NONDESTRUCTIVE CHARACTERIZATION OF COMPOSITE MATERIALS

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ABSTRACT

Increasingly, composite materials are applied to fracture-critical structures of aircraft and spacecraft. While the materials has an effective combination of toughness, specific strength and damage tolerance, they are sensitive to the manufacturing processes, service conditions and aging. Ultrasonics offer the most capable inspection technology and recently developed techniques appear to improve this technology significantly. NDE methods allow the detection and characterization of defects as well as determination of the material elastic properties accessing the material from a single side. Recent progress in ultrasonic NDE of composites will be reviewed.
NONDESTRUCTIVE CHARACTERIZATION OF COMPOSITE MATERIALS

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NEED FOR NDE OF COMPOSITES

* COMPOSITE STRUCTURES CAN BE TAILORED SUPERIOR TO METALS

* DAMAGE TOLERANCE IS CHALLENGED BY DEFECTS, COMPLEX FAILURE MECHANISM AND LACK OF COMPREHENSIVE THEORY

* QUANTITATIVE NDE EMPLOYING IMBEDDED/ATTACHED/REMOTE SENSORS ARE KEY TO THE USE OF MATERIAL FULL POTENTIAL

* ACTUATORS-SENSORS CAN MAKE SMART MATERIALS AND STRUCTURES
JPL’S NDE MAJOR TOPICS

* METHODS OF DEFECTS DETECTION AND CHARACTERIZATION
* MATERIAL PROPERTIES DETERMINATION
* SENSORS FOR IN-PROCESS, IN-SERVICE, AND IN-FLIGHT MONITORING
* ESTABLISH PROCESS SPECIFICATIONS
EFFECT OF DEFECTS

1. DEGRADES MATRIX-DOMINATED PROPERTIES
   - 1% POROSITY REDUCES STRENGTH BY 5% AND FATIGUE LIFE BY 50%
   - INCREASES EQUILIBRIUM MOISTURE LEVELS
   - AGGRAVATES THERMAL-SPIKE PHENOMENA

W

- DEPENDS ON STACKING ORDER AND LOCATION,
  - FOR $[0^\circ, +45^\circ, 90^\circ, -45^\circ]$ LAMINATE;
    - 8.7% STRENGTH REDUCTION DUE TO GAP(S) IN $0^\circ$ PLIES
    - 16.9% REDUCTION DUE TO GAP(S) IN $90^\circ$ PLIES

Ply Waviness

- STRENGTH LOSS CAN BE PREDICTED BY ASSUMING LOSS OF LOAD-CARRYING CAPACITY DUE TO THE WAVINESS
- FOR $0^\circ$ WAVINESS IN $[0^\circ, 45^\circ, 90^\circ, -45^\circ]$ LAMINATE,
  - STATICS STRENGTH REDUCTION IS:
    - 10% FOR SLIGHT WAVINESS
    - 25% FOR EXTREME WAVINESS
- FATIGUE LIFE IS REDUCED AT LEAST BY A FACTOR OF 10

Surface Notches

- STATICS STRENGTH REDUCTION UP TO 50%
- LOCAL DELAMINATION AT NOTCH
- STRENGTH REDUCTION IS SMALL FOR SIZES EXPECTED IN SERVICE

DEFECT/DAMAGE SEVERITY COMPARISON — STATIC STRENGTH (COMPRESSION).
NDE METHODS FOR FRP COMPOSITES

1. ULTRASONICS
2. RADIOGRAPHY
3. HOLOGRAPHY/SHEAROGRAPHY
4. ACOUSTICS
5. THERMOGRAPHY
6. NMR
7. EDDY CURRENT
8. MICROWAVES
9. ACOUSTIC EMISSION
10. VISUAL INSPECTION
11. LIQUID PENETRANT
12. TAP TESTING

NDE METHODS FOR MMC

1. ULTRASONICS
2. RADIOGRAPHY
3. EDDY CURRENT
4. ACOUSTIC EMISSION
5. VISUAL INSPECTION
6. ACOUSTICS
7. THERMOGRAPHY
8. LIQUID PENETRANT
9. TAP TESTING
Ultrasonic C-scan of a graphite/Epoxy laminate with delaminations and porosity.
COMPUTERIZED C-SCAN IMAGING OF IMPACT DAMAGE IN Gr/Ep LAMINATE

DATA HAS BEEN ROTATED IN A MANNER THAT ALLOWS A SIDE VIEW
POLAR BACKSCATTERING (PBS) PHENOMENON

- IT HAS BEEN STUDIED FOR COMPOSITES SINCE 1980"
- PHENOMENON IS SENSITIVE TO DISCONTINUITIES AT BOTH MACRO AND MICRO- LEVELS.
- MOST EFFORTS WERE DIRECTED TO NDE OF POROSITY AND IMPACT DAMAGE.
- APPLICATION TO MMC IS AFFECTED BY THE LARGE FIBER DIAMETER.
- THEORETICAL MODELING SO-FAR HAD LIMITED SUCCESS (ACHENBACH, MILLER, ETC.)
- VARIOUS CHARACTERISTICS OF THE PHENOMENON ARE STILL UNEXPLAINED.

SCHEMATIC REPRESENTATION OF EXPERIMENTAL SET-UP USED TO MEASURE BACKSCATTERING FROM COMPOSITE SAMPLES

WHERE:

\[ a \] – ANGLE OF INCIDENCE

\[ \beta \] – ANGLE BETWEEN Y-AXIS AND THE TRANSMITTER BEAM TRAJECTORY ON THE LAYER PLANE
EFFECT OF SURFACE ROUGHNESS ON DEGREE ANGLE OF ROTATION, K = 30°.
BACKSCATTERING FROM GRAPHITE/EPOXY COMPOSITE $[0^\circ, -15^\circ, -30^\circ, +45^\circ, -60^\circ, +75^\circ, 90^\circ]$s. ANGLE OF INCIDENCE WAS 40$^\circ$. 

![Graph showing relative amplitude vs. angle of rotation (β), degrees. Peaks and troughs indicate scattering events at different angles.]
POLAR BACKSCATTERING IMAGES OF FIBER ORIENTATION IN GRAPHITE/EPOXY LAMINATES TESTED AT 5 MHz AND $\alpha = 30$ DEGREES

\([0, 90, -45, +45]_S\)  \([0, 90]_S\)  \([0]_S\)
BACKSCATTERING FROM [0, 90]_S GLASS/EPoxy COMPOSITE BOTH WITH AND WITH ADDED POROSITY. EPOXY MICRO-BALLONS WERE USED TO INCREASE POROSITY.
POLAR-BACKSCATTERING FROM Gr/Ep LAMINATES USING 5 MHz 1/4-INCH TRANSDUCER

0.7% POROSITY

5.71% POROSITY

VOLTS

1.445
2.673
2.781
3.329
3.956
4.594
5.212
5.840
6.468
7.096
7.724
8.351
8.979
9.607
10.235
BACKSCATTERING SCAN OF QUASI-ISOTROPIC
GRAPHITE/EPOXY SPECIMEN FATIGUE LOADED TO
75% OF ULTIMATE STRENGTH AND 5 deg YC = S
TRANSMITTER

RECEIVER

FLUID

PLATE

N = NULL ZONE

LW = LEAKY WAVE
LEAKY LAMB WAVE (LLW) PHENOMENA

- HAS BEEN STUDIED FOR COMPOSITES SINCE 1983
- PHENOMENA SENSITIVE TO BOUNDARY CONDITIONS AND ELASTIC PROPERTIES
- THEORETICAL MODELING OF THE PHENOMENA HIGHLY SUCCESSFUL
- APPLIED TO INVERT COMPOSITES PROPERTIES AND CHARACTERIZE ON-DINQ

BAR-COMEN AND CHIMENTI 1983.
PULSED SCHLIEREN IMAGE OF LLW PHENOMENON
REFLECTION SPECTRA FOR LEAKY LAMB WAVE IN GRAPHITE/EPOXY AS4/3501-6 [0]32 TESTED AT 22 DEGREES ALONG THE FIBERS
LLW SPECTRA AND DISPERSION CURVE FOR UNIDIRECTIONAL GRAPHITE/EPOXY 0.152 IN. THICK

FREQUENCY (MHz)

AMPLITUDE (VOLTS)

VELOCITY (mm/µSEC)
GEOMETRY OF THE MULTILAYERED LAMINATE PROBLEM (BOTTOM) AND ORIENTATION OF THE Mth LAMINATE RELATIVE TO THE INCIDENT AND REFLECTED RAYS
THEORETICAL AND EXPERIMENTAL DISPERSION CURVES FOR GRAPHITE/EPOXY UNIDIRECTIONAL LAMINATE TESTED ALONG THE FIBERS

a. ASSUMED ELASTIC PROPERTIES

b. INVERTED ELASTIC PROPERTIES
TABLE 1: MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th></th>
<th>INITIAL GUESS</th>
<th>SYSTEMATIC INVERSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{II}$ (GPa)</td>
<td>156.75</td>
<td>157.77</td>
</tr>
<tr>
<td>$E_{22}$ (GPa)</td>
<td>10.41</td>
<td>10.82</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>7.07</td>
<td>7.982</td>
</tr>
<tr>
<td>$G_{23}$ (GPa)</td>
<td>3.50</td>
<td>3.6367</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.31</td>
<td>0.3374</td>
</tr>
<tr>
<td>$\rho$ (gin/cc)</td>
<td>1.58</td>
<td>1.578</td>
</tr>
<tr>
<td>$C_{II}$ (GPa)</td>
<td>160.73</td>
<td>162.729</td>
</tr>
<tr>
<td>$C_{22}$ (GPa)</td>
<td>13.92</td>
<td>14.527</td>
</tr>
<tr>
<td>$C_{12}$ (GPa)</td>
<td>6.44</td>
<td>7.359</td>
</tr>
<tr>
<td>$C_{23}$ (GPa)</td>
<td>6.92</td>
<td>7.25</td>
</tr>
<tr>
<td>$C_{55}$ (GPa)</td>
<td>7.07</td>
<td>7.982</td>
</tr>
</tbody>
</table>
DISPERSION CURVES FOR GRAPHITE/EPOXY
AS4/3501-6 [0]₈

LAMINATE PROPERTIES

\begin{align*}
E_{11} \text{(GPa)} & \quad 157.7700 \\
E_{22} \text{(GPa)} & \quad 10.8200 \\
G_{12} \text{(GPa)} & \quad 7.9820 \\
G_{23} \text{(GPa)} & \quad 3.6367 \\
\nu_{12} & \quad 0.3374 \\
\rho \text{ (gin/cc)} & \quad 1.5780 \\
C_{11} \text{(GPa)} & \quad 162.7290 \\
C_{22} \text{(GPa)} & \quad 14.5270 \\
C_{12} \text{(GPa)} & \quad 7.3590 \\
C_{23} \text{(GPa)} & \quad 7.2500 \\
C_{55} \text{(GPa)} & \quad 7.9820
\end{align*}
DISPERSION CURVES FOR GRAPHITE/EPOXY [0, 90]$_2$S

**PHASE VELOCITY (km/SEC)**

**ORIENT 0 DEG**

**PHASE VELOCITY (km/SEC)**

**ORIENT 45 DEG**

**PHASE VELOCITY (km/SEC)**

**ORIENT 90 DEG**

**FREQUENCY (MHz)**

**PLY PROPERTIES**

\[
\begin{align*}
C_{11} &= 162.73 \text{ GPa} \\
C_{22} &= 15.73 \text{ GPa} \\
C_{12} &= 7.36 \text{ GPa} \\
C_{33} &= 7.25 \text{ GPa} \\
C_{55} &= 7.98 \text{ GPa} \\
\rho &= 1.578 \text{ g/cm}^3 \\
E_{11} &= 157.8 \text{ GPa} \\
E_{22} &= 10.82 \text{ GPa} \\
G_{12} &= 7.98 \text{ GPa} \\
\nu_{12} &= 0.3375 \\
\nu_{23} &= 0.4876
\end{align*}
\]

**OVERALL LAMINATE PROPERTIES**

\[
\begin{align*}
<C_{11}> &= 88.62 \text{ GPa} \\
<C_{22}> &= 88.62 \text{ GPa} \\
<C_{33}> &= 15.73 \text{ GPa} \\
<C_{12}> &= 7.35 \text{ GPa} \\
<C_{13}> &= 7.30 \text{ GPa} \\
<C_{44}> &= 5.00 \text{ GPa} \\
<C_{55}> &= 5.00 \text{ GPa} \\
<C_{66}> &= 7.98 \text{ GPa}
\end{align*}
\]

**INTERFACE PROPERTIES**

\[
\begin{align*}
h &= 7 \text{ m} \\
\rho &= 1.2 \text{ g/cm}^3 \\
\alpha &= 2.1 \text{ km/see} \\
\beta &= 0.95 \text{ km/sec}
\end{align*}
\]

○○ EXPERIMENTAL DATA — THEORETICAL DATA
DISPERSION CURVES FOR GRAPHITE/EPOXY 
\([0, \pm 45, 90]_S\)

**PHASE VELOCITY**
(km/SEC)

**ORIENT 0 DEG**

**ORIENT 45 DEG**

**ORIENT 90 DEG**

**FREQUENCY (MHz)**

**PHASE VELOCITY**
(km/SEC)

**FREQUENCY (MHz)**

**PLY PROPERTIES**

\[ C_{11} = 160.7 \text{ GPa} \]
\[ C_{22} = 20.83 \text{ GPa} \]
\[ C_{12} = 7.45 \text{ GPa} \]
\[ C_{23} = 7.63 \text{ GPa} \]
\[ C_{55} = 8.02 \text{ GPa} \]
\[ \rho = 1.578 \text{ g/cm}^3 \]
\[ E_{11} = 156.8 \text{ GPa} \]
\[ E_{22} = 17.90 \text{ GPa} \]
\[ G_{12} = 8.02 \text{ GPa} \]
\[ \nu_{12} = 0.262 \]
\[ \nu_{23} = 0.356 \]

**OVERALL IN-PLANE PROPERTIES OF LAMINATE**

\[ <E> = 61.97 \text{ GPa} \]
\[ <\nu> = 0.247 \]

**INTERFACE PROPERTIES**

\[ h = 15 \mu m \]
\[ p = 1.2 \text{ gin/cc} \]
\[ a = 2.1 \text{ km/sec} \]
\[ \beta = 0.95 \text{ km/sec} \]

\[ \text{○ ○ ○} \text{ EXPERIMENTAL DATA} \]

\[ \text{-----} \text{ THEORETICAL DATA} \]
GRAPHITE/ALUMINUM .048 INCH THICK UNI DIRECTIONAL LAMINATE TESTED ALONG THE FIBERS USING LLW.

INVERTED ELASTIC PROPERTIES

<table>
<thead>
<tr>
<th>$C_{11}$</th>
<th>$C_{12}$</th>
<th>$C_{22}$</th>
<th>$C_{23}$</th>
<th>$C_{55}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>180.0</td>
<td>16.2</td>
<td>34.9</td>
<td>17.7</td>
<td>16.0</td>
</tr>
</tbody>
</table>
LLW C-SCAN IMAGE OF DEFECTS IN GR/EP [0]_{24} LAMINATE, WHERE COLOR WAS ASSIGNED TO THE DIFFERENT DEPTHS*

*BAR-COHEN AND MAL, 1988
NDE OF AGEING AIRCRAFT USING LASER INDUCED GUIDED WAVES
SENSORS TECHNOLOGY
GENERAL REQUIREMENTS

* DIMENSION, STRAIN, AND GEOMETRICAL VARIATION AND RATE OF CHANGE

* RESIDUAL STRESSES

* DETECTION OF DISCONTINUITIES (IMPACT, DELAMINATIONS, CRACKS, ETC.)

* MATERIAL PROPERTIES DETERMINATION

* REAL-TIME CHARACTERIZATION DURING CURE, AND SERVICE
Figure 1. Eddy Current Probe and Holding Fixture.

Figure 2. Eddy Current Thickness Sensor Setup

Figure 3. Modified Model Vector TXI Unit.
TYPICAL RESPONSE OF CURE MONITORED UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE
PRESSURE SENSOR

Polymide with semi-conductive compound
Spacer-adhesive
Polymide with interdigitating electrodes

Figure 1
FSR Pressure Sensor (Actual Size)

Figure 2
R vs. P log/log scale
TI = 75°F
FSR Pressure Sensor

Measured FSR Resistance (Ω)

Applied Pressure (psi)
TECHNOLOGY TREND

* MATERIALS ARE INCREASINGLY COMPLEX (ANISOTROPIC, HYBRID, ETC.)

* COMBINING INPUTS FROM SEVERAL NDE METHODS PROVIDE DETAILED AND RELIABLE ANSWERS

* DEFECTS CHARACTERIZATION AND PROPERTIES DETERMINATION USING QUANTITATIVE NDE AND AI

* IMBEDDED/ATTACHED SENSORS ARE MAKING A SIGNIFICANT IMPACT ON IN-PROCESS AND IN-SERVICE MONITORING