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On the use of in-situ piezoelectric sensors for the manufacturing and structural health monitoring of polymer-matrix composites: A literature review.

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Abstract

This article aims to provide a general overview of what has been achieved recently in the scientific community on the manufacturing monitoring and structural health monitoring of polymer-matrix composites (PMC) using in-situ piezoelectric sensors. Some industrial applications with the underlying issues and potential solutions will finally be discussed in the concluding section.

Keywords: Polymer-matrix composites (PMCs); In-situ piezoelectric sensors; Process monitoring; Structural health monitoring; Non-destructive testing; Smart materials.

1. Introduction

The last decades have seen a growing use of PMC materials in industrial fields such as aeronautics, astronautics or automotive, due to their very interesting properties. In these industrial sectors, the corresponding composite structures will first have to fulfill very strict requirements imposed by the customers and then will be exposed to harsh environmental conditions, such as outside corrosion, thermal ageing, radiation, various kinds of physical loadings, etc. Consequently, manufacturers must be confident in the quality of the composite parts they have built, and then users must have an efficient and reliable tool to check regularly if these parts are still suitable for service.

To have an idea on the quality of the produced composite parts thanks to a follow-up of the manufacturing process in real-time, that is performing Process Monitoring (PM), Non-Destructive Testing (NDT) techniques can be used. NDT are methods to evaluate material integrity for surface or internal flaws or metallurgical conditions without interfering in any way with the destruction of the material or its suitability for service [1]. These methods can either be used alone or combined, in order to confirm the obtained measurements (redundancy) and to make them more accurate thanks to information coupling. To do so, several teams have already worked on PM using various external NDT methods (the most current ones), which are summarized in **Table 1**.

After the manufacturing of the parts, Structural Health Monitoring (SHM) must be performed on them regularly to follow the evolution of their integrity during their service life. This allows knowing if these parts are still suitable or not for industrial applications. As the use of composite materials allows a profitable weight reduction without decreasing too much mechanical properties, a way to ensure their reliability in service cannot rely on oversizing the parts during their design: that is why using NDT techniques for SHM is an appreciable alternative.

These techniques, generally external, allow the retrieval of information about damage initiation and progression in the material. Using them, one can get either surface or volume information about these damages, which are in the composites field: matrix cracking, fiber breakage, fiber-matrix debonding or delamination. Some of the scientific contributions associated with the use of external NDT in SHM are presented in **Table 2**.

However, even if these techniques are very useful to detect external and/or internal defects in a structure, they have their drawbacks. As they are external techniques, they have to be instrumented on the surface of the part or even out of it, which can be very cumbersome and incompatible with functioning parts. Consequently, the structure to survey has to be put out of service, which can be time and money consuming for its owner. Furthermore, these tests cannot reveal the exact time of damage initiation or progression scheme because they are done in a particular period and not constantly. That is why there is a strong will for functionalization of these structures nowadays, leading to a huge increase in research about in-situ SHM techniques. They are less cumbersome because the sensors are an integral part of the structure, and users can do continuous monitoring of the structure without stopping it because it gathers information about itself automatically. Another advantage of in-situ SHM techniques is that the sensors can be protected from the service environment thanks to its encapsulation [52], which can improve the durability of the measurements they provide. The fact that they are directly embedded inside the material from the manufacturing stage also allows to perform real-time PM, in order to study if the process went well and produced a quality part. This embedding can also allow the in-situ sensor to be more sensitive to damage than an ex-situ one would be [53]–[60]. Different types of systems can be inserted inside PMC structures to perform various in-situ PM or/and SHM measurements. In-situ techniques, though, come also with disadvantages, such as manufacturing/integration difficulties, or intrusiveness risks (the embedded device may degrade the mechanical properties of the monitored structure).

Table 1. Contributions to PM of PMC using external NDT techniques

NDT category	NDT technique	Undertaken work	Reference
Electrical testing	Electrical sensors inside Resin Transfer Moulding (RTM) mold	Estimation of reinforcement permeability during injection	[2]
	Electrodes on the inner faces of the Liquid Composite Moulding (LCM) mold	Numerical reconstruction of the resin flow during injection	[3]
	A polyimide film with interdigitated area-sensor arrays used as a bottom layer of the fibers stack for RTM	Following of in-plane or out-of-plane resin impregnation of the preform	[4]
	Patch-type flexible matrix sensor (electrodes network) based on permittivity measurements, placed between the lower jig and the prepreg	Multipoint cure monitoring of CFRP prepreg when hot formed in an electric furnace	[5]
Ultrasonic (US) testing	US waves generated by an external piezo transducer located on the “mold” external surface. Pulse-echo technique used.	Evaluation of resin polymerization/cooling reaction in an experiment mimicking RTM process, measuring the US wave velocity and attenuation	[6], [7]
	US waves generated by a piezo transducer positioned inside the “resin”. Pulse-echo technique used.	Measurement of US phase velocity and attenuation in oils simulating different resins, in an RTM monitoring context (degree of cure, porosity amount, etc.)	[8]
	US waves generated with a phased array transducer bonded on the external surface of the “mold”. Pulse-echo technique used.	Detection of the appearance of air bubbles in resin alone [9] and their interaction with a fibrous matrix [10] during an experiment mimicking RTM process	[9] [10]
	US waves generated by high-temperature piezo transducers inside an autoclave (bonded to the tool plate). Pulse-echo technique used.	Monitoring of the evolution of resin rheological properties (viscosity, degree of cure, etc.) in an autoclave process with the evolution of US waves velocity and amplitude	[11]

Table 2. Contributions to SHM of PMC using external NDT techniques

NDT category	NDT technique/method	Undertaken work	Reference
Radiographic testing	Conventional radiography (parts of usual thickness)	Detection of large voids, trans-laminar cracks, non-uniform fiber distribution, or fiber misorientation (fiber wrinkles, weld lines)	[12]
	Low-voltage radiography (thin parts)		
	γ -rays radiography (thick parts)		
	Penetrant-enhanced radiography	Detection of small matrix cracks and delamination	[13]
	X-Ray Computed radiography method	Characterization of impact damage in stitched composites: observation of in-plane matrix cracks and overall delamination propagation	[14]
	X-Ray Computed tomography (XCT) method	Gathering of 3D information about internal defects and damages with XCT and identification/classification of them with 3D Wavelet Transform (WT) algorithm	[15]
	Digital radiography method	Assessment of residual properties and corresponding damage states within notched CF/epoxy parts submitted to fatigue loading	[16]
Electromagnetic (EM) testing	EM millimeter wave reflection	Detection of impact damage in CFRP using the variation of the reflection coefficients associated to the incident EM waves	[17]
	Magnetic flux leakage (MFL)	Detection of bending stresses using the impact they have on MFL patterns	[18]
Acoustic Emission (AE) testing	External piezoelectric resonant AE sensors	Detection and identification of the acoustic signature of the different damage modes occurring in polymer-matrix composites.	[19], [20]

		Use of clustering mechanisms to identify damage modes in Glass Fiber Reinforced Plastic (GFRP) composites from AE data obtained during creep tensile tests. Determination of the best descriptors to take into account the non-stationary state of AE signals	[21]
		Use of AE signals to follow corrosion (with and without mechanical loading) of glass/resin laminates. Clustering of AE data and use of different techniques (SEM, etc.) to identify the damages linked to corrosion phenomenon.	[22]
Infrared Thermography (IRT) testing	Passive IRT: IR camera detects the heat energy emitted by the tested part	IRT to monitor thermal effects developing in glass/jute-polypropylene composite during cyclic bending tests: a gathering of information about macromolecular interactions and interfacial micromechanics effects happening inside the material during this test	[23]
		Damage detection, evolution and characterization of CFRP composites subjected to static tensile loading thanks to thermal maps and thermomechanical study	[24]
	Active IRT: the heat energy is transferred to the tested part	Non-destructive evaluation of (hybrid) composites and sandwich composites using lock-in IRT: detection of defects (size, nature, position), evaluation of damage impact extension, etc.	[25]
Optical testing	Optical Transmission Scanning (OTS)	Low velocity impact damage of GFRP specimens evaluated (number, severity) with the measurement of the amount of radiation transmitted through the samples, and validated with conventional NDE techniques (US, dye penetrant testing)	[26], [27]
	Digital Image Correlation (DIC)	Kinematic fields of loaded CFRP specimens obtained by stereo DIC provide information about damage features (location, localization phenomenon, failure mode, etc). DIC successfully coupled with IRT and X-ray tomography	[28]
		Meso-Finite Element (FE) model of textile (CFRP and GFRP) composites validated by full-field strain measurement on the surface of the samples with DIC	[29]

	Shearography	Impact damage assessment (damage detection, strain amplitudes) on CFRP and GRFP sandwich panels. Shearography considered better than C-scan which underestimated damage extension	[30]
		Endoscopic shearography for NDT of composite pipes: ability to detect adhesion flaws inside the flanged joints on the inner surface of the pipes	[31]
		Contactless shearography revealed the defects in the tested parts identifying defect induced-strain anomalies in strain fields. Can also be used as a residual stress measurement tool	[32]
	Holography (phase-shifting pulsed laser Electronic Speckle Pattern Interferometry (ESPI))	Assessment (location, shape, size) of delamination of various sizes inside laminated CFRP plates using laser holography. Holography allows the reduction of measurement disruptions due to the environment compared to traditional ESPI	[33]
		TV holography (holography with a real-time video display of the results) to detect small movements and abnormal surface behavior of laminated and honeycomb structures. Allows the detection of defects and weaknesses such as impact damage. To be combined with other NDT techniques for more accuracy	[34]
		Holographic interferometry and ESPI to detect impact damage in composite laminates. Ok for samples with small thicknesses, but ESPI less sensitive. Both techniques are inadequate if the thicknesses are too important (damage needs to be shallow), compared to volume US C-Scan.	[35]
	Digital Speckle Pattern Interferometry (DSPI)	Portable DSPI device with optical fibers allows the detection of disbonds, delaminations and cracks in aircraft composite parts and a carbon-epoxy plate. Quantitative deformation analysis of the specimens was also made possible. Information of the same or higher resolution than certain holographic laser techniques	[36]
		Identification procedure of delaminations in carbon-epoxy laminates thanks to an inverse problem with DSPI experimental data as input. Quantification of planar location, size, orientation and depth of the defect.	[37]
	Optical Coherence Tomography (OCT)	OCT used to observe successfully fiber tows and voids in different GFRP composites and compared with optical microscopy. The OCT image quality	[38]

		can however be strongly affected by the refractive index mismatch between the fibers and the matrix	
		Artificial delamination presence and growth at different tensile loading stages in GFRP wind turbine blade spar webs are followed using the OCT technique. High resolution cross-sectional and volumetric images were obtained and 3D profile of the crack was reconstructed	[39]
	Optical fibers (OF)	External Chirped Fiber Bragg Grating (CFBG) sensor able to monitor delamination growth in a GFRP cantilever beam, with complementary techniques such as in-situ photography and surface-mounted strain gauges	[40]
		Investigation of the best adhesive system (low and high viscosity) to bond a Fiber Bragg Grating (FBG) sensor onto the surface of GFRP samples, in order to monitor surface displacement during tensile and bending loadings. The low viscosity system was found to be the best (less brittle and better surface adhesion) to give accurate results in accordance with other external techniques	[41]
Ultrasonic (US) testing	Guided (surface/plate) waves	Lamb waves (LW) used to monitor moisture content (S_0 LW mode attenuation) and micro-cracking (LW celerity decrease) inside CFRP plates, with possible application for high-pressure tanks monitoring	[42]
	Volume waves	High resolution C-Scan US maps used to evaluate mechanical damage in GFRP laminates before and after mechanical loading	[43]
	Terahertz (THZ) imaging	THZ B and C-scans evaluation of low-velocity impact damage of Hybrid C&GFRP plates. Inter and intra-laminar damages successfully observed and differentiated, and also the damage 3D evolution through the thickness.	[44]
Acousto-Ultrasonic (A-US) testing	External A-US system (transducer for excitation and AE sensors for detection)	Variation of A-US parameters with the number of induced defects inside metal-CFRP composite bonded joint (single lap joint and double lap joint)	[45]
	A-US: external transducers (PZT discs) used both in active mode (US	Assessment of location (AE better than A-US) and severity (AE and A-US both work well) of impact damage in a CFRP overwrapped pressure vessel. Online damage localization and severity assessment made possible with the combination of the two techniques	[46]

	transducers) and passive mode (AE sensors)		
Electrical testing	Electromechanical Impedance (EMI) method using self-sensing piezoelectric wafer active sensors (PWAS)	EMI measurements with PWAS bonded on a GFRP composite structure was performed for SHM application. Experimental delamination detection was accomplished and a good correlation with 3D FE model results was found for low and high frequencies of excitation	[47]
	Electrical impedance tomography (EIT)	EIT performed on a CFRP laminate plate for damage localization. Results shown that classical EIT cannot provide a distinct location of damage within the laminate. Potential improvements could be the consideration of laminate anisotropy during results processing, isolate the plies for the resistance measurements, or homogenize the anisotropic material for the results processing.	[48]
Electromagnetic (EM) testing	Eddy Current testing	Use of electric induction to detect impact damage in CFRP thanks to fiber conductivity	[49]
Vibration testing	Measure: Laser Vibrometer (LV) Excitation: shaker equipped with a stinger, a force transducer and a spring	SHM of a CFRP T-beam thanks to a vibration-based identification method. Dynamic responses of an intact and locally delaminated beams are measured with a LV and compared in order to detect, localize and estimate the size of the delamination	[50]
	Measure: LV Excitation: shaker or loudspeaker	SHM by a vibration-based method of CFRP and GFRP plates containing artificial delaminations (Teflon films) of various sizes and locations. Different algorithms employing experimental data measured by LV used to predict in-plane locations and sizes of delaminations.	[51]

Speaking about in-situ PM measurements, various techniques have been experienced so far. Some of the scientific works associated to them can be found in **Table 3**.

In-situ SHM of PMC has also gathered noticeable scientific contributions up until now, as shown in **Table 4**.

An alternative to the in-situ PM and SHM techniques previously cited is the use of piezoelectric materials. Actually, a lot of scientific contributions deal with the study of piezoelectric materials such as Lead Zirconate Titanate (LZT or PZT) or PolyVinylidene Fluoride (PVDF). They can be used to create various types of in-situ sensors such as piezoceramic discs, thin PVDF layers, piezoelectric fibers and others: these sensors are then inserted inside composite structures to monitor their health using different measurements such as piezoresistivity, impedancemetry, Lamb waves ore even AE.

This innovative and promising alternative increasingly gathering scientific contributions nowadays, and having so far not being reviewed, the present article will focus on what has been published until now about in-situ PM and SHM of PMCs using in-situ piezoelectric sensors. First, a reminder about piezoelectric effect will be provided. Then, the different kinds of measurements (in-situ PM and SHM) performed with various types of piezoelectric sensors, as well as the obtained results will be shown, before presenting some other potential applications and final discussions in the concluding part.

Table 3. Contributions to PM of PMC using internal NDT techniques

NDT category	NDT technique	Undertaken work	Reference
Electrical testing	Electrical resistivity measurement of carbon reinforcement fiber with the 4W method	Following of epoxy resin curing for carbon fiber/epoxy parts	[61]
	Carbon Nanotube (CNT) “buckypaper” film sensor for in-situ piezoresistivity measurements	Local in-situ monitoring of the cure cycle of a glass-epoxy composite	[62]
	In-situ interdigitated electrodes for dielectric measurements	In-situ and real-time matrix cure monitoring for GFRP composite manufacturing	[63]
	Electrical Impedance measurement	Following of resin curing for carbon/epoxy composite structures in stove or autoclave with flexible electrodes. Detection of defects (vacuum break) occurring during the process	[64]
		Impedance spectroscopy used for online in-situ monitoring of composite materials curing. Comparison with standard LCR bridge measurements are satisfactory, impedance spectroscopy being even more sensitive for the last part of the cure cycle.	[65]
Thermal testing	A pile of thermocouples (dual heat flux sensor) embedded in various depths inside a prepreg stack	Monitoring of resin curing of epoxy/graphite composite prepreg in a thermal press thanks to thermal diffusivity and heat flux variations	[66]
Acoustic testing	Acoustic Emission (AE) waveguides embedded inside the part and coated with resin to detect AE events	Monitoring of composite carbonization process to create carbon/carbon parts (delamination detection, crack formation detection, etc.)	[67]
Optical testing	Optical fiber (OF)	OF sensor inside CFRP composite prepregs for real-time cure monitoring (viscosity measurements) during manufacturing inside a heating press and an autoclave. Good correlation with FE simulation and dynamic dielectric cure analysis	[68]

		OF located at different levels inside the fiber stack to monitor the development of strains during resin curing for a CFRP composite infusion process	[69]
	Fiber Bragg Grating (FBG) sensor	FBG sensor for in-situ Liquid Resin Infusion (LRI) monitoring of a composite part. Dielectric analysis was performed for comparison. FBG sensor able to highlight both the gelation time and the end of solidification of the matrix	[70]
		FBG sensors positioned at the top, middle and bottom of a CF stack to monitor the residual in-plane strains occurring during RTM manufacturing with epoxy resin injection. Debonding of the composite from the mold was also able to be detected, and the reduction of residual strains and stresses could be considered thanks to these sensors	[71]

Table 4. Contributions to SHM of PMC using internal NDT techniques

NDT category	NDT technique	Undertaken work	Reference
Electrical testing	Electrical impedance spectroscopy (EIS)	Following of CFRP laminates electrical impedance during monotonic and incremental cyclic tensile tests to understand better the impact of electrical excitation input (frequency, amplitude) on the impedance response. Results potentially usable to design an electrical tomography SHM device	[72]
	Piezoresistivity using fiber reinforcement electrical conductivity	Identification of delamination location and size in cross-ply CFRP composite beams submitted to interlaminar shear tests.	[73]
		Piezoresistivity coupled with external AE to monitor damage state inside CFRP laminates submitted to cyclic tensile loading. Potential for in-situ SHM on CFRP structures.	[74]
	Piezoresistivity using Z-pins (metallic reinforcement) electrical conductivity	In-situ and real-time detection of delamination cracks (mode I interlaminar loading tests) in CFRP composites reinforced by conductive Z-pins in the through-thickness direction	[75]
	Piezoresistivity using carbon nanofillers (mixed with matrix) electrical conductivity	Real-time SHM technique (electric potential measurement) to detect, locate and quantify damage (impact loadings and drilled holes) in large CFRP composite structures with electrically conductive (including CNTs) epoxy matrix.	[76]

		CFRP composite specimens with carbon black-filled thermoplastic matrix submitted to incremental tensile cycles. Good relationship found between mechanical behavior and electrical resistance variation: a potential indicator of volume damage.	[77]
	Piezoresistivity using carbon nanofillers (as thin films, fibers or fiber coating) electrical conductivity	CNT film sensor inside cross-ply CFRP laminates for SHM applications during uniaxial tension-tension fatigue loading. High strain sensing capability, piezoresistivity can be used as a damage indicator.	[78]
		In-situ SHM of GFRP composites embedded with CNT fiber, submitted to incremental cyclic tensile and three-points bending tests. Direct correlation found between mechanical loading and electrical resistance (ER) change. Damage accumulation also correlated with ER.	[79]
		Glass fibers with electrically conductive CNT or graphene coatings embedded in an epoxy matrix to manufacture piezoresistive GFRP composites. Tensile tests revealed that both are sensitive to strain, but the graphene coating seems to provide more SHM abilities than CNT coating.	[80]
	Electrical tomography (ET)	Detection of transverse cracks in laminated composites is analytically investigated with various geometrical and material parameters. Results shown that ET is only suitable for laminates with low conductivity ratios.	[81]
	Time-domain reflectometry (TDR)	Self-sensing TDR employed to detect impact damage in a conductive CFRP composite plate. Results shown that TDR results are not impacted by a composite with several fiber directions, whereas the damage position influences a lot the ability of the technique to detect it.	[82]
Optical testing	FBG sensors	In-situ strain measurements (cyclic-continuous tensile loading) on unidirectional CFRP specimens with embedded FBG sensor. A novel method to improve reliability and accuracy of the measurements is developed. Results shown that a calibration and an accommodation time of the FBG are needed to get reliable measurements in real-time.	[83]
		Matrix cracking monitored in real time on a GFRP composite embedded with a FBG sensor and submitted to quasi-static tensile tests with incremental strains. The reflected FBG spectra gave real-time information about both strain and crack development and might be used as an in-situ SHM device.	[84]

2. Reminder about piezoelectric effect

Discovered by Pierre and Jacques Curie in 1880, the piezoelectric effect is a multiphysical coupling. Testing certain crystalline minerals, the Curie brothers found that when they submitted them to a mechanical force, they became electrically polarized. Tensile and compression tests were generating voltages of opposite polarity, proportional to the applied force. This behavior was later labeled as the direct piezoelectric effect. Another test revealed the reverse piezoelectric effect: when an electric current was applied to these crystalline materials, it lengthened or shortened according to the polarity of the field, proportionally to its strength [85]. These two combined effects form an electromechanical coupling, as shown in **Figure 1**.

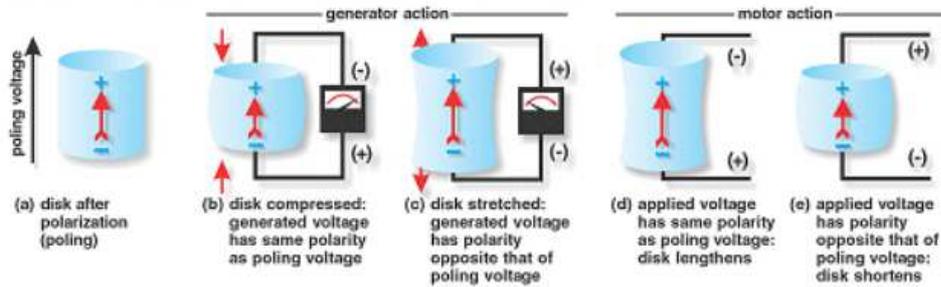


Figure 1. Direct and reverse piezoelectric effects [85]

This coupling can be used for sensing (force or displacement sensors: direct effect, **Figure 2**), actuation (motors, control positioning devices, ultrasonic generators: reverse effect, **Figure 3**) and transduction (energy conversion) applications. Other developing areas of expertise, such as energy harvesting, also rely on the piezoelectric effect (the direct one in this case).

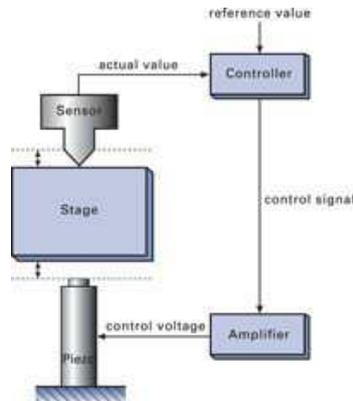


Figure 2. Piezoelectric sensing device (force or displacement sensor) [86]

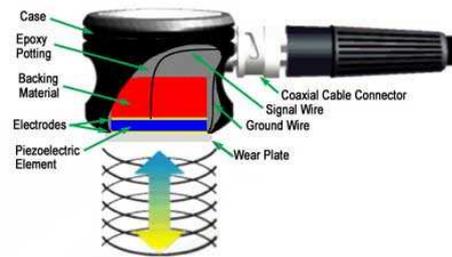


Figure 3. Piezoelectric sensing & actuation device (ultrasonic transducer) [87]

Various types of materials display piezoelectric properties. They can be polymers (PVDF and its copolymers such as PVDF-TrFE) or ceramics (LZT, Barium Titanate), and can take various shapes (films, discs, wafers, fibers, powders, etc.).

The piezoelectric effect can be analytically modeled with an electrical circuit, such as in **Figure 4** which helps to understand how it works, and how to recreate it with purely

electrical components eventually. Modeling this coupling helps researchers to forecast the behavior of piezoelectric materials in various conditions, with the final aim of suppressing experimentations permanently.

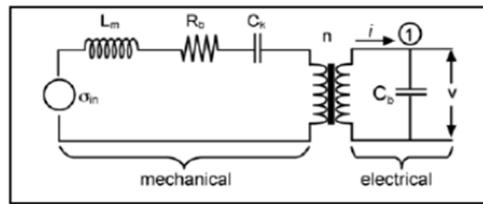


Figure 4. Equivalent piezoelectric circuit model [88]

3. In-situ PM & SHM works achieved until recently in the scientific community

Different kinds of piezoelectric sensors were employed to perform in-situ PM and SHM using various NDT techniques, which will be described in this section as well as the obtained results. The distinction will be done between the piezo elements used as actuators (active mode) or as sensors (passive mode). The intrusiveness, sensitivity and reliability of each solution will be presented if mentioned in the corresponding works.

3.1. Acoustic Emission (AE) monitoring

A first way to perform in-situ measurements is AE. In this case, piezoelectric sensors are used in passive mode. They will only detect the incoming acoustic waves propagating through the composite material.

Masmoudi et al. published several articles ([53]–[58], [60]) and a thesis [59] on the subject. Piezoelectric discs of various dimensions were inserted inside different kinds of composite materials, such as laminates (PZTs between the plies in the neutral plane) and sandwich (PZTs between the upper skin and the foam). The host samples were 2D specimens (1 in-situ PZT) or plates (4 in-situ PZTs forming a square), and 3D structures (3 in-situ PZTs forming a line). Intrusiveness studies have shown that this embedding caused only slight degradation (ex of laminate specimens submitted to three-points bending: see **Figure 5 a**) of the host materials mechanical properties (except for [57]) if the dimensions of the discs did not exceed certain limits. Knowing that, quasi-static tensile, bending (static and creep), combined bending/compression and fatigue tests monitored by AE were performed on pristine samples and on others containing PZTs with adapted dimensions. AE sensors were the embedded PZT disks, and the same disks bonded on the surface of pristine samples in the same planar coordinates, to make a sensitivity comparison between the in and ex-situ techniques. Recorded AE signals were located and classified using the k-means clustering algorithm and Principal Component Analysis (PCA), with the same number of families found for pristine and embedded samples. These families were attributed to different damage modes according to the kind of tested sample. **Figure 5 b** presents the four extracted classes in the case of the 2D laminate ((left) = pristine sample with surface-mounted PZT and (right) = embedded sample) plates submitted to bending. The location of the hits coming from the same laminate 2D plates was also determined. It was found that the in-situ PZTs detected more AE hits than the bonded ones, and these hits had higher amplitudes than the ones sensed by the external PZTs (see **Figure 5 b** left and right) Moreover, the in-situ AE sensors can allow early detection of damage modes compared to the surface-bonded ones [56]. The in-situ sensors are thus more sensitive than the external ones, because the contact between the host material and the sensor is better in the case

of embedded PZTs. According to the available information, damage initiation and final failure have been observed far from the PZT embedding area, as shown in **Figure 6** for laminate specimens after three-points bending. This is confirmed, in the case of tests with located AE events, by the majority of them located away from the PZTs during the tests, which validates the intrusiveness tests previously mentioned. Static and fatigue behavior of all samples are only slightly affected by the embedding of PZTs with adapted dimensions. A particular attention must be carried on the superior influence of the thickness of the disc over its diameter on the resulting intrusiveness, which has been reported several times by the authors. Another remark is that damage occurrence scenarios shown by AE can be different for the embedded and pristine samples made of the same material.

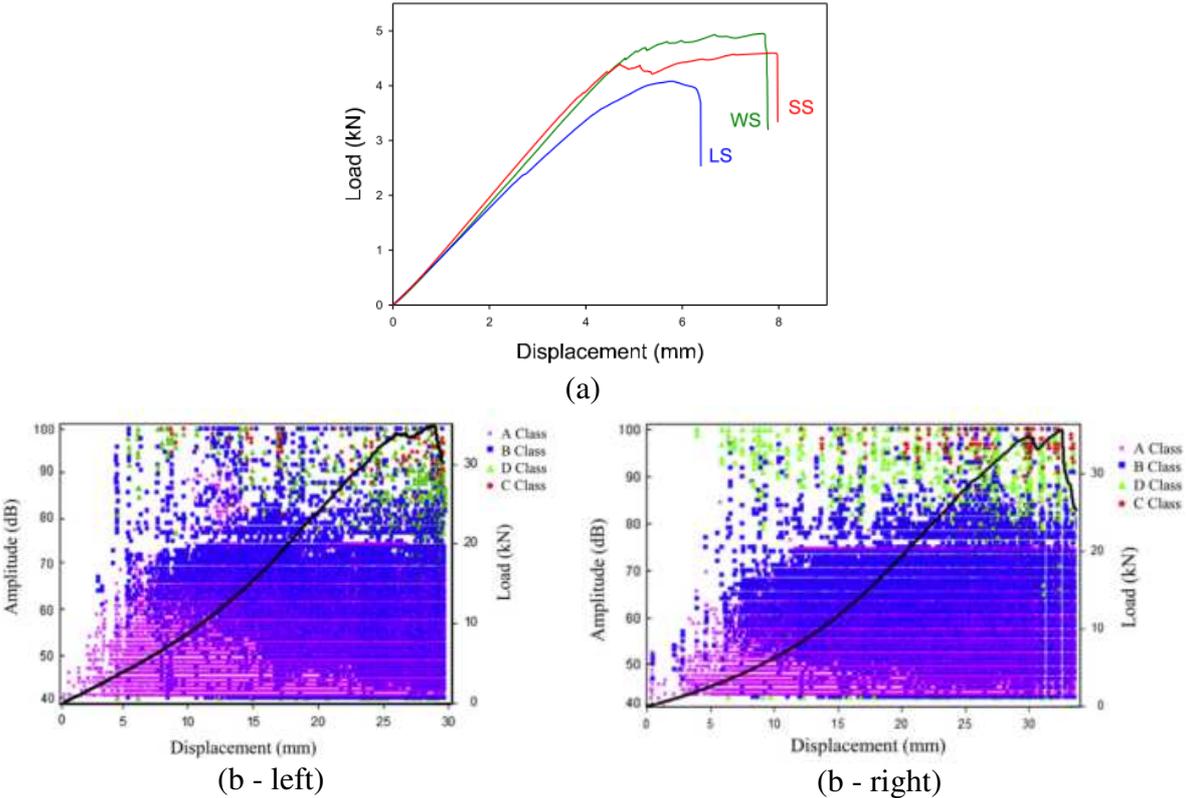


Figure 5. (a) Load-displacement curves measured for pristine (WS), embedded with a small sensor (SS) and embedded with a large sensor (LS) specimens submitted to three-points bending - (b) Amplitude distribution of signals collected versus time for laminated plates: (left) plate without integration, (right) plate embedded with small PZT sensor. A class: Matrix cracking, B class: Fiber-matrix debonding, D class: Delamination and C class: Fibers breaking [54]

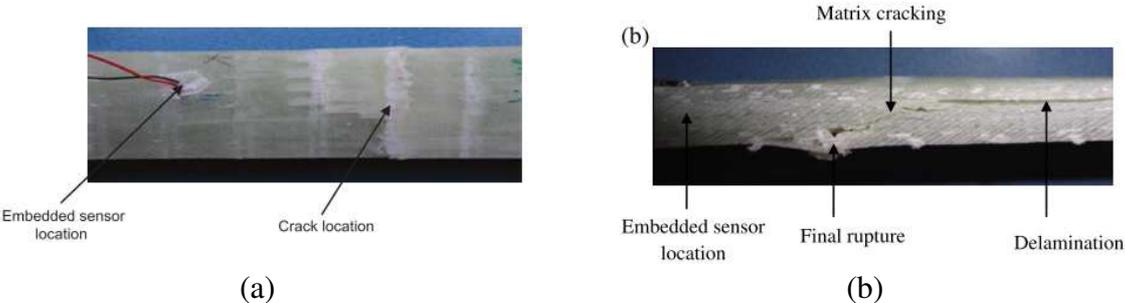


Figure 6. Failure of integrated specimens: (a) unidirectional laminate and (b) cross-ply laminate [58]

PVDF devices have also been studied for in-situ AE. De Rosa et al. [89] and Caneva et al. [90] worked on the integration of commercially available PVDF elements into glass/epoxy [89] and aramid/epoxy [90] composites to perform AE, and prove that these sensors can be used as in-situ low-cost, light, flexible and reliable SHM devices. They manufactured pristine and embedded tensile and three-points bending specimens and, as Masmoudi et al. did, they placed the in-situ (embedded specimens) and ex-situ (pristine specimens) PVDFs in the same spots to make a sensitivity comparison. **Figure 7** a shows the location of the in and ex-situ sensors for a glass epoxy tensile specimen [89]. All the sensors recorded AE activity during the tests. Upstream calibration tests using the Hsu-Nielsen method shown that in-situ PVDF can well-detect and localize simulated acoustic events made by Pencil-Lead Break (PLB, [91]), even if ex-situ resonant PZT sensors are more precise (see **Figure 7** b). Park et al. [92] did the same kind of calibration tests with two PVDF sensors embedded in GF/epoxy single-fiber composites made with different hardeners, and also found a good correlation between generated and detected PLBs. Authors [90] and [92] noticed the PVDF had more difficulties to localize damage coming from long distances, and attributed it to the low sensitivity of PVDF (compared to PZT) and damping of the viscoelastic matrix. Park et al. [92] attributed the variations found in resin damping to the difference of hardeners which changes the matrix toughness. The in-situ PVDF were shown not to be intrusive with differences of 6% in Young's modulus and tensile strength, and 1%/5% in bending strength/bending modulus [89]. AE activity monitoring was found to be more intense in the case of tensile embedded specimens (see **Figure 7** c and d) and was similar for both pristine and embedded bending specimens [89] or even slightly lower for embedded bending specimens [90]. The AE detection ability of in-situ PVDFs is consequently demonstrated to be at least as good as surface-bonded ones. AE families corresponding to damage modes were attributed for both tests ([89], [90]) after AE event parametric analysis and their chronology of appearance were investigated. Post-impact bending tests were also performed. In-situ PVDFs do not modify the post-impact flexural behavior of the samples, slightly lowering the bending strength. A comparison between embedded specimens after bending and post-impact bending tests revealed an increase in AE activity and a shift of significant AE signals towards lower loads for post-impacted glass/epoxy specimens [89], but a decrease in AE activity is observed for post-impacted aramid/epoxy specimens ([90], see **Figure 8** a and b). This is explained by the presence of unstable damage produced at the impact on the brittle laminate, which will become active as soon as bending begins [89] whereas the high impact toughness of aramid fibers lower the production of these damages with more deformation allowed [90]. These tests proved the ability of PVDFs to discriminate the amount of damage coming from the impact part and the post-impact bending part ([89], [90]), to detect the variations in AE patterns and parameters induced by various impact energies [90], and to localize AE events during post-impact bending [90]. Park et al. [92] performed micro-tensile tests on samples vertically and horizontally embedded with PVDFs/P(VDF-TrFE) (see **Figure 9**) as in-situ AE sensors. PZT and PVDF/P(VDF-TrFE) sensors were also surface mounted on the specimens for sensitivity comparison. It was found that PVDFs only detect very energetic signatures (fiber fracture) whereas PZTs were sensitive to more kind of damages (also matrix cracking and interfacial debonding). Embedded PVDFs have more responding sensitivity than surface-mounted ones, surely due to the better transfer of elastic waves coming from deformations. The direction of PVDF embedding influences both its sensitivity (better in the horizontal direction, the whole sensor is embedded) and detection range (better in the vertical direction, less embedded material and shear stress to deform). PVDF and P(VDF-TRFE) have the same damage sensitivity, but AE amplitude and energy were lower in the P(VDF-TRFE) case. Interfacial shear strength (IFSS) was also measured for each case, and the one measured with PVDF was the lowest due to its low sensitivity. As sensor thickness does not seem to affect on the sensing, thinner sensors could be desirable to minimize intrusiveness.

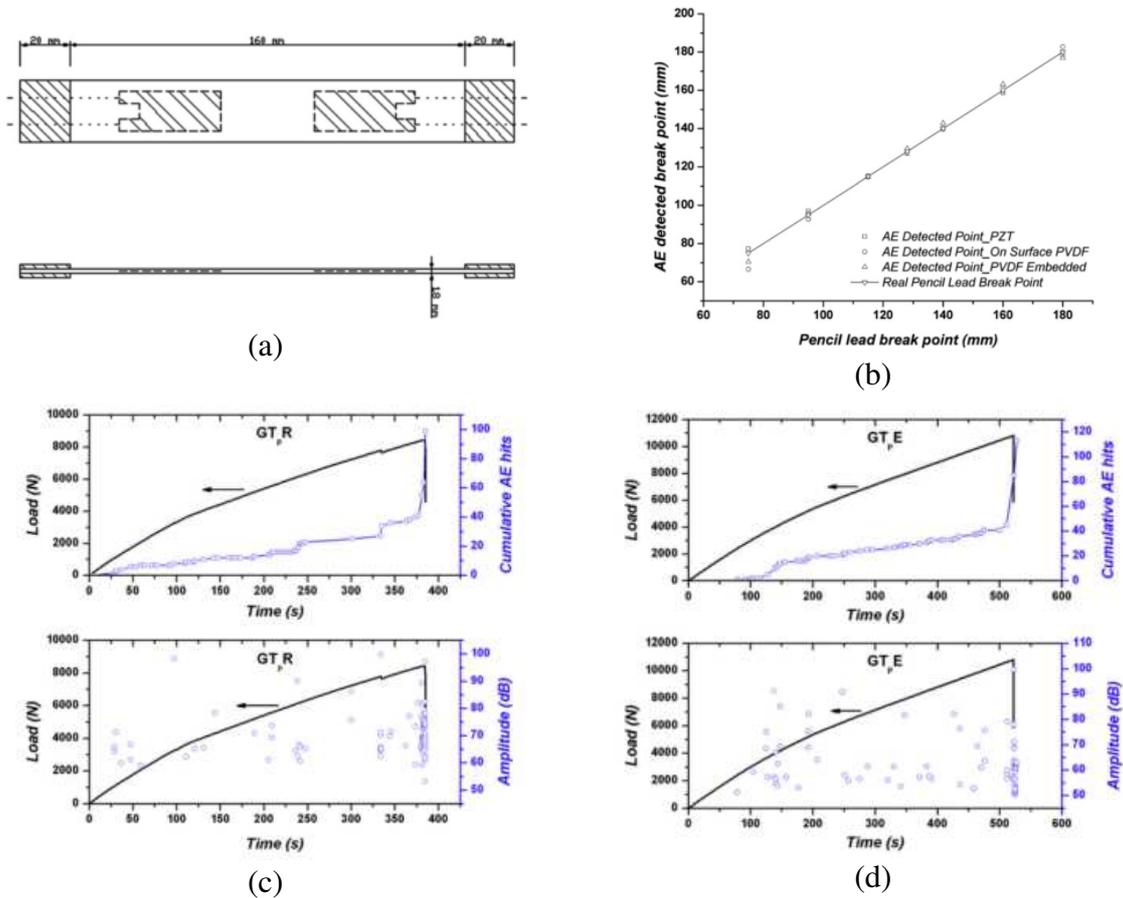


Figure 7. (a) Schematic drawing of tensile specimens - (b) Calibration curves for PZT, on surface and embedded PVDFs - (c) Load and cumulative hits (up) and amplitude distribution (bottom) for GTpR (no embedded PVDFs) specimens – (d) Load and cumulative hits (up) and amplitude distribution (bottom) for GTpE (two embedded PVDFs) specimens [89]

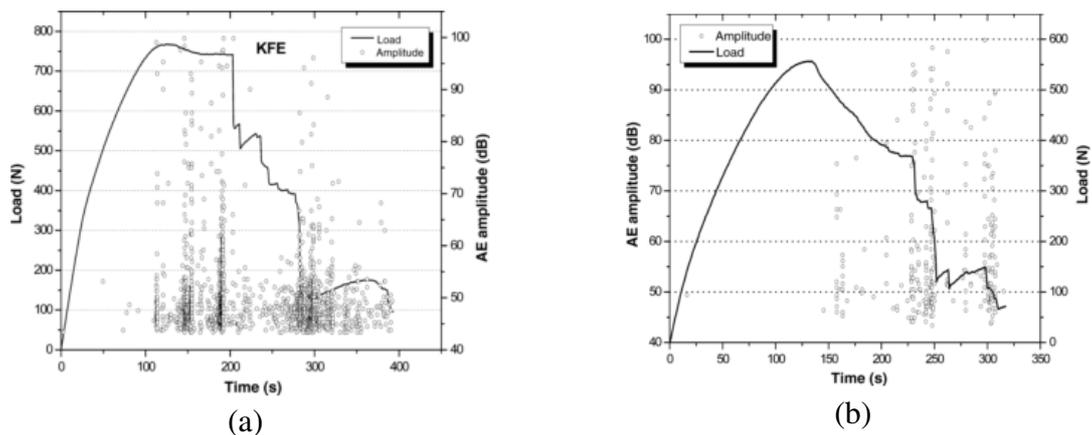


Figure 8. Load and amplitude distribution versus time for (a) KFE (non-impacted) and (b) Ke_15J (pre-impacted at 15J of energy) three-points bending specimens [90]

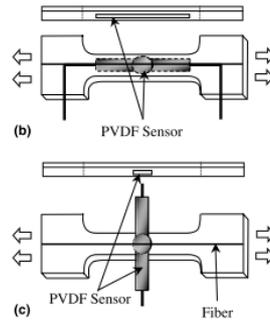


Figure 9. Test specimen of single-fiber epoxy composite with (b) longitudinal embedded and (c) vertical embedded polymer sensor [92]

3.2. Ultrasound (US) monitoring

Ultrasonic measurement has been widely employed to perform in-situ PM and SHM using piezoelectric. This technique needs the piezoelectric transducers to act in both active and passive modes in order to generate and receive US waves. These waves can be volume or plate (Lamb/guided) waves.

In this context, several research teams have used PZT networks. The Stanford Multi-Actuator Receiver Transduction (SMART) Layer device is one of the most used among them, with several articles related to its development in university and then commercial exploitation. The SMART layer, which can come in various shapes and network patterns ([93], [94]), can be used for both in-situ PM ([95], [96]) and SHM ([93], [96]–[99]) of composite materials. The SMART Layer has many advantages due to its thinness, size (a few inches to a few feet) versatility and flexibility even during millions of cycles in fatigue. It has been proven not to degrade too much the mechanical properties of the structures it is embedded into ([93], [95], [96]), it even sometimes tend to improve them (surrounding ply shear strength which defers its delamination ([93], [94]) and to survive various embedding processes (RTM, filament winding, autoclave, etc.). It also shows uniformity and consistency of electrical response over time, after loading ([95], [97]), hygrothermal aging [94] and for a wide frequency range [96]. Lin et al. ([95], [96]) used it to monitor resin curing for an autoclave process (see **Figure 10 a**), thanks to propagation and sensing (pitch-catch method) of US waves with the PZTs of the Layer. They used the evolution in phase delay of the generated diagnostic waves (see **Figure 10 b**) to infer the degree of cure of the resin. Impact identification ([96], [99], [97]) with measurement of the impact force and location (PZTs in passive mode, see **Figure 11 a**) and damage detection (pitch-catch, see **Figure 11 b**) with estimation of their extent, were also performed thanks to an embedded Layer connected to an external signal processing system. Such a system has been developed by the company manufacturing the SMART Layer and named SMART suitcase ([94], [97]), but research teams can also create their own, such as Haywood et al. [99] did. They tested two strategies to detect and localize impact loads on a graphite/epoxy plate using the impact signals detected by an in-situ SMART Layer: an Artificial Neural Network (ANN) and a triangulation procedure using a genetic algorithm. The ANN gave the better results and was integrated into their software to perform automatic impact location and further signal analysis to possibly infer damage extent.

Multiple layers can also be embedded inside the composite to create multiple sensing paths. Wang et al. [97] and Qing et al. [98] built-in-plane paths and through-the-thickness paths by inserting SMART Layers inside a multiple-layer thick ceramic-composite armor panel ([97], see **Figure 12 a**), and a filament-wound bottle ([98], see **Figure 13 a**) to be able to monitor impact damage everywhere in them. They remarked a noticeable change in diagnostic

waveforms generated and received by the Layers (significant reduction in amplitude) when they crossed impacted areas, which indicated the severity of damage. It allowed them to globally estimate the planar and through-the-thickness damage extents on the panel ([97], see **Figure 12** b and c, damaged areas in grey) and to make a signal amplitude gradients cartography of the impact damages and their extent on the bottle surface ([98], see **Figure 13** b and c). A way to improve diagnostic signals jammed by thermal fields to clean damage cartographies was also demonstrated [98]. Qing et al. also noticed that the PZTs contained in the layers fully embedded in the bottle produced stronger diagnostic signals (travel the whole circumference of the bottle) than the one only attached to its surface, which once again confirms the interest of fully in-situ sensor networks.

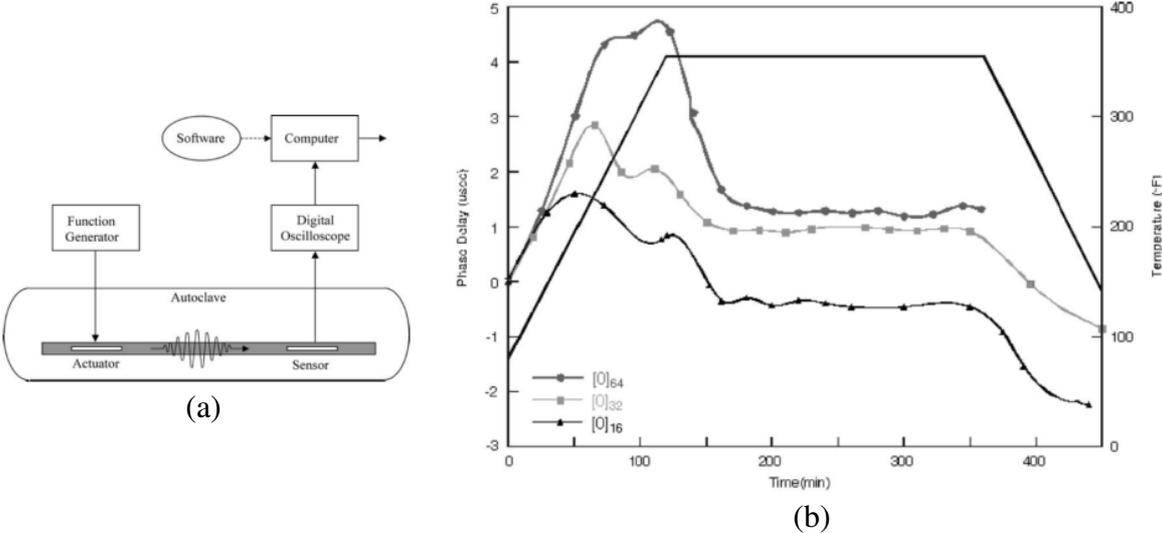
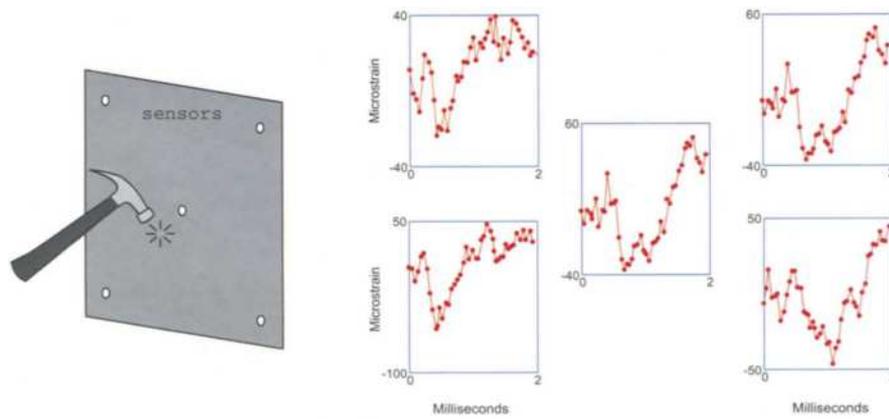
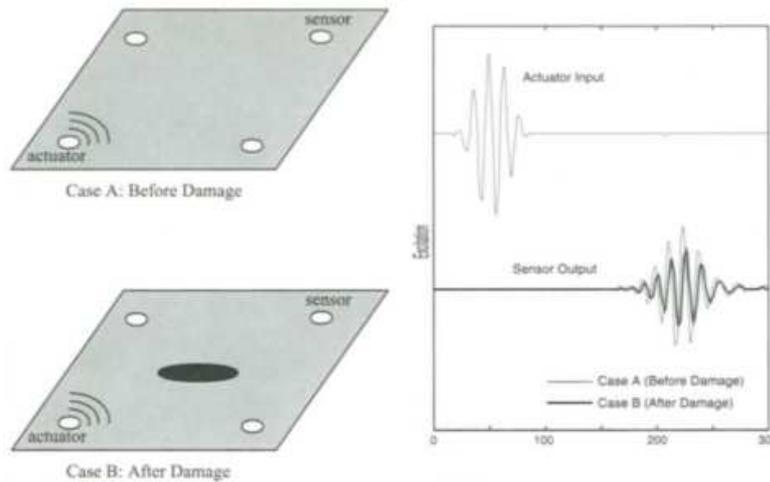


Figure 10. (a) Autoclave process monitoring system setup – (b) Phase delay plotted over the cure cycle. The three traces are experimental data for three laminates of different thickness. The cure cycle temperature is superimposed in the background [95]

Other kinds of piezoelectric arrays have also been investigated. Several teams embedded separated piezoelectric transducers into the composite material to create an in-situ network. Chilles et al. [52] did it with a standard PZT transducer able to remotely send information to an external SHM acquisition unit thanks to a coil system using electromagnetic coupling. This Inductively Coupled Transducer System (ICTS) was used to perform GF/epoxy plates cure monitoring and damage detection thanks to bulk waves (through the thickness propagation, localized coverage) and guided waves (in-plane propagation, large area coverage) generation and reception with a single in-situ ICT sensor performing pulse-echo measurements. Both kinds of waves were able to monitor resin curing more accurately than Differential Scanning Calorimetry (DSC) or dielectric measurements, but only when the resin was not too viscous not to attenuate US waves too much. Guided waves were able to detect impact damage events thanks to a baseline method subtracting damage signals to healthy signals and analyzing the corresponding residues. This technology is fast and contactless, but not completely autonomous because the operator necessitates a wand to transmit and get back diagnostic US waves. The system intrusiveness is still minimized because the data processing unit is deported and there is no wiring at all.

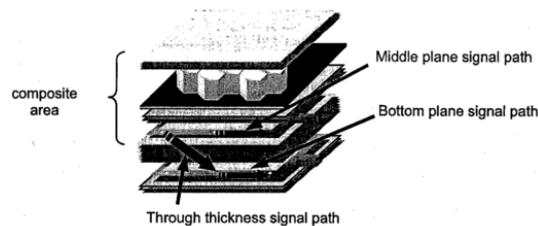


(a)

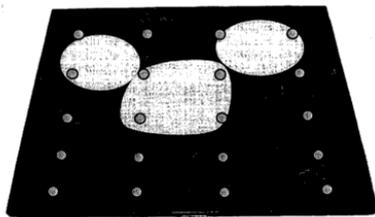


(b)

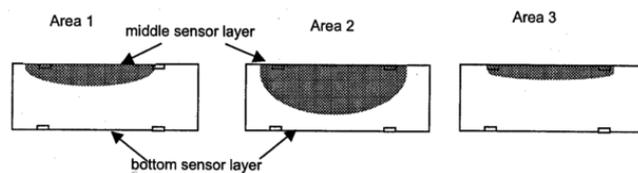
Figure 11. (a) Example of passive sensing diagnostic: identification of the location and force-time history of an external impact – (b) Example of active sensing diagnostic: detection of the size and location of an internal damage [96]



(a)



(b)



(c)

Figure 12. (a) Diagnostic signal paths in a thick composite with two embedded actuator-sensor networks – (b) Estimated damage sizes and depths in multi-layered thick armor panel after the impacts: tile and upper layers – (c) Estimated damage sizes and depths in multi-layered thick armor panel after the impacts: thickness direction [97]

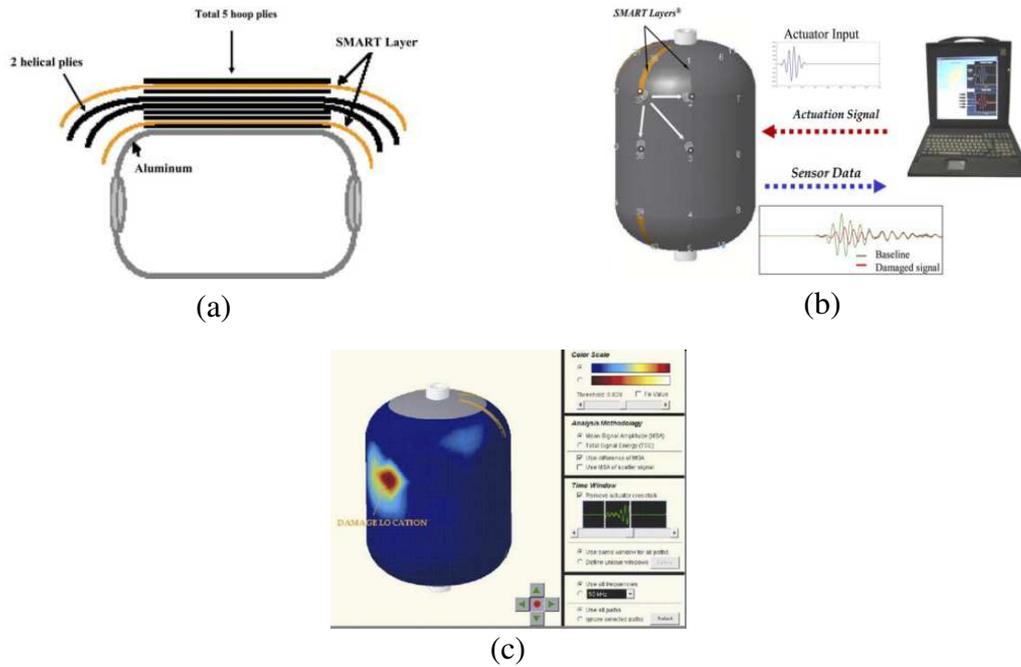


Figure 13. (a) Embedding locations of SMART Layer strips in the filament wound bottle – (b) Schematic of the active diagnostic system – (c) Damage identification result using signals collected by a network of built-in sensors [98]

Wired networks have been widely more used until now. Dziendzikowski et al ([100]–[102]), Katunin et al. [15] and Chen et al. [103] embedded several separated wired PZT devices inside GFRP composite plates ([15], [101]–[103]) and structures [100] to realize impact damage detection/localization ([15], [100], [101]), simulated external damage detection [102] and hand-made hole detection [103]. To do so, they used a pitch-catch transducer configuration with Damage Indices (DI) calculation ([15], [100], [101]), DIs with a Transfer Impedance approach [102] and a guided (Lamb) wave Time of Flight (ToF) approach [103]. Damage Indices are calculated using some comparative characteristics (signal envelopes, etc.) of the signal acquired before and after damage. Dziendzikowski et al. ([100]–[102]) used different kinds (PZT discs ([100]–[102]) and PZT multilayered plates [101]) of embedded and surface mounted transducers to perform a sensitivity comparison. They found in [101] that the best results were obtained with the multilayered plates, which are unfortunately not embeddable, but embedded PZT discs were able to detect (all impacts with different energies well-separated, see **Figure 14** a) damage better than surface-mounted ones. This is due to their high electromechanical coupling coming with their embedding. The indication of damage was also found in [102] to be more significant for embedded sensors compared to surface-attached ones, with good stability and irrespective of PZTs relative orientation, network geometry or material anisotropy. As DIs can only perform damage detection, localization was done with an imaging algorithm (RAPID) displaying damage intensity maps ([101], see **Figure 14** b, c and d). As shown in these figures, the best localization results were obtained for the strongest impacts, and only with the embedded PZT discs and surface-mounted PZT multilayered plates networks (not the case for the external PZT discs network). Authors also mentioned that a modified version of this RAPID algorithm allowed its sensitivity to be improved along the X-axis for GFRP structures [100]. The Y-axis sensitivity still needs to be ameliorated with additional in-situ sensors, which would make the network more homogeneous. Katunin et al. [15] also pointed out the fact of adding more sensors in the embedded network to enhance its accuracy in detecting impacts using DIs. The main drawback of using DIs is that only new damage can be detected. One must take care

analyzing results because DIs can be influenced by the sensor, measurement system and sensor/material coupling properties, and not only by the size and location of damage. Dziendzikowski et al. [102] also warned that DI maps can be altered by improper wiring configuration of the embedded transducer network when wires of an actuator and sensor run too close to each other or cross themselves.

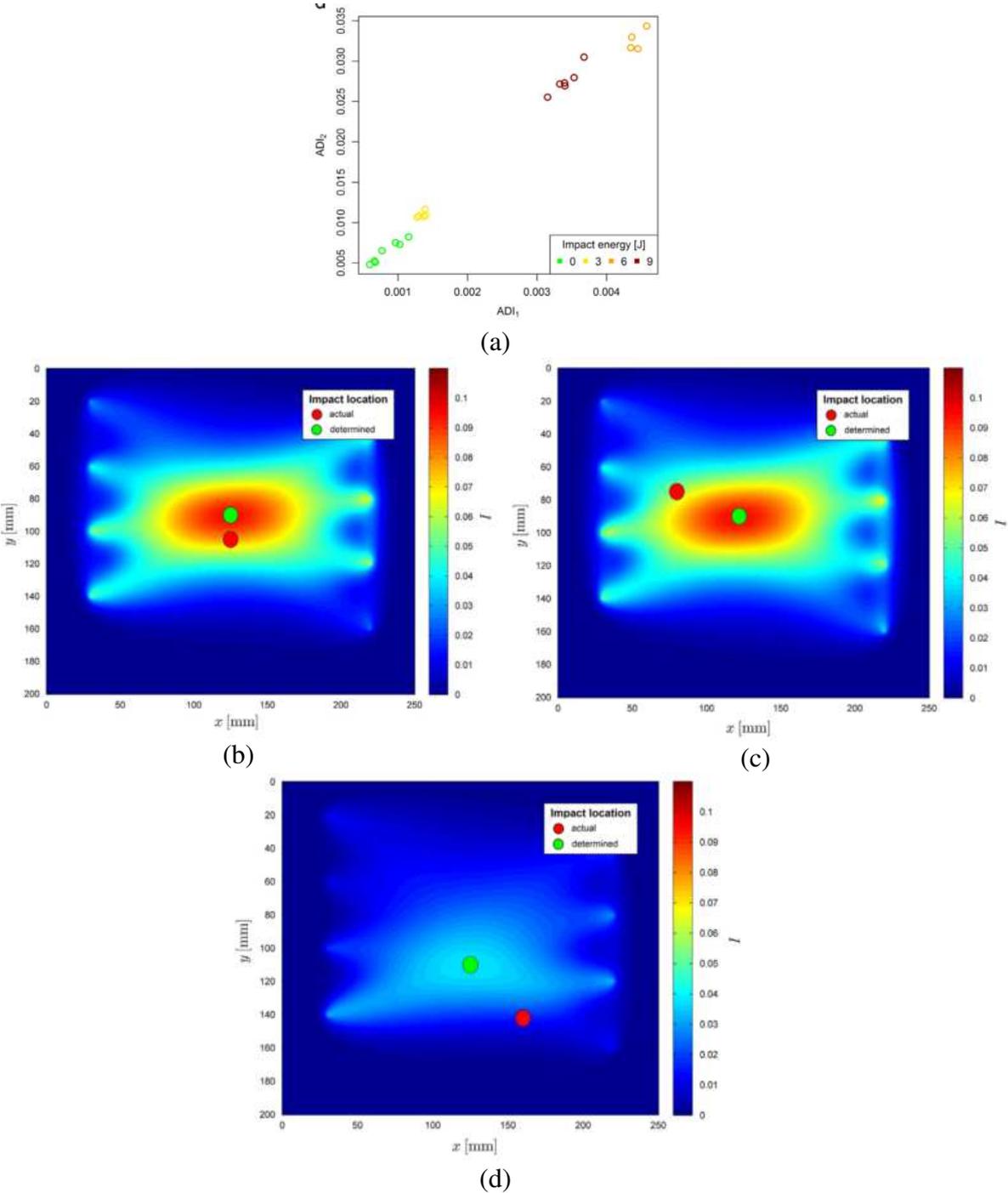


Figure 14. (a) The best separated ADIs for the Network 2 – (b) The bare damage intensities obtained for the Network 2 with RAPID algorithm: I_{bare} after 9 J impact – (c) The bare damage intensities obtained for the Network 2 with RAPID algorithm: I_{bare} after 6 J impact – (d) The bare damage intensities obtained for the Network 2 with RAPID algorithm: I_{bare} after 3 J impact [101]

Chen et al. [103] succeeded in showing a relationship between the Lamb waves ToF (see **Figure 15 a**), i.e. duration measurement of the propagation of the waves, and the increasing diameter of a hand-made hole in their tested composite plate. This is due to the change in material properties (hole) wherein the waves travel. A Fast Fourier Transform (FFT) was also performed on each of the captured waves, and shew a strong correlation with damage increase (see **Figure 15 b**): this increase provokes a reduction in waves vibration energy, lowering their FFT amplitude. This method is then suitable for in-situ SHM.

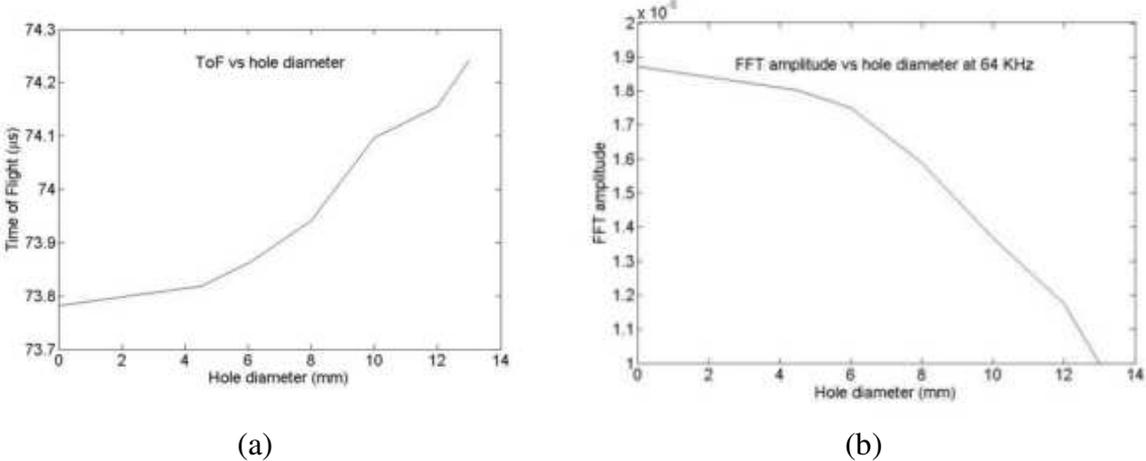


Figure 15. Tendency for different hole diameters: (a) ToF and (b) FFT amplitude [103]

Su et al. [104] also used an in-situ piezoelectric network composed of miniaturized circuited wafers to locate and gauge delamination in CF/epoxy laminate thanks to Lamb wave sensing (see **Figure 16 a** and **b**). The wafers were miniaturized to minimize the impact of the network on composite structural integrity. Information (wave propagation characteristics) obtained from multiple sensing paths were fused using the Hilbert transform, signal correlation and probabilistic searching. This technique shown excellent identification results combined to good robustness to environmental noise and very good stability and repeatability in data acquisition, when compared to ex-situ sensors methods.

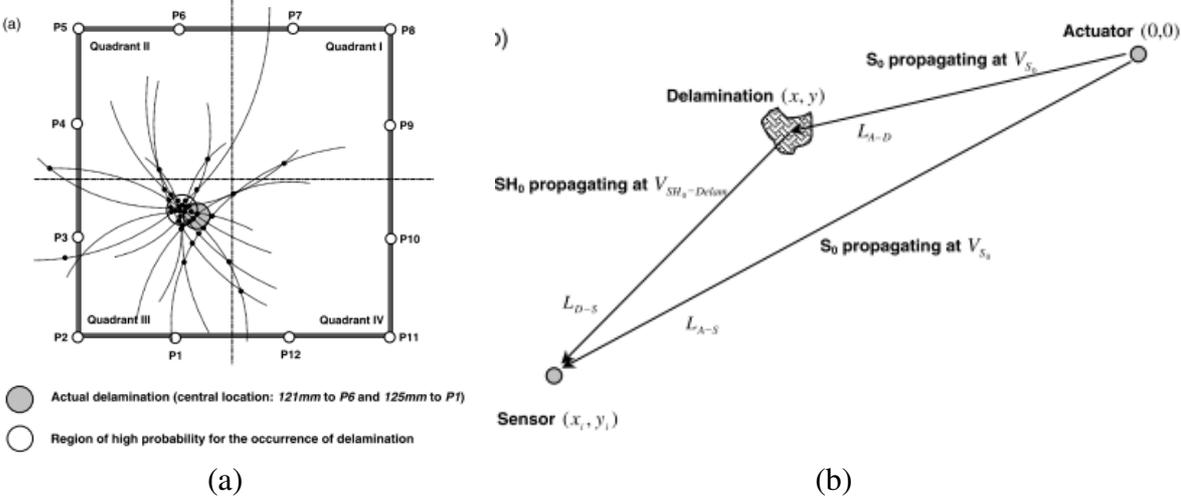


Figure 16. (a) Delamination searching strategy and results, (b) illustration of damage triangulation [104]

Several research teams preferred using piezo films to perform in-situ US measurement. PVDF films have gathered many publications. Blanas et al [105], Schulze et al [106] and Bae et al [107] embedded them into GF/epoxy plates ([105], [106]) and CF/epoxy plates [107] to realize in-situ impact detection thanks to the film detecting the propagation of the elastic wave generated by the impact (see **Figure 17** and **Figure 18**). Bae et al. [107] shew their sensors intrusiveness (Young’s modulus and Interlaminar Shear Strength degradation rate) to be low thanks to tensile and short beam shear tests, even if it was increasing with the increasing ply stacking angle of the laminates. All sensors ([105]–[107]) were able to detect the impact events. Schulze et al. [106] and Bae et al. [107] noticed in their work that the sensor signal varies according to the impact location and impact drop height (see **Figure 19** a, b and c) for an unidirectional impacted (UDI) [0/90]_{10S} specimen, and this signal is not stronger when the impact is directly at the vertical of the sensor ([106], see **Figure 18**). It means that the thickness mode of the sensor is not relevant for low-velocity impact detection. Bae et al. [107] noticed that in-situ PVDF sensors are capable of detecting both the stress wave released by damage formation (matrix cracking, delamination) associated to the impact and the signal vibrations induced by this same impact. It allowed them not only to detect but also to locate damage using the amplitude of the received signals associated to the damage-induced stress wave, and the position of the corresponding sensors. Damage nature was also performed thanks to an analog model of impact energy containing the sensor-generated voltage associated to the damage-induced stress wave, and the stiffness of the impacted structure. This computed energy was associated to a pre-developed material damage database to attribute it with a certain type of damage.

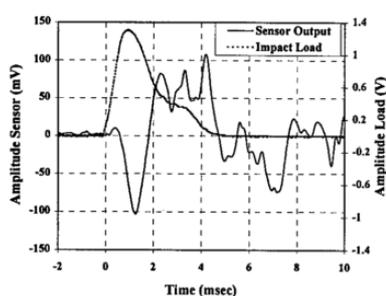


Figure 17. Typical response of composite sensors to impact load from modal hammer [105]

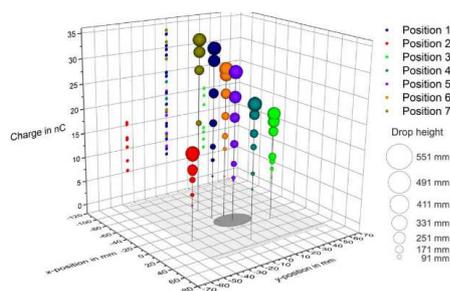


Figure 18. Maximum charge as a function of impact location tested with non-destructive impact testing [106]

Another kind of piezoelectric sensor employed for in-situ monitoring by US measurement is Piezoelectric Fiber Composite (PFC), declined in two versions: Active Fiber Composite (AFC) and Macro Fiber Composite (MFC). Konka [108] used in-situ AFC (PFC in the referenced thesis) and MFC sensors inside GF/epoxy composite laminate (see **Figure 20** a) to perform impact damage detection. The method is based on energy transfers between the different layers of the composite when the impact-induced waves travel through the thickness of the laminate, this one embedded with a pair of PFCs at different depths. According to the through-the-thickness position of a potential damage, the ratio of the output voltages of the pair of sensors will change, giving information about the damage existence and intensity. This change is due to externally applied (impact) mechanical energy absorption by the internal defects to detect. **Figure 20** b shows the ability to well correlate this output ratio with the increase of an artificial delamination size (linear relation with R^2 close to 1), which makes this technique suitable for SHM. One can notice the higher ratio developed by PFC sensors, which makes it more sensitive than MFC for this particular purpose.

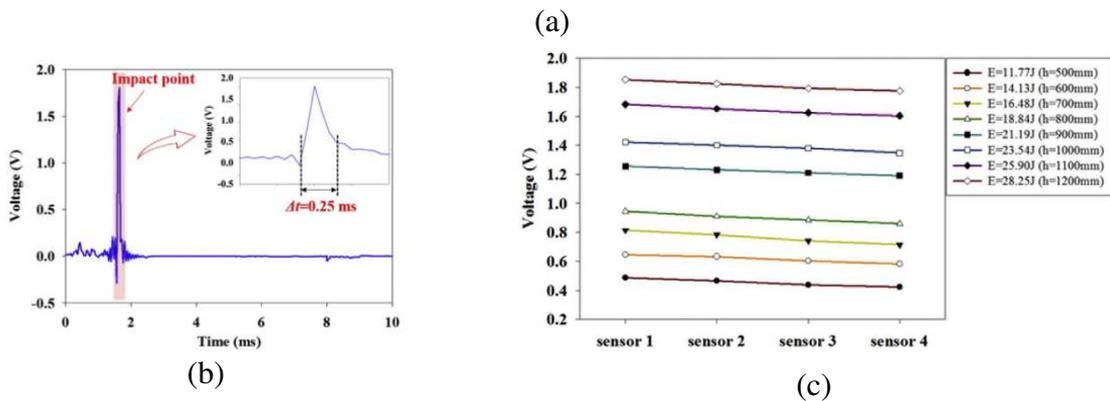
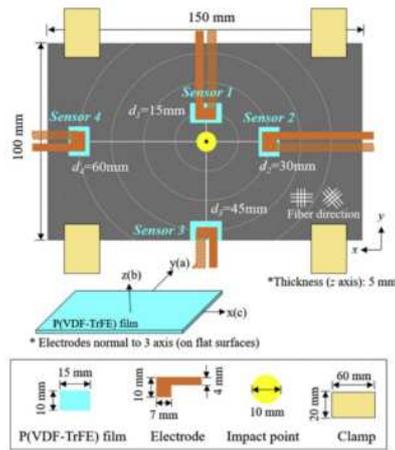


Figure 19. (a) Impact test: specimen configuration and boundary condition – (b) P(VDF-TrFE) film sensor signals from impact tests: representative signal from a film sensor embedded in a composite laminate – (c) P(VDF-TrFE) film sensor signals from impact tests: maximum voltage generated in composite laminates of UDI[0/90]10S (E =impact energy, h =impact height) [107]

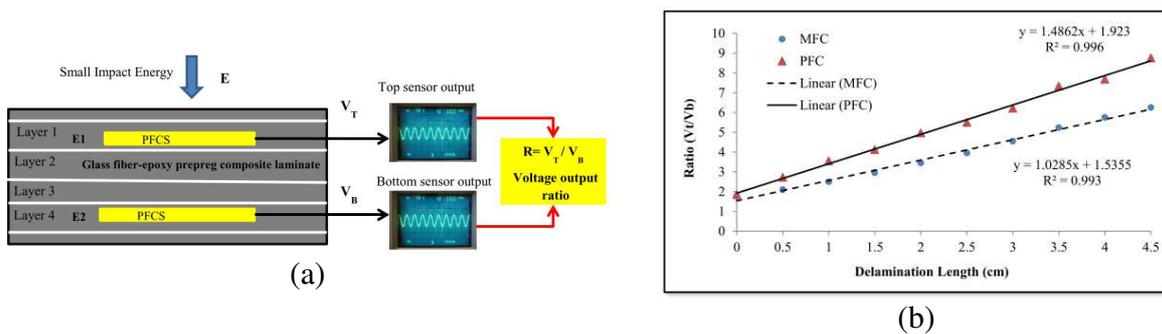


Figure 20. (a) Block diagram of the experimental setup and concept – (b) Changes in the voltage output ratio with the increase in the delamination area [108]

3.3. Electrical monitoring

Both results obtained with basic electrical measurements but also impedancemetry will be presented in this subsection.

3.3.1. Electrical measurements (voltage, electric charge)

Using piezoelectric devices, these techniques have the objective to replace or at least confirm more conventional ones such as strain gauges. The difference lays in the use of different physics

for the two techniques. For strain gauges, piezoresistivity allows inferring the amount of produced strain thanks to the variation of electrical resistance whereas piezoelectric devices will do the same using piezoelectric coupling. To perform this kind of measurement, the in-situ sensors are used in passive mode to perform either PM or SHM.

Several articles deal with the use of PVDF and piezo films in general. Chrysochoidis et al. [109] embedded thin PVDF films into sandwich composite panels (inside the GFRP skin) to perform strain measurement during static and dynamic three-points bending tests. For each of the two composite specimens (S1 and S2), one large PVDF was embedded and two smaller ones were surface-mounted as well as conventional strain gauges. All the sensors were housed on the lower tensile face of the sandwich specimens. In-situ PVDFs were shown not to be intrusive during these tests, their embedding having no marked reduction on the tensile strength for a wide range of loading paths and magnitudes. The resilience of the embedded sensors was also considered satisfactory, even up to the point of structural failure. According to the authors, during cyclic three-points bending, in-situ PVDFs sensitivity (in $\mu\text{strain/volt}$) was shown to increase (see **Figure 21 1**), which could be an indication of a degradation in either the film, the laminate or their interface. The authors suspected micro cracks formation on the tension face to be responsible for this degradation, which could be considered as a damage indicator. Embedded PVDFs were able to generate a signal until final core crushing of the sandwich laminates which can be seen in **Figure 21 1** by a sudden increase in PVDF sensitivity. Surface-mounted PVDF signals were found to be repeatable. Embedded PVDFs generated low voltage output compared to ex-situ ones whatever the loading history was (see **Figure 21 2**), mainly due to the strain field orientation and spreading over the in-situ film length, which reduces its impact on the film, and thus the charge generated.

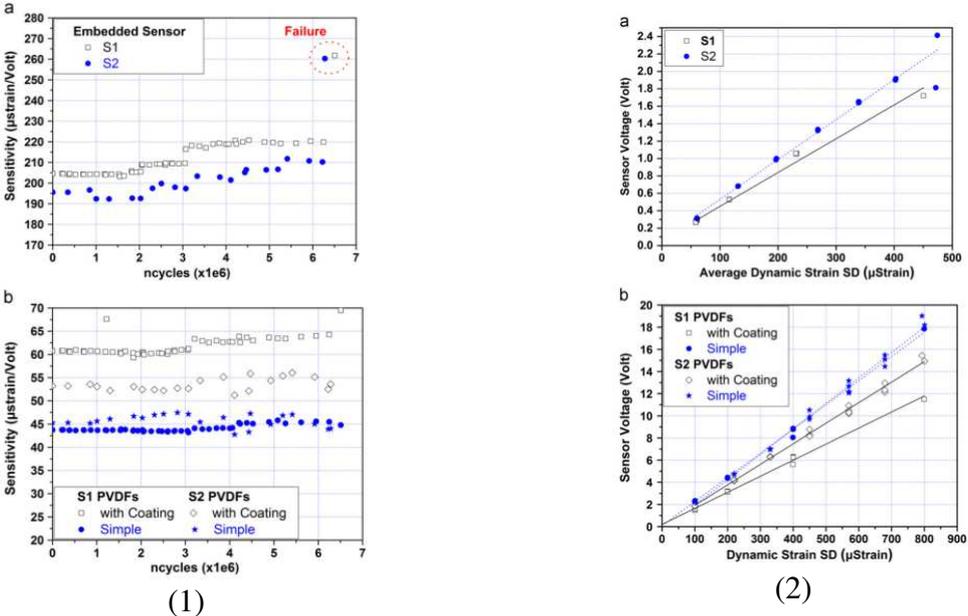


Figure 21. (1) Variation of sensitivity as a function of the number of cycles for both specimens: (a) embedded piezopolymer and (b) small surface-attached PVDF sensors – (2) Sensor voltage versus the standard deviation of the dynamic applied strain for (a) embedded sensor, and (b) surface- attached PVDFs [109]

Mills [110] embedded PVDFs inside GF/thermoset resin to monitor the curing of the resin during manufacturing by VARTM. He tested the sensors and concluded that although they may be useful in instantaneous testing and load monitoring, they are not suitable for long-term monitoring of stress, strain or temperature. This is due to the decay (see **Figure 22 a**) of the generated charge within the charge amplifier circuit (see **Figure 22 b**), built to convert the electric charges produced by PVDFs to a voltage output. He also determined that PVDFs could be used for temperature spikes measurements and shock loading situations in post-cure health monitoring approach. According to its results, Metal Foil Strain Gages (MFSG) were a lot more appropriate for all the previously cited purposes, as they are easily calibrated and temperature compensated.

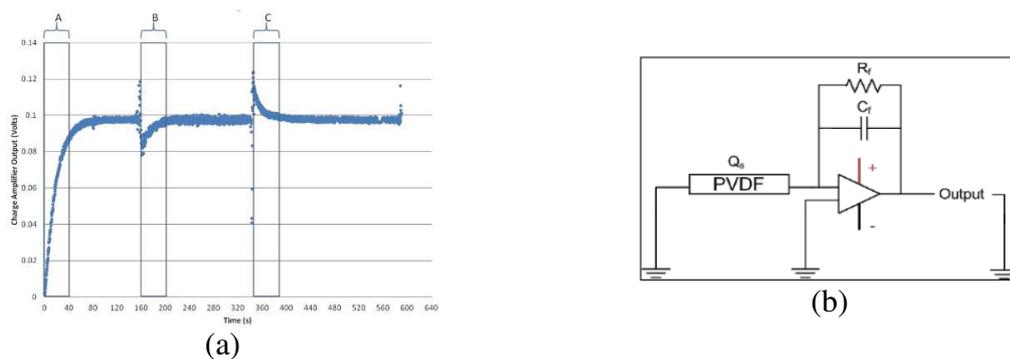


Figure 22. (a) Output from PVDF (Volt) during bending test showing decay of charge as load is held – (b) Schematic of a simple PVDF charge amplifier circuit [110]

Blanas et al. [105] realized in-situ electric measurement using both embedded doped PVDF and piezocomposite films, but for SHM purposes. They monitored strain evolution of embedded [0]25 GF/epoxy beams and plates submitted to various cyclic loads, comparing the results to a surface-bonded strain gauge (SG). Two film arrays composed of 4 sensors each (2 PVDFs and 2 piezocomposite films) were embedded in two different depths (5 and 10 layers down from the surface) inside the tested plates, whereas simply one film of each kind were inserted along the beams centerline, 5 layers down from the surface. The doped PVDFs signals reproduced well the ones given by SGs, both for in plane (beams, see **Figure 23 a**) and out of plane (plates, see **Figure 23 b**) sinusoidal loads. One can notice that the signals are out of phase, but the authors attributed that to a probable measurement artifact in this frequency range. Piezocomposite films have also shown interesting results when embedded beams were submitted to periodic square loads (see **Figure 23 c**). Embedded sensors were able to follow the rises and falls of the square signal just like the SGs did, but produced a zero signal during the steady plateaus due to the dynamic nature of the piezoelectric response. Both signals were also out of phase. The films were considered capable of monitoring transient applied loads, even if external SGs gave slightly better results. Schulze et al. [106] and Geller et al. [111] monitored the electrical charge generated by P(VDF-TrFE) films [106] and PZT layers [111] embedded inside GF/epoxy laminates submitted to three-points bending. In Schulze et al. [106] work, the sensors did not seem to get damaged during the tests, and a dependency of the generated charge in relation to the bending displacement was observed for displacements over 5mm (see **Figure 24**), which allows the authors to perform bending displacement monitoring. Geller et al. [111] performed their bending tests on plates containing layers made of different PZT materials, such as continuous fibers, fiber fragments and pearls. The amount of generated charges were different according to the nature of the PZT material, the shape of the PZT

constituents inducing more or less deformation into the layer during mechanical loading. However, the three layers were all capable of monitoring the bending crosshead displacement during cyclic loading (see **Figure 25**). The authors also realized compression tests, but the differences between the three layers were small in this case. They highlighted a correlation between increasing voltage polarization of the sensor and its sensitivity (generated charges) to crosshead displacement.

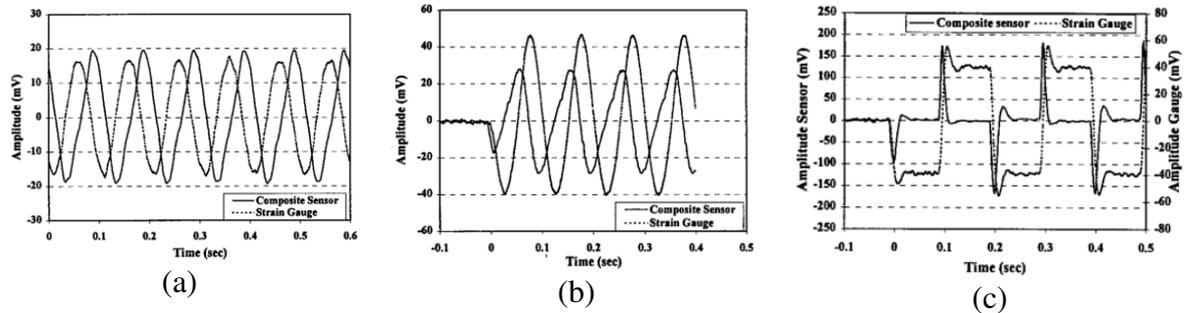


Figure 23. (a) Typical response of composite sensors to: (a) in-plane sinusoidal load (10Hz) - (b) out of plane sinusoidal load (10Hz) – (c) in-plane square cyclic load (5Hz) [105]

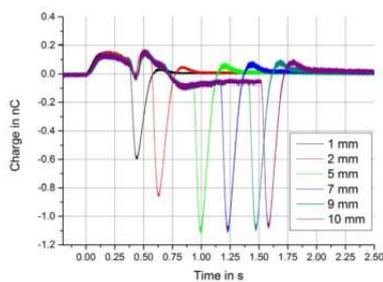


Figure 24. Generated electrical charge measured for different bending displacements [106]

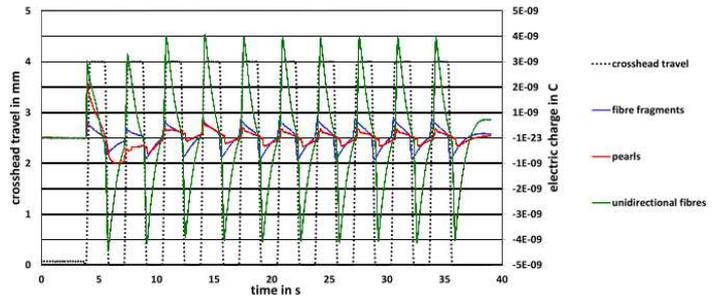


Figure 25. Detected electric charges of sensors with different piezoceramic components in dependency of the crosshead travel [111]

PFC sensors have also been considered to realize in-situ electric measurements in composite materials. Melnykowycz et al. ([112], [113]) embedded AFCs inside CFRP and GFRP laminates (see **Figure 26 a**) using insertion and interlacing techniques, to test their in-situ strain sensing ability during a monotonic cyclic loading test (see **Figure 26 b**). The sensors were embedded far from the center, in relation to the middle plane of the laminates. Using external AE measurements during the cyclic test [112] and monotonic tensile tests [113], AFC intrusiveness was investigated. The authors [113] noticed no important change in Young's modulus between pristine samples and inserted or interlaced ones but a decrease in maximum stress for embedded samples. Using AE monitoring during tests in [112], they found intrusiveness to be dependent of the embedding technique, with the least intrusiveness obtained with the interlacing method with the damage remaining more localized in the sensor area. The sensor performance curves they obtained shew a decrease in AFC signal amplitude during loading associated with a signal recovery during unloading. The authors noticed no clear difference between inserted and interlaced sensors performances, but the host material (cross-ply CFRP or woven GFRP) was shown to have an impact on the sensor sensitivity. As shown in **Figure 26 c**, the AFC embedded inside GFRP specimens had a higher signal amplitude on the whole deformation range and a better signal recovery during unloading than the one inside CFRP specimens. One can also notice the immediate decrease of the signal coming from the AFC inside CFRP specimens whereas it stays relatively steady until around 0.2% strain for the

AFC inside GFRP specimens. The decrease in sensor signal during loading corresponds to progressive PZT fiber breakage inside the AFC, induced by strain. The difference in amplitude between the GFRP and CFRP specimens can be explained by the differences in their ply architecture and stiffness. According to these two parameters, the force transfer from the plies to the embedded AFC will be more or less pronounced, making this one more or less sensitive. The standard deviation of the CFRP-embedded sensor signals was higher than the one obtained from the GFRP-embedded sensor, which can be explained by fiber misalignment of the cross-ply CFRP composite plies inducing variability in force transfer from the plies to the AFC and thus in its performance. In the woven composite case, the sensor is embedded inside a more homogeneous environment, and the misalignment effect would not be so pronounced. But as the strain increases, the fibers get realigned in the tensile direction, and the standard deviation is lowered. Both AFC sensor performance and damage behavior when submitted to mechanical loadings have to be considered to find the right layer to embed the AFC into, according to the kind of laminate. A ‘packaging’ technique consisting of embedding the AFC in prestressed laminate before integrating them inside laminate specimen was also discussed and could help to improve AFC strain sensing range. In [113], in-situ AFC signals were found to be linear with strain increase up to a threshold (see **Figure 27**) which could correspond to the discharge of the capacitor.

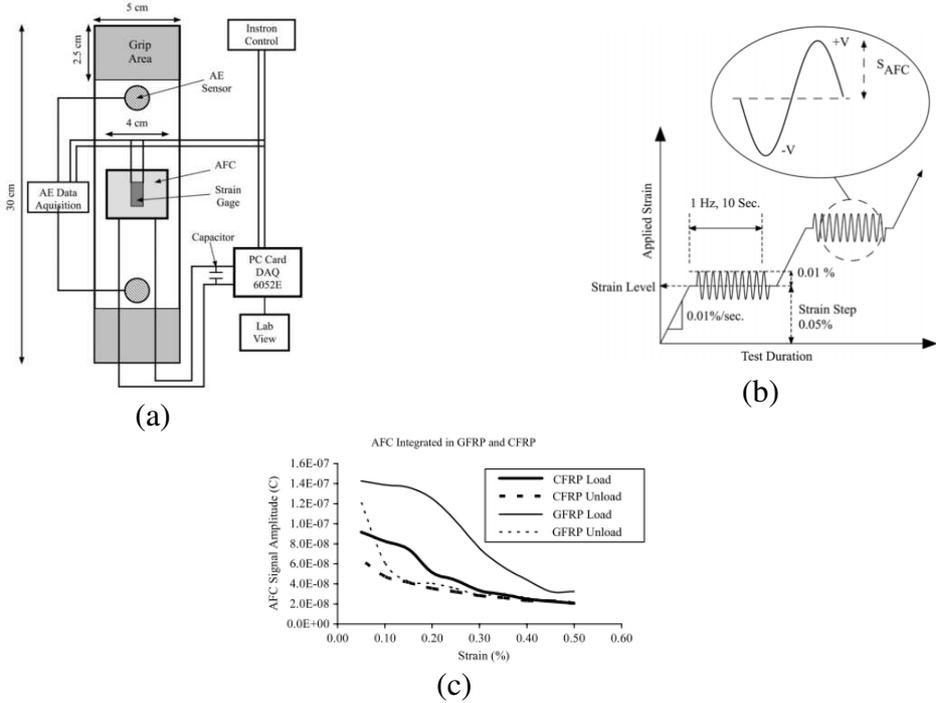


Figure 26. (a) Experimental setup for the monotonic cycle test of 30 cm × 5 cm tensile specimens – (b) Applied strain program for the monotonic cycle test – (c) Performance curves for AFC integrated into GFRP and CFRP [112]

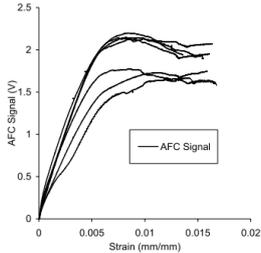


Figure 27. AFC signal in response to tensile strain [113]

Konka et al. wrote several articles ([114]–[116]) and a thesis [108] on in-situ monitoring of composite structures using PFCs. They integrated both AFCs and MFCs into GF/epoxy laminate [115] and GF/epoxy-foam core sandwich [114] composites. The sensors were embedded in the neutral plane and center of the laminates (one sensor per laminate), and in the neutral plane and center of each composite laminate skins for sandwiches (2 sensors per sandwich). PZT sensors were also embedded in separated laminate specimens for comparison. These structures were submitted to various mechanical loadings such as in-plane tensile, in-plane tension-tension fatigue, short-beam ([108], [114], [116]) and flexural ([108], [114]) strengths tests to evaluate the intrusiveness of the in-situ PFC sensors. For all manufactured composites, the intrusiveness of flexible PFCs was found minor according to the previously cited mechanical tests (in-plane tensile results for laminate specimens shown in **Figure 28** a and for sandwich specimens in **Figure 28** b), whereas intrusiveness of highly rigid and brittle PZTs was more important. The most intrusive behaviors were found for embedded sandwiches submitted to in-plane tensile tests (7% reduction in ultimate strength and 7.2% in final strain) and for embedded laminates under short-beam shear strength tests, with a 7% strength reduction for PFC-embedded laminate specimens and a 15% reduction for PZT-embedded ones. The authors concluded that PFCs are a better choice than PZTs for embeddable sensors into laminates due to their high flexibility and compatibility with composites.

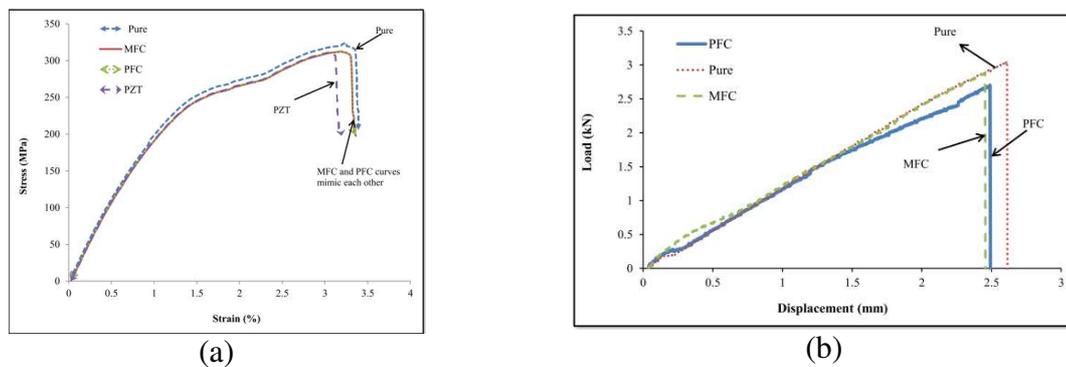


Figure 28. (a) Stress vs. strain response for the laminate specimens – (b) Load vs. displacement response for the sandwich specimens [108]

Stress monitoring was then performed on laminate ([108], [115]) and sandwich ([108], [114]) specimens submitted to tension-tension fatigue (see **Figure 29** a), with PFC capacitance periodic check to verify the sensors were not de-poled. **Figure 29** a shows that with the increase in the input loading comes an increase in the amplitude of PFCs (MFCs) voltage output. Sensitivity analysis of MFC and AFC embedded sensors was also performed, and a linear relationship can be observed between input stress amplitude and sensor voltage output for both laminate (see **Figure 29** b) and sandwich (see **Figure 29** c) specimens. Konka [108] also performed three-points bending tests (see loading on **Figure 29** d) on PFC-embedded laminate, continuously monitoring the response of the embedded sensor (see **Figure 29** e). One can notice that the in-situ sensor is able to detect the slope changes in the flexion loading curve, but unexpectedly lose its signal at point C during load increase. As the sensor was found not to be deteriorated, this event was explained by a delamination appearance at that time, which lowered load transfer from the host material to the sensor and thus make its signal decrease. This sensor output signal was found to be repeatable when loading and unloading continuously in bending the embedded specimens, but within a design load range. If the force exceeded this range (point C in **Figure 29** d), the signals started to become discontinuous and unrepeatable. All these experiments improved in-situ stress/strain monitoring of composite structures using embedded PFCs.

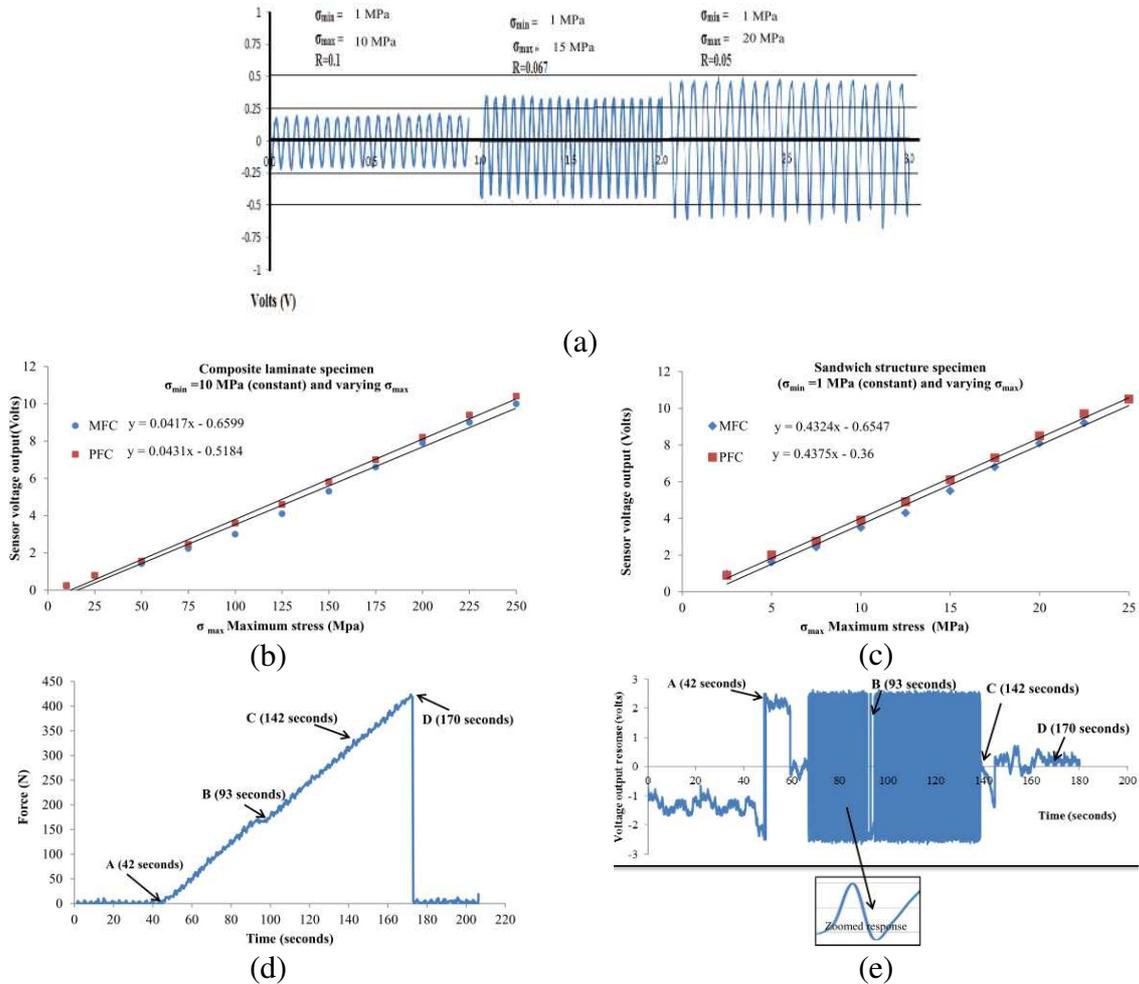


Figure 29. (a) Voltage output response from embedded PFCS (MFC), when the specimen is loaded at different stress ratio – (b) Voltage output response from embedded PFCS (MFC and PFC), when the specimen is loaded at different σ_{max} and maintaining $\sigma_{min} = 10 \text{ MPa}$ (constant) – (c) Voltage output response from embedded PFCS (MFC and PFC), when the specimen is loaded at different σ_{max} and maintaining $\sigma_{min} = 1 \text{ MPa}$ (constant) – (d) Force vs. time curve for the composite laminate sample during the 3-point bend test – (e) Sensor output response recorded during the 3-point bend test [108]

Another kind of device, named PZT sensor-cells network, has been used in research by Hufenbach et al. [117] to perform in-situ electrical measurements of SHM of GF/epoxy composites. The intrusiveness of the cells was investigated by US and optical microscopy on embedded samples, before and after having performed tensile tests on them. It was shown that no significant damage occurred during sensor embedding stage, as well as after tensile testing except small delaminations in the cell zone (see **Figure 30 a**) before sample failure. The total amount of damage for each damage stage was found to be equal for both pristine and embedded samples, and the degradation of mechanical properties (Young modulus, tensile strength) was in a range from 5% to 20% with no impact of the sensor position in the sample thickness direction. Cells were thus not considered too intrusive, having in mind that this intrusiveness would be even lower when going from samples to entire structures. Damage detection using in-situ cells network was performed for various laminate configuration, continuously monitoring strain during tensile loading. **Figure 30 b** and **c** show the cells sensing history (voltage evolution) for two different embedded laminates. The authors were able to make a

correspondence between this sensing history and damage evolution inside the samples, dividing it into three steps: no damage, damage initiation and finally damage propagation with final failure. They remarked that the increase in sensor activity could be regarded as a good indicator for the occurrence of critical damage, making this in-situ technique suitable for SHM of composites.

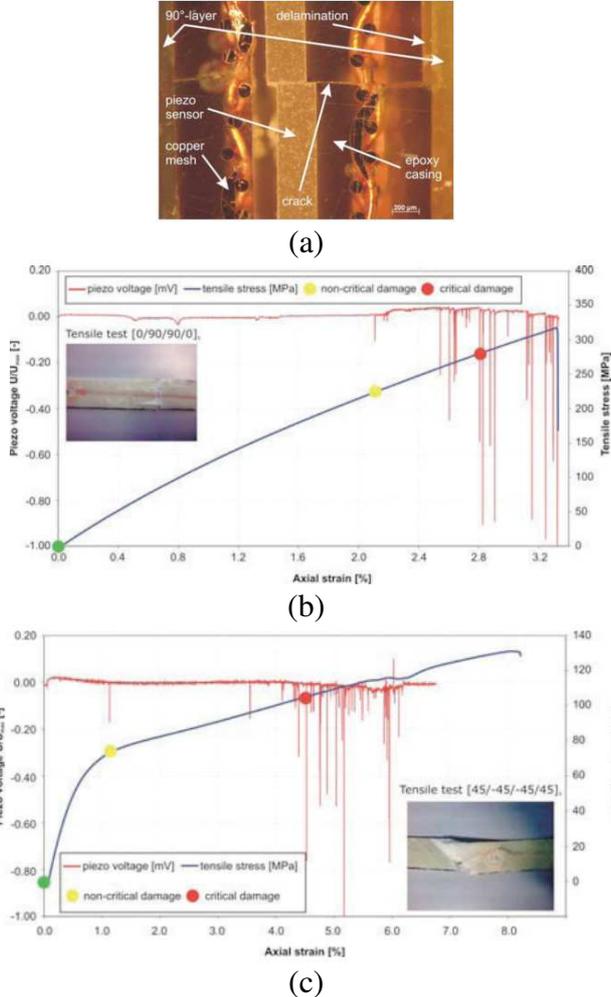


Figure 30. (a) Micrographs of a [0/90]s tensile specimen with the integrated sensor after total failure – (b) Stress-strain curves vs. sensor data of a [0/90]s tensile specimen – (c) Stress-strain curves vs. sensor data of a [±45]s tensile specimen [117]

3.3.2. Impedancemetry

This technique, which deals with the measurement of the electrical impedance of a sensor in order to infer the physical properties of its surrounding medium, is another way to perform in-situ monitoring of composites. Saint-Pierre et al. [118] inserted a piezoceramic PZT disc inside a GF/epoxy material to monitor resin cure during manufacturing and hydrolytic degradation during service life with thanks to impedancemetry. The measurements of the disc electrical impedance (PZT used in passive mode) during manufacturing allowed the authors to compute the velocity of US waves propagating in the media surrounding the PZT as well as their attenuation, giving them information about matrix reticulation. **Figure 31** a shows the evolution of the computed velocities C_L as a function of curing time, and one can observe that the velocities get closer and closer to C_{L0} which is the propagation velocity in the fully cured material. The Barcol hardness measurement performed on the same specimen shew the same trend (see **Figure 31** b), confirming this results. This velocity measurement does not take into

account the fiber amount inside the composite, only giving information about resin curing. The authors submitted their embedded composite sample to hydrolytic degradation (30 days in water at ambient temperature), monitoring the experiment by impedancemetry. The results shew that water absorption induced important variations in electrical impedance (see **Figure 31** c), increasing the US waves velocity computed thanks to these measurements. This increase is attributed to water diffusion into the polymeric network of the resin, which raises its modulus. Impedancemetry has been shown to be applicable for both PM and SHM thanks to these results.

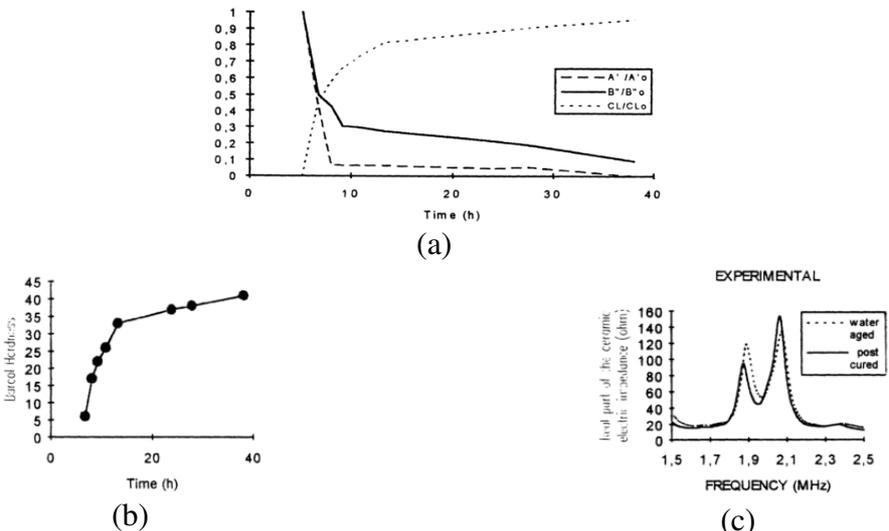


Figure 31. (a) Relative evolution of CL compared to CL0 as a function of curing time – (b) Barcol Hardness evolution as a function of curing time – (c) Real part of the ceramic electric impedance (Ohm) as a function of frequency for water aged (degraded) and post cured (not degraded) samples [118]

3.4.Frequency response & modal analysis monitoring

This technique focuses on the analysis of the frequency domain of the received diagnostic waves traveling inside the composite material, and of their natural modes. Piezoelectric devices are used in both active and passive modes.

Among the related articles, Guzman et al. [119] used an integrated network of PVDF patch transducers to perform in-situ SHM of a wing-like CFRP structure. The PVDFs were embedded on the inner surface of the demonstrator. The network goal is to sense waves propagating in the structure by natural excitation, such as wind, or imposed excitation generated by the PVDFs when a natural excitation source is absent or insufficient. Natural vibration frequencies and mode shapes are then extracted from the sensed waves thanks to modal analysis, and used to infer changes in mechanical properties (ex. stiffness) of the structure. As it exists a quadratic relation between structural stiffness and natural frequencies, stiffness evolution monitoring can be used to infer a structural aging pattern or to detect local damage. After optimal transducer placement inside the demonstrator, realized thanks to an algorithm, two modal analysis were performed and compared. They were Experimental Modal Analysis (EMA) where the excitation/response acquisition was carried out thanks to an impact hammer/accelerometer combination, and Operational Modal Analysis (OMA) with excitation performed naturally (unknown source) with a simulated airstream and sensing done thanks to the in-situ PVDF network. The results shown that EMA and output-only OMA are statistically equivalent, i.e., the mean difference between the natural frequencies measured by the two techniques is low. The authors also shew that a combined excitation of the structure using both the airstream and

PVDFs in actuation mode improved the OMA accuracy. Indeed, their synergistic cooperation allowed the combined OMA to extract natural frequencies closer to the ones found with the reference (EMA), and with a lower standard deviation compared to the individual excitation OMA. This technique could then be used for in-situ SHM of structures. The authors also successfully performed hygrothermal aging monitoring of the demonstrator thanks to the embedded PVDF network.

The use of PFC sensors was also considered as an option. Previously cited Konka [108] and Konka et al ([114], [115]) used their embedded PFCs to realize damage detection on laminates ([108], [115]), see **Figure 32** a) and sandwich ([108], [114]) beams using modal analysis (MA). The sensors were inserted in the middle thickness of the beam for the laminate, and in the bottom face skin for the sandwich. A change in natural frequencies of these beams, extracted from PFCs output signals (see **Figure 32** b for the laminate) with a FFT, can indicate that damage as occurred. Different kinds and quantities of damage were simulated, such as delamination (between layers or between top face skin and core) and cracks, and then monitored with MA. The authors found a correlation between the amount of damage inside the beams, namely the percentage of delamination (see **Figure 32** c for the laminate) and crack length (see **Figure 32** d for the laminate), and the values of the natural frequencies of the beam for the two first modes. Damage can effectively cause changes in dynamic parameters of the beams, and embedded PFCs were able to detect them, which makes these sensors able to perform SHM with MA technique.

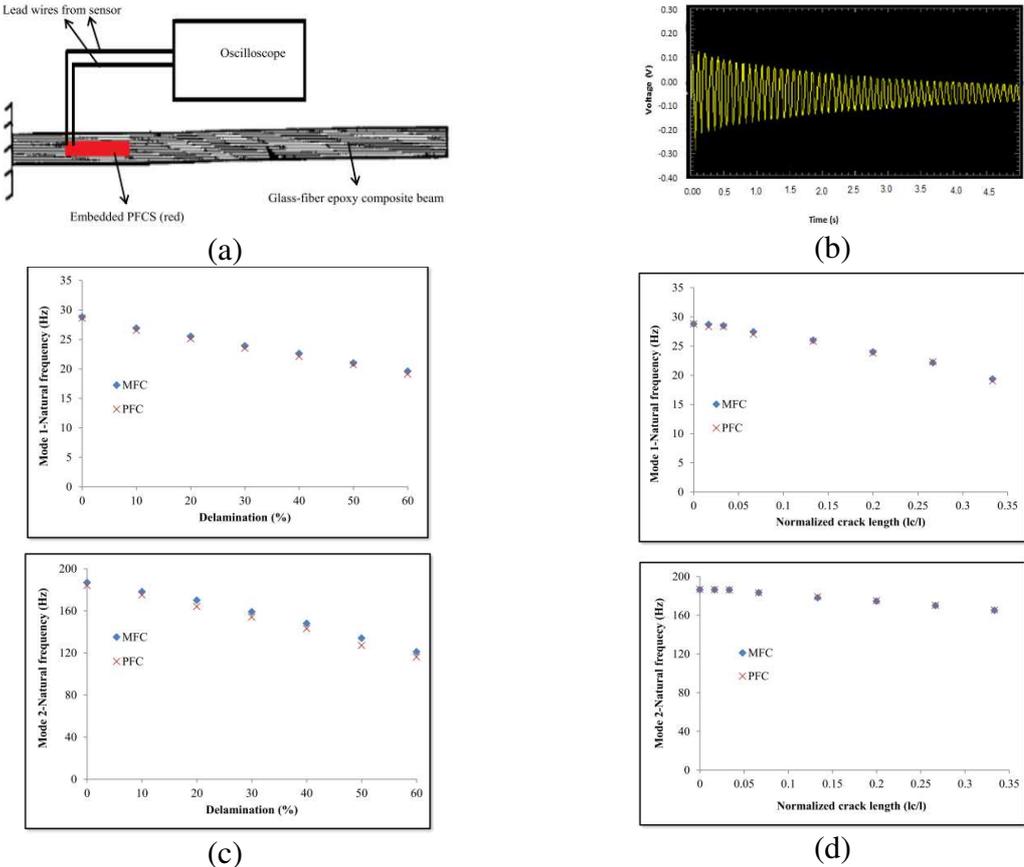


Figure 32. (a) Composite cantilever beam with embedded PFCs – (b) Typical output response of the PFCs (MFC) captured with oscilloscope when the tip of the cantilever is displaced to about 12.7 mm – Changes in the Mode1 and Mode2 natural frequencies of the composite laminate beam with (c) various levels of delamination and (d) cracks of various lengths assessed by the PFCs output response [108]

4. Conclusions & outlook

In this article has been presented a range of techniques, as wide as possible, which are able to perform in-situ PM and SHM for polymer-matrix composite materials. Each of these techniques brings interesting results, and has its own advantages and drawbacks. As authors do not systematically describe these last ones and sometimes only focus on one kind of sensor inside a particular host material, making a detailed comparison of their intrusiveness, sensitivity to damage and reliability is difficult. Some general trends can be reminded yet. First of all, in most of the studies, the used sensors have been considered non-intrusive regarding some of the mechanical properties of the studied materials. Concerning the sensitivity, the general trend shows that in-situ sensors are more sensitive to damage than surface-mounted sensors of the same kind. Finally, reliability has been investigated very little, except fatigue tests done for some configurations which did not show the in-situ sensors to degrade the fatigue properties of the tested specimens. It has also been explained that in-situ PVDFs have a very low intrusiveness. PZTs have also been found more intrusive than PFCs because more rigid and brittle. However, it is important to note that in-situ PZTs have a much more important actuation power than in-situ PVDFs, even if these last ones are considered as very good sensors.

The presented results show it was possible to perform PM and SHM of composite materials thanks to different in-situ piezoelectric devices. However, one must keep in mind that each of these devices used alone cannot provide measurement rich enough to infer with precision the presence, location, amount and nature of damage all at once. That is why multi-technique monitoring is of particular interest nowadays. In-situ piezoelectric devices can be coupled with others, such as IRT, DIC, optical fibers or strain gauges. Chen et al. [120] developed in Stanford a multifunctional stretchable sensor network which fits this objective. This network contains 41 sensors including thermistors, strain gauges and PZT transducers placed on a polymeric substrate (see **Figure 33** a and b). This network has been successfully manufactured, characterized and connected; the next step being its integration inside a composite airplane wing to perform SHM.

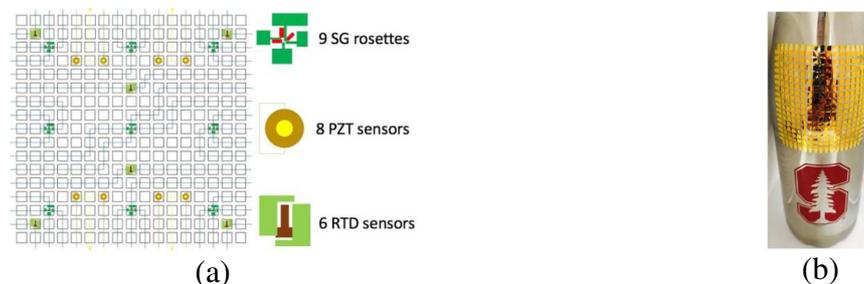


Figure 33. (a) 17 by 17 array of nodes with 9 strain gauge rosettes in matrix, 8 piezoelectric transducers and 6 resistance temperature detectors distributed over the network – (b) A flexible network around an irregular shaped water bottle [120]

As previously said in the introduction part, there is a strong request for real-time in-situ SHM and PM of composite materials. That is why previously described works must be transposed from the “lab” scale to the industrial scale. Some authors like those in the team which developed the SMART Layer have already gone for it, with the corresponding patent currently improved and sold by Acellent Technologies. Many other teams were also thinking about this transition at the end of their papers, giving the potential applications of their smart materials at the “structural” scale and sometimes the corresponding issues which would arise. For SHM, most of the works had for final goal the use of the ‘in-lab’ developed smart composites in the aerospace industry, to perform in-situ real-time SHM of airplanes. The potential issues that could arise from this technology transfer can be numerous. In order not to make mistakes, manufacturers and users should follow a strict approach which could take that form:

- Understanding the potential kind of damages to occur and their possible locations: depends on the kind of composite material the structure is made of, and of the type of mechanical solicitations it will be submitted to during its service life.
- Choosing the type of sensor to embed: can depend on various parameters, such as the nature of composite material (sensor/composite compatibility), the shape of the structure (flexibility of the sensor if complex structure), the size of the structure and the nature of the manufacturing process to obtain the structure.
- Finding the number of sensors: depends on the surface of the structure to monitor and on the ability of them to perform remote sensing inside the chosen composite material with the chosen monitoring technique.
- Choosing the embedding positions of sensors (in 3D): can be a global network, a separated network, or separated sensors. The position will depend on the location of the hot points to monitor, on the positions having to stay pristine (no degradation due to sensor intrusiveness because they 'work' a lot in service),
- Positioning and wiring of the sensors: these two questions have to be thought in a mass production context, to allow ease and fastness in smart parts manufacturing. Manufacturers have to find where the wires will pass, if they are going to cross themselves or not, and where they are going to exit the structure to make information retrieval easy. To do so, the manufacturing process has to be adapted, that is why the question of survival of the transducers to the process conditions remains crucial.
- Retrieving of information during manufacturing thanks to the embedded sensors: to perform in-situ PM, manufacturers have to know the kind of information they want to obtain, and in which way to use my embedded transducers to do so.
- Testing the sensors for manufacturing survivability: a testing procedure has to be implemented to recommend which parameters to test.
- Testing the intrusiveness of the sensors: these tests will show if the sensors location choice was adapted, and if the compromise between mechanical properties degradation and SHM ability is worth it. A testing procedure must also be documented, including tests mimicking as well as possible the in service conditions of the structure.
- Implementing in-situ SHM during service life of the structure: users must find an easy way to retrieve information from the in-situ sensors and exploit them. They have to decide if they want to perform these tasks directly inside the structure in service (if there is permanently operators in it) or if they centralize information in a particular place so that operators can remotely follow the health of the structure.
- Checking the integrity of the network regularly: users have to be sure that the in-situ sensors are still providing reliable information about structural health and are not damaged instead. A way to do so is planning extra out of service inspections which can also serve to inspect the structure by means of external techniques to confirm data transmitted by the in-situ sensors.
- Defining damage thresholds according to the information supplied by the in-situ sensors: users must know when and if the structure has to be repaired or definitively put out of service according to the in-situ measurements.

Embedded transducers can also serve for energy harvesting, vibration control/suppression, environmental conditions recording and so one, according to their nature. The retrieved information about real-time health monitoring can also help designers to work on better and more durable design of components and structures, whether it is airplanes, spacecrafts, buildings or bridges. These new designs can be coupled with the information obtained from in-situ PM to help manufacture the improved parts, as the manufacturing processes are better understood thanks to the data got from the in-situ devices. Smart manufacturing and structures are the future of composite materials in industry, and a lot is still to be discovered on the subject.

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