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Nina Kergosien, Ludovic Gavérina, Guillemette Ribay, Florence Saffar, Pierre Beauchêne, et al.. Optimization of a Structural Health Monitoring systems integration in laminated composite cured in autoclave. IWSHM 2021 - 13th International Workshop on Structural Health Monitoring, Mar 2022, Stanford, United States. 10.12783/shm2021/36271 . hal-03772212

HAL Id: hal-03772212

<https://hal.science/hal-03772212>

Submitted on 8 Sep 2022

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Title: Optimization of a Structural Health Monitoring systems integration in laminated composite cured in autoclave

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ABSTRACT

Composites represent approximately 50% of the weight of structural parts in new aircraft as Airbus 350 or Boeing 787. Damages could occur on these parts and their monitoring is required for the safety of users. A Structural Health Monitoring system composed by a Lamb's waves generator and a sensor is a privileged candidate to detect such damages. The flexibility of composite manufacturing allows the integration of such a system. The topic of this study is to optimize the integration of a Structural Health Monitoring system in aircraft structural parts.

The present article focuses on the optimization of the integration method of a piezoelectric Lead Zirconate Titanate transducer into laminated composite (Carbon/Epoxy), cured in autoclave according to aircraft manufacturing requirements. The health state of the integrated transducer with three connecting methods is evaluated using X-ray scanning. Punctual stress is responsible for the crack of the transducer occurred during composite curing. The connecting method with aluminum sheet and silver joint is selected because it minimizes local stresses and keeps the transducer integrity. The cohesion between the integrated transducer and the host material is observed by optical microscopy, it shows the presence of void zones located in the PZT edges. A Laser Doppler Vibrometer scanning shows the ability of the integrated piezoelectric transducer to generate Lamb waves.

INTRODUCTION

To reduce the cost of inspection, it is possible to use a Structural Health Monitoring (SHM) system, which is used as an alert system to initiate a maintenance operation. Indeed, SHM systems would allow establishing a diagnosis of the health state of aircrafts.

The aimed materials are composites, which are increasingly used in aircrafts to optimize their design, with the curing of complex structures and consequently the reduction of the number of parts. Composite materials give the possibility to integrate a monitoring system into the material. The integration allows protecting the system from

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external environment [1], avoiding bonding problems [2], monitoring the manufacturing process [3][4], providing data regarding possible damages in structures that are not accessible to standard Non-Destructive Inspections (NDI) and enhancing the wave detection by a better coupling between transducer and composite material [5].

Hence, the aim of this study is to integrate a SHM system into laminated composite aircraft structures, designed to detect damage or defect while minimally altering their nominal mechanical properties. In the case of defects detection, SHM system must include at least a wave generator and a sensor.

The integration requires minimizing transducer intrusivity and materials properties reduction, preserving the transducer integrity and limiting variation of transducer properties. The transducer integrity depends on its resilience to the temperature and pressure level required for structural piece manufacturing. Namely, the pressure level required of this type of composite during the curing is 0.7 MPa, a lower pressure may induce a too high porosity rate for structural application [6].

A piezoelectric Lead Zirconate Titanate (PZT) compatible with the curing parameters (180°C and 0.7 MPa) is selected for this work. The PZT transducer is chosen because of its capacity of resilience to thermal curing parameter [7], [8], its ability to generate Lamb waves in the structure as an actuator and its capability to detect guided waves and their interaction with possible defects, as a sensor. Moreover, this choice is motivated by the existence of a similar integration in the literature: Andreades and *al.* study [9]. Their work consists of a PZT integration into laminated composite, on the same basis of components and condition of composite curing than this present study. The addition of the present study is the analysis of the health state after curing of the integrated transducer, of the coupling between transducer/composite, and of the change on the surface/integrated transduction, with multiple methods.

Firstly, the material and curing process are presented to introduce the common parameters of the curing in aeronautic domain. The integration method must be adapted to preserve the integrity of the transducer. Thus, three methods of integration are tested: the first one with (i) tin soldering and copper wires, the second one with (ii) silver soldering and copper wires and the last one with (iii) silver soldering and aluminum sheet. Then the results of X-rays scanning and optical microscopy observation are presented, the former aiming at checking the physical integrity of the PZT and the latter aiming at checking the cohesion between transducer and composite. Finally, Laser Doppler Vibrometer (LDV) scanning are presented to checking the PZT capability to generate Lamb waves.

COMPOSITE MANUFACTURING

Three integration methods are tested with autoclave curing. The laminate is put under a vacuum bag and an additive pressure is applied in the autoclave chamber. The temperature is applied by convection. The carbon/epoxy composite T700/M21, produced by Hexcel [6], is selected in the form of unidirectional prepregs. The stacking is [0,90,0,90,0]_s. The final composite plate is around 2.6 mm-thick. The PZT transducer is positioned between the 2nd and 3rd ply. A picture of the experimental set-up in the autoclave chamber and an example of stacking is presented in Figure 1.

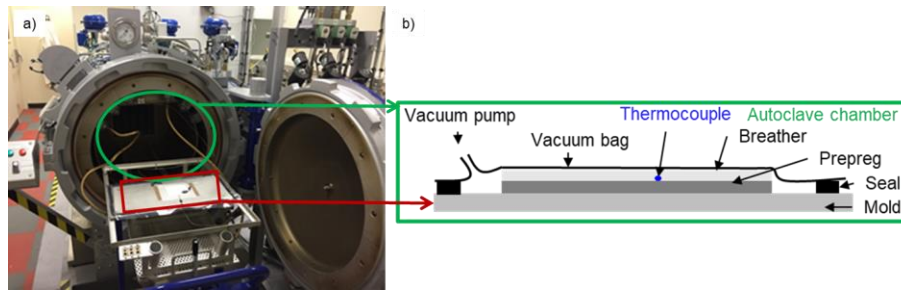


Figure 1. a) Autoclave and b) Schematic draping

The elaboration cycle is made of one first temperature plateau at 130°C during 1 hour to improve the evacuation of porosity and a second temperature plateau at 180°C during 1 hour [6]. Two pressures of curing are used: 0.7 MPa (industrial curing) and 0.3 MPa. The two cycles (temperature and pressure) are presented in Figure 2 (in the case of 0.7 MPa).

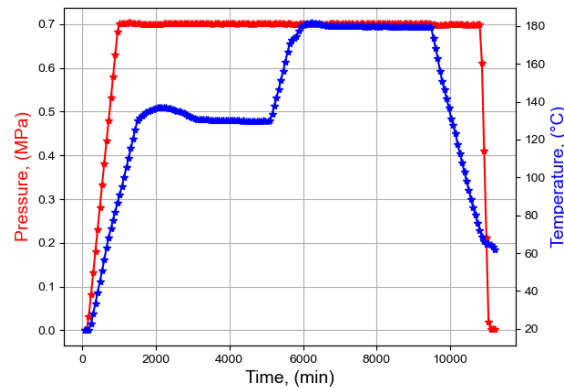


Figure 2. Temperature and pressure (0.7 MPa) curing

TRANSDUCER INTEGRATION

The first connecting method (i) as shown in Figure 3, consists in soldering PZT electrode and copper wire with tin. The PZT has 10 mm diameter and a 0.2 mm thickness, and wrapped electrode. The solders joints are handmade and are between 1 and 2 mm-thick. The wires diameter is 160 μm including polyurethane varnish coating. Transducers with wires welding can be found off-the-shelf, but wires have large diameter and their coatings do not withstand manufacturing temperature. Nevertheless, an advantage of the welding in commerce is the thickness of around 0.5 mm. The first experiments were done with this method with a 0.7 MPa pressure applied during the manufacturing cycle.

The second connecting method (ii) as shown in Figure 3, consists in soldering PZT electrode and the copper wire with silver paint. A new geometry of PZT without wrapped electrode is chosen. This geometry allows the electrodes to be isolated from each other in the case of contact with composite carbon fiber. The PZT has a 7 mm-wide diameter and is 0.2 mm-thick. The thickness of the solder joint is around 0.5 mm, namely the same order as off-the-shelf ones. For the application of this method, the

manufacturing pressure is reduced to 0.3 MPa. If this method gives satisfying results, the pressure level will be increased to an adapted pressure manufacturing.

The third method (iii) as shown in Figure 3, consists in soldering PZT electrode and an aluminum sheet of 15 μm thickness with silver paint. The PZT diameter is 7 mm and it is 0.2 mm-thick. The thickness of the solder joint is around 0.08 mm. Both pressure levels (0.3 and 0.7 MPa) are applied with this soldering method.

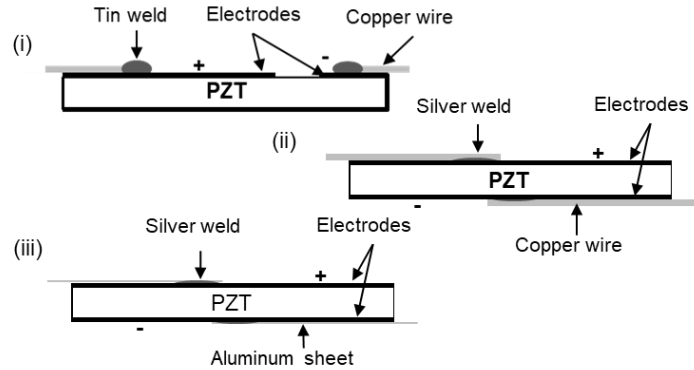


Figure 3. (i) PZT with wrap electrode (black) with tin weld (dark grey) and copper wire (light grey) – (ii) PZT (black) with silver weld (dark grey) and copper wire (light grey) – (iii) PZT (black) with silver weld (dark grey) and aluminum sheet (light grey) - sketch not to scale

Effect of the transducer integration

In this section, the performance of the three integration methods are tested. The first controlled parameter is the physical integrity of the transducer. For this purpose, a NDT method as X-ray scanning is used to visualize the integrated transducer. Then the cohesion between PZT transducer and laminated composite is observed with microscopy. Finally, a verification with LDV scanning is made to check the ability of the integrated PZT to generate acoustic waves.

Radiography inspection

A X-ray scanning allows visualizing potential PZT cracks. Figure 4 presents two integrated PZT after the second connecting methods with 0.3 MPa of manufacturing pressure (ii) and the third connecting methods with 0.7 MPa of manufacturing pressure (iii).

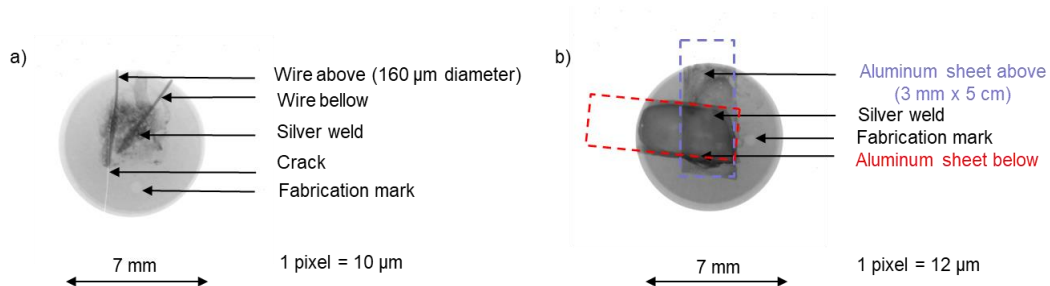


Figure 4. X-rays of the integrated PZT a) The PZT cracks with the second connecting method (0.3 MPa) , b) The PZT is uncracked with the third (iii) connecting method (0.7 MPa)

With the tin welds and copper wires connecting method, multiple cracks centered on the soldering location are previously observed but not presented in this article. The effect of the pressure (0.7 MPa in this case) on the punctual solder joint creates a stress concentration zone, leading to breakage of the PZT.

With the silver welds and copper wires connecting method, the radiographic picture presents a crack along the cooper wire. The diameter of 160 μm is also too large and induces a localized pressure on the PZT, even with a reduced curing industrial pressure of 0.3 MPa. The radiographic picture also shows the X-ray scanning method ability to detect cracks (see a) in Figure 4).

With the silver welds and aluminum sheets connecting method (see b) in Figure 4), no crack is observed on the radiographic picture. Finally, the thickness and the repartition of the soldering permit to preserve the integrated PZT integrity, with the curing industrial pressure of 0.7 MPa.

Microscopic observation

The goal of this microscopic observation is to analyze the cohesion between the PZT and the laminated composite for a high transfer of PZT effort. A cut is realized on the integrated PZT with the third method of integration and a curing of 0.3 MPa. The cutting procedure and orientation observation is presented in Figure 5-a), the microscopic observation is presented in Figure 5-b).

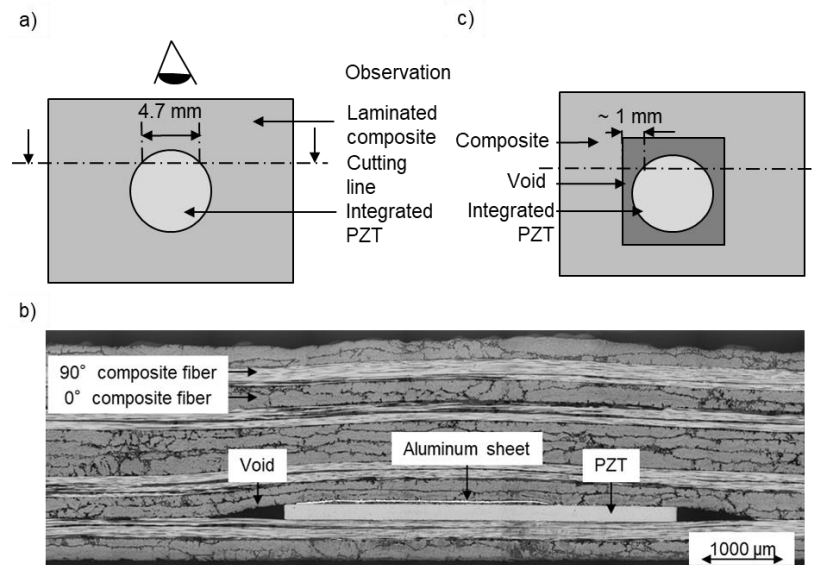


Figure 5. a) Observation configuration b) Microscopy picture along the cutting line and c) Schematic of the gap surrounding the integrated PZT

The microscopic picture shows voids around PZT, whose length is around 1 mm and no delamination generated by the integration. This observation allows estimate the void gap surrounding the integrated PZT with the schematic of the Figure 5-c). The application of the industrial pressure of 0.7 MPa could reduce voids around PZT. With this future characterization, the PZT and laminated composite coupling and the integrated PZT Lamb waves generation capability could be linked.

Lamb waves generation with integrated PZT

A Laser Doppler Vibrometer allows recording the out-of-plane vibration velocity when the integrated PZT generates Lamb waves. A chirp signal with frequency ranging from 20 kHz to 200 kHz is generated by the integrated PZT with a peak to peak amplitude of 10 V. A 10 cm x 10 cm area, is scanned with a step of 2 mm, with the integrated PZT in its center. This controlled is made with the third connecting method with curing pressure of 0.7 MPa. Scanning Laser Doppler Vibrometer images of the Lamb wave propagation are presented in Figure 6. The images of displacement are displayed in nm.

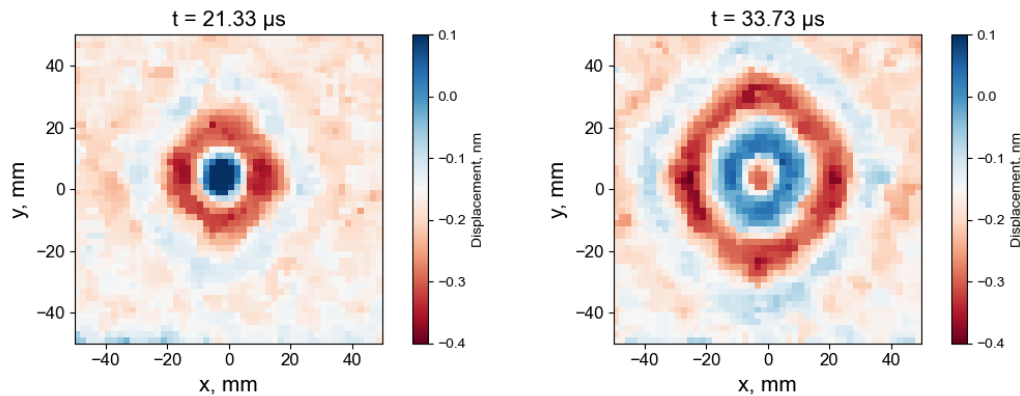


Figure 6. Two times scanning of plate with integrated PZT with the third connecting method and 0,7 MPa of manufacturing pressure (displacement in nm)

According to the results of LDV scanning acquisition, an anisotropic propagation is observed, confirming that the integrated PZT is likely intact and able to generate Lamb waves. In future work, the mode of Lamb wave and the directional effect of composite could be deduced from these measurements, and the amplitude of the transmitted wave could be compared to that transmitted by a surface bonded PZT.

CONCLUSION AND PERSPECTIVES

The first results of this work in progress show that the third method of integration, which consists in using aluminum sheet with silver joint is conclusive to avoid crack in the integrated PZT. In fact, the thickness of the solder joint and the stresses distribution on the PZT obtained with this method make it the best solution for an integration in autoclave with 0.7 MPa of structural laminate composite curing pressure. According to LDV scanning, the integrated PZT transducer is able to generate and transmit Lamb waves in the laminated composite.

Future research will focus on Lamb waves generation and emission comparison between integrated and surface mounted PZT transducer. This transduction will be characterized. The PZT and laminated composite coupling will be studied and linked with integrated PZT Lamb waves generation capability. Depending on the future characterization results, the integration method could be improved.

In regards to the literature about the properties weakening of the composite with a PZT integration transducer, a smaller sensor than PZT sensor could be integrated. For this purpose, further work will consist in integrating Fiber Bragg Grating (FBG) sensor in the laminate, with the possibility to multiply their number them into the structure with the same manufacturing parameters. The final goal is to constitute a hybrid SHM system: PZT transducer could be used as a transmitter and FBG as a receiver, for defect inspection.

ACKNOWLEDGEMENT

This thesis researches were supported by a technical collaboration between ONERA and CEA. The authors would like to thank Caroline Vienne (Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France), with whom the radiographic pictures are taken and Philippe Nunez (DMAS, ONERA, Université Paris-Saclay, F-92322, Châtillon, France), who cut and prepare sample for microscopic observations.

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