EXPERIMENTAL METHODS FOR
IDENTIFYING FAILURE MECHANISMS

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Fiber composite

Single ply

**MICROSCOPIC**
- Matrix failure (tensile, compressive, shear)
- Bond failure
- Fiber failure

**MINISCOPIC**
- First-ply failure
- Lamina failure criteria

**MACROSCOPIC**
- Laminate failure criteria

Scales of observation of failure
1. **Photoelastic** (2-D, 3-D, Microphotoelastic, Dynamic, Birefringent Composites, Birefringent Coatings)

2. **Moiré**

3. **Strain Gages**

4. **Interferometric and Holographic Methods**

5. **Nondestructive Evaluation** (Ultrasonics, Acoustic Emission, X-ray, Thermography)

6. **Fractography**

**Experimental methods**

**Stress-Optic Law**

\[ \sigma_1 - \sigma_2 = 2nf/t \]

where

- \( \sigma_1 - \sigma_2 \) = difference of "secondary" principal stresses
- \( n \) = fringe order
- \( f \) = material fringe value (constant for material)
- \( t \) = specimen thickness

**Photoelastic method**
\[ \varepsilon = \frac{1}{S_g} \left( \frac{\Delta R}{R} \right) \]

where

\[ S_g = \text{gage factor (function of alloy and backing of gage)} \]

\[ \frac{\Delta R}{R} = (\delta - \alpha) S_g \Delta T + \gamma \Delta T \]

\[ \alpha = \text{thermal coefficient of expansion of gage material} \]

\[ \beta = \text{thermal coefficient of expansion of base material} \]

\[ \gamma = \text{coefficient of resistivity of gage material} \]

Electrical resistance strain gages

Mechanism of formation of Moire fringes
Strain-optic law:

\[ \varepsilon_1^c - \varepsilon_2^c = \varepsilon_1^s - \varepsilon_2^s = \frac{N f_c}{2h} = N f_e \]

where:
- \( f_e \) = strain fringe value
- \( N \) = fringe order
- \( h \) = coating thickness
- \( c,s \) = refer to coating and specimen, respectively.

Conditions at boundary:

At interface between coating and specimen,

\[ \varepsilon_{22}^c = \varepsilon_{22}^s = -v_{12} \varepsilon_{11}^c \]

At top surface of coating,

\[ \varepsilon_{22}^c = -v_e \varepsilon_{11}^c = -v_e \varepsilon_{11}^s \]

Principal strain along boundary,

\[ \varepsilon_{11}^c = \frac{N f_c}{2h} \cdot \frac{1}{1 + \nu_c} \]

Photoelastic coating method (refs. 1 to 4)

Hologram recording

Reconstruction

Holographic processes
Failure model of unidirectional composite under longitudinal tension (ref. 5)
Sequence of photographs showing distribution of fiber breaks in unidirectional composite under longitudinal tension
Sequence of photographs showing distribution of fiber breaks in unidirectional composite under longitudinal tension
Fixture for dynamic tensile loading of composite models

Transient isochromatic fringe patterns in a glass-plastic composite model under dynamic tension (Camera speed: 200,000 frames per second)
Failure pattern in model of preceding figure

Stress-strain curves of (±θ) angle-ply glass/epoxy laminates
Characteristic failure patterns of three graphite/S-glass/high-modulus epoxy specimens under uniaxial tensile loading

Isochromatic fringe patterns around hole in $[0/\pm 45/0/\bar{90}]$ boron/epoxy specimen for applied uniaxial stresses of 166 MPa (24.0 ksi), 225 MPa (32.6 ksi), and 293 MPa (42.4 ksi)
Typical failure pattern around hole in \([0/\pm 45/0/90]_s\) boron/epoxy specimen under uniaxial tensile loading

Sequence of Moiré fringe patterns corresponding to vertical displacements in \([0/\pm 45/0/90]_s\) glass/epoxy specimen at various applied uniaxial stresses
Strength reduction as a function of hole radius for $[0_2/\pm 45]_2$ graphite/epoxy plates with circular holes under uniaxial tensile loading

\[
\sigma_y (x,0) = \sigma_o \left( 1 + \frac{1}{2} \rho^{-2} + \frac{1}{2} \rho^{-4} + \frac{1}{2} (k_o - 3) (5\rho^{-6} - 7\rho^{-8}) \right)
\]

\(\sigma_o\) = far field stress
\(\rho = x/a\)
\(k_o\) = anisotropic stress concentration factor

Strength Reduction Ratio

\[
\frac{S_{yy}}{S_o} = \frac{2}{(1+\xi) \left( 2 + \xi^2 + (k_o - 3) \xi^4 \right)}
\]

\(\xi = \frac{a}{a_o}\)
\(a_o\) = characteristic length dimension

\(S_{yy}, S_o\) = strengths of notched and unnotched laminates, respectively.

Strength reduction of uniaxially loaded composite plate with hole according to average stress criterion
Moire fringe patterns around crack in glass/epoxy composites $[0/90/0/90]_s$ at three levels of applied stress

 Isochromatic fringe patterns in photoelastic coating around 1.27-cm (0.50 in.) crack of $[0/\pm 45/90]_s$ graphite/epoxy specimen at various levels of applied stress
Isochromatic fringe patterns in photoelastic coating of $[0/\pm45/90]_g$ graphite/epoxy specimen with 2.54-cm-diameter (1 in.) hole under equal biaxial tensile loading (Far-field biaxial stress marked)

Fringe order and circumferential strain at two locations on the hole boundary for $[0/\pm45/90]_g$ graphite/epoxy specimen with 2.54-cm-diameter (1 in.) hole under equal biaxial loading
Failure pattern in [0/±45/90]_s graphite/epoxy specimen with 1.91-cm-diameter (0.75 in.) hole under equal biaxial tensile loading.

Strength reduction as a function of hole radius for [0/±45/90]_s graphite/epoxy plates with circular holes under 1:1 biaxial tensile loading.
Moiré fringe patterns around crack in uniaxially loaded [0/±45/90]_s graphite/epoxy specimen for three levels of applied stress

Crack opening displacement and far-field strain for [0/±45/90]_s graphite/epoxy specimen with a 1.27-cm (0.50 in.) horizontal crack
Failure patterns in $[0_2/\pm 45]_s$ graphite/epoxy specimens with holes of various sizes under uniaxial tension (Hole diameters are 2.54 cm (1 in.), 1.91 cm (0.75 in.), 1.27 cm (0.50 in.), and 0.64 cm (0.25 in.))

A - audible failure
B - audible failure
C - visible delamination on vertical axis

Vertical strains along horizontal axis of $[0_2/\pm 45]_s$ graphite/epoxy specimen with 1.91-cm-diameter (0.75 in.) hole under uniaxial tensile loading
Failure patterns of boron-epoxy tensile panels with holes

Isochromatic fringe patterns in photoelastic coating around hole in boron/epoxy specimens of two different stacking sequences ($\sigma_y = 392$ MPa (56.8 ksi))
Failure patterns of boron-epoxy panels with holes of various laminate constructions

Isochromatic fringe patterns in photoelastic coating around hole in boron/epoxy specimens

[0/90/0/90]_s; \( \sigma_y = 170 \text{ MPa (24.6 ksi)} \)

[±45/±45]_s; \( \sigma_y = 77 \text{ MPa (11.1 ksi)} \)
Failure patterns in uniaxially loaded $[0/\pm45/90]_S$ graphite/epoxy plates with cracks of various lengths (Crack lengths are 0.64 cm (0.35 in.), 1.27 cm (0.50 in.), 1.91 cm (0.75 in.), and 2.54 cm (1.00 in.))

Strength reduction as a function of notch size for $[0/\pm45/90]_S$ graphite/epoxy plates with circular holes and horizontal cracks under uniaxial tensile loading
Critical stress intensity factor as a function of crack length for \([0/±45/90]_s\) graphite/epoxy plates with horizontal cracks under uniaxial tensile loading.

\[ K_Q = S \sqrt{n(a^2)} \]

Stress transformations of the far-field biaxial state of stress around a crack:

\[ \sigma_x = \frac{1 + k - (1-k)\cos^2 \theta}{(1-k)\sin^2 \theta} \]

\[ \tau_{xy} = \frac{(1-k)\sin 2\theta}{(1-k)\sin^2 \theta} \]
Biaxial loading of \([0/\pm45/90]_s\) graphite/epoxy specimens with cracks

\[
\sigma_{yy} = 392 \text{ MPa (42.4 ksi)} \quad \sigma_{yy} = 303 \text{ MPa (43.9 ksi)} \\
\sigma_{yy} = 260 \text{ MPa (37.7 ksi)} \quad \sigma_{yy} = 278 \text{ MPa (40.3 ksi)}
\]

Isochromatic fringe patterns in photoelastic coating around 1.27-cm (0.5 in.) crack in \((0/\pm45/90)_s\) graphite/epoxy specimen under biaxial loading - \(\sigma_{yy} = 2.03\sigma_{xx}\) at 30 deg with crack direction
Comparison of experimental and theoretical results for strength ratio for 
[0/±45/90]_s graphite/epoxy plates with cracks under biaxial loading.
Thermally induced holographic fringe patterns in fatigue-loaded $[0/\pm 45/90]_s$ graphite/epoxy specimen with circular hole

TBE enhanced X-ray photographs showing fatigue-induced damage in $[(0/\pm 45/90)_s]_2$ graphite/epoxy specimens
Ultrasonic C-scans of \([0/\pm45/90]_2\) graphite/epoxy specimen with a film patch

Flaw growth under spectrum fatigue loading in \([(0/\pm45/90)]_2\) and \([02/\pm45]_2\) graphite/epoxy specimens with four types of initial flaws  (Ambient environment)
Acoustic emission and corresponding load spectrum as a function of elapsed time for 
$[0_2/±45]_{28}$ graphite/epoxy specimens with holes   (Time increases from right to left)
REFERENCES


