Damage analysis in polymer matrix composites

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BSSM Workshop:
Challenges in X-ray computed tomography for materials behaviour assessment
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Introduction

- Composites, particularly continuous carbon fibre materials have come a long way since 1965!
  - Large primary structures now commonplace
- Yet we still do not have a usable understanding of many aspects of strength, toughness, durability
  - Design remains generally conservative
  - We do not push the limits of the materials’ capability
- **DATA RICH MECHANICS**
  - Dramatic evolution in availability and resolution of various full-field and/or volumetric (‘full volume’?) sensing modalities, *e.g.* CT
    - Model initialisation and validation at various lengths scales to inform physically-based engineering simulation
    - Realise a predictive ‘virtual testing’ approach, reducing cycle times, design/certification costs, whilst improving efficiency and expanding the effective design envelope
CFRP laminate testing

- Notched tensile failure
- \([90/0]_s, [0/90]_s, [90/+45/-45/0]_s, [90/0/90]_T\) CFRP laminates
  - Alternative matrix toughness levels
  - Al particulate (~ 4\(\mu\)m) fiducial markers

- Double edge notch samples produced using abrasive waterjet machining
  - Width = 4mm, notched radius = 1mm
  - Thickness = 0.25mm per ply
  - 10 and 25mm wide samples also compared

- Imaging at ESRF/ID19, 1.4\(\mu\)m voxels, 20kV, 100ms exp., \(D = 35\text{mm}\)
Results

- 3D view of notched region
Damage Propagation

$[90/0]_s$ 50% UTS (nominal)

- 90°
- 0°
- 90°

500 µm

- notch

TPC
- 0° split
- Delamination

50% UTS
Damage Propagation

$[90/0]_s$ 60% UTS (nominal)
Damage Propagation

$[90/0]_s$ 70% UTS (nominal)
Damage Propagation
$[90/0]_s$ 80% UTS (nominal)

notch

500 µm

80% UTS

TPC
0º spilt
Delamination
Damage Propagation

$[90/0]_s$ 90% UTS (nominal)
Damage Propagation

\([90/0]_s\) 100% UTS (nominal)

notch

TPC
0° split
Delamination

100% UTS

500 µm
Damage Propagation

$[90/0]_s$ 110% UTS (nominal)

90° 0° 0° 90°

notch

500 µm

110% UTS

TPC

0° spilt

Delamination
Notched PMCs: Mechanisms

- Delamination evolves discontinuously from both toughening particles and fibres
  - 3D, multi-mechanistic failure mode
Notched PMCs: Mechanisms

- Semi-cohesive 3D failure zone at interface in toughened systems
Notched PMCs: Simulation

Experiment

Model
Notched PMCs: Simulation

A-FEM (augmented finite element method)
Hansbo and Hansbo, 2004
Yang et al., 2008

- **Ghost elements** add extra crack displacement
- **Local** – can set up as ABAQUS user element

- Incorporate CZM
- Arbitrary crack initiation
- Stochastic processes

Round hole cracking, multiple plies
- 2D plane stress A-FE for each ply
- 3D A-FEs for all interfaces
  - initiation criterion:
    \[ \left( \sigma_{22} \dot{\sigma} \right)^2 + \left( \tau_{12} \dot{\tau} \right)^2 = 1.0 \]
  - propagation criterion:
    \[ \frac{\mathcal{G}_I}{\Gamma_{lc}} + \frac{\mathcal{G}_{II}}{\Gamma_{IIC}} = 1.0 \]
- shear nonlinearity explicitly considered
A-FEM Parametric comparison

Matrix A

Matrix B

Matrix C

40% UTS  60% UTS  80% UTS
A-FEM Parametric comparison

$\Gamma_{IC} = 491 \text{ J/m}^2$; $\Gamma_{IC} = \Gamma_{IIIc} = 1682 \text{ J/m}^2$

$\tilde{\sigma}_n = 62 \text{ MPa}$; $\tilde{\sigma}_r = \tilde{\sigma}_t = 92 \text{ MPa}$

Notch center
Results

• 3D view of notched region
Fibre break analysis

**Pre-preg laminate:** large co-planar clusters (max = 12plet)

**Filament wound:** smaller, dispersed clusters

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Initial Model and Experimental comparison

- RVE simulation, with Weibull fibre failure, debonding & load transfer to neighbours [After A.E. Scott, I. Sinclair, S.M. Spearing, A. R. Bunsell, A. Thionnet. Submitted to Composites A]
Multi-scale/built-up structures

Hybrid Al-alloy/CFRP/GFRP tube

Voxel Resolution: 75µm

Macro-structure μCT

Meso-structure μCT

Micro-structure SRCT 25
Laminography & CAI

- Compression after impact (CAI)
  - Materials & structure dependent ➔ length scales
  - Imaging post-impact, and *in situ* (compression)
  ➔ Micromechanical toughening & macroscopic deformation
Loading devices

200kN

1kN

14MPa hydrostatic pressure/4 °C
Laminography

SRCL
CT & CL: Direct comparison
μCT
4.3μm resolution

SRCT
1.4μm resolution

SR Laminography
0.7μm resolution

Showing same sample at similar location

Showing different sample with similar damage
Damage Area

Scanned Regions

Scan A
Scan B
Scan C
Scan D

Toughened

Non-Toughened

Scan A
Scan B
Scan C
Scan D

紫色：Matrix Crack 2nd Ply 90°
粉红色：Matrix Crack 3rd Ply -45°
红色：Matrix Crack 4th-5th Ply 0°
黄色：Matrix Crack 6th Ply -45°
绿色：Matrix Crack 7th Ply 90°
橙色：Matrix Crack 8th Ply +45°
蓝色：Delamination
Summary

- CT and related methods provide considerable opportunities in composite failure analysis
  - Material geometry, failure processes and simulation requirements conducive to CT assessment
  - Key failure processes visualised and quantified at fibre, lamina and laminate scale as a function of load
  - Larger samples/structures assessed by a combination of methods

- An exemplar of contemporary ‘data rich mechanics’ approach?
  - Last 10 years has seen an shift in both experimental and computational capacity in relation to micromechanics of failure
  - Novel experimental fidelity for model initialisation and validation, at scales that can inform engineering simulation
  - Aim: replacing extensive, relatively uninformative test programs with highly informative strategic investigations and integrated simulation strategy
  - Support ‘Virtual testing’ approach
An interdisciplinary CT imaging centre for engineering, biomedical, environmental and archaeological sciences