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: <u>Process monitoring (PM)</u>. 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:

Walid HARIZI	**Zoheir ABOURA**
Associate professor Université de Technologie de Compiègne Roberval laboratory CS 60319, 60203 Compiègne Cedex Phone: +33 (0)3 44 23 46 23 E-mail: walid.harizi@utc.fr https://www.researchgate.net/profile/Walid_Harizi	Professor Université de Technologie de Compiègne Roberval laboratory CS 60319, 60203 Compiègne Cedex E-mail: zoheir.aboura@utc.fr https://www.researchgate.net/profile/Zoheir_Aboura

References

C.Tuloup, W. Harizi, Z. Aboura, Y.Meyer, B. Ade, K. Khellil. ***"Detection of the key steps during Liquid Resin Infusion manufacturing of a polymer-matrix composite using an in-situ piezoelectric sensor"***. March 2020. Materials Today. DOI:10.1016/j.mtcomm.2020.101077.

C. Tuloup, W. Harizi, Z. Aboura, Y. Meyer, K. Khellil, R. Lachat. **"*On the use of in-situ piezoelectric sensors for the manufacturing and structural health monitoring of polymer-matrix composites: A literature review"***. Composite Structures vol. 215, pp. 127–149, 2019.

C. Tuloup, W. Harizi, Z. Aboura, Y. Meyer, K. Khellil and R. Lachat. **"*On the manufacturing, integration, and wiring techniques of in situ piezoelectric devices for the manufacturing and structural health monitoring of polymer–matrix composites: A literature review"***. Journal of Intelligent Material Systems and Structures 30(16), pp. 2351-2381, 2019.

C. Tuloup, W. Harizi, Z. Aboura and Y. Meyer. ***"Real-time monitoring of the infusion process of a polymer-matrix composite with an embedded piezoelectric transducer"***. SMART 2019: IX ECCOMAS Thematic Conference on Smart Structures and Materials. Paris, France. July 2019.

C. Tuloup, W. Harizi, Z. Aboura and Y. Meyer. ***"Structural health monitoring of smart polymer-matrix composite during cyclic loading using an in-situ piezoelectric sensor"***. ICCM22: 22nd International Conference on Composite Materials (ICCM22). Melbourne, Australia. August 2019.

Chaki, S., Harizi, W., Bourse, G., Ourak, M. ***"Multi-technique approach for non-destructive diagnostic of structural composite materials using bulk ultrasonic waves, guided waves, acoustic emission and infrared thermography"***. Composites Part A, Volume 78, 10 November 2015, pages 358-361.