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Determining Fracture Properties for Predicting Damage Propagation from Notches in Composite Structures

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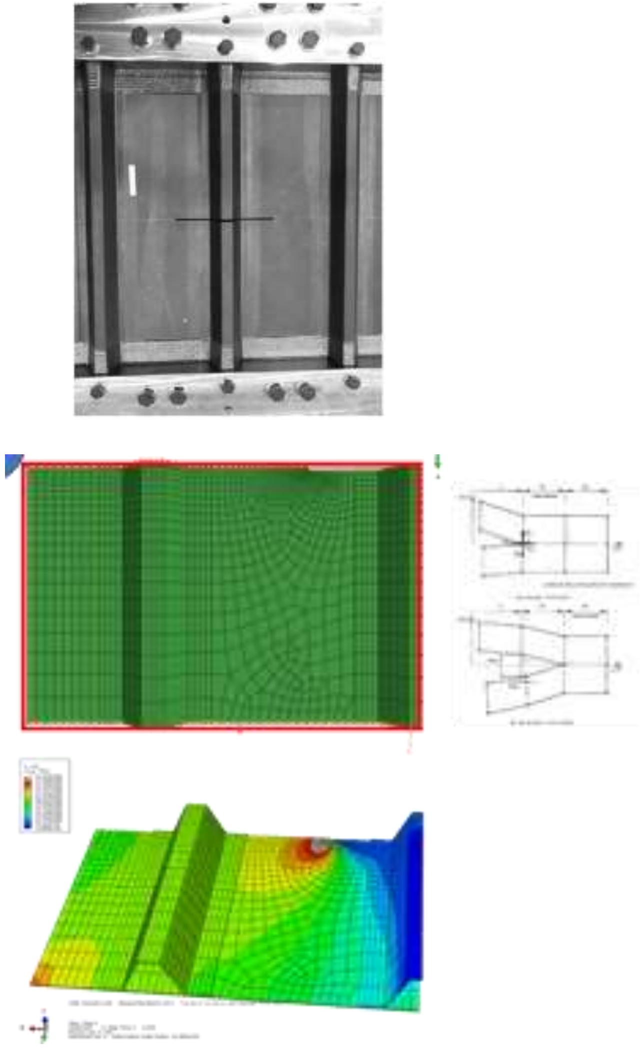
Introduction

- How can fracture mechanics be applied to predict failure of notched structures?
- Composites exhibit distributed damage rather than sharp cracks, but LEFM may still be applied
- FE of notched stiffened panel can give useful results
- What translaminar fracture properties to use?



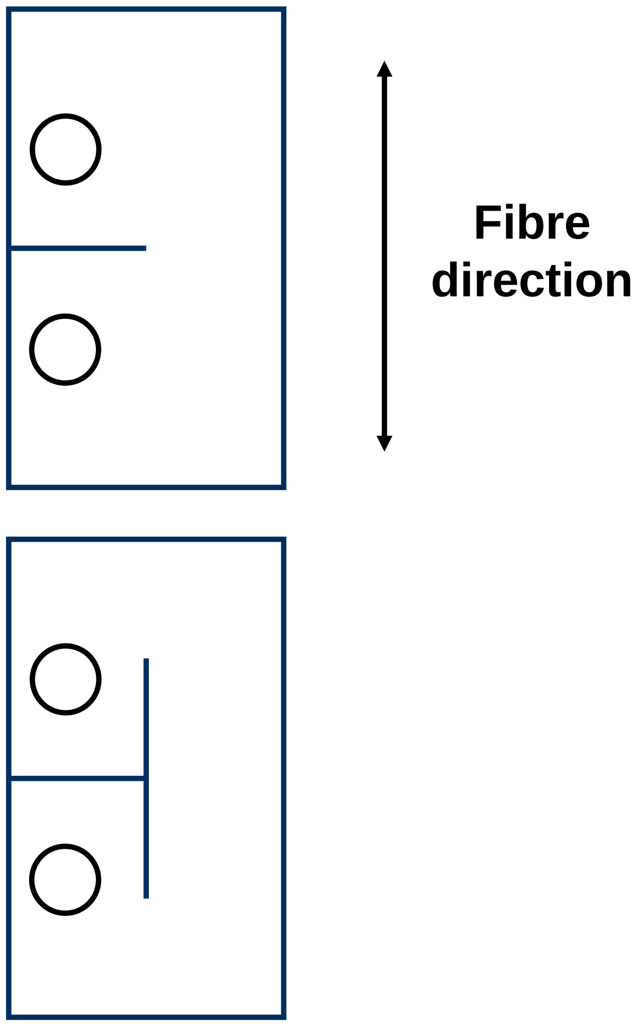
Xu et al, 2017

Overview

- Is translaminar fracture toughness a material or laminate property?
- Single value or R-curve?
- How to measure properties?

Translaminar fracture toughness

- Cannot measure Gc for a UD composite
- Material will split at the notch rather than fibre failure propagating from the crack tip
- Can back-calculate from laminate tests
- Splitting also occurs at notches in laminates
- Amount of damage and hence Gc depends strongly on the layup



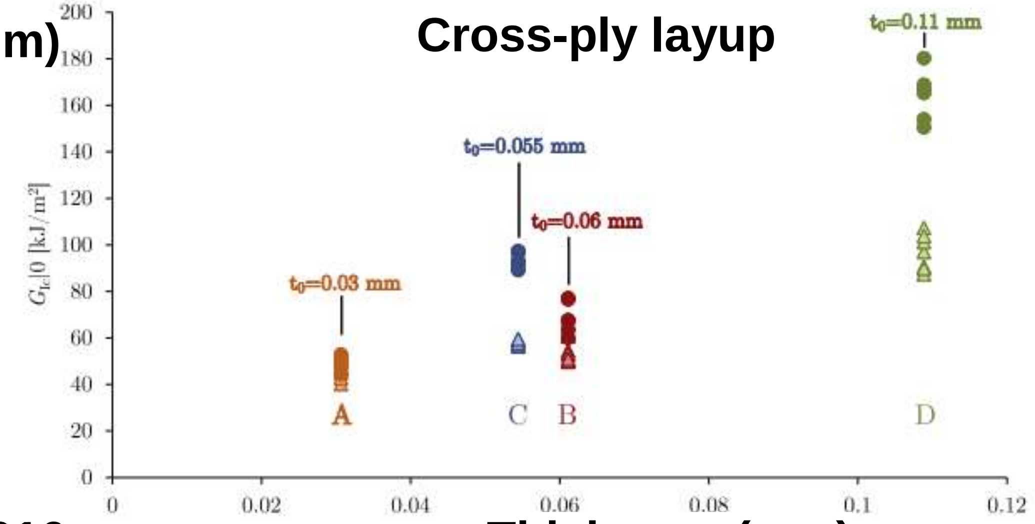
Effect of layup on Gc

- Increases with ply block thickness:

Layup	GIc (kJ/m²)
$[45/90/-45/0]_{2s}$	104.2
$[45_2/90_2/-45_2/0_2]_s$	212.3
$[45_4/90_4/-45_4/0_4]_s$	297.2

Li et al, 2009

- Decreases with thin plies:

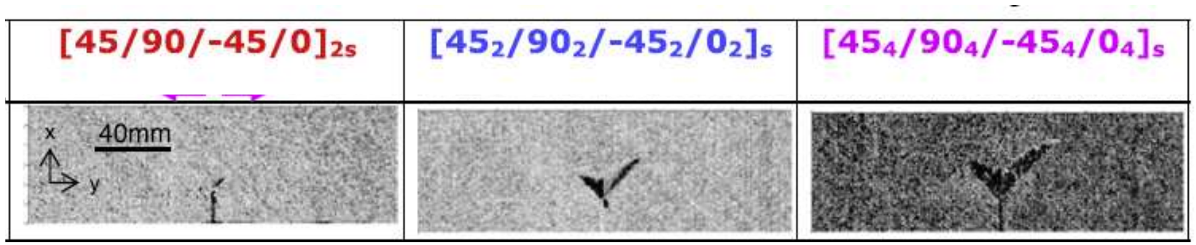


Teixeira, Pinho & Robinson, 2016

- Values typically higher for QI than CP due to greater damage

Effect of layup on Gc

- Damage zone size and hence Gc depends on layup

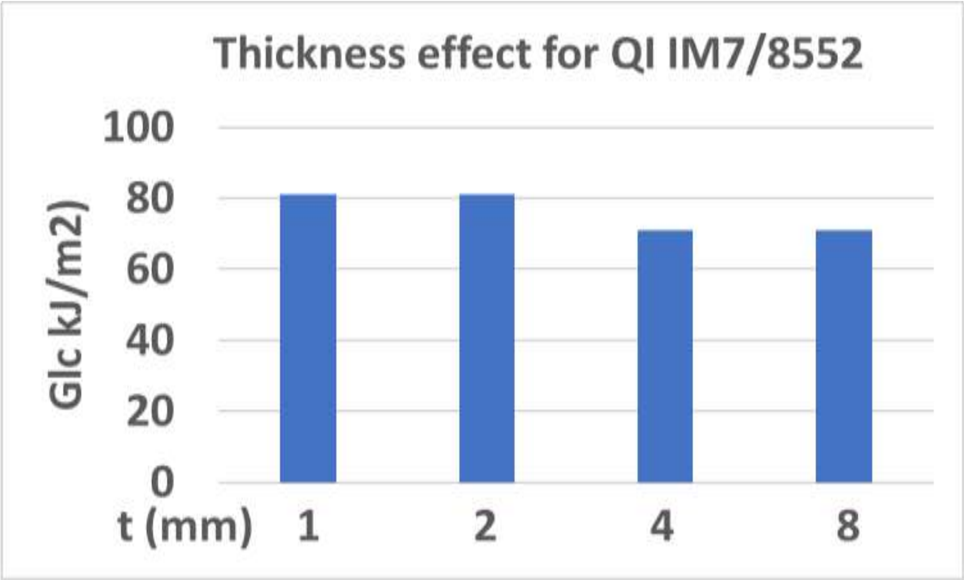


Li et al, 2009

- Gc also depends on absolute thickness

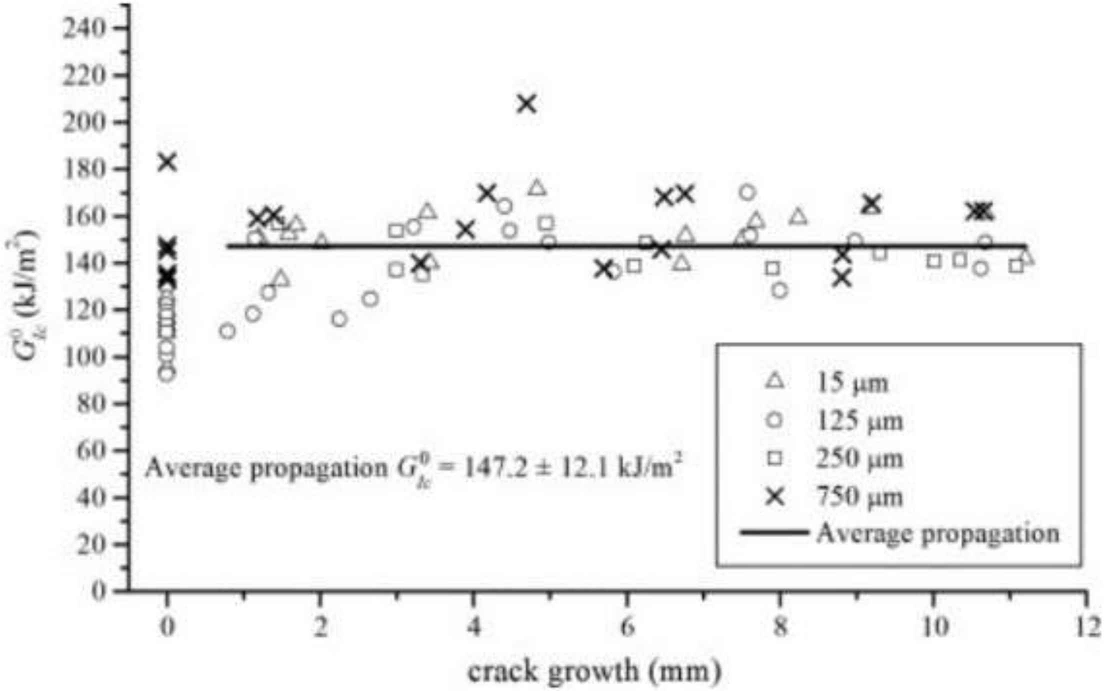
- Gc is a laminate NOT a ply property

Xu, Paul & Wisnom, 2019

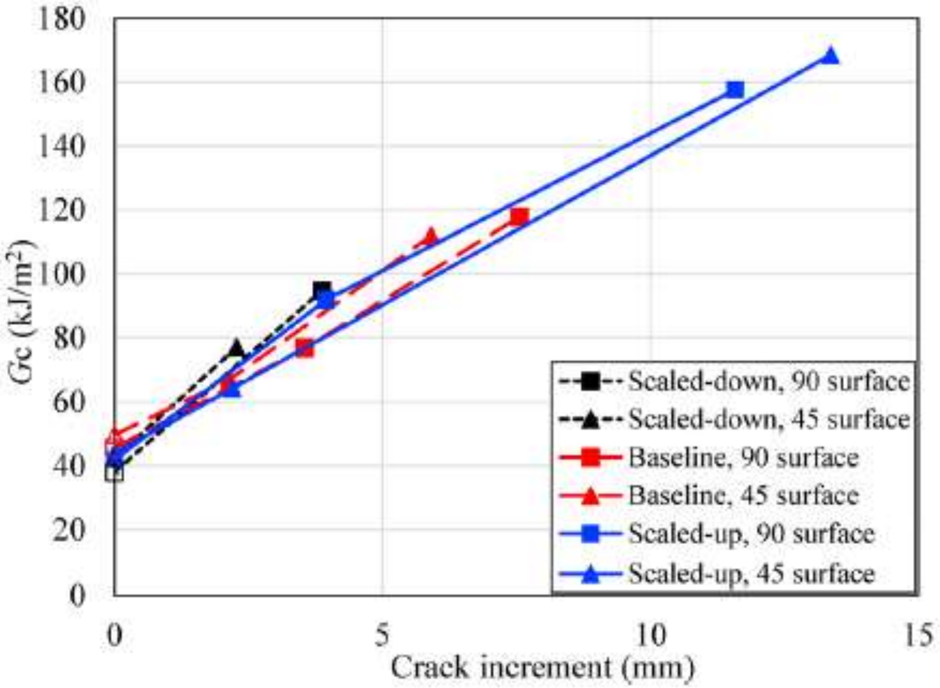


Glc – single value or R-curve?

Some data suggests a single value of laminate Glc is sufficient, but other results indicate a significant R-curve for IM7/8552



Laffan et al, 2011



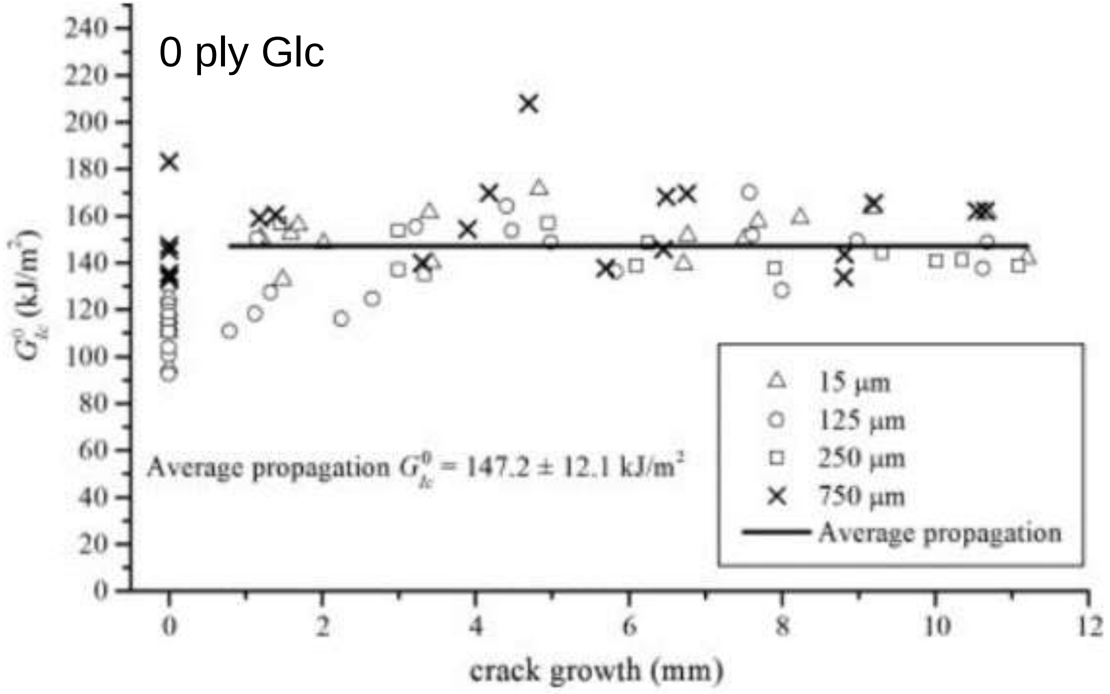
Xu et al, 2021

Effect of layup on R-curve

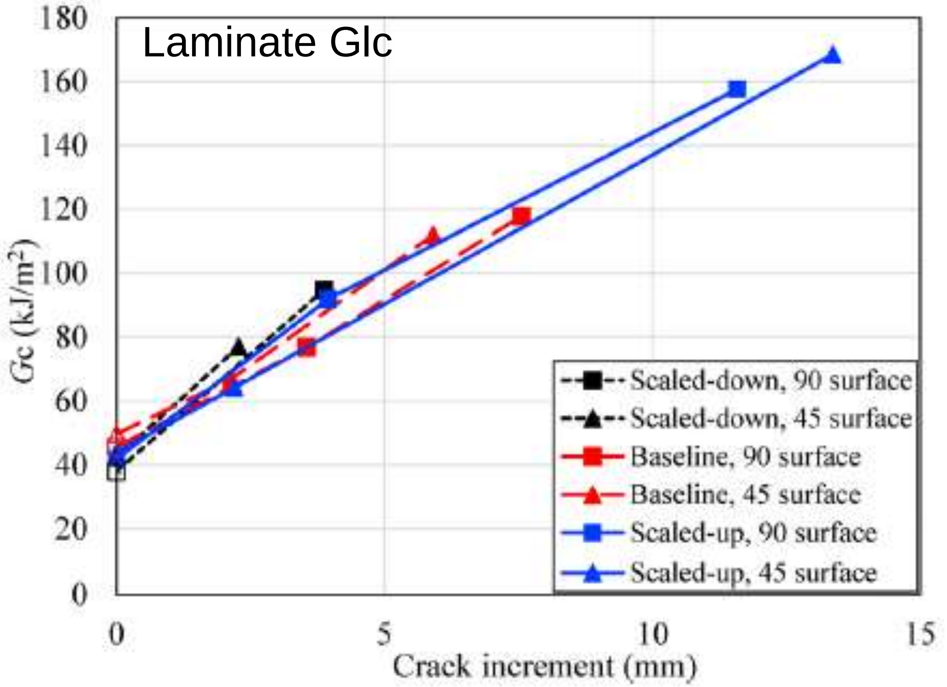
QI laminates show greater R-curve than CP for same IM7/8552

Growth of larger and more complex damage zone

$[(90/0)_8/90]_s$

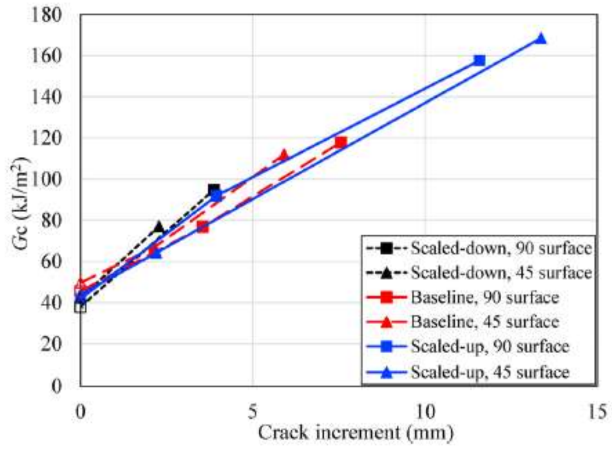


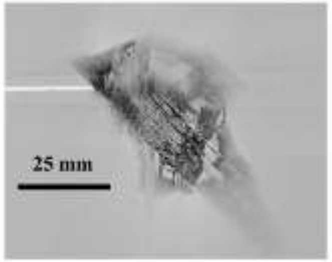
$[90/45/0/-45]_{4s}$ and $[45/90/-45/0]_{4s}$



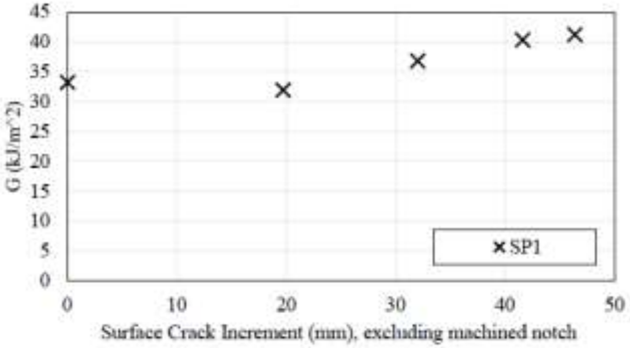
Thin plies show less R-curve

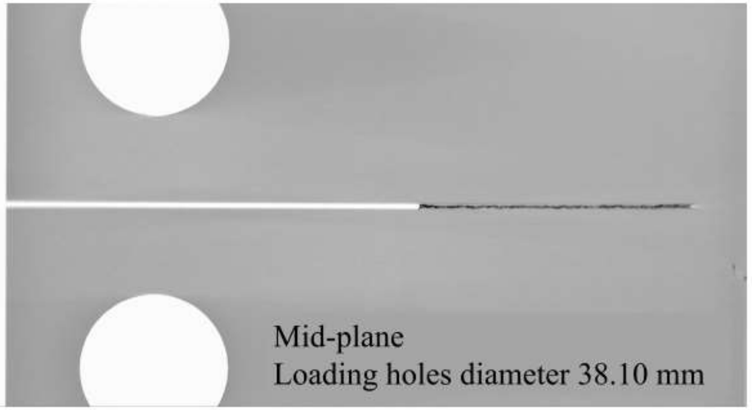
- IM7/8552 t_{ply}=0.125 mm
  $[90/45/0/-45]_{4s}$
  OCT, 416x212mm
- Large damage zone, substantial R-curve
- MR40/K51, t_{ply}=0.03 mm
  $[45/90/-45/0]_{16s}$
  CT, 183x191 mm
- Very sharp crack, little R-curve





Xu et al, 2021

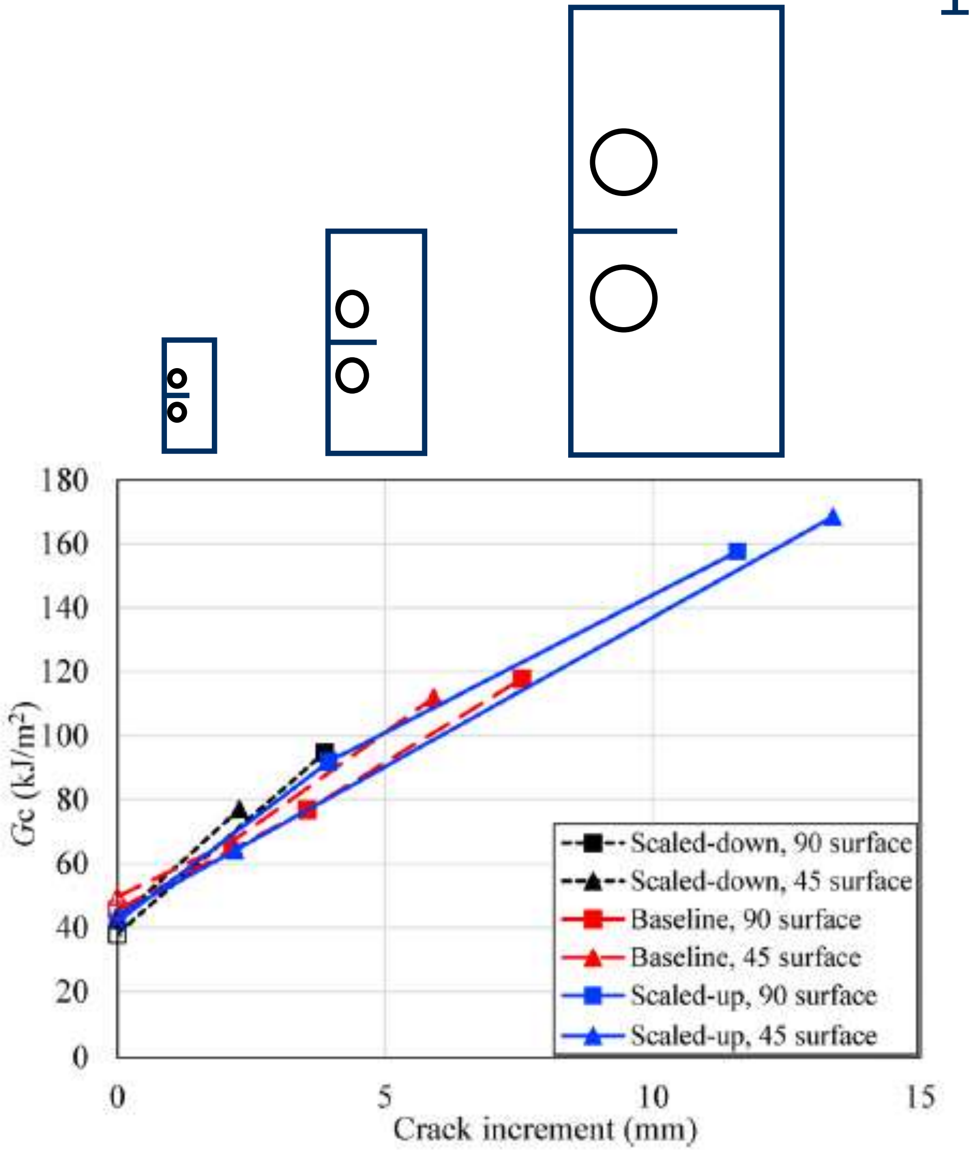




Sun, 2023

Measuring R-curves

- OCT reduces risk of compressive failure
- Tests on scaled OCT specimens
- 104x53, 208x106, 416x212 mm
- Linear increase in GIc continues as specimen size increases
- Even biggest specimen is too small!
- Increased risk of buckling



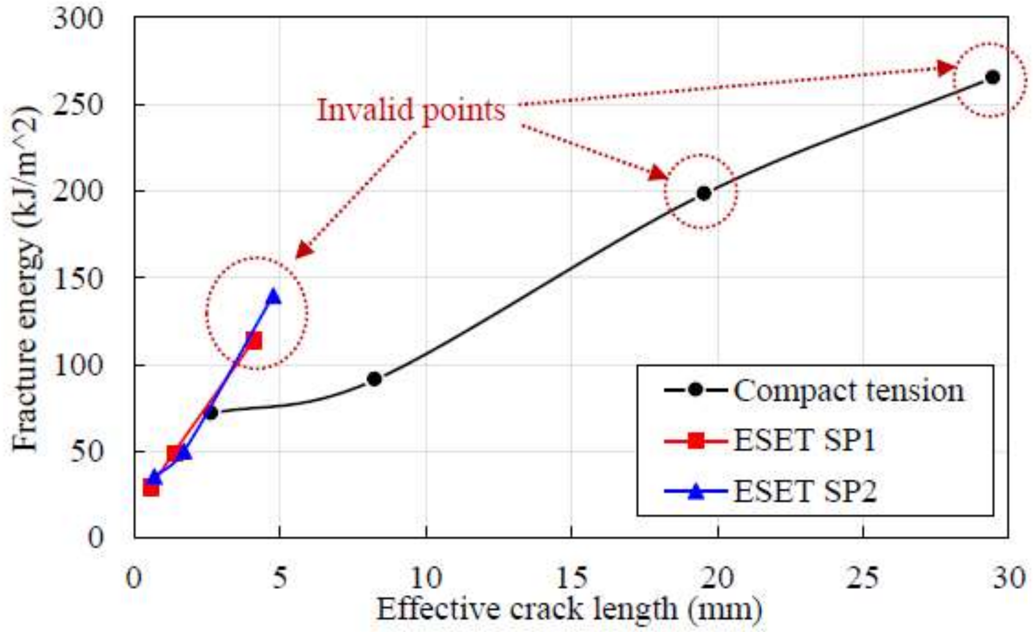
Xu et al, 2021

Validity of data reduction method

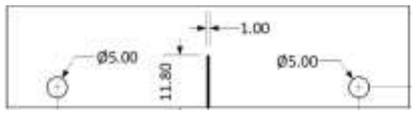
- GIc may be invalid if crack is too long compared to ligament width
- E.g. ASTM D5045 criterion:

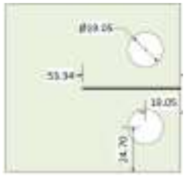
$$W - a > 2.5\left(\frac{K_{IC}}{\sigma_u}\right)^2$$

- Tests on QI NCF material give invalid points
- Risk of misinterpreting R-curve if invalid points are not omitted
- Needs further investigation



ESET



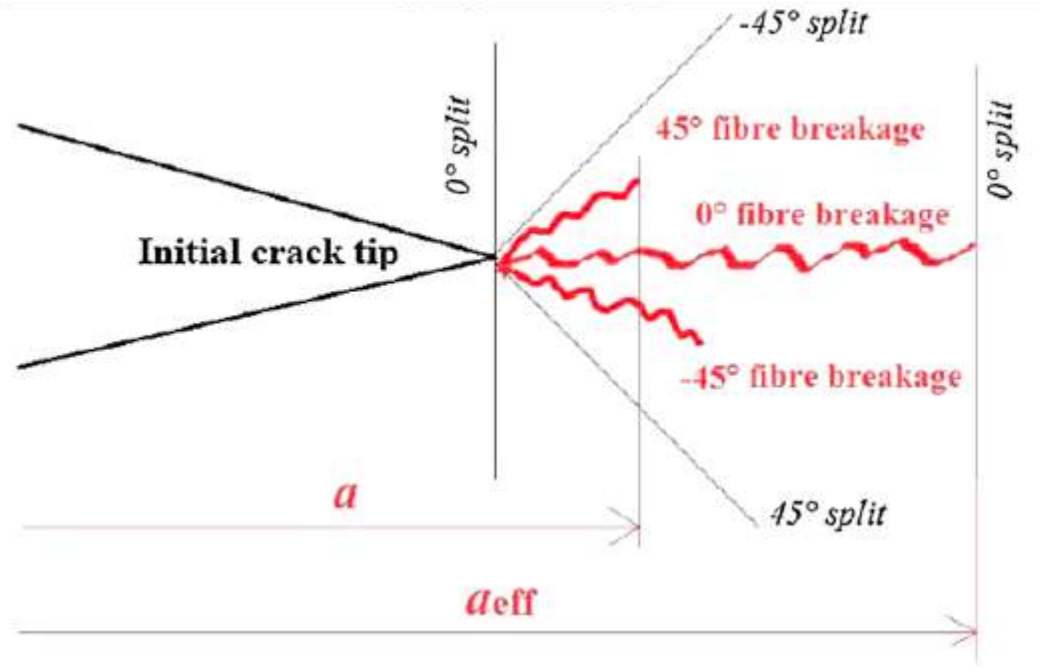


CT

Sun, 2023

What is the crack length?

- Complex damage, not sharp crack
- In QI, 0° plies break before 45s
- "Crack" length is when all plies broken
- Region with broken 0s is process zone
- Include process zone in effective length
- Analogous to plastic zone in metals

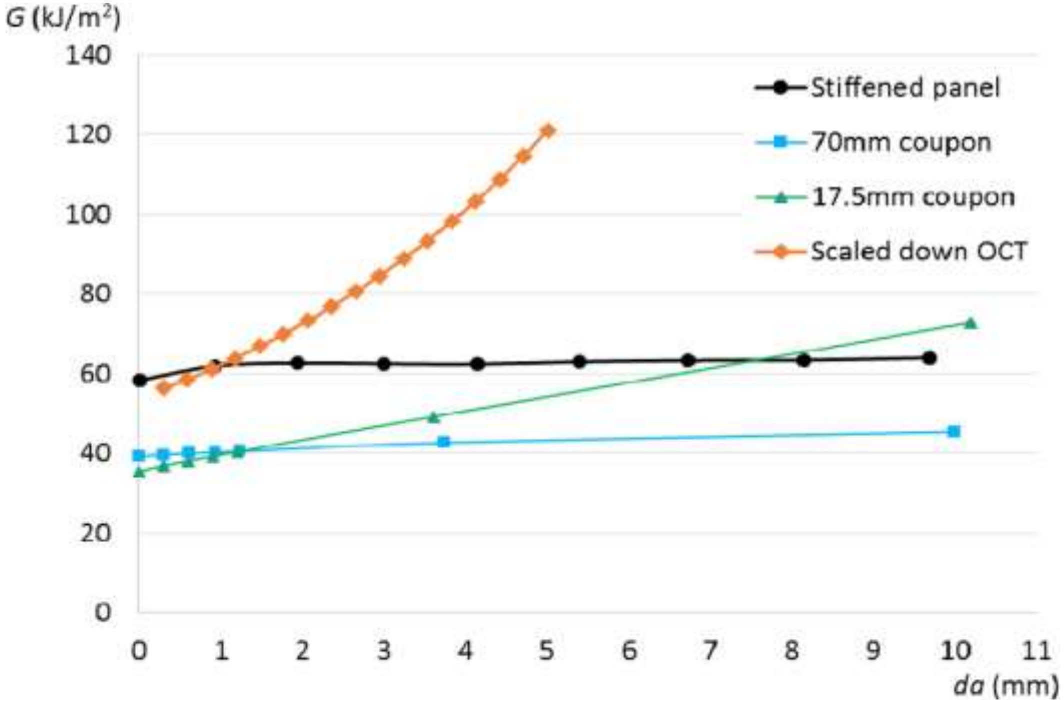


Xu, Wisnom & Hallett, 2019

Inconsistent results using initial crack length

- Four different specimens

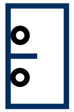
16mm	17mm	70mm	200mm
			
104x53	300x210	300x210	900x750mm



- G curves plotted at the experimental damage initiation loads
- Not consistent – very different G

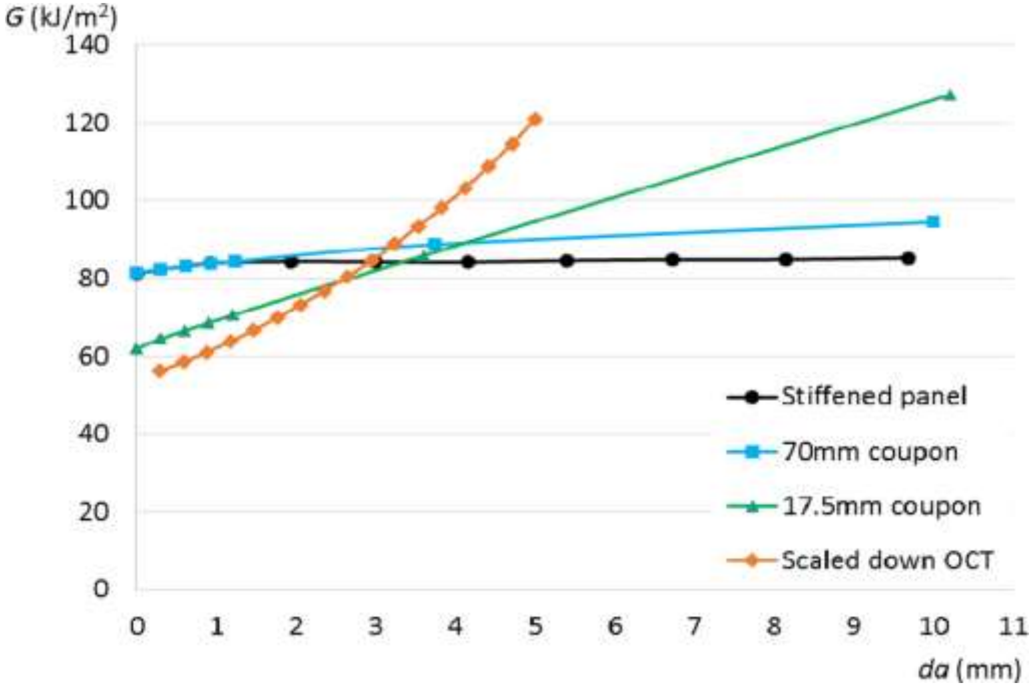
Consistent results when account for process zone

16mm **17mm** **70mm** **200mm**



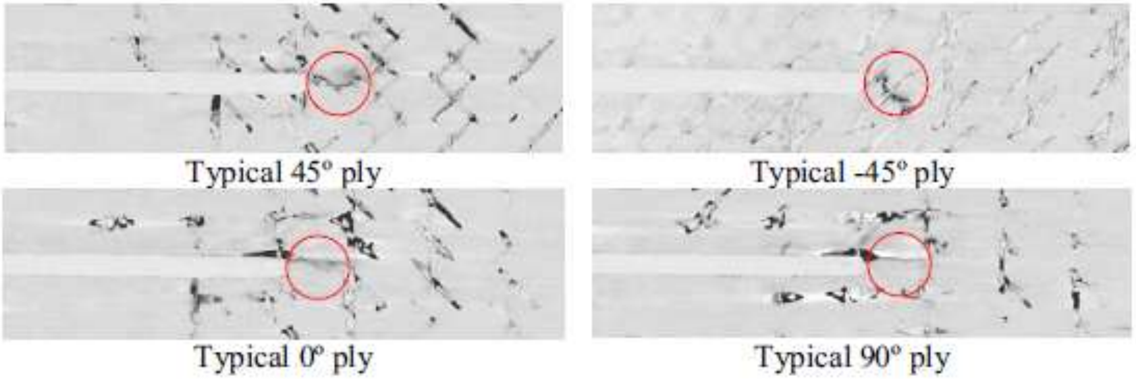

104x53, 300x210, 300x210, 900x750mm

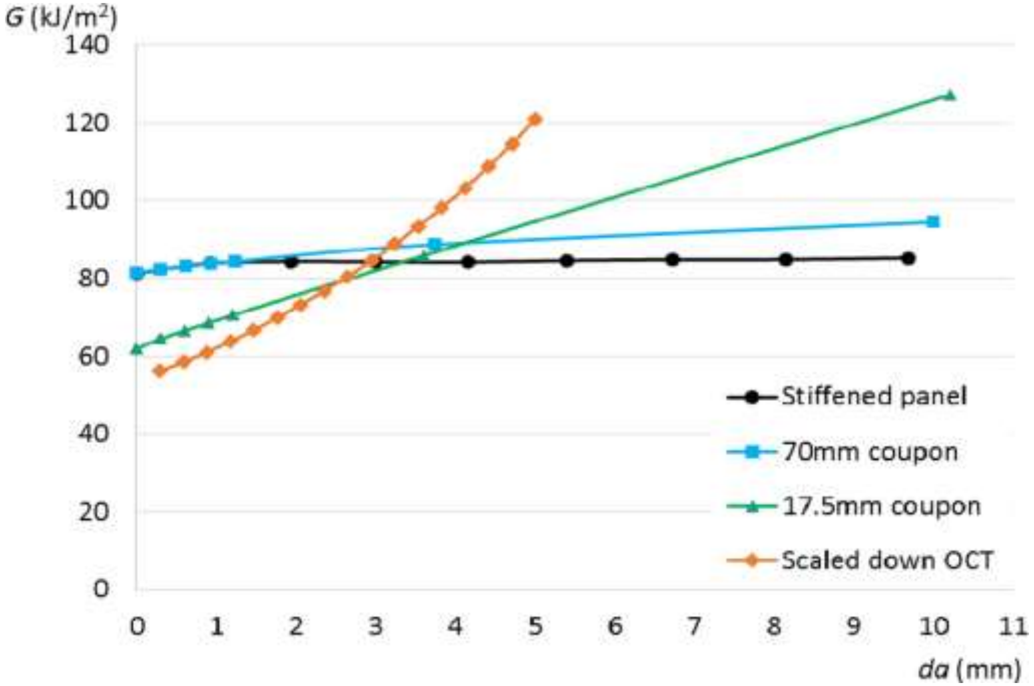
- G curves plotted at the initial damage propagation loads
- Based on failure of gauges at 5mm
- Now G values coalesce at 3mm
- Corresponds to fracture process zone size



Measurement of fracture process zone

- OCT test interrupted just after peak

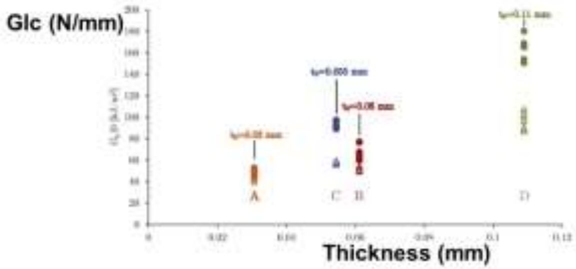


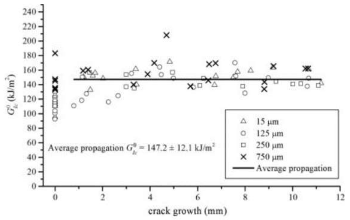


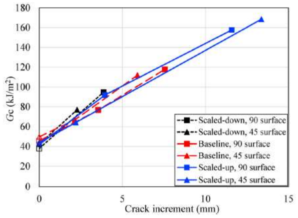
- Process zone of 3mm (red circle)
- Including process zone in effective crack length and G calculation gives consistent results for all four specimen sizes

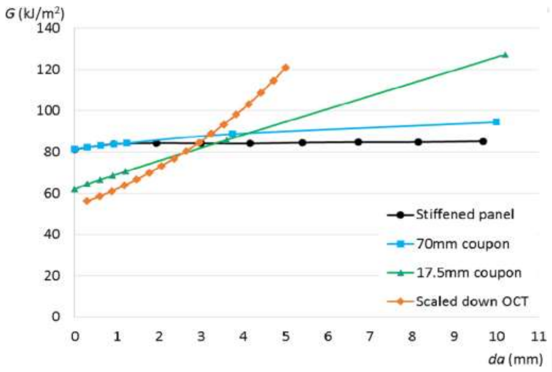
Conclusions

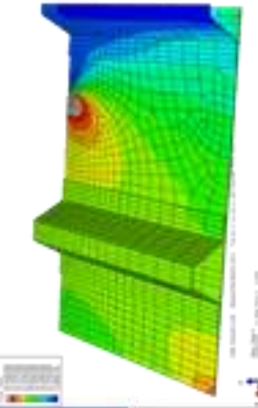
- Translaminar fracture toughness is a laminate not ply property
- Depends on layup, ply and absolute thickness
- R-curves also depend on layup
- Greater R-curve for QI and thick plies
- Need large specimens to measure full R-curve
- Consistent results by including fracture process zone in crack length and G calculation
- Enables LEFM prediction of structural response











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