**Novel Procedure for Designing, Manufacturing and Assembly of Smart Composite Structures with Integrated Acousto-ultrasonic (AU)- Structural Health Monitoring (SHM) sensors**

***Exposé Dissertation***

***Tasdeeq sofi***

***FIDAMC***

***TU Clauthal***

*Supervisors:*

*Dr. Maria Rodriguez Gude*

*Dr. Diego Castillo del Saenz*

*Prof. Peter Wierach*

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# **Introduction and problem statement**

Structural health manufacturing (SHM) is defined as a process of collecting and analyzing data from a distributed network of sensors that are mounted on or embedded inside a structure to obtain information about the health of the structure [1]. By monitoring the response of the sensors embedded or attached to the structure and performing the appropriate post-processing techniques, it can result in the detection and localization of the defects. During recent years SHM has emerged as an interesting technology for many industries because of its capability to reduce maintenance costs and therefore reducing labor and downtime with an increment of the operational availability. SHM information has the potential to not only reduce by billions the expenditure on asset maintenance, but also to drastically change the way the composite structures (and their associated assets) are designed, built, and maintained. Prognostics and health management (PHM) is an extension of SHM that can make predictions of remaining useful life (RUL) using timely updated data from the sensors. PHM predicts the RUL of an engineering systems by combining sensor technology, structural engineering, data science and Artificial intelligence to enable cost-effective risk-based maintenance schedules based on predictions of the RUL as opposed to periodic inspections.

However, despite these advantages, SHM system is still not reflected in the real-life applications as expected because of the lack of industry practices, guidelines, and standards that the system must fulfil for the different applications in industries such as aerospace applications. There are many challenges faced in the multi-disciplinary SHM technology ranging from manufacturing of such smart structures, sensor diagnostics, performance of the monitoring systems in real structures under realistic conditions, probability of detection and isolation of signals, monitoring of large structures, need of generating understandable data or information to the structural engineer and airworthiness compliance.

The main focus of this work is on the designing, manufacturing, and assembly of composite structures with integrated Piezoelectric (PZT) sensors for SHM. The main challenges and open research areas in this domain are:

* Sensors joined by epoxy adhesive are difficult to be repaired/removed in case they become damaged. Therefore, the need is to replace the epoxy adhesives with new sensor bonding materials that are repairable and removable while giving the same performance as epoxy adhesives. For example, using low melt thermoplastic (TP) films that could be removed by heating.
* The current method of joining the sensors manually is slow, costly and requires enhanced effort. The challenge is to develop and test novel sensor joining techniques that are fast, cost saving and can be automated. Example joining sensors through welding in case of thermoplastics.
* Need to test the integrability, survivability, and reliability of the integrated sensors under different loading and realistic aircraft conditions.
* Lack of efficient sensor diagnostics process.
* Improved PZT sensors that can survive and remain durable and reliable in harsh aerospace conditions and in high-temperature applications.
* Replacing the heavy and difficult to manage cables and connections with lightweight circuits that give similar performance as traditional wires.
* Survivability, durability, and reliability of the printed circuits produced by printed electronics utilizing silver inks, conductive paint, Carbon Nanotube (CNT), graphene etc.

# **Objective and scope of the research**

Based on the challenges and open research areas in the field of designing, manufacturing, and assembling smart composites with integrated sensors for SHM, the main objectives of this research work are:

* To develop a controllable process to achieve repeatable bond quality by using adhesive films (Epoxy and TP).
* To test new materials for bonding the sensors. The sensors bonded with these new materials should be easily removable and repairable. The films should be readily available from the market as well as compatible with TP based composites.
* To develop a novel sensor joining method which is fast, less costly and requires less effort.
* To investigate the integrability, survivability, and reliability of the sensors bonded with epoxy and new material in different loading conditions and aircraft operational environment (AOE).
* To develop an improved sensor and efficient sensor diagnostic process.
* Minimize and replace the traditional wires by ultra-light and compact circuits.
* Manufacturing and characterization of the conducting paths produced by materials such electric paint and conductive epoxy using filler material such as CNT and graphene.

The work aims to develop a novel procedure for manufacturing smart composites with integrated sensors. Through this new procedure an improved sensor will be developed, the sensor joining method could be greatly improved in terms of quality, effort, and cost; the bonded sensors could be easily removed and repaired; the faulty sensors can be identified and the weight and management of the connections and cables for the sensors can be significantly improved.

The novelty and objectives of this work lies in testing new bonding material that is repairable; developing new sensor joining methods that are easy, fast and can be automated; studying and evaluating the integrability, survivability, and reliability of the integrated sensors to the composite structures joined by new material and by new joining methods; improvement of the existing sensor to overcome the limitations of the current design and developing printed circuits to replace the traditional wire system that adds an additional weight and are difficult to manage as shown in Figure 1.

The work will mainly focus on integrating sensors with high performance thermoplastic composites structures such as PEEK/CF using secondary bonding. Thermoset based composites will be used only during embedding the sensors in the composite, co-bonding and in case of process monitoring. The tests will be restricted mainly to coupons and small structural elements such as stringers which will be manufactured with vacuum bagging-oven curing and in-situ consolidation. The sensors used will be PZT DuraAct sensors supplied by Pi-Ceramic and will be bonded with the host structures using high performance epoxy adhesive and thermoplastic films. The equipment used to make different measurements to evaluate the condition of the sensors will be impedance analyzer and an Oscilloscope. The materials to create printed light circuits will be silver ink, conductive paint, CNT, and graphene.

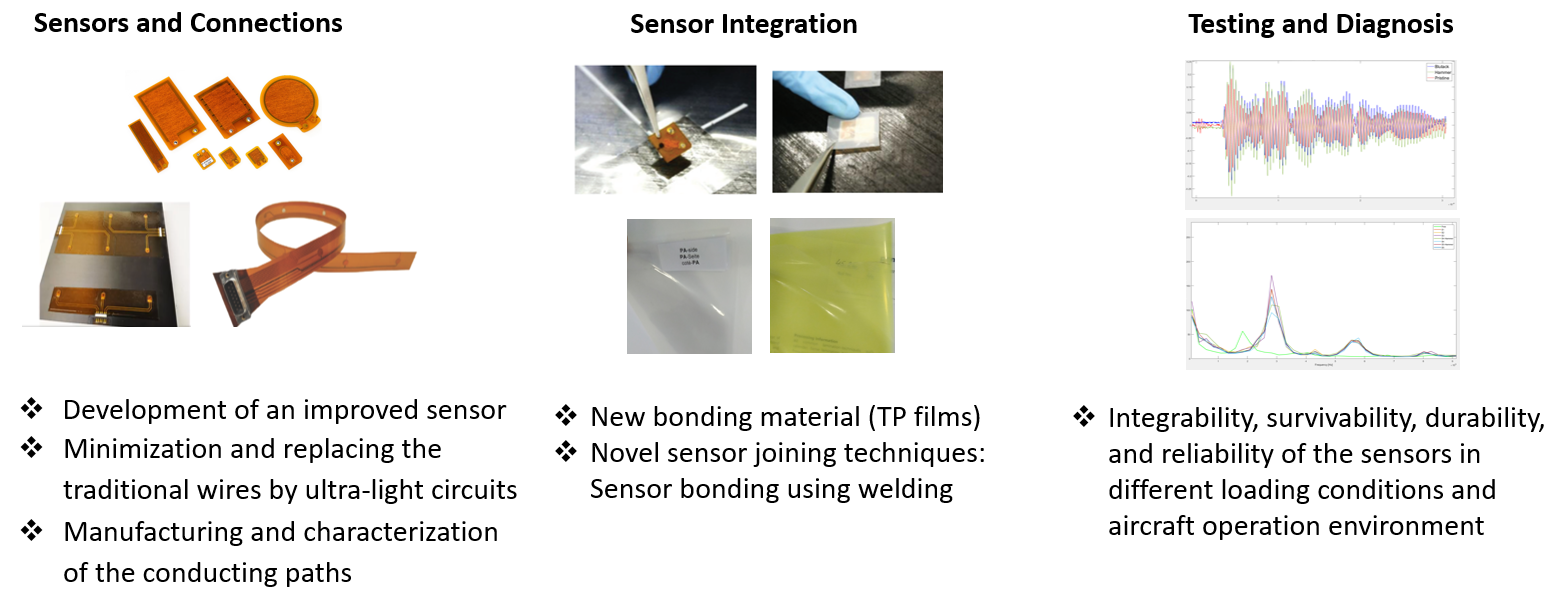


Figure 1: Objective summary

# **Work packages**

## **3.1. WP1: Integration, survivability, and reliability of Acousto-ultrasonic (AU) sensors, sensor improvement and process monitoring**

### **3.1.1. Integration, survivability, and reliability of sensors bonded with epoxy and new TP films**

**Motivation:**

The state-of-the-art for bonding PZT sensors to the composite surface is by generally using aerospace grade high-performance epoxy adhesives. However, the following limitations are faced in using an epoxy adhesive:

* Epoxy adhesives have to be transported and stored in a refrigerator because of their limited shelf life in normal conditions. However, this is not the case with TP material which has a long shelf life and can be stored at room temperature.
* Thermoplastic films are more compatible with thermoplastic based composites as compared epoxy adhesives.
* A sensor after bonded by epoxy adhesive cannot be removed without mechanical abrasion and damaging the host surface. The removal of the sensor becomes important when a sensor gets damaged and needs to be replaced on the host structure. If the sensor is not removed it will lead to additional weight and the management of the sensor layout and the connections will become difficult. More importantly, if the sensors are placed in an optimized layout the same layout cannot be achieved again if the sensor is not replaced at the same location.
* One of the key benefits of using TP films is their weldability property. Therefore, the TP films can be used to integrate the sensors with the host structure through welding which is not possible with epoxy adhesive material. Through welding, high weld strength can be obtained at a fraction of time and cost as compared to manual bonding. Besides, welding has the potential to automate the sensor bonding procedure.

**Aims:**

* Selection of at least three potential over the shelf TP films that could be used for bonding the sensors to the composite surfaces and replace epoxy adhesives as a bonding material.
* To characterize and evaluate the integration, survivability, durability, and reliability of the sensors bonded by the novel TP films. For this evaluation and characterization electromechanical properties namely capacitance, impedance/admittance and guided wave measurements of the sensors integrated with the coupons will be carried out before and after the following (loading conditions) mechanical tests:
  + Bending test
  + Fatigue test
  + Impact test
  + Real aircraft operational conditions (Temperature and thermal shock, hot-wet and altitude).
* Self-diagnostic of sensor health and bonding by characterizing guided wave behavior, differentiate between wave changes to the wave by sensor failure or structural damage.
* Investigate the bonding of the sensors by TP films through welding

**Methodological Approach:**

The bonding of the piezoelectric (PZT) sensors by TP films in place of using epoxy adhesives is feasible and has been briefly carried and tested out by Yue et al [2]. However, more comprehensive work in needed in this area such as testing the survivability and reliability of these TP films in AOE.

This work will investigate the bonding of PZT sensors with epoxy and TP films, new joining techniques, and test the integrability, survivability, durability, and reliability of the sensors bonded with epoxy and TP films under different conditions (bending, fatigue, AOE) that have not been investigated by previous researchers. Bonding with epoxy will serve as a reference as this is the standard method of joining the sensors and gives desired performance [2–5]. The step by step produce of the methodological approach is described below:

#### **Selection of the TP films:**

The first most important step is to choose the TP films that can be used to bond the sensors to the composite surfaces. The TP films should be available over the shelf and fulfill the following criteria:

* + Melting temperature less than 150°C: The melting temperature should be less than the maximum allowable temperature of the sensor and should not exceed the glass transition temperature of high-performance composite such as PEEK.
  + Deflection temperature greater than 85°C: The deflection temperature should not be less than the service temperature of the host structure (Aircraft structures) in order not to deflect during the operating temperature of the structure.
  + Compatibility with PEEK: Integration should be possible with high-performance TP structures such as PEEK and PEKK.
  + High shear strength: The bond should be able to resist high shear stress and not fail during the normal loading conditions.

The melting and processing temperatures of the TP films will be obtained by the Differential scanning calorimetry (DSC) test. The shear strength of the films will be obtained by standard Shear lap test (EN 2243-1). The boning strength of the TP films will be obtained by T-/climbing drum peel strength test. The bond strength of the films will be compared to the epoxy adhesive which is state-of-the-art to bond the sensors.

Initially eight TP have been identified which fills the mentioned criteria and are listed in Table 1. After performing the mentioned tests three films with the best-desired properties will be selected to bond the sensors with the composite structures for further investigation.

Table 1: Identified thermoplastic films

|  |  |  |
| --- | --- | --- |
| **Adhesive film** | **Material** | **Remarks** |
| Loctite EA 9695 | Epoxy |  |
| Pontocal 22.100 | Polyolefin | Suitable for ultrasonic welding |
| Pontocal 46.302 | Polyurethane | Suitable for ultrasonic welding |
| Pontocal 45.200 | Polyolefin/copolyamide (multi-layer) | Suitable for ultrasonic welding |
| Pontocal 45.350 | Polyolefin/ Polyurethane (multi-layer) | Suitable for ultrasonic welding |
| PI 284 | Polyimide |  |
| PA250-HV | Polyamide |  |
| PA250-LV | Polyamide |  |
| 230110 | EVA |  |

#### **Sensor integration methods:**

The following methods will be used to integrate the sensors with the host structures:

* **Curing/Consolidation:** The sensors will be integrated with the host structure with an epoxy adhesive (Loctite EA 9695) by curing the adhesive under vacuum. This is the state-of-the-art method and well-proved for joining the sensors to the host structures [2–5]. If the sensors are integrated with the host structure with TP films, they are melted and consolidated under vacuum.
* **Welding:** The second method to integrate the sensors with the TP films will be using welding. Different types of welding are used in the composite industry for joining thermoplastics. Among them the main categories are thermal, frictional, and electromagnetic welding [6]. The most likely and feasible type of welding that could be used in joining the sensors to the TP host through thermoplastic films is ultrasonic (US) welding a type of frictional welding. (Other welding type)?

**Ultrasonic welding:**

Ultrasonic welding falls under the frictional welding category. And is an ultrafast process of joining plastic parts. In US welding the US waves vibrate ten’s of thousands of times per-second. This oscillation is transferred to a contact surface that is directly in contact with the plastic parts. Since the boundary of the welding area has a large acoustic impedance high temperature are generated due to friction. Plastic being a pretty poor conductor of heat cannot dissipate the it before it changes the melts the plastic interfaces. By applying a little pressure, the two parts are joined together as shown in Figure 2. It is independent of using a particular material at the interface, as required in resistance and other welding methods. Ultrasonic welding will be suitable to join the sensors because the sensors consist of PZT material and therefore they will be good medium to transmit the oscillations to the bonding material at the interface which generate heat due to friction to melt the thermoplastic material in order to create the bond. This process is a solid-state process no external heat is added for welding.

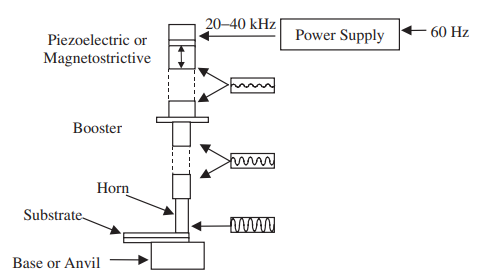


Figure 2: Schematic of ultrasonic welding [6]

#### **Preparation of samples**:

**Bond strength measurement: Shear lap test (EN 2243-1)**

TP film

PEEK

100

1

25

Figure 3: Dimensions (mm) of the specimen

The shear strength is given by *F\*L/W*

R = Shear strength, P = Failing load, L = Length of overlap, W = Width of overlap

#Specimen: Three samples for each thermoplastic film and three for epoxy adhesives

**Bending test (Dimensions according to the test requirement)**

TP2

TP1

EP

TP3

Figure 4: Sample for bending test

**Fatigue tests (Tension and compression: Dimensions according to test requirement)**

**Top side**

TP1

EP

**Bottom side**

TP2

TP3

Figure 5: Sample for fatigue test

Where EP = Epoxy, TP1,2 and 3 are thermoplastic films 1,2 and 3.

**Impact tests**

* Coupons and small structural elements

#### **Methods to investigate the integration, survivability, durability, and reliability of the sensors**

The standard methods for testing the integrability, survivability, and reliability of the PZT sensors bonded to metal or composite structures are measuring the electro-mechanical properties namely Capacitance, impedance/admittance, charge measurements and guided wave measurements of the sensors before and after various loading conditions simulated through mechanical tests. The most important parameter is the admittance signatures, that carries information pertinent to the health and bonding condition of the sensor.

Various authors [2, 7–12] has used these methods to study the survivability, durability, and reliability of the bonded PZT to the composite. Therefore, these standard methods will be used to study and evaluate the performance of the sensors bonded by novel proposed TP films to the composite structures. A change in the mentioned electro-mechanical properties of the sensors can indicate if they are healthy and well bonded and generates the same signal as in the pristine condition. The following sensor failures can occur during the service time of a sensor.

* Dis-bonding of the sensor from the host surface
* Breakage or Crack of the sensor
* Dent and spalling of the sensor
* Mechanical degradation of the sensor

The Capacitance, Impedance/admittance, voltage/charge, and Guided wave measurements can be used to identify these sensor failures as summarized in the table 2 and hence can be used to evaluate the integrability, survivability, durability, and reliability of the sensors.

Table 2: Test method for identification of sensor damage and dis-bonding

|  |  |
| --- | --- |
| Test method | Sensor failure mode that can be identified |
| Impedance/admittance measurement Capacitance measurement | All sensor failures: Bonding, Electric and Mechanical degradation, Sensor Breakage |
| Charge/Voltage measurement | Electric and Mechanical degradation, Sensor Breakage |
| Guided wave transmission | All sensor failures: Bonding, Electric and Mechanical degradation, Sensor Breakage |
| Micrographs (only if the other three are not sufficient to draw a conclusion) | Sensor breakage, bonding, bonding area analysis: to understand failure modes |

The following mechanical tests will be carried out to simulate the different loading conditions that the sensor can experience during its service life**.**

* **Bending test:** The bending load will be applied in ramps
* **Fatigue test**: Tensile and compression: 100K-200K cycles with a load factor 0.1
* Aircraft operational conditions: DO-160 standard tests will be carried out, which is a standard for the environmental testing of avionics hardware.
  + **Temperature cycling:** Increase or decrease the temperature to max (70 °C) & min (-55 °C) from the ambient conditions and hold constant for at least three hours.
  + **Thermal shock:** Temperature will be ramped between the extreme low (- 55°C) and high temperatures (70 °C) with a rate of 10°C.
  + **Altitude:** 11.6 KPa (Absolute) and maintained for 120 minutes at ambient temperature.
  + **Hot-wet:** Maintain the chamber temperature at 50±2 °C and humidity at 95±4 % RH for six hours. During the next 16-hour period, decrease the temperature gradually to 38±2 °C or lower. During this period, keep the humidity as high as possible and do not allow it to fall below 85 % RH. Repeat these steps until a total of two cycles (48 hours of exposure) have been completed.
* **Impact test:** Impact over the sensors integrated by different materials and around sensor area to study their survivability and reliability during these impact tests.

**Assumptions:** Transducers and connection network will be internally mounted, in a non-temperature-and pressure-controlled area and not at extreme temperature areas, e.g., engine cowling or exhaust outlets. The test conditions for the standard DO-160 have been obtained from <https://app.do160.org/>.

#### **Flow chart of the work**

**Baseline measurement of the electro-mechanical properties of the sensors**

**Preparation of specimen**

**Selection of thermoplastic bonding films**

**Mechanical and AOE tests**

**(simulate loading and aircraft conditions)**

**Measure the electro-mechanical properties of the sensors**

**- DSC test**

**- Shear lap test**

**Coupons (dimensions as per mechanical tests)**

**Joining techniques:**

**- Curing/consolidation**

**- Welding**

**- Capacitance**

**- Impedance/admittance**

**- Guided wave measurements**

**- Bending tests**

**- Fatigue tests**

**- Aircraft condition tests**

**- Capacitance**

**- Impedance/admittance**

**- Guided wave**

**measurements**

**Outputs:**

* Feasibility and performance of the new thermoplastic bonding films
* Integrability, survivability, and reliability of the PZT sensors (bonding and health) during different loading conditions
* Feasibility of joining sensors with new techniques such as welding
* Sensor self-diagnostics

Figure 6: Flow chart of the work plan

### **3.1.2. Improvement to the sensor (Preliminary ideas)**

**Motivation:**

* Optimizing the sensor by overcoming the limitations of the current sensor.

**Aims:**

* Improve the sensor for better performance to survive harsh conditions, high strains and extend the maximum service temperature of the sensor which currently is 150 ° C.
* Manufacturing sensor arrays
* Understanding the sensor failure mechanisms and finding out how to improve the sensor performance.

**Methodological approach:**

* The PZT could be embedded into higher temperature polymer or glass prepreg to increase its service temperature
* Sensor arrays can be manufactured by placing a number of sensors on a Kapton film or glass fiber prepreg or Aramid fiber prepreg.
* Studying and analyzing the sensor failure modes during different mechanical test like impact, bending and fatigue tests.

Table 2: Methods for studying the sensor failure

|  |  |
| --- | --- |
| Test method | Sensor failure mode that can be characterized |
| Micrographs | Sensor breakage, bonding, bonding area analysis: to understand failure modes |

### **3.1.3. Process monitoring**

**Motivation:**

* Multi-function sensor: Process monitoring and SHM.
* It will enable the integration of sensors for SHM in the earliest phase of the life cycle for an additional cost-benefit.

**Aims:**

* Monitor the degree of the cure during the manufacturing process of composite structures and hence optimize the curing time and maintain the quality of the part.

**Methodological approach:**

One way to monitor the degree of cure of the prepreg is by looking at the change in resin property. Many aspects of the resin property change during polymerization, including its mechanical property, electrical property, thermal property, chemical property, etc. Wave propagation is governed by the material property, the geometry, and the boundary condition. During prepreg curing only the material property is changing. Therefore, by monitoring the changes in the propagating wave, the change in the property of the resin and hence the progress of the cure can be monitored.

Lamb waves are excited and recorded by piezoelectric transducers as shown in Figure 7. Lamb waves travel through the thickness of a plate along the path from actuator to sensor. The transmitted energy, attenuation, and velocity of the waves are influenced by the mechanical properties of the excited material. This allows conclusions to be made about the degree of cure of the prepreg.

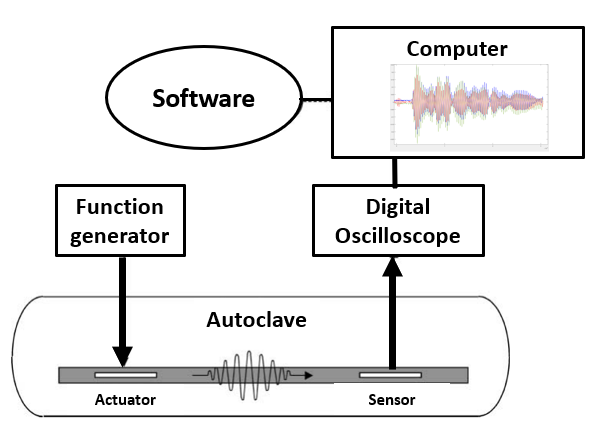


Figure 7: Cure monitoring using guided wave through PZT transducers

## **3.2**. **WP2: Minimization of number and weight of the cables by printed circuits**

**Motivation:**

One of the most important factors affecting the scaling up of an SHM system to real-scale applications is additional weight caused by wires and connecting elements. The most delicate part of the SHM system are the connecting elements (wires, circuits, and connectors) between the sensor and the interrogator system. Currently, the state of the art is to use cables to connect the sensors with the diagnostic hardware. However, this leads to a significant increase in weight of the SHM system and the handling of the wires can become very difficult especially while monitoring a large area with a huge number of cables.

**Aims:**

* Reduce the number of cables with extremely lightweight circuits e.g., using inkjet-printed circuits, conductive paths/epoxy, CNT, etc.
* Assessment of the integrity and reliability of the printed circuits and conductive paths produced using different materials.
* Using a single surface-mounted connector instead of several required connectors.

**Methodological approach:**

### **3.2.1. Materials**

**Materials to produce circuits:**

* Printed polymer layer/Thermoplastic film layer/Kapton layer (For insulation)
* Conductive ink (Silver/Copper)
* Conductive paint/ conductive epoxy
* CNT and Graphene as conductive fillers

**Producing the paths:**

The first step is to place a dielectric layer over the carbon fiber composite. This can be achieved by placing, printing, stamping, or welding of polymer layer or TP layer e.g., low melt TP films or Kapton over the composite surface.

Once a di-electric layer has been formed then a layer of circuits will be produced by printing of conductive inks and conductive paths using conductive paint or conductive epoxy, or manual applying of silver paste, conductive paint, or conductive epoxy on the composite surface. The last step is to place another polymer film over the printed circuits or conductive paths in order to protect them.

**Preparation of specimen:**

Coupons will be prepared with printed circuits and conductive paths using different materials as mentioned above and then the coupon will go under different tests as described in next section (3.2.2).

`

Printed polymer layer/Thermoplastic films\*/Kapton layer

Composite

Printed circuit/conductive paths using different materials

Protective layer

Figure 8: Coupons for testing printed circuits

### **3.2.2. Methods**

**Measurement of performance of printed circuits as compared to the traditional cables**

* Signal amplitude of lamb waves
* Resistance measurement

**Integrity and Reliability Assessment of the printed circuits:**

* Tension and compression tests
* Mechanical and electric fatigue tests
* Thermal and humidity
* Impact test
* Identifying damage on the printed circuits using guided waves

# **Activities planning**

The draft time and work plan and the place where these activities will be carried is given in the table below:

Table 3: Activities planning

|  |  |
| --- | --- |
| Place | Work |
| FIDAMC  Nov. 2020 - Dec.2021  July 2022 – Oct. 2023 (including second secondment\*) | * Manufacturing of coupons/elements * Bending test * Fatigue tests * Aircraft conditional tests * Temperature and thermal cycling * Altitude * Hot-wet/Humidity * Formulation of functional inks * Development and characterization of the printed circuits and conductive paths |
| DLR  First Secondment  Jan 2022-June 2022 (Planned) | * Fatigue tests * Improvement to the sensor |
| \* Second secondment  Not planned/decided yet | * Welding of sensors * Print lightweight circuits on the composite surface |

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