University of BRISTOL

Predicting Failure in Composites

Michael R. Wisnom

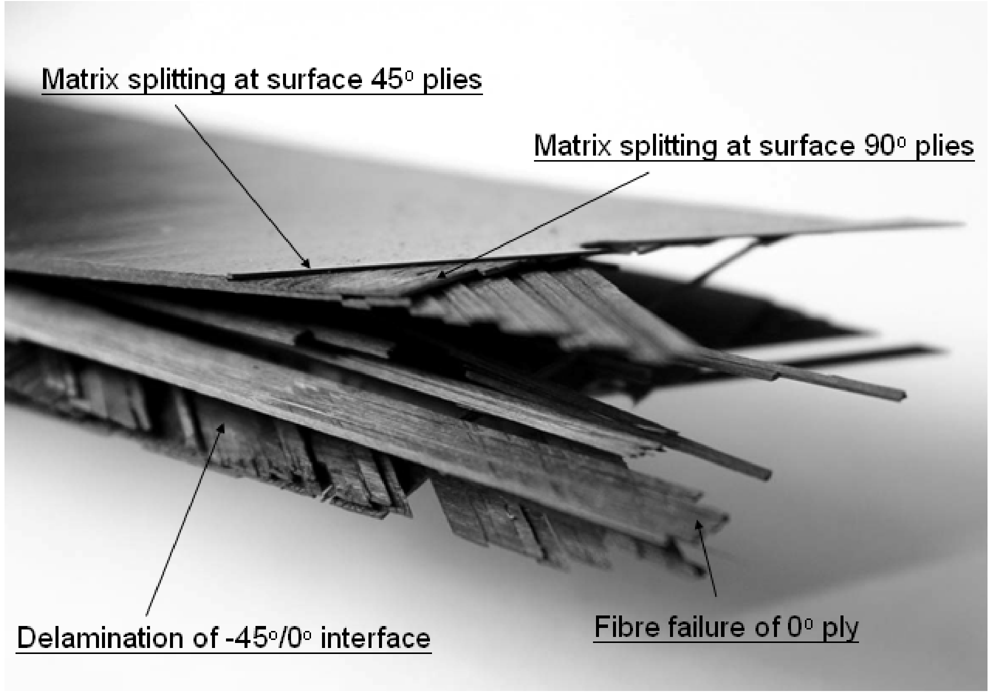
Stephen Hallett

www.bris.ac.uk/composites

ADVANCED COMPOSITES CENTRE FOR INNOVATION & SCIENCE

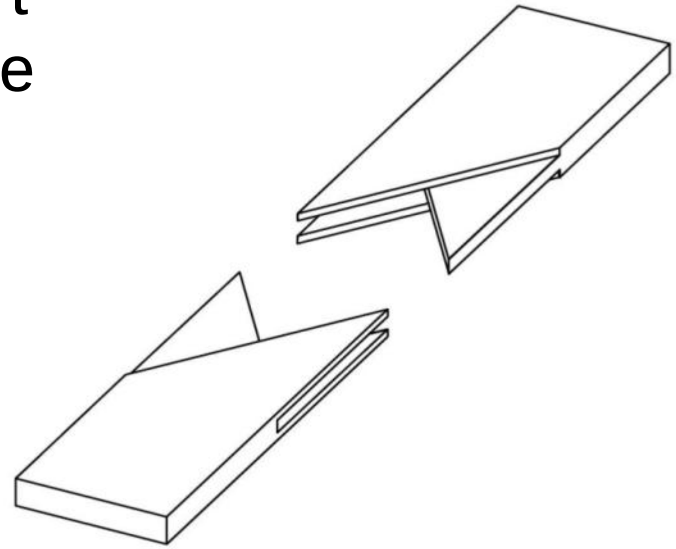
Overview

- Fracture is complex, with interacting damage modes
- Discrete nature of fracture is crucial
- Cohesive zone interface elements are very effective at representing discrete fractures
- Good predictions can be made provided correct failure mechanism is captured
- Range of examples:
  - Un-notched and notched tension
  - Defects
  - Impact
  - Tapered laminates
  - Fatigue



Importance of discrete failure

- Low transverse strength causes early matrix cracks and delaminations
- Form discrete fractures that join up and interact
- Provides alternative mechanism to unload fibres
- Important in controlling ultimate failure
- Homogeneous models can represent reduction in stiffness due to damage
- Cannot capture discrete nature of final fracture

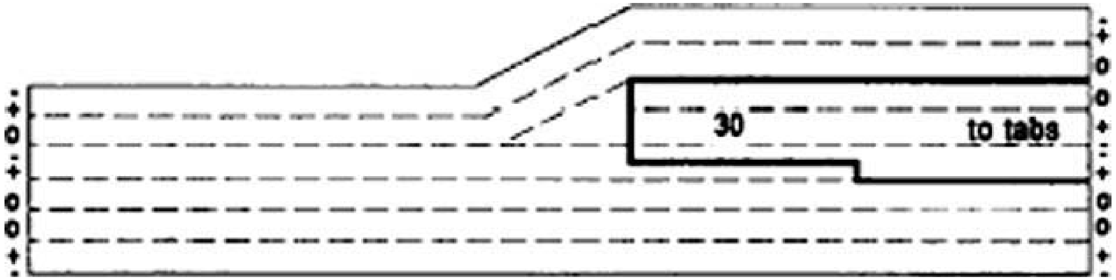


Other examples of discrete failure

- Fibre dominated failure of quasi-isotropic carbon/epoxy in tension

  Factor of 3 variation in strength with stacking sequence and ply block thickness

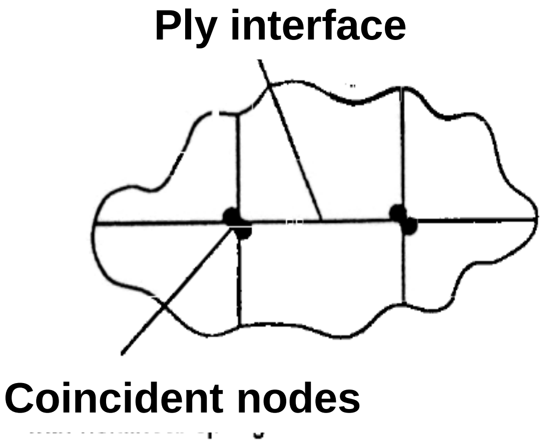
- Ply drops – complete block of material can shear out

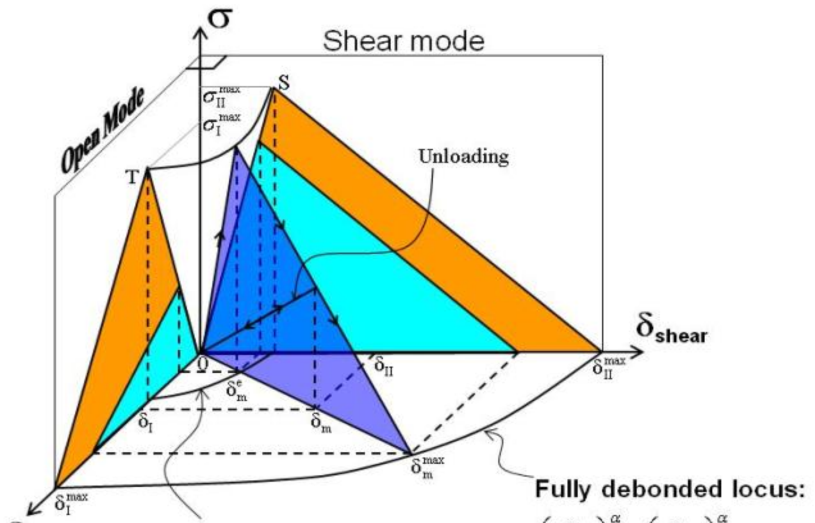


Wisnom, 2010

Interface elements

- Interface elements relating tractions to relative displacements are a good way to model discrete failures
- Unify stress-based and fracture mechanics approaches to failure
- Can handle initiation and propagation
- Physically realistic and numerically convenient approach
- Can be applied to both delaminations and discrete transverse cracks
- Interface elements available now in many commercial programs





Damage initiation locus:

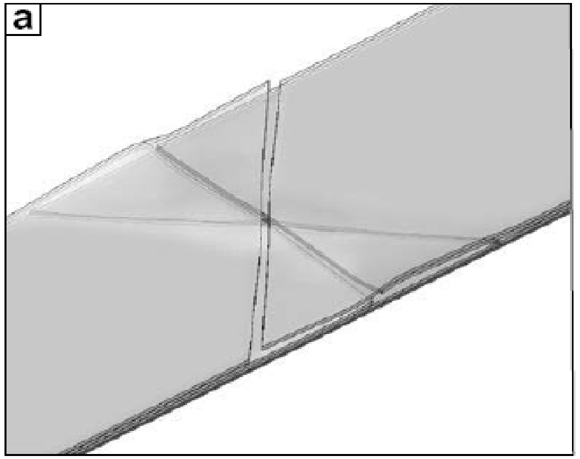
$$\left(\frac{\max(\sigma_I,0)}{\sigma_I^{max}}\right)^2+\left(\frac{\sigma_{II}}{\sigma_{II}^{max}}\right)^2=1$$

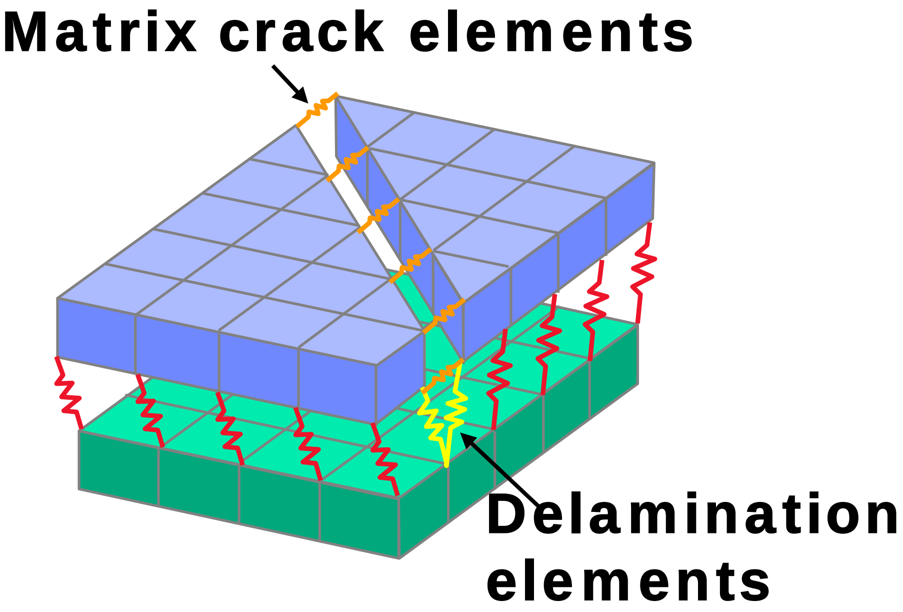
Fully debonded locus:

$$\left(\frac{G_I}{G_{IC}}\right)^\alpha+\left(\frac{G_{II}}{G_{IIc}}\right)^\alpha=1$$

Interaction of delamination and matrix cracks

- IM7/8552 carbon-epoxy laminate
- $(45_4/90_4/45_4/0_4)_s)$ layup
- Uniaxial tension loading
- Fails by delamination before fibre failure
- Cohesive elements at all ply interfaces
- Potential splits also represented with interface elements

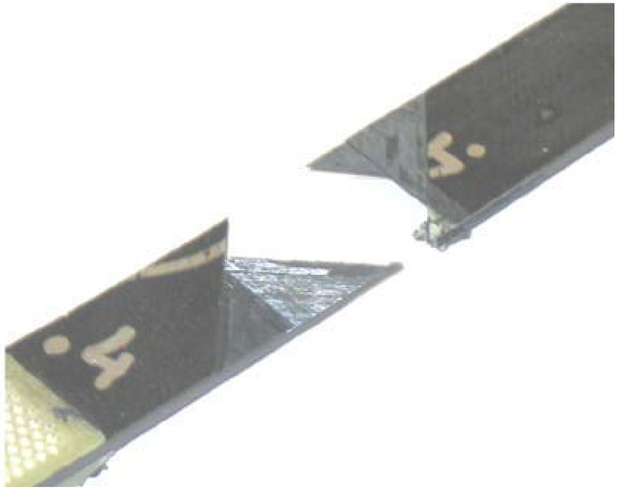


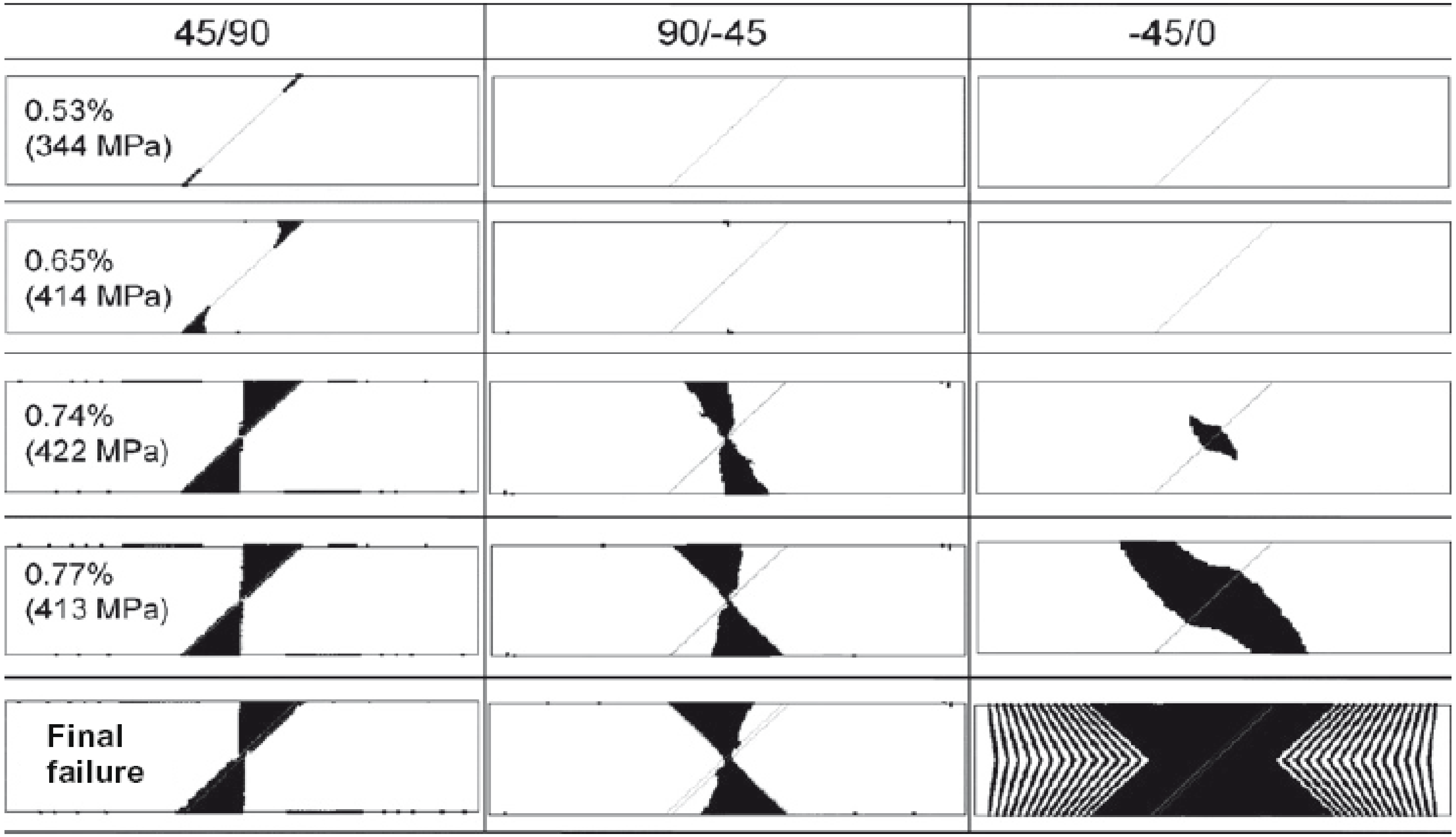


Comparison with experimental observations

Interaction of delamination and cracks captured

Predicted failure stress within experimental scatter

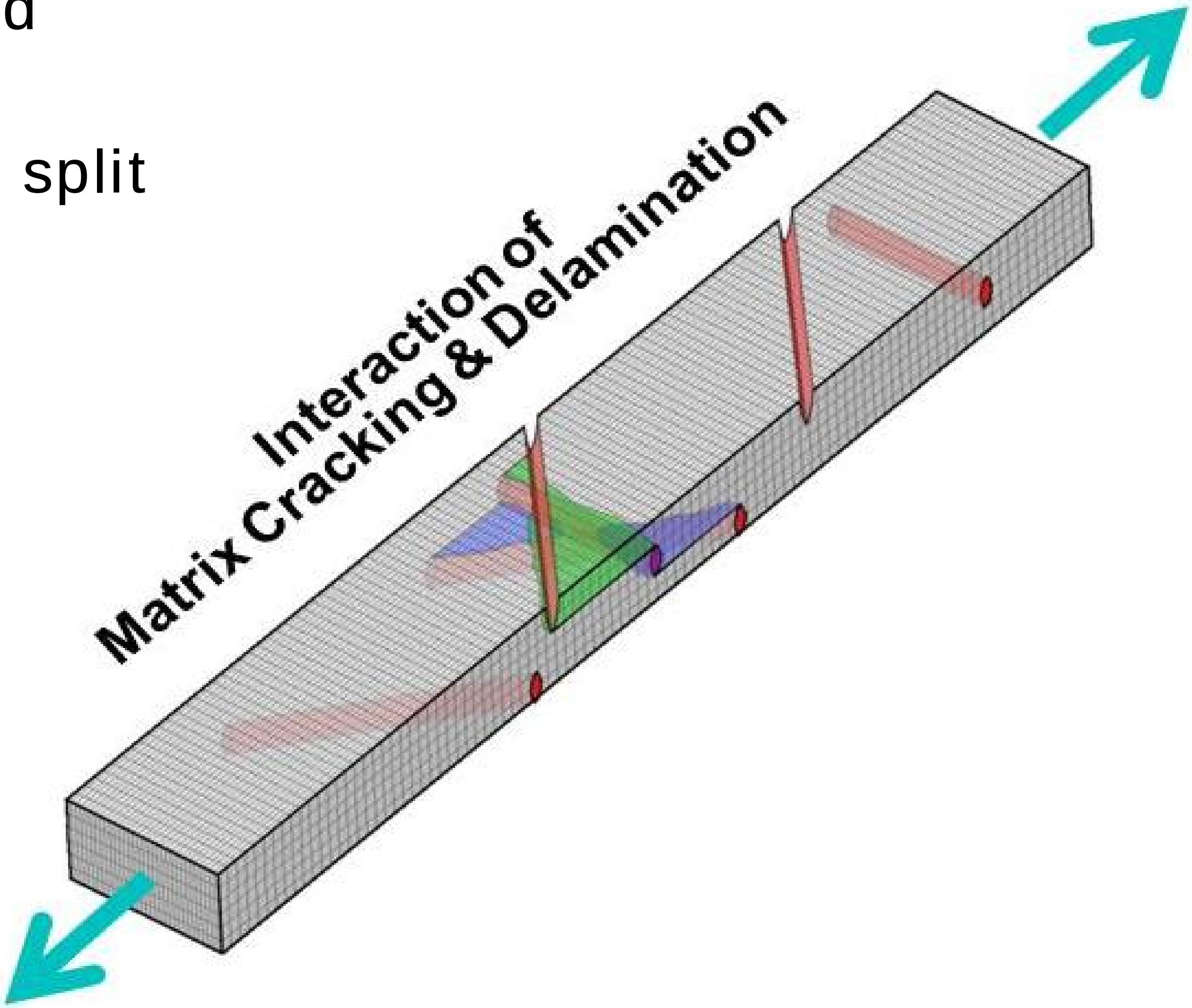




Hallett et al, 2008

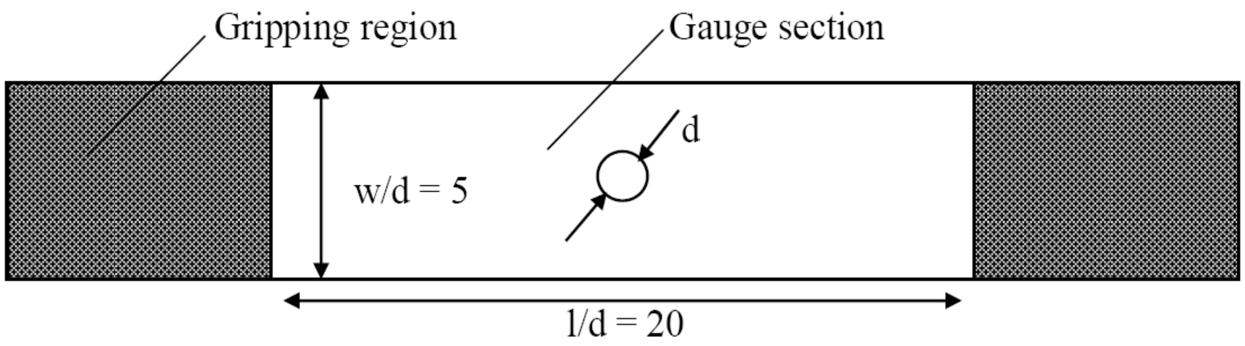
Extended FEM

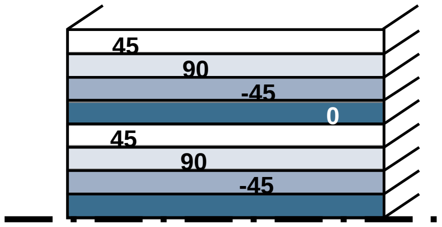
- Some effect of assumed relative split locations
- XFEM allows automatic split insertion



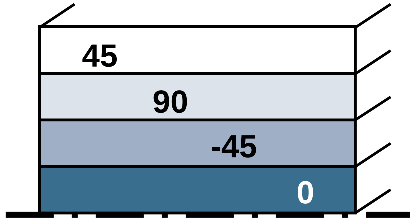
Iarve et al, 2011

Open hole tension





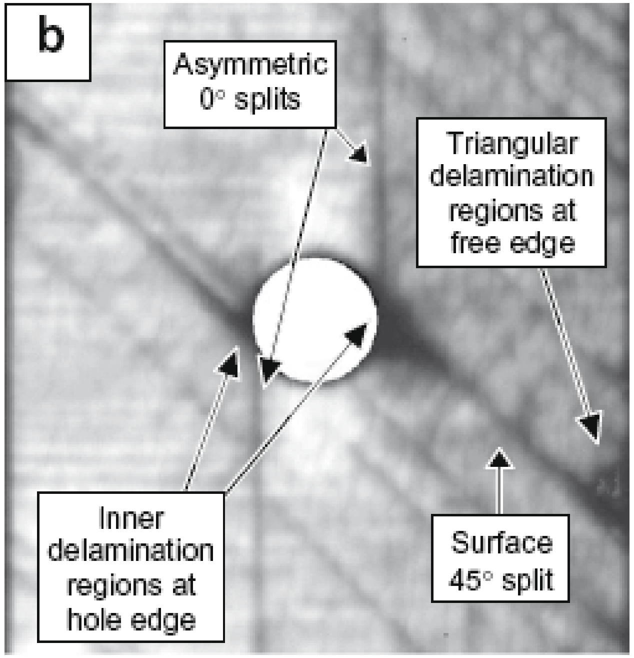
Dispersed plies



Blocked plies

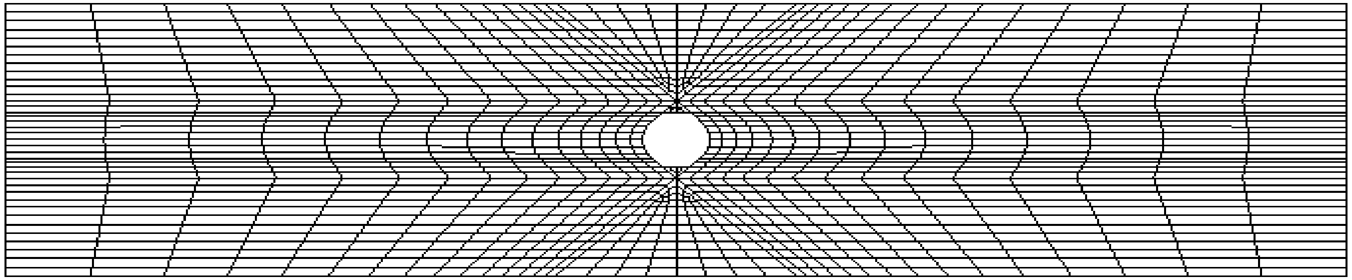
- Hexcel IM7/8552
- $(45_m/90_m/-45_m/0_m)_{ns}$ layup
- All specimens scaled
- Two methods of thickness scaling
- Complex damage development:

  Matrix cracking, splitting, delamination



Hallett et al, 2009

Finite element analysis



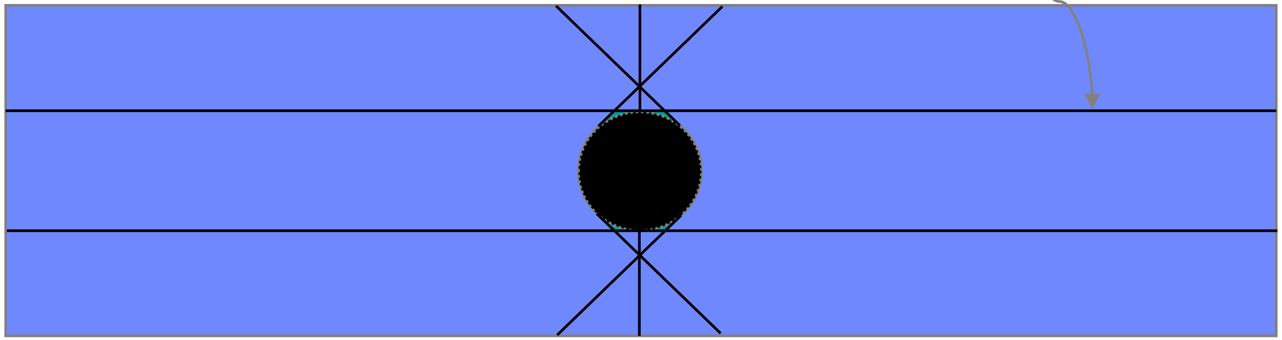
LS_Dyna

Weibull fibre failure criterion

$$\sum_{i=1}^{No.\,of\ Elements} V_i \left(\frac{\sigma_i}{\sigma_{unit}} \right)^m \geq 1$$

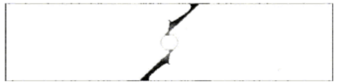
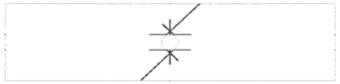
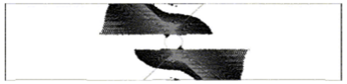
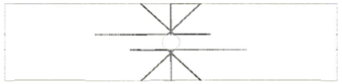
Interface elements between all plies

Potential splits within plies

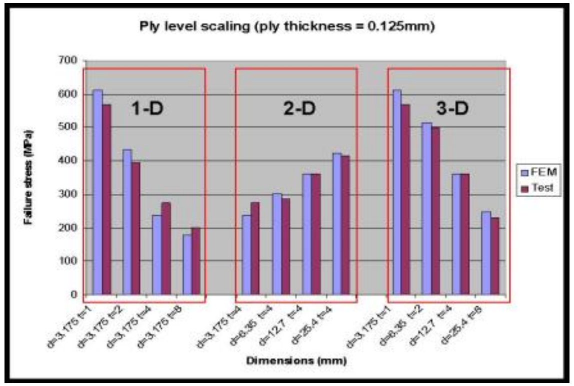


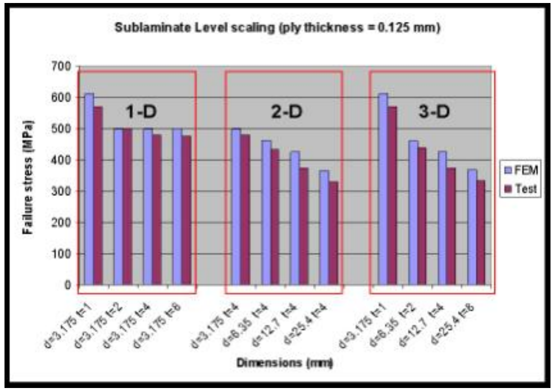
Not to scale

Predicted damage, t=4mm,d=25mm

Stress level (MPa)	Location of interlaminar interface			Location of splitting within plies
	45°/90°	90°/-45°	-45°/0°	All layers (superimposed)
152				
184				
423				
372				

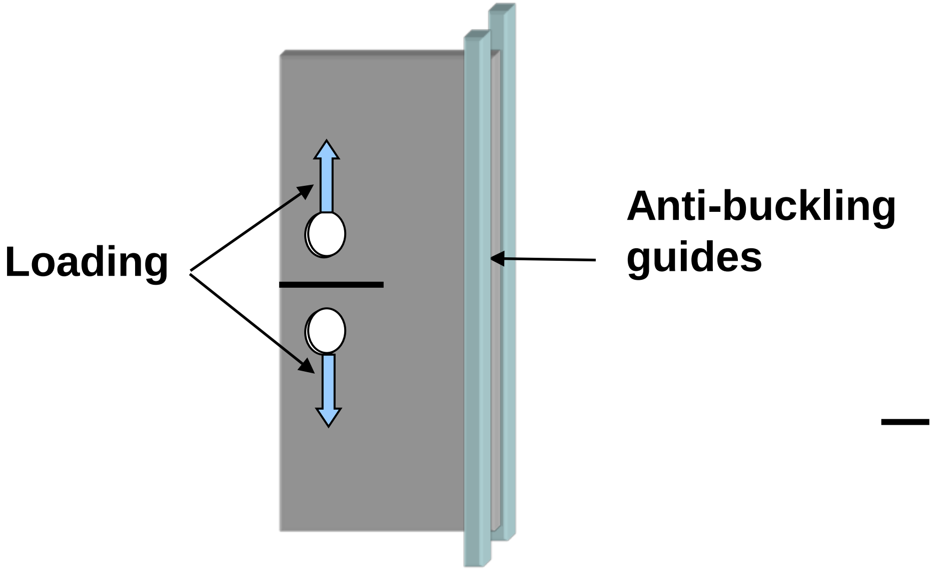
- Damage mechanisms captured well
- Good correlation of test and analysis failure stresses

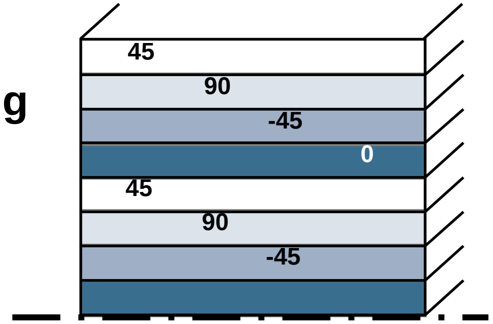




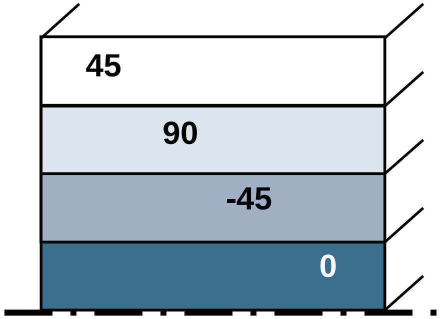
Overheight Compact Tension specimens

- Fibre failure catastrophic in open hole specimens
- OCT tests produce gradual failure
- Specimen size supposed to be sufficiently large to allow development of damage “process zone” ahead of notch tip
- Two stacking sequences – dispersed and blocked plies
- IM7/8552 carbon/epoxy





Dispersed plies



Blocked plies

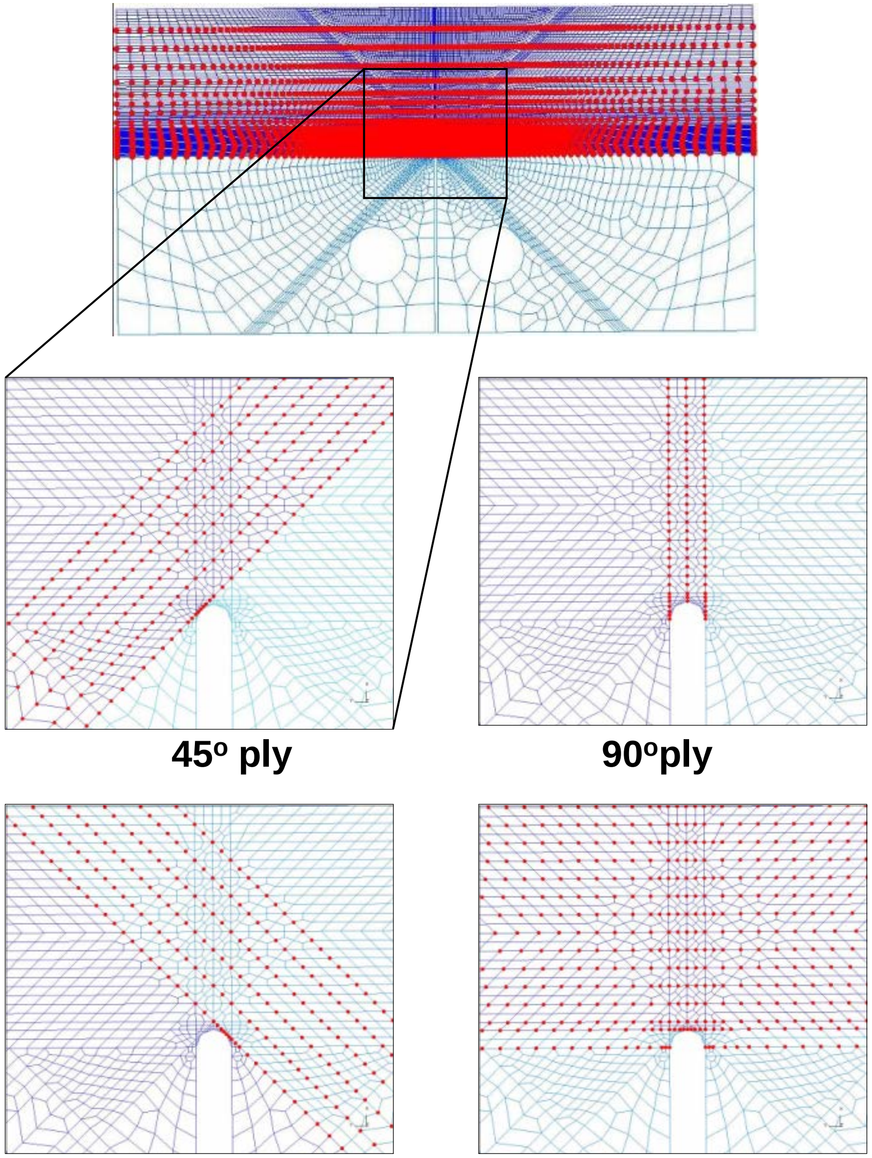
Li et al, 2013

FE mesh and fibre failure

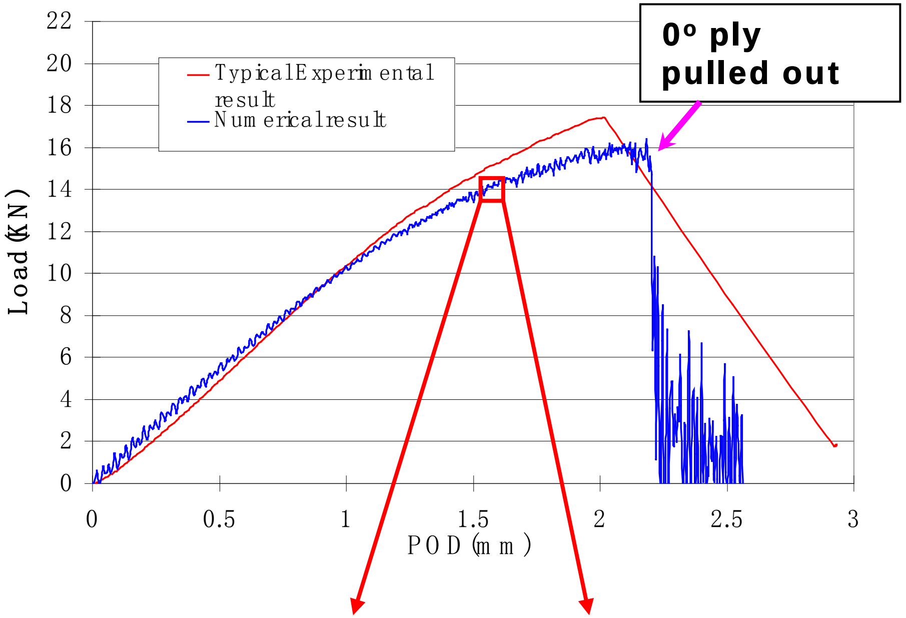
- Multiple potential crack sites inserted ahead of notch tip
- Interface elements between all plies
- Fibre failure modelled by progressive Weibull criterion

$$\sum_{i=1}^{No.\,of\;Elements} V_i \left(\frac{\sigma_i}{\sigma_{unit}}\right)^m \geq 1$$

- Maximum stress element is removed
- Load redistributed by FE
- Weibull criteria re-evaluated at next time increment

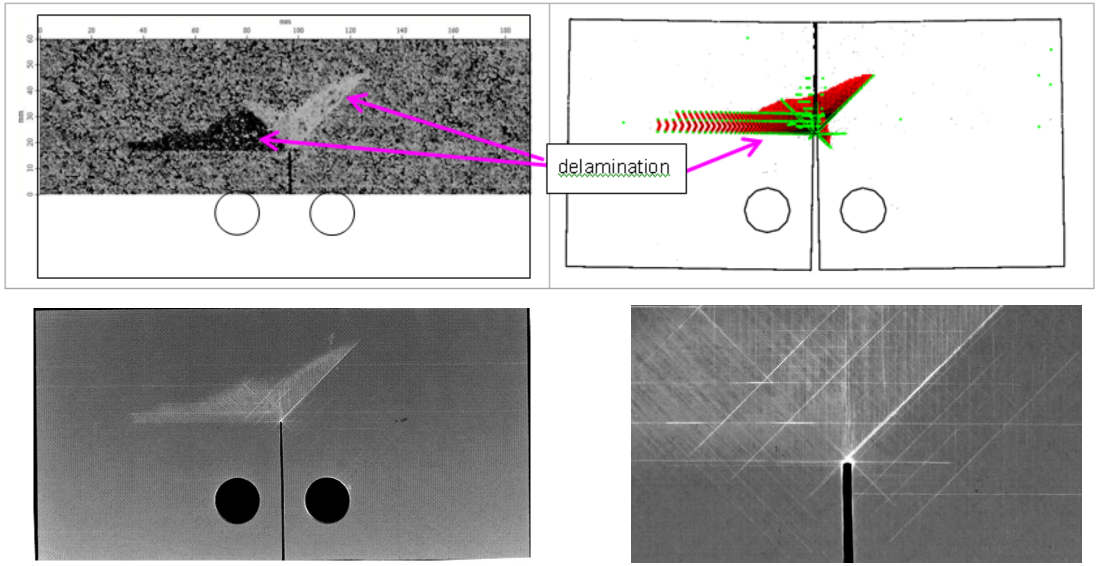


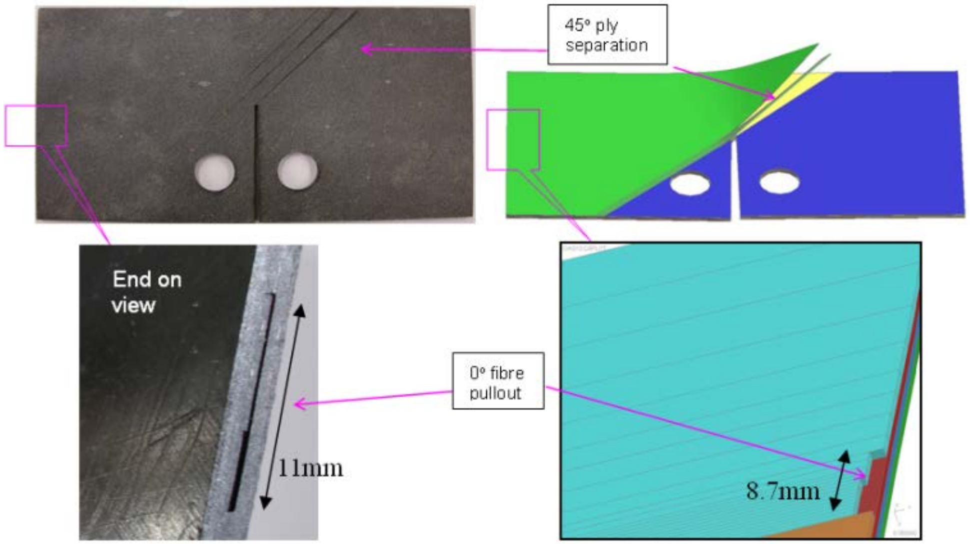
Layup $[45_4/90_4/-45_4/0_4]_s$ (4mm)



0° ply pulled out

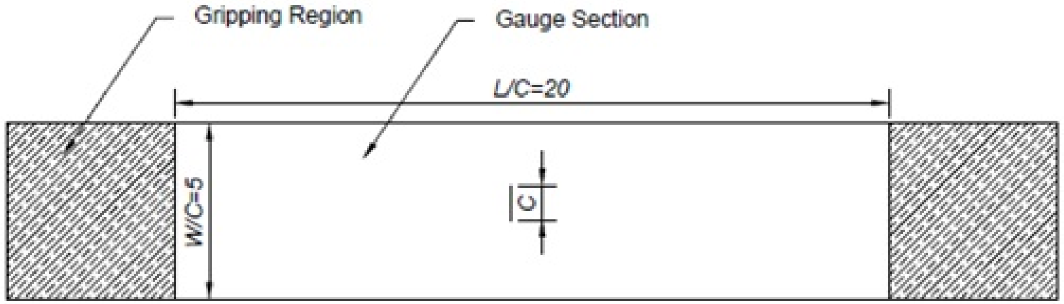
- Thick ply blocks promote matrix cracking and delamination
- 0° ply cracks ahead of the notch blunt crack
- No fibre failure observed
- Failure by pullout of 0° ply block



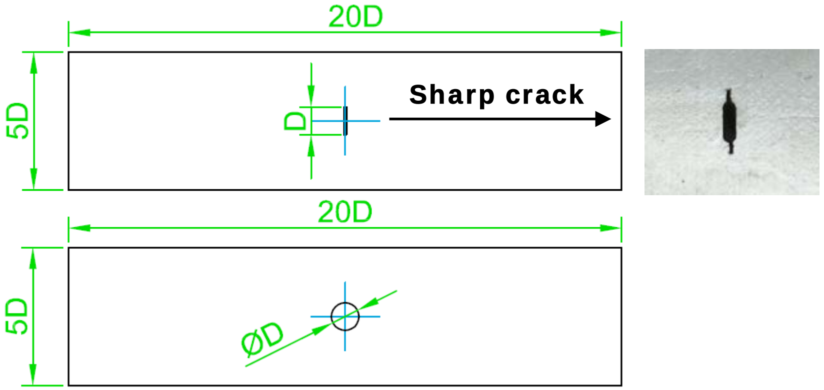


Scaled Centre Notch Tension tests

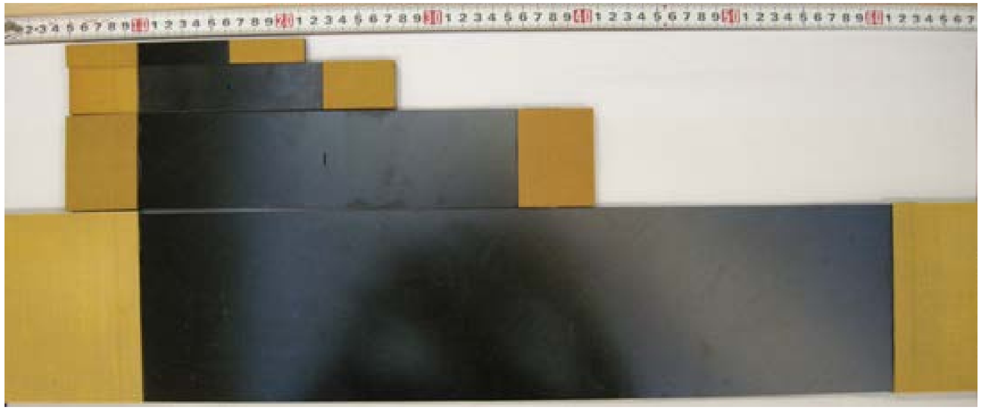
In-plane scaled IM7/8552 $[45/90/-45/0]_{4s}$ laminates



***C*=3.175mm, 6.35mm, 12.7mm, 25.4mm**



Central-crack and open-hole specimens

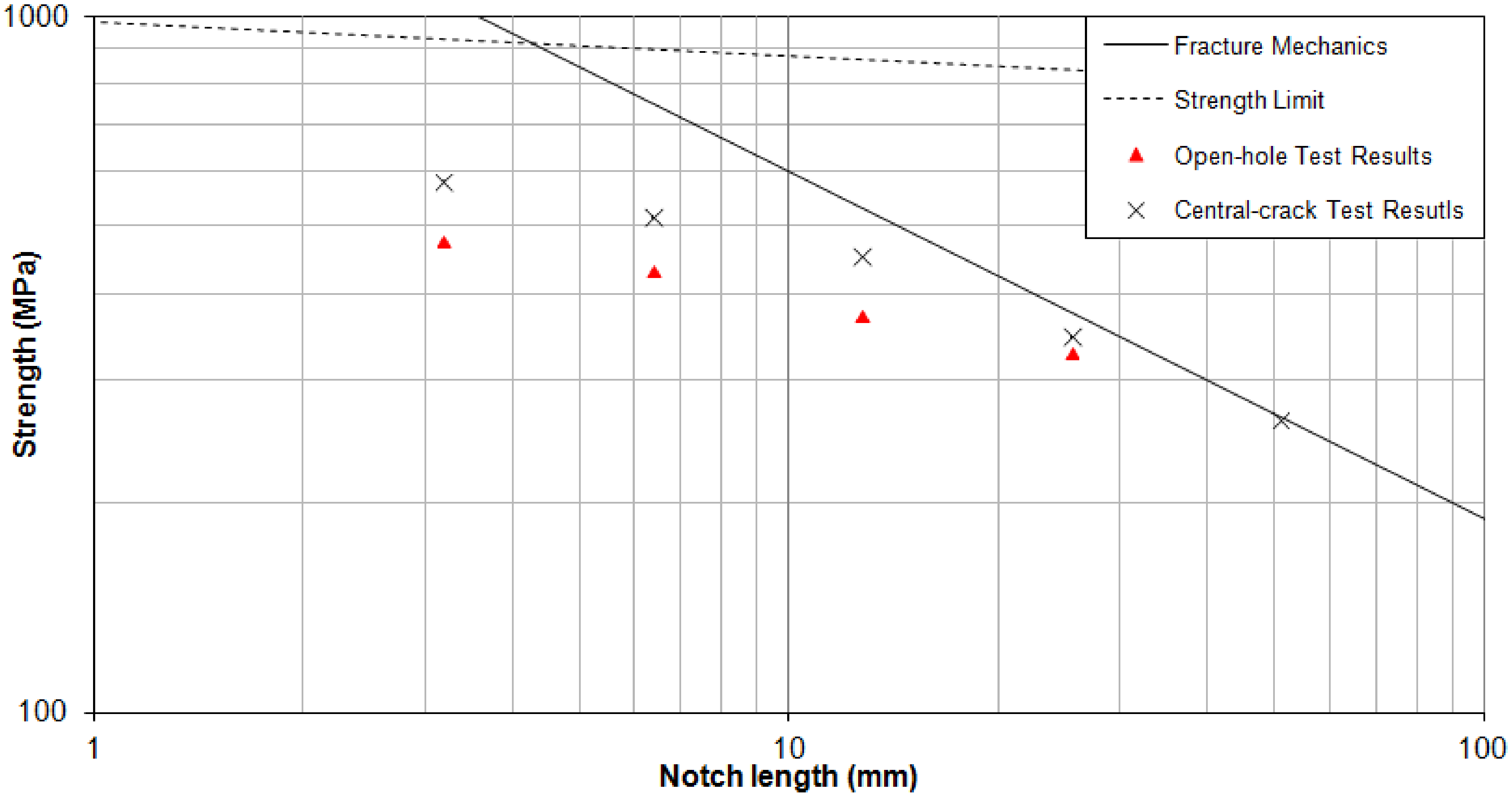


In-plane scaled test specimens

Failure of specimens

X Xu

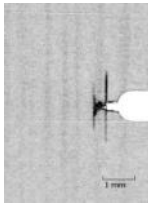
Size effects in notched laminates



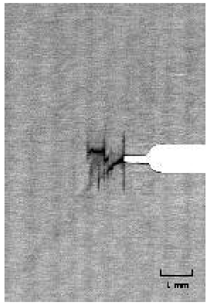
- Strength reduces with size, but less than predicted by LEFM
- Similar scaling trends for open holes and centre notches
- Specimens with cracks stronger than holes!

Failure mechanism (fixed scale)

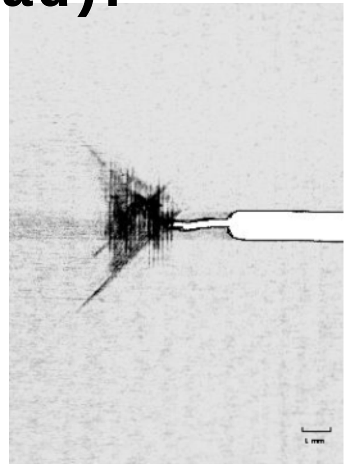
Interrupted tests (95% failure load):



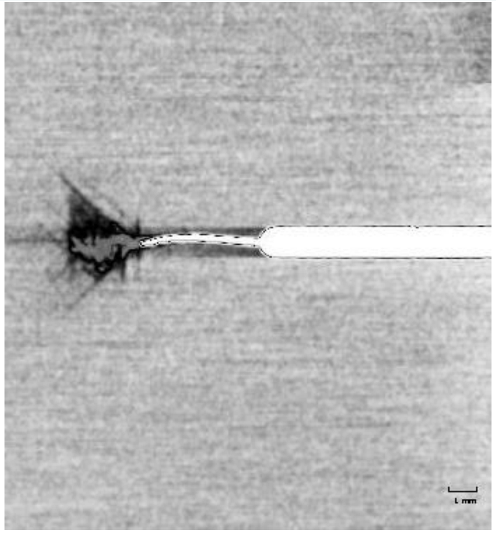
C=3.175mm



C=6.35mm

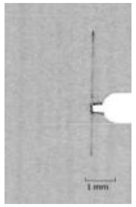


C=12.7mm

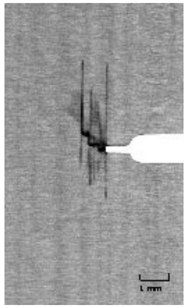


C=25.4mm

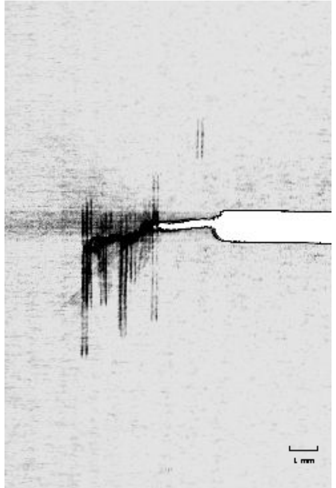
Single 0 degree ply



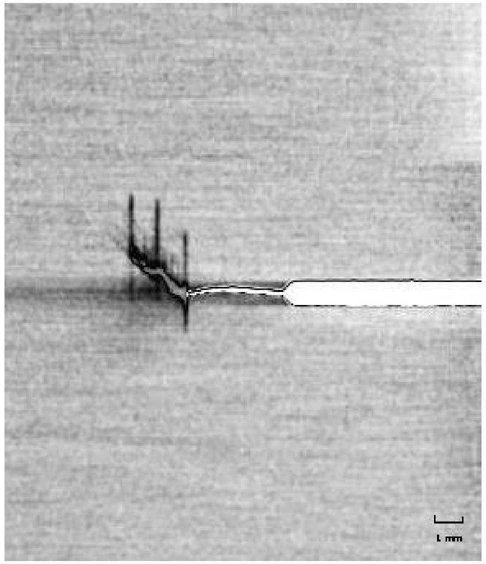
C=3.175mm



C=6.35mm



C=12.7mm

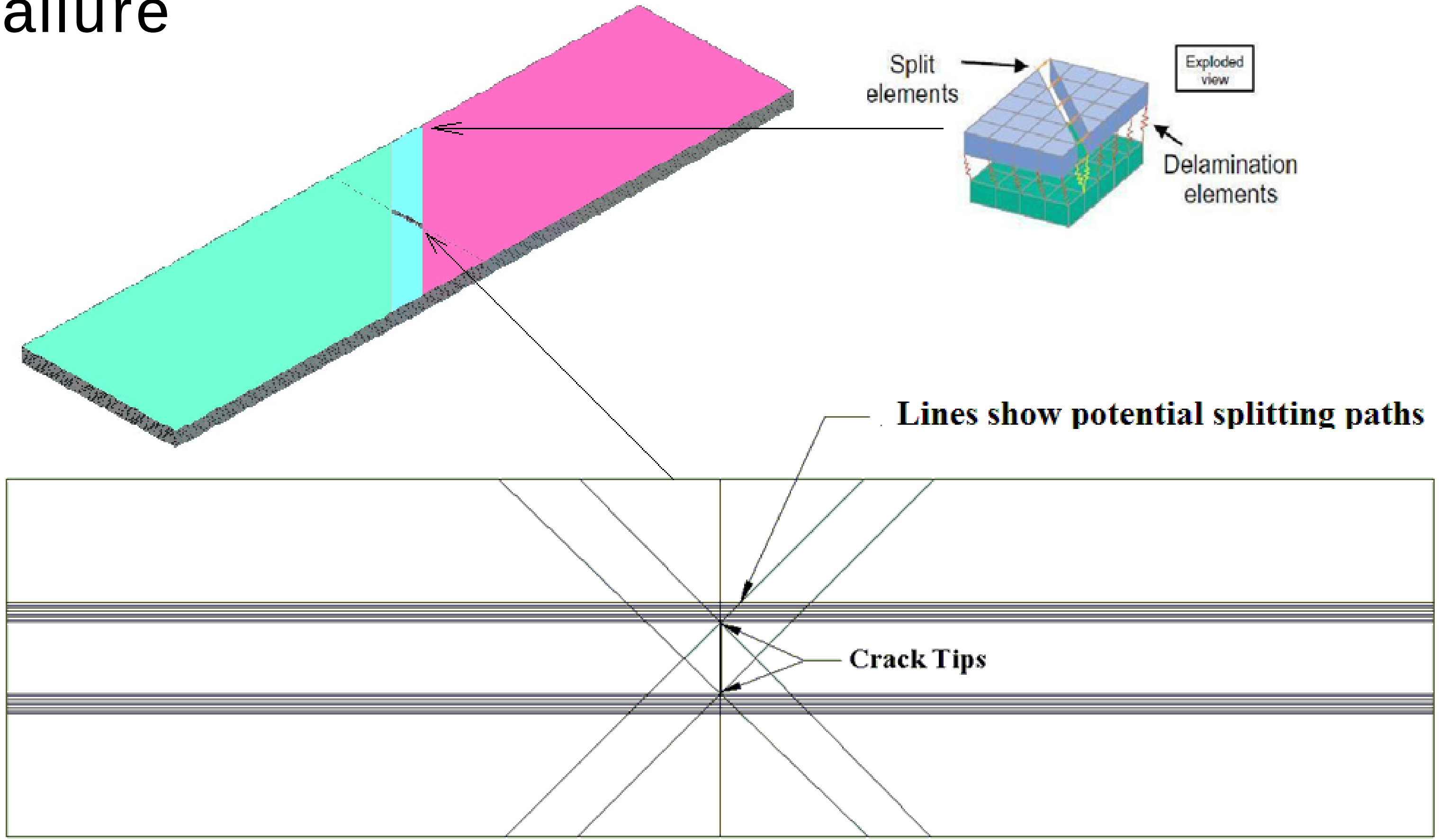


C=25.4mm

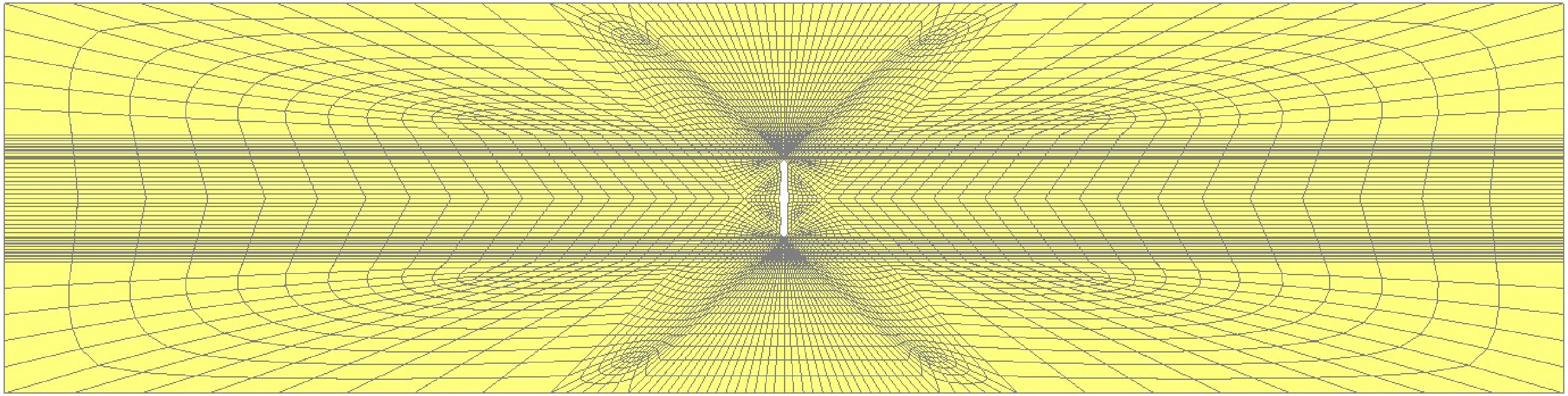
Central double 0 degree ply

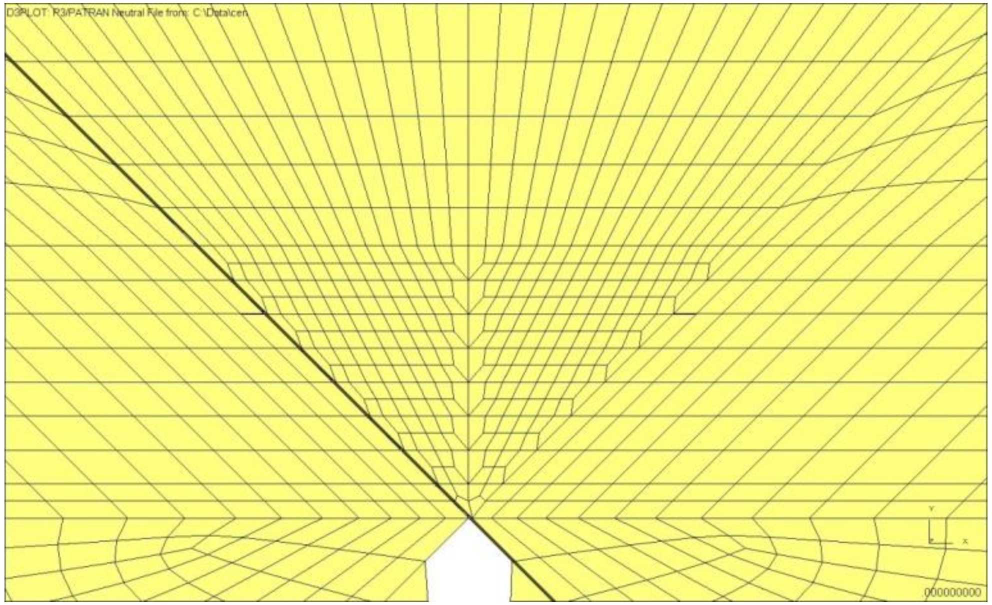
FE modeling

- Delamination elements between all plies
- Potential split elements along multiple paths at crack tips
- Weibull failure criterion and element removal for continuous fibre failure



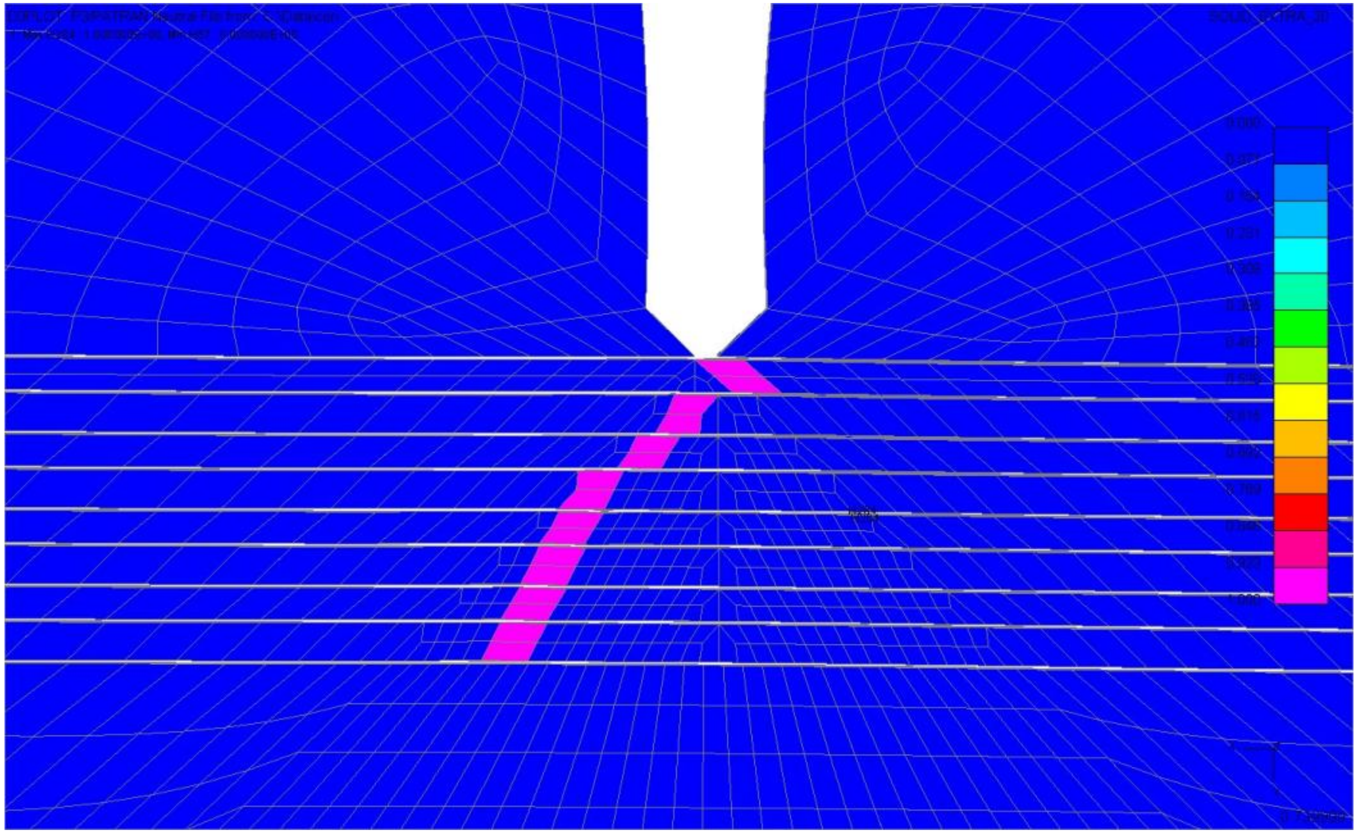
FE mesh (Baseline c=3.175mm)





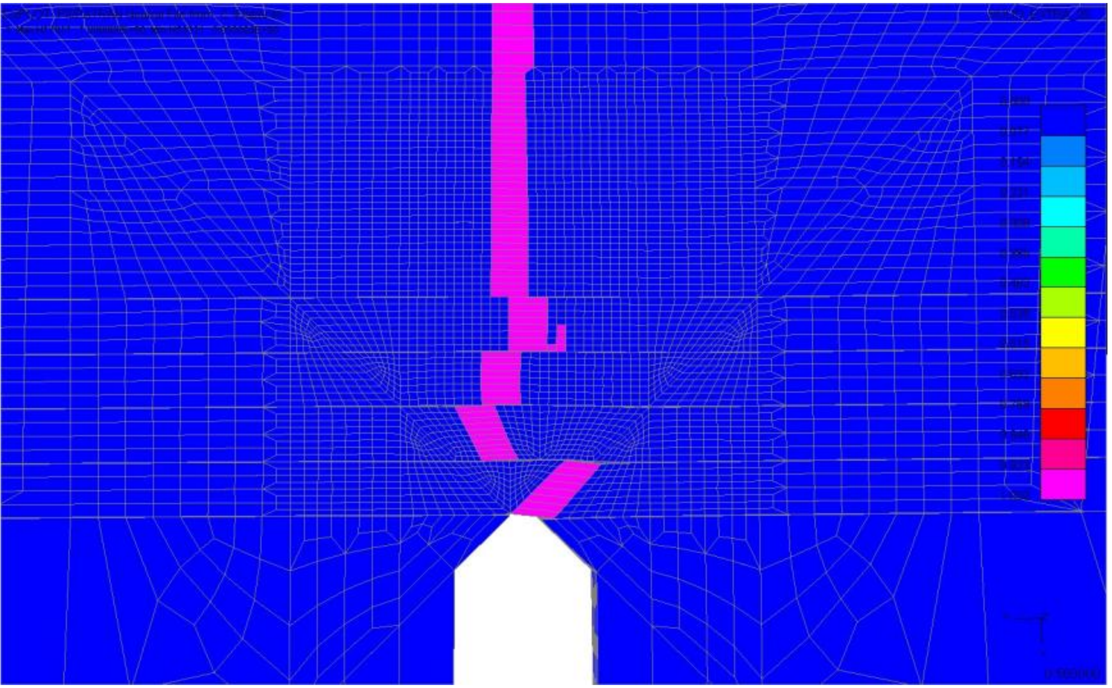
Mesh size 0.06mm

Failure mechanisms (Baseline c=3.175mm)

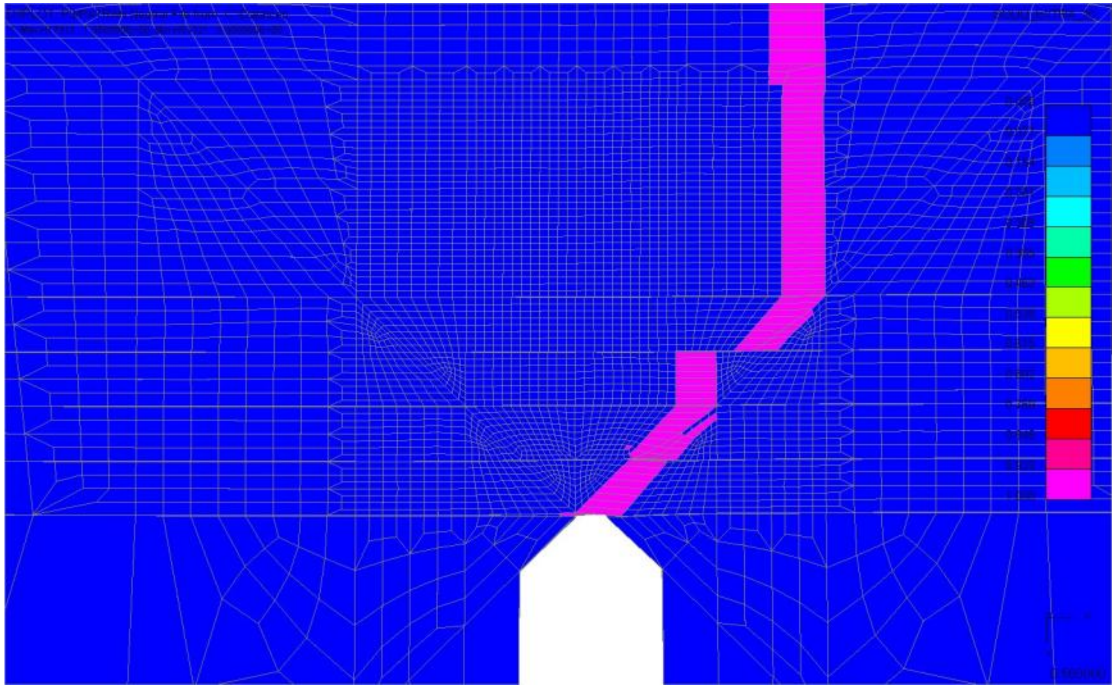


- Fibre failure growth before final failure in single 0 plies
- No fibre failure in central double 0 plies
- Matches experimental observations

Failure mechanisms (Scaled up c=25.4mm)



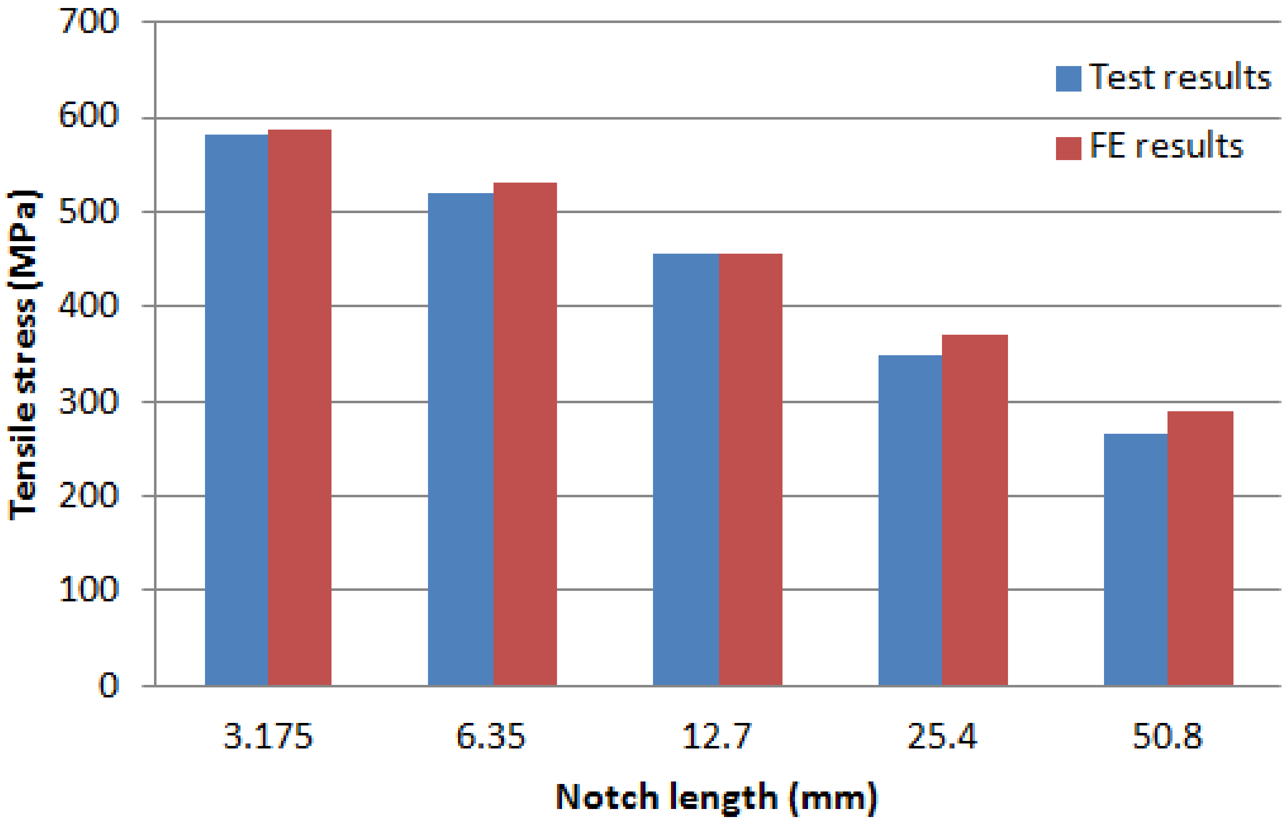
Single 0 plies



Double 0 plies

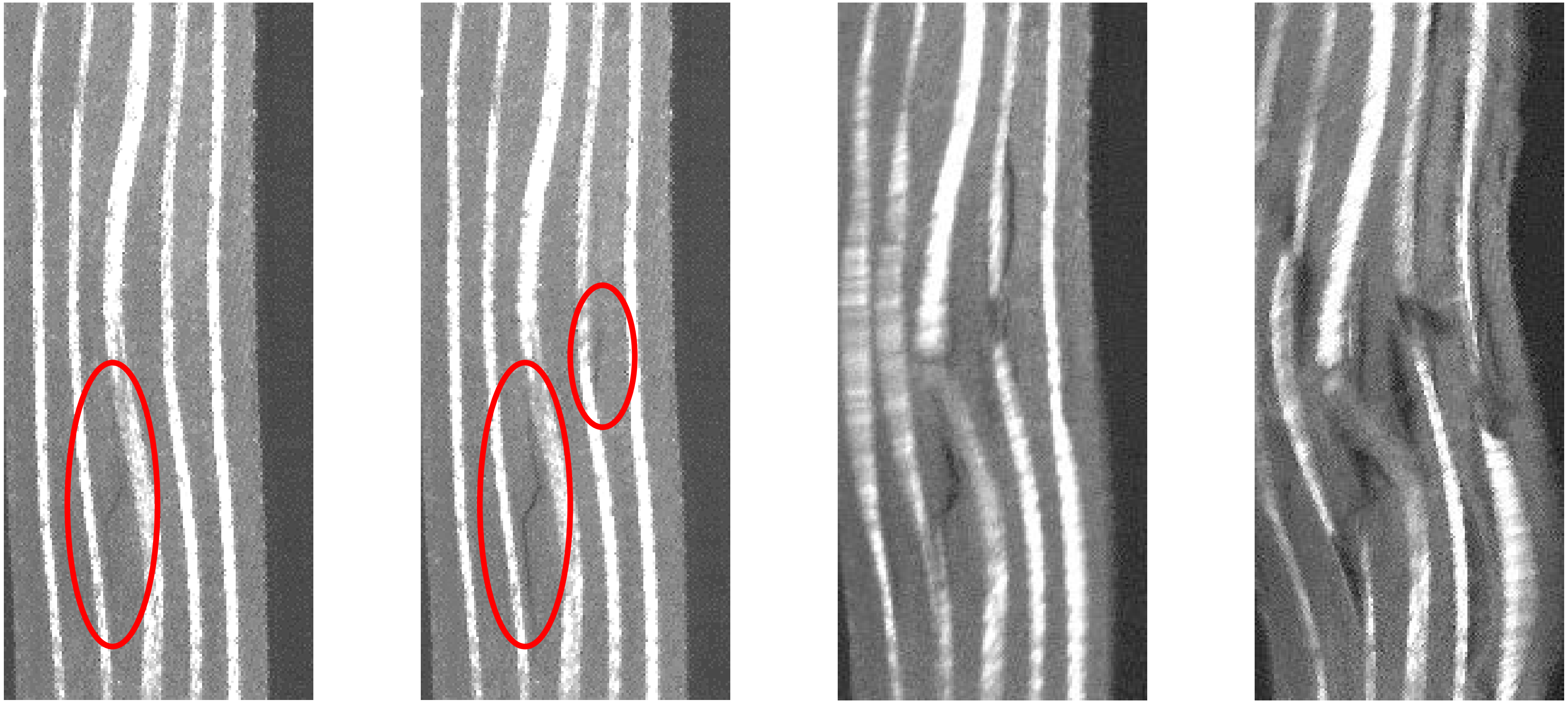
- Fibre failure growth before final failure in ALL plies
- Consistent with experimental observations

Results correlation



- Good overall correlation
- FE is able to predict damage and scaling trends
- Damage zone size increases with specimen size, and so fracture toughness increases

Out-of-plane wrinkling compression test



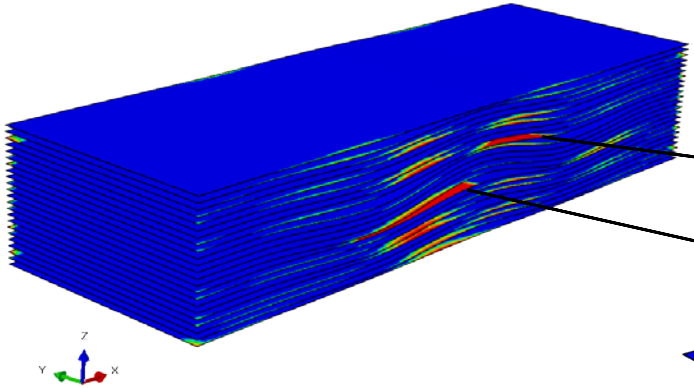
Specimen 3 - Final 4 frames @ 90,000 FPS

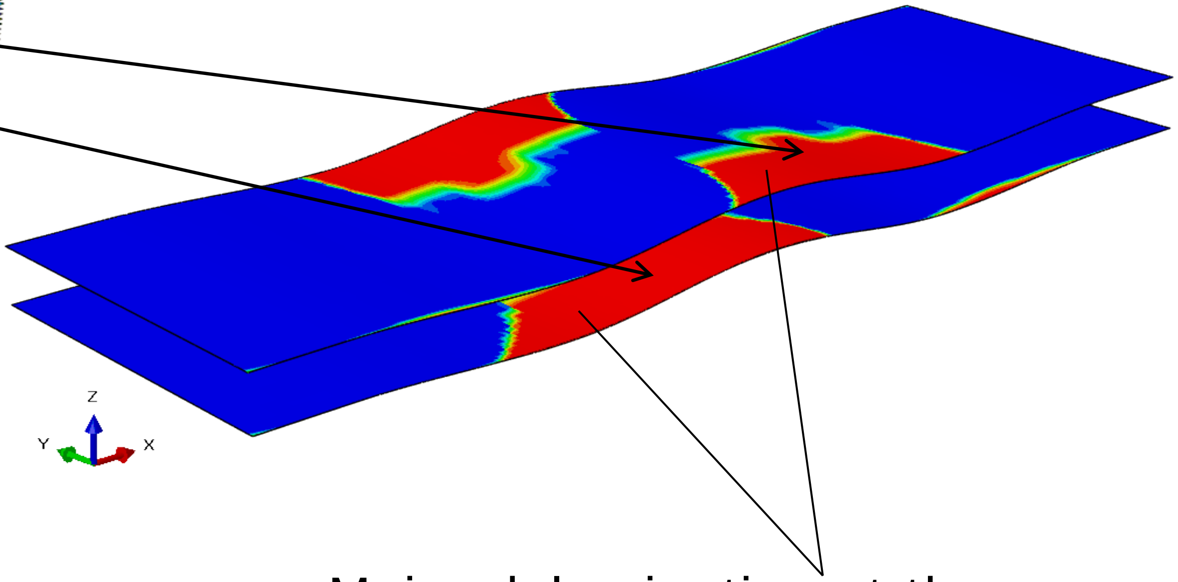
IM7/8552 $[+45, 90, -45, 0]_{3S}$

M Jones

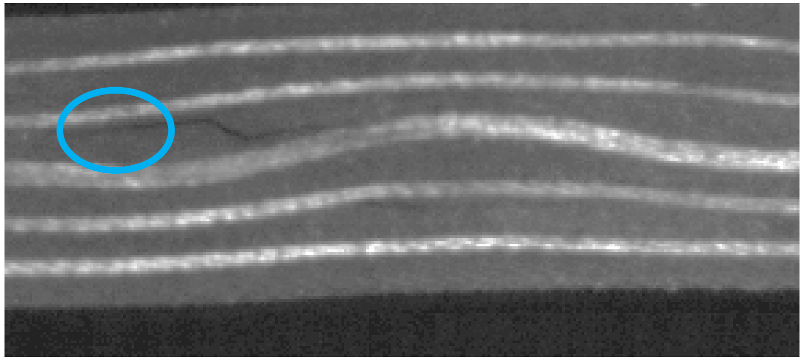
Analysis results – compression

- 3D FE model with cohesive elements at all interfaces
- Captures delamination initiation from the edge
- Failure at 455 MPa cf experimental average of 457 MPa





Major delamination at the 45°/90° ply interface

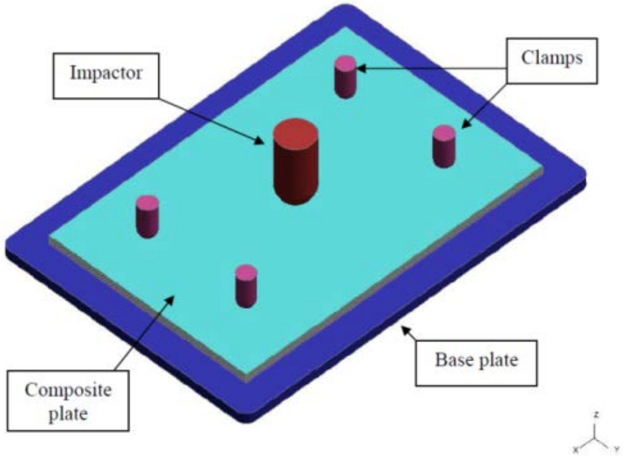


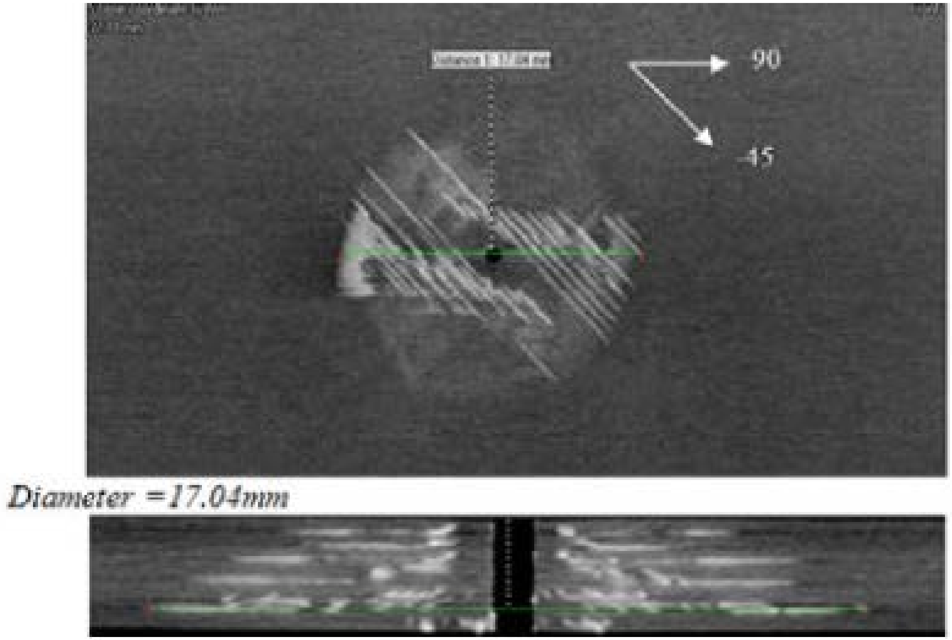
Delamination at 45/90 interface observed in experiment

S Mukhopadhyay

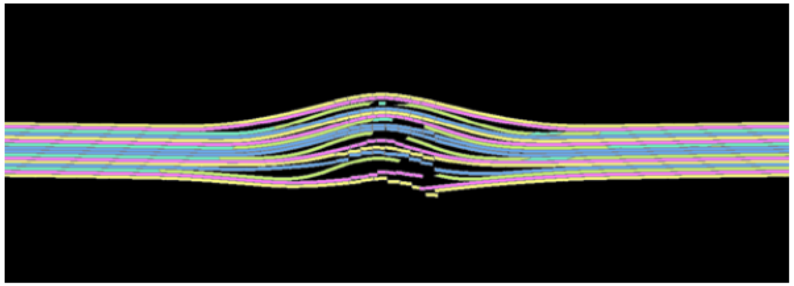
Impact and compression after impact

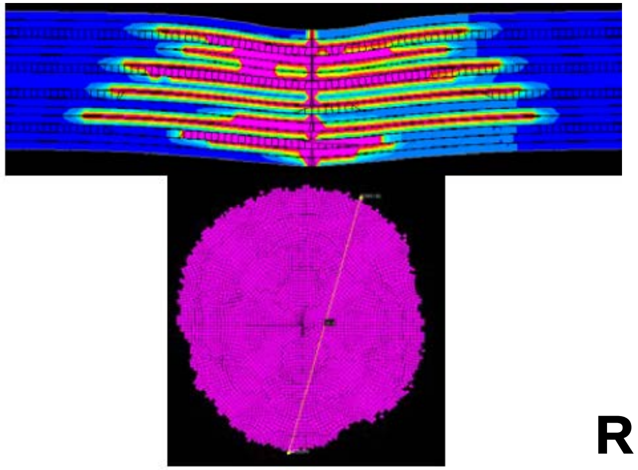
- Impact damage mechanism with multiple delaminations well captured





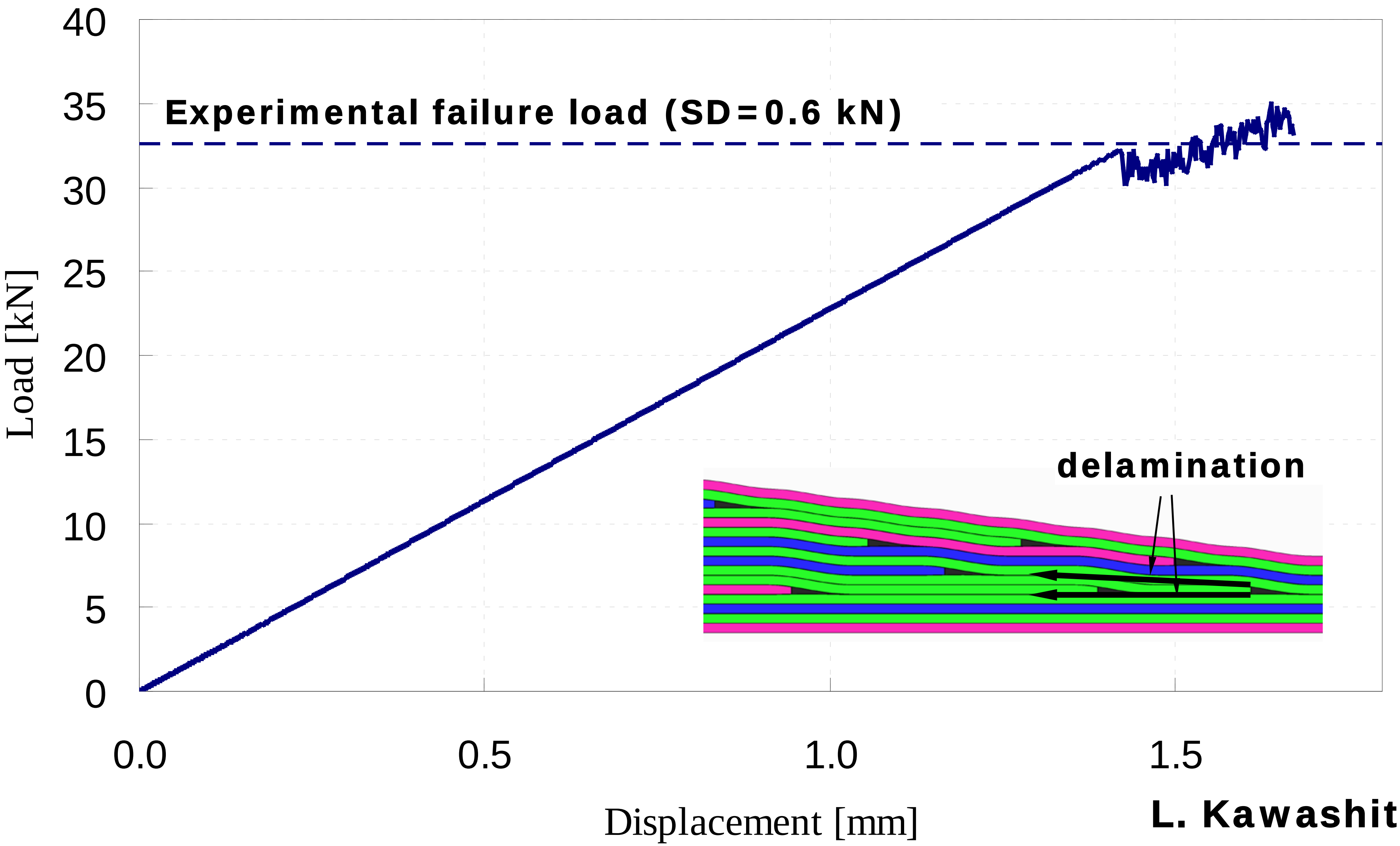
- CAI response can also be modelled





R. Sun

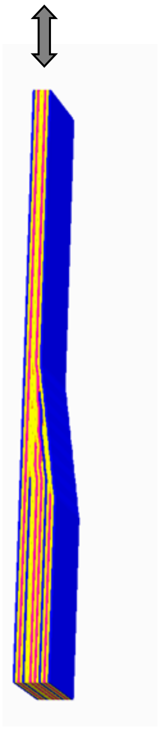
Prediction of delamination in tapers

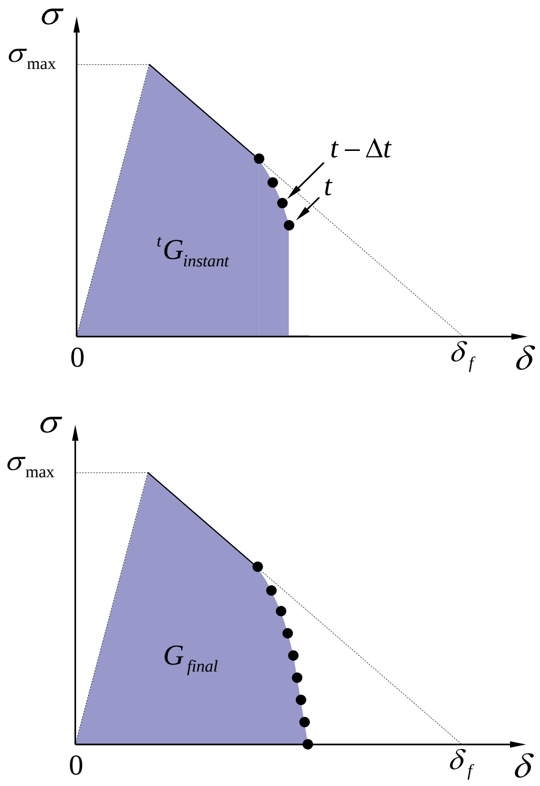


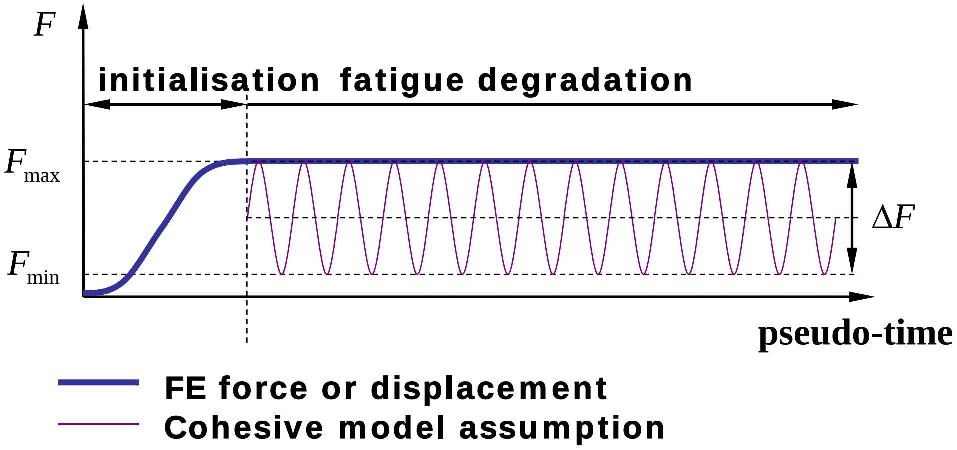
L. Kawashita

Fatigue delamination growth

- Novel cohesive formulations can model fatigue as a function of the SERR amplitude and number of cycles
- Paris-law regime, R-ratio (trough/peak loads) of 0.1
- Envelops of forces and displacements modelled

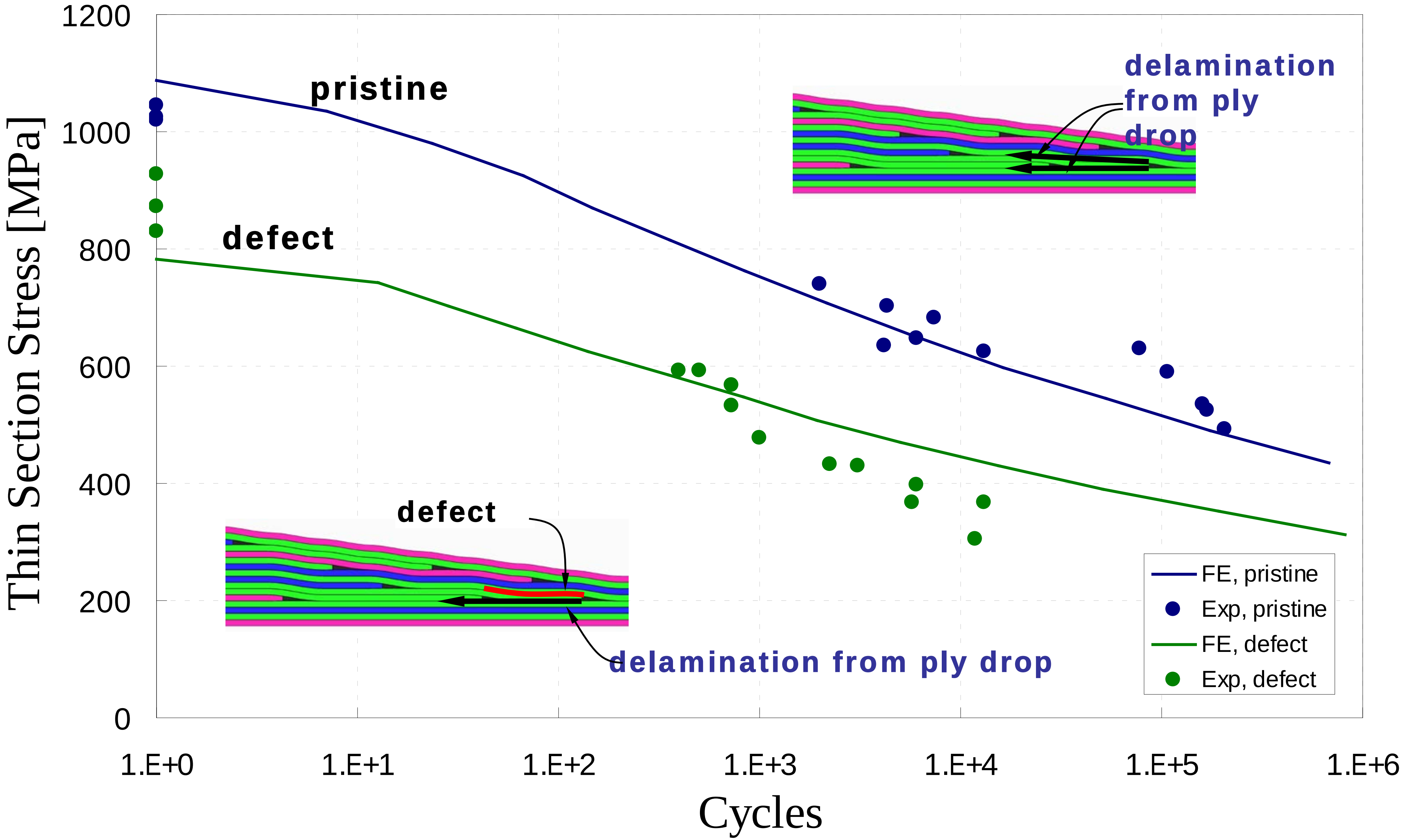




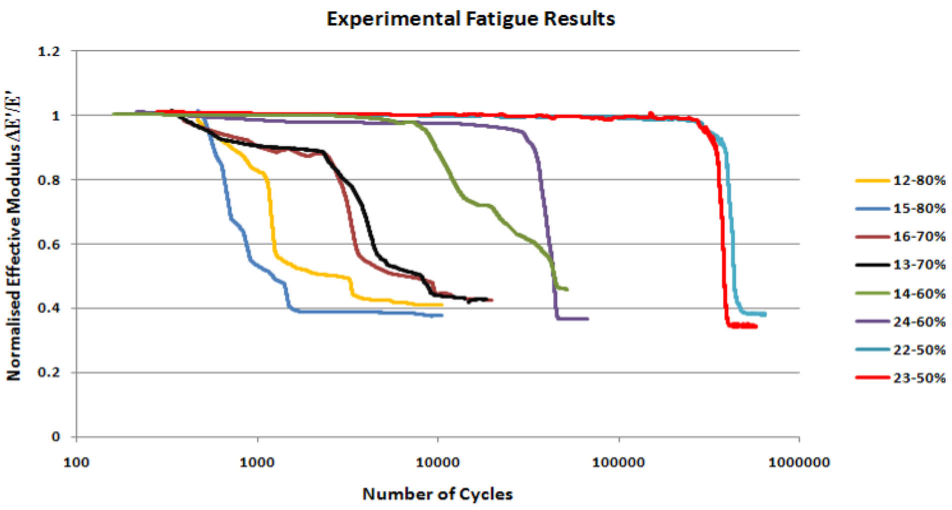


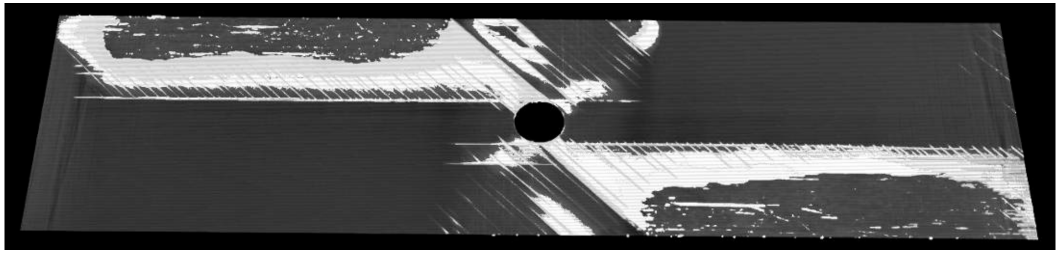
P. Harper

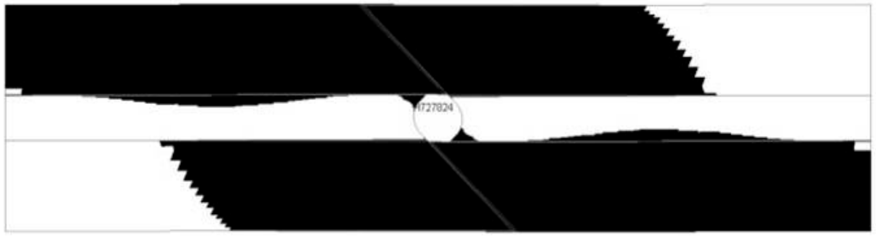
Model-test correlation: cyclic loading

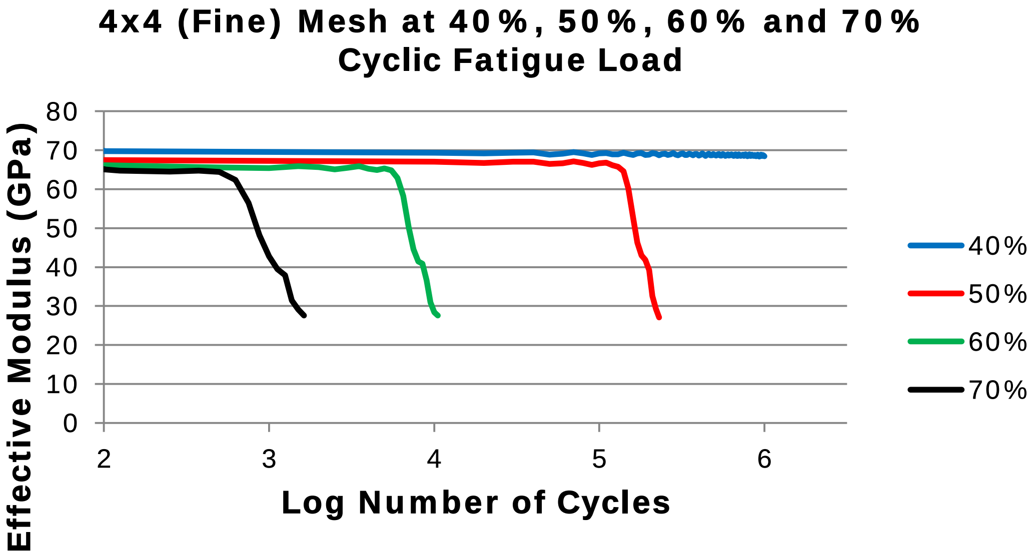


Open hole tension fatigue





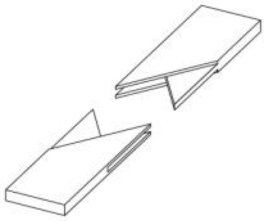


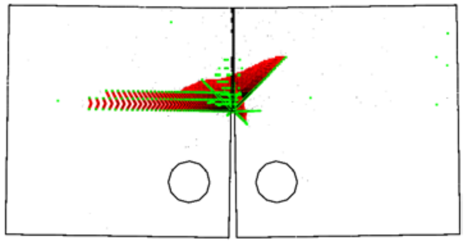


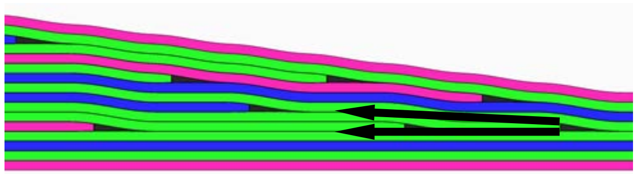
O. Nixon-Pearson

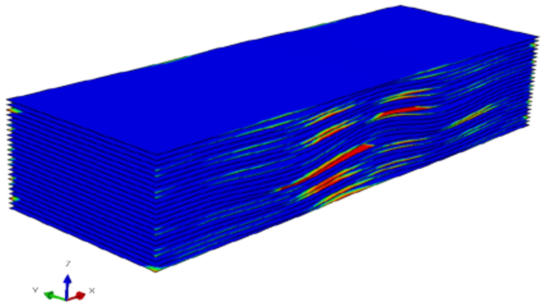
Conclusions

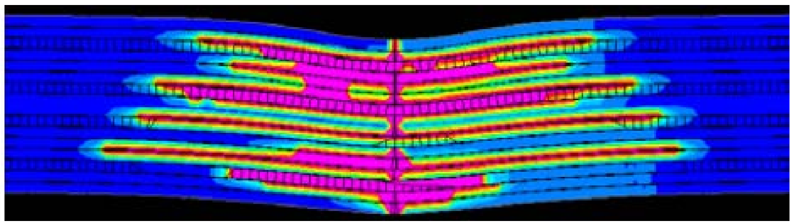
- Discrete delaminations and splits are crucial in controlling failure
- Good predictions can be made provided mechanisms are correctly captured:
  - Notched and unnotched tension
  - Tapered laminates
  - Impact and compression after impact
  - Defects e.g. out-of-plane wrinkling
- Approach also works for fatigue











Papers

- Hallett SR, Jiang W-G, Khan B, Wisnom MR, 2008. Modelling the interaction between matrix cracks and delamination damage in scaled quasi-isotopic specimens. Composites Science and Technology 68:80-90.
- Hallett SR, Green BG, Jiang WG, Wisnom MR, 2009. An experimental and numerical investigation into the damage mechanisms in notched composites. Composites Part A 40:613-624.
- Iarve EV,Gurvich MR, Mollenhauer DH Rose CA, Dávila CG, 2011. Mesh-independent matrix cracking and delamination modeling in laminated composites, International Journal For Numerical Methods In Engineering 88:749–773.
- Kawashita LF, Jones M, Giannis S, Hallett SR, Wisnom MR, 2011. High fidelity modelling of tapered laminates with internal ply terminations. 18th International Conference on Composite Materials (ICCM18), Jeju, Korea, 21-26 August 2011.
- Li X, Hallett SR, Wisnom MR, 2013. Numerical investigation of progressive damage and the effect of layup in overheight compact tension tests. Composites Part A, online.
- Mukhopadhyay S, Jones MI, Hallett SR, 2013. Modelling of out-of-plane fibre waviness; tension and compression tests, ECCOMAS Thematic Conference on the Mechanical Response of Composites, September 2013.
- Nixon-Pearson OJ, Hallett SR, Withers P and Rouse J, 2013. Damage development in open hole composite specimens in fatigue, submitted.
- Wisnom MR, 2010. Modelling discrete failures in composites with interface elements. Composites Part A 41:795–805.