precend

SHM-France

COFREND
Confédération Française pour les Essais Non Destructifs

13 Mars 2019, IFSTTAR, Champs sur Marne

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

Les capteurs Quantum Resistive strain Sensors (sQRS) pour la mesure des déformations au cœurs des composites

Pr Jean-François FELLER

IRDL CNRS

Smart Plastics

University of South Brittany (UBS) – Lorient FRANCE

UBS 1995

Smart Plastics 2004

SENSE in 2018

2016 IRDL CNRS

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

PRT1 "Composites"

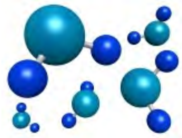
- Stimulable nanoComposites & Smart materials
- BioPolymers & BioComposites
- Additive manufacturing of Polymers & Composites

http://www.smartplasticsgroup.com

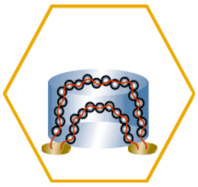
Stimulable nanocomposite can be smart plastics !

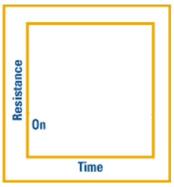
Thermo-stimulable

Electro-stimulable



Chemo-stimulable





Piezo-stimulable

Magneto-stimulable

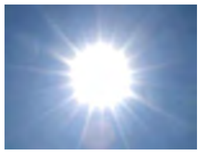
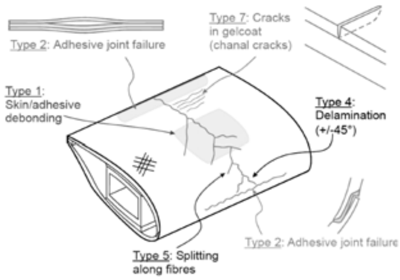


Photo-stimulable

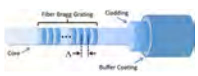
☞ Such kind of materials are able to interact with their environment

J. F. Feller, M. Castro, B. Kumar, Polymer CNT conductive nanocomposite for sensing, Whoodhead Pub., Chap. 25, 760-803 (2011)

There is a need for damage anticipation in composite structures



Gauge

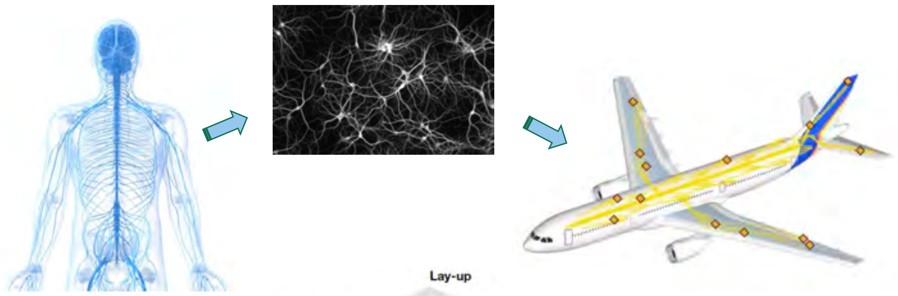


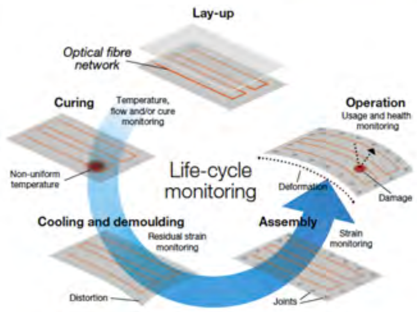
Bragg grating

PZT

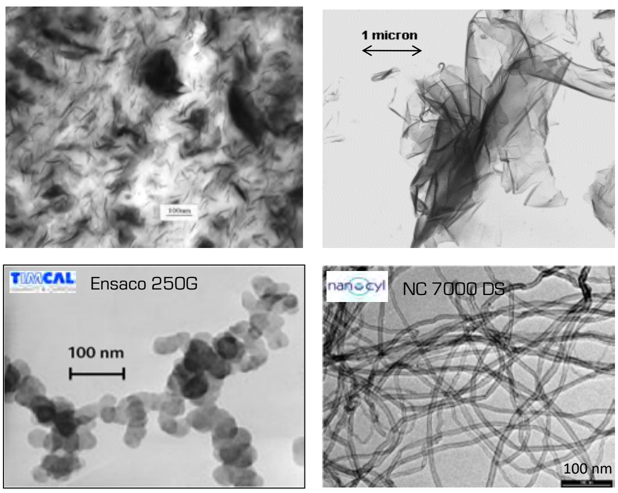
- ✓ Right now structural health monitoring fails at predicting the complex damage behaviour of composites
- ✓ It is necessary to combine different kinds of monitoring and develop data analysis to make a pertinent diagnosis and implement new sensors such as sQRS

Composite materials that would feel pain thanks to a neural network all along their life





Which nanofiller building blocks choosing?



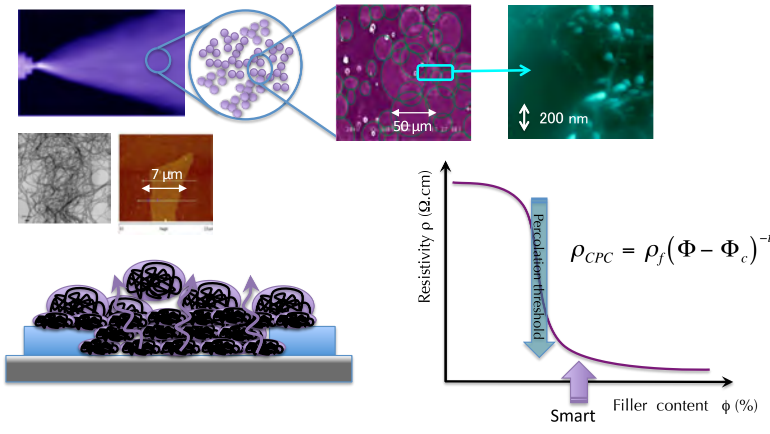
Clay and carbon Nanoplatelets (MMT & GR)

Carbon nanoparticles & nanotubes (CNP & CNT)

- ✓ MMT, GR and CNF which have high shape factors and specific surface (1-10 $m^2.g^{-1}$ to 250-1000 $m^2.g^{-1}$) act on crystallization, transition temperatures, visco-elastic & rheological properties, mechanical, thermal & **electrical conductivity**

I. Pillin, J. F. Feller, **Macromolecular Materials & Engineering**, 291, 11, 1375-1387 (2006)

Structuring CPC sensors by additive fabrication, i. e., spray layer by layer (sLbL)



$$\rho_{CPC} = \rho_f(\Phi - \Phi_c)^{-t}$$

Nano Scale → Controlled Architecture → Macro Scale

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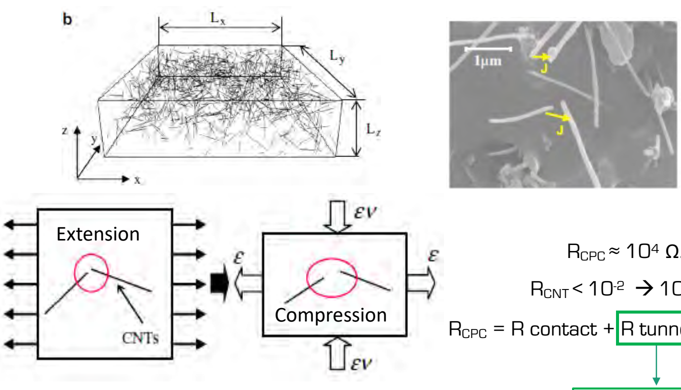
J. F. Feller, H. Guézénoc, H. Bellégou, Y. Grohens, **Macromolecular Symposia**, 222, 1, 273-280 (2005)

Principle of Quantum Resistive strain Sensors sQRS



$R_{CPC} \approx 10^4$ Ω.cm^{-1}

$R_{CNT} < 10^{-2} \rightarrow 10^{-5}$ Ω.cm^{-1}

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

$$\rho = a\, e^{(b\, Z)}$$

- ✓ 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

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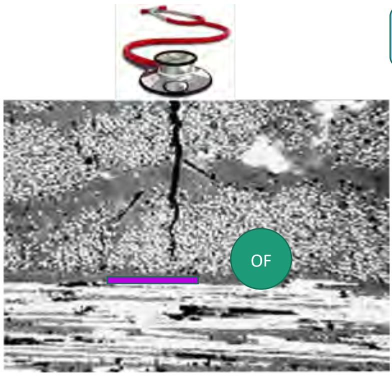
C. Li, E. T. Thostenson, and T.-W. Chou, **Applied Physics Letters** 91 (2007) 223114
N. Hua, Y. Karube , C. Yan , Z. Masuda , H. Fukunaga, **Acta Materialia** 56 (2008) 2929–2936

The need for Structural Health Monitoring to secure polymer composites' development



Cost ?

Weight ?

Efficiency ?

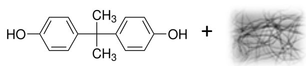
Intrusivity ?

Robustness ?

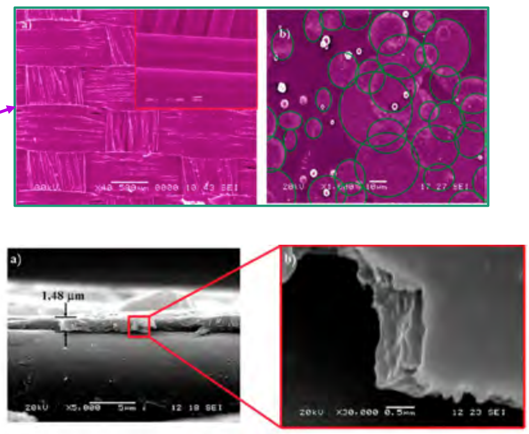
- ✓ SHM devices are already in development, but they ultimately aim to optimize the materials by following and anticipating their damage all along their lives
- ✓ Nanocomposites based sensors sQRS, because of their potentially homogeneous nature with the composite and quasi non-intrusivity, can provide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

J. F. Feller, Chap 605: Electrically conductive nanocomposites, in Vol. 6: Nanocomposites and Multifunctional Materials, Ed. T. Peijs, E. T. Thostenson, in **Comprehensive Composite Materials II**, 2nd edition, Ed. C. H. Zweben, P. Beaumont, Elsevier, 4608 p

Strain QRS "sensing skin" concept applied to textile deformation monitoring



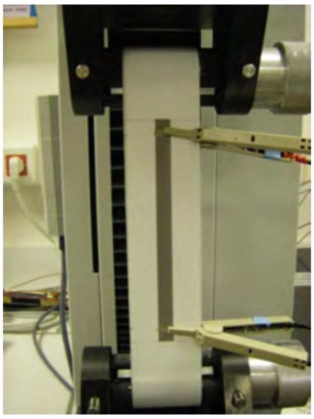
Groupama Team – America's cup



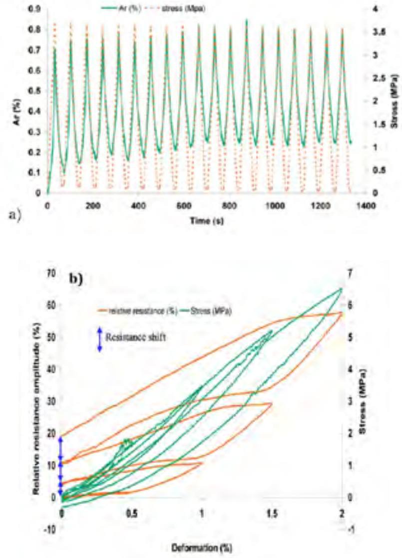
C. Robert, J. F. Feller, M. Castro, Sensing skin for strain monitoring made of PC-CNT conductive polymer nanocomposite sprayed layer by layer, **ACS Applied Materials & Interfaces**, 2012, 4, 7, 3508-3516

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

JF Feller – sQRS for SHM – COFREND Paris - 14/05/2019



- ✓ The transducers' size can be tailored on demand provided that the CPC formulation is adapted



C. Robert, J. F. Feller, M. Castro, Sensing skin for strain monitoring made of PC-CNT conductive polymer nanocomposite sprayed layer by layer, **ACS Applied Materials & Interfaces**, 2012, 4, 7, 3508-3516

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sQRS skins for smart textiles

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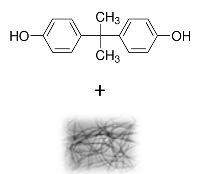

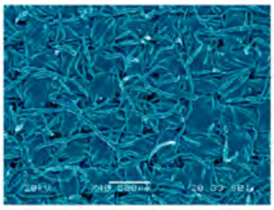

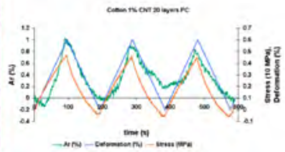

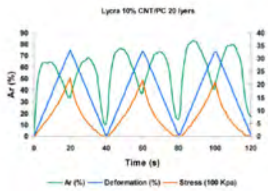

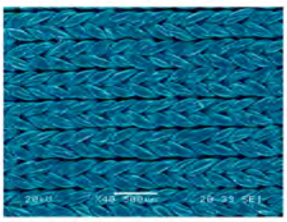

- ✓ The piezo-resistive responses are very diferent depending on the textile on which the sQRS skin is deposited, cotton (up) of lycra (down)
- ✓ sQRS is an interesting tool to understand materials' mechanical behaviour and develop strain monitoring applications

C. Robert, J.F. Feller, M. Castro, **ACS Appl. Mater. & Interf.** (2012) 4, 7, 3508-3516

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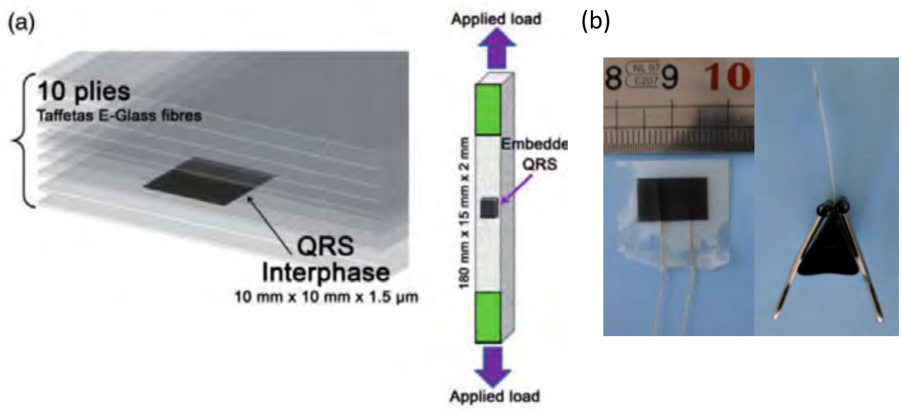
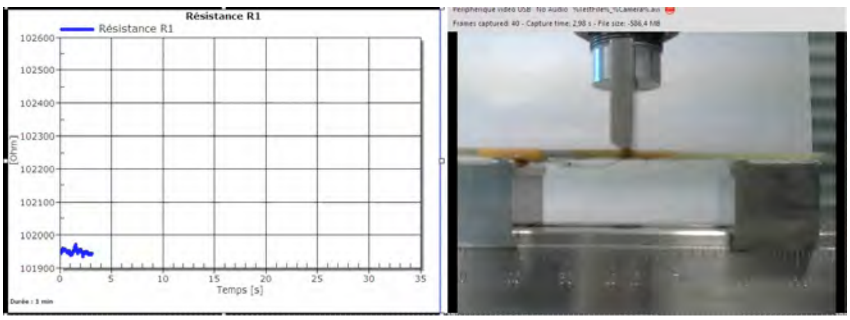
Fabrication and integration of sQRS for core monitoring



- ✓ 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

Nag-Chowdhury, S., Bellegou, H., Pillin, I., Castro, M., Longrais, P., Feller, J.F., **Composite Science & Technology**, 123, 286–294 (2016)

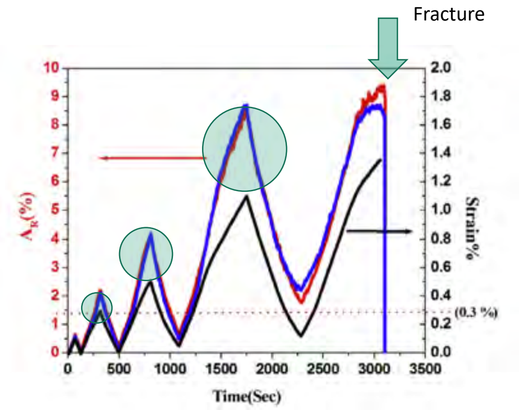
Strain monitoring with sQRS on the surface of composite samples in the linear domain



- ✓ 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

Nag-Chowdhury, S., Bellegou, H., Pillin, I., Castro, M., Longrais, P., Feller, J.F., **Composite Science & Technology**, 123, 286–294 (2016)

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

S. Nag-Chowdhury, H. Bellegou, I. Pillin, M. Castro, P. Longrais, J. F. Feller, Non-intrusive health monitoring of infused composites with embedded carbon quantum piezo-resistive sensors, **Composites Science & Technology**, 123 (2016) 286–294.

JF Feller – sQRS for SHM – COFREND Paris - 14/05/2019

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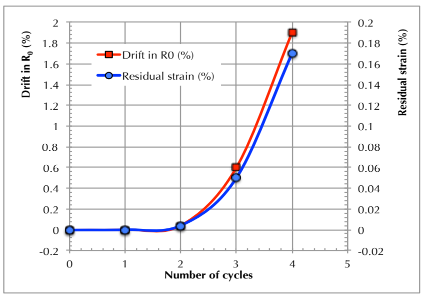
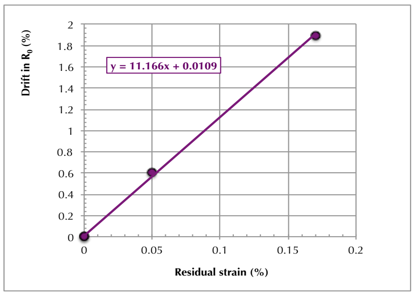
Damage accumulation followed by R_0 drift





- ✓ 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

S. Nag-Chowdhury, H. Bellegou, I. Pillin, M. Castro, P. Longrais, J. F. Feller, Non-intrusive health monitoring of infused composites with embedded carbon quantum piezo-resistive sensors, **Composites Science & Technology**, 123 (2016) 286–294.

JF Feller – sQRS for SHM – COFREND Paris - 14/05/2019

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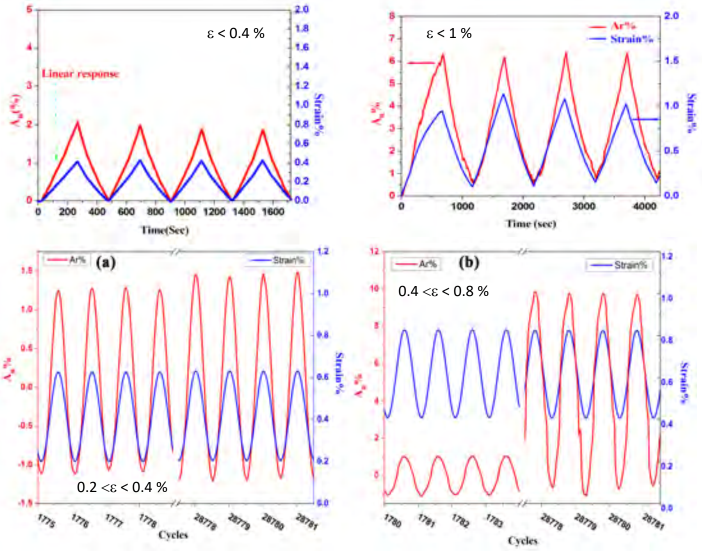
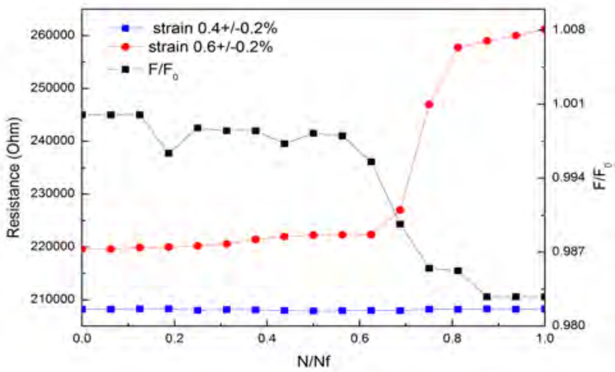
Limit of elasticity in short and long cycling



S. Nag-Chowdhury, H. Bellegou, I. Pillin, M. Castro, P. Longrais, J. F. Feller, Non-intrusive health monitoring of infused composites with embedded carbon quantum piezo-resistive sensors, **Composites Science & Technology**, 123 (2016) 286–294.

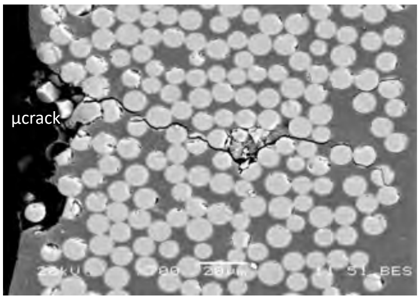
Fatigue damage followed in the core of the composite

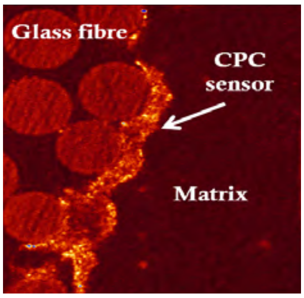


✓ Variation of resistance along strain cycles for two different amplitudes : (red) strain 0.4 +/-0.2% (blue) strain 0.6 +/-0.2%

S. Nag-Chowdhury, H. Bellegou, I. Pillin, M. Castro, P. Longrais, J. F. Feller, Non-intrusive health monitoring of infused composites with embedded carbon quantum piezo-resistive sensors, **Composites Science & Technology**, 123 (2016) 286–294.

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?

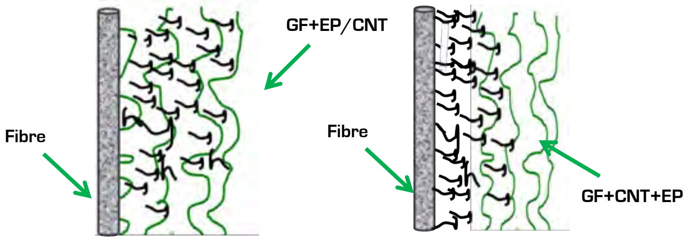
I. Pillin, M. Castro, S. Nag-Chowdhury, J.F. Feller, Robustness of carbon nanotube-based sensor to probe composites' interfacial damage in situ, **J. Compos. Mater.** 50 (2016) 109–113

Core sQRS morphology control and intrusivity cheking

Test mode	Modulus (GPa)	Stress at break (MPa)	Strain at break (%)
Tension without sensor	15.9 ± 0.5	170.0 ± 5.2	1.30 ± 0.1
Tension with sensor	15.1 ± 0.8	169.1 ± 7.4	1.23 ± 0.2

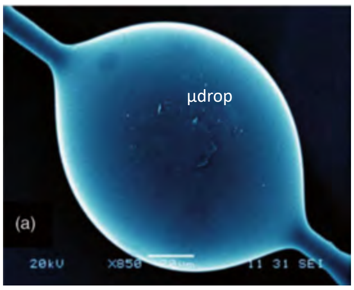
- ✓ The introduction of a sQRS in a 0/90° GF-EP composites does not change much mechanical properties
- ✓ Which is the best way to introduce CNT at the interface

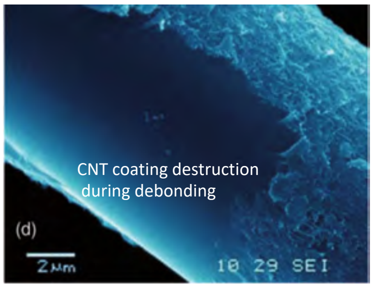
Mechanism of interfacial debonding



I. Pillin, M. Castro, S. Nag-Chowdhury, J. F. Feller, Robustness of carbon nanotube-based sensor to probe composites' interfacial damage in situ, **Journal of Composite Materials**, 50 (2016) 109–113.

Study of the interface μdebonding





Mode of testing	GF+EP	GF+EP-CNT+EP	GF+CNT+EP
Contact angle (°)	58.7 ± 3.2	49.1 ± 3.8	45.7 ± 3.4
IFSS (MPa)	45.2 ± 5.9	45.4 ± 6.1	40.5 ± 5.9

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

I. Pillin, M. Castro, S. Nag-Chowdhury, J.F. Feller, Robustness of carbon nanotube-based sensor to probe composites' interfacial damage in situ, **J. Compos. Mater.** 50 (2016) 109–113

Thanks

Sponsors

Collaborateurs

Smart Plastics

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