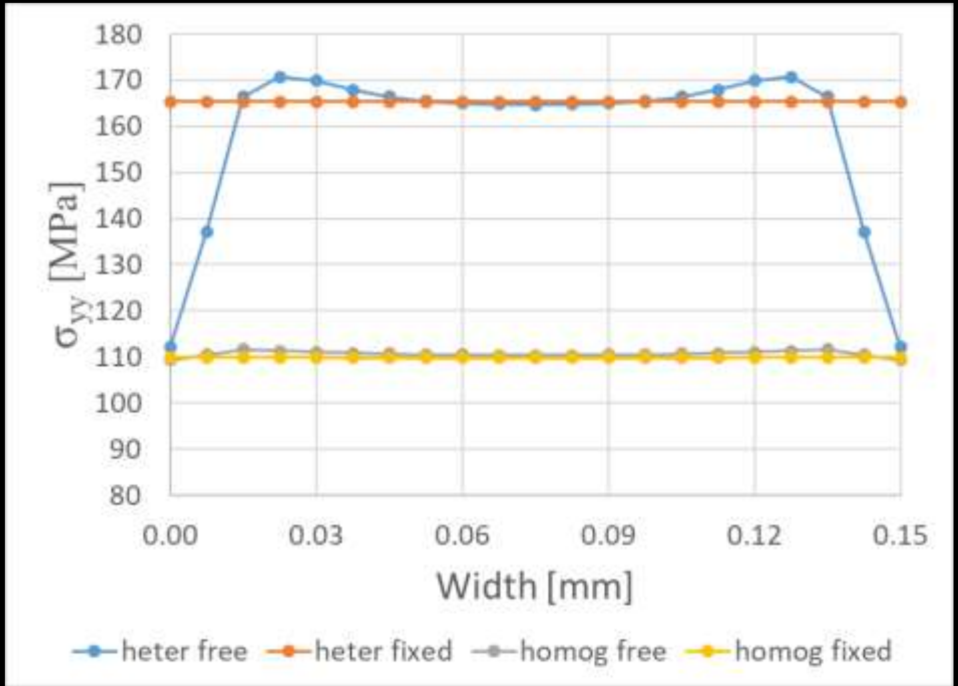

- σ_{yy} is not zero at the free edges!
- Needs further investigation
- Mesh refining and interpolation may reduce this issue according to Esquej et al. *Comp Struct* 98 (2012).