13 Mars 2019, IFSTTAR, Champs sur Marne

2ème journée nationale
« Contrôle Santé HM & Monitoring de structures »

Les capteurs Quantum Resistive strain
Sensors (qQRS) pour la mesure des
déformations au cœur des composites

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IRDL CNRS & UBS has 250 researchers in
Materials & Mechanical Engineering
IRDL = LIMAT® @ UBS + LBMS @ ENSTA

PRT1 "Composites"
- Stimulable nanoComposites & Smart materials
- BioPolymers & BioComposites
- Additive manufacturing of Polymers & Composites

http://www.smartplasticsgroup.com
Stimulable nanocomposite can be smart plastics!

![Images of different stimuli: Thermo-stimulable, Electro-stimulable, Piezo-stimulable, Magneto-stimulable, Chemo-stimulable, Photo-stimulable]

Such kind of materials are able to interact with their environment.


There is a need for damage anticipation in composite structures

- Right now structural health monitoring fails at predicting the complex damage behaviour of composites.
- It is necessary to combine different kinds of monitoring and develop data analysis to make a pertinent diagnosis and implement new sensors such as sQRS.
Composite materials that would feel pain thanks to a neural network all along their life

Which nanofiller building blocks choosing?

- MMT, GR and CNF which have high shape factors and specific surface (1-10 m².g⁻¹ to 250-1000 m².g⁻¹) act on crystallization, transition temperatures, visco-elastic & rheological properties, mechanical, thermal & electrical conductivity
Structuring CPC sensors by additive fabrication, i.e., spray layer by layer (sLbL)

- Filler content $\phi$ (%)
- Resistivity $\rho$ ($\Omega \cdot cm$)

$\rho_{CPC} = \rho_{f}(\Phi - \Phi_c) - \epsilon$

Percolation threshold

Macro Scale
Controlled Architecture
Nano Scale

Principle of Quantum Resistive strain Sensors sQRS

- In a CPC the global resistance is driven by tunnelling conduction
- The resistance at tunnel junctions depend on the gap
- Any tiny variation of the gap results in exponential variation of the resistance

$R_{CPC} \approx 10^4 \Omega \cdot cm^{-1}$
$R_{CNT} < 10^{-2} \rightarrow 10^{-5} \Omega \cdot cm^{-1}$

$R_{CPC} = R_{contact} + R_{tunnel} + (R_{nanotubes})$

$\rho = a \cdot e^{b \cdot Z}$
The need for Structural Health Monitoring to secure polymer composites’ development

- SHM devices are already in development, but they ultimately aim to optimize the materials by following and anticipating their damage all along their lives.
- Nanocomposites based sensors sQRS, because of their potentially homogeneous nature with the composite and quasi non-intrusivity, can provide valuable information on the behaviour of composites parts and thus secure their development.


Cost ?
Weight ?
Efficiency ?
Intrusivity ?
Robustness ?

Strain QRS “sensing skin” concept applied to textile deformation monitoring


Groupama Team – America’s cup

Piezo-resistive response of sQRS deposited on a composite sails sample

The transducers’ size can be tailored on demand provided that the CPC formulation is adapted.


sQRS skins for smart textiles

The piezoresistive responses are very different depending on the textile on which the sQRS skin is deposited: cotton (up) of lycra (down)

sQRS is an interesting tool to understand materials’ mechanical behaviour and develop strain monitoring applications.

Fabrication and integration of sQRS for core monitoring

- sQRS can be fabricated in situ directly onto plies (a)
- They can also be prefabricated and later integrated (b)
- Large versatility of the precessing towards non intrusive core monitoring


Strain monitoring with sQRS on the surface of composite samples in the linear domain

- The piezo-resistive signal of sQRS is perfectly following the mechanical solicitation imposed by the operator in the elastic domain of deformations up and down
- No particular event is seen as no damage is expected, the behaviour is reversible

Core monitoring with sQRS embedded between composite plies in the non-elastic domain of deformation

- Over the linear range of deformation, the piezo-resistive response is becoming non-linear as, both non-reversible plastic and breakage are taking place
- Good reproducibility of the sensors (blue and red)
- The analysis of this signal could help to predict damage


Damage accumulation followed by $R_0$ drift

- Electrical resistance and strain evolution of Epoxy/CNT during incremental cyclic tensile test
- Over 0.3% of deformation, i.e., the third cycle, there is a strong drift in residual strength correlated with a drift in initial resistance evidencing plastic deformation and damage

Limit of elasticity in short and long cycling

\[ e < 0.4 \% \]

\[ e < 1 \% \]

\[ 0.2 < e < 0.4 \% \]

\[ 0.4 < e < 0.8 \% \]

Fatigue damage followed in the core of the composite

✓ Variation of resistance along strain cycles for two different amplitudes:
  (red) strain 0.4 +/-0.2% (blue) strain 0.6 +/-0.2%
Is it possible to monitor damage with sQRS embedded at the interface?

✓ sQRS can be integrated in situ at the interface between glass fibres and epoxy matrix
✓ But which kind of signal can be obtained with interfacial sQRS?


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Core sQRS morphology control and intrusive checking

<table>
<thead>
<tr>
<th>Test mode</th>
<th>Modulus (GPa)</th>
<th>Stress at break (MPa)</th>
<th>Strain at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension without sensor</td>
<td>15.9 ± 0.5</td>
<td>170.0 ± 5.2</td>
<td>1.30 ± 0.1</td>
</tr>
<tr>
<td>Tension with sensor</td>
<td>15.1 ± 0.8</td>
<td>169.1 ± 7.4</td>
<td>1.23 ± 0.2</td>
</tr>
</tbody>
</table>

✓ The introduction of a sQRS in a 0/90° GF-EP composites does not change much mechanical properties
✓ Which is the best way to introduce CNT at the interface

Mechanism of interfacial debonding

Study of the interface µdebonding

Mode of testing  
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<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Contact angle (°)</td>
<td>58.7 ± 3.2</td>
<td>48.1 ± 3.8</td>
<td>45.7 ± 3.4</td>
</tr>
<tr>
<td>IFSS (MPa)</td>
<td>45.2 ± 5.9</td>
<td>45.4 ± 6.1</td>
<td>40.5 ± 5.9</td>
</tr>
</tbody>
</table>

- Contact angle and Interfacial Shear Strength (measured on 50 µdroplets)
- Bad connection of CNT on fibres' surface can lead to brittle interface


Thanks

Collaborateurs

Smart Plastics

http://www.smartplasticsgroup.com

Sponsors

Dr M. Castro
Dr T. T. Tung
Dr A. Le Martinel
Dr S. Nag-Chowdhury

Startup

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