University of BRISTOL

High-strain rate effects on open hole tensile strength of composites

– experimental and numerical results

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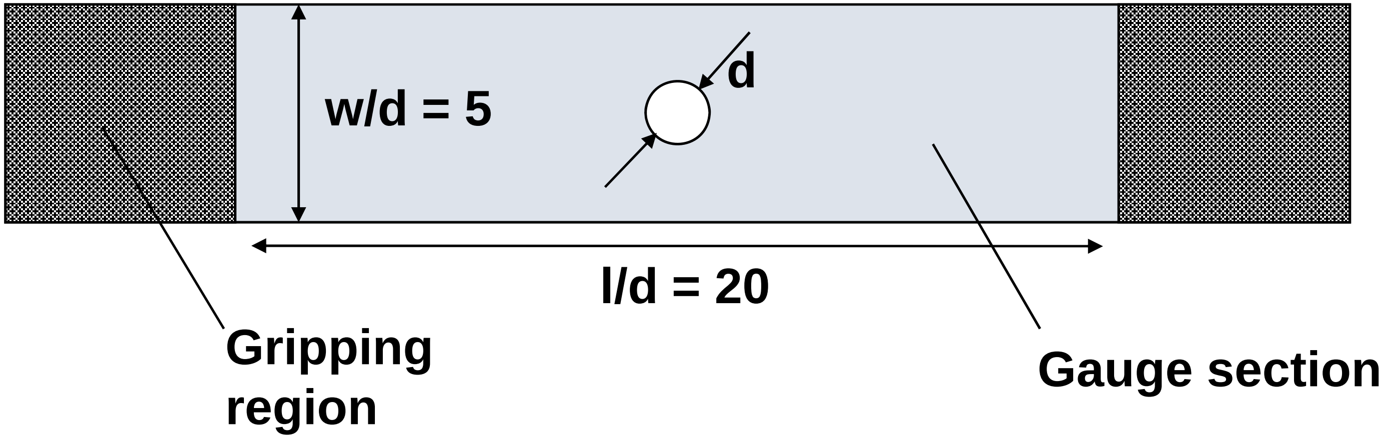
ADVANCED COMPOSITES CENTRE FOR INNOVATION & SCIENCE

Open Hole Tensile Testing

- Notched strength is an important design driver for design of composite components
- Extensive experience of open hole tensile testing at Bristol
- Initially aimed at understanding scale effects
- Lead to fundamental understanding of underlying failure mechanisms
- Finite element modelling approach developed to predict failure based on understanding and physical damage
- Desire to understand high strain rate behaviour of notched strength – does design remain conservative in this regime?
- Can modelling predict effects and reveal insights to failure

Experimental Overview

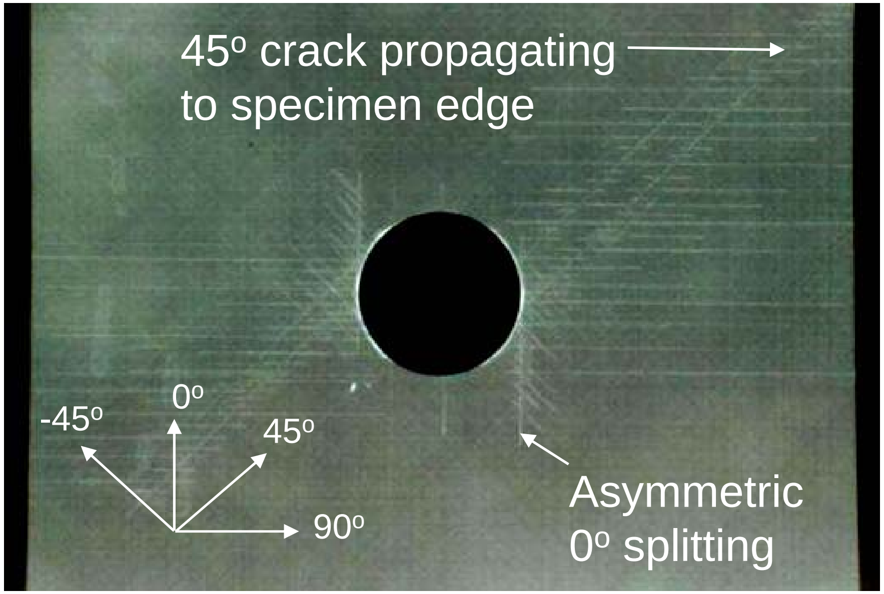
- Carbon fibre / Epoxy pre-preg system - IM7/8552
- 0.125mm/ply
- Baseline layup - Quasi-isotropic $[45/90/-45/0]_s$



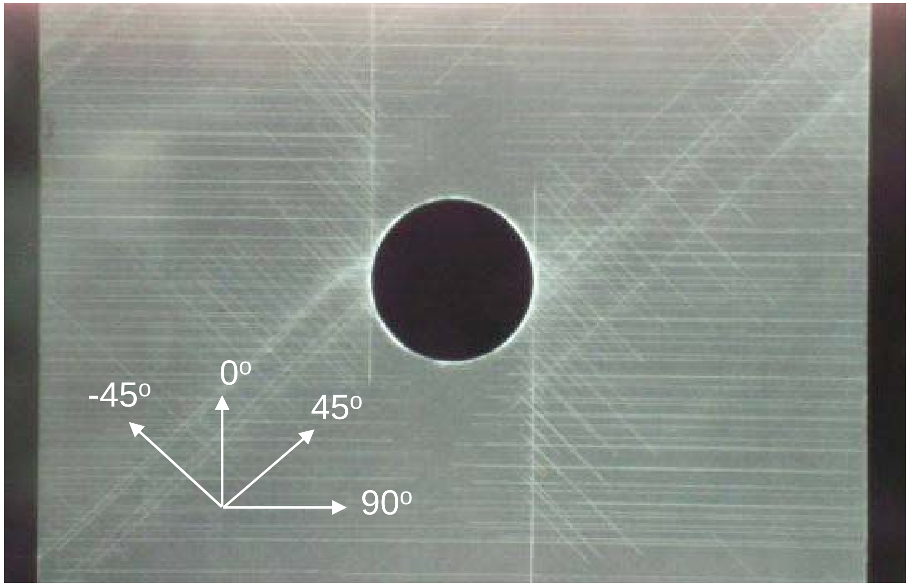
Quasi-static specimen geometry

Damage mechanisms in OHT

- Sub-critical damage develops at load levels well below final failure
- Splits form within the plies
- Starting at the hole edge, propagating in fibre direction
- Secondary cracks also occurs



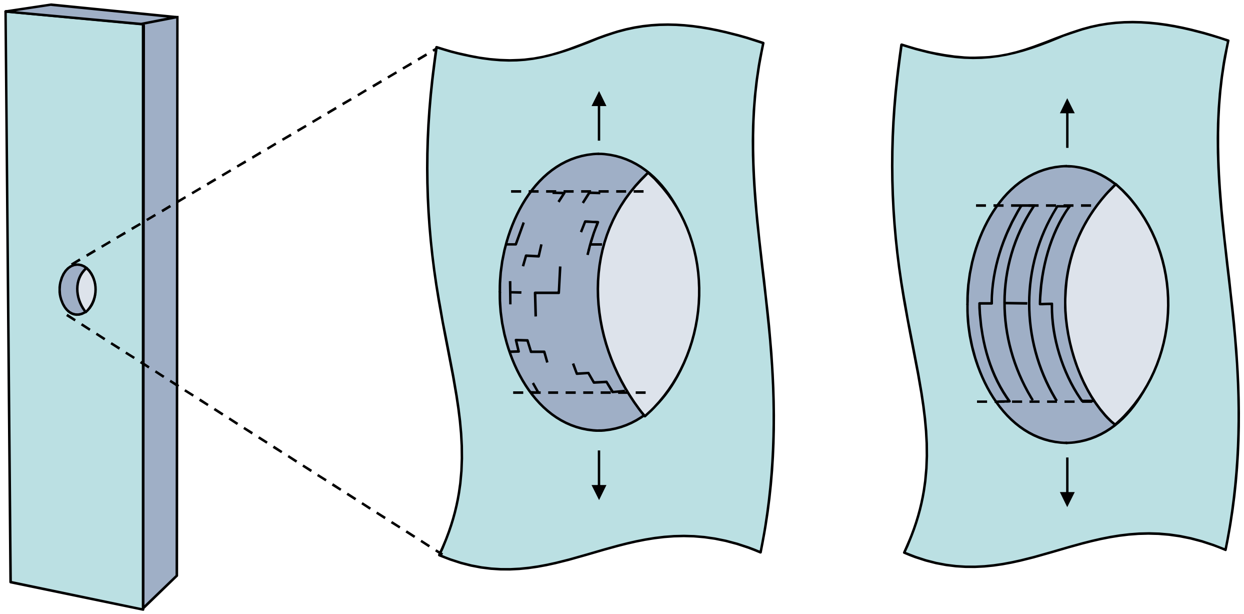
60% failure load

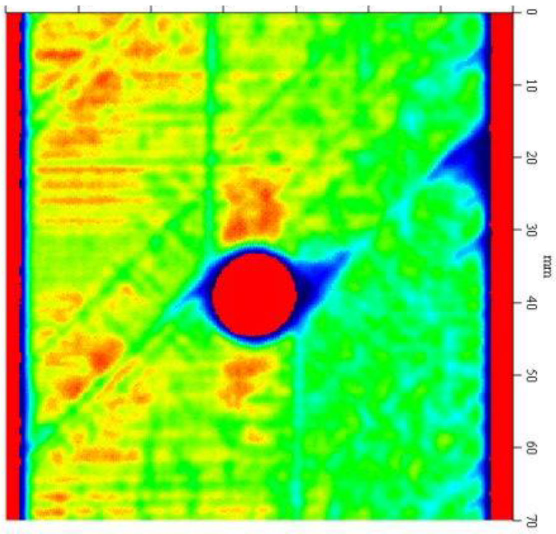


95% failure load

Damage mechanisms in OHT

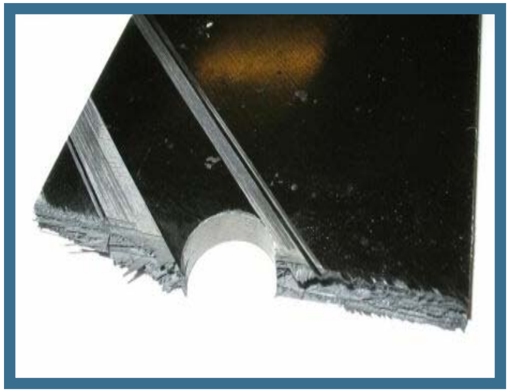
- Splits initially isolated
- Eventually join up, connected by delaminations
- Delaminations propagate across the width of specimen
- Cracks and delaminations also initiate and propagate from the free edge



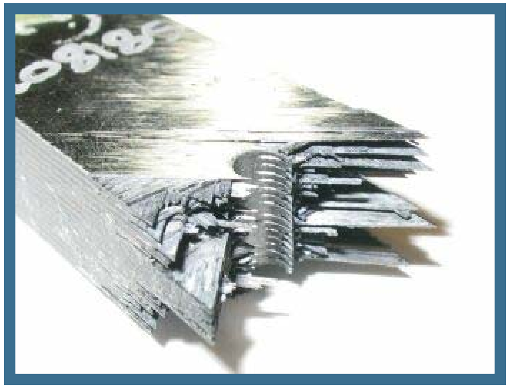


Damage mechanisms in OHT

- Fibre failure can occur at any point in this sub-critical damage process
- Dependant on the relative stress levels of each damage event
- Results in three significantly different failure modes



Brittle



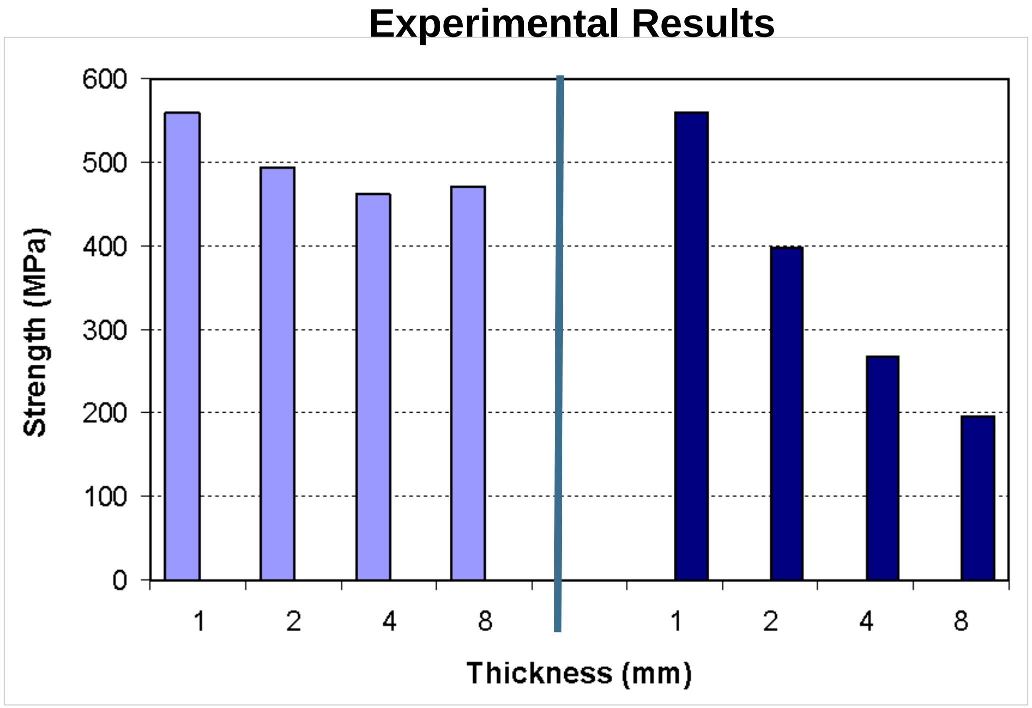
Pull-out

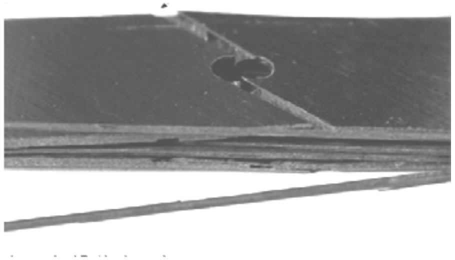
Delamination

Thickness (1D) Scaling

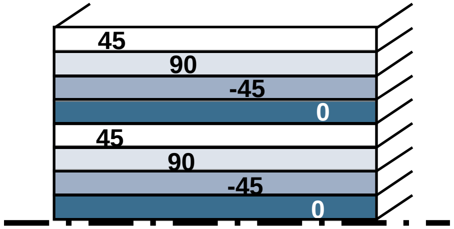
- 3.175mm diameter hole

Pull out



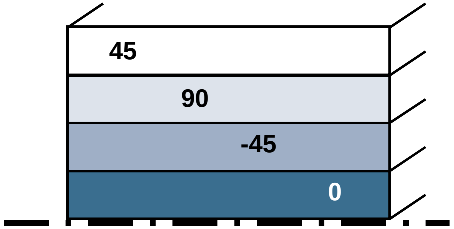


Predominantly delamination



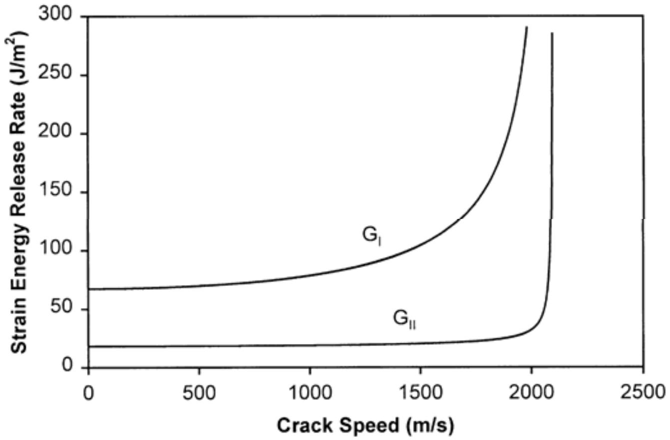
Sub-laminate scaled

Ply level scaled



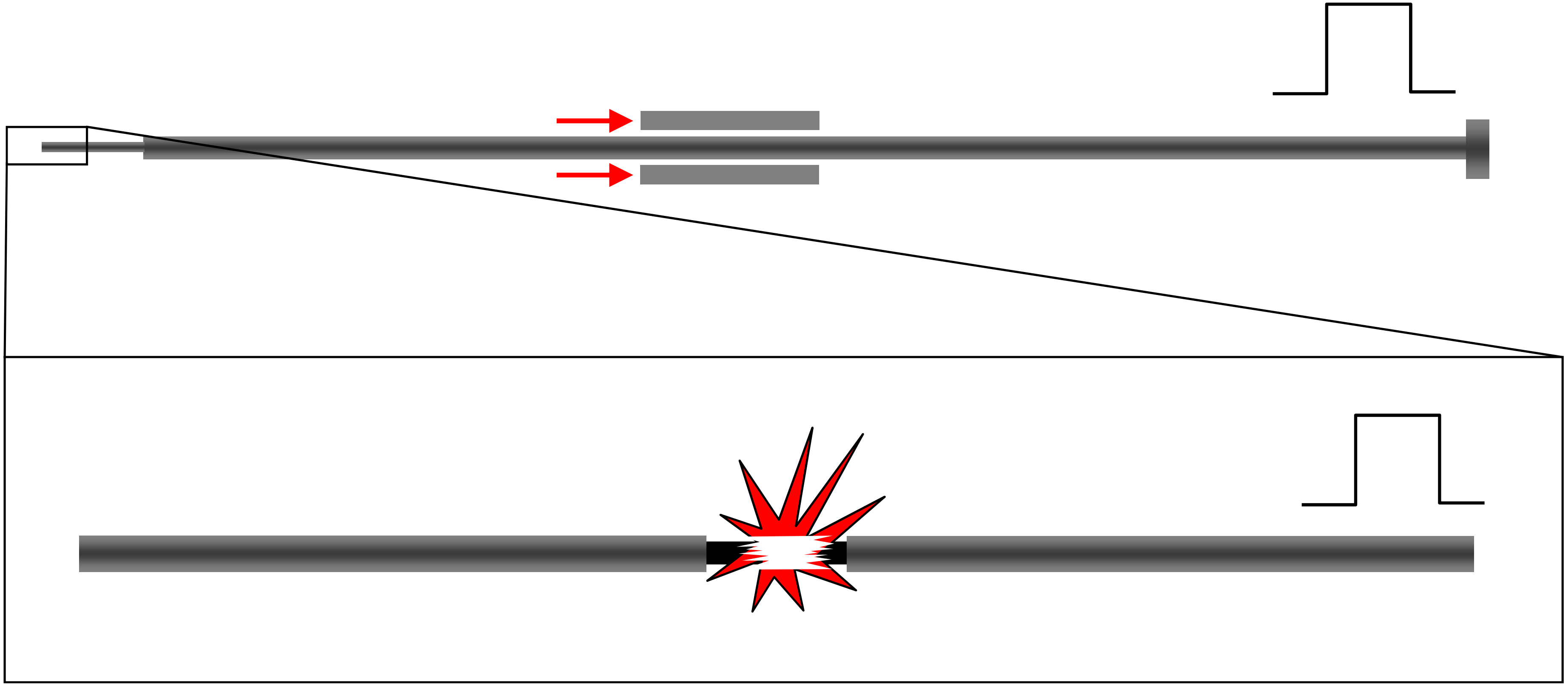
High Rate Effects

- It is clear that sub-critical damage affects the ultimate strength of open hole tension specimens
- Will the rate of damage be constant with increasing strain rate? And will this affect strength?
- Literature has shown variable results for effect of strain rate on interlaminar fracture toughness – a controlling parameter
- An increasing fracture toughness will reduce sub-critical damage and hence notched strength

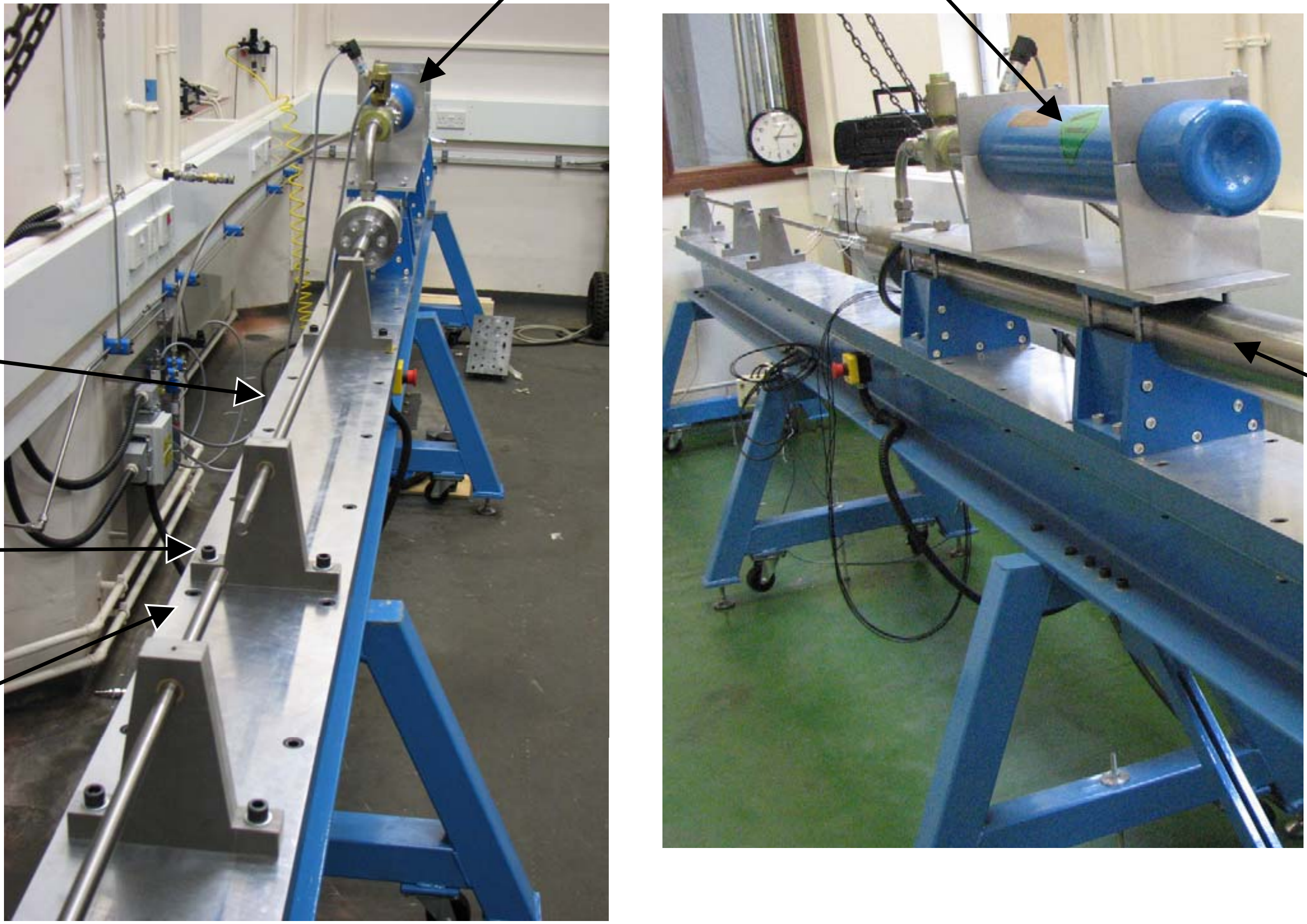


J.L. Tsai, C. Guo, C.T. Sun, Dynamic delamination fracture toughness in unidirectional polymeric composites, Composites Science and Technology 61 (2001) 87±94

Hopkinson Bar Operation

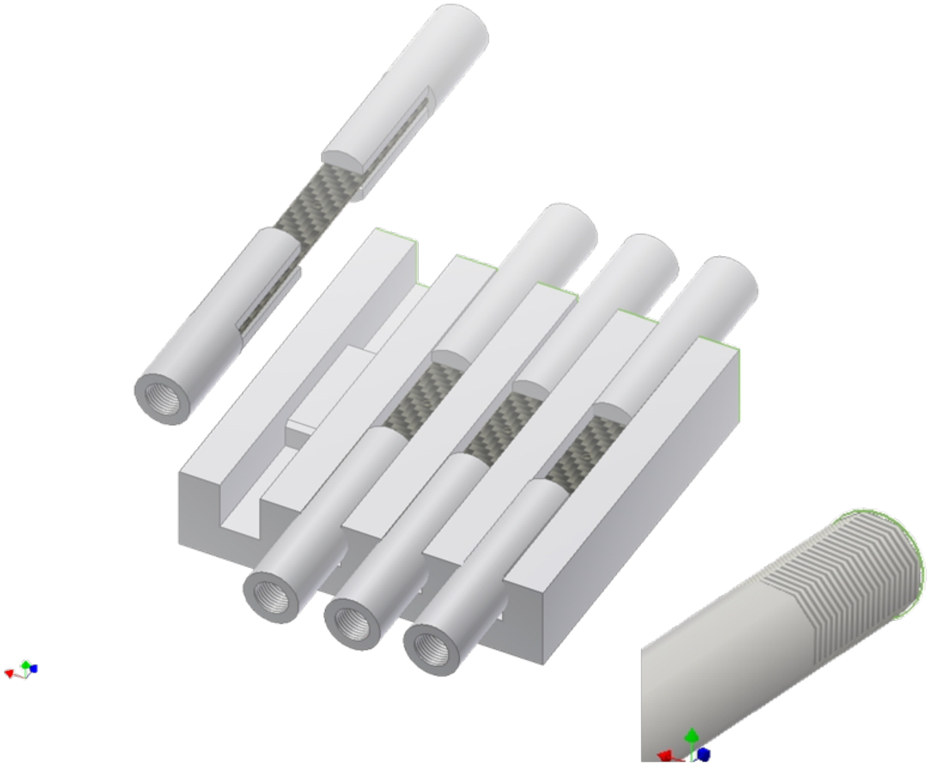


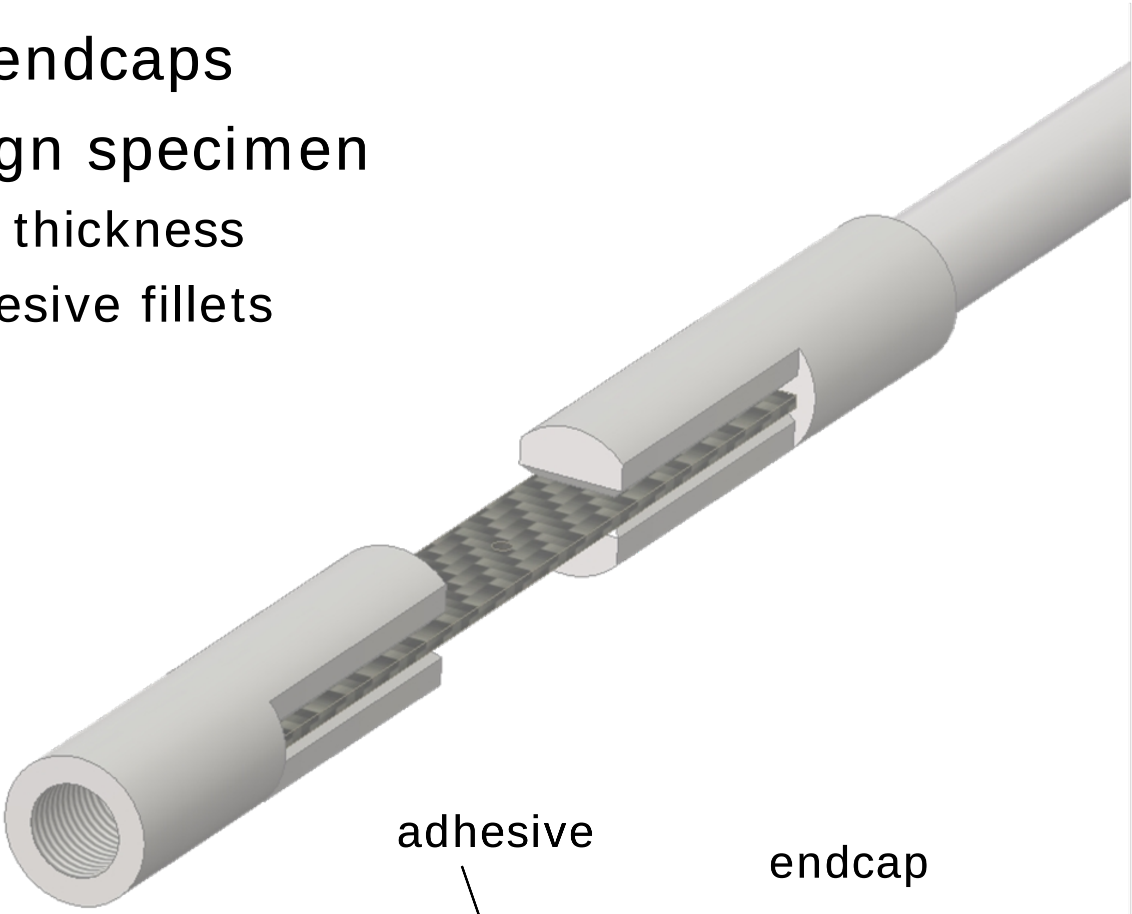
Hopkinson bar overview



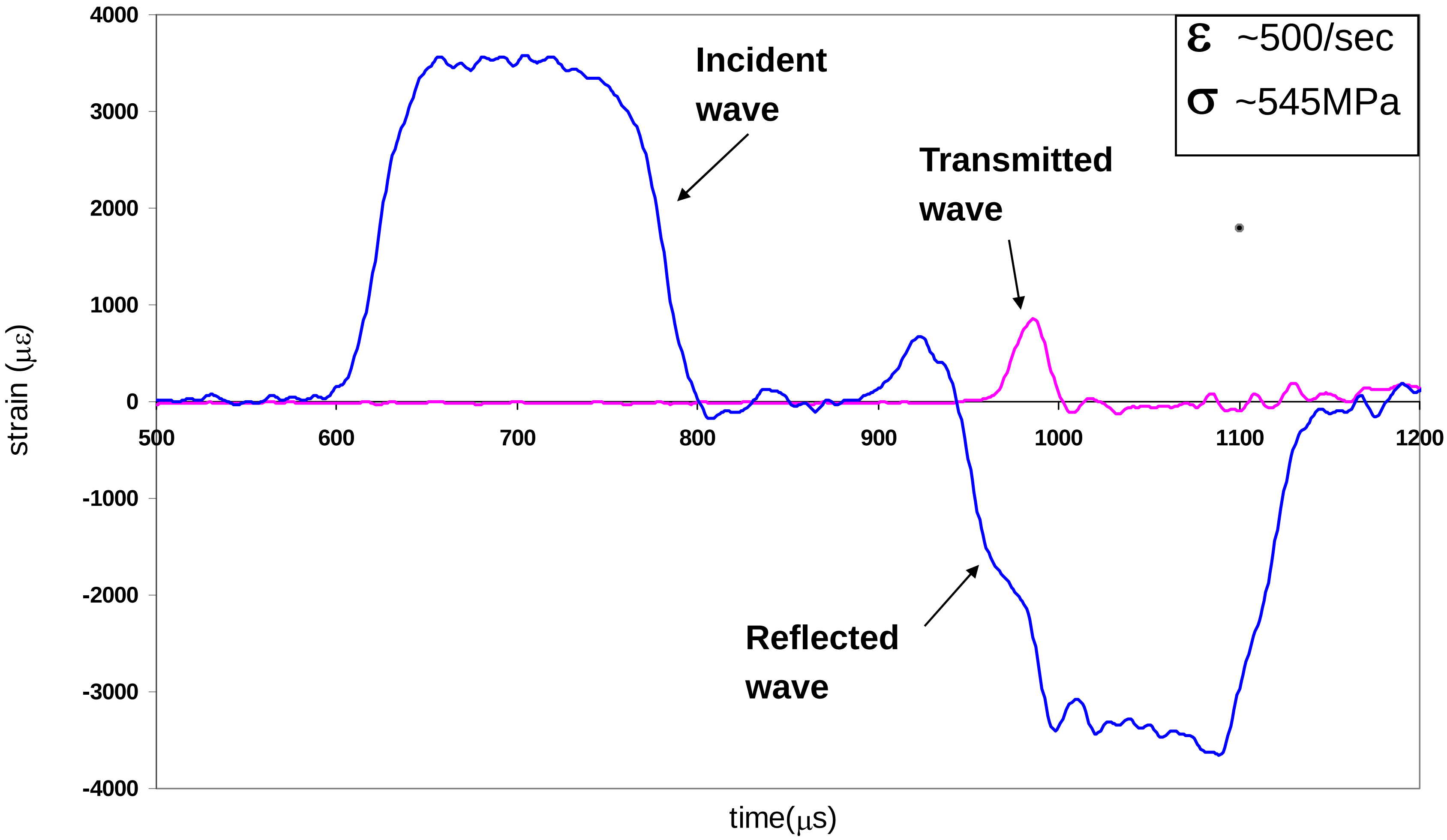
Specimen mounting

- Specimen is bonded into endcaps
- Special fixture used to align specimen
  - Ensures accurate bond-line thickness
  - Creates well controlled adhesive fillets





Typical wave pulse



Strain Rate Calcualtion

- Specimen's strain rate and stress can be calculated from the strains of the bars

1-wave model
(equilibrium)

$$\frac{d\varepsilon_{\mathrm{s}}}{dt} = -\frac{2C_{\mathrm{O}}}{L}\varepsilon_{\mathrm{R}}$$

$$\varepsilon_{\mathrm{s}}(t) = -\frac{2C_{\mathrm{O}}}{L}\int \varepsilon_{\mathrm{R}}\,dt$$

3-wave model
(no equilibrium)

$$\frac{d\varepsilon_{\mathrm{s}}}{dt} = -\frac{2C_{\mathrm{O}}}{L}\left(\varepsilon_{\mathrm{T}} - \varepsilon_{\mathrm{I}} + \varepsilon_{\mathrm{R}}\right)$$

$$\varepsilon_{\mathrm{s}}(t) = -\frac{2C_{\mathrm{O}}}{L}\int \varepsilon_{\mathrm{R}}\,dt$$

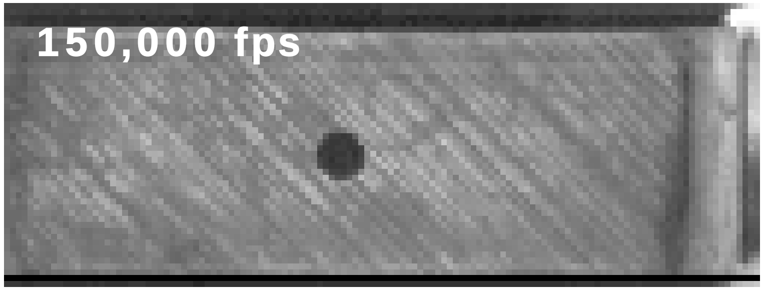
- Both calculations gave similar results
- This was cross-checked against readings from strain gauges mounted on selected specimens and direct optical measurement techniques

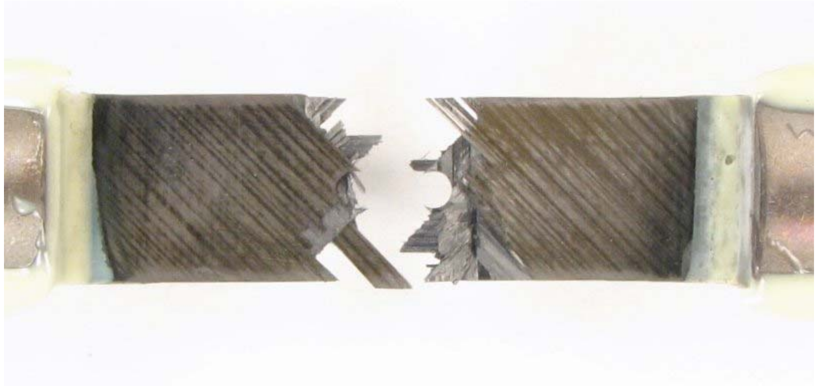
Experimental

	Strength MPa (CV)		
	1mm	**2mm**	
		Sublaminate	**Ply-level**
Static (~0.001/s)	**570** (7.69)	**500** (3.95)	**396** (5.18)
	Pull out	Pull out	Delamination
Dynamic (~500/s)	**271** (23.20)	**409** (23.84)	**470** (19.46)
	Pull out	Pull out	Delamination

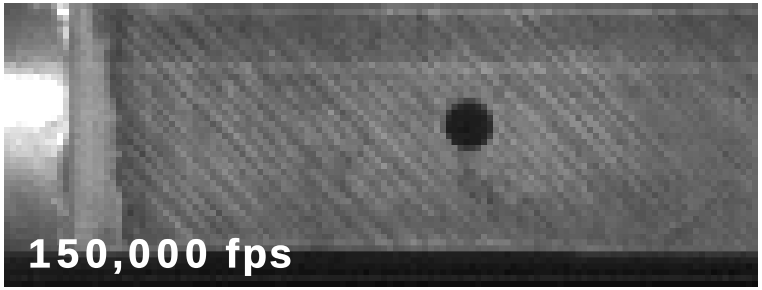
Failure process

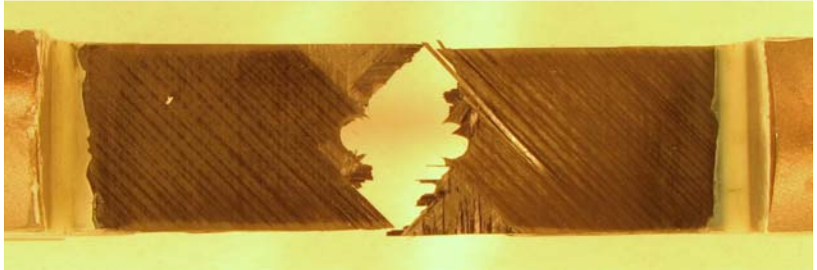
1mm baseline



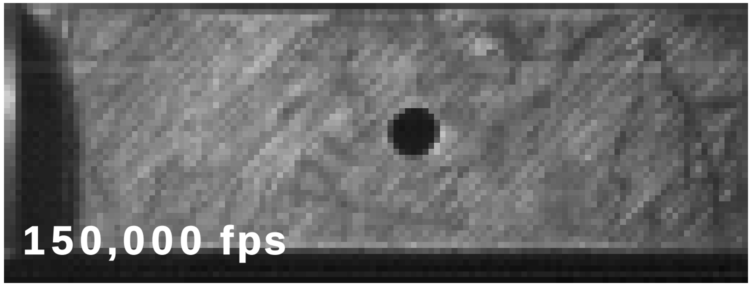


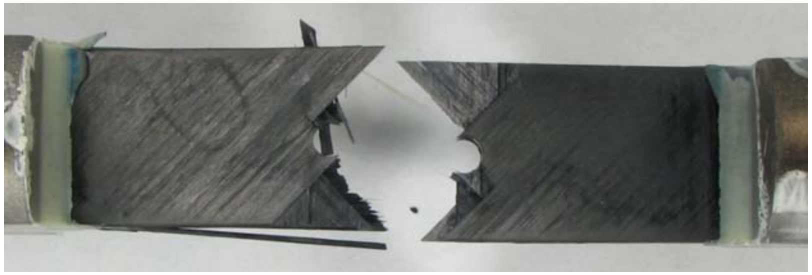
2mm sub-laminate level scaled





2mm ply level scaled





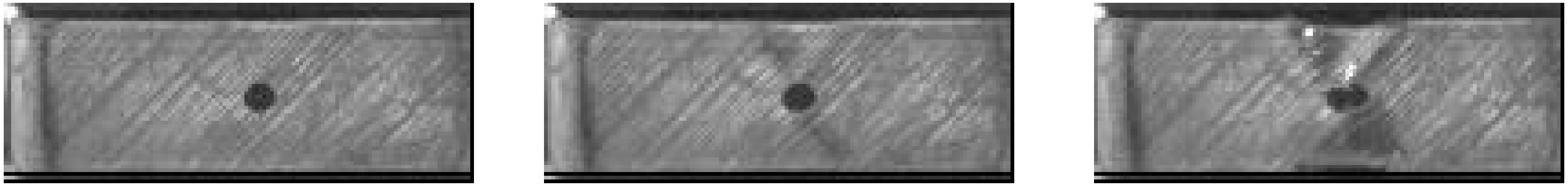
Failure process

1mm baseline

1st crack

Full-width crack

Separation



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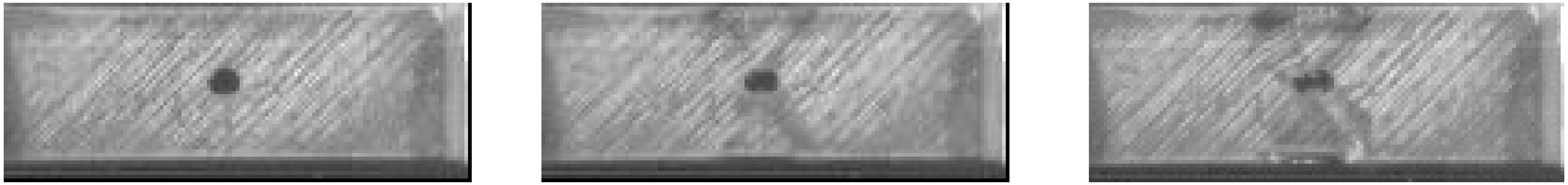
2mm sub-laminate level scaled



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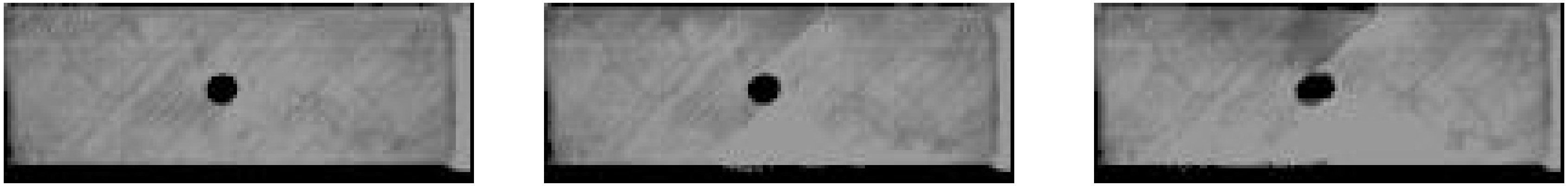
2mm ply level scaled



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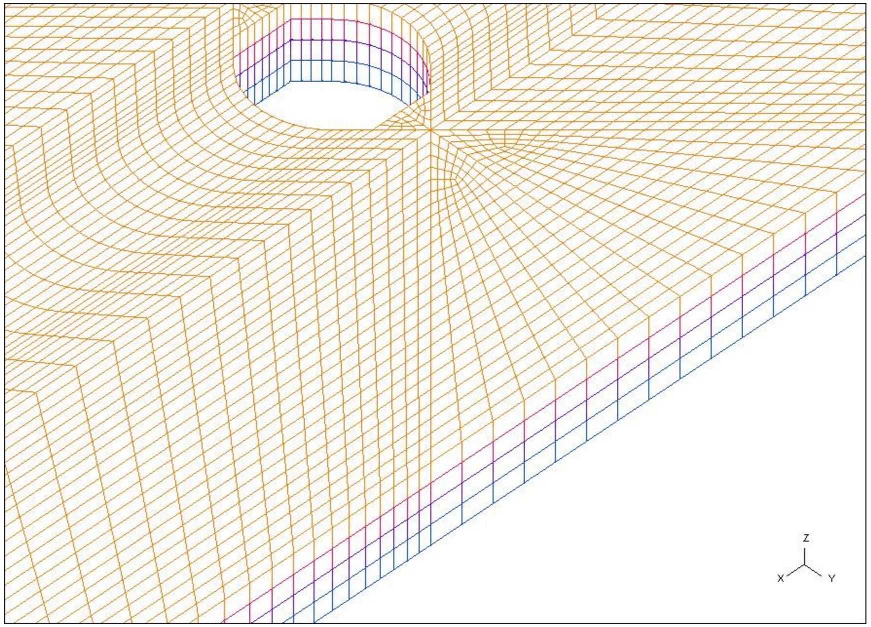
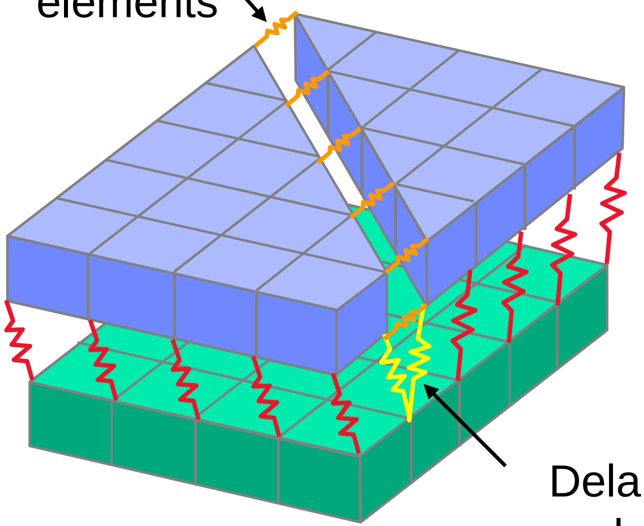
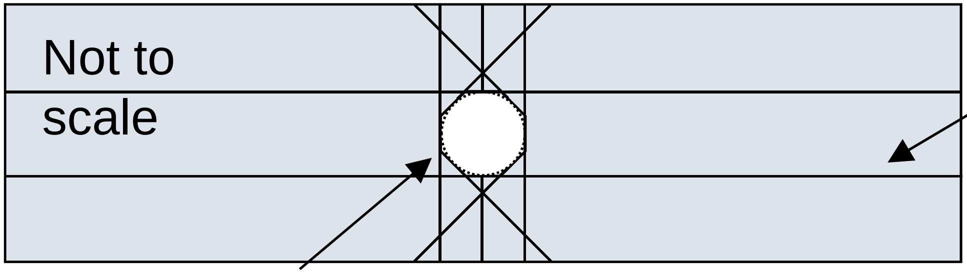
Modelling Approach



LS-Dyna



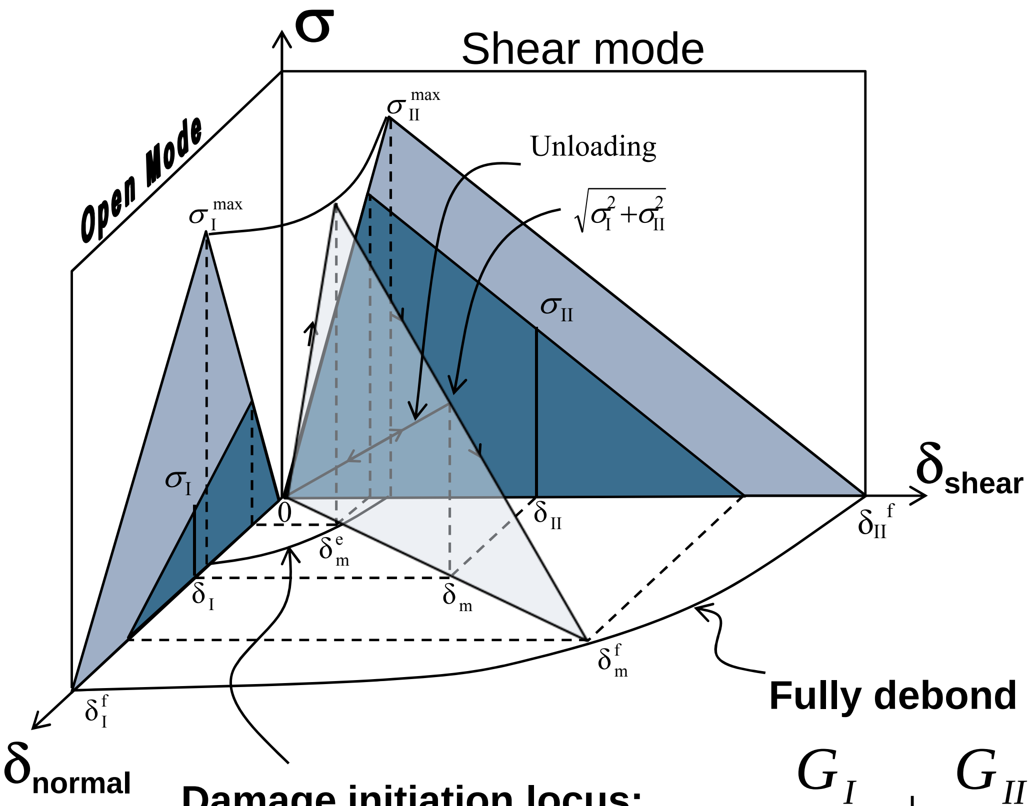


Lines show the splits within plies (superimposed) introduced in the FE model

The small degenerated areas are neglected to avoid small degenerated element, thus the hole is approximated as an octagon

Interface Elements

- Assume a linear elastic traction-separation law prior to damage
- Quadratic stress criterion for damage initiation
- Fracture energy based failure criterion
- Damage process is a progressive degradation of the material stiffness



Fully debond locus:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIc}} = 1$$

Damage initiation locus:

$$\left(\frac{\max(\sigma_I, 0)}{\sigma_I^{max}}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_{II}^{max}}\right)^2 = 1$$

Fibre Failure

Weibull strength theory:

- For two tests on different specimens, for equal probability of survival, the following equation can be derived:

$$\int_{V_1} \sigma^m \cdot dV = \int_{V_2} \sigma^m \cdot dV$$

where *m* is Weibull modulus

- For simplicity, we can choose the UD test as a reference state, then we have

$$\sigma_0{}^m V_0 = \int_V \sigma^m \cdot dV$$

- From UD tests on IM7/8552, we have m=40.1 and σ_0=3131MPa for 1mm^3 volume material

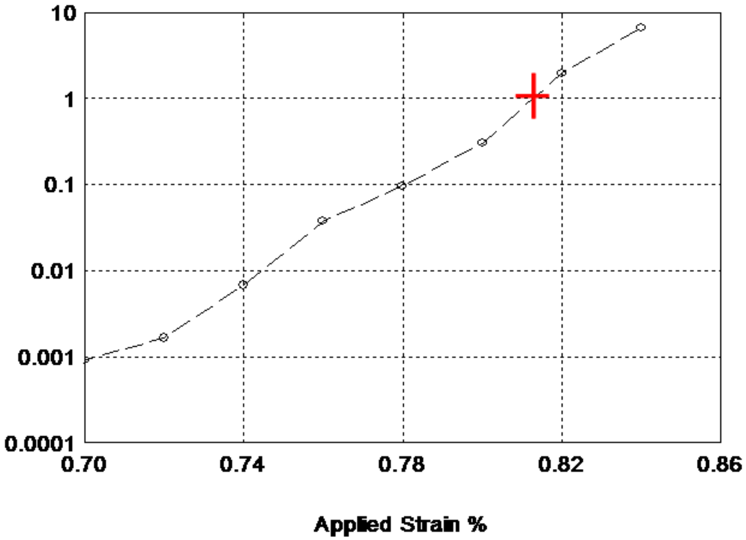
Implementation of Weibull theory in FEA

- A post-processing procedure has been performed to find the critical fibre failure stress level to satisfy the Weibull equation
- Using the discrete form:

$$\int_V \sigma^m \cdot dV = \sum_{i=1}^{overall\,elements} \sigma_i^{\,m} V_i \quad \geq \quad \sigma_0^{\,m} V_0$$

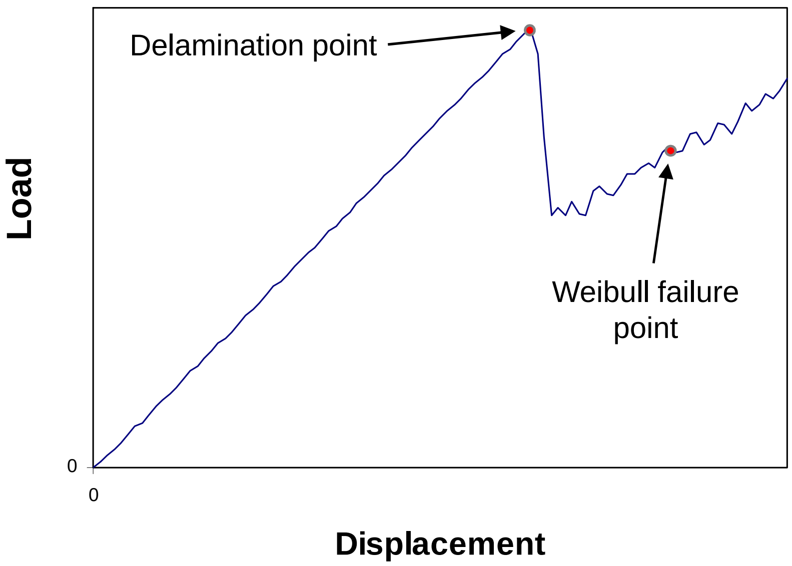
Sample plot of

$$\int_V \sigma^m \cdot dV \Big/ \sigma_0^m V_0$$

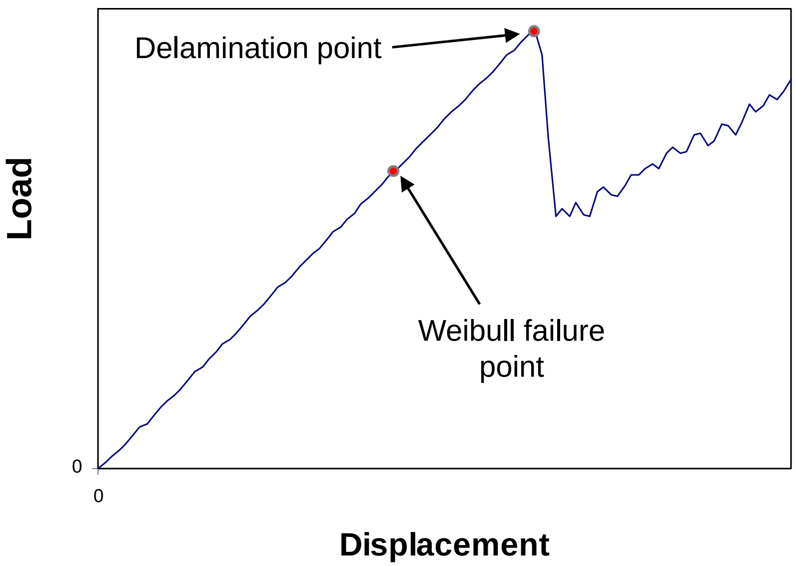


Discrimination of Failure Mode

Delamination Failure



Brittle or Pull-out Failure

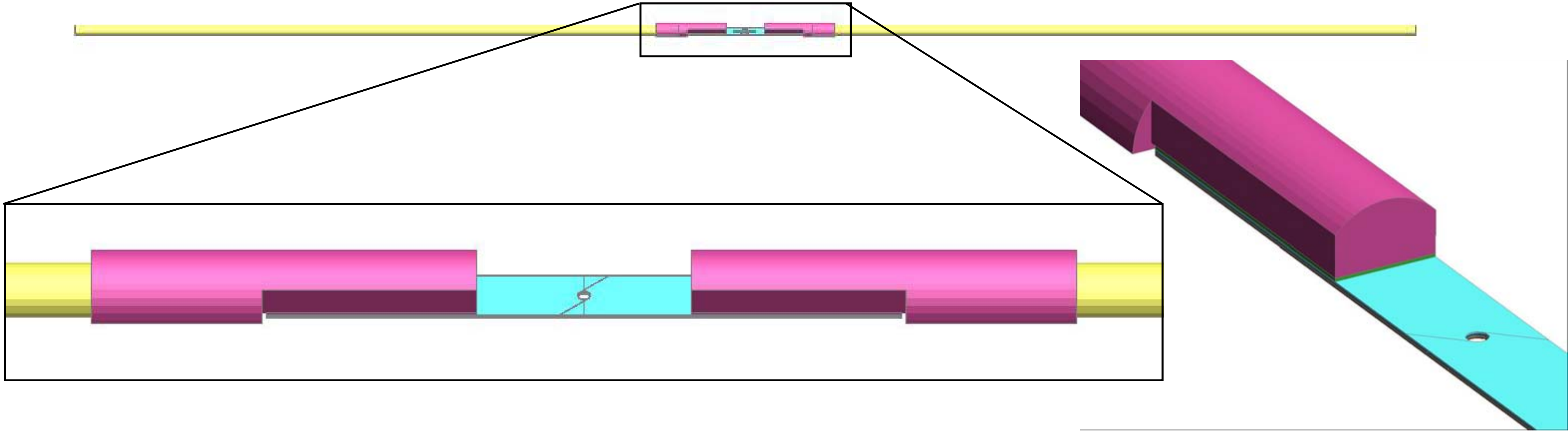


Significant delamination occurs before Weibull failure criterion is met

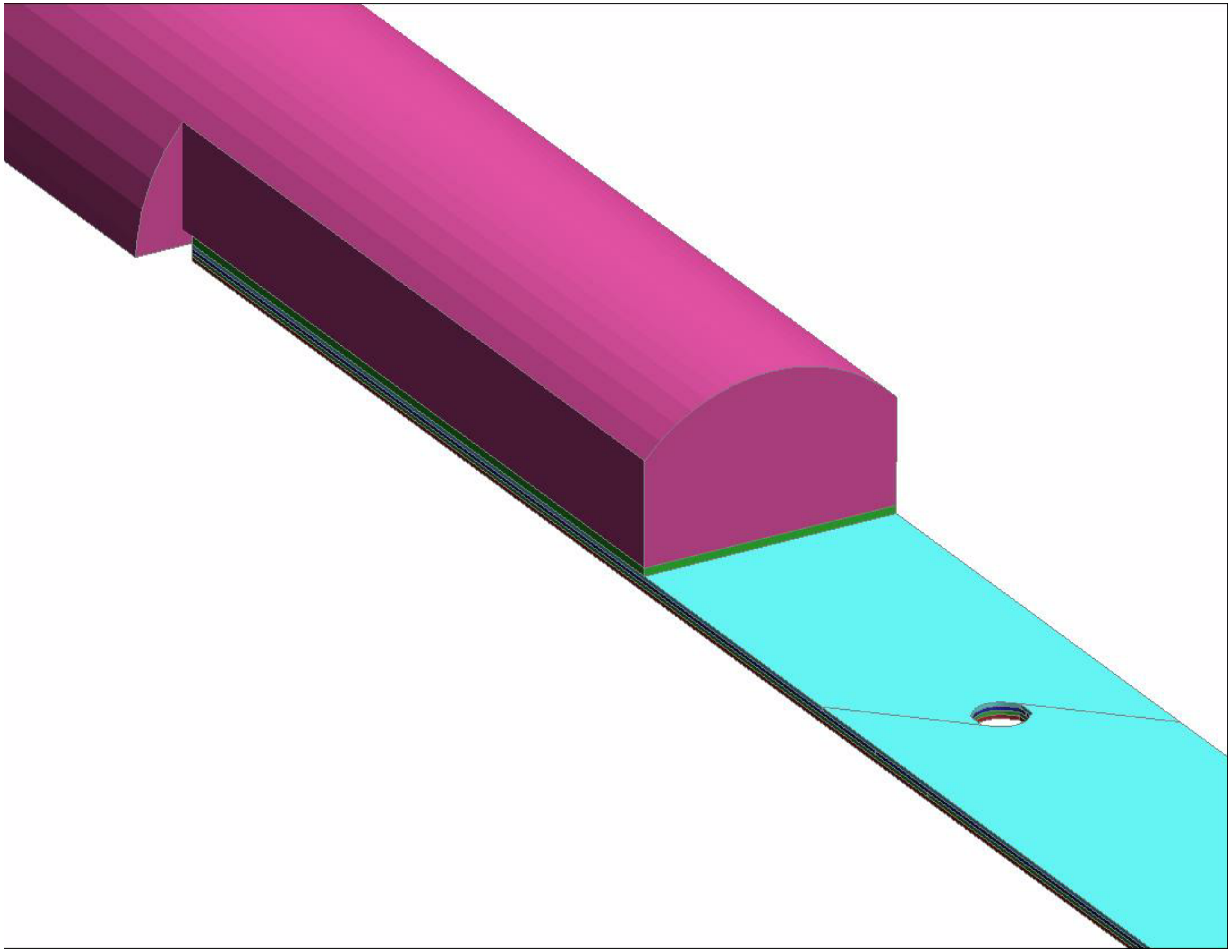
Weibull failure criterion is met before significant delamination occurs

Analysis

- For static analysis good correlation with experimental results has been obtained
- For dynamic analysis it is necessary to include the input and output bars for correct modelling of dynamic wave propagation
- This has included explicitly modelling the end caps and adhesive layer



2mm Ply Level Scaled

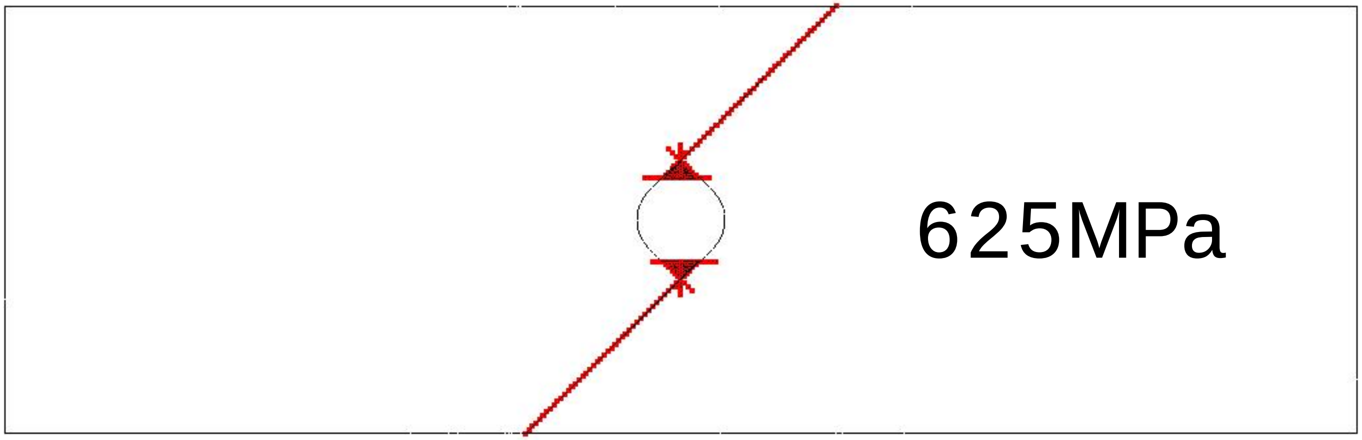


Test vs. Analysis

	Strength MPa (CV)					
	1mm		**2mm**			
			Sublaminate		**Ply-level**	
	Test	Analysis	Test	Analysis	Test	Analysis
Static (~0.001/s)	**570** (7.69)	**625**	**500** (3.95)	**500**	**396** (5.18)	**416**
	Pull out	Fibre	Pull out	Fibre	Delam	Delam
Dynamic (~500/s)	**271** (23.20)	**557**	**409** (23.84)	**496**	**470** (19.46)	**520**
	Pull out	Fibre	Pull out	Fibre	Delam	Delam

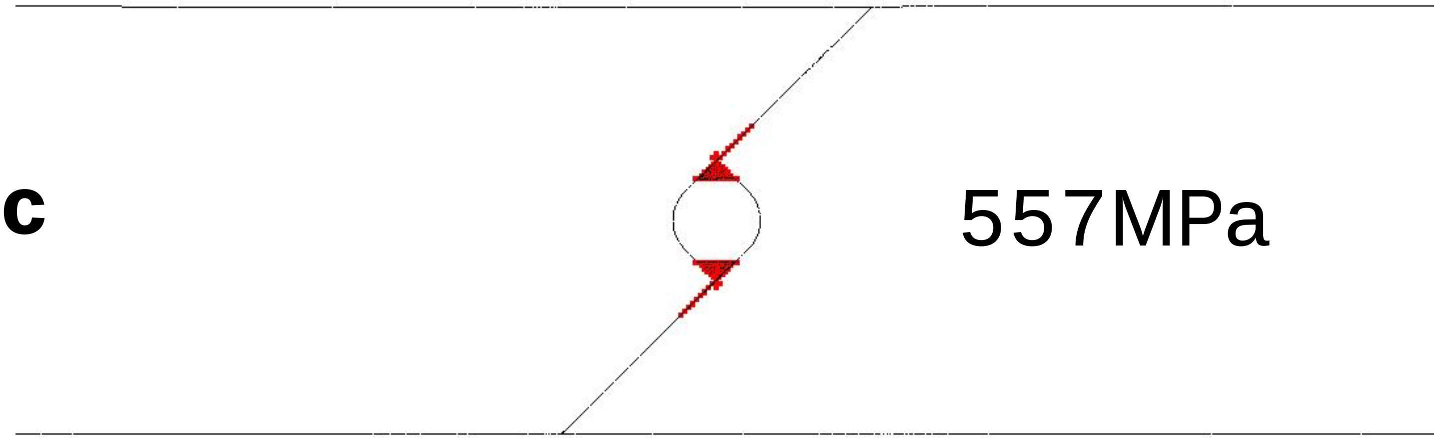
1mm – Splitting at failure load

Static



625MPa

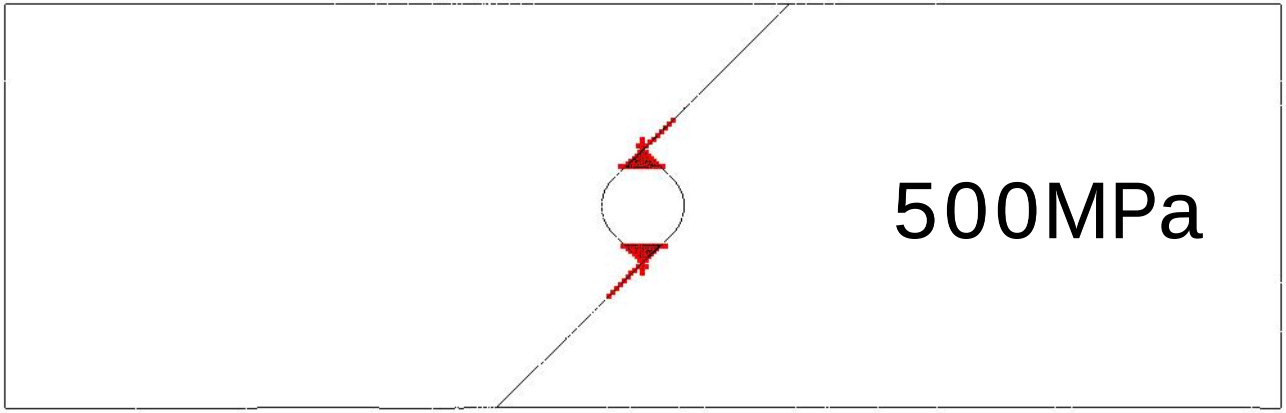
Dynamic



557MPa

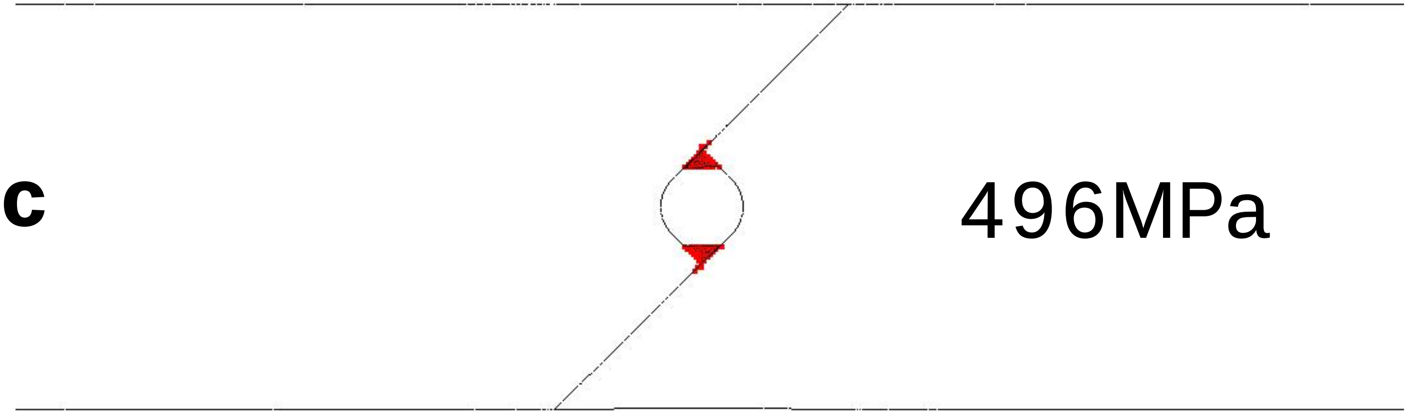
2mm Sublam. – Splitting at failure load

Static



500MPa

Dynamic

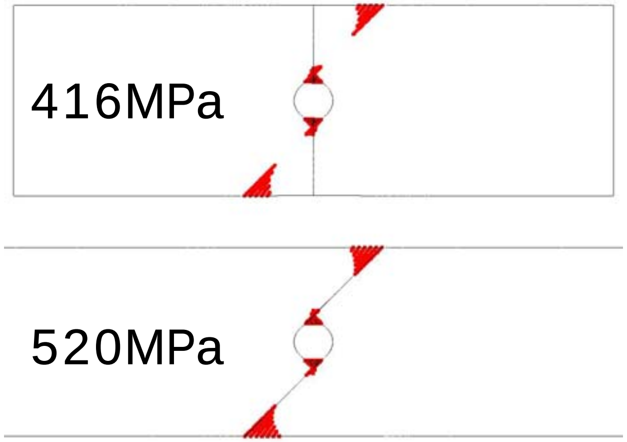


496MPa

2mm Ply Scaled– Delam. development

Delamination at max load

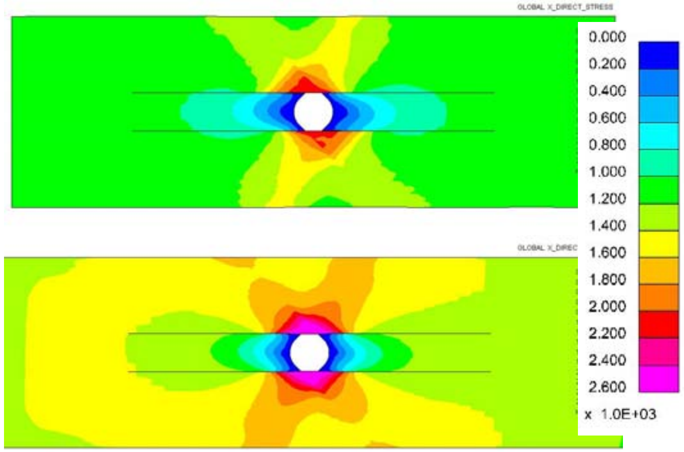
0° ply fibre dir. σ at max load


416MPa

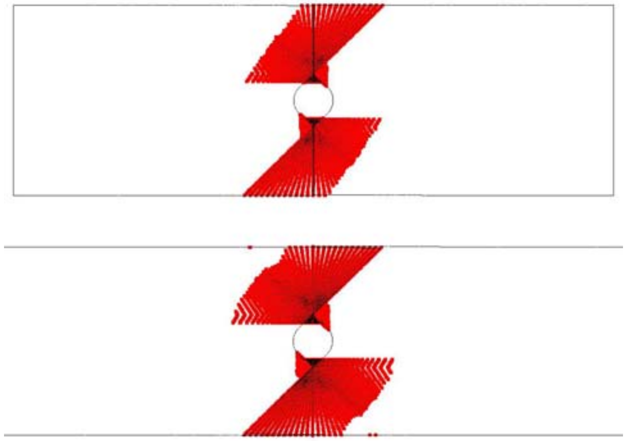
520MPa

Static

Dynamic

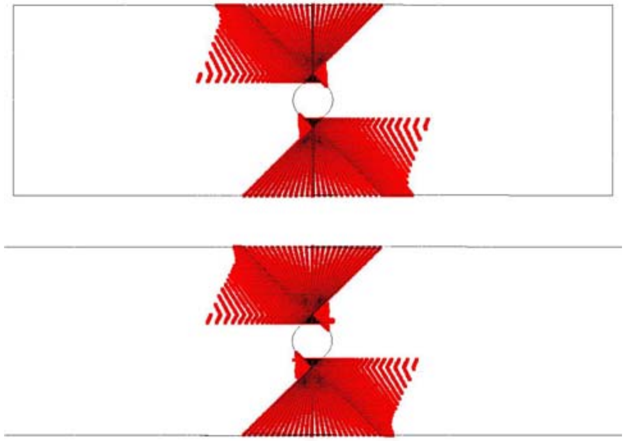


Subsequent delamination development sequence



Static

Dynamic



Conclusions

- Open hole tensile specimens have been successfully tested up to strain rates of 500/s
- Three configurations studied
- Pronounced strain rate effect observed
  - Sub-laminate level scaled specimens have a reduced strength with increasing strain rate (less sub-critical damage)
  - Ply level scaled specimens have an increased strength with strain rate
- Very high CV makes quantitative strength results difficult to be definitive – trends are likely to be accurate
- Failure modes remain unchanged with strain rate
- Finite element modelling consistent with trends but significant difference in absolute values