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# STRUCTURAL HEALTH MONITORING OF SMART POLYMER-MATRIX COMPOSITE DURING CYCLIC LOADING USING AN IN-SITU PIEZOELECTRIC SENSOR

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**Keywords:** Polymer-matrix composites, In-situ piezoelectric sensor, Structural health monitoring, Smart materials

## ABSTRACT

This article investigates the Structural Health Monitoring (SHM) potential of a piezoceramic (PZT) disk embedded into a Polymer-Matrix Composite (PMC) material submitted to a cyclic loading test. To do so, several samples were extracted from a PMC (glass fiber/polyester resin) plate manufactured using the Liquid Resin Infusion (LRI) technique, each one embedded with a connected PZT transducer. Cyclic (loading-bearing-unloading) incremental tensile tests were then performed on these embedded samples until failure. The electrical capacitance signature of the PZT was acquired during the whole test using a multimeter, and all samples were equipped with a multi-instrumentation system including two Non-Destructive Testing (NDT) devices: two Acoustic Emission (AE) sensors and Stereo-Digital Image Correlation (S-DIC) cameras on both face and thickness of each specimen. Results showed that the in-situ PZT capacitance signature is able to follow well the mechanical loading, and allows to give information on the start and progression of the damage happening inside the tested material when comparing the capacitance signal with the two other NDT signatures. The PZT can thus be considered as an efficient NDT device for real-time SHM of PMC structures.

## 1 INTRODUCTION

Due to their very interesting characteristics, such as lightness combined to good mechanical properties, composite materials are widely used in various industries nowadays. However, like every other known materials, there are not infallible. As they are more and more employed in industrial sectors whose requirements are very strict, such as aeronautics, aerospace or wind, and as their highly heterogeneous and anisotropic properties make their damage modes very complex, the need for their surveillance is primary. The corresponding parts or structures can be submitted to difficult environmental conditions (temperature, humidity, radiation) and various physical loadings (tensile, shear, torsion, etc.). Consequently, it is crucial to have an idea of their structural health regularly in order to decide when to put them out of service for maintenance or replace them. To do so, that is to say performing Structural Health Monitoring (SHM), Non-Destructive Testing (NDT) techniques can be used, such as ultrasound (US) [1,2], Infrared Thermography (IRT) [3,4], Acoustic Emission (AE) [5,6], electrical [7,8]/electromagnetic [9,10] testing and others. Yet, even if these techniques can provide useful information, they remain external. Consequently, as the corresponding instrumentations are often cumbersome and cannot remain on the structure (or out of it) permanently, this one has to be put out of service regularly to be checked, which is time and money consuming industrially speaking. Furthermore the data cannot provide information about exact damage initiation and progression scenarios because they are gathered punctually and not in real-time. That is why “smart” composite materials are of particular interest nowadays, this interest going together with the actual tendency for functionalized structures used for various applications such as energy harvesting, vibration control, morphing and SHM. As these “smart” structures are integrated with in-situ NDT systems, it is possible to perform their SHM in real-time without any of the previously cited disadvantages. It also allows NDT systems to be protected from environmental conditions thanks to their host composite structures

[11], and to be more sensitive to damage than ex-situ devices would be [12]. Different types of devices have already been embedded into composite structures by research teams to perform in-situ SHM, such as optical fibers [13], various kinds of piezoresistive elements such as conductive fiber reinforcement [14], nanofillers [15,16], Z-pins [17], tuft threads [18]; and also piezoelectric sensors. These last ones are particularly investigated in the in-situ SHM literature, with the use of PolyVinylidene Fluoride (PVDF) [19] or Lead Zirconate Titanate (LZT or PZT) [12] as main base materials. Once manufactured, these piezoelectric devices which can be piezoceramic PZT disks, thin PVDF layers, piezoelectric fibers and others, are inserted inside PMC materials to perform their real-time and in-situ SHM using various NDT techniques such as electric charges variation [20], impedancemetry [21], Lamb waves [22] or even AE [23]. The literature on this subject being very profuse, the authors dedicated a full review article [24] to it and invite the reader to consult it for more information.

The same review concluding on the obvious potential of piezoelectric devices for in-situ and real-time SHM of PMCs, the authors decided to pursue this research axis by using thin PZT disks embedded into PMC specimens to achieve their surveillance during a cyclic tensile loading. Tensile specimens were manufactured using the Liquid Resin Infusion (LRI) process, using twill 2/2 glass fiber fabric and orthophthalic unsaturated polyester matrix, and integrating one PZT disc per specimen before performing resin injection. After consolidation and cutting, these specimens were submitted to a cyclic loading-bearing-unloading tensile test until failure. During the whole experiments, the electrical capacitance of the in-situ PZTs was acquired with a multimeter. Stereo-Digital Image Correlation (S-DIC) was performed in the same time on the face and thickness of each specimen using four high resolution cameras to investigate the corresponding strain field evolution, and two AE sensors were also glued on the face of the sample to gather the acoustic signature of the occurring damages. The aim of this multi-instrumentation was to correlate both in-situ (capacitance) and ex-situ (S-DIC, AE) signatures, in order to understand the variations of this capacitance and use them to infer information about damage scenarios (beginning, spreading, etc.). Results show that the PZT signature is highly sensitive to the mechanical loading scheme during the cyclic testing. The use of strains computed using S-DIC both in the face and thickness of each specimen allow to understand the behavior of this capacitance signal. As singular behaviors (peaks, various slope changes) can be observed on the capacitance curves, the remaining work consists on coupling these behaviors with S-DIC and AE information, in order to explain their occurrence and use them for SHM purpose (defining damage thresholds for example).

## 2 MATERIAL AND METHODS

Piezoceramic PZT disks (Wealthland) with 25mm diameter and 0.135mm in thickness (Fig. 1 a) are used in this study. After testing their static capacitance with a digital multimeter (Keithley DMM7510), they were embedded in the middle plane of a 2/2 twill glass fiber preform (symmetric and balanced stacking) composed of 22 plies. Their electrical connection was realized using tinned copper wires of 210 $\mu$ m in diameter. Manufacturing of the “smart” plates, containing 5 PZT each is then performed using LRI manufacturing (Fig. 1 b), injecting an unsaturated polyester resin (Norester 822 Infusion) mixed with 2.5% wt hardener (Methyl Ethyl Ketone Peroxide MEKP, Butanox M50) through the dry preform. The resulting plates (Fig. 1 c) were unmolded and cut into samples of 300mm\*40mm\*5mm, each one containing 1 PZT sensor located in its mass center. Four PMC heels were then glued on the four ends of each sample, using bi-components Araldite 2015 A/B glue. One of the resulting tensile specimen is shown on Fig. 1 d.

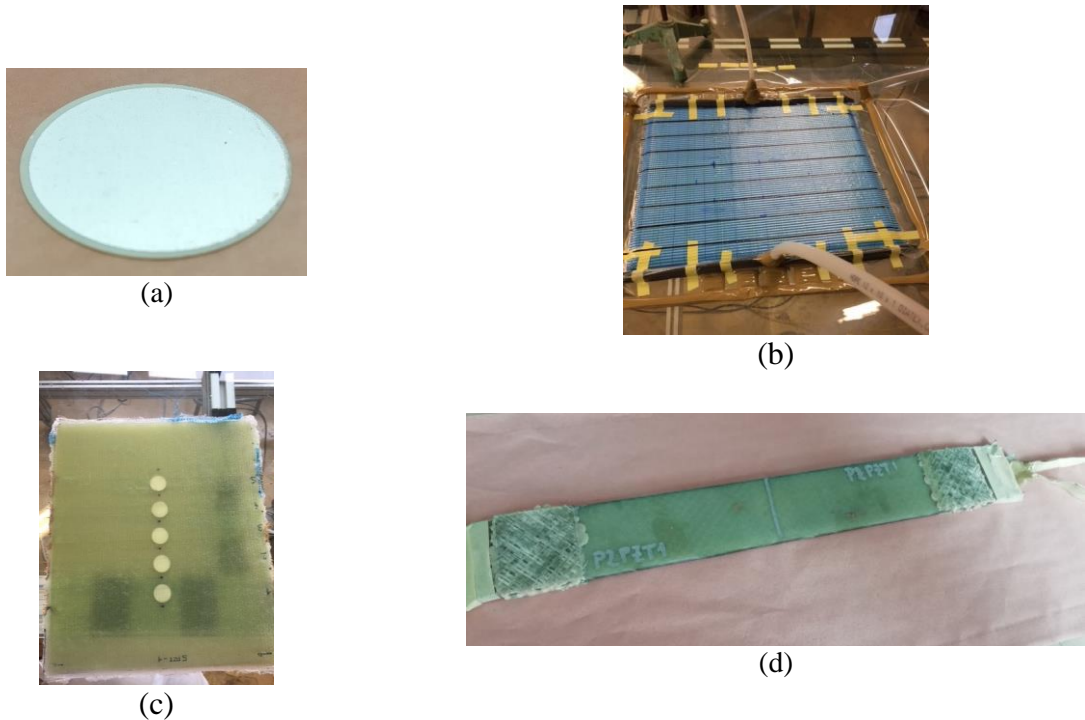


Figure 1: (a) PZT disc – (b) Manufacturing of one plate using LRI – (c) one obtained plate, with 5 embedded PZTs – (d) one “smart” sample with glued PMC heels and isolated exiting wires

Cyclic (unloading-bear-loading) incremental tensile-tensile tests are conducted on the embedded samples, acquiring in-situ PZT electrical capacitance in real-time using the digital multimeter. During these tests (loading scheme in Fig. 2), samples are also surrounded by several ex-situ NDT systems: 2 S-DIC systems composed of 2 high resolution Pike cameras each (VIC3D software), one system focused on a face of the sample and the other on its thickness, and two wideband AE sensors PAC Micro80 (200-900 kHz, amplitude threshold = 35dB). The positioning of the whole multi-instrumentation is presented on Fig. 3. Results are presented and discussed in the next section.

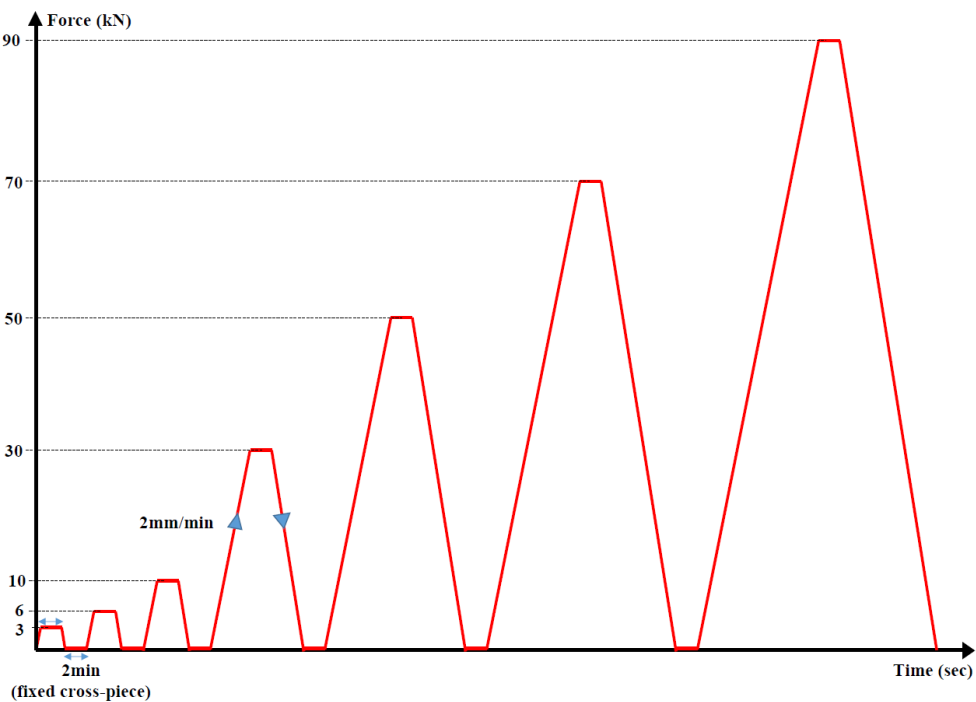


Figure 2: Schematic representation of the mechanical loading profile

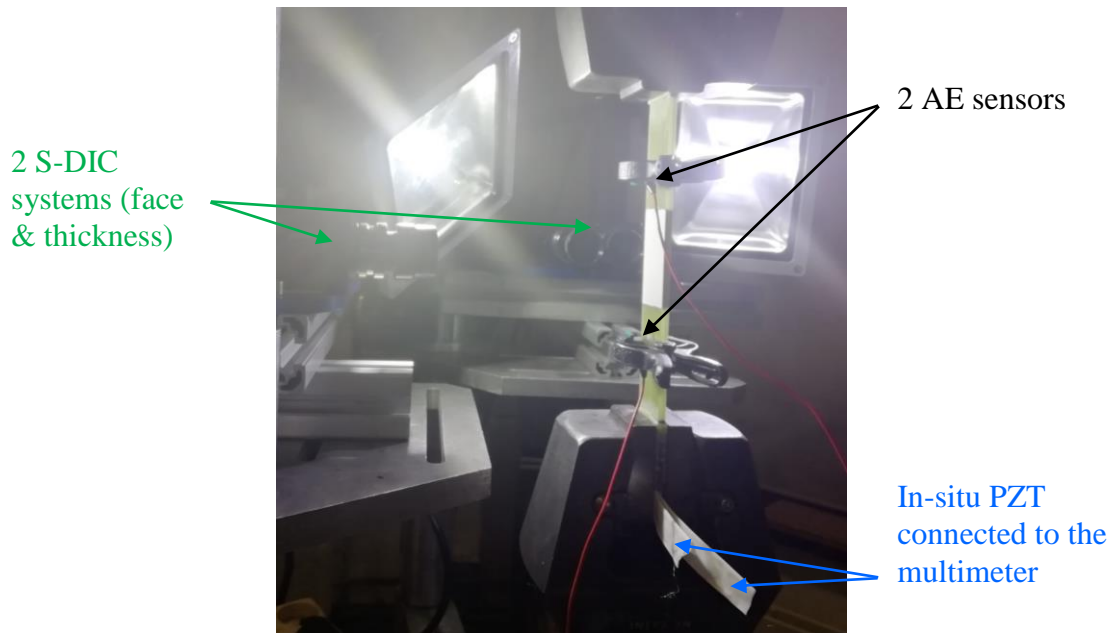


Figure 3: The multi-instrumented test

### 3 RESULTS AND DISCUSSION

As this work is still in progress, only the preliminary results are presented for a reference sample, named “Sample 1”. AE data are still to be processed.

Fig. 4 exposes the obtained results for the “smart” Sample 1. It is important to point out that the strain curves have been computed on the whole speckled zones (face & thickness), this zone (60mm in length) ‘containing’ the embedded PZT transducer area. One can notice that the in-situ PZT electrical capacitance ( $\Delta C$ ) follows well each load-bearing-unload cycle. This behavior is linked to the fact that constraining more or less a piezoelectric material in its environment induces variations of its electrical capacitance [25]. This statement can be correlated to the S-DIC measurements, as it can be seen that the negative  $\varepsilon_{xx}$  (strain along sample width) and  $\varepsilon_{zz}$  (strain along sample thickness) are contributing to a Poisson’s effect in both these directions. Looking closer at the capacitance curve, some special tendencies can be extracted from it. First,  $\Delta C$  progressively recedes from zero during unloading phases, as loading cycles go by and increase. The main hypothesis explaining this behavior is that as loading becomes higher and higher, the charge phases create and enlarge the walls of a cavity inside which the PZT is inserted, this cavity being created in the first place due to PZT/composite interfacial shear. As these walls enlarge themselves, bringing them closer to each other during each progressive unloading step becomes more and more difficult. The PZT becoming thus less and less compressed at the end of each unloading cycle compared to its initial state, it explains the drift as compression induces capacitance decrease. A second interesting point is the progressive change in  $\Delta C$  slopes (both increasing and decreasing ones) and amplitudes as loading cycles go by. One can also notice other kinds of capacitance slope variations, these ones occurring during a loading step and start from the 5<sup>th</sup> block to the end of the test. All these variations and changes could advise on damage initiation and progression when confronted to AE data (such as signals amplitude, energy or time of occurrence and signals location & labeling) and SDIC information (stress and strain maps & curves computed in precise spots of the sample) taken at the same time. A last thing to observe is the presence of spikes of  $\Delta C$  framing each loading plateau, which are still under investigation. However, one remarkable thing about these spikes is that the ones framing the left sides of the bearings only appear from the 4<sup>th</sup> block, the following block starting to have a capacitance slope change during its loading phase: this phenomenon could also be an information carrier about damage initiation, and will be coupled with S-DIC and AE data for deepening.

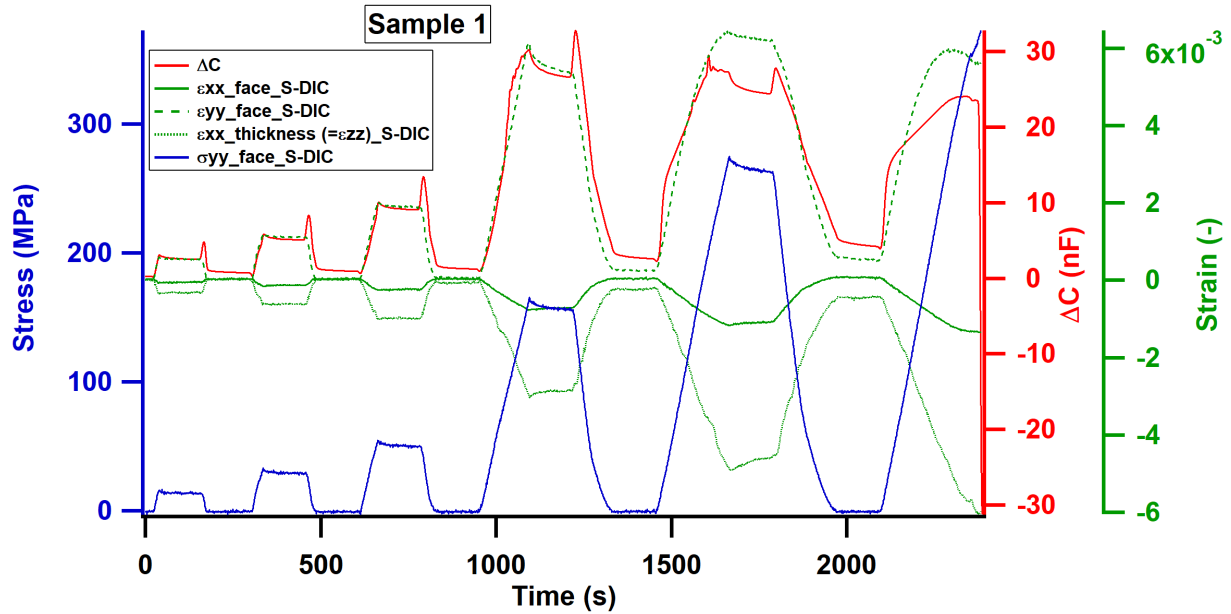


Figure 4 : Results for the multi-instrumented cyclic test performed on Sample 1

#### 4 CONCLUSION AND OUTLOOK

This paper is investigating the potential of in-situ PZT discs sensors for continuous SHM of PMC materials submitted to mechanical loadings. As it was shown, the electrical capacitance signature of the PZT is sensitive to the conducted cyclic and incremental tensile loading-bearing-unloading tests. Plenty of phenomenon have been noticed on the capacitance curve as well, and the continuity of this study will aim to explain them, by coupling these peculiar variations with both AE and S-DIC data. An important thing to do as well will be to confirm whether these  $\Delta C$  variations are due to composite damage, PZT damage or the damage of their interface. Once again S-DIC (maps and curves) and AE analysis will help to do so, when comparing them for embedded and pristine (no embedded PZT) specimens submitted to these same loading conditions. Another discrimination tool could be the use of in-situ X-ray tomography (volume information) conducted on the same kinds of embedded samples submitted to similar loading conditions, to have a precise idea of the interface behavior during the test and to determine more accurately the nature, location and spreading of the damages. The PZT/host composite interface study will be of primary importance as all the load transfer coming from the solicited PMC material to the PZT, allowing the direct piezoelectric effect to impact the PZT capacitance signal, goes through this interface. As global stiffness loss ( $1 - E_i/E_0$ ) can be a good damage indicator, a last task will consist on computing it for both loading and unloading steps, and then use it to assess the quality of a potential new damage index calculated in the same phases:  $1 - \Delta C_i / \Delta C_0$ . All of this work done and to be done points out the potential of these in-situ sensors for real-time SHM of composite structures, which open the way to their implementation in industry, whether used alone or networked.

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