

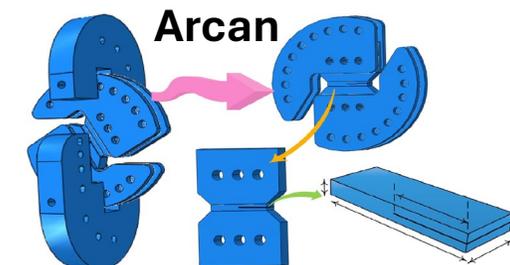
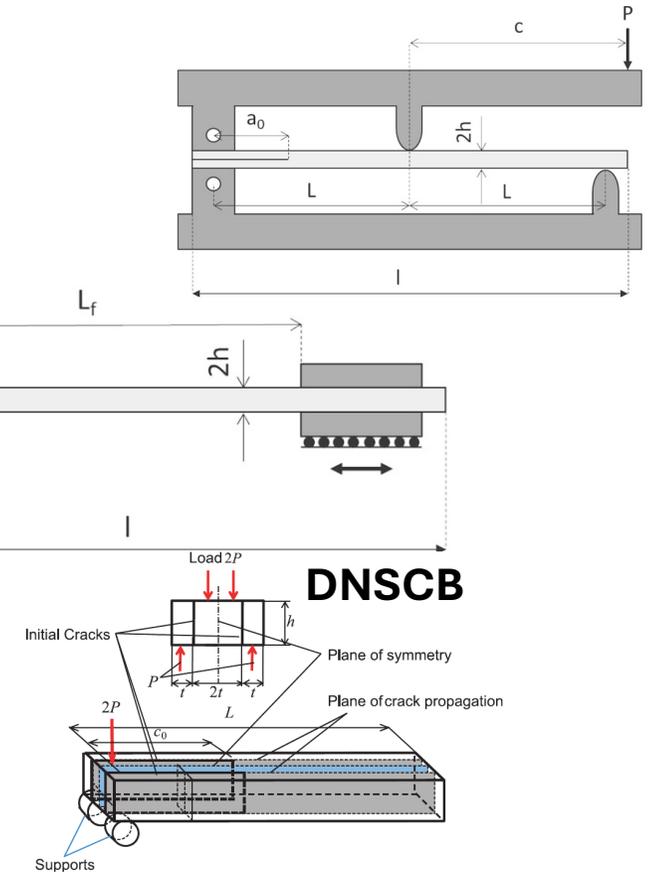
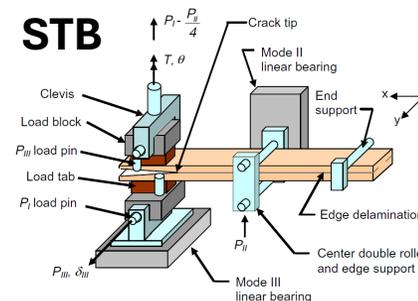
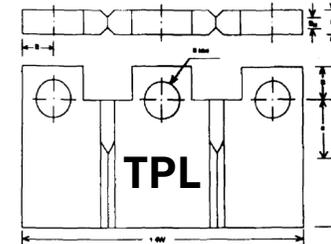
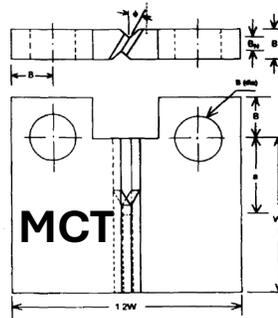
Mixed-Mode and Mode III Fracture of FRP composites: Do we have to test, and if so, how?

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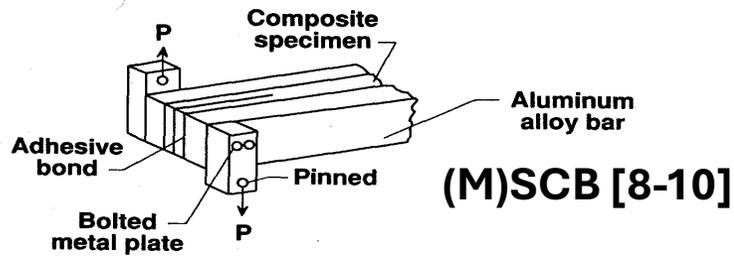
Quasi-static Mixed Mode Fracture

- Only Mixed Mode standard test is ASTM D6671 [1] Mixed Mode Bending (MMB), rig is adaptable for a range of mode I/II ratio
- Alternative, not standardised, is Fixed-Ratio Mixed Mode (FRMM), with Mode I : Mode II ratio of 4:3 [2]
- Many different Mixed Mode setups found in literature: e.g., I-III MCT / TPL [3], II-III DNSCB [4], WTELS [5], I-II-III STB [6], Arcan-based [7]

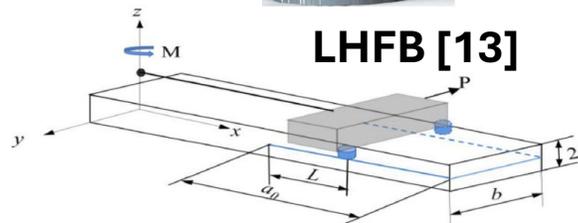
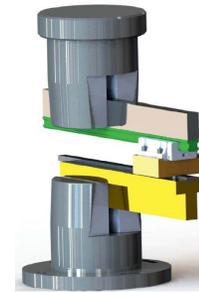
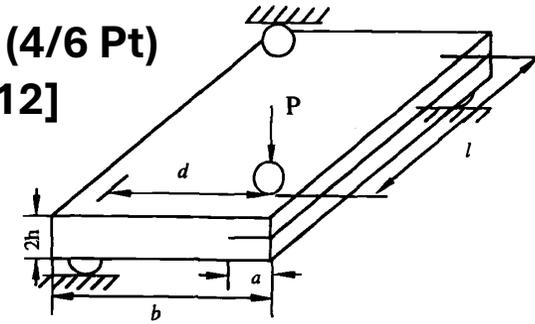
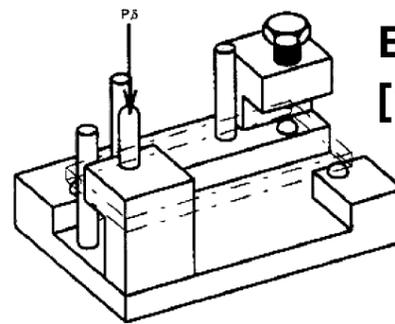


Quasi-static Mode III Fracture

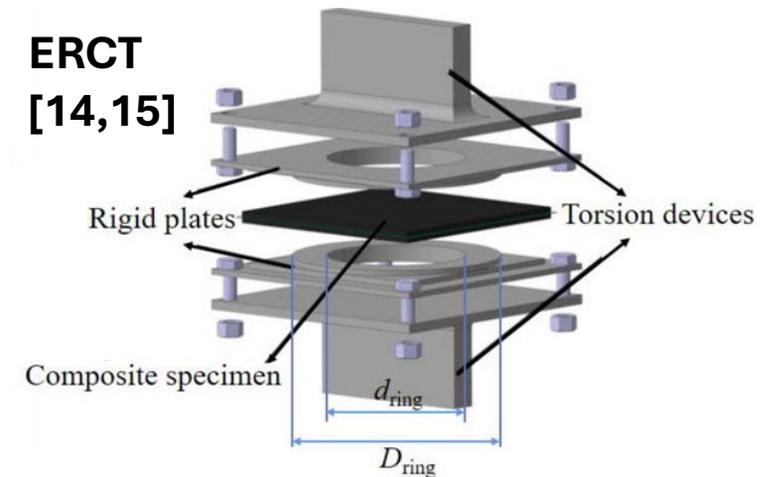
- Many tests proposed, none standardized yet, one ASTM Round Robin (on 4-point ECT)



- Many tests use **plate-type specimens** and have additional mode II components, i.e., are mixed mode II/III, except ERCT, but that is unstable, hence propagation R-curves cannot be determined

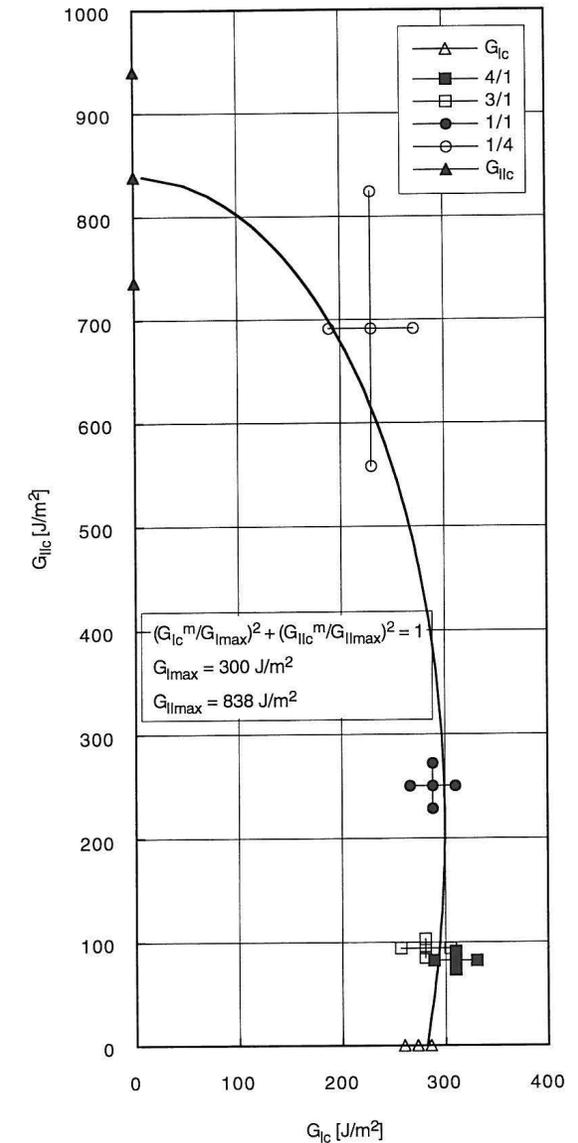


ERCT [14,15]



Quasi-static Mixed Mode I/II Data (I)

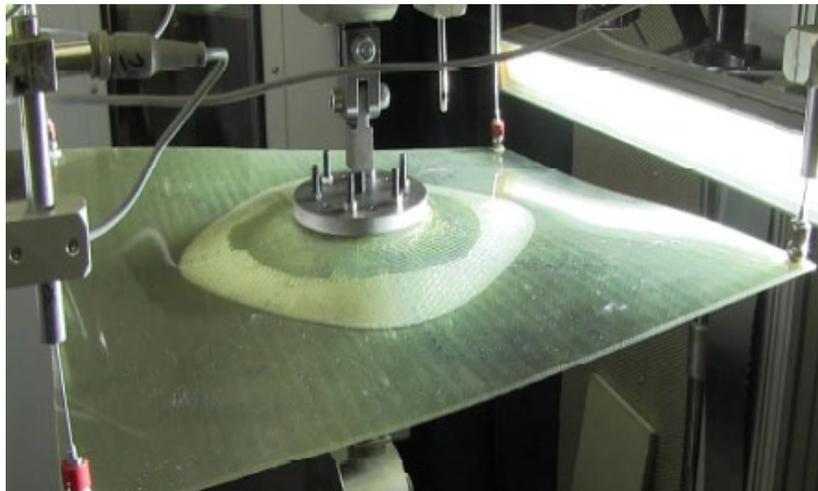
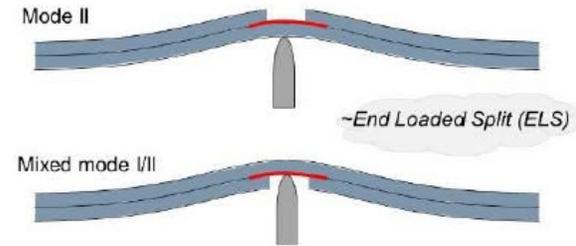
- Mode I, Mode II and Mixed Mode I/II tests yield empirical failure envelopes, e.g., graph from [16]
- Delamination propagation in FRP structures is often due to mixed mode loading [17]
- Repeatability (standard deviation) roughly $\pm 10\%$, reproducibility (in RR [18]) roughly $\pm(15-25)\%$, measurement resolution yields around $\pm 5\%$ [18]
- However, **do we really need mixed mode I/II data** as noted in [17] for «safe» structural design?
- Quasi-static Mode I (opening tensile) yields lowest initiation values compared to other modes, may, e.g., with 2-3 standard deviations, yield «safe» design limits



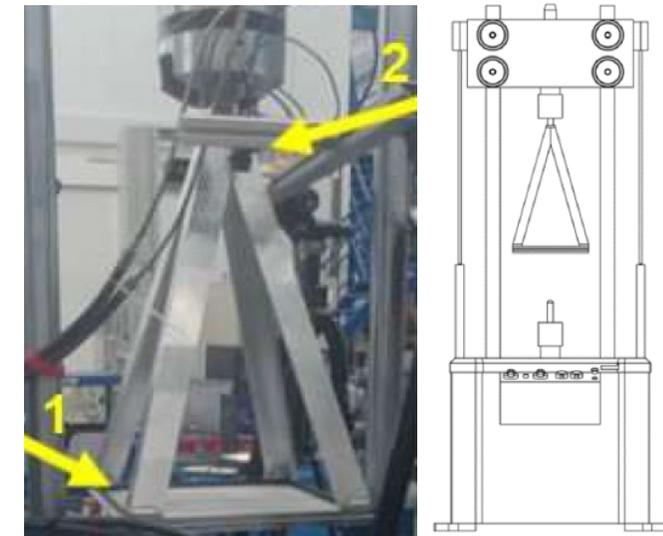
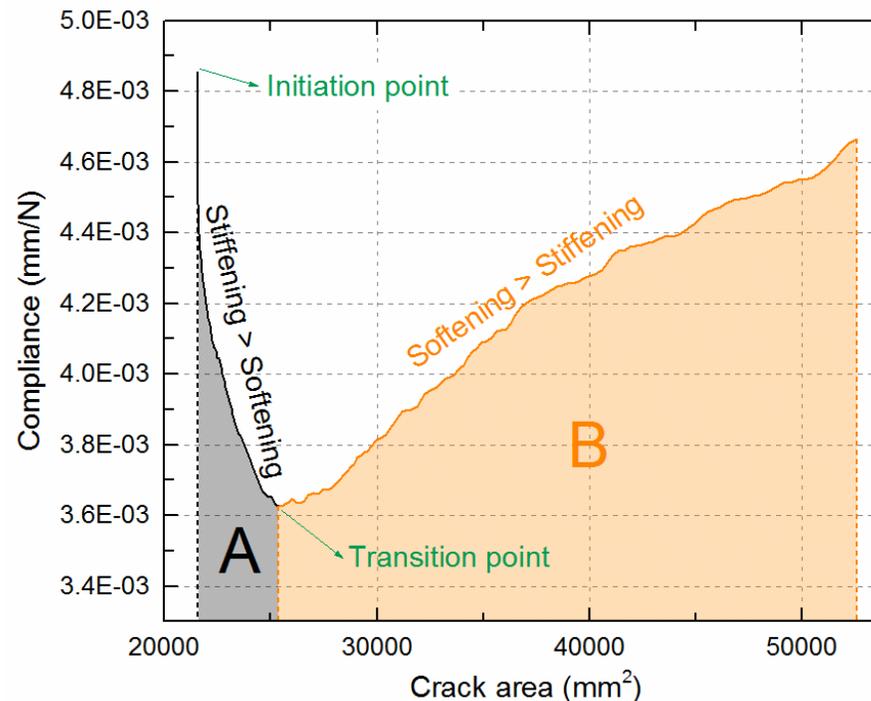
**Toughened CF-epoxy
R5259/G30-500/12k**

Quasi-static Mixed Mode I/II Data (II)

- Delaminations in FRP structures (e.g., thin shells) will **yield 2D propagation**, hence Mode I and Mixed Mode I/II tests on plate specimens instead of beams



Quasi-static Mode I [19]



Quasi-static Mode II and Mixed Mode I/II [20]

Summary & Outlook

- Failure envelopes from quasi-static Mode I, Mode II and Mixed Mode I/II tests do not yield useful predictions of delamination propagation in FRP structures yet [21, 22]
- Quasi-static 2D Mixed-Mode I/II tests on FRP plates [19, 20] possibly provide better predictions, but require much higher effort and hence test cost
- Fiber-bridging plays a role, highlighting the importance of fiber orientation or laminate lay-up, but also specific 2D effects, e.g., stiffening-softening behavior in 2D Mode I fracture tests
- Quasi-static Mode I from beam specimens with safety margin (to be specified) as only design limit: Is it too conservative?
- What about multiple delaminations in FRP structures and their interactions (see, e.g. [23])?
- Real structures in-service are often subject to **variable fatigue loads** (both, amplitudes and frequencies) as well as to **variable environmental exposure** (temperature, humidity, etc.): Possibly, topics for later workshops?

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