



Universidade do Porto

Faculdade de Engenharia

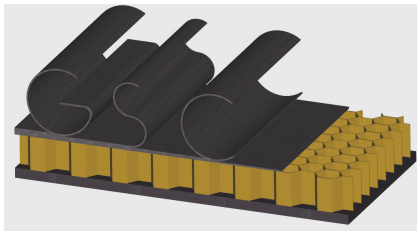
FEUP



Departamento de Engenharia
Mecânica e Gestão Industrial



Instituto de Engenharia
Mecânica e Gestão Industrial



**Imperial College
London**

Aeronautics

The Composites Centre

for research, modelling, testing and training in advanced composites

Modelling failure of laminated composites

17th November 2005

Silvestre T Pinho, P Robinson & L Iannucci

Objective

By using

- physically-based failure onset criteria and
- smeared formulations,

it is possible to reproduce (in FE) key aspects observed during damage propagation in laminated composite materials, during static or dynamic loading.

Outline

Failure onset
FE Implem.
F. Toughness

Matrix

Kinking

Propag.

Smeared

Matrix

Fibre

Applications

Conclusion

- Physically-based failure onset criteria
- Finite element implementation
 - failure propagation
 - smeared formulation and decohesion elements
- Measuring the fracture toughness for different failure modes
- Applications
- Conclusion

Failure onset criteria

Matrix failure. Which fracture plane?

Failure onset

Matrix

Kinking

Propag.

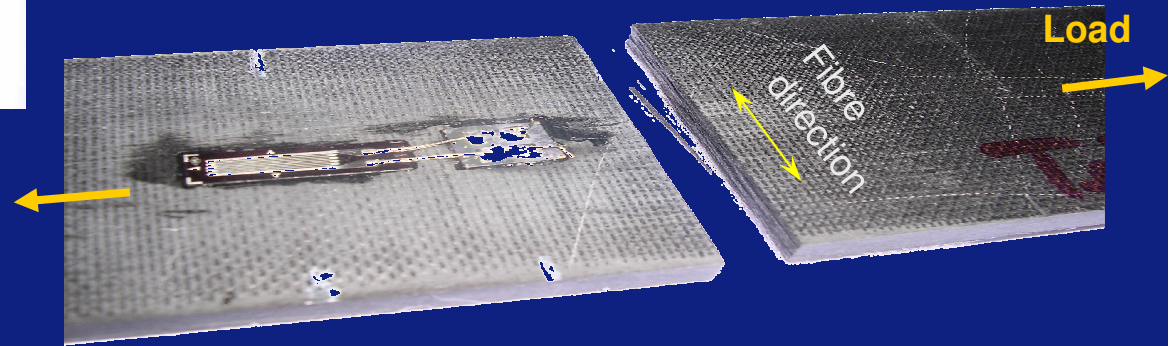
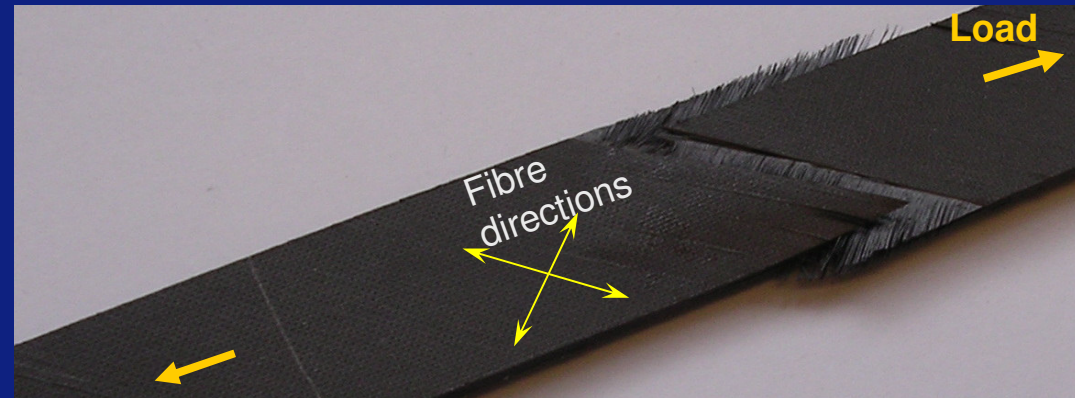
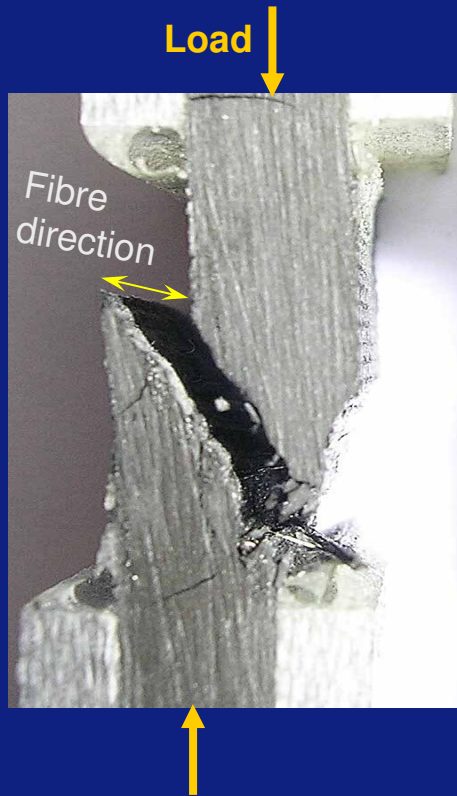
Smeared

Matrix

Fibre

Applications

Conclusion



Failure onset criteria

Matrix failure

Failure onset

Matrix

Kinking

Propag.

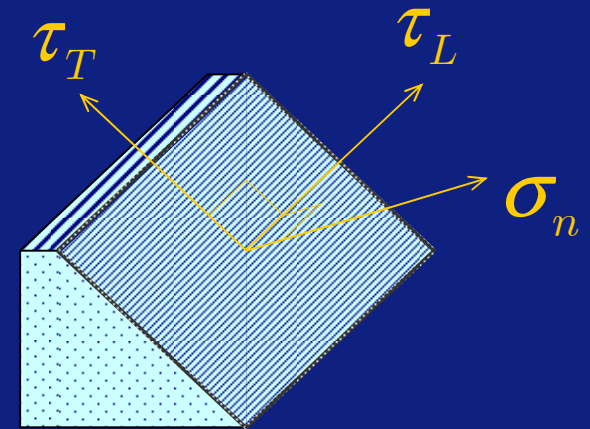
Smeared

Matrix

Fibre

Applications

Conclusion



- The traction on potential fracture planes is computed
- For compression, a 3D version of the Mohr-Coulomb criterion is used to predict failure
- Approach by Puck (1998,2002) and Dávila (2002)

Failure onset criteria

Fibre kinking. Which kink plane?

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

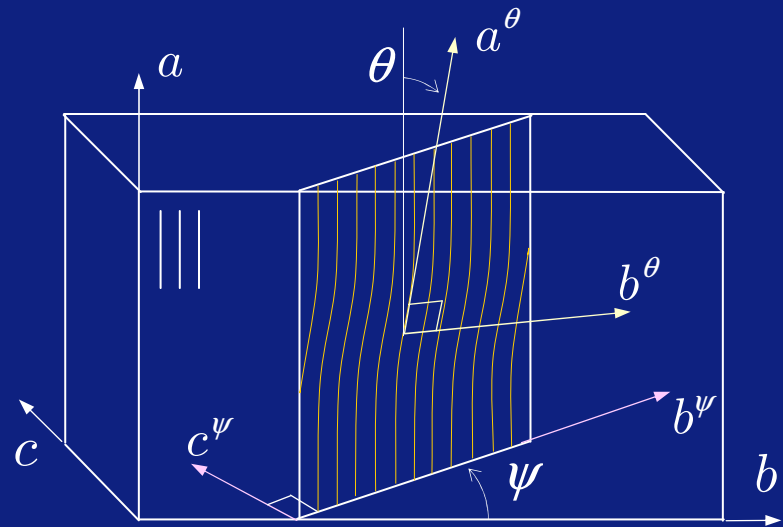
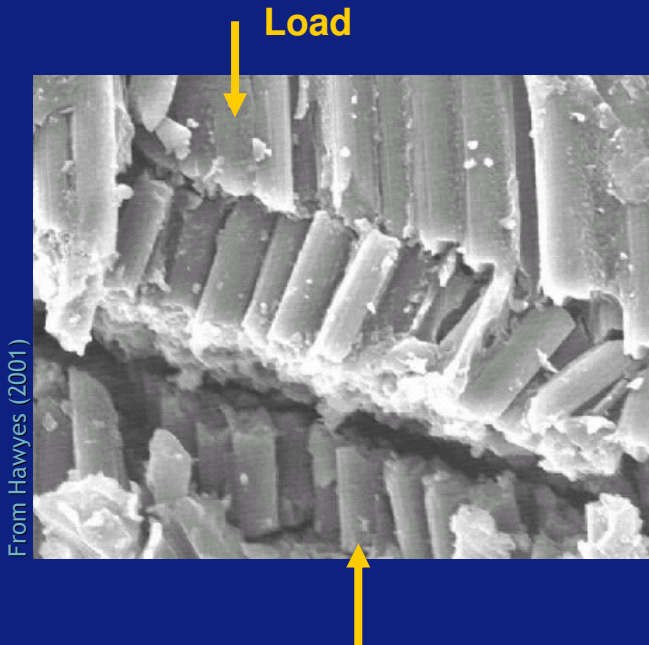
F. Toughness

Matrix

Fibre

Applications

Conclusion



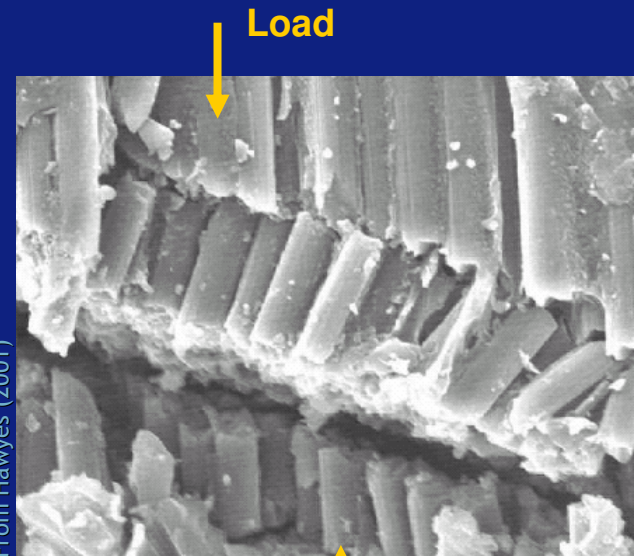
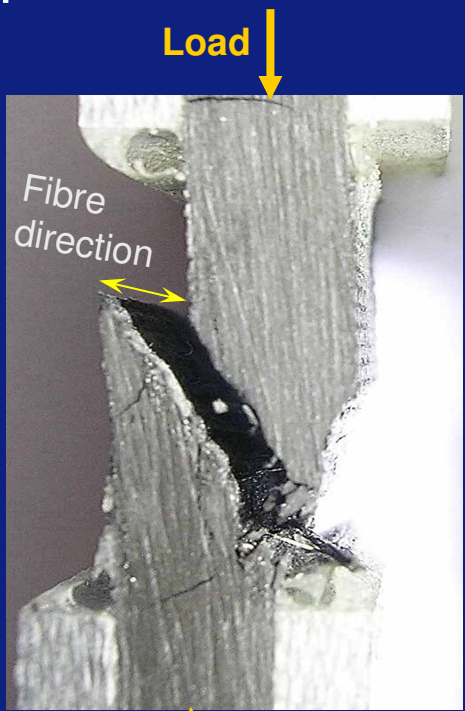
- Fibre kinking is assumed to be a consequence of matrix failure
- Matrix failure results from the high shear stresses due to fibre misalignment (Argon, 1972)

Finite element implementation

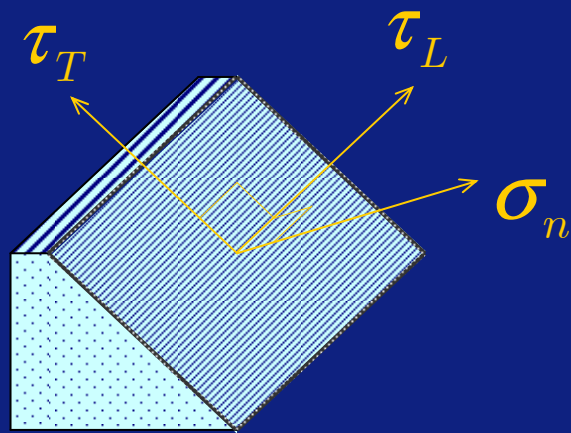
Failure propagation. How to model it?

Failure onset	Matrix
	Kinking
FE Implem.	Propag.
	Smeared
F. Toughness	Matrix
	Fibre
Applications	
Conclusion	

- Reduce traction on the fracture plane to zero



From Hawkes (2001)

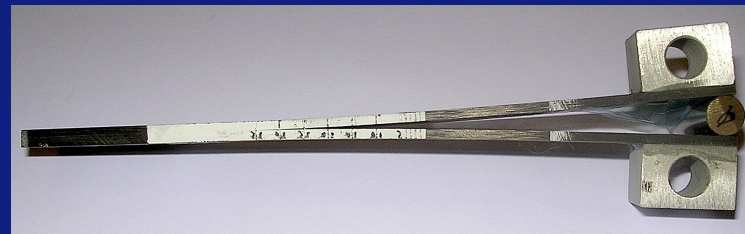


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Finite element implementation

Is mesh-dependency a problem?

Not for delamination.



DCB



4ENF



MMB

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

F. Toughness

Matrix

Fibre

Applications

Conclusion

Finite element implementation

Use of decohesion elements for delamination

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

F. Toughness

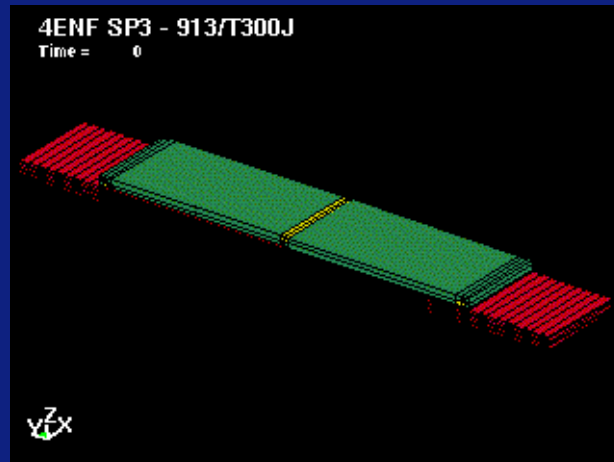
Matrix

Fibre

Applications

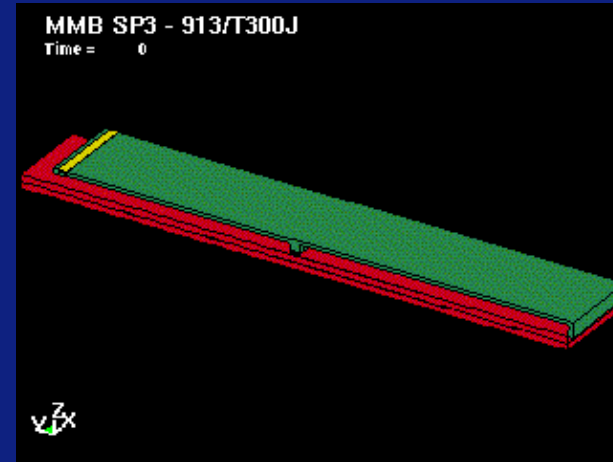
Conclusion

4ENF



DCB

MMB



Finite element implementation

Use of decohesion elements for delamination

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

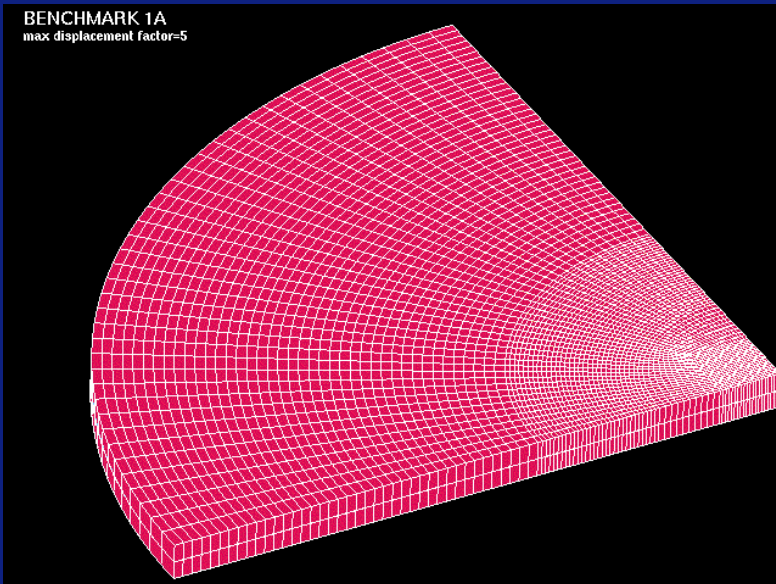
F. Toughness

Matrix

Fibre

Applications

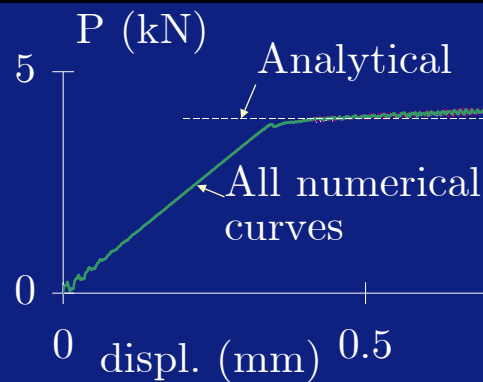
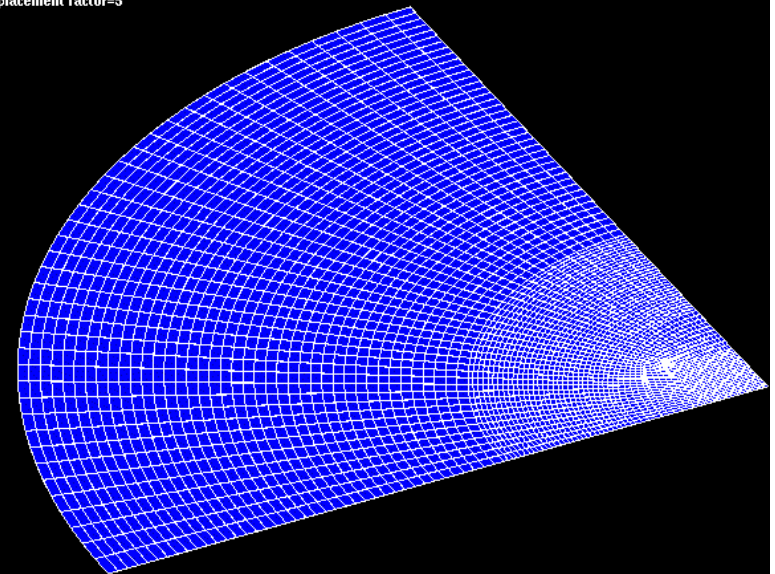
Conclusion



Circular plate with central point load

Delamination at the mid-plane

BENCHMARK 1A
max displacement factor=5



17th November 2005 [more...](#)

Finite element implementation

Smeared formulation

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

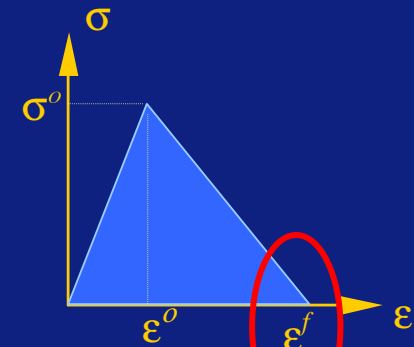
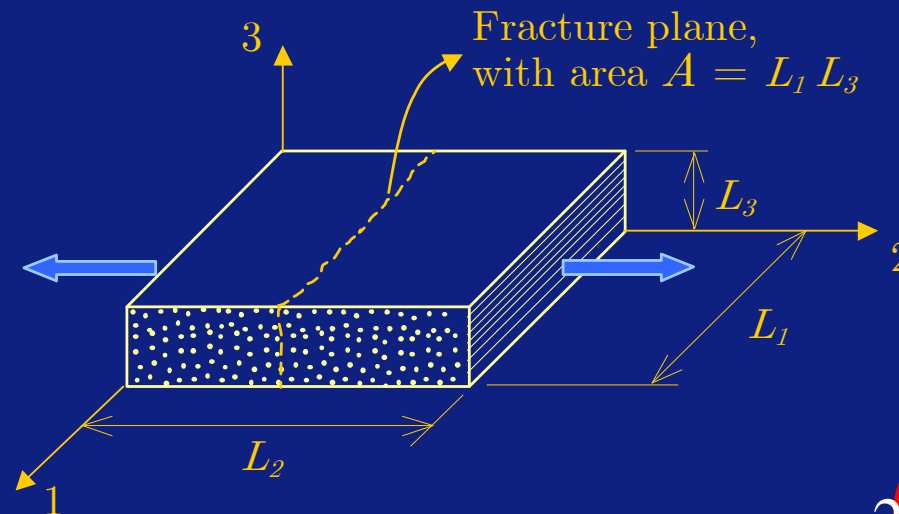
F. Toughness

Matrix

Fibre

Applications

Conclusion



$$\epsilon^f = \frac{2\Gamma}{\sigma^0 L}$$

$$L = \frac{V}{A}$$

- Fracture energy correctly accounted for
- Length parameter in the constitutive law

Fracture toughness

Is it possible to measure?

Failure onset
FE Implem.

Matrix

Kinking

Propag.

Smeared

F. Toughness

Matrix

Fibre

Applications

Conclusion

- For all failure modes of interest?

Fracture toughness

Intralaminar, matrix tensile fracture

F. Toughness

FE Implem.

Failure onset

Matrix

Matrix

Kinking

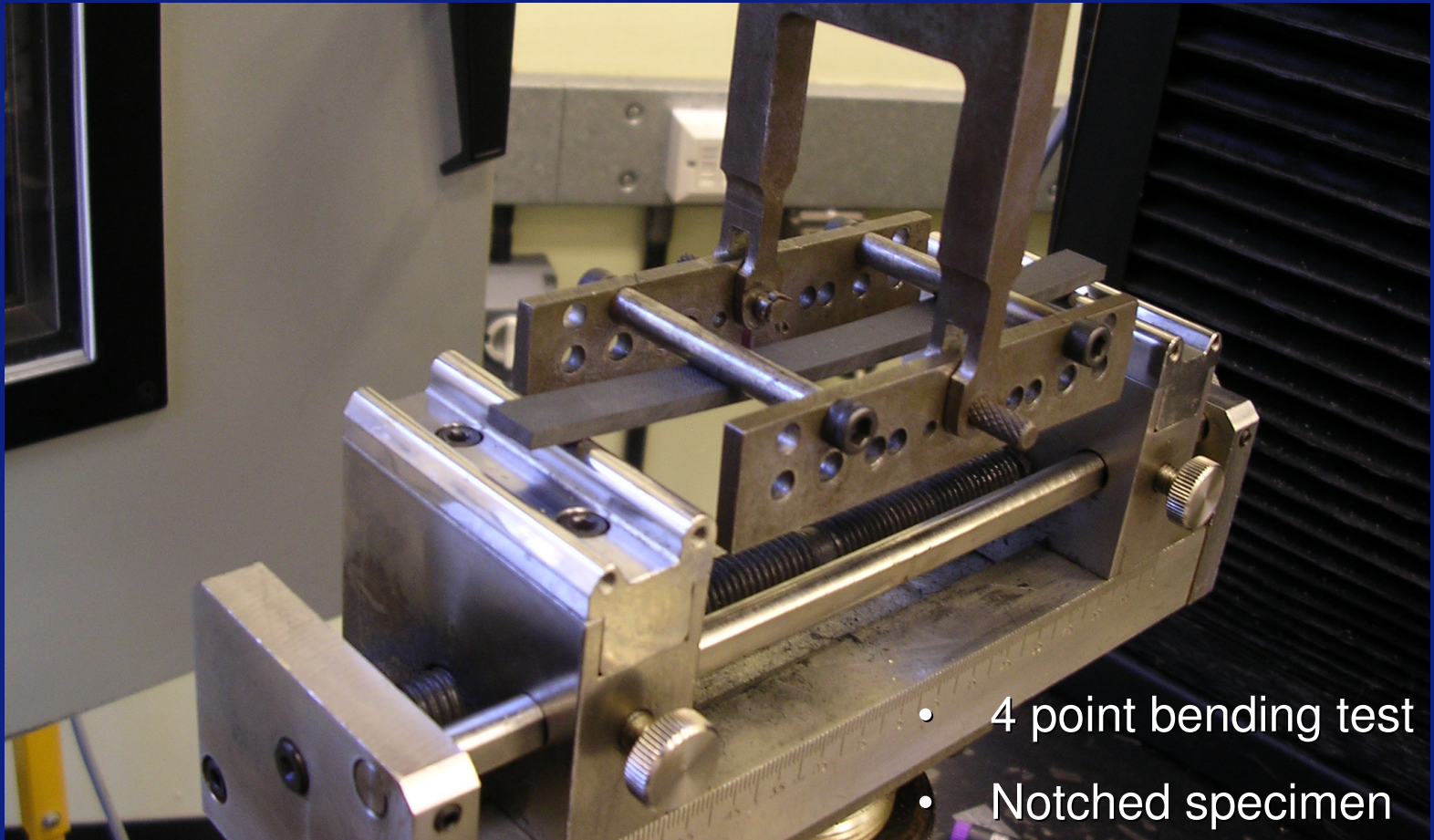
Propag.

Smeared

Fibre

Applications

Conclusion



- 4 point bending test
- Notched specimen

Fracture toughness

Intralaminar, matrix tensile fracture

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

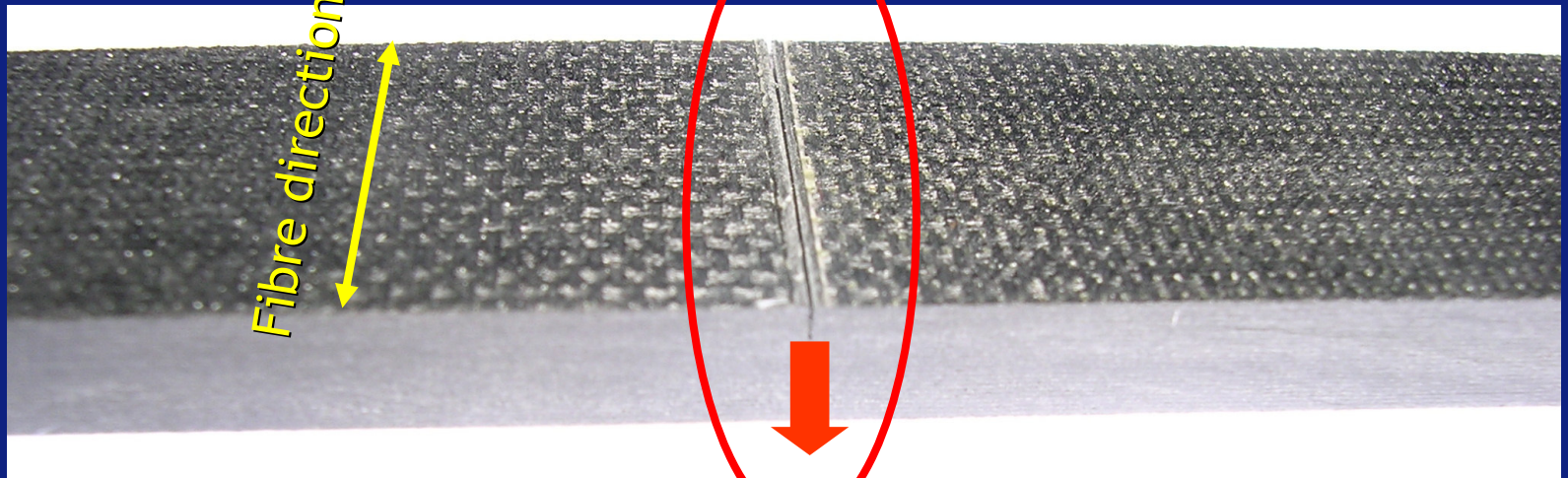
F. Toughness

Matrix

Fibre

Applications

Conclusion



Fracture toughness

Intralaminar, matrix tensile fracture

Failure onset
FE Implem.

Matrix

Kinking

Propag.

Smeared

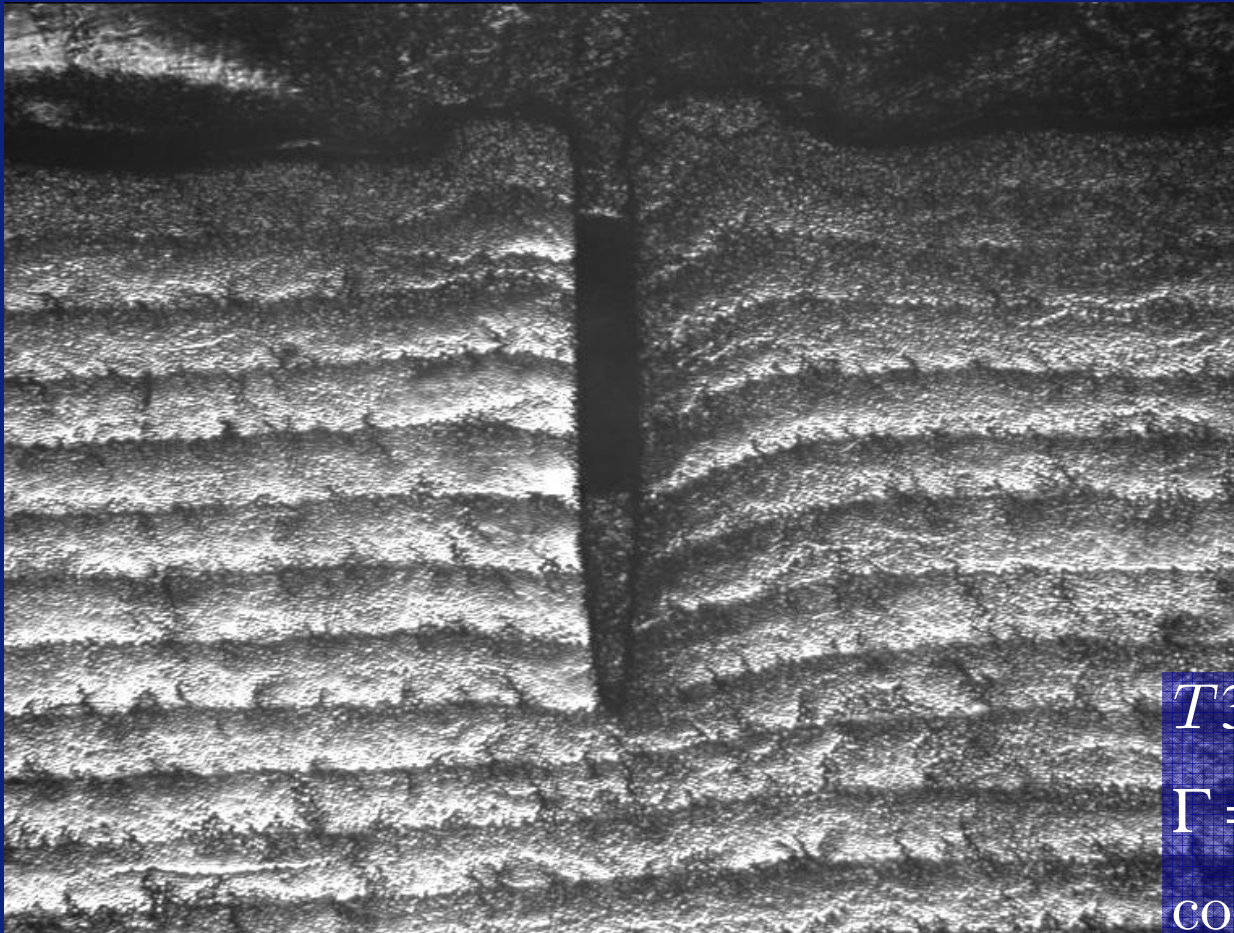
F. Toughness

Matrix

Fibre

Applications

Conclusion



T300/913

$$\Gamma = 211 \text{ J/m}^2$$

coef. var. = 6.4%

Fracture toughness

Fibre tensile fracture

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smear

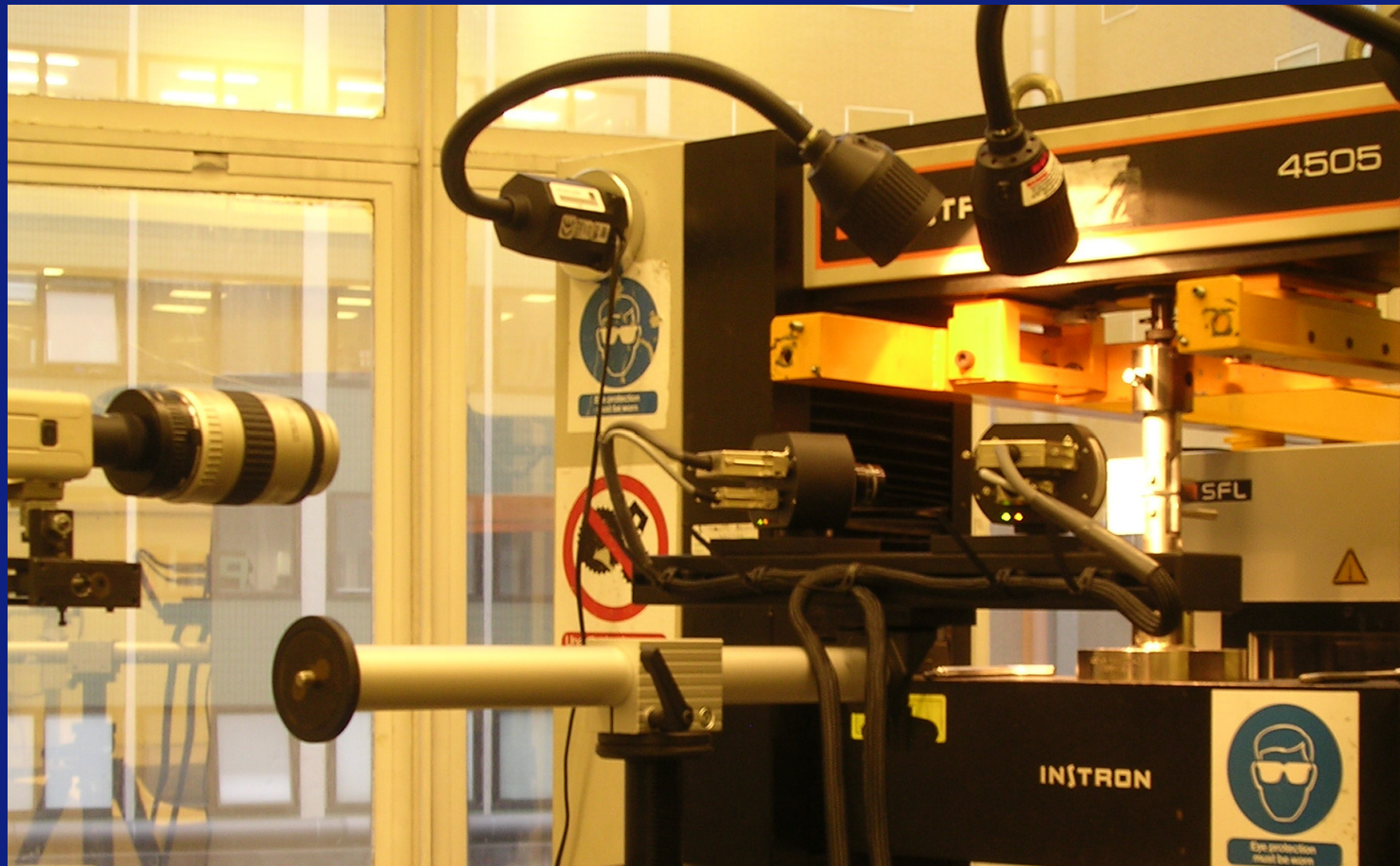
F. Toughness

Matrix

Fibre

Applications

Conclusion



Fracture toughness

Fibre tensile fracture

FE Implem. Failure onset

Matrix

Kinking

Propag.

Smearred

F. Toughness

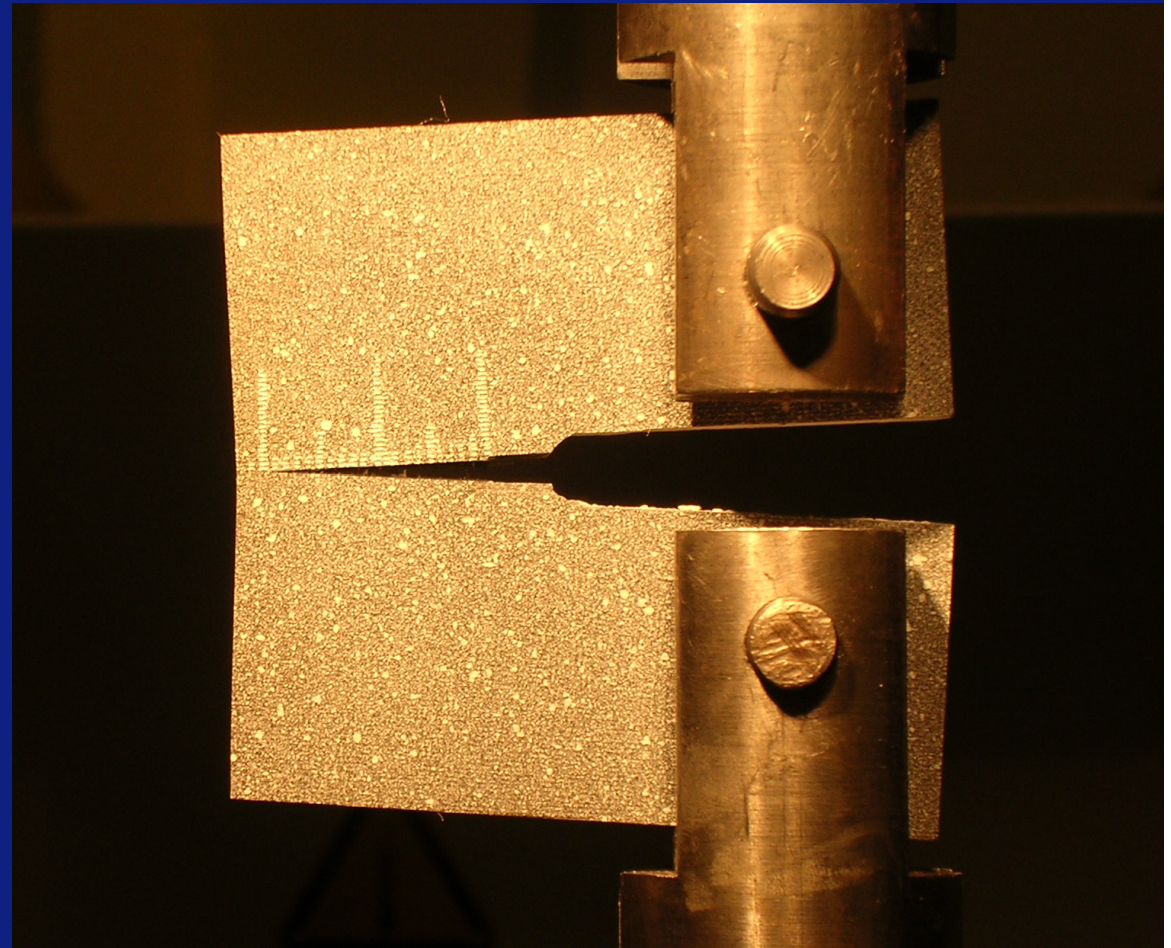
Matrix

Fibre

Applications

Conclusion

- CT scpecimen
- $(0,90)_{nS}$ layup



Fracture toughness

Fibre tensile fracture

Failure onset
FE Implem.

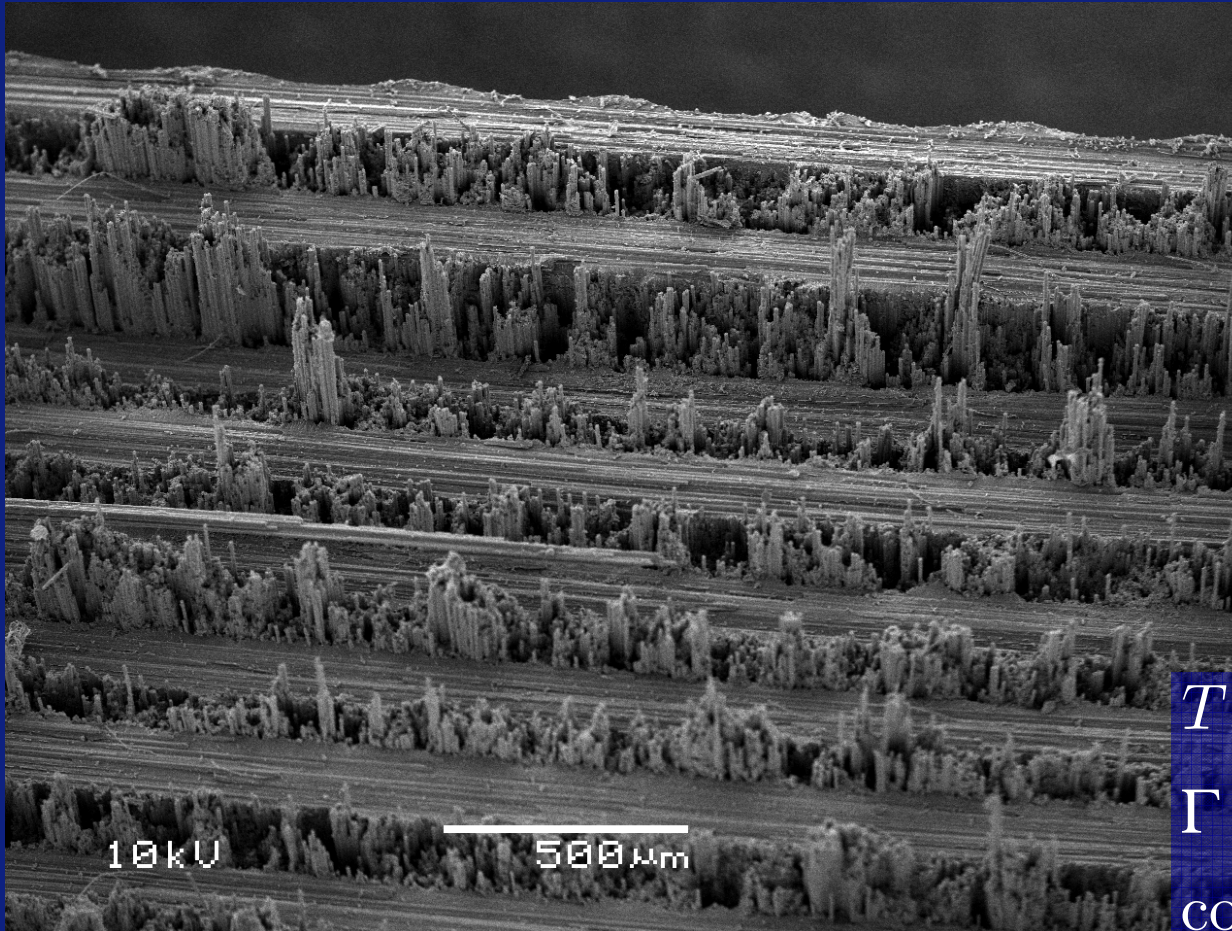
Matrix
Kinking

Propag.
Smeared

F. Toughness

Matrix
Fibre

Applications
Conclusion



T300/913

$\Gamma = 91.6 \text{ kJ/m}^2$

coef. var. = 6.7%

Fracture toughness

Fibre kinking

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

F. Toughness

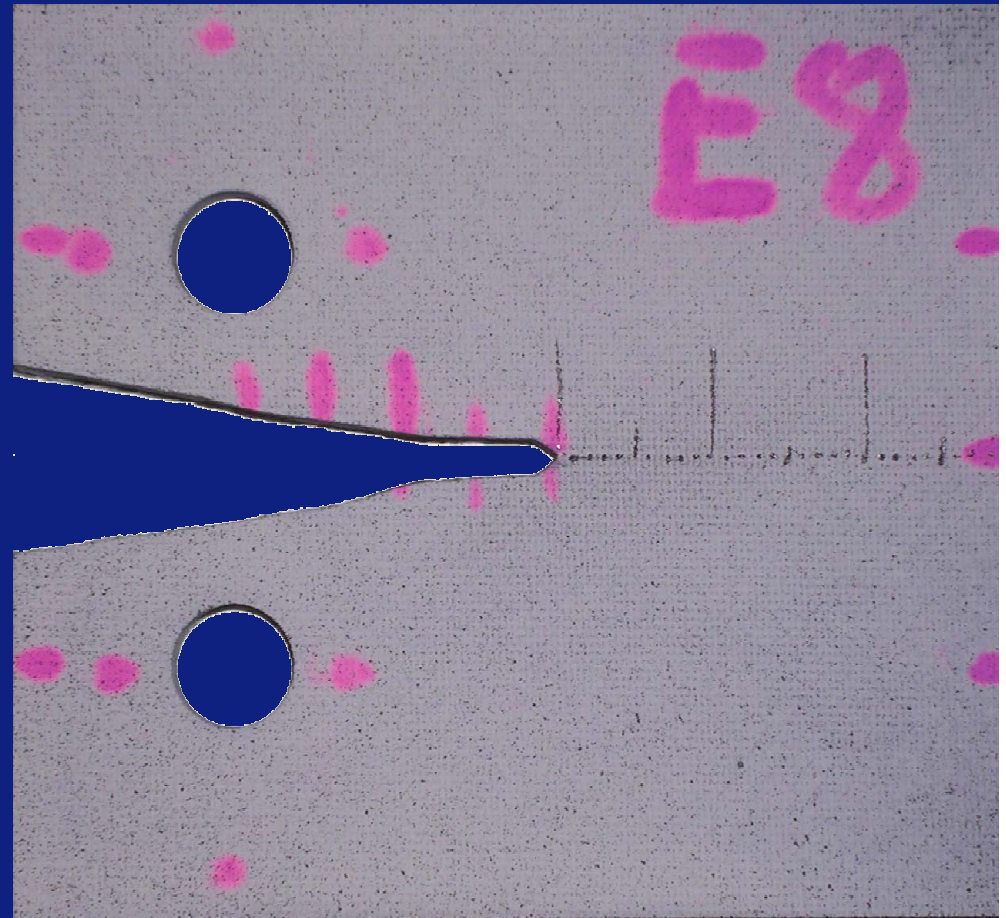
Matrix

Fibre

Applications

Conclusion

- CC specimen
- $(0,90)_{nS}$ layup



Fracture toughness

Fibre kinking

Failure onset
FE Implem.

Matrix

Kinking

Propag.

Smeared

F. Toughness

Matrix

Fibre

Applications

Conclusion



T300/913

$\Gamma = 79.9 \text{ kJ/m}^2$

coef. var. = 7.7%

Applications

Matrix compressive failure

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smearred

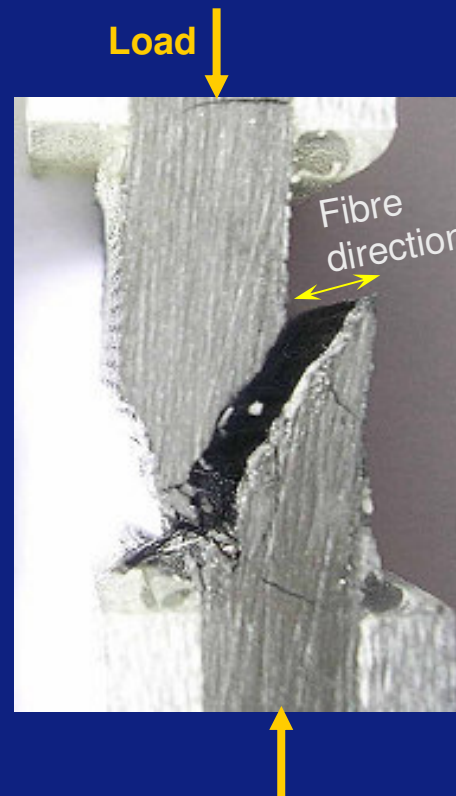
F. Toughness

Matrix

Fibre

Applications

Conclusion



Applications

Matrix compression failure

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

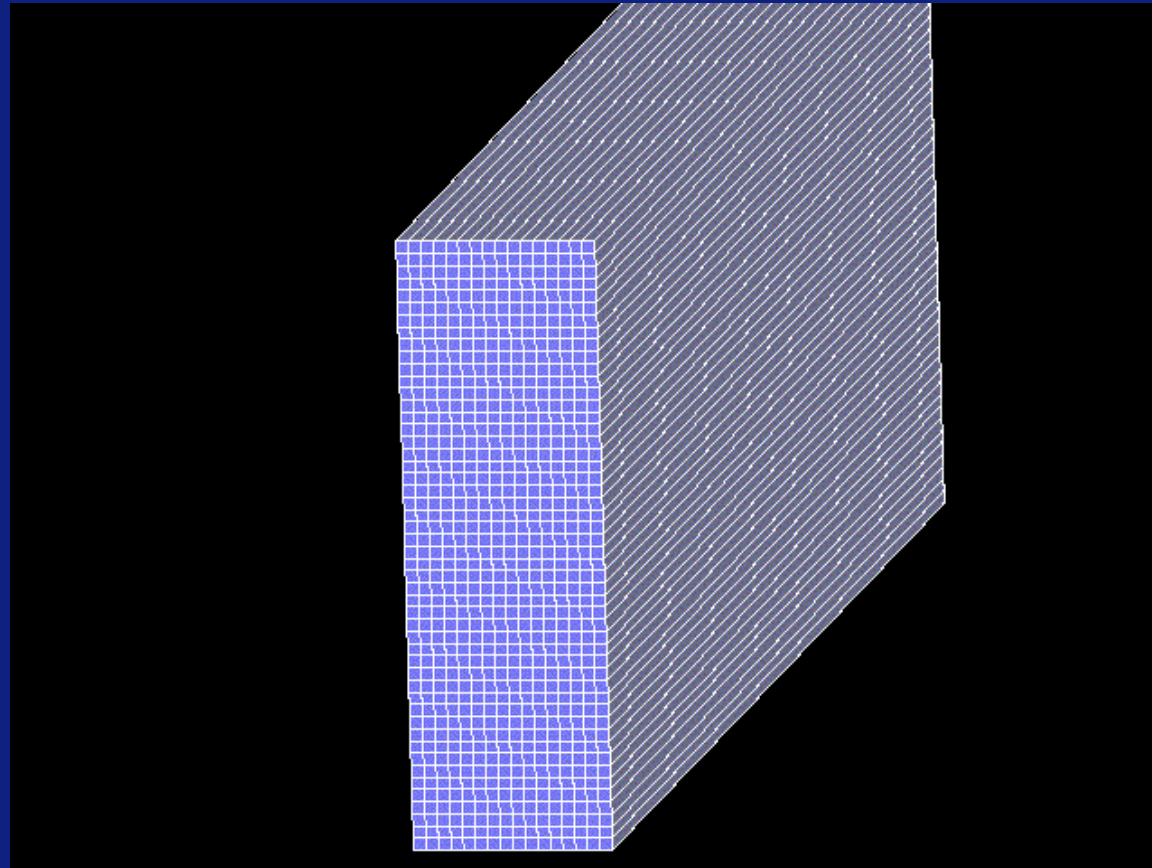
F. Toughness

Matrix

Fibre

Applications

Conclusion



Applications

Matrix shear failure

Failure onset
FE Implem.
F. Toughness

Matrix
Kinking

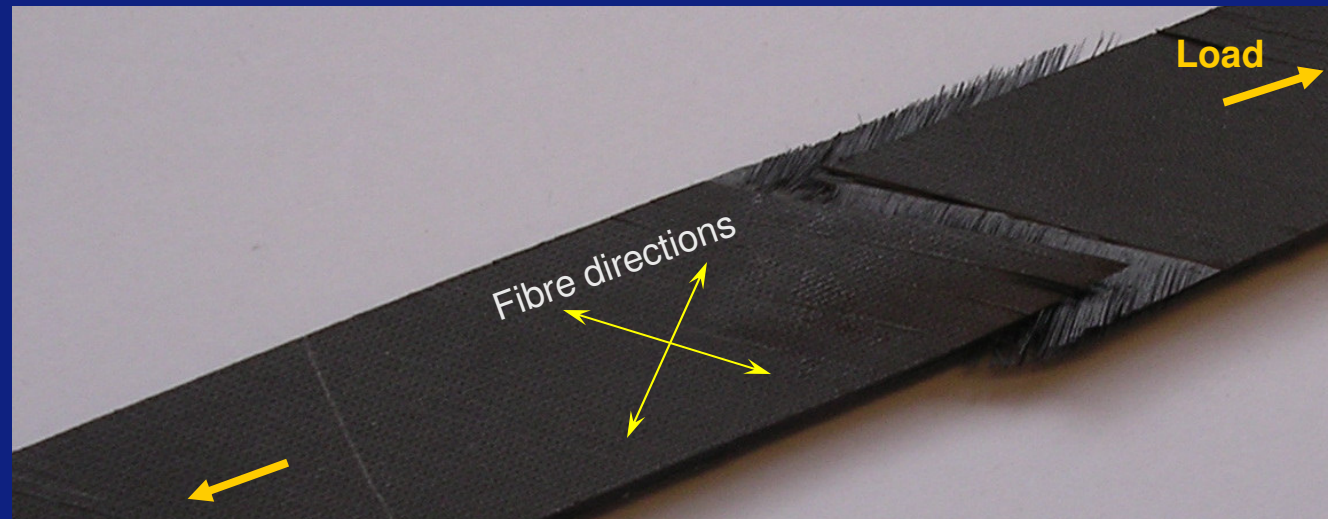
Propag.
Smeared

Matrix
Fibre

Applications

Conclusion

- $(\pm 45)_{8S}$ specimen tested in tension



Applications

Matrix shear failure

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

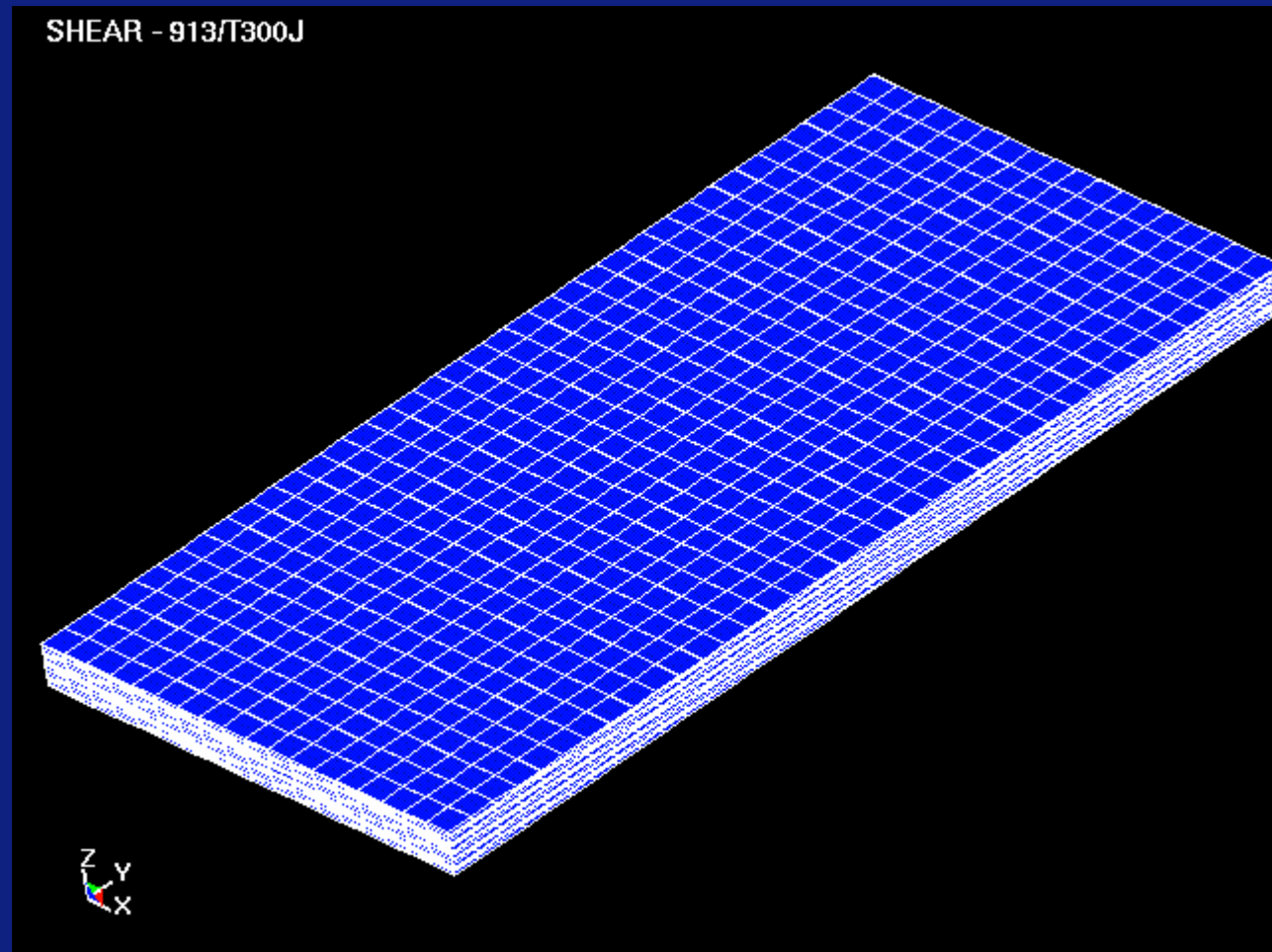
F. Toughness

Matrix

Fibre

Applications

Conclusion



Applications

Fibre kinking

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

F. Toughness

Matrix

Fibre

Applications

Conclusion



Applications

Fibre kinking

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

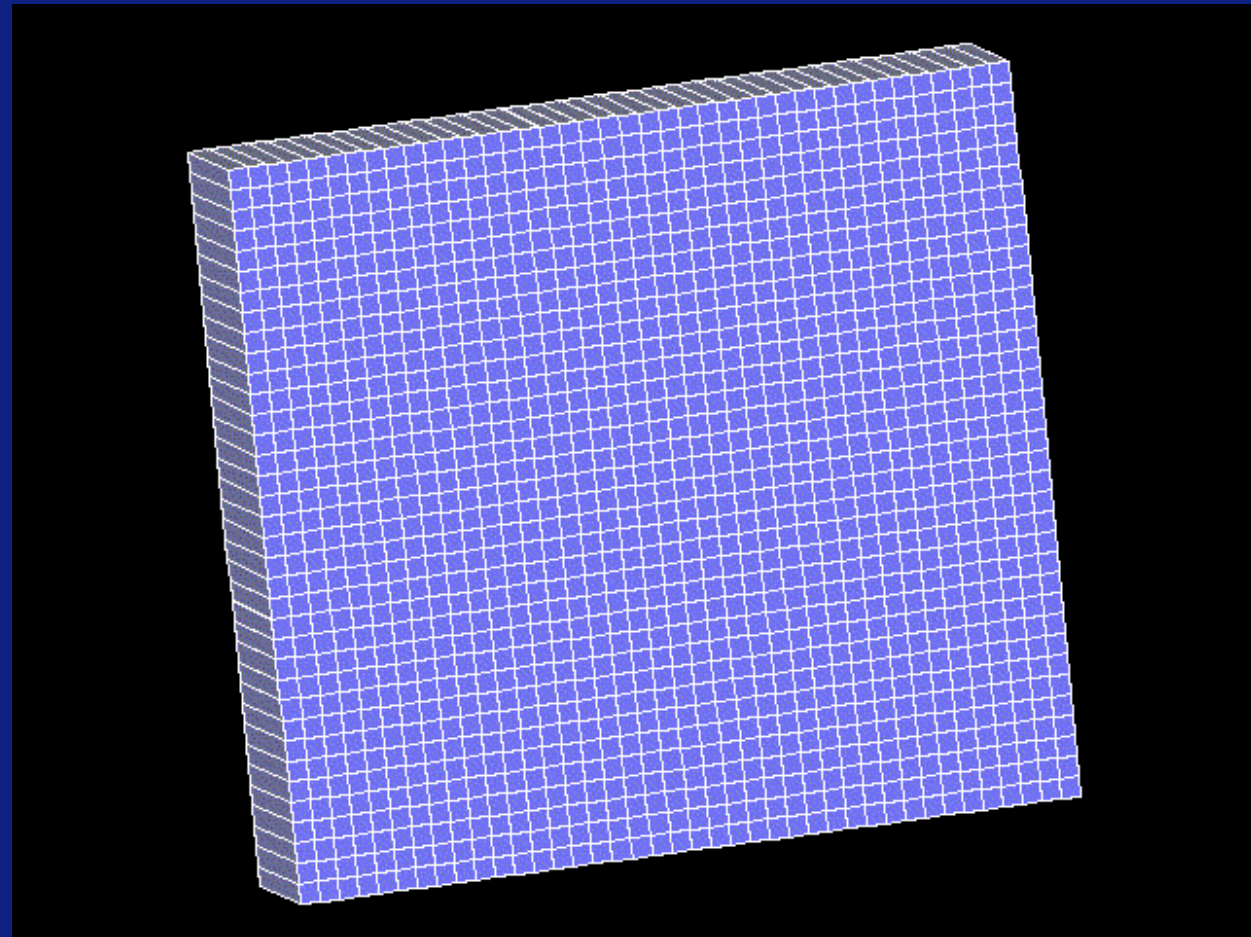
F. Toughness

Matrix

Fibre

Applications

Conclusion



Applications

Crush of a composite $(-45_2, 45_2)_S$ column

Failure onset
FE Implem.
F. Toughness

Matrix

Kinking

Propag.

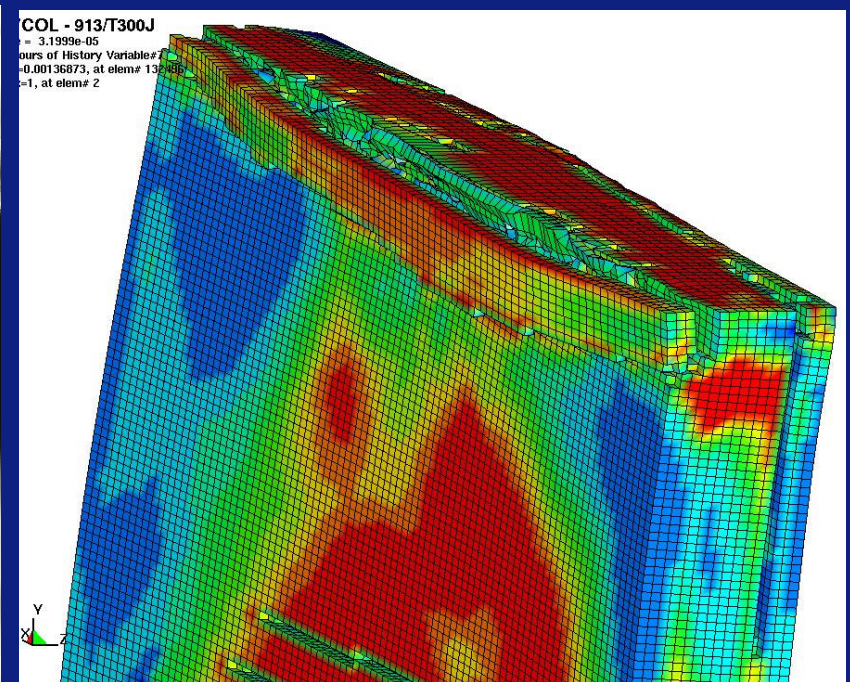
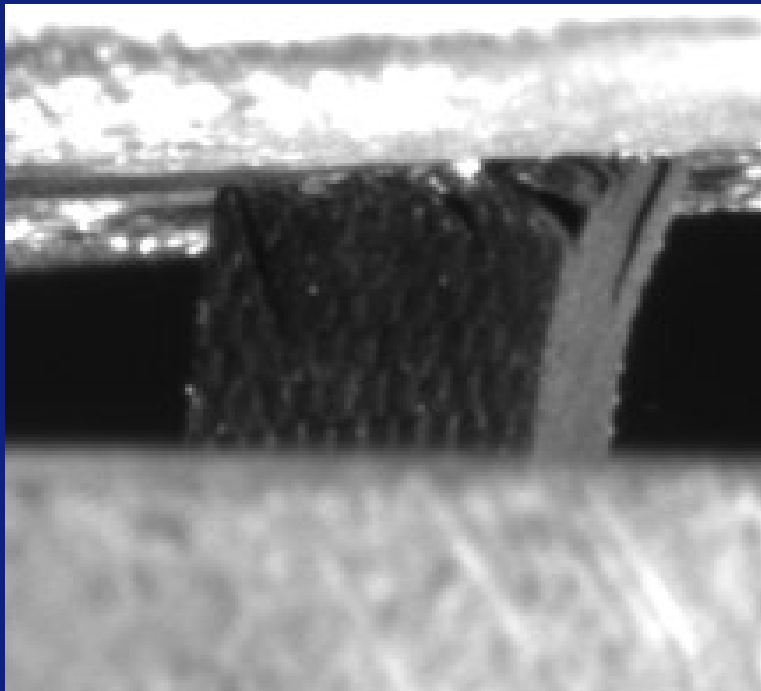
Smeared

Matrix

Fibre

Applications

Conclusion



Applications

Crush of a composite $(-45_2, 45_2)_S$ column

F. Toughness
FE Implem.
Failure onset

Matrix

Kinking

Propag.

Smeared

Matrix

Fibre

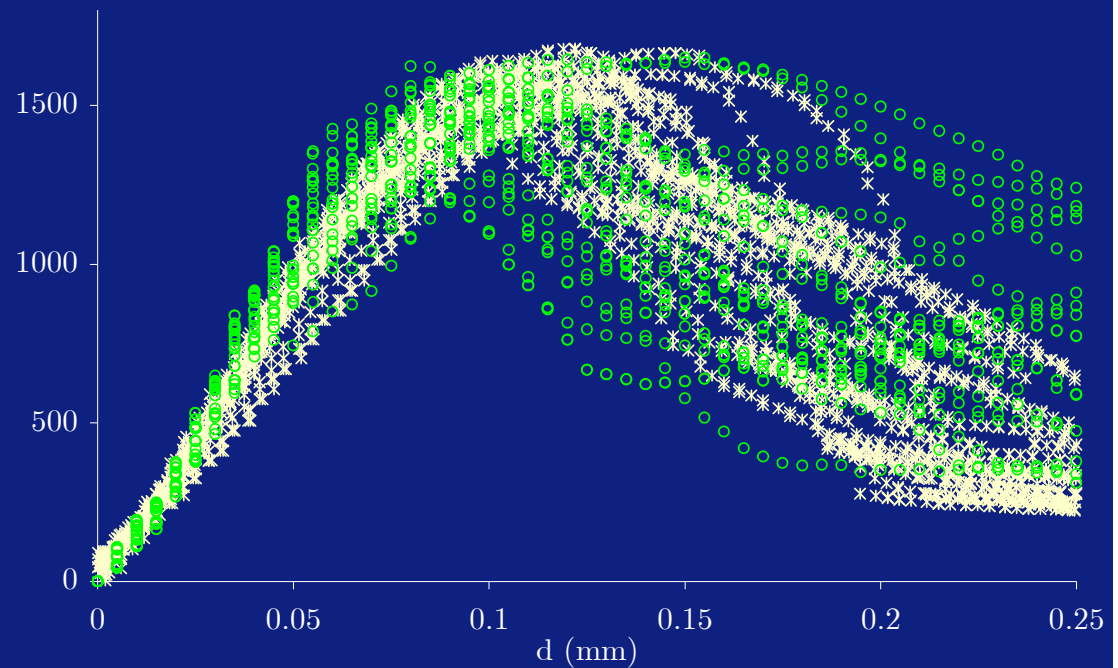
Applications

Conclusion

Numerical variables changed:

- rigid surface velocity (factor of 10)
- Friction coefficient (0 and 0.05)
- Inclination of the rigid surface (2 and 2.5 degrees)
- Mesh refinement (1 and 2 elements per layer thickness)
- Instant when the failed elements are deleted

Load (N)



Conclusion

Failure onset
FE Implem.
F. Toughness
Applications

Matrix

Kinking

Propag.

Smeared

Matrix

Fibre

Applications

Conclusion

- Physically-based 3D failure models implemented in FE with smeared formulations can be successful in reproducing key aspects observed in fracture, failure, impact and crush of composite structures

Thank you. Any questions?

Failure onset

Matrix

Kinking

FE Implem.

Propag.

Smeared

F. Toughness

Matrix

Fibre

Applications

Conclusion

Acknowledgments:

The scholarship from the Portuguese Foundation for Science and Technology is acknowledged