Hybrid joints monitoring by nanotechnologies

A. Zucchelli, T. M. Brugo, D. Cocchi
Dept of Industrial Engineering

G. Selleri, D. Fabiani,
Dept. of Electrical, Electronic and Information Engineering

E. Maccaferri, L. Mazzocchetti, L. Giorgini
Dept. of Industrial Chemistry

A. Pirondi, F. Moroni
Engineering and Architecture Department, University of Parma

Industrial partners

A. Marrani, I. Falco
Solvay Specialty Polymers Italy s.p.a.

F. Campanini
ELANTAS Europe Srl

F. Varrasi
MIND srl
Introduction

Adhesive joints are becoming increasingly popular since they
1. reduce stress concentrations,
2. enable uniform load distribution,
3. have better fatigue properties,
4. can join different kinds of material (e.g., steel and fiber reinforced polymer (FRP))

Airbus A380 features bonded joints for instance in the rear pressure bulkhead, the ailerons, the vertical tail plane and the radome as illustrated in figure.

T. Löbel, D. Holzhüter, M. Sinapius, C. Hühne, A hybrid bondline concept for bonded composite joints, International Journal of Adhesion and Adhesives, Volume 68, 2016, Pages 229-238, ISSN 0143-7496,
Introduction

1. Lack of design guidelines or modeling techniques to
   • accurately capture the maximum load carrying capacity
   • understand their behavior and failure mechanisms have
     led to overly conservative designs.

2. Different types of failure
   • the adhesive-adherent interface,
   • the adherent depending

3. They are often considered as the weak link among structural elements.
   As a result, mechanical fasteners such as bolts are often added alongside the adhesive layer.

Thus there is a crucial need to monitor potential damage in the adhesive joints.
Introduction

What we expect from a sensing constituent in composite and hybrid joints?

1. To be pervasive and not invasive:
   - to be everywhere
   - not to change materials and joints physical characteristics (weight, geometry)
   - not to reduce material and joint performances (mechanical and chemical)

2. to be friendly
   - not to require external energy

3. to be able to precept the right stimulus
   - to be sensible
Introduction

State of the art:

• fiber bragg grating [1],
• ultrasonic technique [2].
• acoustic-laser technique [3],
• carbon nanotubes (CNT): debonding between the adherents is detected by directly dispersing CNTs in the adhesive [4] [5] or by coating a nonwoven mat with CNTs [6].

2. S. Yashiro, J. Wada, Y. Sakaida, A monitoring technique for disbond area in carbon fiber–reinforced polymer bonded joints using embedded fiber Bragg grating sensors: development and experimental validation, Struct Health Monit, 16 (2) (2017), pp. 185-201
Introduction

State of the art drawbacks

- Fiber Bragg Grating
- Ultra-thin polymer Bragg grating sensor foils

FIBER BRAGG GRATING

Problems

- integration problems of rigid and bulky sensors in the composite laminate, such as Fiber Bragg Grating or piezoelectric ceramic transducers, can dramatically reduce the inherent strength of the laminate
- Reliability
- External energy is required
- Cost

- CNTs
  - Processing problems related to abnormal increment of viscosity of adhesives when CNTs are dispersed in it
  - Environmental and health issues
  - External energy is required
  - Cost
Introduction

A new candidate to realize self-sensing hybrid joints

Objects composed of nanofibers are characterized by: **High porosity**

Non-woven mat made of polymeric nanofibers obtained through electrospinning

**Porosity 80-90%**
Introduction

Electrospinning of polymeric solution
Introduction

Example of NanoFibrous mat and adhesive infiltrated NF mat
Piezoelectric behavior of PVdF films are well known while limited literature deals with nanofibrous PVdF materials.

- Films: if integrated in other hosting materials can lead to delamination and fracture inception
- Nanofibers can be integrated without reducing mechanical properties (on the contrary they increase the delamination toughness)

**PVDF nanofibers improve fracture toughness** (crack onset and propagation) when interleaved in composite laminates.

• Electrospun nanofibrous membrane in adhesive joint can be used and they enhance mechanical properties

Nanostructured piezoelectric GLARE laminate

- Structurally the self-sensing laminate is similar to Glass Laminate Aluminum Reinforced Epoxy (GLARE):
  - Known for its superior impact strength:
  - Interleaving GLARE laminate with PA66 nanofiber increase impact strength.
Sensor real-time piezoelectric response
Sensor Sensitivity & Linearity (LV Impact load)

Features:
- Sensitivity: 27 mV/kN
- Linearity: $R^2 > 0.99$

 impacted at different height (1-5 cm)

$F_p = V_p \times 10 \times 3.65$

$\Delta V = 0.274F_{\text{max}} + 0.047$

$R^2 = 0.9916$
Destructive impact tests: Mechanical response

- At different impact energies, for the Reference and Nano GLARE laminates:
  - the force vs displacement curves are similar;
  - the maximum force, absorbed energy and residual deformation are statistically comparable.

Shielded cables for collecting piezoelectric signal

1.3 kg impactor with load cell

Self-sensing laminate
**Signal response** of the piezoelectric laminate compared to the force measured by the impactor load cell.

- For all impact energies, the **force measured by the piezoelectric laminate** (dotted lines)copy the contact force measured by the **impactor load cell** (solid lines) up to 1.5 kN, to then remarkably diverge.
- The deviation of the piezoelectric signal from the force is due to the delamination onset and matrix cracking which causes breakage of the embedded sensor. Therefore, the **abrupt increase of the signal value** can be used as
  **alarm threshold for damage detection.**
Destructive impact tests: 
Post-impact Piezoelectric response

Signal response of the piezoelectric laminate compared to the force measured by the impactor load cell after impact destructive tests

- After 5 J and 10 J impacts, the force measured by the piezoelectric laminate (dotted lines) is similar to the contact force measured by the impactor load cell (solid lines), due to the small damage developed.

- After 20 J impact, the force measured by the piezoelectric laminate diverges from the contact force, due to the large damage developed in the laminate, hence in the sensor.
Destructive impact tests: Micrograph analysis

- For all impact energies, the laminates show the same damage mechanism and magnitude:
  - debonding and plasticization of the upper and lower aluminum laminas;
  - matrix cracking and small delamination onset in the GFRP layers.
Conclusions

- Piezoelectric nanofibers are successfully manufactured.
- Piezoelectric nanofibrous mat was successfully integrated into the composite to achieve self-sensing GLAREGLARE self-sensing demonstrated mechanical performance in line with that of the standard.
- The piezoelectric signal of GLARE self-sensing was linear as the maximum impact value varied.
- Destructive impacts were measured by the GLARE self-sensing and demonstrated the ability to generate alarm signals in case of material failure.
- Repeated impact tests on the damaged material showed that the material is still able to generate an alarm signal demonstrating its effectiveness.
Future developments

1. Realization of self-sensing hybrid junction (metal-composite)
2. Realization of a miniaturized electronic circuit for onboard installation
3. Design of smart circuit for failure detection

Applications on hybrid components components for safety and structural health monitoring