Damage and failure modelling of 2D braided composites using DIC method

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Plan of the presentation

- Braided composites
  - presentation
  - applications
  - material investigated & manufacturing

- Failure mechanisms
  - DIC presentation
  - tensile failure in fibre direction
  - compressive failure in fibre direction
  - shear failure – fibre rotation

- Damage and failure modelling
  - Modelling approach
  - Ladevèze damage model

- Conclusions and future work
1. Introduction

A potential material for the automotive industry due to:

- high specific stiffness
- high specific strength
- good impact resistance and damage tolerance
- good specific energy absorption
- better manufacturing flexibility compared to conventional tape laminates (near-net shape components)
1. Introduction

Mercedes SLR

Energy absorbers

Courtesy of Mercedes McLaren
1. Introduction

Potential application: Car bumper beam (Cranfield Project)

Preliminary study

Steel bumper

Braided composite bumper

Prototype (STS carbon fibre, 24k, Ø100mm + LY3505/XB3403 resin system)
1. Introduction

Near net shape preform

Example of a 2D maypole braider

Courtesey of Eorocarbon (http://www.eurocarbon.com)
2. Materials investigated

Heavy tows 24k, 100mm diameter

- STS carbon fibre, 1x1, 24k
- E-glass fibre, 1x1, 24k

Plain weave (1x1)

-θ° braider yarn
+θ° braider yarn

RUC
3. Manufacturing

- Outlet
- Vacuum bag
- Inlet
- Sealant tape
- Flow media
- Braided preform layers
- Fine peel ply
- Coarse peel ply
- Vacuum bag
- Aluminium sheets
- Sealant tape
- PVC beam mould
- Vacuum chamber
- Resin pot
1. Digital Image Correlation

- Choice of the appropriate subset size
2. Monotonic tension on $[0-90]_4^s$ coupons

- **Woven fabric** - linear elastic behaviour
- **Braid** – non-linear elasto-plastic behaviour

![Graph showing stress-strain behavior of woven and braided composites](image)
2. Monotonic tension on [0-90]4s coupons

**Tow straightening mechanism**

- **WF failure mode**
- **Braid failure mode**
- **Whitening at tow intersection (Intra-laminar delamination)**
- **Inter-layer delamination**

- **Axial tow**
- **Transverse tow**
- **Delamination between longitudinal and transverse tow in a single layer**
- **Longitudinal tow stretching and failure**
2. Monotonic tension on $[0-90]_{4S}$ coupons

Tow intersection

Cross-sectional view

High tensile strain concentration – matrix deformation

Low tensile strain concentration due to tow reinforcement

Longitudinal tow

Resin

Transverse tow
2. Monotonic tension on [0-90]_{4s} coupons

High tensile strain localisation (long. Strain)
2. Monotonic tension on $[0-90]_{4S}$ coupons

Braid layer delamination (3D plot – specimen surface)
3. Monotonic compression on $[0-90]_{4S}$ coupons

Compressive rig designed from the IITRI standard

Wedges holding specimen

Wedge (machined surface)

16N.m torque applied on each wedge screw

Specimen alignment rig
3. Monotonic compression on [0-90]_{4S} coupons
3. Monotonic compression on $[0-90]_{4S}$ coupons
Braided composites

1. Monotonic compression on [0-90]4S coupons
3. Monotonic compression on $[0-90]_{4S}$ coupons

Test results

- Comparable results using either DIC or strain gauges at low strains
- Excellent test repeatability for elasticity parameters
- Inconsistency for stress and strain at failure
- ROI chosen relatively too small for heavy tow braid
- Rig modifications (on going work)
4. Cyclic tension on $[\pm 45^\circ]_{2S}$ coupons

- STS/LY3505 braided composite, 1x1, 24k
- E-glass/LY3505 braided composite, 1x1, 24k

$\sigma_{xx}$ [MPa]

$\varepsilon_{xx}$
4. Cyclic tension on $[\pm 45^\circ]_{2S}$ coupons

AA - undamaged

AA - damaged
4. Cyclic tension on $[\pm45^\circ]_2S$ coupons

Accelerated movie

Longitudinal strain plot
4. Cyclic tension on $[\pm 45^\circ]_{2S}$ coupons

STS carbon

E-glass
1. Modelling approach

- $[\pm \theta^\circ]$ biaxial layer $\iff$ two $+\theta^\circ$ and $-\theta^\circ$ unidirectional plies
- tow waviness neglected (consider straight fibre)
- ply thickness equals to $\frac{1}{2}$ of the braid layer
- uniform damage through ply thickness / damage varies from ply to ply
2. Damage model – elementary ply

- The damaged material elastic strain energy $E_D$,

\[
E_D = \frac{1}{2} \sigma : \varepsilon^e
= \frac{1}{2} \left[ \frac{\sigma_{11}^0}{E_{11}} - \frac{2\nu_{12}}{E_{11}} \sigma_{12} \sigma_{22} + \frac{\langle \sigma_{22} \rangle}{E_{22}} + \frac{\langle \sigma_{22} \rangle}{G_{12}} \frac{\sigma_{12}^2}{(1 - d_{12})} \right]
\]

- Shear damage variable $d_{12}$ calculated from stiffness variation (cyclic loading),

\[
G_{12}^D = G_{12}^0 (1 - d_{12})
\]

- Quantity governing shear damage evolution,

\[
Y = \frac{\partial W^d}{\partial d_{12}} = \frac{1}{2} G_{12} (2\varepsilon_{12}^e)^2
\]

- Damage/plasticity coupling with effective stress,

\[
\sigma_{12} = \frac{\sigma_{12}}{(1 - d_{12})}
\]

Plasticity criterion,

\[
f(\bar{\sigma}, R) = \sqrt{\bar{\sigma}_{12}^2 + \alpha^2 \bar{\varepsilon}_{22}^2} - R(\bar{p}) - R_0
\]
3. Validation of the model

Example: 4 point bend loading on carbon and glass braided beams

Fixed impactors connected to load cell

Moving frame at velocity \( v(t) = 1.5 \text{mm/min} \)

Top view

Hydraulic compressive machine

ROI

Stereo camera system
3. Validation of the model

**PAM-CRASH™ Prediction**

*Results for the carbon braided beam: Comparison of test and simulation*

![Graph showing load vs. displacement for experiment and simulation.](image)

- Similar post-failure behaviour
- Load spreaders
- Total damage

*Legend:*
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
1. Conclusions

- Benefits from DIC
  - Characterisation of the main failure modes in heavy tow braided composites
  - Large deformations measurement on degrading surfaces

- Modelling of braided composites
  - Method proposed using elementary unidirectional plies
  - Progressive damage and plasticity
  - Failure

- Successful validation
  - Specimens and beams
2. Future work

- **Applications**
  - Beam is the first step in the bumper beam design
  - Modelling approach allows to account for fibre angle variation

- **Improvements**
  - Intra-ply damage – no delamination
  - Study on inter-laminar-delamination
  - Calibration of the interface element in PAM-CRASH\textsuperscript{TM} ($G_{Ic}$, $G_{IIc}$)
Subset size determination

Example of a 9x9 pixels subset
Subset size determination
Subset size determination

45x45 (pixels) subset required to obtain good coverage of grey patterns displacements

Light reflection leading to correlation errors