DECID2 : THE SMART-COMPOSITE-PLATEFORM OF LARGE DIMENSIONS (EMBEDDED SENSORS)

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Polymer-Matrix Composite?

Matrix (polymer) + Fibers (Glass, carbon …)

- Process routes (Many, including Pultrusion …)
Carbon Composites Based Cables (Tokyo Rope, JAPAN)
FRP-Superstructure Applications

- Focus on light weight and fast installation

- Permanent Vehicle Bridges
  - For Fast Installation

- Temporary Vehicle Bridges
  - Bypass adjacent to permanent bridge
  - Same load and deflection requirements
  - Rural areas with long detour options

- Temporary Equipment Bridges
  - Work Trestle
  - Cranes, support vehicles and personnel
Composite Bridges in USA (107 bridges)

**DURASPAN – MARTIN MARIETTA**

- New York State
- Oregon State
- California State
- Maryland State
Applications in Civil Engineering
Double Structural Health Monitoring Smart Composite Deck Using Low Diameter Optical Fiber an Micrometric Ultrasonic Sensors
FUI-Contract – Ministry of Industry (FRANCE)

- Smart composite structure (L = 20m x l = 3.5m)
- 3 years project starting from Sept 08
- Total Budget : 3.8 M€
- 2.3 M€ (Department of Industry & Local government)
- Partners (Industries & Universities)
- Composite structure made of glass composites (Pultrusion)
- Glass composites with embedded optical sensors
- Double SHM : Embedded optical fibers (FBG) & patch-based ultrasonic sensors
SMART COMPOSITE MATERIALS?

PROCEDURES

- Reliability
- Reduced maintenance
- Extended life
- etc.
Why The Project DECID2?

- Issues pertaining to bonded-sensors...
- Structural Health Monitoring Instead of Inspection...
- Reliability of Embedded Sensors
- Structural Health Monitoring up a distance ... Wifi...
NDT Techniques & Sensors ...

- Nanoindentation for Surface Characterization
- Acoustic Emission for Damage Monitoring
- Optical Fiber’s Sensors for Strain Monitoring and Structural Health Monitoring
- Ultrasonic Patchs for Structural Health Monitoring
UV-Exposure (THE SPHERE)

The SPHERE (Simulated Photodegradation via High Energy Radiant Exposure)

- Developed at NIST (Gaithersburg, Md, USA),
- the sphere provides a source of UV radiation of wavelengths between 290 nm to 400 nm
- The flux received is about 150W / m²
Microstructural Observations
Roughness of Tested Specimens
Theoretical Background
Nanoindentation Basics

- Investigate the near surface mechanical properties of materials
- Load is applied to indenter contacting film surface
- The applied load and the resulting depth of penetration are recorded by instrument as load is applied from an initial value (zero) to a desired maximum and then unloaded back to zero
- Load versus depth of penetration recorded and used to determine material’s hardness and elastic modulus
- Types of indenter shapes:
  - Conical
  - Spherical
  - Pyramidal: Berkovich (most common), Knoop, Vickers, Cube-Corner

Berkovich diamond indenter
How does nanoindentation work?

A. Material assumptions

Continuum: No structural length scales e.g. grain size, film thickness
Homogeneous: One phase
Elastoplastic: Deforms via plastic yielding, rather than fracture, phase transformation

B. Indenter considerations

E_i >> E_s: Ideally, deformation occurs only in sample material
Primarily diamond (hardest natural material)

Spherical:
* Elastic, THEN plastic
* Difficult to machine diamond

Sharp:
* Immediately elastic AND plastic
* Can facet diamond into pyramids, not cones

Vickers
Berkovich
What is nanoindentation?

SiC (ceramic)

PE (polymer)
Theoretical Background

Analysis of indentation experimental data

- Modern day method based almost entirely on work by Oliver and Pharr in 1992 – Commonly referred to as the “Oliver and Pharr” method
- Curve shown in (b) contains the necessary experimental data needed to obtain elastic modulus and hardness

\[
\frac{1}{E_r} = \frac{1 - \nu^2}{E} + \frac{1 - \nu_i^2}{E_i}
\]

\[
S = \frac{dP}{dh} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A}
\]

\[
A(h_c) = 24.5h_c^2 + C_1h_c^1 + C_2h_c^{1/2} + C_3h_c^{1/4} + \ldots + C_8h_c^{1/128}
\]

\[
H = \frac{P_{max}}{A}
\]

After Reference [9]
Current Research and Applications
Current State of the Art

- High tech, extremely accurate instruments available on the market from a variety of distributors
- Capabilities
  - Scratch testing, micro wear testing, elevated temperature testing, acoustic emission detection, in situ AFM imaging

Hysitron TriboIndenter®
MTS Nano Indenter® XP
ASMEC Universal Nanomechanical Tester
Nanoindentation Tests

Indentation sur du vinylester

Indentation sur du composite

Charge (mN)

Déplacement de la pointe (nm)
Nanoindentation on Cross-Section
Nanoindentation on Composite Specimens

Graphs showing:
- Young's modulus (GPa) vs. distance from the sample edge (µm)
- Hardness (GPa) vs. distance from the sample edge (µm)

Data points and trend lines for non-exposed, 2 weeks, and 4 weeks exposure conditions.
Mechanical behavior - Acoustic Emission

- First phase starts at the beginning of the trial and ends at the registration constraint of the first acoustic emission events (No damage).
- Second phase extends from $\varepsilon = 0.22\%$ to the end of proportionality (Multiple matrix damage, along with the failure of weakest fibers).
- Third phase begins at the end of proportionality and ends at the maximum stress (Progressive failure of fibers in large numbers).
- Forth phase is reached when a critical number of fibers failures at the peak load.
- The final phase consists of an increase in mode II cracking (Delamination).
Acoustic Emission

Figure: Evolution of AE during load/unload test

Figure: Felicity Ratio as a function of the strain

Dahmène & al., 2013, submitted

Figure: Evolution of AE during fatigue
Diameter of silica = 80mm – High performance polymer coating = 10 mm

Static Tension : 2.5N – Time under loading : 7 days

Good adhesion between silica and polymer – No decohesion at the interface even for high speed tests (Micrographies : Sangleboeuf et al., 2010)
Fiber-Optic Sensors

Fiber-Bragg Gratings

Physical Variables
Temperature
Deformation

Longueur d'onde de la lumière incidente

Intensité
Rétro-diffusion Rayleigh
Rétro-diffusion Raman (Anti-stokes)
Rétro-diffusion Brillouin
Rétro-diffusion Raman (strokes)

Amplitude dépendante de la température
dépendant de la température et de la déformation

\[ \lambda_B = 2 n_{eff} \lambda_0 \]

Lumière incidente
Lumière transmise
Cœur de la fibre optique
Modulation périodique de l'indice de réfraction

Transmission
Longueur d'onde
Monitoring of Pultrusion

Essai n°1 : FO + tube
Optical Fiber Pultrusion – OBR signals
Load-Unload data – FBGs Signals

Figure: Standard amplitude of FBG as a function of the wavelength
Fatigue Tests – FBGs signals ...

- The strain measured using FBG is smaller than the one displayed by the mechanical testing machine.

- Result of the difference between the strain measured by the mechanical testing machine at the extreme of the area under tension and the position of the optical fiber inserted into the heart of the area under tension, but closer to the neutral axis.

Figure: Comparison of strain values delivered by FBG and the mechanical testing machine.
Presence of optical fibers – Effects on the toughness, $K_{TL}$

- ASTM E1922 Standard Test Method for Translaminar Fracture Toughness of Laminated and Pultruded Polymer Matrix Composite Materials

- Tests at NASA GLENN (Cleveland, OH)

- $K_{TL} = 0.5 \text{ MPam}^{1/2}$ (Variation of 6% with a notch of 30%)
Fatigue – Effects of embedded sensors
US Sensors – Damage Monitoring …

Scope: Development of US-based patches sensors (guided waves) to monitor highly stressed areas: Contact, bonded and rivetted areas, etc. (N. TERRIEN – CETIM)

Qualification of AE sensors

Guided waves in a pultruded specimen
DECID2 SMART COMPOSITE PLATEFORM (IFSTTAR Nantes Center)
Conclusions & Perspectives ...

The future of High-performance polymer composites is linked to the concept of smart composite.

- The capacity to integrate embedded sensors that are reliable ...
- Keeping intact the thermomechanical performance ....