Structural health monitoring of polymer-matrix composite (PMC) structures using a network of embedded piezoelectric transducers

General context
Polymer-matrix composites (PMCs) are largely used in various industrial fields (aeronautic, aerospace, automotive, railway, pressure vessels, etc.) because they are lightweight materials, resistant to corrosive environments and exhibiting remarkable mechanical and physical properties. However, more than three decades since their appearance, the widespread acceptance of PMCs as a reliable class of engineering materials remains an issue. Their manufacture has several phases; the most critical is the crosslinking of the thermosetting polymer matrices. During this phase, the material changes from a pure dry preform to a rigid state in which the resin polymerization is often accompanied by the appearance of defects in the form of closed porosities whose shape, size and distribution are highly variable depending on the material and manufacturing process. Similarly, a misalignment of fibers in a layer of a laminate will decrease the stiffness in the direction of the uniaxial stress in which the composite was optimized, or a bad stacking of the fibrous reinforcement in a laminate composite may show a higher degree of anisotropy than originally planned. In this context, Non-Destructive Testing and Evaluation (NDT&E) methods have proved invaluable both in detecting the initial defect and monitoring the damage process of PMCs. Recent NDT&E applications for damage monitoring of polymeric materials include the use of non-contact optical or thermal methods, acoustic-based techniques, as well as electrical potential/resistance approaches. Although such efforts have had some success in characterizing the damage behavior of composite materials, a complete NDT&E approach which could effectively and reliably track and quantify both damage initiation and subsequent damage evolution is needed. In fact, a commonly encountered difficulty in the NDT&E domain is the lack of a reference method that would be able to unambiguously evaluate total damage developed in a composite material under mechanical loading, where the damage phenomenon is very complex. Indeed, damage occurs within the material (internal defects), from different sources and with an anisotropic distribution according to the material architecture and the manufacturing process. Likewise, all conventional NDT&E techniques, in particular, acoustic emission (AE), infrared thermography (IRT), ultrasound (US), are based on surface instrumentation: the transducers are conventionally glued to the material or placed at a well-determined distance with remote electronics. In addition, only a few techniques are capable of monitoring damage in real-time, with specific constraints: no accessibility to the hottest and/or loaded areas, coupling problem for the US in contact, dramatic drop in the ratio signal/noise due to the unsuitability of the impedances for the US generated in the air, etc.

Methodology
In order to overcome these difficulties, and drawing inspiration from the human nervous system which is a set of interconnected entities transmitting information to the different organs, we propose during this study to instrument PMCs, as soon as they are implemented, by very fine piezoelectric sensors (Lead Zirconate Titanate LZT or PZT and/or PolyVinylidene Fluoride PVDF) in order to develop intelligent PMC structures (plates, stiffeners, omegas, etc.), searchable, and carrying information (Figure 1). These sensors, embedded in the PMC materials, can form a planar (distributed over the entire length of the structure) or through-the-thickness networks. They can operate in passive mode as AE sensors, or active form as generators of ultrasonic waves (Lamb waves) and planar capacitors. Therefore, the piezoelectric transducers will be sensitive to the different phases of crosslinking of the polymer matrix during the manufacture of the PMC structures by infusion or RTM (Resin transfer molding), which allows monitoring of the manufacturing process: Process monitoring (PM). Once the PMC
structure is mechanically loaded statically or dynamically (tensile, bending and fatigue tests),
damage can manifest itself in four main forms: matrix cracking, interfacial debonding between
fibers and their polymer matrix, fiber breakage and delamination between layers. These damage
mechanisms will be revealed, in real-time and in-situ, by the piezoelectric sensors integrated
into the heart of the fibrous material: Structural Health Monitoring. These damage signatures
will be compared with others coming from the conventional NDT&E techniques (AE, IRT, US)
instrumented on the structure surface. A coupling between internal (from piezoelectric sensors
inside of the PMC material) and external (from the outside sensors used for AE, IRT and US)
signatures will be established and will require the use of heterogeneous data processing
methods. To do this, we will apply the classification methods, as k-means and neural networks
methods, and the theories of data fusion, which will make the conclusion of this study.

*Figure 1: Development of intelligent materials for the high-tech structures by inspiration of
the human nervous system*

**Keywords:** Polymer-matrix composites (PMCs); Piezoelectric transducers; Intelligent
materials; Process Monitoring (PM); Damage; Non-destructive Testing & Evaluation
(NDT&E); Data classification & fusion; Structural Health Monitoring (SHM).

**Host laboratory:** Roberval (Mechanics, energy and electricity)
The Roberval Laboratory (research unit in mechanics, energy and electricity - FRE UTC-CNRS
2012) positions itself on the design of innovative mechanical / multi-physical components and
systems, by proposing to carry out scientific and technological research work in an
interdisciplinary context, a necessary condition for the design and study of the behavior and
sustainability of complex systems. In particular, the Unit makes a fundamental contribution to
defining a framework for the study of these complex systems (choice between systemic or
mechanistic approach; choice of relevant scales for the study of variability; ...).

**Research team:** Materials & Surfaces

**Skills areas:** Engineering science; Mechatronics; Computer science; Electronic.

**Working modalities**
After a doctoral student training phase, very regular meetings will be organized during the thesis
duration.

**Material resources**
Experimental platform of the “Materials and Surfaces” unit research of Roberval laboratory
using the multi-instrumentation approach (AE, DIC, IRT, video-microscopy, testing machines,
electrical measurement means ...).
Co-direction
This thesis is co-directed by:

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