Challenges in determination of cohesive laws from R-curves of composites experiencing delamination

Comptest 2023 conference

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Outline

1. Basic characteristics of composite materials: R-curve behavior
2. Problems encountered during DCB testing of thin laminates and a solution
3. Test setup, testing and observations
4. Comparison of R-curve behavior of two different materials
5. Determination of cohesive laws
6. Summary and outlook

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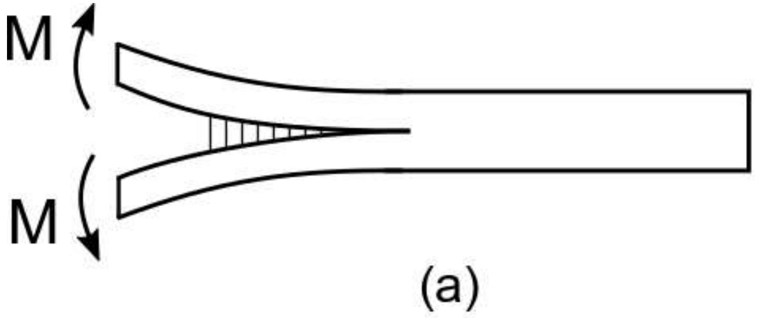
Fracture mechanics test for characterising R-curve

J integral specimen for determination of cohesive laws

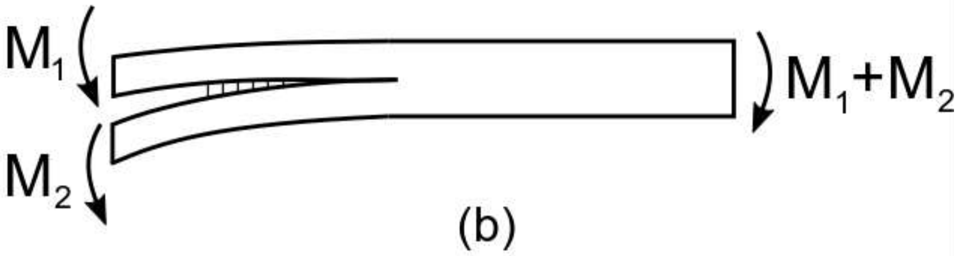
Mode I:

- Double cantilever beam (DCB) specimen loaded with pure bending moments
- measure normal end-opening



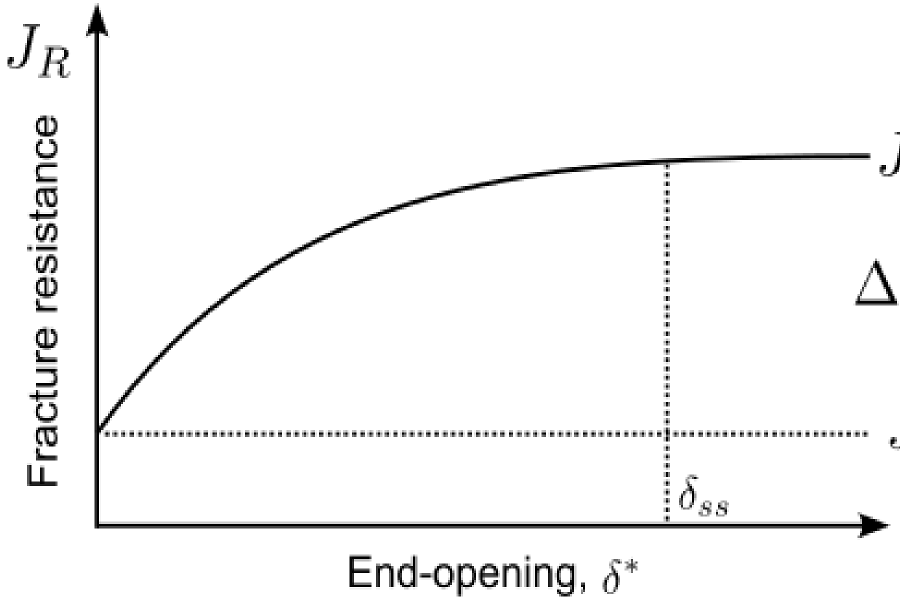
Mixed mode:

- DCB specimen loaded with uneven bending moments
- measure normal end-opening and end-sliding

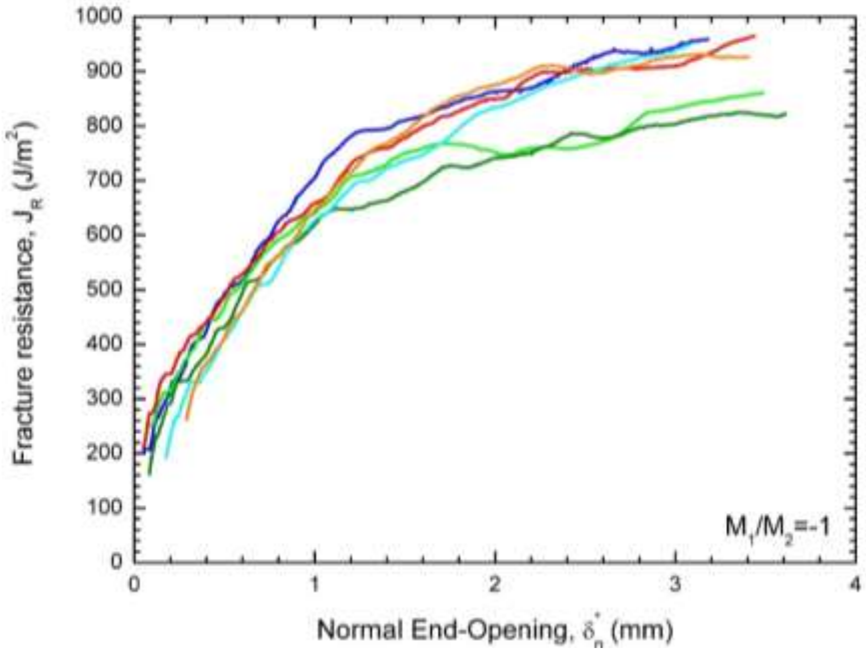


Damage tolerant composite materials

Crack growth under monotonic loading: R-curve behavior



Mode I



[Sørensen and Jacobsen, 2009]

'R-curve' behavior implies

'increasing fracture resistance'

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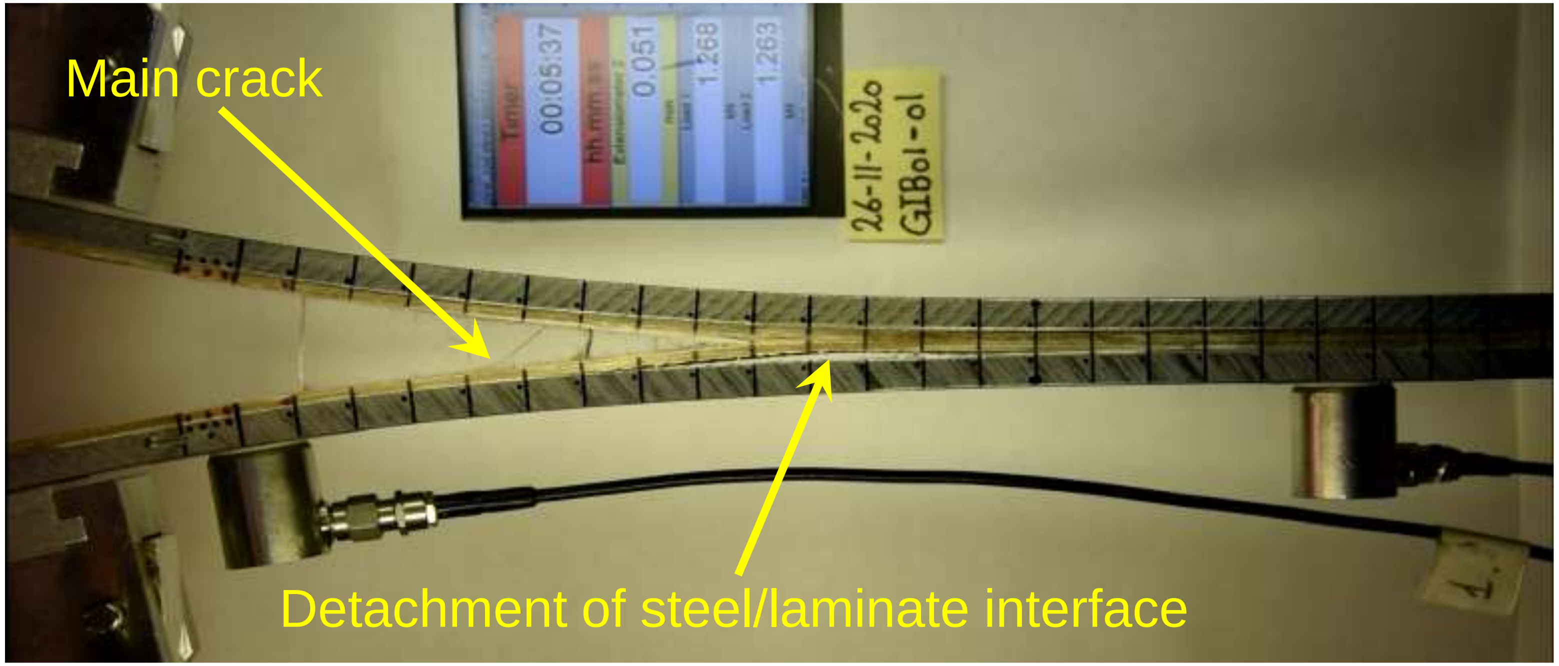
Problems encountered during DCB testing

- Conventional design in case of thin laminates/high fracture resistance: Reinforcement from steel beams (adhesively bonded)
- Problem 1: Detachment between steel/laminate interface
- Problem 2: Plastic deformation in steel beams



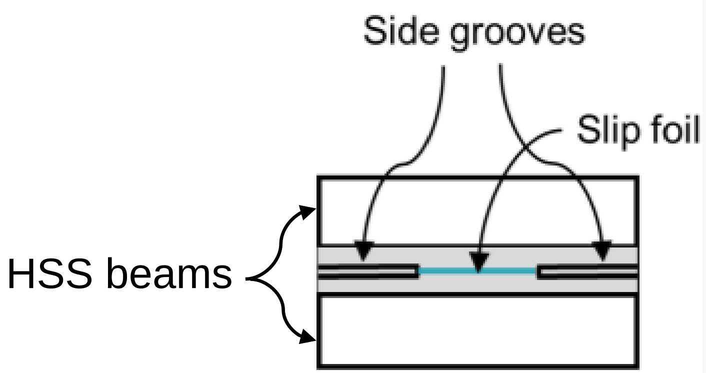
Countermeasures to the problems: Modified DCB specimen

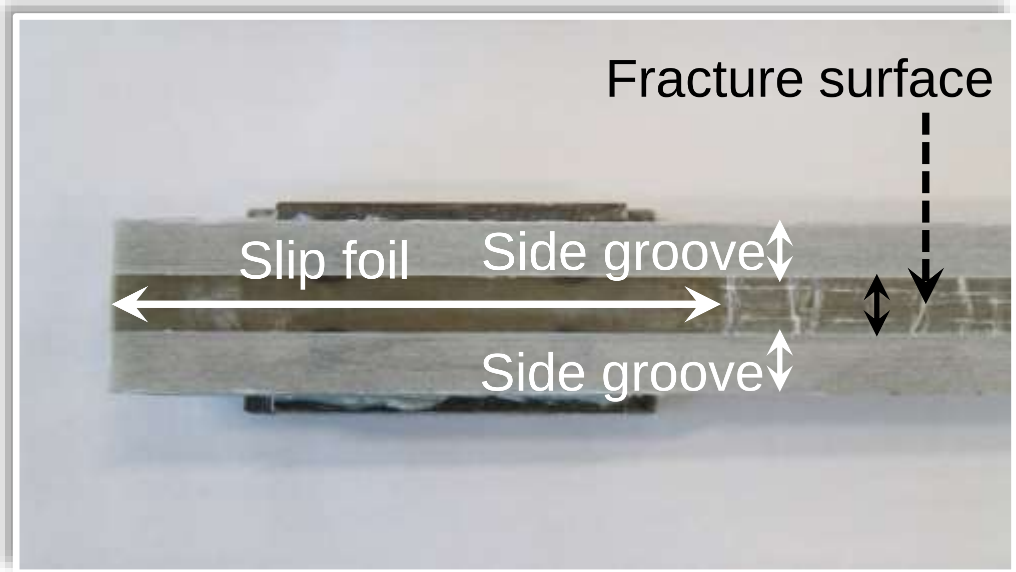
Solution:

- Machine laminate surface before bonding to get down to fibres & improve bonding
- Machine side grooves to make fracture width narrower to reduce load
- Use steel beams with higher strength steel (HSS) to avoid yielding

Top view

Side view





3. Test setup, testing and observations

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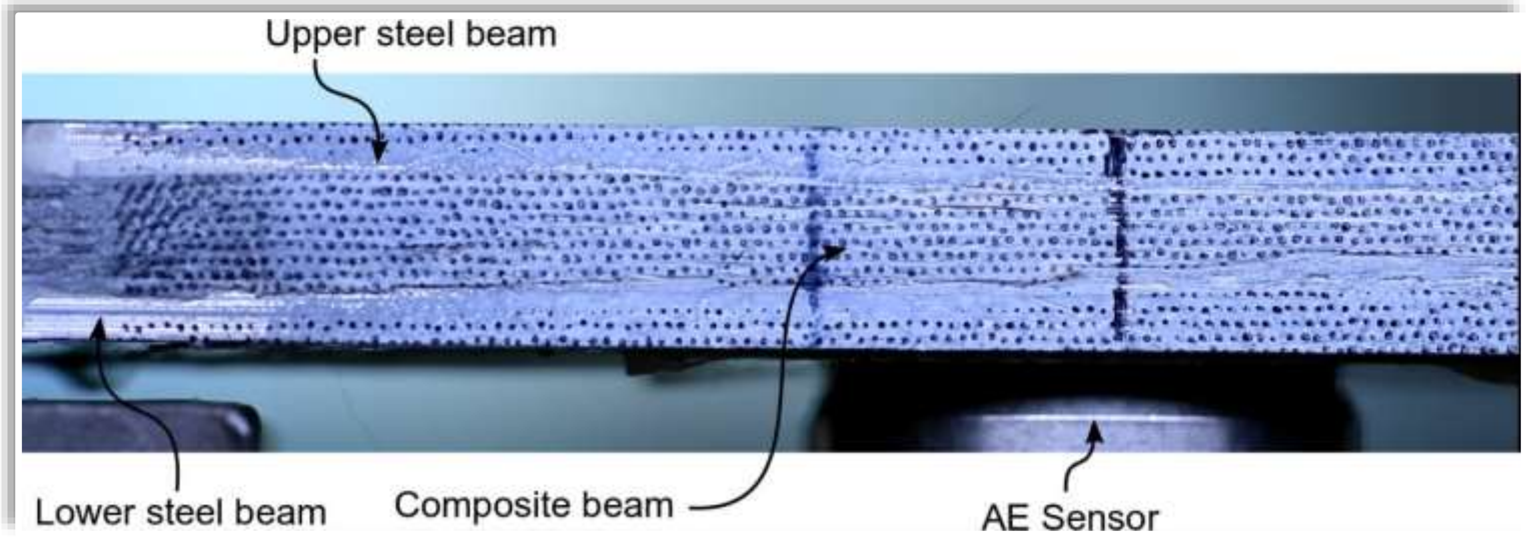
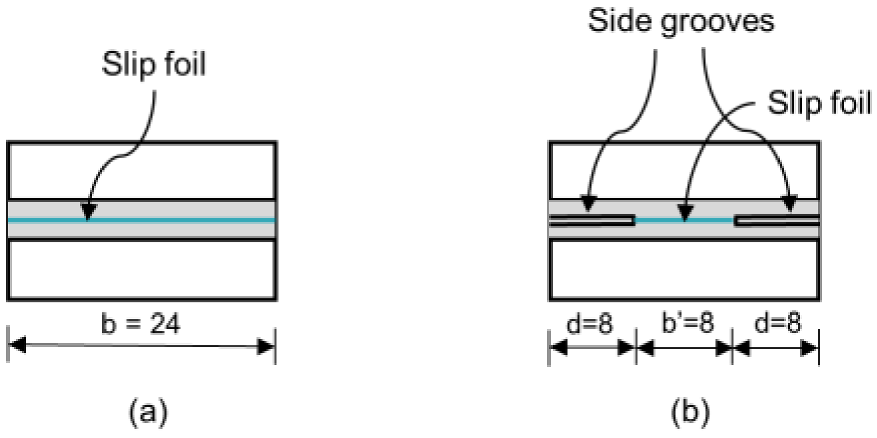
DCB testing setup

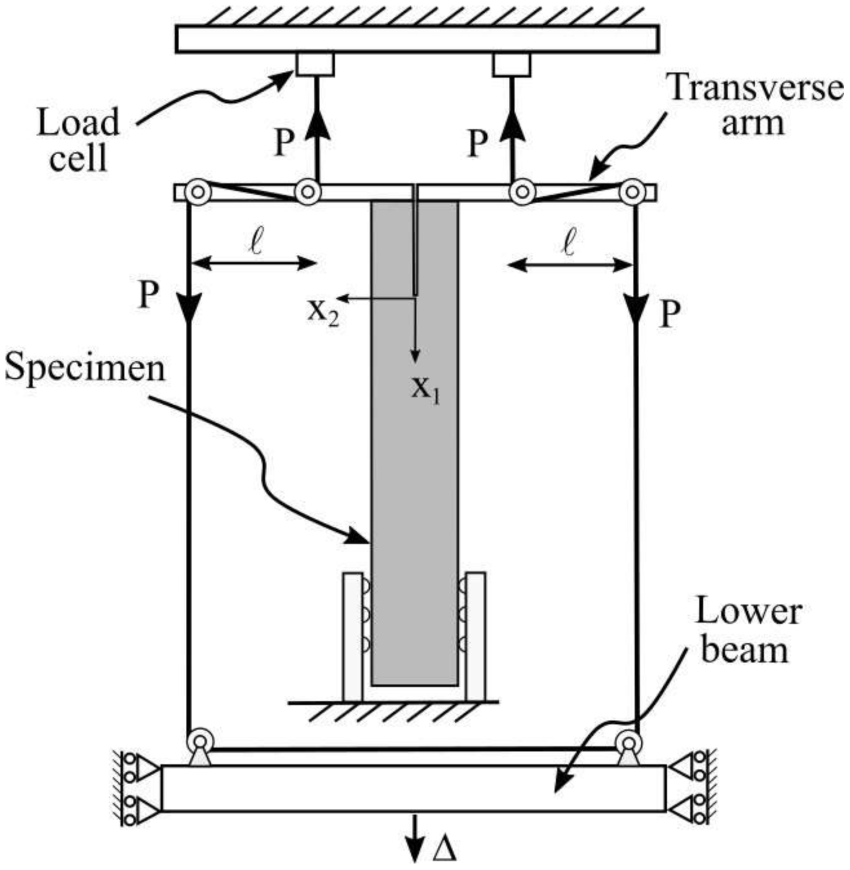
Front view



Side view



DTU test configuration

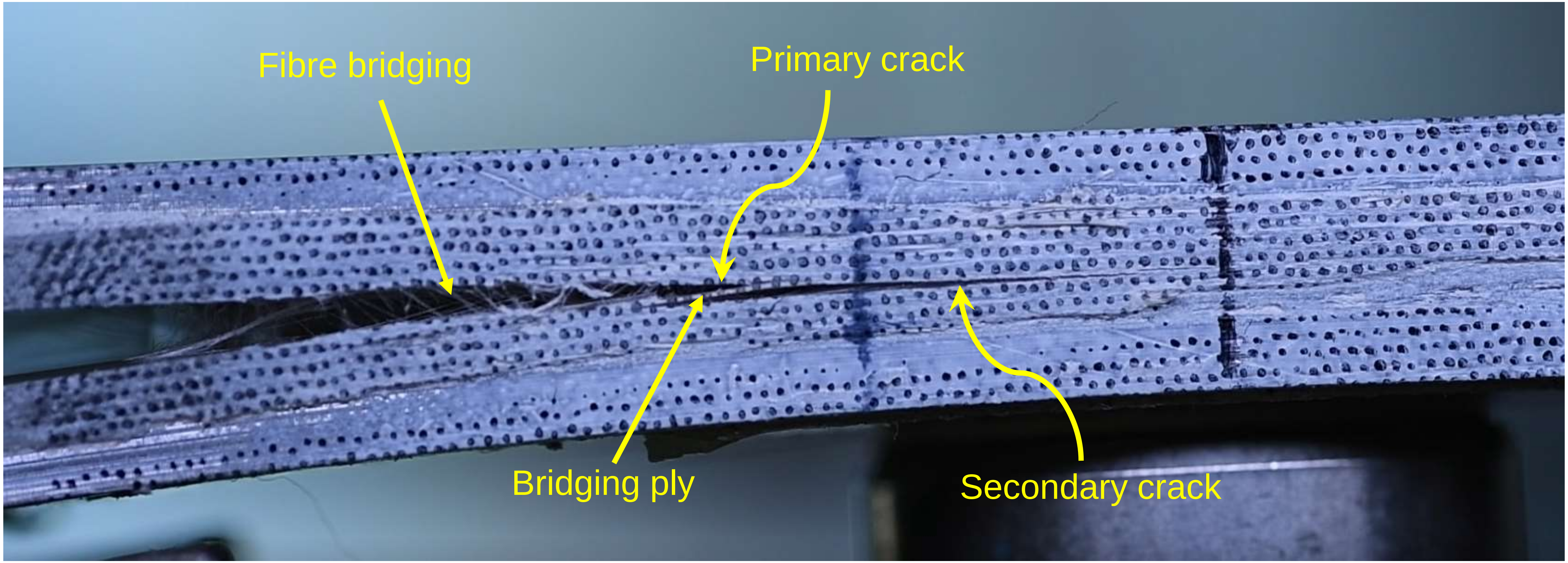


Schematic illustration of the test fixture to apply pure bending moments

NOTE: All dimensions are in mm

Formation of secondary crack: multiple fracture zones

Full-width DCB specimen



4. R-curve behavior of two different materials

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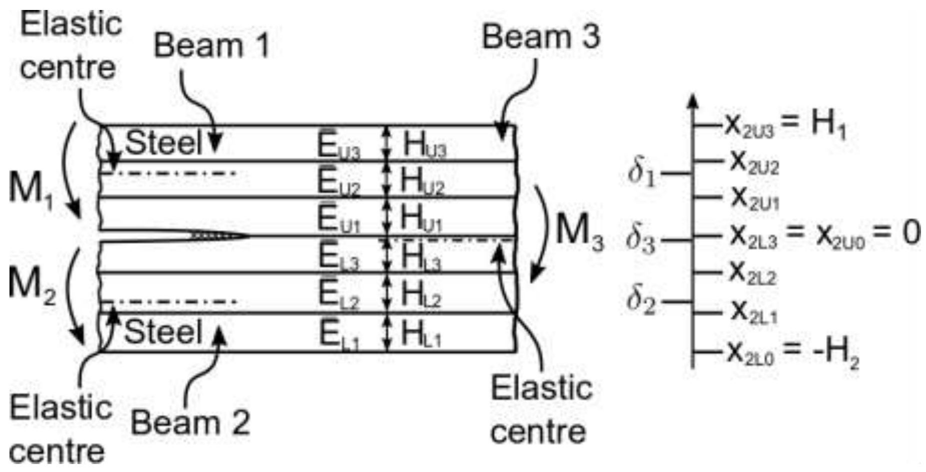
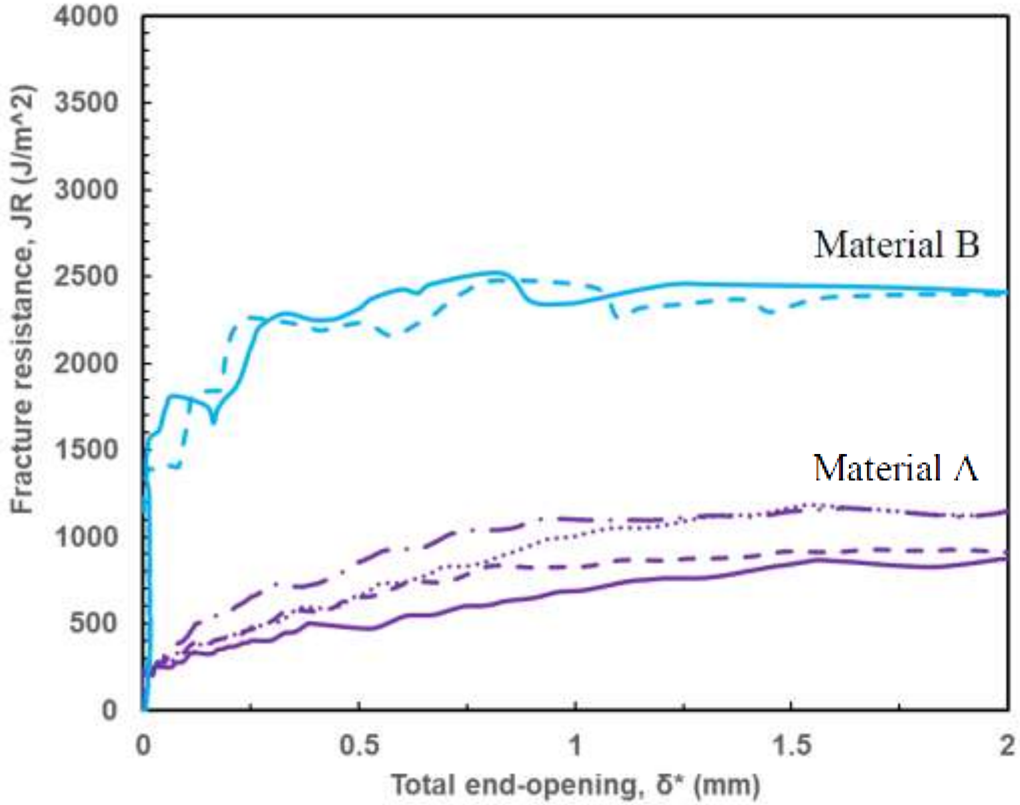
Measured fracture resistance: R-curves



$$J_R = \frac{M_1^2}{2b(EI)_1} + \frac{M_2^2}{2b(EI)_2} - \frac{M_3^2}{2b(EI)_3}$$

[Toftegaard and Sørensen, 2019]



Materials (Mode I)	J_0 (J/m²)	J_{ss} (J/m²)
Material A (Vinylester)	222 ± 15	1382 ± 184
Material B (Vinylester with high elongation)	699 ± 42	4340 ± 169

5. Determination of cohesive laws

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Cohesive laws

- Fracture resistance curves were fitted with a quadratic polynomial up to J_0 and with the below eq. from J_0 to J_{ss}

$$J_R = J_0 + \Delta J_{ss} \left(\frac{\delta - \delta_0}{\delta_{ss}} \right)^{\zeta}$$

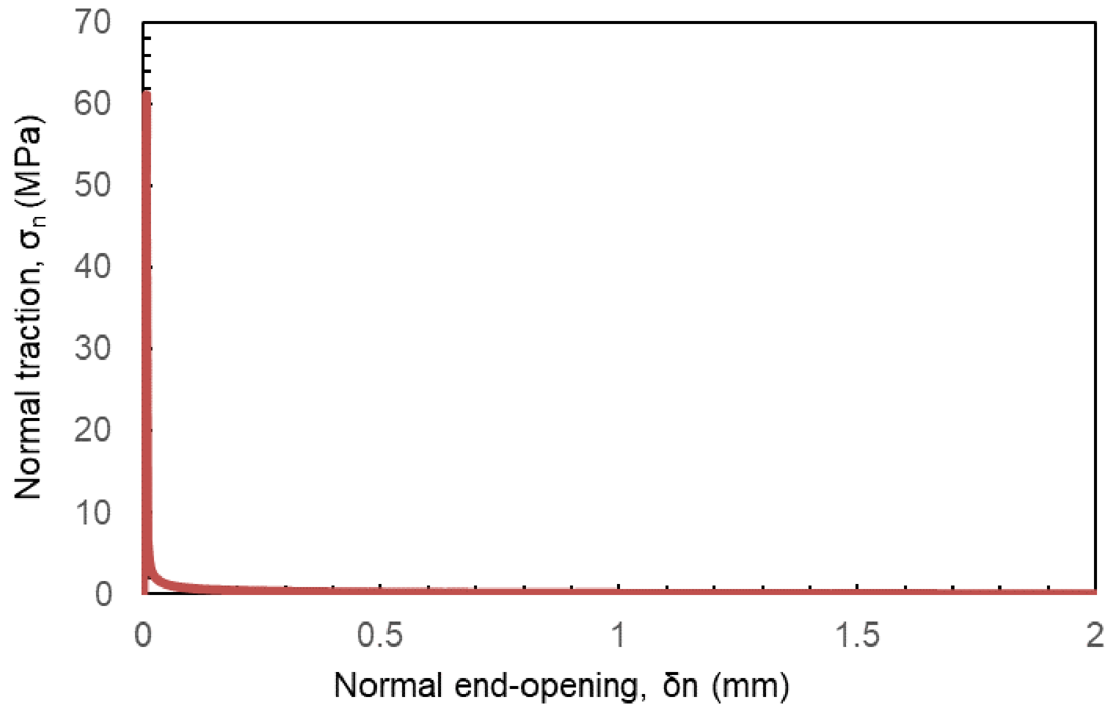
- By differentiating the fracture resistance curve, the cohesive law is obtained as

$$\frac{\partial J_R}{\partial \delta} = \frac{\Delta J_{ss}}{\delta_{ss}} \zeta \left(\frac{\delta - \delta_0}{\delta_{ss}} \right)^{\zeta - 1}$$

[Erives et al., 2022]

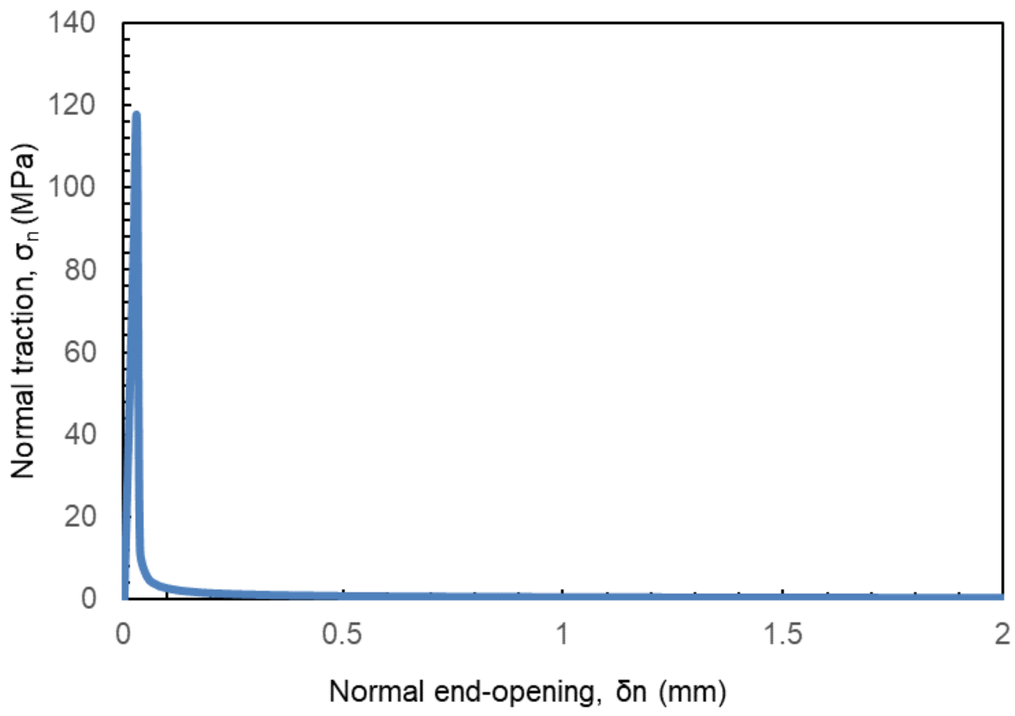
Cohesive laws

Material A



Peak normal traction 61 MPa

Material B



Peak normal traction 117 MPa

Summary and outlook

- Fibre bridging causes the rising fracture resistance (R-curve behaviour)
- Material B (vinylester with high elongation) has significantly higher fracture resistance (J_0 and J_{ss}) than Material A
- Sometimes weaker secondary interface leads to two fracture process zones and increased J_{ss}
- In the future work, one can investigate if weaker fibre/matrix bonding can facilitate increased fibre bridging

Acknowledgements:

- DACOMAT (Damage Controlled Composite Materials) project

DTU

DACOMAT

Thank you for your attention

Questions/comments ?

Countermeasures to the problems

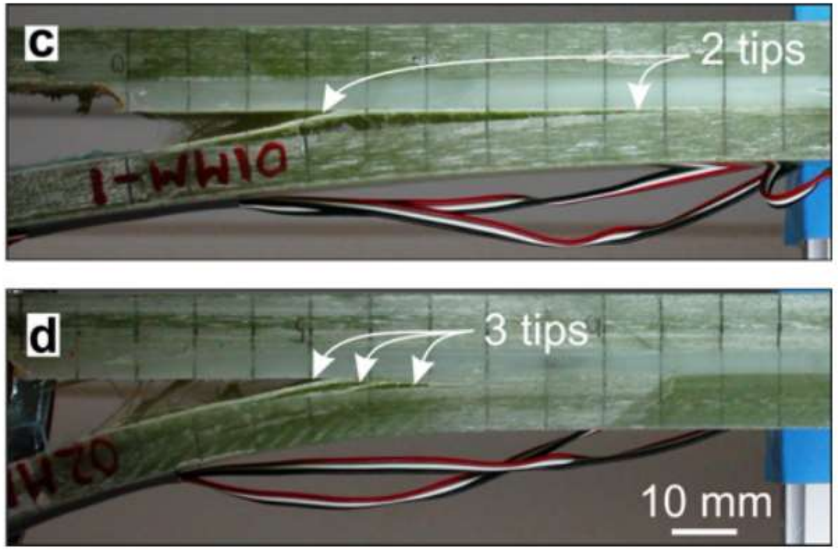
Solution:

- Machine laminate surface before bonding (to get down to fibres, improve bonding)
- Machine side grooves to make fracture width narrower (reduce load to the specimen)
- Use steel beams with higher strength steel (avoid yielding)

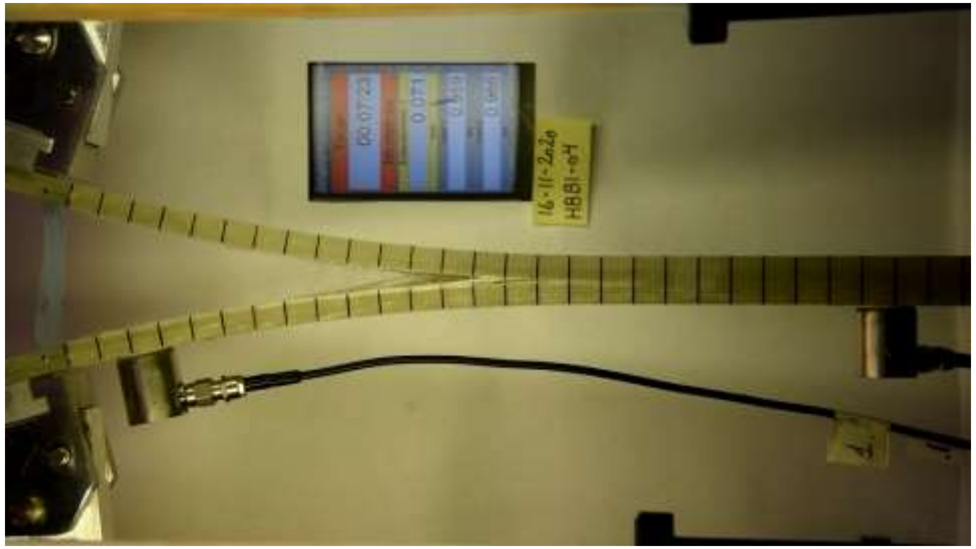
Criteria set up:

- Maximum moment (avoid adhesive failure): $M_{max}/B = 1.56$ Nm/mm
- High mode II fracture resistance capability: $J_{IImax} = 40.000$ J/m2
- Avoid large displacements and large rotations (keep radius of curvature below 0.2 m, or equivalently that the curvature $\kappa \leq 5$ m-1)

Multiple fracture process zones by plasma treatment of interfaces



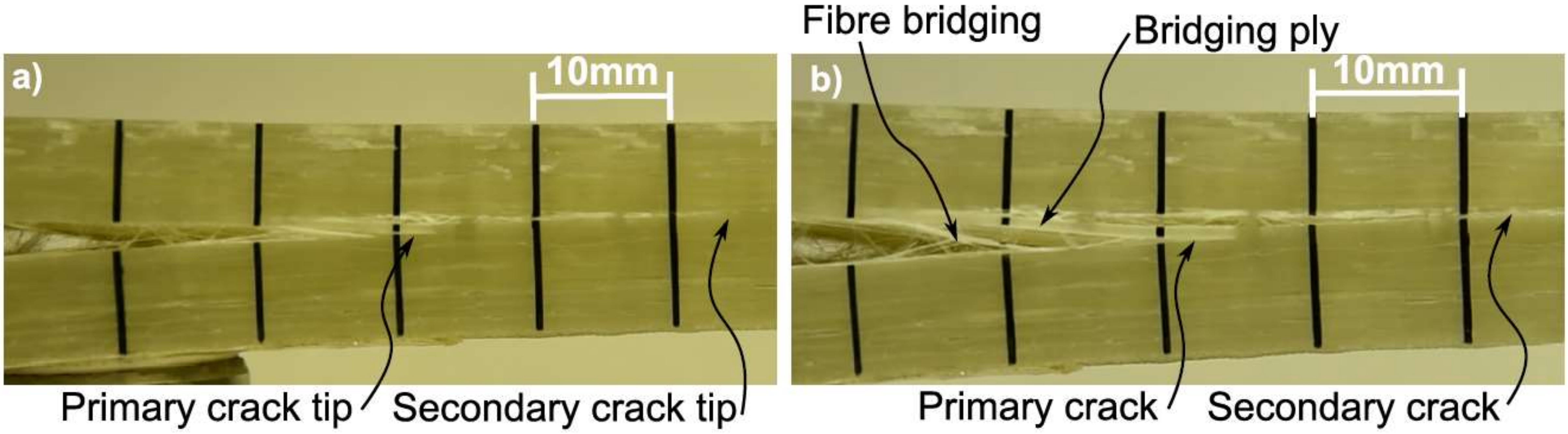
Mixed mode DCB specimen showing multiple fracture process zones [Rask & Sørensen, 2012]



Mode I DCB specimen showing multiple cracks [D. J. H. Cederløv]

- Serendipituous discovery from Rask and Sørensen (2012) has been replicated
- Controlled formation of multiple cracks in DCB composite specimen
  – achieved by plasma fluorination of selected fibre mats before laminate manufacturing

Controlled formation of multiple fracture process zones by plasma treatment of interfaces



- Two advancing fracture process zones gives the double fracture resistance
- Controlled interfaces between layers (weak secondary interface) by plasma treatment

[Daan J. H. Cederløf, "Enhanced damage tolerance Of composite materials by multiple delaminations", PhD-Thesis, 2022]

Fibre bridging -fracture resistance enhancement due to secondary fracture process zone induced by plasma treatment

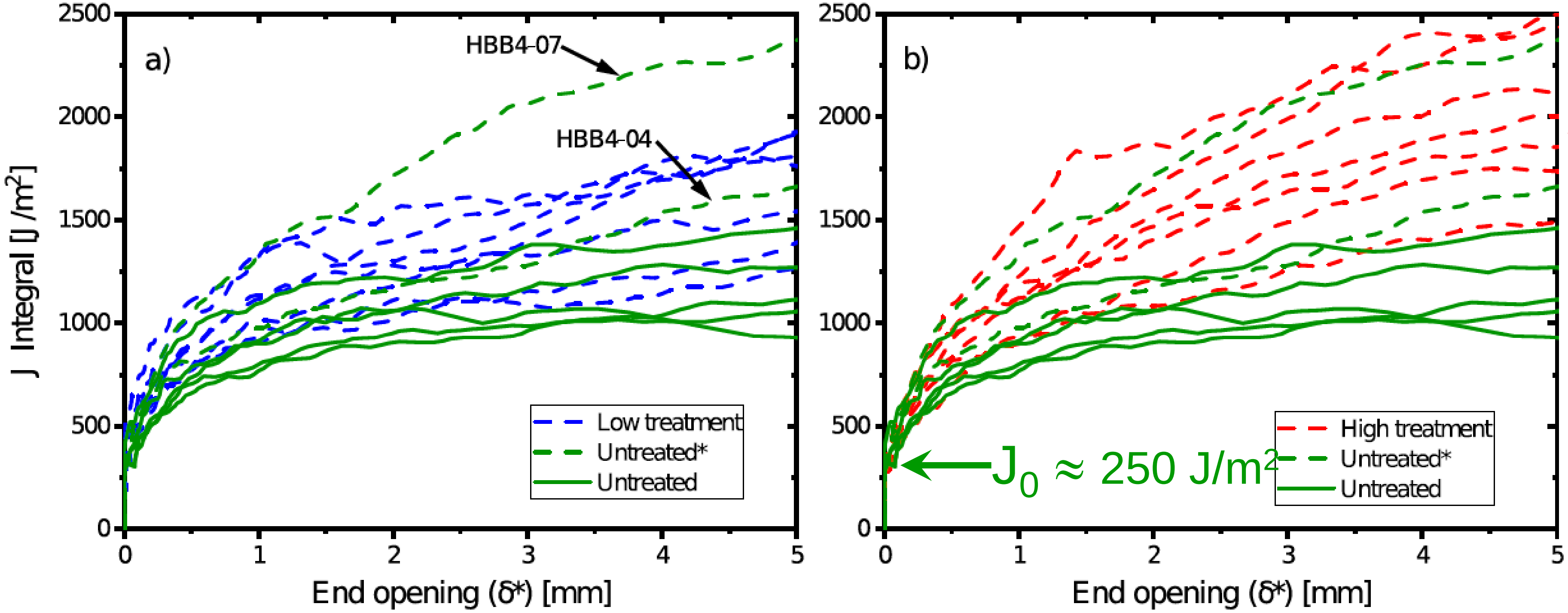


Figure 4.9: Fracture resistance of untreated laminates vs laminates with low treatment **a)** and high treatment **b)**. The dashed lines labelled with HBB4-04 and HBB4-07 are untreated DCB specimens that developed two cracks with large scale fibre bridging.

Two fracture process zones:

$J_{ss} \approx 2000$ J/m^2

$J_{ss} \approx 1200$ J/m^2

(one fracture process zone)

[Daan J. H. Cederløf, "Enhanced damage tolerance Of composite materials by multiple delaminations", PhD-Thesis, 2022]