X-Ray Tomography Assessment of Shear Damage in Carbon Fiber Laminates

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5. CONCLUSIONS
Fracture of multiaxial fiber-reinforced laminates is triggered by failure of the fibers oriented in the loading direction and occurs at low strains. On the contrary, off-axis plies deformed in shear can withstand very large strains prior to fracture.

Shear deformation is an ideal situation to study the nucleation, development and interaction of different damage mechanisms in composites using state-of-the-art XCT.

**MATERIAL**

Matrix: Hexcel M21 epoxy resin  
Fibers: T800 (57%)  
[±45]_2s panels of 300 x 300 mm² manufactured in autoclave

**MECHANICAL TESTS**

- Tensile tests on [±45]_2s coupons of 200 x 20 mm²  
- Strains were measured with an extensometer and DIC  
- Tests were carried out in plane and open hole specimens

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soaking liquid
The tomograms were collected at 90 kV and 100 μA using a W target. 2000 radiographs were acquired for each tomogram with 750ms exposure time. Tomogram resolution was set to ≈10 μm/voxel. Automatic evaluation of fiber rotation and matrix cracking.
Fiber orientation in each ply was obtained from the orientation of matrix cracks. Orientation results correspond to the unloaded condition (residual rotation).

- **Volume is broken down into separated plies**
- **Crack segmentation by thresholding in ply**
- **Calculation of the principal moments of inertia of each crack**
- **Crack orientation is given by the orientation of the first principal moment of inertia**
- **Average crack orientation is computed for each ply**
MATRIX CRACKING

Selection of the central part (8.5 x 8.5 mm$^2$) of each ply

Application of Canny edge detection algorithm

Application of Hough transform

Volume is broken down into separated plies

Determination of crack orientation $\theta$ and crack distance to the origin $\rho$
2 tests up to failure, 1 test up to failure with periodic unloading-reloading cycles. 2 tests were periodically stopped, the specimen was soaked in taken out from the machine, soaked with a ZnI solution, analyzed by XCT and reloaded. Shear stress-strain curves were practically superposed in all cases.
Evolution of the shear modulus with strain was obtained from the dashed line corresponding to each unloading-reloading cycle. The shear modulus decreased dramatically with strain in the plateau region and increased slightly afterwards.
INITIAL DAMAGE

Results

$[\pm45]_2s$ plain

DAMAGE at $\gamma=0.032$
EVOLUTION of MATRIX CRACKING

Results

[±45]_2s plain
EVOLUTION of MATRIX CRACKING

Results

$[\pm 45]_{2s} \text{ plain}$ 

$\gamma=0.032$
$\tau=57.1\text{MPa}$

$\gamma=0.150$
$\tau=77.9\text{MPa}$

$\gamma=0.107$
$\tau=63.4\text{MPa}$

$\gamma=0.183$
$\tau=88.4\text{MPa}$
Delamination developed at interplies 1/2 & 6/7
Very little delamination was observed at the inner interplies

Results

$[\pm 45]_{2s}$ plain
Residual fiber rotation $\theta_r$ from XCT

$$\theta = \theta_r + \theta_e$$

$$\theta_e = \pi - 2 \arctan \left( \frac{1 - \epsilon_{xx}}{1 + \epsilon_{yy}} \right)$$

Fiber rotation increased linearly with the shear strain.
It was independent of the ply location and specimen.
(kinematically controlled)
Matrix cracking develops during the plateau region: $2 \rightarrow 3$

The initial crack density is higher in the central ply (double thickness) and in the external plies because of their lower strength.

Maximum crack density is achieved in the inner plies ($2, 3, 5, 6$).
Matrix cracking begins by the external plies, followed by the central ply. External plies and central ply reached saturation at the end of the plateau. Crack density of the inner plies (2, 3, 5, 6) increased rapidly during the linear hardening region prior to failure.
2 tests up to failure, 1 test up to failure with periodic unloading-reloading cycles. 1 test was periodically stopped, the specimen was soaked in taken out from the machine, soaked with a ZnI solution, analyzed by XCT and reloaded. Shear stress-strain curves were practically superposed in all cases.
Damage develops by two shear bands from the equator of the void at ±45º.

Shear bands lead to:
- matrix cracking parallel to the fibers
- localized fiber rotation (when the shear band is perpendicular to the fiber)
EVOLUTION of MATRIX CRACKING
EVOLUTION of MATRIX CRACKING

Results

$[\pm 45]_{2s}$ hole
Cracking is initially localized in ±45 shear bands starting from the hole equator. Maximum crack density is achieved in the inner plies (2, 3, 5, 6) and minimum crack density in the central ply. No differences in the final crack density between regions where the shear band is parallel or perpendicular to the fibers.
Fiber rotation is more marked in the regions where shear is perpendicular to the fibers.
A methodology has been developed for automatic quantification of matrix cracking and fiber rotation using XCT in fiber-reinforced laminates. It has been demonstrated during shear deformation of plain and open hole laminates.

This methodology, together with new in situ testing capabilities, open extraordinary capabilities to analyze the complex interaction among different deformation and damage mechanisms in composites.

Research Projects

Ministry of Science and Innovation, National Program on Materials (MAT09-14396)
EU projects DEFCOM, MAAXIMUS, SIMUCOMP, COMPOSIMPA
SOON COMING UP ...

X-ray beam

Detector

Ply 2
-45

Ply 3
+45

Ply 4
-45

Ply 5
+45

5 MPa

186 MPa