Non-destructive damage evaluation of composite structures by
optoelectronic holography methodologies

Cosme Furlong and Ryszard J. Pryputniewicz
NEST – NanoEngineering, Science and Technology
CHSLT – Center for Holographic Studies and Laser micro-mechaTronics
Mechanical Engineering Department
Worcester Polytechnic Institute
Worcester, MA 01609

ABSTRACT

Demands for increased performance and efficiency of mechanical and electromechanical components impose challenges on
their engineering design and optimization, as well as on the types of materials utilized in their construction. Demands on
materials imposed by new and rigorous applications have become so diverse and severe that single-component materials
used alone cannot meet them. It is frequently necessary to combine two or more distinct materials into a composite to define
a new material with enhanced properties. In this paper, nondestructive, noninvasive, and full-field-of-view optoelectronic
holography (OEH) methodologies are applied to experimentally determine material properties and to perform damage
evaluation in composite materials. Specifically, high-performance glass reinforced epoxy laminates utilized in electronic
packaging applications are investigated. Analytical, computational, and experimental solution (ACES) methodology is applied
in the studies. With ACES, orthotropic material properties of the composite laminates are determined with a maximum
uncertainty on the order of 5% and deformation measurement accuracy on the order of 5 nm are achieved, which allows us to
successfully identify delamination defects.

Keywords: composite laminates, nondestructive testing, optoelectronic holography, damage evaluation, material properties.

1. INTRODUCTION

Composite materials are utilized in increasing number of fields and applications because they have the advantage of exhibiting
the best qualities of their constituents and often some enhanced qualities that neither constituent possesses, which may be
new and/or unique. In addition, they make it easier and less costly to obtain certain properties than it is possible with single
solid materials.

Commonly accepted types of composite materials include [1,2]: (a) fibrous composites, which consist of fibers embedded in a
softer constituent forming the matrix; (b) laminated composites, which consist of layers of various materials; and (c) particulate
composites, which are composed of particles in a matrix. New composite materials, nanocomposites, are formed by utilizing
such nanoparticles as nanotubes, nanospheres, and different types of polymers mixed at the nanometer scale [3].
Nanocomposites have potential for defining new materials with enhanced strength, temperature resistance, flame resistance,
UV-resistance, improved optical properties, etc. Therefore, nanocomposites having impressive technological applications.

Design of structural components using composite materials involves the concurrent application of material and structural
designs. That is, properties of composite materials and structural aspects are designed simultaneously [2,4]. Desired
composite properties can be determined using a broad range of values, which the designer selects based on analysis and
simulation. Although analysis and simulation are useful in determining and predicting structural properties of composite
materials, experimental investigations are necessary for achieving satisfactory designs. In this paper, nondestructive,
noninvasive, and full-field-of-view optoelectronic holography (OEH) methodologies are applied to experimentally determine
material properties and to perform damage evaluation in composite materials. Specifically, laminated composites utilized in
electronic packaging applications are investigated.

2. METHODOLOGY

Composite materials investigated are copper-clad laminates, which are widely used as flexible printed circuit (FPC) boards,
which combine balanced mechanical, thermal, electrical, and chemical properties suited for demanding electronic packaging
applications. Table 1 summarizes pertinent characteristics of the samples investigated [5]. Laminates are high-performance
FR-4 epoxy structures designed with a low dielectric constant and low dissipation factor and are utilized in circuit designs
requiring fast signal speeds and improved signal integrity. In addition, laminates utilize a dual functional epoxy resin core that
provides UV and fluorescence blocking capabilities, which facilitate inspection of FPC boards using automated computer
vision systems. Figures 1 and 2 show samples of the FR-4 laminates utilized.
Methodology consists of applying analytical, computational, and experimental solutions (ACES) methodology [6]. Analytical solutions are utilized to identify constitutive stress-stain relationships applicable to the materials of interests, while finite element method (FEM) and optoelectronic holography (OEH) solutions are used to determine material properties and to perform damage evaluation of the FR-4 laminate samples of interest.

Table 1. Pertinent characteristics of the FR-4 laminates investigated [5].

<table>
<thead>
<tr>
<th>Thickness, mm</th>
<th>Density, g/cm³</th>
<th>Equivalent modulus of elasticity, GPa</th>
<th>Equivalent Poisson’s ratio</th>
<th>CTE-x, CTE-y, CTE-z, ppm / °C</th>
<th>Surface resistivity (min), MΩ</th>
<th>Dialectic breakdown, kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.077</td>
<td>24.13</td>
<td>0.127</td>
<td>14, 13, 175</td>
<td>2 x 10⁵</td>
<td>55</td>
</tr>
</tbody>
</table>

2.1. Analytical considerations

The constitutive stress-stain relationship indicates that [1,2]

\[
\sigma_{kl} = C_{klmn} \cdot \varepsilon_{mn},
\]

where \(\sigma_{kl}\) is the stress tensor, \(C_{klmn}\) are the elastic material constants, and \(\varepsilon_{mn}\) is the strain tensor. Equation 1 is expressed in index notation and indicates the existence of 81 constants defining the properties of a material. Symmetry of \(C_{klmn}\) with respect to the last two indexes reduces the number of material constants to 36. Furthermore, it can be demonstrated that [7,8]

\[
C_{klmn} = C_{mnkl},
\]

which indicates that the number of independent elastic material constants is reduced to 21. Equations 1 and 2 define the generalized Hook’s law for an anisotropic, linearly elastic material, expressed in Cartesian coordinates as

\[
\begin{pmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\sigma_{xz} \\
\sigma_{yz}
\end{pmatrix} =
\begin{pmatrix}
Q_{11} & Q_{12} & Q_{13} & Q_{14} & Q_{15} & Q_{16} & \varepsilon_{xx} \\
Q_{22} & Q_{23} & Q_{24} & Q_{25} & Q_{26} & \varepsilon_{yy} \\
Q_{33} & Q_{34} & Q_{35} & Q_{36} & \varepsilon_{zz} \\
Q_{44} & Q_{45} & Q_{46} & \varepsilon_{xy} \\
Sym. & Q_{55} & Q_{56} & Q_{57} & \varepsilon_{xz} \\
Q_{66} & & & & \varepsilon_{yz}
\end{pmatrix}
= [Q]
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{yz} \\
\varepsilon_{xz}
\end{pmatrix},
\]

where \([Q]\) is the elastic stiffness matrix [1,2]. Equation 3 shows that in order to fully define the stress-stain relationship, 21 independent elastic material constants need to be determined.

Fig. 1. FR-4 laminate sample plate of 160 x 160 mm². Nominal thickness of the plate is 1.5 mm. Copper-clad foil is 25 µm thick.

Fig. 2. FR-4 laminate sample plates. Copper-clad has been removed in the sample shown on the right-hand-side to reveal epoxy laminate core.
Samples investigated are manufactured by stacking series of woven glass reinforced epoxy lamina orientated in alternating orthogonal directions [2]. Figures 3 and 4 show a schematic and scanning electron microscope (SEM) picture, respectively, of a section of a lamina used to manufacture the laminate plates of interest.

By performing detailed investigation of the microstructural characteristics of the lamina, Fig. 4, a reasonable assumption is that an orthogonal elastic stiffness matrix can be used to define the constitutive stress-strain relationship for the composite material of interest. Therefore, Equation 3 reduces to [7,8]

\[
\begin{pmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xz} \\
\sigma_{yz}
\end{pmatrix} =
\begin{pmatrix}
Q_{11} & Q_{12} & Q_{13} & 0 & 0 \\
Q_{12} & Q_{22} & Q_{23} & 0 & 0 \\
Q_{13} & Q_{23} & Q_{33} & 0 & 0 \\
0 & 0 & 0 & Q_{44} & 0 \\
0 & 0 & 0 & 0 & Q_{55} \\
0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xz} \\
\varepsilon_{yz}
\end{pmatrix} =
[Q]
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xz} \\
\varepsilon_{yz}
\end{pmatrix},
\]  \hspace{1cm} (4)

indicating that there are 9 independent elastic material constants needed to defined the elastic stiffness matrix \([Q]\). In addition, based on plate theory, it is reasonable to assume that laminate is macroscopically homogeneous and orthotropic, subjected to states of plane stress, and that Kirchhoff hypothesis, which indicates that the neutral plane of a plate remains unstrained, is valid. Therefore,

\[
\sigma_{zz} = 0, \sigma_{xz} = 0, \sigma_{yz} = 0.
\]  \hspace{1cm} (5)

By taking the directions of fiber orientation parallel to the principal geometrical axes, \(x\)-\(y\), Fig. 3, the constitutive stress-strain relationship for the laminate composite of interest can be expressed as

\[
\begin{pmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{xy}
\end{pmatrix} =
\begin{pmatrix}
Q_{11} & Q_{12} & 0 \\
Q_{12} & Q_{22} & 0 \\
0 & 0 & Q_{66}
\end{pmatrix}
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{xy}
\end{pmatrix} =
[Q]_r
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{xy}
\end{pmatrix},
\]  \hspace{1cm} (6)

where \([Q]_r\) is the reduced stiffness matrix for plane stress. The components of \([Q]_r\) are related to the engineering material constants by [7,8]

\[
Q_{11} = \frac{E_{11}}{1 - \nu_{12} \nu_{21}},
\]  \hspace{1cm} (7a)
\[ Q_{22} = \frac{E_{22}}{1 - \nu_{12} \nu_{21}} , \]  
\[ Q_{12} = \frac{\nu_{21} E_{11}}{1 - \nu_{12} \nu_{21}} = \frac{\nu_{12} E_{22}}{1 - \nu_{12} \nu_{21}} , \]  
\[ Q_{66} = G_{12} , \]

where \( E_{11}\) and \( E_{22}\) are the moduli of elasticity in the two principal orthogonal axes, \( x-y \), respectively, \( G_{12}\) is the in-plane shear modulus, and \( \nu_{12}\) is the major Poisson’s ratio. Equations 7 indicate that there are 4 independent material constants, \( E_{11}, E_{22}, G_{12}, \) and \( \nu_{12}\), and one dependent constant, \( \nu_{21}\), which can be determined from Eq. 7c as

\[ \nu_{21} = \frac{\nu_{12} E_{22}}{E_{11}} . \]

The elastic material properties and other composite properties change as in-plane loading direction changes with respect to fiber orientations. Therefore, of particular interest is the determination of elastic properties along nonprincipal axes, \( x'-y' \), orientated at the angle \( \theta \), Fig. 3. Such determination is performed by applying a rotational transformation to the reduced stiffness matrix \([Q]_r\), which yields to the following relationships between the engineering material constants

\[ \frac{1}{E_{x'}} = \cos^4 \theta \frac{E_{11}}{E_{11}} + \left( 1 - \frac{2 \nu_{12}}{E_{11}} \right) \frac{\sin^2 \theta}{E_{22}} + \frac{\sin^4 \theta}{E_{22}} , \]
\[ \frac{1}{E_{y'}} = \frac{\sin^4 \theta}{E_{11}} + \left( 1 - \frac{2 \nu_{12}}{E_{11}} \right) \frac{\cos^2 \theta}{E_{22}} + \frac{\cos^4 \theta}{E_{22}} , \]
\[ \frac{1}{G_{x'y'}} = 2 \left( \frac{2}{E_{11}} + \frac{2 \nu_{12}}{E_{22}} - \frac{1}{G_{12}} \right) \frac{\cos^2 \theta \sin^2 \theta}{E_{22}} + \frac{1}{G_{12}} \left( \sin^4 \theta + \cos^4 \theta \right) , \]
\[ \nu_{x'y'} = E_{x'} \left[ \frac{\nu_{12}}{E_{11}} \left( \sin^4 \theta + \cos^4 \theta \right) - \left( \frac{2}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}} \right) \frac{\sin^2 \theta}{E_{22}} \right] . \]

Equations 9 will be applied in the following Sections for the experimental determination of the 4 independent material constants, \( E_{11}, E_{22}, G_{12}, \) and \( \nu_{12}\), by using computational and OEH solutions [9].

### 2.2. Computational considerations

Closed form analytical solutions of the governing strain-displacement equations for composite plates and shells [7,8,10] are difficult to obtain or are nonexistent. Therefore, computational techniques are necessary. In this paper, finite element methods (FEM) are utilized to solve, in an approximate discrete approach, the strain-displacement equations for composite plates and shells. Homogeneous and orthotropic FEM formulations including layered and sandwich plate approximations are considered [11,12]. Particularly, FEM are applied to solve the reduced strain-displacement equation for dynamic loading conditions, which is obtained by assuming plain stress, negligible bending-extension coupling, and negligible shear or twist effects. The reduced strain-displacement equation for dynamic loading conditions is given by [10-12]

\[ D_{11} \frac{\partial^4 w}{\partial x^4} + 2(D_{12} + 2D_{66}) \frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22} \frac{\partial^4 w}{\partial y^4} = \rho \frac{\partial^2 w}{\partial t^2} , \]
\[ D_{ij} = \frac{1}{3} \sum_{k=1}^{N} (Q_{ij})_{k} \cdot (h_{k}^{3} - h_{k-1}^{3}) \text{, for } i, j = 1, 2, 6 \]  

(11)

in which \( N \) is the number of lamina defining the laminate, \( Q_{ij} \) are coefficients of the reduced stiffness matrix for plane stress, Eq. 6, and \( h_{k} \) is the thickness of the \( k \)-th lamina. Equation 10 is solved by FEM using appropriately specified boundary conditions and the 4 independent orthotropic material constants, \( E_{11}, E_{22}, G_{12}, \) and \( v_{12} \), characterizing the \( k \)-th lamina.

2.3. Experimental considerations

Figures 5 and 6 depict major components of a currently operational optoelectronic holography (OEH) system specifically setup to perform high-resolution surface shape and deformation measurements [9,13]. The light source is an infrared laser diode (LD) with an operational wavelength centered at 780 nm, wavelength tuning capabilities, horizontal linearly polarized output, and driven by the controller (LDD), Fig. 5. The output of the LD is directed through a Faraday optical isolator (OI) providing back reflection isolation. After the OI, light is launched into a single mode fiber optic directional coupler assembly (FA), Fig. 6, by means of a fiber coupler (FCA), which is comprised of a GRIN lens, a 5 degrees of freedom stage, and an FC/AP connector port. The main components of the FA are three single mode fiber optic directional couplers (DC1, DC2, DC3), four piezoelectric cylinders (PZT1, PZT2, PZT3, PZT4), and FC connectorized I/O’s.

In the experimental arrangement shown in Figs 5 and 6, the OEH is configured in the one illumination and three reference beams mode. In this mode, the higher output beam from the FA is utilized as the object beam (OB) to illuminate the object of interest (OBJ), and one of the lower output beams is used as the reference beam (RB). Object and reference beams are recombined in the interferometer (IT) and the resultant detected irradiances are transmitted to an image-processing computer (IP) through the use of a CCD camera providing video frames with a resolution of 660 x 494 pixels and digitized to 8- and 10-bits. The two additional lower output beams are utilized for monitoring the optical characteristics of the LD. Specifically, one of the lower output beams is utilized as input to the optical wavelength meter (WM), providing absolute wavelength measurements with a resolution of 0.0001 nm, and the additional lower output beam is utilized for monitoring the optical power of the LD. In this experimental configuration, the ceramic piezoelectric cylinder PZT1, Fig. 6, is controlled by the IP and used for application of phase stepping algorithms. In addition, the ceramic piezoelectric cylinder contained in the RB can be utilized for quantitative analysis of time-average interferograms in situations requiring characterization of both, surface shape, and dynamically induced deformations [9,13].
One OEH approach used to perform static, dynamic, and shape measurement investigations of objects consists of acquiring and processing two sets, $I(u,v)$ and $I'(u,v)$, of phase-stepped speckle intensity patterns, recorded before and after, respectively, event effects of which are to be measured \[9,13,14\]. The first set of phase-stepped speckle intensity patterns is described by

$$I_n(u,v) = I_B(u,v) + I_M(u,v) \cos[\Delta \varphi(u,v) + \delta_n]$$ \hspace{0.5cm} (12)

where

$$I_B(u,v) = I_o(u,v) + I_r(u,v)$$ \hspace{0.5cm} (13)

is the background irradiance, and

$$I_M(u,v) = 2[I_o(u,v) \cdot I_r(u,v)]^{1/2}$$ \hspace{0.5cm} (14)

is the modulation irradiance. In Eqs 12 to 14, $I_o(u,v)$ and $I_r(u,v)$ are the irradiances of the object and reference beams, respectively, $\Delta \varphi(u,v) = \phi_o(u,v) - \varphi_r(u,v)$, with $\phi_o(u,v)$ representing a random phase due to light scattering from the object of interest and $\varphi_r(u,v)$ representing a uniform phase from a smooth reference beam wavefront, $\delta_n$ is the applied $n$-th phase step, value of which is obtained during calibration procedures applied according to the specific phase stepping algorithm that is implemented, and $(u,v)$ represents Cartesian coordinates of the image space defined by the CCD camera.

The second set of phase-stepped speckle intensity patterns is described by

$$I_n'(u,v) = I_B(u,v) + I_M(u,v) \cos[\Delta \varphi(u,v) + \Omega(u,v) + \delta_n]$$ \hspace{0.5cm} (15)

In Eq. 15, $\Omega(u,v)$ is the change in the optical phase that occurred between acquisition of the two sets of phase-stepped speckle intensity patterns. $\Omega(u,v)$ is known as the fringe-locus function, which when transformed to the absolute coordinate system $x$-$y$ \[9,13\],

$$\Omega(u,v) \Rightarrow \Omega(x,y)$$ \hspace{0.5cm} (16)

relates to the unknown deformation vector $L(x,y)$ by the equation \[14,15\]

$$[K_2(x,y) - K_1(x,y)] \cdot L(x,y) = K(x,y) \cdot L(x,y) = \Omega(x,y)$$ \hspace{0.5cm} (17)

where $K(x,y) = K_2(x,y) - K_1(x,y)$ is the sensitivity vector characterizing specific OEH recording geometry, Fig. 5.

### 3. REPRESENTATIVE APPLICATIONS

Two representative applications are presented to illustrate capabilities of OEH methodologies to perform nondestructive testing and damage evaluation of the FR-4 laminates of interest: (a) determination of orthotropic elastic material properties using OEH methodologies in the dynamic mode of operation, and (b) defect detection using OEH methodologies in the static mode of operation.

#### 3.1. Determination of elastic material properties

Analytical, computational, and experimental solutions (ACES) methodology is applied to determine orthotropic elastic material properties of the FR-4 laminates of interest. The methodology consists of:

1) utilizing constitutive stress-strain relationship, Eq. 6, and corresponding orthotropic elastic material transformations, Eqs 9, to design computational simulations and experimental conditions,

2) apply results obtained in step (1) to define computational models and to manufacture samples,

3) utilize OEH methodology in the dynamic mode of operation to perform modal analysis of manufactured samples,

4) utilize analytical and computational methodologies to perform the solution of an inverse problem and recover elastic material properties while utilizing experimentally obtained modal analysis results from OEH,

5) validate analytical, computational, and experimental results and perform uncertainty analysis.
Based on this methodology, samples were manufactured as shown in Fig. 7. Results obtained indicate that the FR-4 laminates of interest are characterized by $E_{11} = 25.02 \pm 1.5$ GPa, $E_{22} = 21.40 \pm 1.1$ GPa, and $G_{12} = 6.78 \pm 0.52$ GPa. $\nu_{12} = 0.127$, as specified in Table 1 was utilized during the evaluations. Figure 8 shows representative computational and OEH results obtained with ACES methodologies.

![Image](image_url)

**Fig. 7.** Cantilever beam samples. Width of samples is $24.35 \pm 0.012$ mm and height is $106.36 \pm 0.012$ mm. The longest dimension of the samples is parallel to the principal axes of the plate. Samples with longest dimension orientated at 45 deg relative to the principal axes were constructed and tested.

![Image](image_url)

**Fig. 8.** Representative FEM and OEH results. Height of cantilever beam is parallel to the principal $x$-axis of the plate. Effective height is $32.51$ mm. (a) first mode of vibration computed at $748.52$ Hz, (b) first mode of vibration measured at $758$ Hz, (c) first torsional mode of vibration computed at $2298.82$ Hz, (d) first torsional mode of vibration measured at $2056$ Hz.

### 3.2. Damage detection

Nondestructive evaluation of delamination in specific FR-4 laminates was investigated using OEH. Samples with known delamination defects were considered. By realizing that the CTE in the $z$-direction of the FR-4 laminates is more than one order of magnitude larger than the CTE’s in the $x$- and $y$-directions, Table 1, thermal loading was applied, independently, to both $x$-$y$ surfaces of an FR-4 cantilever plate and out-of-plane (i.e., $z$-direction) deformations were measured. Therefore, the OEH recording geometry was set to be sensitive to out-of-plane deformations. Delamination defects were detected successfully. Figures 9 and 10 show representative results. Quantified thermally induced deformations, Fig. 10, were measured with an accuracy on the order of $5$ nm.

![Image](image_url)

**Fig. 9.** OEH measured thermally induced deformations of laminates containing known delamination defects: (a) thermal load uniformly applied to surface being observed, and (b) thermal load uniformly applied to opposite surface. Field of view is $30 \times 30$ mm$^2$. 

![Image](image_url)

**Fig. 10.** Quantified thermally induced deformations of laminates containing known delamination defects: (a) first mode of vibration computed at $2298.82$ Hz, (b) first torsional mode of vibration measured at $2056$ Hz.
4. CONCLUSIONS AND FUTURE WORK

Nondestructive, noninvasive, and full-field-of-view OEH methodologies were applied to experimentally determine material properties and to perform damage evaluation in high-performance glass reinforced epoxy laminates utilized in electronic packaging applications. ACES methodology was applied in the investigations. With ACES, orthotropic material properties of the composite laminates were determined with a maximum uncertainty on the order of 5% and measurement accuracies on the order of 5 nm were achieved. Known delamination defects were successfully identified with OEH, demonstrating capabilities of OEH for nondestructive damage evaluation in composite laminates. Future work includes identification and quantification of damage in structures manufactured with advanced composite materials, including particulate composites based on nanoparticles.

5. REFERENCES