An Experimental Study of the Fracture Behaviour of Stitched RFI Composites – Evaluation of the Damage Process Zone to Calibrate a Strain-Softening Model

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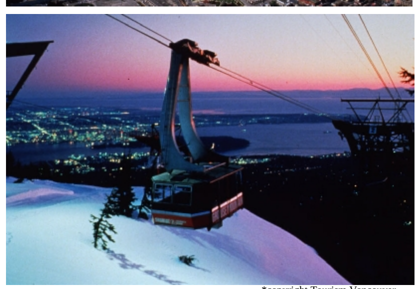

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Outline

- Introduction
- Materials
- OCT Testing
- Post OCT Tests
- Damage
- Preview of Numerical Predictions
- Conclusions
- Future Work

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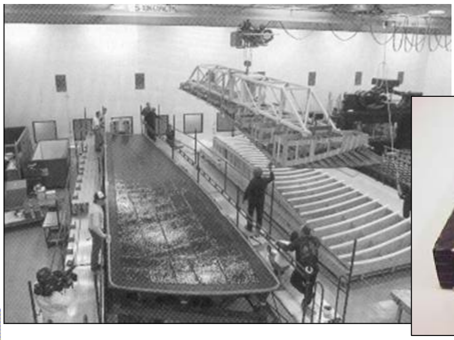
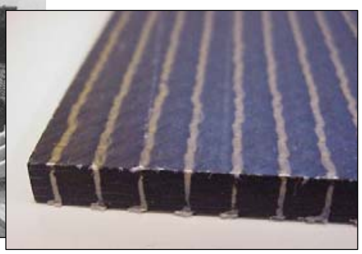
Stitched Resin Film Infused Materials

- S/RFI is one approach to compensate for poor out-of-plane properties of composite laminates
- The aim is to improve damage tolerance to a level competitive with metallic materials, as well as other benefits





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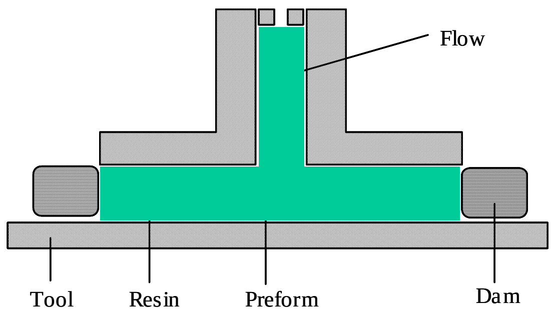
Stitched Resin Film Infused Materials

- Produced by stitching a preform
- Resin is infused via vacuum and heat from a partially cured film placed under the preform
- S/RFI material used here developed by The Boeing Company under the NASA ACT Program



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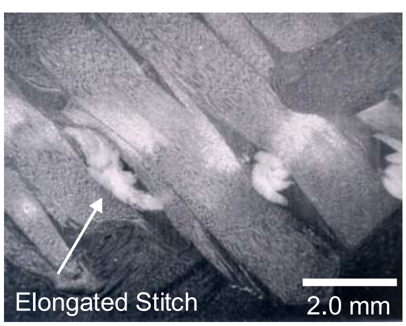
Stitched Resin Film Infused Material

- Advantages of stitching
  - Shown to improve delamination resistance under low velocity impact loading
  - Large stitched preforms easier to handle, cost effective
  - Removes the need for traditional mechanical fasteners
- Disadvantage of stitching
  - Imparts fibre damage; spreading and breakage

Top of Stitch



Side of Stitch

Aims of Study

There appears to have been no research into the effect of stitching on fracture response of notched composites. Other research has been mainly involved with inhibiting the initiation of damage or reducing amount of delamination caused by impact loading. Thus:

1. To gain a fundamental understanding of how damage initiates and propagates in notched RFI materials.
   - allowing for more accurate physically based inputs to a continuum damage mechanics strain softening model
2. To investigate what effect the introduction of stitching may have on in-plane fracture response of notched RFI materials.

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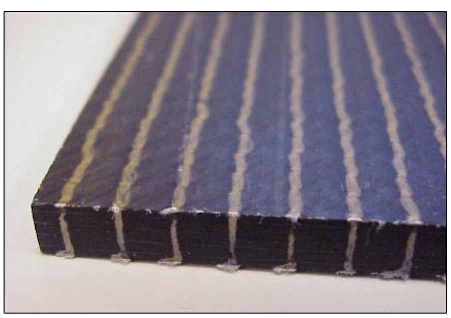
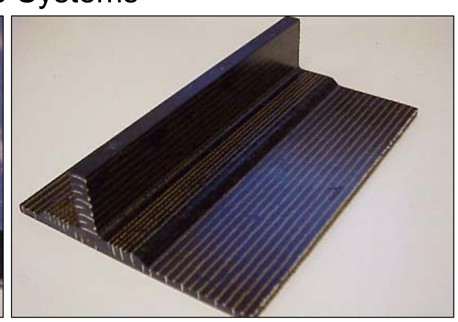
Materials Examined in this Study

Stitched and Unstitched Resin Film Infused (RFI) Laminate Systems



Stitched/RFI Panel



Panel and Stiffener – joined by Kevlar® Stitching

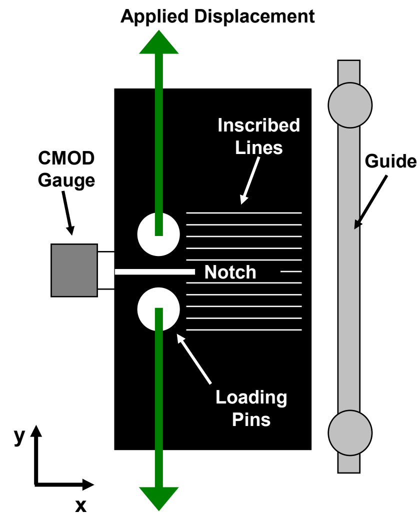
Carbon Fibre (std. and intermediate modulus fibres) – Epoxy Resin (3501-6)

Lay-up $[+45/-45/0_2/90/-45/+45]_s$ (where s=4, 5 or 6)

though-thickness reinforcement (S) compared to none (U)

Experimental Method
Overheight Compact Tension (OCT) Tests

- Overheight Compact Tension (OCT) test methodology based on work of Kongshavn and Poursartip[1].
- Loaded from pins on notch flanks
- Saw-cut slightly blunt notch
- Lines inscribed to measure local surface displacements (line analysis)
- Extensometer records crack mouth opening displacement (CMOD) of notch



[1] Kongshavn and Poursartip, 1999

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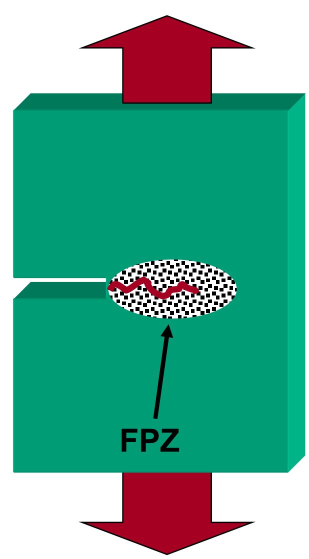
Why use the OCT?

- Geometry has been shown to promote stable damage growth in tape composites
- Small specimen size
  - 207× 104 mm
  - Material waste kept to a minimum
- Damage includes fibre fracture in a small specimen
  - usually only seen in large specimens
- Fracture Process Zone (FPZ) is large enough for post-test analysis.



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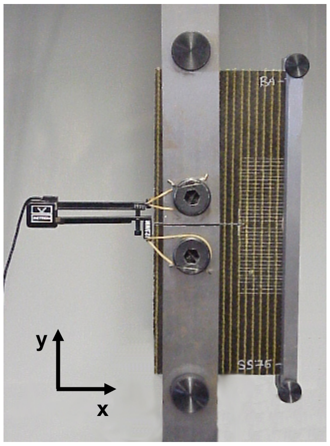
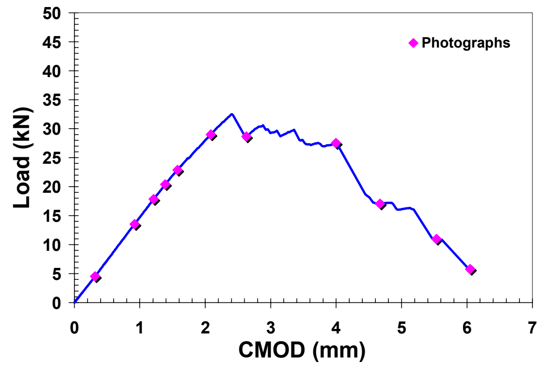
Test Apparatus



Specimen loaded in Instron Universal Testing Machine

Load – Crack Mouth Opening Displacement Curve



Typical Stitched 5-stack Material Behaviour (Test # SS67-s0)

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Tests Conducted

17 Tests Performed			
Unstitched (4/6)		Stitched (4/5/6)	
4		13	
0°	90°	0°	90°
2	2	10	3

- Specimens were tested in both the primary principal (0°) and the transverse principal (90°) directions
- Fewer unstitched experiments were performed as results compared favourably with data from previous research

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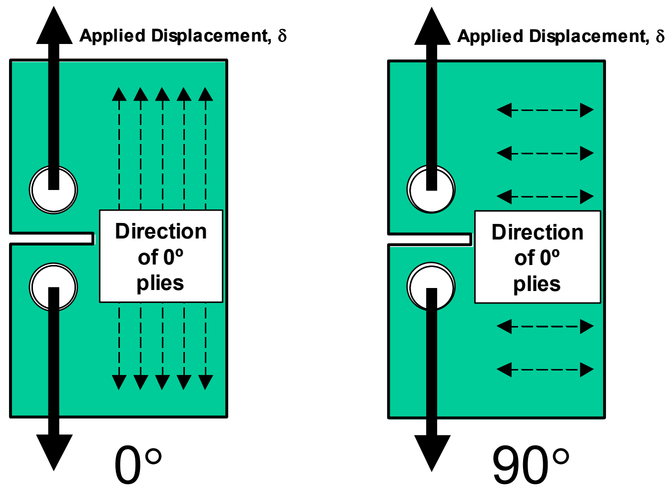
Test Orientations

Specimens were tested in both the primary principal (0°) and the transverse principal (90°) directions.



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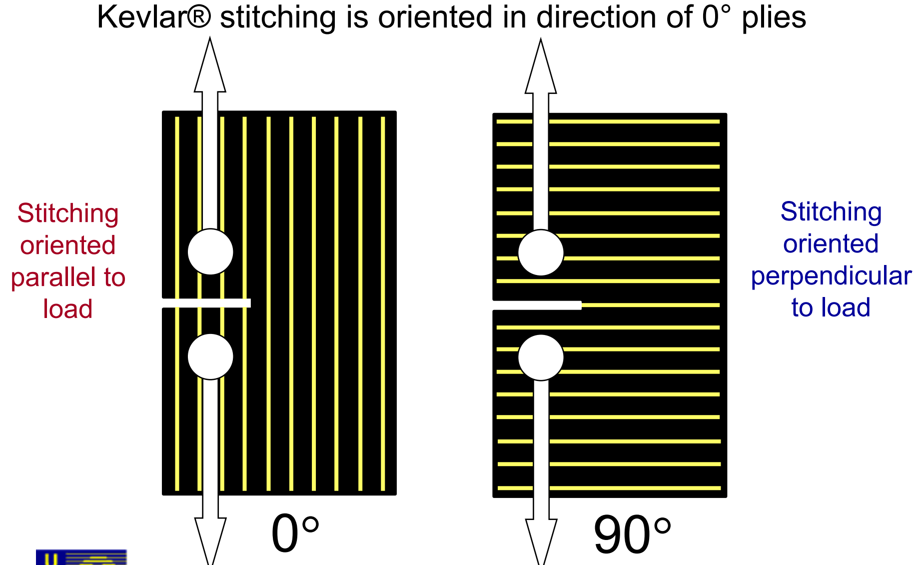
Test Directions (Stitching)

Kevlar® stitching is oriented in direction of 0° plies



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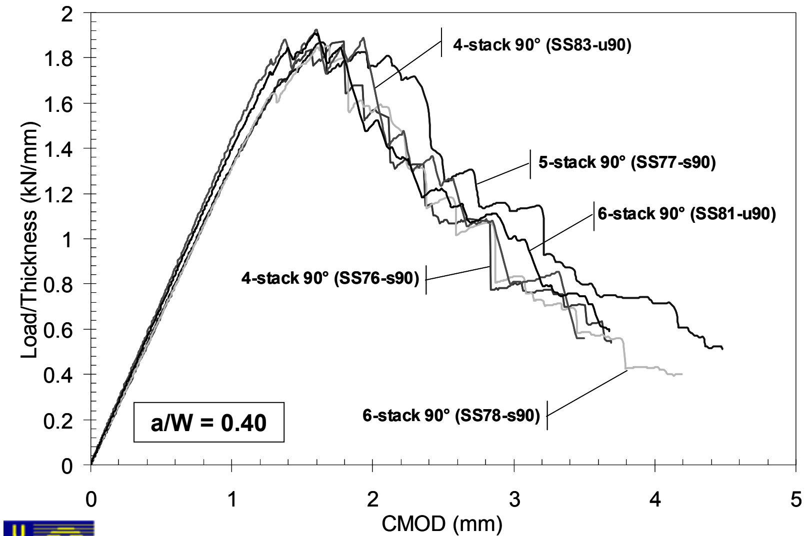
Effect of Thickness and Stitching on 90º Specimens



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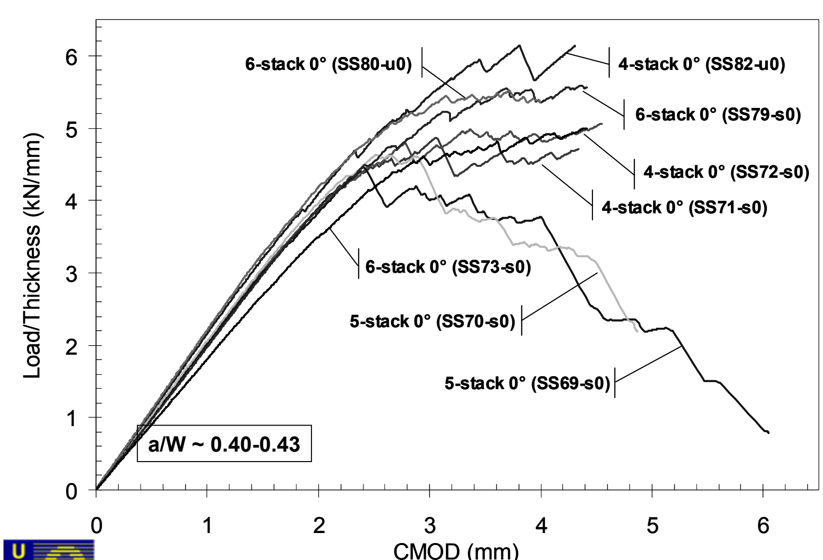
Effect of Thickness and Stitching on 0º Specimens



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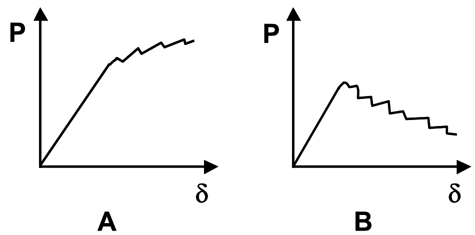
Summary of P-δ Response Types



	Stitched		Unstitched	
	0°	90°	0°	90°
4	A	B	A	B
5	B	B	-	-
6	A	B	A	B

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Post Test Analysis

- Used to evaluate the fracture response
  - Damage initiation and propagation
- To investigate the damage evolved in Fracture Process Zone:
  - ***Sectioning --*** (fibre damage, delamination, matrix damage)
  - ***Deplying --*** (fibre damage, fracture path)
- To investigate progression of damage across specimen width
  - ***Surface Line Displacement Analysis***
    - measures material displacement in front of notch tip

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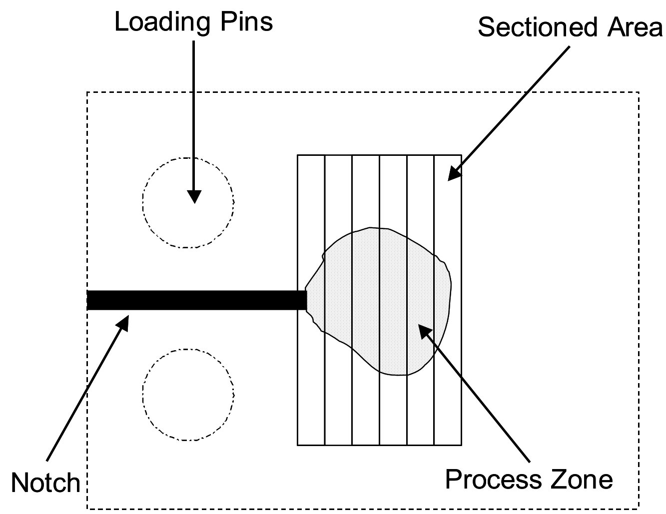
Sectioning



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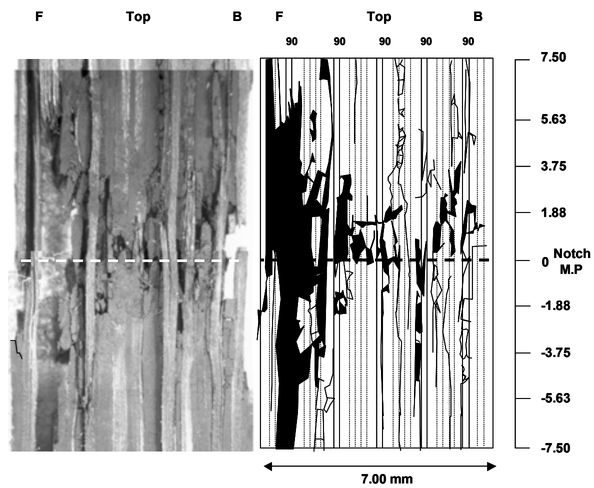
Sectioning (Example)



Cross-sectioning technique performed on a stitched 5-stack 0° specimen (SS70-s0-B) at 2.00 mm in front of the notch tip.

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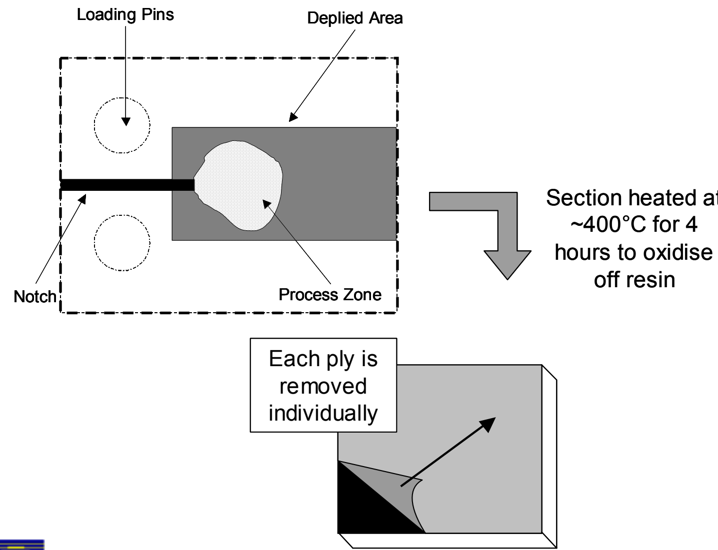
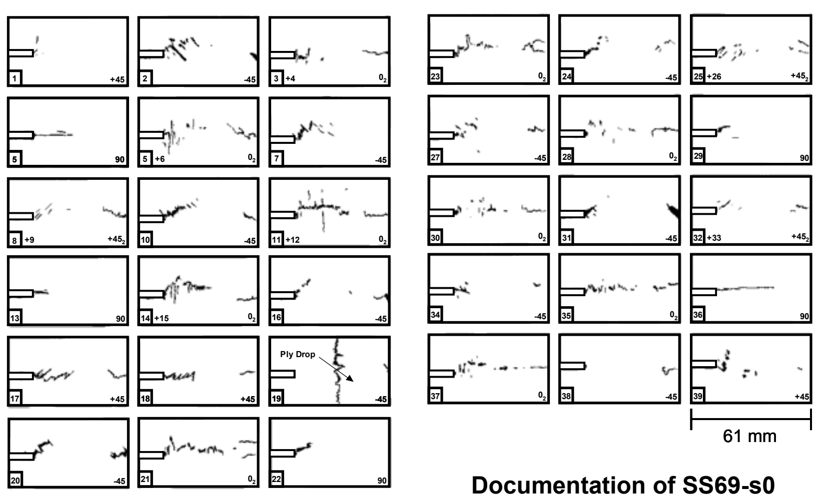
Deply



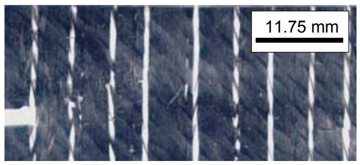
Deply (Example)

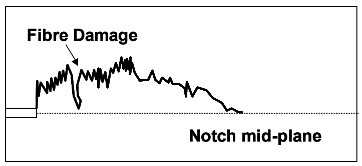


Documentation of SS69-s0
5-stack S/RFI 0°

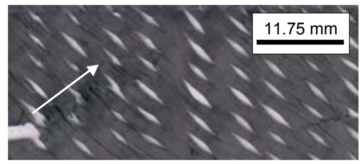
Significant Fibre Breakage

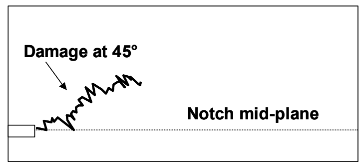
This example: 5-stack 0°





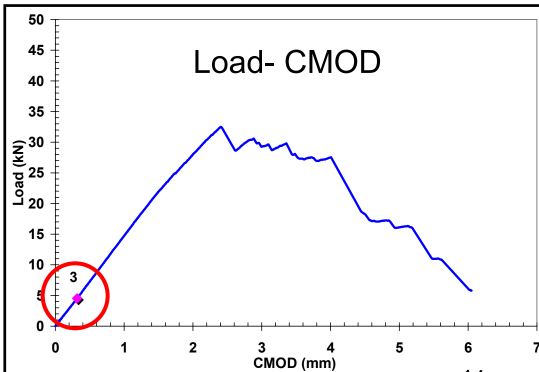
damage growth in 0° plies

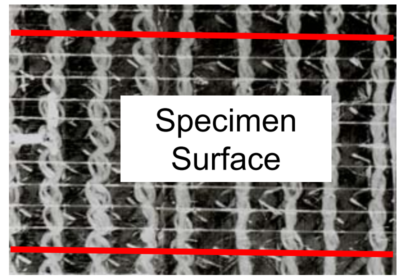


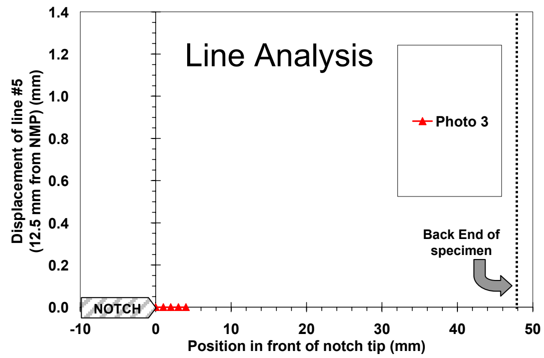


damage growth in -45° plies

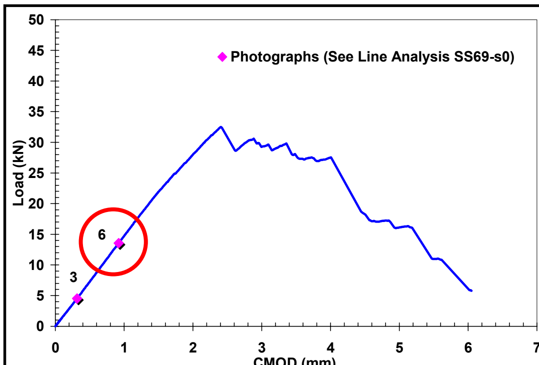
Surface Line Analysis

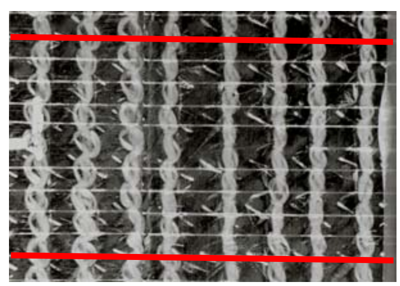


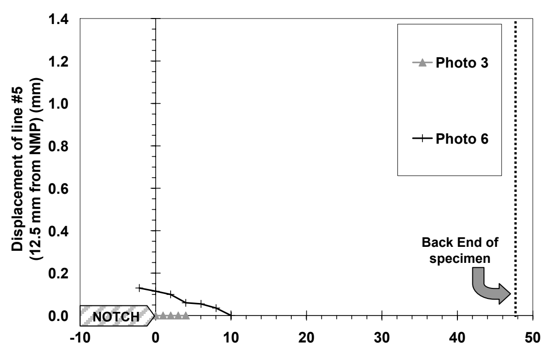




Relating P-CMOD curves to Surface Line Analysis Plots

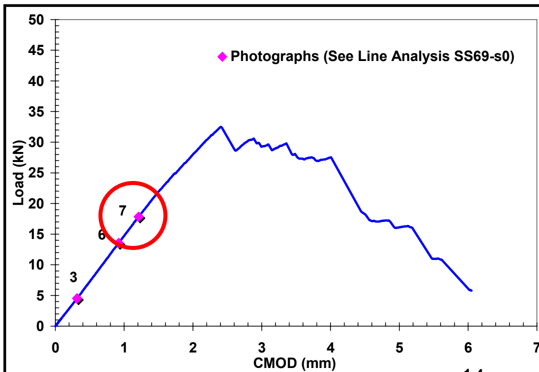


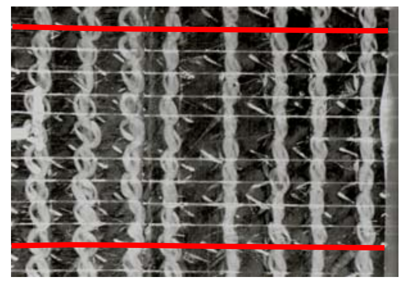


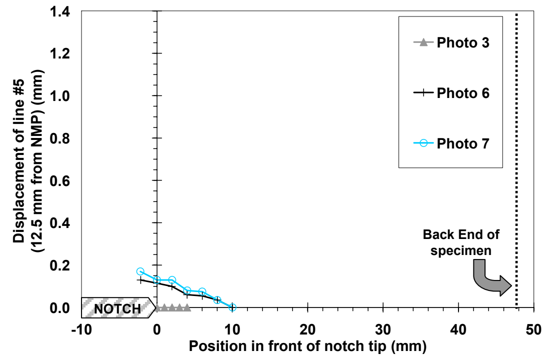


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 6

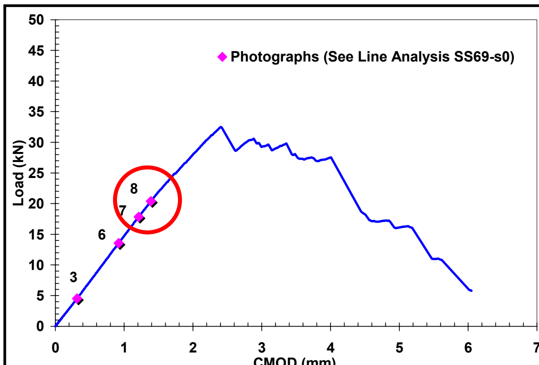


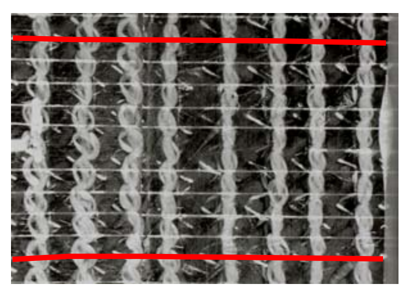


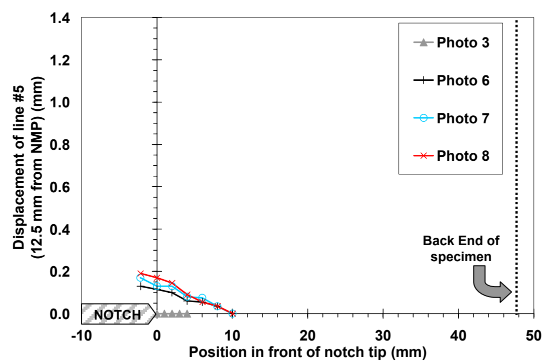


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 7

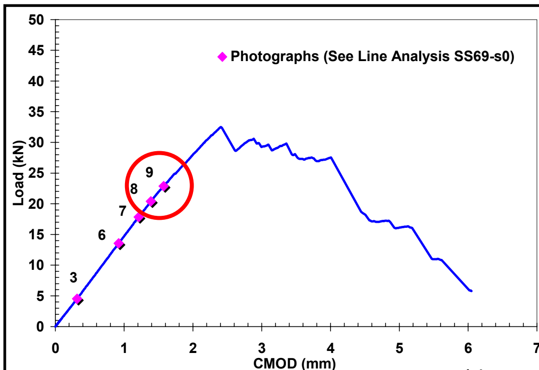


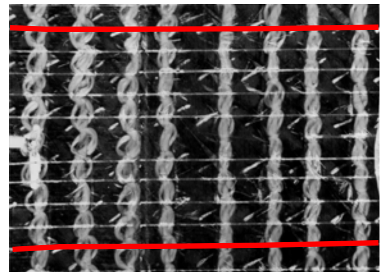




Relating P-CMOD curves to Surface Line Analysis Plots

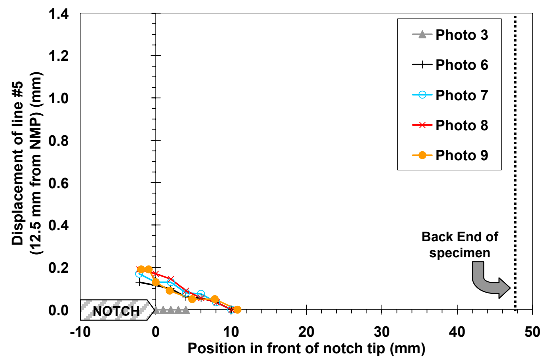
Photo 8

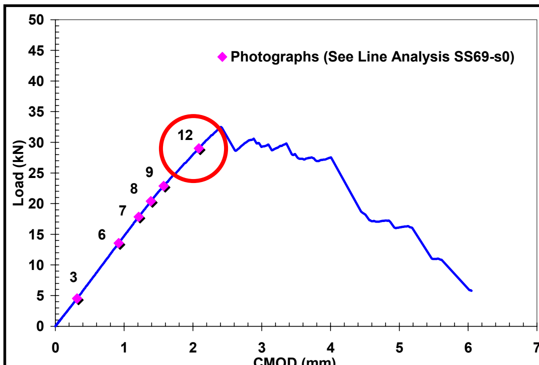


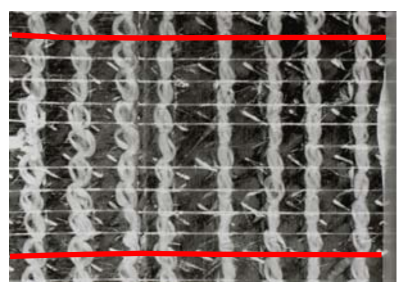


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 9

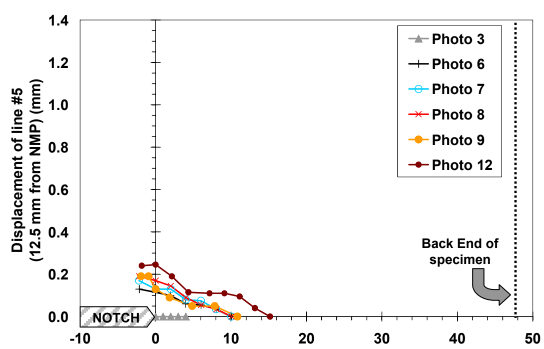


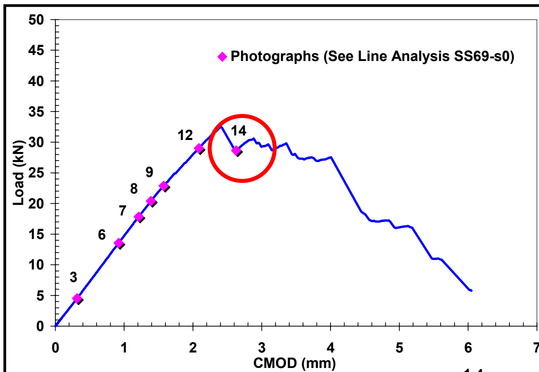


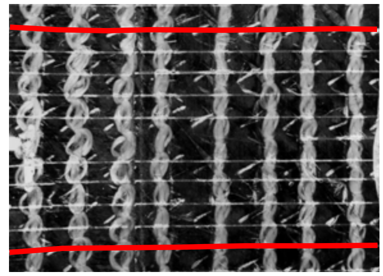


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 12

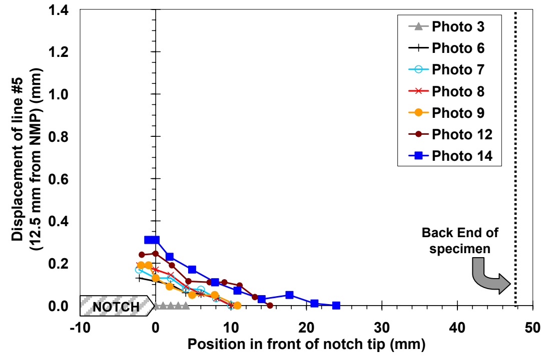


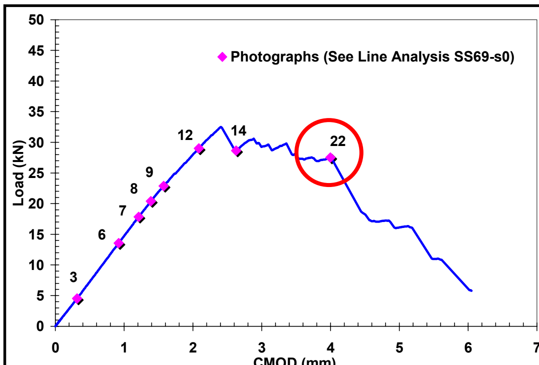


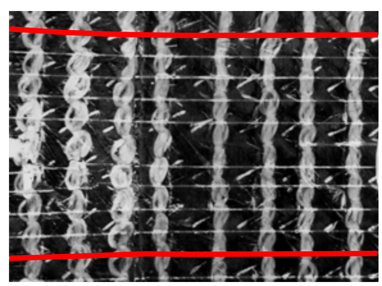


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 14

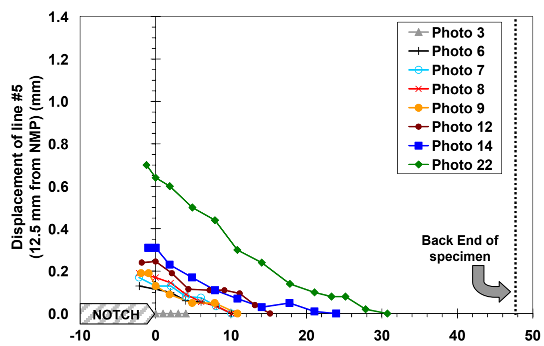


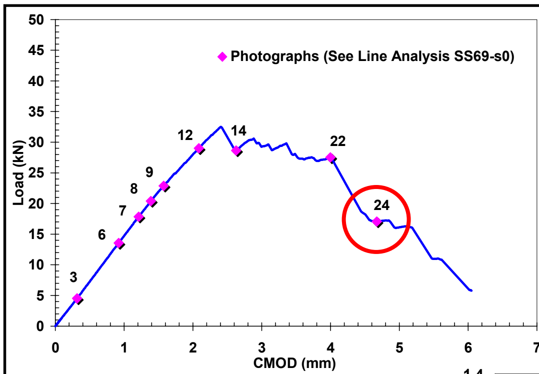


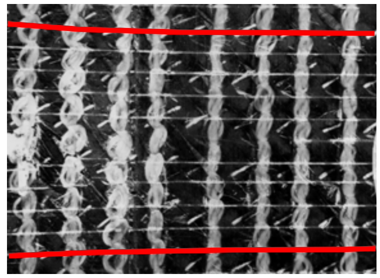


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 22

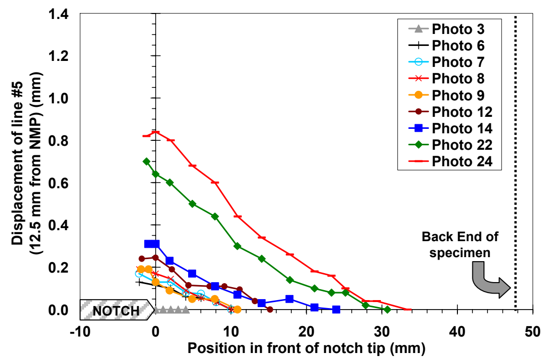


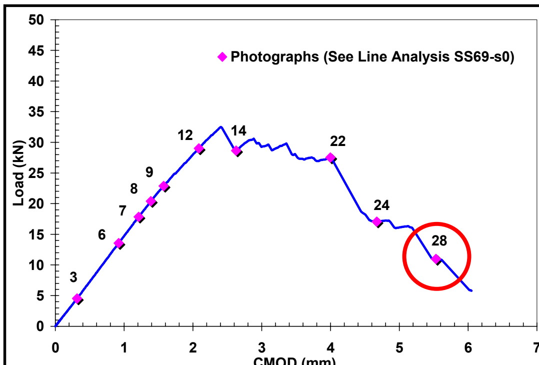


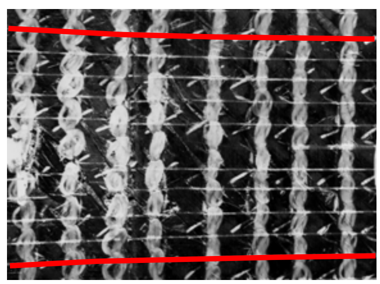


Relating P-CMOD curves to Surface Line Analysis Plots

Photo 24

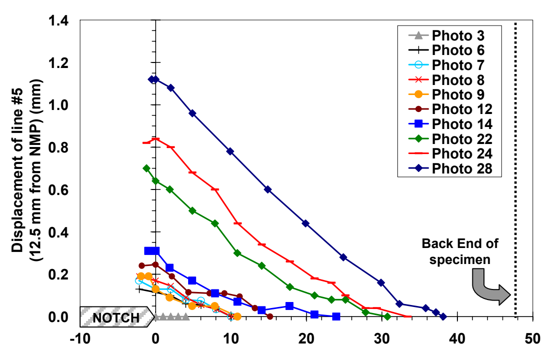


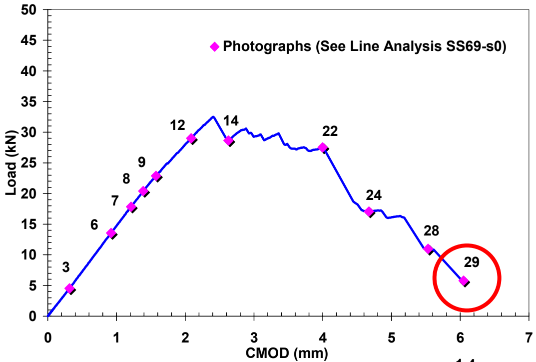


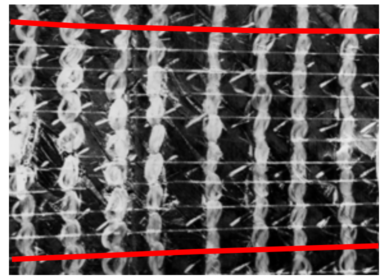


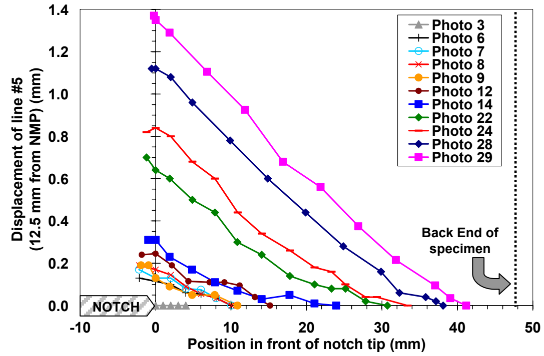
Relating P-CMOD curves to Surface Line Analysis Plots

Photo 28







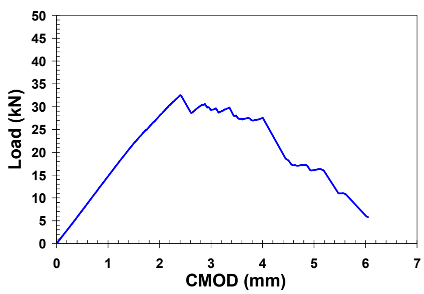


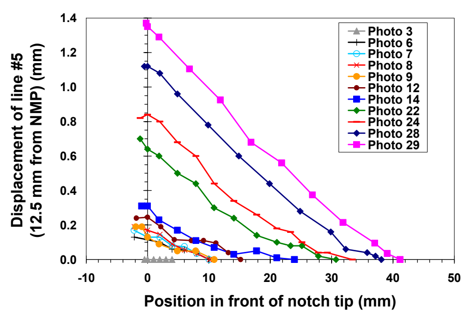
Relating P-CMOD curves to Surface Line Analysis Plots

Photo 29

Correlation of P-CMOD Curves and Line Analysis

SS69-s0 Stitched 5-stack





- Self-similar damage growth is associated with:
  - load-softening behaviour in P-CMOD
  - steady moving damage front in Line Analysis plot

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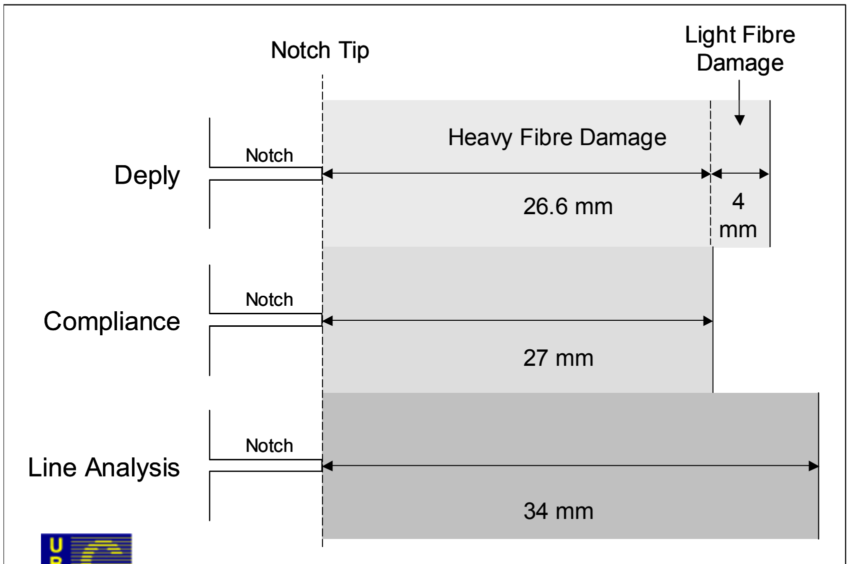
Techniques are consistent



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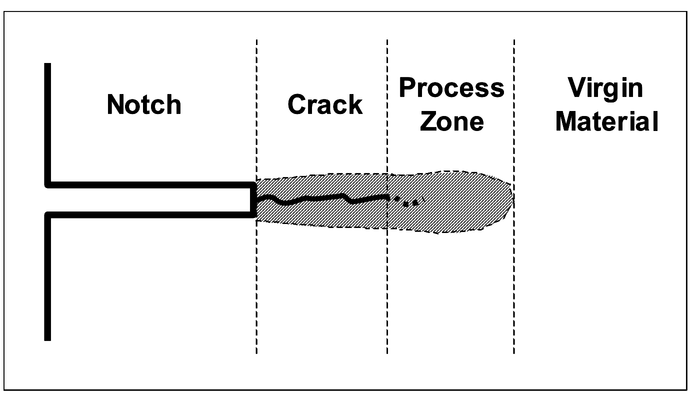
Self-similar Crack Growth (A)



All 90º and 5-stack 0º materials

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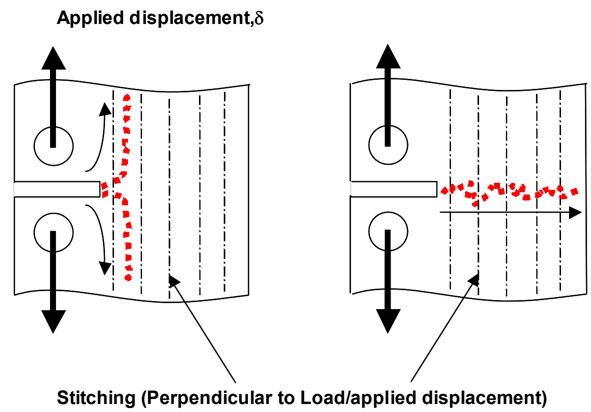
0º Behaviour: 4 and 6-stack vs. 5-stack

4 and 6-stack 0º Behaviour

Stitched and Unstitched

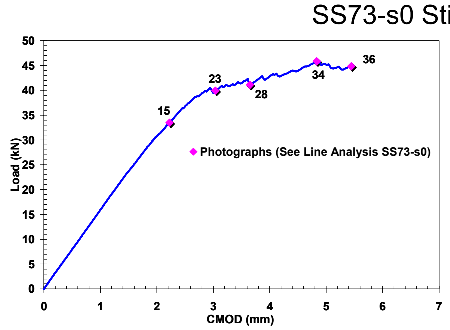


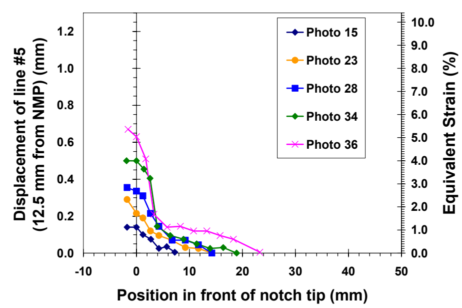
5- stack (and 4, 5 and 6-stack 90º Behaviour)

- Only the stitched 4 and 6-stack 0°did not show significant amount of fibre damage
  - delamination damage, blunting few millimeters from notch tip

Correlation of P-CMOD Curves and Line Analysis

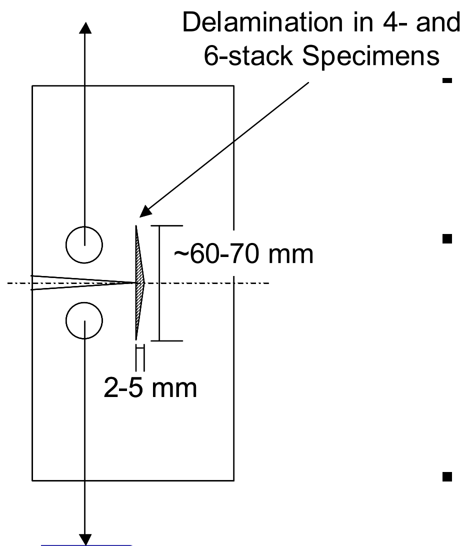
SS73-s0 Stitched 6-stack





- Blunting (Delamination) fracture response is associated with:
  - absence of load-softening in P-CMOD
  - characteristic kinks in the Line Analysis plot

Blunting and Specimen Size Effect



- There was no self-similar crack growth in the OCT specimen for the 4 and 6-stack 0º materials
- However, this is because the damage height is 60-70 mm as opposed to the ~5 mm seen for the all 90º specimens and 5-stack 0º material
- To get self-similar crack growth, specimen size must be large enough

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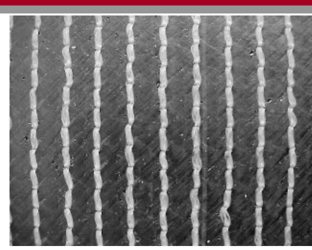
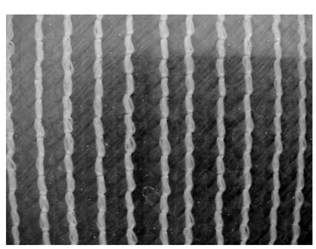
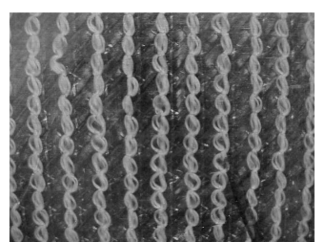
Surface Loops in stitched/RFI material



4-stack



6-stack



5-stack

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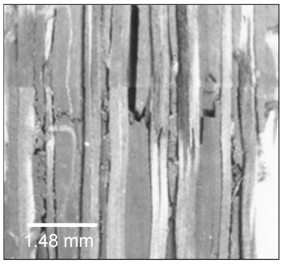
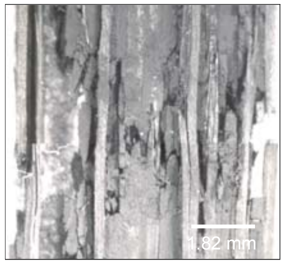
Tight Stitching vs. Loose Stitching

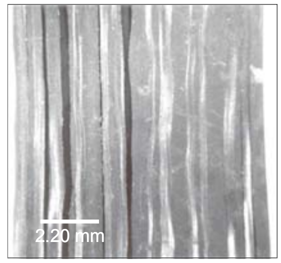
Sections 2 mm ahead of notch at notch mid-plane



4-stack (SS70-s0)
stitched 0°
Blunting Response
Tight Stitching



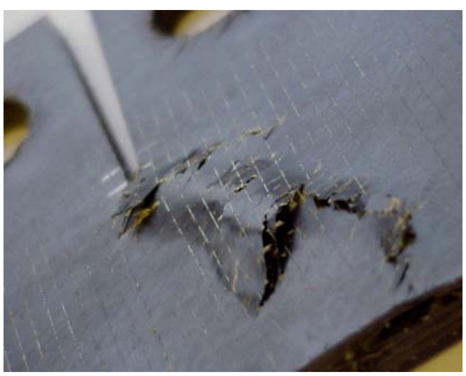
5-stack (SS69-s0)
stitched 0°
Brittle Response
Loose Stitching



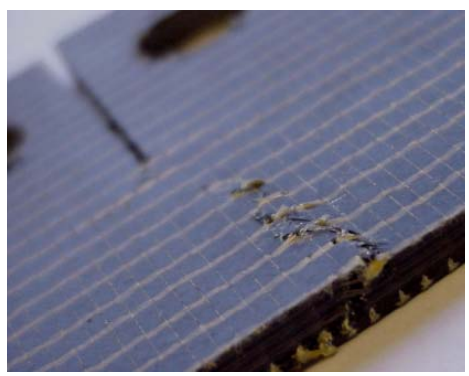
6-stack (SS73-s0)
stitched 0°
Blunting Response
Tight Stitching

- For this notched geometry, tight stitching does not inhibit the natural tendency of these materials to delaminate
  - Damage height does not change as much

Stitching Inhibits Surface Delamination



4-stack un-stitched 0° specimen (SS82-u0)

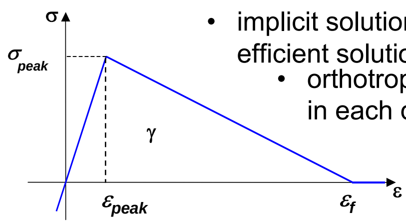


4-stack stitched 0° specimen (SS72-s0)

Strain-softening material model

A simple bilinear damage model has been implemented in ABAQUS finite element code.

- Three parameter input:
- fracture energy release rate G_F
- material tensile strength σ_{peak} or strain at σ_{peak}
- initial modulus E_0



- implicit solution scheme allows efficient solution of quasi-static tests
  - orthotropic → parameters defined in each direction

G (J/m^2) = γ x h_e

McClennan M.A.Sc work 2004

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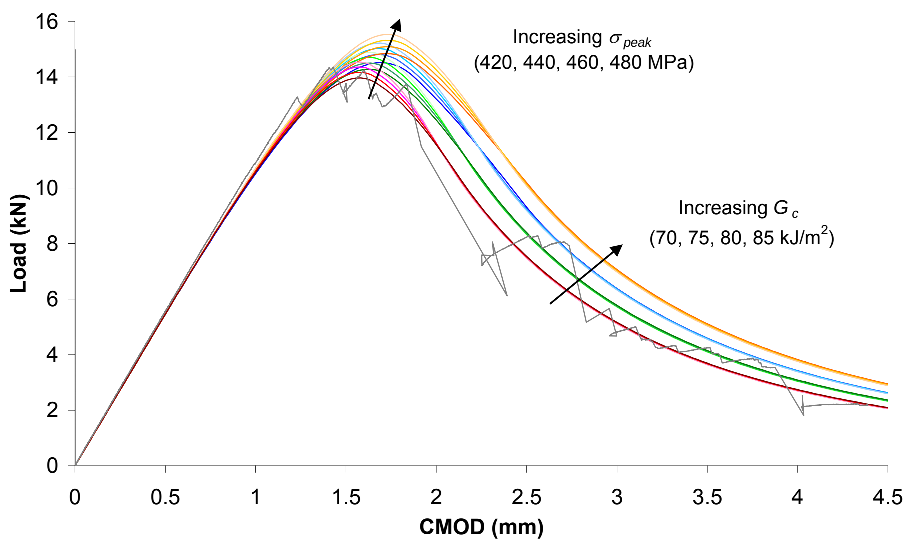
Numerical Predictions: Parametric Study



McClennan M.A.Sc work 2004

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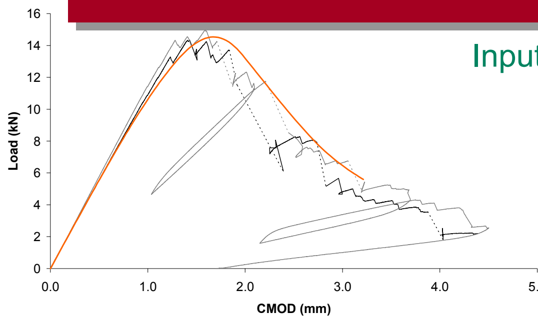
Load - CMOD Results



Input Parameters:

E_0 = 32 GPa

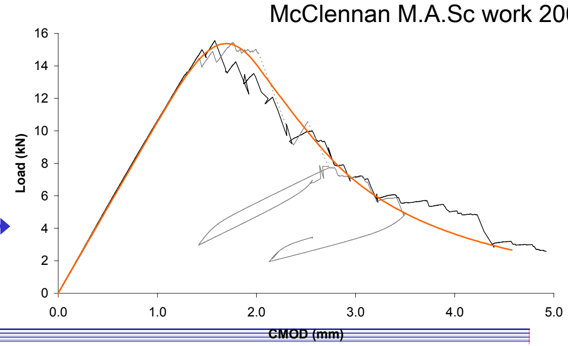
G_F = 80 kJ/m^2

σ_{peak} = 460 MPa

McClennan M.A.Sc work 2004

ρ = 1 mm

ρ = 4 mm



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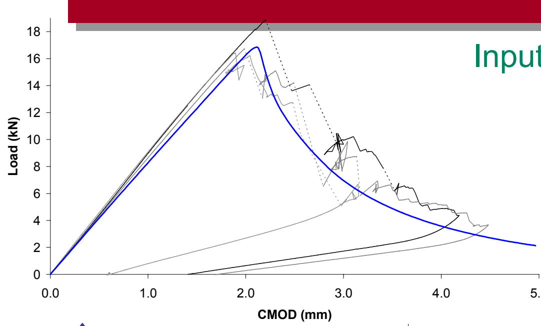
Load - CMOD Results



Input Parameters:

E_0 = 32 GPa

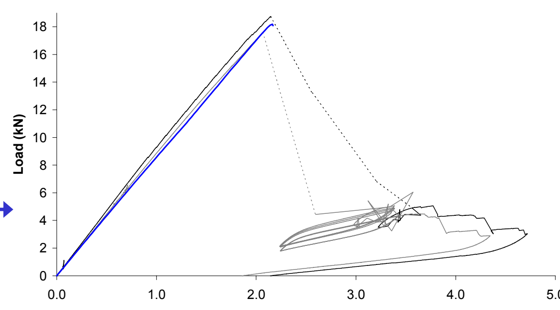
G_F = 80 kJ/m^2

σ_{peak} = 460 MPa

McClennan M.A.Sc work 2004

ρ = 32 mm

ρ = 38 mm



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Conclusions

- Self-similar crack growth consisting of a process zone that coalesces into a through crack observed
  - For 3 out of 4 cases tested using OCT geometry
  - Damage height was ~5 mm, consisting of fibre breakage, matrix cracking and delamination
- One case (0º 4 and 6-stack) did not show self-similar growth, and blunted in this OCT geometry
  - Much larger damage height at ~65 mm, and thus unable to grow in self-similar manner in this OCT geometry
- In this OCT geometry, tight stitching had no effect on behaviour of 0º specimens
  - Large delamination height leading to blunting.
  - Fibre damage due to stitching present but did not affect measured behaviour

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Conclusions (2)

- However, loose stitching, as observed in 5-stack panel, had an effect, inhibiting delamination and leading to self-similar crack growth
  - Poses question regarding stitch tension control and quality control
- Combination of P-δcurves, line analysis, sectioning, and deply provides very coherent and consistent picture of response
  - Combined with other tests such as tensile and bend tests, allows for calibration of damage and strain-softening models
- A simple strain-softening model does good job of predicting response
  - Including transition from stable to unstable response

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