Embedded Piezoelectric Sensors and Actuators for Control of Active Composite Structures

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Abstract

This paper illustrates the results obtained at Composite and Smart Materials Laboratory of Politecnico di Milano by an industrial-academic team, that designed, developed and produced a technological demonstrator for space structures, embedding piezoelectric sensors/actuators and optical sensors. The selection of optical sensors, the use of PZT material, and their embedding techniques into composite laminates are described in the following, as well as embedding a sensing/actuation pack, i.e. robust and easy to handle sensor\actuator unit, in the demonstrator structure. Finally, actuation/sensing capability have been tested to validate both the embedded sensors/actuators and the technologies adopted for the manufacturing process.

Introduction

The development of light-weight, robust and stiff structures is the main aim of the designer of aerospace systems. The large number of new materials and technologies made available in the last years, from micro electronic devices to innovative materials (such as shape memory alloys, piezo-ceramics, electro active polymers and so on), allows to predict the application of smart materials in many aerospace and ground commercial applications, such as shape and vibration control of large space structures, acoustic control for noise reduction in civil aircraft, health monitoring and in-site structure identification. In the field of smart structures, piezoelectric sensors/actuators and fibre optic sensors are widely know and their technology readiness allow to test their capabilities in many applications [1,3,4,9]. Nevertheless, the manufacturing technique to embed active components within the load-carrying structure is still a leading edge application. Advantages that could derive from having both actuators and sensors embedded into the structures, rather than bonded to the outer skin, are:

- actuation in spots hardly accessible from outside because of shapes ties;
- protection of actuation system inside host structure, sheltered from all atmospheric agents that could reduce its performances;
- use of active structures even in those cases where the need of a clean surface forbids the adoption of external devices;
- better performances in actuation (for embedded plates, compared to external ones, an increase of 27% in axial tensile and 40% in bending can be obtained).

For many years experimental research at Composite and Smart Materials Laboratory of Politecnico di Milano was carried on for embedding micro-actuators or sensors into composite laminates (in particular composites with shape memory alloys NiTiNOL wires, piezo-polymeric films, optical fibres, piezo-ceramic plates and fibres).

The technological demonstrator described in this paper was produced by an industrial-academic team (Politecnico di Milano, CGSpace, JRC - European Commission Joint Research Centre of Ispra) for the European Space Agency (ESA): it consists in a smart structure made of a carbon/epoxy laminate with piezoelectric actuators and sensors and fibre optic sensors embedded.

The baseline geometry of such a breadboard refers to the Hypseo satellite momentum wheel support frame, where a higher level of damping is required to control the wheel-induced vibration disturbances, and cannot be achieved by passive devices. This application was suggested by specific requirements issued by the industrial partner, within the frame of small satellites design and performance optimization, but it potentially represents the first step toward general applications, where a structure is controlled when subject to a vibration source.

The breadboard was manufactured on the basis of the main existing technologies developed for manufacturing piezoelectric materials, as well as for embedding transduction and actuation devices into composite materials.

Generalities on composites smart materials

One structure may be defined “intelligent” if it is able to monitor the operating environment, to gather and explain information and then react suitably. To accomplish these tasks, the structure must be equipped with a sensor set, an acquisition and elaboration data system and an actuation system. Sensors have to monitor the structure response and provide useful system-state readings. Particularly, mechanical (loads, strains, vibrations, etc.), thermal (thermal gradients acting on the structures) and chemical measuring (for the analysis of the corrosion and the erosion) should be carried out. The acquisition and elaboration system should include two main blocks: the elaboration block that analyses, correctly and quickly, input data from the sensors system, reducing them to a suitable size; the control block that, knowing the ideal behaviour of the structure, gives controls to the actuators system. Finally, the actuation system aims to suite structure characteristics to inputs.

The concept of actuation is associated to the capability of controlled energy absorption or release. In any case, the actuation of the structure should minimize unusual load condition effects to reduce fatigue phenomena and compensating heavy local conditions.

Ideal sensors and actuators should be as light as possible, not much intrusive and must have the less possible effect on the dynamics of the system. They both should be bonded to the surface or embedded into the structure, discrete or distributed-way and they should be designed to cooperate with the structure to resist to its loads.

Intelligent structures design should even consider the coexistence of sensors and actuators with the others basic elements of the structure. A typical problem for embedded components concerns the possible incompatibility among their characteristic pressure or temperature levels and the manufacturing ones of the host material. Polymerization temperature of composite materials resins, for example, is normally higher than activation ones for NiTiNOL wires or Curie one of many piezos.

Host materials, Actuators, Sensors

The host material is composed of different layers of composite (CFRP and GFPR) while the actuators are made of PZT plates. The sensors consist of PZT plates and optical fibres (FBGS). The following subsystems can be identified.

Host material/structure

Among the composite materials, the carbon fibre (CFRP) is the most suited for space environment and has a wide use in structural space application. Unfortunately, it cannot be used in direct contact with piezoelectric actuators because of its electrical conductivity that could induce a short circuit. To avoid such a problem, glass fibre (GFRP) can be conveniently used to isolate the electric elements from the CFRP. For this reason composite layers are been made by GFRP and CFRP fabric prepreg. The data of the characterization tests related to the selected composite material are reported in the following table (Table 1).

	CarbonFRP	**GlassFRP**
Name	CYCOM 950	SEAL EE106
Nominal thickness (pre-curing) [mm]	0.30	0.14
Real thickness (post-curing) [mm]	0.25	0.11
E [GPa]	71	22
ν	0.034	0.13
Curing temperature [°C]	121	125
Curing pressare [atm]	3	3.5

Table 1: CFRP and GFRP mechanical data.

PZT actuators/sensors

Several piezoelectric materials and shapes are suitable for integration and actuation-sensing properties when integrated in a host composite structure. Piezoelectric plate actuators are chosen in compliancy with the development of procedures for their embedment into laminate structures. Two possibilities are theoretically available: piezoelectric fibres or piezo patches can be used.

Fibres would offer the advantage of an anisotropic actuation, since they would act only in the axial direction, and, if conveniently poled, they would use the "d33" effect. By contrast, not perfect fibres alignment would heavily influence their actuation performances.

The piezo plates should possess the following characteristics:

- piezoelectric constants as high as possible;
- Curie temperature higher than temperatures achieved during operational life and, above all, during the curing process;
- suitable thickness/shape of both active and host components (according to Eulero-Bernoulli's beam model, the ratio between host material and piezo thickness should vary from 2 to 5 to guarantee a satisfactory level of actuation);
- presence of electrodes on the piezo plates.

The following table (Table 2) reports the characteristics of the chosen PZT plates.

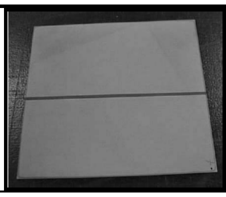
Part Number	**Thickness [mm]**	**Capacitance [nF]**	
T105-A4E-602	0.127	650	
Composition	Lead Zirconate Titanate		
Electrode	Nichel		**72.4 mm square**
Initial Depolarization Field E_c [Volts/meter]			5x 10^5
Curie's temperature [°C]			350

Table 2: PIEZO INC plate.

FBGS sensors

Fibre optics strain sensors show several advantages when compared to more conventional electrical strain gauges: they are passive devices, immune to E.M. noise and perfectly safe in almost any environment. Their small size (typical diameter is 125 micrometers) is comparable with the thickness of the layers employed in composite structures and some of the coatings available to protect optical fibres show very good characteristics of adhesion to the resins generally used in composite materials. This means that fibre optics sensors can be easily embedded into composite structures without inducing damage.

The choice to use FBGS is due to the fact that such sensors possess a wide number of advantages with respect to the other presently available optical measurement systems: this fact indicates them as very promising for future applications.

As a matter of fact, together with the already mentioned advantages of generic optical systems, the use of a Bragg grating sensor gives other advantages: absolute measurements, high resolution, linear on a large range of use, multiplexing capability and modest cost/channel.

The selected Bragg grating sensors are based on standard telecom 125 micron fibres design (external diameter for polyimide coated 135 micron). The fibres coating shall be polyimide-coated to allow integration and curing inside the composite in the 120-170 °C range.

PZT actuators: Cutting, etching, soldering

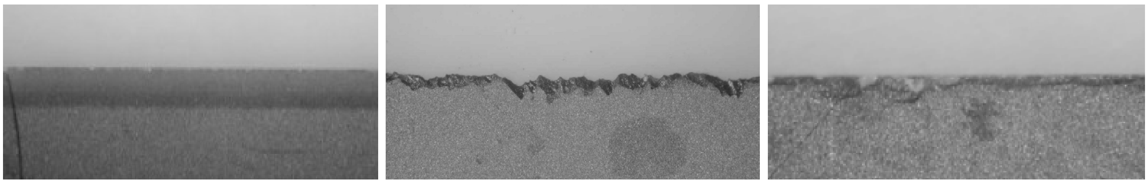
FBGS can be used in their shelf condition, while PZT plates need an accurate preventive processing.

Cutting

The dimensions of purchased PZT plates were 76, 2x76, 2x0.127mm. Firstly, they had to be cut to the desired shape. Because of their small thickness and high brittleness many techniques were investigated, such as cutting by diamond saw, water jet and LASER (Table 3 and Figure 1).

Characteristics of cutting techniques investigated		
Type	**Pro**	**Against**
Diamond saw	Edge sharpness of the cut surface	High difficult to cut plates corners
	Low costs	Simple geometries
	Minimum loss of material (50micron)	Low cutting rate
Laser	Edge sharpness of the cut surface	High costs
	Complex geometries	Transfer of heat to plates
	Minimum loss of material (100micron)	The cut surface need the finishing touch
Water jet	Not changes in temperature	Poor edge of the cut surface.
	Complex geometries	High costs
	Minimum loss of material (200micron)	

Table 3: Characteristics of cutting techniques investigated.



(a) (b) (c)

Figure 1: edge of the cut surface: (a) original edge; (b) water jet; (c) diamond saw.

Table 3 summarizes the main characteristics of the three examined technologies, particularly in view of their application to the available PZT plates. Water jet technology seems to be particularly interesting, thanks to the absence of thermal deterioration (un-desired heat treatments may cause local depolarization of plates) and to the capability to very easily produce complex shapes. Nevertheless, as shown in Figure 1b, at the moment such a technology is not able to produce an acceptably good finish of edges surface. The impact of the water-jet causes a strongly irregular cutting line showing typical “saw-toothed” appearance, which may compromise the plate’s functionality. Besides, some cracks might originate between one saw-tooth and the other, whereas at the tip of every saw tooth electric charges existing in nickel layers gather (point effect) exposing plate surfaces to the risk of short circuit.

By contrast, a diamond rotary blade guarantees a sharp cut of the dielectric material and only some small irregularities of the electrodes, like inter-laminar cracks between the electrodes and the dielectric.

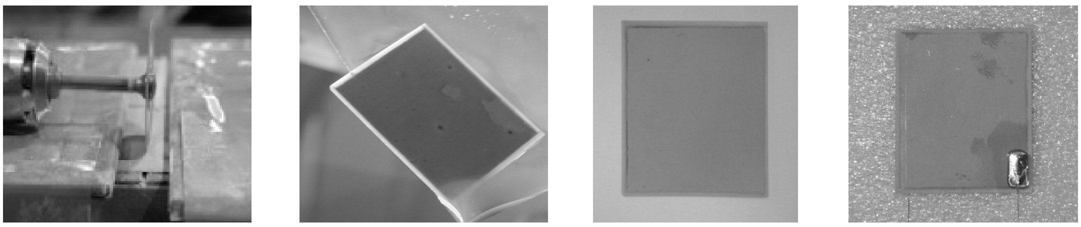
Etching

The following step consists in the etching of the PZT electrodes. It is necessary to minimize the possibility that fragments of conductive material, produced during cutting phase, could short the electrodes during the following manufacturing phases. For this reason, it is necessary to remove a small portion of the electrodes from the edges of the patch. The optimal etching technology, even requiring dedicated tools, is the one adopted at printed circuit board manufacturing factories. Two approaches were implemented, both able to provide a flexible process and satisfactory results. A first attempt was made to perform etching by immersion of the plate edge is acid solution. This process can provide good results for straight edges but it is difficult to remove less than 2 mm nickel because the acid climbs on the plate for capillarity (Figure 2).

(a) (b)

Figure 2: (a) etching process by immersion; (b) etched actuator\sensor plate.

A further technique used was based on standard copper circuits production technique, based on UV polymerized protective coats (Photoresist). This process requires common laboratory tools and consist of 4 steps: covering (both surfaces are covered with Photoresist spray), masking (positioning of a negative master, coating polymerization by UV machine and development by a 7% Sodium Hydroxide solution), etching (by Iron Chloride solution), stripping (removal of the mask by Acetone).



(a) (b) (c) (d)

Figure 3: cutting (a), etching (b) and soldering (d) of plate.

Soldering

Requirements for electric wires are: electric insulation capability (because they are going to be embedded into conductive material); resistance to curing temperature (during manufacturing cycle of composite laminates), small cross section (for having small thickness in soldering area). The copper wires used for the PZT actuator/sensor were the ones typically used for condenser manufacturing; they were enamelled with modified poly-ester-imide resins, coated with amide-imide resins. The electric wires were soldered to the plates using the flux and soft-solder suggested by the supplier of the piezos. After a series of soldering and integration tests, wires 80 micron in diameter were selected. Soldering temperature should be as low as possible, to avoid danger of local plate de-polarization. Besides, the soldering must should be very smooth (Fig.3d) not to give rise to cracks during embedding process.

Characterization tests

Once completed these activities, each piezoelectric plate was checked according to the following tests list:

Test	Scope	Success criterion
Microscope inspection	To find microcracks	Not cracks
Microscope inspection of the soldering	To validate soldering quality	Soldering correspondent aerospace standards
Resistance measurement	To find shorts	MegaOhm measured
Capacitance measurement	To control performances	Value close to theoretic cap.

Table 4: Characterization tests.

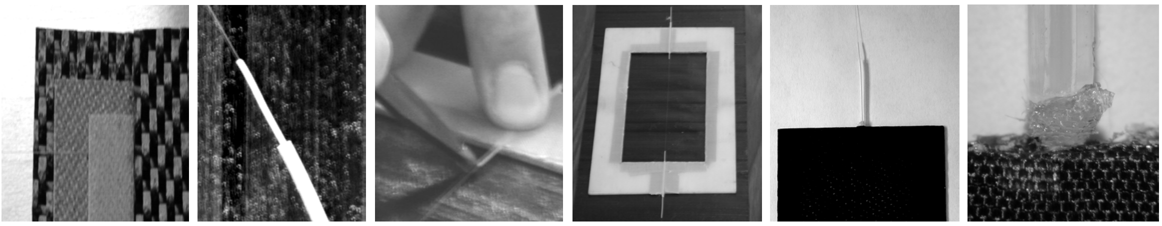
Sensors and actuators embedding

The second phase work was devoted to the assessment of embedding procedures.

Fibre Optics: embedding technique

Fibre optics possess an appreciable strength to tensile stress, whereas they become extremely brittle when subjected to shearing stress. When fibres are embedded into a laminate, they are protected by the same laminate. The problem is localized at the edge of the composite panel, where fibre optics come out from the laminate. Resin in excess, which is extremely fluid during the first part of the curing process, due to capillarity flows along the length of fibres external to the laminate. Once cured, it induces an elevate pressure around the fibres themselves, so inducing a mechanical constraint that makes it fragile.

This fact was solved by protecting the fibre optics with a small PTFE pipe (0,2 mm internal diameter) that had a 10-mm length embedded into the laminate. The void between fibre and pipe existing at the edge of the panel was filled with general-purpose bi-component epoxy glue. A GFRP frame was used to guarantee the correct positioning; it was used during curing process as well, for obtaining a good final surface polishing of specimen edges. Figure 4f show that resin reached, in low quantity, the external surface of protective pipe passing trough frame splines. The same protection used for fibre optics was implemented for electrical wires.



(a) (b) (c) (d) (e) (f)

Figure 4: (a) plies sequence; (b) and (c) ruggedized fibre protection in the final egress point with Teflon tube for safe handling; (d) frame in GFRP; (e) and (f) manufactured specimen.

PZT plates: embedding technique

PZT plates can resist to typical curing cycles pressure levels (about 3÷4 bar) without particular reactions. This is no more true in presence of soldering and electric wires that, in spite of their low thickness (less than 100 micron), give up a localized pressure peak producing the breaking of the plate itself (Fig. 1a). This problem can be avoided by producing the laminate in two curing phases rather than one. The first step consists in the embedding of the plate in two GFRP plies of small size; a curing cycle at pressure level lower than 2 bar is then performed. In this case laminate is put among two special Nexus pads (Nexus consists in a dry fabric, extremely thin, generally used inside composite laminates for absorbing resin in excess): it reduces thickness in-homogeneity due to wires and soldering. As a consequence, a good pressure distribution is guaranteed. So doing, a little panel (Quick Pack) inside which PZT plate is well protected, in obtained. Then, such a Pack is embedded inside CFRP plies and subjected to the second curing cycle, performed at normal pressure, to provide a sufficient compaction degree to the laminate. Wires cannot be protected by PTFE pipes in correspondence of the edges of the Pack, since they should be too much intrusive when embedding the sensing/actuation Pack inside carbon fabric. Nevertheless, since this Pack is made with two single GFRP plies, during its curing process there is a minimum release of resin and this makes possible to protect wires using small Nexus patches (Fig.5b).

(a) (b) (c) (d)

Figure 5: (a) cracked plate owing to the soldering; (b) protection wires with Nexus in the first polymerization; (c) placement of Sensing\Actuation Pack; (d) protection of wires using Teflon tubes in the second polymerization.

Characterization tests

To verify fibre optics integrity within laminate panels, signal continuity was tested. Test consisted in sending a 1-mW light signal and measuring the output power: in case of heavily-damaged fibres, the complete absence of signal should be noted.

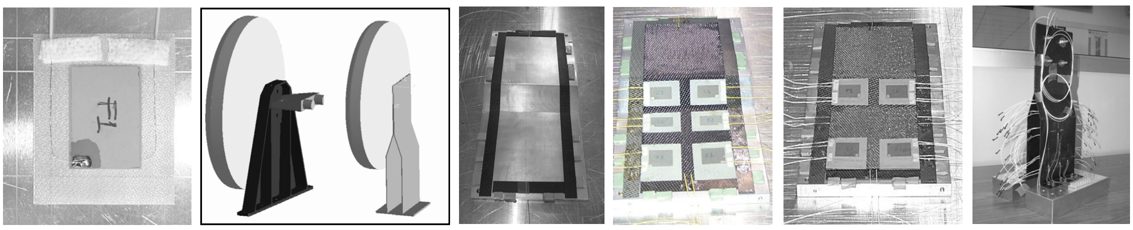
All specimens tested in this way gave positive result, showing signal losses lower than 30%; this is probably due to micro-reflections caused by fabric. To validate embedding technologies, the plate capacitance was monitored in real-time and then analyzed through X-ray inspection.

Preliminary specimen, Quick Pack, breadboard

Every laminate was produced by heated-platen press technology. Pre-series specimens were produced to preliminary evaluate materials and manufacturing technologies. Those were sample beams manufactured and tested according to the same procedures as for the breadboard.

The Sensing/Actuation Quick Pack (size 40x30x0.36mm), created to insulate plates, showed to be a robust and easy-to-handle sensor/actuator unit: therefore, it represented a good solution to be embedded in several applications (Figure 7a).

Thanks to the baseline design a breadboard solution was derived, taking into account viable composites manufacturing techniques and additional requirements for optimizing sensing and actuation capability. The final Y-shape consisted of 4 CFRP plies. For improving performances, packs were placed at different through-the-thickness positions of stacking sequence (Figure 6d, Figure 6e).



(a) (b) (c) (d) (e) (f)

Figure 6: (a) Sensing/Actuation Quick Pack; (b) base line and breadboard design; (c) frame for holding resin; (d) and (e) Quick Pack embedding; (f) final breadboard.

Sensing/actuation tests

All the manufacturing technologies were validated through sensing/actuation tests. Results were compared to the outcomes of numerical simulations.

Dynamic sensing test for strain: the comparison of the results from PZT sensor and co-located standard strain gauges (SG) provided results in tight agreement.

Dynamic actuation test*:* such a test was performed by recording FRF data from a PZT co-located with respect to actuated one and two PZT at the same position of the actuated ones, but placed on the other main plate. The result of the actuation test showed that the use of just two PZT and a low voltage input (10V), the PZTs positioned at the bottom of the structure are able to induce vibration in the structure.

Static sensing test for strain: the comparison of static strain measurement of FBGS and standard SG provided a very good agreement considering the different position of the sensors with respect to the neutral axis of the lamina. (FBGS sensors were embedded, while the SG sensors were surface-mounted).

Concluding Remarks

The described activity investigated, by means of a simplified breadboard, the engineering issues related to design, manufacturing and verification of smart structures made of composite embedding PZT and optical sensors/actuators. These concepts show a potential for being applied in more general fields of structures design as well, such as structure identification and health monitoring.

Moreover, some fields were identified where technology improvements are needed, i.e. PZT plates cutting for general shapes; PZT insulation using advanced coatings to reduce the embedded plate thickness; continuous evaluation of new available PZT raw materials shapes for optimization of embedding process.

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