Structural health monitoring of polymer-matrix composites (PMCs) using embedded piezoelectric transducers: experimental and numerical approaches

General context

Polymer-matrix composite (PMC) materials are nowadays an exciting alternative to metallic materials conventionally used in the industry. They bring many structural and functional advantages: mechanical resistance, lightness, electrical insulation and freedom of forms. Their growth is mainly linked to the development of the transport industry: aeronautics, aerospace, rail, naval and automotive. However, due to their heterogeneous, anisotropic and multilayer structure, the damage of PMCs under mechanical stresses is a fairly complex phenomenon whose experimental characterization is far from being mastered despite the abundance of research work carried out on the subject since now a few years. Indeed, the nature of the damage and the mechanisms behind its appearance and propagation are very different from those encountered in metallic materials. Thus, depending on the considered scale, damage such as rupture of the reinforcement, matrix cracking, interfacial debonding, or even delamination can be the cause of the premature failure of a PMC structure.

The complexity of this phenomenon and the absence of a “reference” characterization method, applying both at the laboratory stage for the R&D aspect and in-situ for the monitoring and health control aspects of the structures (SHM: Structural Health Monitoring), motivate the positioning of this study in the field of non-destructive characterization of the damage of composite materials. Nevertheless, all conventional Non-Destructive Testing & Evaluation (NDT&E) methods, in particular, acoustic emission (AE), infrared thermography (IRT), ultrasound (US) are based on surface instrumentation: the transducers are conventionally glued to the surface of the material or placed at a distance well determined with remote electronics. Likewise, only a few NDT&E techniques are able of monitoring damage in real-time, with specific technology constraints: no accessibility to the hottest and/or loaded areas, coupling problem for the US in contact, the dramatic drop in the ratio signal/noise due to the unsuitability of the impedances for the generated US in the air, etc.

Methodology

In order to overcome these constraints, the solution is to integrate, from the manufacturing stage, piezoelectric transducers inside the material and thus develop smart searchable composite structures. The main objective of this thesis would be to instrument PMC structures with a network of piezoelectric sensors (Lead Zirconate Titanate LZT or PZT and/or PolyVinylidene Fluoride PVDF) to monitor their health state in real-time during their lifespan. These sensors can be used in passive (as acoustic emission sensors or planar capacitors) or active modes (Lamb wave generators).

The scientific and technological challenges to develop the SHM of composite structures are very numerous. These include:

- The integration of sensors in a fibrous environment: what about intrusiveness?
- Relationship between the physical phenomena due to damage and the response of the PZT sensors integrated within the material?

☞ In the case of a complex PMC structure, the positioning choice of the sensors related to the damage to be detected?

The design of health monitoring systems for composite structures, based on embedded piezoelectric sensors, requires the use of numerical tools able to deal with the complex mechanics of layered materials, as well as, multifield problems. Classical Finite Element Models have been proved to be inaccurate in the analysis of layered structures and extremely computationally expensive when high accuracy, obtained using three-dimensional elements, is required. A new generation of numerical models is thus required to predict/detect the failure of composite materials. These models must ensure the following capabilities:

1) **Three-dimensional stress field prediction**. The actual numerical tools are mainly based on classical structural models, that is, when two-dimensional models are considered, through-the-thickness stresses are neglected even though they play a crucial role in the failure mechanics, e.g., in the delamination.
2) **Stress concentrations**. The use of embedded sensors leads to local stress concentrations at the interface between the active material and the structure. These stress concentrations make the sensor a possible source of failure itself.
3) **Multifield capabilities**. The simulation of the piezoelectric actuator/system requires to extend the analysis at the electric field and to predict its interaction with the mechanical one. A fully coupled electro-mechanical formulation must be used to predict the electrical response that comes from a deformation of the structure.
4) **Numerical efficiency**. The requirements at points 1 to 3 can nowadays be fulfilled using three-dimensional classical finite elements. At the same time, the high computational cost of solid elements makes their use unpractical for real structures and is relegated to the study of coupons or specimens.

The development of a new family of numerical tools able to deal with the points listed above requires switching from classical to advanced models. The **Carrera Unified Formulation** (CHF) provides a numerical tool to generate refined kinematic models with an arbitrary level of accuracy. The use of refined kinematic models leads to the prediction of complex displacement/stress fields. The following features of the **CUF** could be exploited to address the problem:

- **Equivalent Single Layer (ELS) VS Layer-Wise (LW) models**. The use of different kinematic models makes it possible to consider a layered structure as an equivalent laminate (ESL) or, eventually, each lamina can be considered as an independent entity (LW). Layer-wise models can be used to predict accurate three-dimensional stress fields, including the interlaminar stress that causes delamination.
- **Global-to-local models**. The efficiency of the numerical models can be increased using refined kinematic models only in those areas where complex stress fields are expected to reduce the computational costs using classical models elsewhere. The local refinement of the model can be achieved using the Node-dependent kinematic approach, recently developed in the CUF framework, and the multi-dimensional approach where 1D, 2D and 3D elements can be connected exploiting models with compatible kinematics.

- **Multifield models**. Refined kinematic elements have been successfully used in the solution of electro-mechanical problems. The use of advanced models and three-dimensional constitutive equations provide a 3D solution in both sensor/actuator cases.

Keywords: Polymer-matrix composites (PMCs); Piezoelectric transducers; Intelligent materials; Damage; SHM; NDT&E; Carrera Unified Formulation; Multifield models.

Host laboratories: The thesis will be conducted between the Roberval laboratory of "Université de Technologie de Compiègne" - France and Mul2 Research Group of Aerospace Engineering Department of "Politecnico di Torino" - Italy.

Material means: Experimental platform of the "Materials and Surfaces" team research of Roberval laboratory using the multi-instrumentation approach (AE, DIC, IRT, video-microscopy, testing machines, electrical measurement means ...) & Equipment of modeling and numerical simulation at the Polytechnic School of Turin.

Co-direction

This thesis is co-directed by:

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Required Skills: Looking for an engineer level student (bac + 5) or master 2, with strong scientific skills in the science of materials, composite materials, NDT&E methods and above all good skills in modeling and numerical simulation by finite element method.

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Please contact first the thesis supervisors before applying online on:
https://webapplis.utc.fr/admissions/doctorants/accueil.jsf

References

Carrera E., Cinefra M., Petrolo M., Zappino E. **"Finite Element Analysis of Structures Through Unified Formulation"**, 2014, John Wiley &Sons, Chichester, West Sussex.

Carrera E. **"Multilayered Shell Theories Accounting for Layer-wise Mixed Description, Part 1: Governing Equations"**, 1999, AIAA Journal, Vol. 37(9), pp. 1107-1116.

Zappino E., Li G., Pagani A., Carrera E. **"Global-local analysis of laminated plates by node-dependent kinematic finite elements with variable ESL/LW capabilities"**, 2017, Composite Structures, 172, pp. 1–14.

Zappino E., Carrera E. **"Multidimensional Model for the Stress Analysis of Reinforced Shell Structures"**, 2018, AIAA Journal, 56(4), pp 1647-1661.

Carrera E., Zappino E., Li G. **"Analysis of beams with piezo-patches by node-dependent kinematic finite element method models"**, 2018, Journal of Intelligent Material Systems and Structures, 29 (7), pp. 1379-1393. DOI: 10.1177/1045389X17733332.

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.