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STRUCTURAL HEALTH MONITORING (SHM) OF SMART SANDWICH COMPOSITES DURING THREE-POINT BENDING TESTS

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Abstract. This article presents the Structural Health Monitoring (SHM) study conducted on the smart sandwich composites under three-point bending tests. Piezoelectric transducers (PZT and P(VDF-TrFE)/CP) were integrated inside the Polymer-Matrix Composite (PMC) skins to make them "smart". Several Non-Destructive Testing (NDT) techniques have been used: the classical ones (external Acoustic Emission (AE), thermocouples, strain gauges…) and new ones using the embedded transducers (internal Acoustic Emission (AE), Electrical Capacitance and Ultrasonic testing (US)) were combined simultaneously. The monotonic and load/unload three-point bending tests introduced progressive damages in sandwich composite specimens and the combined NDT techniques made it possible to monitor, in real-time and in situ, the different damage signatures before, during and after the mechanical tests. The obtained results of the non-destructive approach show a multiphysics (thermal/mechanical/acoustic and ultrasonic) coupling in the detection and monitoring of the different damage mechanisms of sandwich composite materials.

Key words: Smart sandwich composites; Damage; Structural Health Monitoring (SHM); Embedded piezoelectric transducers; Non-destructive approach.

1 INTRODUCTION

Nowadays, Polymer-Matrix Composite (PMC) materials are used in many domains and applications: aeronautics, automotive, wind power, sports... Thanks to their high mechanical properties and low weight, they are gradually replacing more traditional materials, such as metals. This is why understanding their damage mechanisms and being able to detect/locate/identify/quantify them effectively is a popular research area, this is called Structural Health Monitoring (SHM). In this context of SHM, a material that can self-carry the information about its health and automatically give a conclusion about its service continuity is highly sought; such kind of material is called Smart material. The PMCs are a nice candidate to make them Smart, this can be done by the insertion of Optical Fiber, Piezoelectric Transducers, …

In this present work, smart sandwich composites were made by integrating two types of piezoelectric transducers (PZT and P(VDF-TrFE)/CP) using the experimental methodology developed in the work of Tuloup [1]–[8]. Acoustic Emission (AE), Electrical Capacitance and Ultrasonics (US) have been used with these transducers, in order to obtain exact information

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about different types of damage and their evolution scenarios within the material. Three-point bending tests have been made to introduce progressive damages in PMC specimens and to collect data before, during and after the tests. The smart PMC embedding piezoelectric transducers were also inspected with external NDT techniques such as classical AE, thermocouples, strain gauges… The goal of this combination was to get as much data as possible about the damages that occurred. The final step of this work is the development of a data fusion approach in order to automatically give robust information about damages. To improve its robustness, a large amount of data is necessary, through the variation of several factors (the specimens, the mechanical tests, the damage level, the damage position, …). The configuration and test introduced in this article are preliminary tests to evaluate the possibilities and the difficulties which can be encountered, this will help to find the best configuration for the full SHM campaign.

2 SMART SANDWICH COMPOSITES

In this work, two types of sandwich composite specimens were manufactured: Smart (with embedded piezoelectric transducers) and Non-Smart (without). To start, 3 non-smart sandwiches were prepared, in order to choose the correct loading steps, check the intrusiveness of piezoelectric transducers and their effect on the mechanical properties.

2.1 PMC skins and sandwiches manufacturing

The PMC skins were made from fiberglass and polyester resin (fiber volume rate = 45%), with Liquid Resin Infusion (LRI) fabrication. A first plate with the dimension of 310x180mm^2 was made, in order to cut the wanted dimension for the skins (180x40mm^2). Computer Numerical Control (CNC) machine was used to cut the wanted dimension.

After the skins were prepared, the sandwiches were created with a crosslink PVC foam as core material. This foam was also cut at the wanted dimension from the CNC and an epoxy adhesive was used to join the two skins to the core (**Figure 1**).

Figure 1: Sandwich specimen made of PMC skins and crosslink PVC core

The information about sandwich components are given:

- Fibers: 6 plies of 180x310mm^2 of glass fibers 2/2 twill fabric (0.2mm of thickness, from Gazechim Composites);
- Resin: An orthophthalic unsaturated polyester resin (pre-accelerated) Norester 822 for infusion (from Nord Composites), with a degassing pressure or -0.4 bar during 4 min and an injection pressure of -0.8bar during the LRI;
- Hardener: 1% wt. of methyl ethyl ketone peroxide (MEKP) ketanox B180 (from C.O.I.M s.p.a.);

- Adhesive: 5g of Araldite 420A/B epoxy adhesive (from Amber Composites);
- Core: 180x40mm2 of a Crosslink PVC foam Airex C70 (from Sicomin);

2.2 Piezoelectric transducers

The piezoelectric transducers used in this work were PZT (Wealthland) with 9mm in diameter and 80µm in thickness, and copolymer P(VDF-TrFE) (CP) (Piezotech) with 9mm and 25mm of diameter and 30µm thickness (**Figure 2**). The PZTs were used as actuators and sensors, while the CPs only as sensors.

(a) (b)

Figure 2: PZT (a) and P(VDF-TrFE) (b) of 9mm in diameter

The transducers were integrated into the PMC specimen using the experimental procedure developed in the work of Tuloup [8], during Liquid Resin Infusion (LRI) process. Tinned copper wires of 210µm diameter have been used to wire the transducers. The static capacitance is measured before and after the LRI, to ensure that the transducers are still working. Each sandwich beam with the dimension 180x40x13mm^3 has 6 piezoelectric transducers (**Figure 3**):

- 2 CPs 9mm at the interface between skin and foam, in the middle of the length and the width;
- 1 CP 25mm et 1 PZT 9mm in the middle plane of the upper skin, in the middle of the width and spaced 100m apart in the length;
- 1 CP 25mm et 1 PZT 9mm in the middle plane of the lower skin, in the middle of the width and spaced 100m apart in the length (the position on lower and upper skins are inversed);

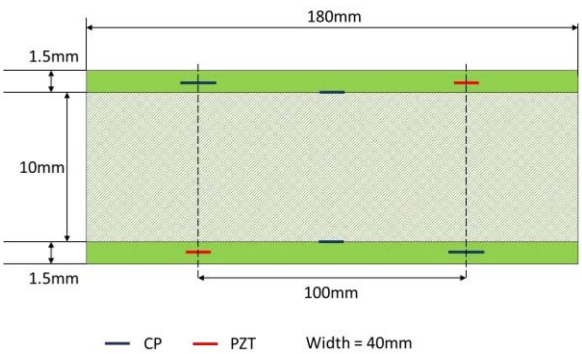


Figure 3: Schematic of the smart sandwich beam

3 EXPERIMENTAL TESTS

3.1 Setup

The tests were performed on an electrical machine (Instron 1186) with a speed of 1mm/min, a roller diameter of 10mm and a distance between the lower rollers of 160mm. A strain gauge was glued on the lower surface to get the longitudinal strain. A laser was used to measure the deflection during the test.

In addition, two external AE sensors (Micro-80 from Physical Acoustics Corporation) were used, at the same position, at the surface, as the lower PZT and CP which were also used as internal AE sensors. This makes it possible to compare the sensitivity of the classical AE and the embedded piezoelectric sensors. And finally, three thermocouples are positioned on the edge of the beam, one at the lower interface skin/core, one in the middle of the core and one at the upper interface skin/core. The capacitance of the transducers was measured from an LCR Bridge (HM8118 from Rohde & Schwarz). The US tests were performed with an Arbitrary-Function Generator (AFG-3021 from Tektronix) and an oscilloscope (DSO-X 2002A from Agilent Technologies) (**Figure 4**). A modulated sinus was used to excite the PZT.

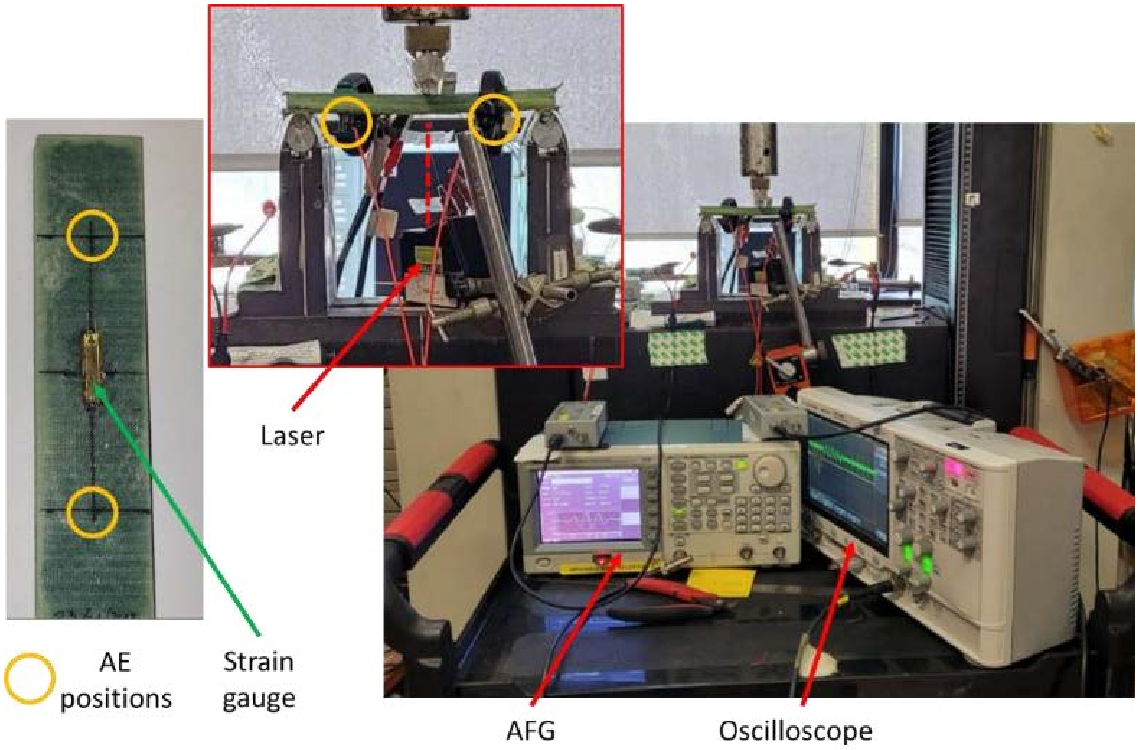


Figure 4: Experimental setup of the 3-point bending tests conducted on the sandwich composites

3.2 Procedure

Firstly, a test was performed on a non-smart beam, in order to get the mechanical behavior of the sandwich composite material. This helped to adjust the different loading levels for the following experimentation. This test was performed with the AE sensors, a strain gauge and a laser system.

Secondly, three-point bending tests consisting of 8 cycles of loading, holding and unloading were performed on all beams (3 pristine and 3 smart beams). For these tests, the holding time was 5 minutes after each load and unload, this permits the comparison between loaded and unloaded specimens, to avoid any fake alarms caused by the applied stress during the US tests. The sequencing of the physical measurements and the chronology of the loading steps are distributed as follows:

- Before: US, capacitance measurement for the smart beams;
- Loading:
  - For the pristine beams: AE with 2 micro-80 on the lower skin, thermocouple, strain gauge and laser;
  - For the smart beams, we added: AE with 1 PZT and 1 CP in the lower skin, and the capacitance was measured for the sensors localized at the interface skin/core;
- Holding:
  - For the pristine beams: strain gauge, laser and thermocouples;
  - For the smart beams, we added: US and capacitance measurements;
- Unloading:
  - For the pristine beams: AE with 2 micro-80 on the lower skin, thermocouple, strain gauge and laser;
  - For the smart beams, we added: AE with 1 PZT and 1 CP in the lower skin, and the capacitance was measured for the sensors localized at the interface skin/core;

4 RESULTS AND DISCUSSION

4.1 Monotonic 3-points bending test

This first test helped to build the protocol for the load/unload next experimentation. The beam broke on its upper skin, under the upper contact. We can see that the load started to lose linearity around 700N and broke around 1000N. From these results, we choose 150N as the step increment for the following experiments, from 0 to 1200N, which permits us to observe 4 steps in the linear part, 2-3 in the nonlinear part and 1 step to break the beam (**Figure 5**). From the end of the linear part, higher amplitude hits occurred and the Cumulative Absolute Energy (CAE) slowly increased, to reach a huge increase at the rupture of the sandwich material.

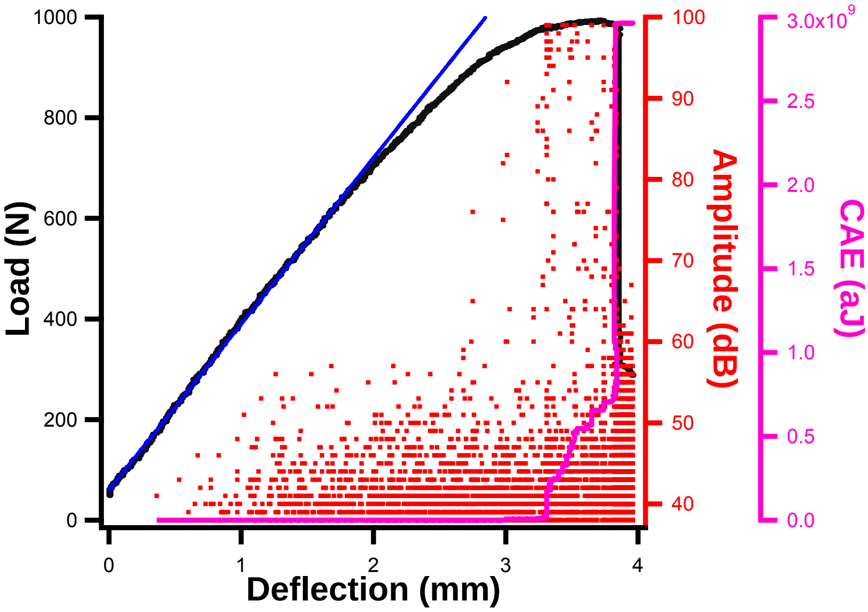
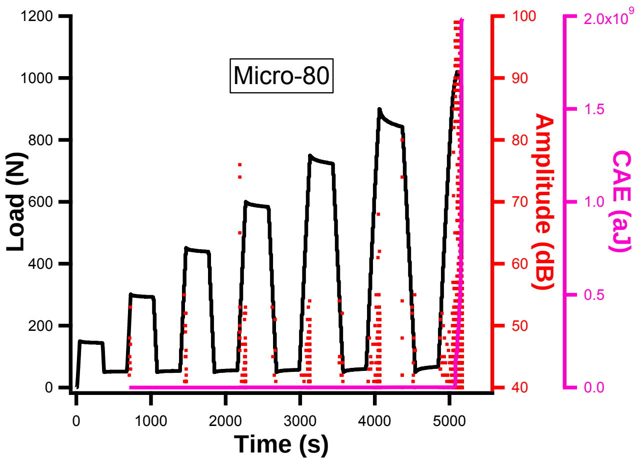


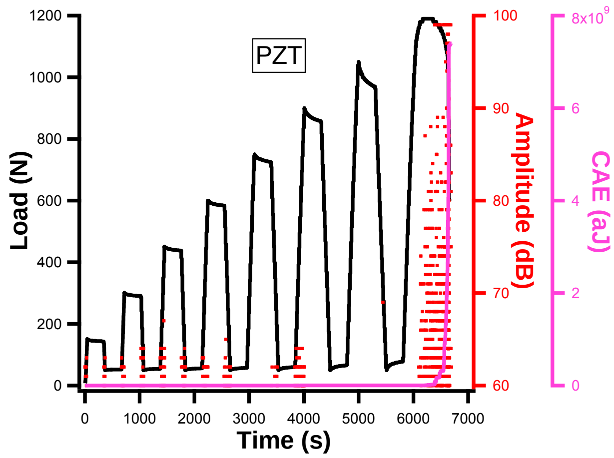
Figure 5: Load/deflection curve of the monotonic 3-point bending test with AE amplitude and CAE

4.2 Load and unload 3-points bending test

In **Figure 6**, the load/unload results are illustrated with the classical AE sensor for the pristine specimen and the PZT for the smart one. We can notice similar behavior for both sensors, the hits amplitude increased just before the rupture occurrence and the hits occurred mainly during the loading steps.



(a)



(b)

Figure 6: Load/time curves and AE for (a) a pristine specimen with micro-80 sensors and for (b) a smart specimen with PZT

The US shots are visualized in a voltage/time curve and the Time of Flight (ToF) is taken at the beginning of the received signal (**Figure 7**), this will help to calculate the velocity of the guided wave and to define damage indicators.

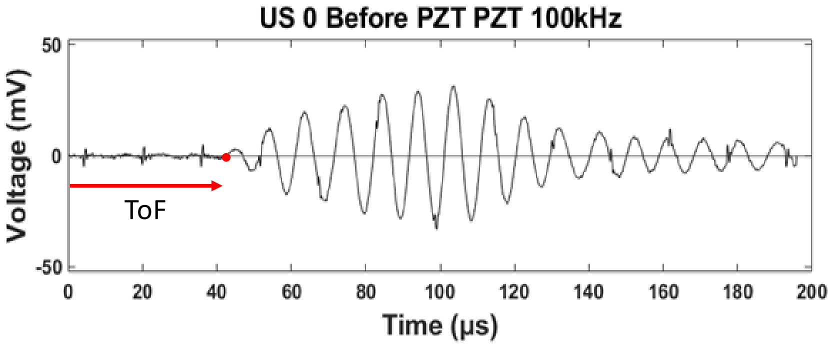


Figure 7: Voltage/time curve for the US shot from PZT to PZT (diagonal shot)

In **Table 1**, we can observe that the ToF increases with the increasing loading level. This means that the speed decreases while the load increases. Further investigations will be done to decouple the effects of the damage influence and the load application on the wave velocity.

Table 1: ToF of the wave propagation at each loading level in US tests from PZT to PZT shot

Load step (N)	Before	150	300	450	600	750	900	1050
ToF (µs)	42.8	43.3	43.3	43.5	43.8	43.8	44.3	44.4

During the whole test, the Electrical Capacitance was measured for the CPs localized in the interface core/skin. The Electrical Capacitance followed the load application until the final failure (**Figure 8**).

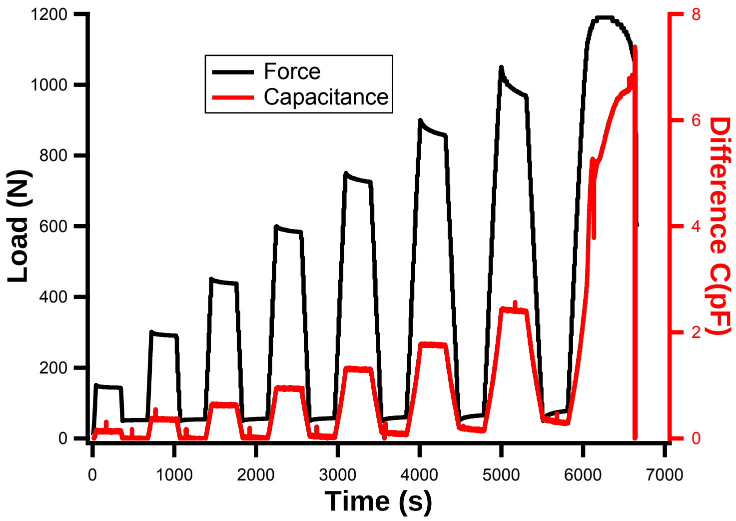


Figure 8: Load/time curve and difference of capacitance

5 CONCLUSIONS

This preliminary experimental campaign presented many interesting results, which will help us to better design the future studies. The piezoelectric transducers showed efficiency in US, AE and Electrical Capacitance measurements, however some parameters still need to be improved. Future work will be to define damage indicators to implement within the data fusion procedure, in order to get a robust conclusion regarding the health of the sandwich composite structure.

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