**Novel Procedure for Designing, Manufacturing and Assembly of Smart Composite Structures with Integrated Acousto-ultrasonic Sensors for Structural Health Monitoring**

***Exposé Dissertation***

***Tasdeeq Sofi***

***FIDAMC***

***TU Clausthal***

***Supervisors:***

*Dr. Maria Rodriguez Gude*

*Dr. Maria Isabel Martin*

*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 conditions in aerospace industry. 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 very difficult to be repaired in case they become damaged. Therefore, the need is to replace the epoxy adhesives with new bonding materials which are repairable while giving the same performance as epoxy adhesives. For example, using low melt thermoplastic (TP) films that could be removed by heating or chemical treatment.
* The current method of joining the sensors is manual therefore 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 TPs.
* 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 and therefore development of the same.
* Improved PZT sensors that can survive, remain durable and reliable in harsh aeronautical 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 and conductive paths using metallic (silver) inks, conductive paint, Carbon Nanotubes (CNTs), graphene nanoplatelets (GNPs) 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 TP adhesive films.
  + To test new materials for bonding the sensors. These new bonding materials should be easily repairable, relatively easier to process, economically and readily available from the market as well as compatible with TP based composites.
  + To develop a novel sensor joining method that is fast, less costly and requires less effort.
* To investigate the integrability, survivability, and reliability of the sensors bonded with new material in different loading conditions (Bending test, impact, and tension fatigue) and aircraft operational environment (AOE) conditions.
* Minimize and replace the traditional wires by ultra-light and easy to handle circuits.
* Manufacturing and characterization of the conducting paths produced by materials such as printed silver inks, electric paint and conductive epoxy using filler material such as CNTs and graphene nanoplatelets.

The work aims to develop a novel procedure and a new approach for designing and manufacturing smart composites structures with integrated sensors. Through this new approach the sensors bonded to the composite surface can be easily repaired by using new bonding materials; the sensor bonding process could be greatly improved in terms of quality, effort, and cost; and the weight and management of the connections and cables for the sensors can be significantly improved by using lightweight circuits manufactured using multi-functional inks. The aims are shown pictorially in Figure 1. Therefore, significantly improving over the existing state-of-the-art smart composite manufacturing techniques and thus leading to an efficient way of manufacturing these systems.

The novelty and objectives of this work are: The utilization of 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 and developing printed circuits to replace the traditional wire system that adds an additional weight and are difficult to manage.

The work will mainly focus on integrating sensors to high performance TP composites structures such as Poly-Ether-Ether-Ketone (PEEK) and/or Poly-Ether-Ketone-Ketone (PEKK) and Carbon fiber by using secondary bonding. Thermoset based composites will be used only during embedding or co-bonding of the sensors to the composite structure. 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 TP films. The epoxy adhesive will serve as a reference during the whole study as its performance has been studied and verified in various studies [2–5]. 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, CNTs, and GNPs.

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*Figure 1: Thesis objective summary*

# **Work packages**

## **3.1. Work Package 1: New bonding material for sensor integration**

**Motivation:**

The state-of-the-art for bonding PZT sensors to the composite surface is by generally using aerospace grade high-performance epoxy adhesives. New bonding materials that can overcome the limitations of epoxy-based adhesives need to be investigated. Low melt TP adhesive films are promising bonding materials that have the potential to replace existing epoxy-based adhesives for sensor bonding because of the following advantages:

* Epoxy adhesives have to be transported and stored in a refrigerator because of their limited shelf life in ambient conditions. However, this is not the case with TP materials that have a long shelf life and can be stored at room temperature.
* TP based adhesives are more compatible with TP based composites and have shorter bonding cycle time as compared to the epoxy-based adhesives e.g., Loctite EA 9695 epoxy adhesive has a cycle time of 120 minutes at 121 °C while as selected TP films can a have a cycle time of 10-20 min at 130-140 °C.
* A sensor bonded with epoxy adhesive cannot be removed without mechanical abrasion and damaging of the host structure 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. TP material can be remelted therefore the damaged sensors can be easily removed from host structure.
* One of the key benefits of using TP films is their weldability property. Therefore, TP films can be used to bond the sensors to 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.
* The aircraft industry is shifting its focus towards TP based composites for future aircraft composite structures. Therefore, there is a need to develop a new approach for integrating sensors to TP based composites. The proposed use of TP based adhesive films is one of the strategies towards this new approach and it would allow efficient integration of sensors to TP based composite structures.

**Table 1: Comparison of TP adhesive films and epoxy-based adhesives**

|  |  |  |
| --- | --- | --- |
| Property/Parameter | TP adhesive | Epoxy (thermoset) adhesives |
| Storage | No refrigeration required | Refrigeration required |
| Shelf life at room temperature | Long | Short |
| Cycle times | Shorter | Longer |
| Repairability | Yes | No |
| Weldability | Yes | No |

**Aims:**

* Selection of at least three 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 new 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 mechanical tests:
  + Quasi static test: Bending test and pure tensile test
  + Dynamic test: Fatigue test
  + Real aircraft operational conditions (Temperature and thermal shock and hot-wet).

**Methodological Approach:**

The bonding of the PZT sensors by TP films in place of using epoxy adhesives is feasible and has been briefly carried out and tested by Yue et al [4]. However, more comprehensive work is needed in this area such as testing the survivability and reliability of these TP films in bending tests and AOE conditions.

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 procedure 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 off the shelf and fulfill the following criteria:

* + **Melting temperature less than 145°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 or equal to 75 °C:** The deflection temperature of the adhesive films should not be less than the service temperature of the host structure (Aircraft structures) or the higher operating temperature as defined by the DO-160 standard (70°C) for internal electronic components.
  + **Compatibility with TP composites:** Integration should be possible with high-performance TP structures such as PEEK and PEKK.
  + **Relatively high shear strength:** The bond should be able to resist high shear stress and not fail during the normal loading conditions. Only crystalline or semi-crystalline TP films will be selected because of their better mechanical performance, chemical resistance and predictable behavior as compared to the amorphous polymer films [6]. For e.g., polyurethane based TP adhesive films because polyurethane has good resistant to petrochemicals, much better recovery after elongation.

Initially at least eight TP adhesive films have been identified which meets the above-mentioned criteria and are listed in Table 2. The films will then be compared on the basis of their processing temperatures, bonding strengths, and ability to be removed after bonding. Finally at the end three films with the best-desired properties will be selected to bond the sensors with the composite structures for further investigation.

The melting and processing temperatures of the TP films will be obtained by the Differential Scanning Calorimetry (DSC) test. The boning strength of the TP films will be obtained by standard shear lap strength test (EN 2243-1). The bond strength of the films will be compared to the epoxy adhesive which is state-of-the-art to bond the sensors.

#### **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 of joining the sensors will be through a novel approach i.e., through welding using TP films which makes it the second work package of this work. The detailed motivation, the aims and the methodological approach is described in section 3.2.

*Table 2: Initially identified TP films*

|  |  |  |  |
| --- | --- | --- | --- |
| Adhesive film | Material | Polymer structure | Remarks |
| Loctite EA 9695 | Epoxy | N/A | Reference |
| Pontocal 22.100 | Polyolefin | Semi-Crystalline |  |
| Pontocal 46.302 | Polyurethane (PUT) | No crystallinity found |  |
| Pontocal 45.200 | Polyolefin/copolyamide (multi-layer) | Semi-Crystalline | Two- component film |
| Pontocal 45.350 | Polyolefin/ PUT (multi-layer) | Semi-Crystalline | Two- component film |
| PI 284 | Unknown | Semi-Crystalline |  |
| PA250-HV | Polyamide | Semi-Crystalline |  |
| PA250-LV | Polyamide | Semi-Crystalline |  |
| 230110 | EVA | Semi-Crystalline |  |

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

For both new bonding material and new sensor integration method it is necessary to study and validate the sensor integration (bonding quality) with the host structure, their survivability, durability, and reliability. This is studied by measuring the electro-mechanical properties of the sensors namely Capacitance, impedance/admittance, charge, and guided wave measurements before and after various loading conditions simulated through different tests. The most important parameter is the impedance/admittance signatures, that carries information related to the health and bonding condition of the sensor. In addition to the mechanical tests, micrographs of bond interface between the sensor and the host will be made for evaluating the bond quality. The results from the mechanical tests and micrograph images can be further correlated in order to learn how the interface quality can influence the mechanical properties of the bond. Furthermore, non-disturbance tests such as pure tensile and bending tests will be carried out to prove that the mechanical performance of the host is not affected by the integration of the sensors.

Various authors [4, 7–12] have 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 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 to the structure.

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 caused by low velocity impacts
* 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 3 and hence can be used to evaluate the integrability, survivability, durability, and reliability of the sensors.

*Table 3: 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 | Sensor breakage, bonding, bonding area analysis: To correlate the bond quality and mechanical properties. |

#### **Mechanical tests**

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 test will be used to characterize the critical strain (strain at failure) of the sensors; their durability and reliability at different strain levels; and to determine the strain levels that will be used during the dynamic tests (Fatigue tests). Another interesting point in focus during the bending tests will be the strain on the sensors bonded with TP as compared to thermoset adhesive films. This is because thermoset polymers typically have higher elastic modulus but the strain at break is small indicating brittle type behavior. TP polymers on the other hand have lower elastic modulus but much larger elongation (strain) at break i.e., they can undergo large strains before failure and have much better recovery after elongation as shown in Figure 2.

A non-standard 4-point (4-pt) bending test in which the sensor will be in tensile and compressive configuration will be carried out. A 4-pt bending test will be used because:

* It offers a flexibility in the coupon size
* The sensor can be placed at a location where the stress distribution is homogenous.
* The stress concentration of a three-point test is small and concentrated under at the mid-point, whereas the stress concentration of a four-point test is over a larger region thus giving a more flexibility for the placement of the transducer.
* 4-pt bending test has zero shear in the central region which gives a region of pure bending which is not possible in 3-pt bending test.

Diagram

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*Figure 2: Stress-strain curve for TP and thermoset based polymers [13]*

In bending tests for each bonding material i.e., epoxy adhesive and three different TP films at least three coupons will be prepared as shown in Figure 3. A single sensor will be integrated to each coupon by corresponding bonding material through secondary bonding.

The test procedure is as follows:

* The load velocity will be less than 0.001 mm/s. The maximum applied load should be less than 1.71 KN.
* A succession of quasi-static loading-unloading ramps will be applied starting at 0.05% strain and increasing the strain with a of step of 0.1% until sensor failure is observed.
* Transducer Electro-magnetic Impedance (EMI) measurements will be carried out before and after each loading step (ramp) in the range of [10 HZ-1 MHz].
* During the mechanical loading the monitoring of the transducers will be achieved through the measured electric charge and strain data.
* The test setup is shown in Figure 3. It has been calculated for a coupon of dimension of 300 mm, 60 mm, and 2 mm prepared from APC2 PEEK/ Carbon fiber composite.
* Distance of external rollers (S) = 240.0 mm (10% of the coupon length should overhang on each end).
* Distance of internal rollers (L) = 120.0 mm (so (S-L)/2 is at least S/4 according to ASTMD6272 Standard).

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L = 120 mm

S = 240 mm

30

60

1.71 KN

Sensor bonded at center (150, 30) by either EP/TP1/TP2/TP3

300

60

2

*Figure 3: Test setup and test coupon for bending test (One adhesive film on a single coupon)*

Where EP = Epoxy, TP1, TP2 and TP3 are three different TP films

#### **Fatigue test:**

Fatigue test is one of the most important integrity tests to demonstrate long term survivability, durability, and reliability of the sensors. Cyclic mechanical loading will be carried out to analyze long-term behavior of the sensor by establishing its life diagram and to study the change in the sensor properties under repeated loading. Fatigue testing will be carried by means of tension-tension and bending fatigue. The procedure for both tests is defined as follows:

**Tension-Tension fatigue:**

* A single coupon with a dimension of 300 mm\*60 mm \*2 mm will be prepared.
* Four sensors will be bonded to the coupon using three TP adhesive films (with best performance) and one epoxy adhesive film (for reference) as shown in Figure 4. Two sensors on one side of the coupon and the other two on the other side of the coupon. All dimensions are in mm.
* The test parameters are:
  + 100K cycles
  + A load factor or stress ratio of 0.1 (σmin= 0.1σmax) will be used which is often used in aircraft component testing.
  + A low frequency of 3-5 Hz will be used to avoid rate dependency during the tests.
* After each fatigue cycle the EMI and voltage output measurements will be carried out.

**Bending fatigue:**

* A single coupon with a dimension of 300 mm\*60 mm \*2 mm will be prepared.
* The obtained mean value of strain values obtained from bending tests will used to determine the three strain levels in the fatigue tests.
* 100K bending cycles with a strain of 3 levels (30, 60, and 80%) of critical strain
* The sensors will be tested in both tensile and compressive configurations. If possible two sensors will be attached to a single coupon with one in tensile configuration and the other in compressive configuration and tested simultaneously rather than individually.
* The test coupon will be tested at different strain levels with a specific number of cycles for a certain strain level.
* After each fatigue cycle the EMI and voltage output measurements will be carried out.

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300

2

EP

**Top side**

TP3

TP2

**Bottom side**

TP1

60

**1000**

**30**

*Figure 4: Test setup [4] and coupon for fatigue test*

#### **Aircraft operational conditions tests:**

At some point of the time the SHM system will become airborne therefore it is necessary to analyze its performance i.e., its survivability, durability, and reliability in environmental conditions similar to those which may be encountered in airborne operation of the system. These tests will be carried out through the standard DO-160, which provides standard procedures and environmental test criteria for testing airborne equipment for the entire spectrum of aircraft. In this study the assumptions are:

* The aircraft category is D2 i.e., that the aircraft has maximum operating altitude of 50,000 ft.
* 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. There is no definition of test sample dimensions.
* The coupon size in these tests will be 300\*60\*(1-2) mm.

The tests procedures are defined as follows:

*Operating low and high temperatures:*Operating low temperatures are the lowest and the highest temperature at which transducer will normally be exposed and be required to operate defined in the standard DO-160 section 4.5.2 and 4.5.4 under category D2. Figure 5 shows the operating low and high temperature tests.

The procedure for minimum operating temperature test is described below:

* Step 1: Set the test chamber at standard ambient condition (23°C).
* Step 2: Adjust the temperature to -55°C with any rate preferably 3°C/minute.
* Step 3: Stabilize the equipment temperature to -55°C.
* Step 4: After the equipment temperature has stabilized, operate the equipment at -55°C for at least 2 hours.

The procedure for maximum operating temperature test is described below:

* Step 1: Set the test chamber at standard ambient condition (23°C).
* Step 2: Adjust the temperature to 70°C with any rate preferably 3°C/minute.
* Step 3: Stabilize the equipment temperature to 70°C.
* Step 4: After the equipment temperature has stabilized, operate the equipment at 70°C for at least 2 hours.

Diagram

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*Figure 5: Operating low and high temperature tests*

*Thermal cycling:* This test determines performance characteristics of the equipment during temperature  
variations between high and low operating temperature extremes as per D0-160. Components may experience temperature variations during normal operation e.g., during take-off and landing. This test is intended to be a dynamic temperature test and is defined in the standard DO-160 section 5.3.1 under category B. Figure 6 shows the thermal cycling test.

The test procedure is as follows:

* Step 1: Start at standard ambient temperature (23 °C)
* Step 2: Lower the temperature in the chamber to the operating low temperature level (-55 °C) at a rate of 5 °C/min.
* Step 3: Stabilize the equipment in the operating mode at this operating low temperature level (-55 °C) for about 1 minute.
* Step 5: Increase the temperature in the chamber towards the operating high temperature level (70 °C) at a rate of 5°C/min. During the temperature change test, the equipment.
* Step 6: Stabilize the equipment in the operating mode at this operating high temperature level of (70 °C) for a time of 1 minute.
* Step 7: Switch off the equipment under test and maintain the equipment in a non-operating state for 2 minutes.
* Step 9: Turn the equipment on
* Step 10: Lower the temperature in the chamber towards the operating low temperature level (-55 °C) at a rate of 5°C/min
* Step 11: Stabilize the equipment in the operating mode at this operating low temperature level of (-55 °C) for a time of 1 minute
* Step 12: Turn off the equipment and wait 30 minutes
* Step 14: Change the temperature of the chamber towards the ambient temperature (22 °C) at the applicable rates of 5 degrees Celsius minimum per minute)
* Step 15: Stabilize the chamber and the equipment at ambient temperature
* Step 16: Repeat steps 3 to 15 for another time (Total of 2 cycles)

Diagram

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Figure 6: Thermal cycling test

*Hot-wet:* This test determines the ability of the equipment to withstand either natural or induced humid atmospheres. The main adverse effects to be anticipated are:

* Corrosion.
* Change of equipment characteristics resulting from the absorption of humidity.

Note: The humidity test shall not be conducted prior to the temperature/altitude tests and vibration test.

The test procedure is as follows as also shown in Figure 7:

* Step 1: Install the test item in the test chamber.
* Step 2: Stabilize the test item at a temperature of 30±2 °C and Relative Humidity (RH) of 85±4 %.
* Step 3: Over a two-hour period, ±10 minutes, raise the chamber temperature to 50±2 °C and increase the RH to 95±4 %.
* Step 4: Maintain the chamber temperature at 50±2 °C with 95±4 % RH for six hours minimum.
* Step 5: During the next 16-hour period, ±15 minutes, decrease the temperature gradually to 38±2 °C or lower. During this period, keep the RH as high as possible and do not allow it to fall below 85 %.
* Step 6: Steps 3, 4 and 5 constitute a cycle. Repeat these steps until a total of two cycles (48 hours of exposure) have been completed.
* Step 7: At the end of the exposure period, remove the equipment from the test chamber and drain off (do not wipe) any condensed moisture. Within one hour after the two cycles are completed, apply normal supply power, and turn on the equipment. Allow 15 minutes maximum following the application of primary power for the equipment to warm up. For equipment that does not require electrical power for operation, warm up the equipment for 15 minutes maximum by the application of heat not to exceed the short-time operating high temperature test as required by applicable equipment categories. Immediately following the warm-up period, make such tests and measurements as are necessary to determine compliance with applicable equipment performance standards.

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*Figure 7: Hot-Wet test*

The flowchart describing the step-by-step process of work package is shown in Figure 8.

#### **Flow chart of the work package 1**

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

**Preparation of specimen**

**Selection of thermoplastic bonding films and using new manufacturing method**

**Mechanical and AOE tests**

**(Simulate loading and aircraft conditions)**

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

**- DSC test**

**- Shear lap strength test**

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

**Integration techniques:**

**- Curing/consolidation**

**- Welding**

**- Capacitance**

**- Impedance/admittance**

**- Guided wave measurements**

**- Bending tests**

**- Fatigue tests**

**- AOC tests (D0-160)**

**- 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 diagnostics

*Figure 8: Flow chart of the work plan*

## **3.2. Work package 2: Novel sensor integration method through welding**

**Motivation:**

* The current method of joining the sensors is manual and therefore slow, costly and requires enhanced effort. The need is to develop and test novel sensor joining techniques that are fast, cost saving and can be automated. One of the promising techniques that can be used to joining sensors is through welding. This is possible in case of TP adhesive films because of their weldability property.
* In some welding types such as US and induction welding the heat is localized at the interface and the bonding time is very fast therefore the melting temperature range of the TP films can be increased. Due to localized and short heating time, the amount of heat transferred to the sensor is significantly decreased. Hence TP films with higher melting temperature (above maximum temperature of the sensor) can be used.
* In some welding types a number of sensors can be joined at the same time for example in induction welding which is a continuous type of welding. Therefore, significantly decreasing the sensor integration time and making it suitable for industrial purposes.

**Aims:**

* To test different welding methods for joining the sensors to the TP based composites using TP films.
* To evaluate the feasibility of bonding the sensors with this novel bonding method.
* To test the integration, survivability, and the reliability of sensors bonded with welding using different testing and loading conditions. The mechanical testing will only be carried out for the films that have been found reliable through previous testing where sensors were bonded using consolidation (section 3.1.1).

**Methodological approach:**

There are various welding methods discussed in literature that are used to join TP polymers or composites. Among the main categories are thermal, frictional, and electromagnetic welding [14], which includes ultrasonic, induction, conduction, resistance, gas, and tool welding. Based on a preliminary study the most suitable methods that could possibly be used to weld the surfaces to composite surfaces are ultrasonic, induction and conduction welding. Other welding types of welding such as hot gas, hot tool, friction stir welding, laser welding etc. cannot be used because it is most likely that the sensor will be degraded during the welding. For e.g., the main obstacle in using laser for welding TP polymers is the high intensity of laser beams, which very quickly decomposes (burn) the TP polymers even at low laser power levels [14]. While as in hot-tool welding the tool first melts the surfaces to be weld and then the tool is withdrawn which is not possible in welding the sensors through TP films [14]. The possible methods namely ultrasonic, induction and conduction welding with their possibilities and limitations have been summarized in Table 4.

When testing the feasibility and durability of the above-mentioned possible welding types only those TP films will be considered which are compatible with welding and have passed the survivability and reliability tests as described in section 3.1.1. This is to make sure that the TP bonding films themselves are not responsible for the poor performance during the welding process. Furthermore, only critical mechanical tests such as bending, and fatigue will be considered to evaluate the survivability and reliability of the sensors integrated by welding.

*Table 4: Possible types of welding for sensor integration*

|  |  |  |
| --- | --- | --- |
| Welding type and principle | Possibilities | Limitations |
| Ultrasonic (US) welding:  In US welding the US waves vibrate tens 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[15, 16]. | * Ultrafast and good bonding quality can be achieved * Localized heating [14], higher melting temperature TP films can be used. * Independent of using a particular material at the interface, as required in resistance and other welding methods. * Solid-state process no external heat is added for welding | * High pressure and vibrations on the adherents * High shear forces at the bond line * Size of the parts to be weld * Spot welding at only one location at a time continuous welding still in development [15] |
| Induction welding:  Induction welding is a form of welding that uses electromagnetic induction to heat the workpiece. The induction coil generates a high-frequency electromagnetic field that acts on either an electrically conductive or a ferromagnetic workpiece. In an electrically conductive workpiece, the main heating effect is resistive heating, which is due to induced currents called eddy currents. In a ferromagnetic workpiece, the heating is caused mainly by hysteresis, as the electromagnetic field repeatedly distorts the magnetic domains of the ferromagnetic material. The heat melts the material to create a weld[17–19]. | * Low pressure * Continuous welding as compared to spot welding. A number of sensors can be bonded at once * Size is not a problem * Can be designed such that no heat is produced outside of the desired weld area. Therefore, higher melting temperature TP films can be used * It will be interesting to see how the susceptor like metallic mesh or carbon fiber and TP films composite will influence the bond mechanical performance like shear strain and bond strength. | * May require susceptor/implant * Harder to focus the heat at the weld-line * Thicker bond line because of the insertion of the susceptor |
| Conduction welding via hot press | * Simpler and economical method as compared to US and induction welding | * Bonding a number of sensors at once may not be possible * Heat is not localized therefore only low melt TP films can be used * Sensor in direct contact with hot surface can damage the sensor |

#### Ultrasonic welding:

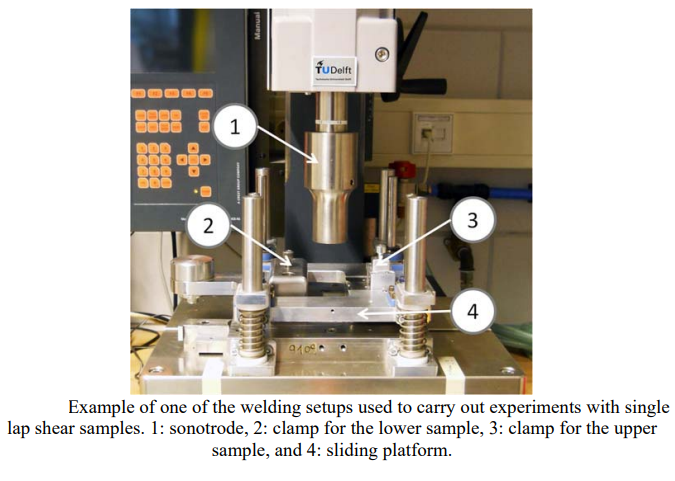
During the US welding of the sensors to the composite surface, a TP film will be kept between the sensor and the host surface. Then pressure and high frequency and low amplitude vibrations will be applied on the top surface of the upper adherend i.e., the sensor through a sonotrode. Following the vibration phase, a solidification phase, will be applied during which the weld is allowed to cool down under pressure.

The machine settings in most of the US welder can be controlled and this will be selected depending upon the contains such as the maximum pressure that the sensos can endure before degrading custom-made clamping setups can be designed based on the sensor shape and dimensions [15].

In the beginning a hand US welder will be used as a proof of concept. Different machine settings and methods will be tested to protect the sensor in case of any degradation to the sensor due to pressure and vibrations. Once the feasibility tests are carried out, then trials can be conducted on a US machine which has more control on the process parameters for further investigation. Figure 9 show the ultrasonic machine at TU delft and hand US machine at FIDAMC.

**Possible challenges:**

* The combined effect of pressure and vibration can prove very crucial and can lead to the degradation and damage to the sensors during the welding. The control and fine tuning of the pressure, vibration (amplitude and frequency) and power can be a deciding factor in the feasibility of this technique for joining the sensors.
* The direct contact of the sonotrode and the sensor surface can lead to damage and degradation of the sensor.
* The static compressive strength of the sensor according to the manufacturer datasheet is 600 MPa [20].Compressive tests will be conducted to see the maximum compressive force that the sensor can withstand before complete failure. This will give an idea about the amount of force that can be applied.



*Figure 9: US welding machine setup at TU-Delft [15] and Hand US welding machine (FIDAMC*)

#### Induction welding:

The DuraAct sensor which is a PZT material embedded in an epoxy matrix is neither electrically conductive nor electromagnetic. The sensors will be joined to the composite surfaces through TP films which will be kept in between the sensors and the host structure. Since the TP film is not electrically conductive therefore it is necessary to use a susceptor to melt the TP film. In the literature different types of susceptors have been used such as metal additives and carbon fiber in the form of uniformly dispersed particle, powder, and woven structures [17, 21]. The usage of the susceptor material should be minimized as much as possible in order to decrease their effect on bond quality and on the actuation and reception of ultrasonic waves. The suitable susceptors that can be used for joining the sensors to the composite surfaces are the following (Figure 10):

* Metallic mesh or metallic fibers
* Carbon fiber
* Small and uniformly dispersed particles

Metal mesh/Carbon fiber/ Dispersed particles

Thermoplastic film

Thermoplastic film

Sensors

Composite surface



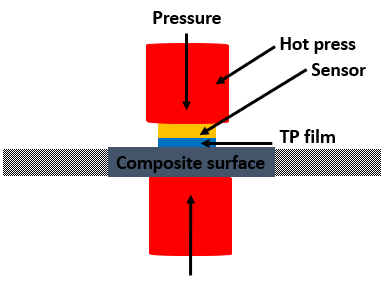
*Figure 10: Layout of the bonding films in the induction welding*

**Possible challenges:**

* **Bond thickness:** Due to the susceptor material being sandwiched between two TP films the overall thickness can be large. This can lead to the decrease in the signal amplitude of the guided waves send and received by the sensors. This can be solved by minimizing the amount of the susceptor being used.
* **Heat distribution over the melt region**: The heat should be uniformly distributed in the region of the TP film so that a uniform bonding quality is achieved. This is sometimes difficult to achieve in induction welding particularly when power is used as a susceptor.

#### Conduction welding via hot Press:

The press technique can be another option that can be used to weld the sensors. The heat in this this case is transferred to the TP film through the sensor via conduction. During the heat transfer the sensor and the bonding surface held together under pressure as shown in Figure 11.



*Figure 11: Schematic of conduction welding*

**Possible challenges:**

* **Sensor degradation:** Direct contact of the hot press and the sensor surface can degrade the sensor. Therefore, it is necessary to protect the sensors surface from the hot press.
* **Degradation due to heat:** Since the heat is transferred to the TP films via conduction therefore it is possible that the temperature limits of the sensor might be exceeded which can degrade the sensor. Therefore, TP films with lower melting temperature will be chosen so that the temperature limit of the sensor is not exceeded before the TP adhesive film melts.

## **3.3**. **Work Package 3: Minimization of number and weight of the cables and development of new connection system**

## **3.3.1. Printed circuits for Minimization of number and weight of the cables**

**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 [26]. 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. A few studies have tried to solve the problem by replacing the cables with printed circuits and proved the feasibility of such concepts to some extent [26–28]. In most of these studies silver ink has been used to produce the conductive paths. Recently CNTs and GNPs have also been used to produce conductive paths in other applications such as conductive paths for de-icing systems [29], producing printed sensors [30, 31] and printed paths for energy harvesting [32]. The aim of this study will be producing conductive paths using CNTs and GNPs in addition to silver inks. The CNTs and GNPs will be an interesting choice due to their excellent electrical and thermal properties, lower power consumption, controlled conductivity, and their ability to be 3D printed [29].

**Aims:**

* Reduce the number of cables with extremely lightweight circuits.
* Testing different materials for creating the conducting circuits metallic ink (silver ink), CNTs and GNPs.
* Characterization and assessment of the integrity and reliability of the printed circuits or conductive paths produced using different materials.
* Comparing the guided wave signal actuation and reception between traditional cables and light weight conductive paths.

**Methodological approach:**

**Materials and methods:**

The following materials will be used to produce the lightweight conductive paths:

* Printed polymer layer/TP film layer/Kapton layer for insulation form carbon fibers
* Conductive metallic ink (Silver/Copper) for printing conductive circuits.
* Conductive inks based on epoxy matrix or paint doped with CNTs and/or GNPs for producing conductive paths.

The first step is to place a dielectric layer over the carbon fiber composite. This can be achieved by printing, stamping, or welding a polymer layer e.g., low melt TP films (same use for bonding the sensors) or Kapton over the composite surface. Once a di-electric layer has been formed then the conductive paths will be produced by printing silver ink and epoxy, or paint doped with CNTs and GNPs conductive ink. The final optional step is to place another polymer film over the printed circuits or conductive paths in order to protect them and reduce the crosstalk effect. Table 5 summarizes the different inks to be used with their deposition process and possibilities and limitations.

In SHM by guided waves using PZT sensors the typical working voltages range is input (-90 to 90 V) and output (-50 to 50 V). The capacitance range of these sensors is about 4 to 20 micro-Farad (μF). Therefore, the charge intensity range is about -360-1800 micro-Coulomb (μC). In this study DuraAct sensors are being used, the input voltage range will be around 6-20 voltage, Capacitance 8 nano-Farad (nF) and therefore the charge range is 48-160 nC. The thickness of the conductive paths is an important parameter, and this will be chosen based on the conductivity required.

**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 following sub sections. The layout of the conductive paths is shown in Figure 12. The coupons under consideration will be flat coupons and curved coupons with small curvature.

Printed polymer layer/Thermoplastic film layer to bond the Kapton layer on to the composite surface

Composite

Kapton layer/ TP layer that has good adhesion properties

Printed circuit/conductive paths using different materials

Protection layer (To reduce the crosstalk effect)

*Figure 12: Layout of the printed paths using different inks*

*Table 5: Ink types and their possibilities and limitations*

| Ink | Di-electric printing substrate | Deposition process | | Advantages and  dis-advantages |
| --- | --- | --- | --- | --- |
| Silver or copper ink  Epoxy or paint doped CNTs/GNPs | * Kapton/other durable and material with high surface adhesive properties * Low melt TP films | * Ink deposition by additive manufacturing (inkjet printing) * Printing of multiple layers to decrease resistivity in a width of 1-2 mm * Ultra-violet post-curing treatment or sintering after printing the ink i.e., heating for a specific time a particular temperature to remove solvents and fuse the ink with the substrate**.** | **Advantages**   * Relatively easier to produce the ink * More literature available   **Dis-advantages**   * Lower mechanical properties than CNTs and GNPs * Dimensional distortion * Controlling the deposition of droplets when depositing through ink-jet printing * Adhesion to the composite surface | |
| * Kapton/other durable and material with high surface adhesive properties * Low melt TP films | * Preparation of epoxy/paint doped CNT/GNP inks by calendering dispersion process [29]. * Deposition of inks on composite surfaces through 3D printing * Epoxy based conductive inks doped with CNTs | | **Advantages**   * Excellent mechanical, electrical, thermal and piezoresistive properties * CNTs allow for increasing the electrical conductivity of the nanocomposite by several orders of magnitude by adding low filler contents (below 1 wt.%) [30]   **Dis-advantages [33]**   * Viscosity * Dispersion quality * A minimum percolation threshold is required |

**Measurement of performance of printed circuits as compared to the traditional cables will be carried out by the following measurements:**

* Signal amplitude of lamb waves
* EMI measurement

**Integrity and reliability assessment of the printed circuits (as discussed in section 3.1 “Mechanical tests”):**

* Tensile tests
* Mechanical and electric fatigue tests
* Hot-wet

In the integrity and reliability assessment of the printed circuits electric fatigue will be carried out in addition to the tests described in section 3.1. The description of the fatigue test is described below:

The influence of several excitation cycles on signal amplitude will be investigated. The conductive paths will be electrically fatigued using a 250 kHz five-cycle Hanning-windowed tone-burst with an output voltage of 6 V for 0, 108, 5 *×* 108, 109, and 2 *×* 109 cycles. The range of selected voltage amplitude is generally used for excitation of ultrasonic Lamb waves in SMH applications [26]. At the end the maximum signal amplitude of the reference specimen will be compared with the fatigued ones to see whether there is any degradation.

## **3.3.2. Connection between sensor and printed circuits**

**Motivation:**

Another important element to be considered are the connections between the printed paths and the sensors. Some authors have used conductive epoxy [31] to connect sensors with the conductive paths, however it is likely to fail under high loads. This is a critical element that needs to be designed in such a way that the connection between the sensors and the printed circuits is secured, is able to survive during different loading conditions and should not be too complex and bulky.

**Aims:**

* Development of a new connecting element between the sensors and the printed paths.
* Using a single surface-mounted connector instead of several required connectors.

# **Planning of Activities**

The draft time and work plan and the place where these activities will be carried is given in the table (Table 6) below:

*Table 6: Activities planning*

|  |  |
| --- | --- |
| Place | Work |
| FIDAMC  Nov. 2020 - Dec.2021  July 2022 – Oct. 2023 (including second secondment\*) | * Manufacturing of coupons/elements * Bending test * Fatigue tests (Tensile) * AOC tests * Temperature and thermal cycling * Hot-wet/Humidity * Formulation of functional inks * Development and characterization of the printed circuits and conductive paths * Welding of sensors |
| DLR  First Secondment  Jan 2022-June 2022 (Planned) | * Fatigue tests (Bending) * Development of the connection system |
| Second secondment  Not planned/decided yet  Proposed TU-Delft | * Welding of sensors |
| Universidad Rey Juan Carlos | * Printing of conductive paths |

**References**

1. M H Ferri Aliabadi & Z Sharif Khodaei (2018) Structural Health Monitoring for Advanced Composite Structures Computational and Experimental Methods in Structures: Chapter 1, Structural Health Monitoring for Advanced Composite Structures. World Scientific, London

2. Eckstein, Bach, Bockenheimer, Cheung, Chung, Zhang, Li Large Scale Monitoring of CFRP Structures by Acousto-Ultrasonics—A Flight Test Experience

3. Salmanpour MS, Sharif Khodaei Z, Aliabadi MH (2016) Airborne Transducer Integrity under Operational Environment for Structural Health Monitoring. Sensors (Basel) 16. https://doi.org/10.3390/s16122110

4. Nan Yue, Zahra Sharif Khodaei, M.H. Aliabadi An innovative secondary bonding of sensors to composite structures for SHM application

5. Marzani A, Testoni N, Marchi L de et al. (2020) An open database for benchmarking guided waves structural health monitoring algorithms on a composite full-scale outer wing demonstrator. Structural Health Monitoring 19:1524–1541. https://doi.org/10.1177/1475921719889029

6. Djukic S, Bocahut A, Bikard J et al. (2020) Mechanical properties of amorphous and semi-crystalline semi-aromatic polyamides. Heliyon 6:e03857. https://doi.org/10.1016/j.heliyon.2020.e03857

7. Park G, Farrar CR, Di Scalea FL et al. (2006) Performance assessment and validation of piezoelectric active-sensors in structural health monitoring. Smart Mater Struct 15:1673–1683. https://doi.org/10.1088/0964-1726/15/6/020

8. Eric F Structural Health Monitoring Using Statistical Pattern Recognition: Data Acquisition II: Piezoelectric Devices

9. Giurgiutiu V (2014) Structural health monitoring with piezoelectric wafer active sensors. Academic Press an imprint of Elsevier, Amsterdam

10. Lin B, Giurgiutiu V, Pollock P et al. (2010) Durability and Survivability of Piezoelectric Wafer Active Sensors on Metallic Structure. AIAA Journal 48:635–643. https://doi.org/10.2514/1.44776

11. Inka Buethe, Maria Moix-Bonet, Peter Wierach et al. Check of Piezoelectric Transducers Using the Electro-Mechanical Impedance

12. Moix-Bonet M, Buethe I, Bach M et al. (2014) Durability of Co-bonded Piezoelectric Transducers. Procedia Technology 15:638–647. https://doi.org/10.1016/j.protcy.2014.09.025

13. Jelena Proceedings DR-MR.pdf

14. Yousefpour A, Hojjati M, Immarigeon J-P (2004) Fusion Bonding/Welding of TP Composites. Journal of TP Composite Materials 17:303–341. https://doi.org/10.1177/0892705704045187

15. Palardy V Smart Ultrasonic Welding Of TP Composites

16. Bhudolia SK, Gohel G, Leong KF et al. (2020) Advances in Ultrasonic Welding of TP Composites: A Review. Materials (Basel) 13. https://doi.org/10.3390/ma13061284

17. Ahmed TJ, Stavrov D, Bersee H et al. (2006) Induction welding of TP composites—an overview. Composites Part A: Applied Science and Manufacturing 37:1638–1651. https://doi.org/10.1016/j.compositesa.2005.10.009

18. Moser L (2012) Experimental analysis and modeling of susceptorless induction welding of high performance TP polymer composites. Zugl.: Kaiserslautern, Techn. Univ., Diss., 2012, Als Ms. gedr. IVW-Schriftenreihe, vol 101. Inst. für Verbundwerkstoffe, Kaiserslautern

19. Dhondt MC Induction welding of high performance TP composites

20. PI-Ceramic GmbH Piezoelectric Ceramic Products Datasheet

21. Bayerl T, Duhovic M, Mitschang P et al. (2014) The heating of polymer composites by electromagnetic induction – A review. Composites Part A: Applied Science and Manufacturing 57:27–40. https://doi.org/10.1016/j.compositesa.2013.10.024

22. Hudson TB, Yuan F-G (2018) Automated In-Process Cure Monitoring of Composite Laminates Using a Guided Wave-Based System With High-Temperature Piezoelectric Transducers. Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems 1. https://doi.org/10.1115/1.4039230

23. Lin M, Chang Fu-kuo (2002) The manufacture of composite structures with a built-in network of piezoceramics. Composites Science and Technology 62

24. Holst C-A, Lohweg V, Rockemann K et al. (2019 - 2019) Lamb wave-based Cure Monitoring of Carbon Fibre Reinforced Polymers for On-site Aircraft Repairs. In: 2019 IEEE 5th International forum on Research and Technology for Society and Industry (RTSI). IEEE, pp 384–388

25. Chilles JS, Koutsomitopoulou AF, Croxford AJ et al. (2016) Monitoring cure and detecting damage in composites with inductively coupled embedded sensors. Composites Science and Technology 134:81–88. https://doi.org/10.1016/j.compscitech.2016.07.028

26. Bekas DG, Sharif-Khodaei Z, Aliabadi MHF (2018) An Innovative Diagnostic Film for Structural Health Monitoring of Metallic and Composite Structures. Sensors (Basel) 18. https://doi.org/10.3390/s18072084

27. D G Bekas, Z Sharif Khodaei, M.H. Aliabadi Structural health monitoring of scarfed repaired composite panels using inject-printed patterns

28. Bekas DG, Saenz-Castillo D, Sharif Khodaei Z et al. (2019) Smart Bondline Monitoring of an Efficient Industrial TP Aircraft Window Frame. KEM 827:470–475. https://doi.org/10.4028/www.scientific.net/KEM.827.470

29. Cortés A, Jiménez-Suárez A, Campo M et al. (2020) 3D printed epoxy-CNTs/GNPs conductive inks with application in anti-icing and de-icing systems. European Polymer Journal 141:110090. https://doi.org/10.1016/j.eurpolymj.2020.110090

30. Cortés A, Sánchez-Romate XF, Jiménez-Suárez A et al. (2021) Complex Geometry Strain Sensors Based on 3D Printed Nanocomposites: Spring, Three-Column Device and Footstep-Sensing Platform. Nanomaterials (Basel) 11. https://doi.org/10.3390/nano11051106

31. Bekas DG, Sharif-Khodaei Z, Baltzis D et al. (2019) Quality assessment and damage detection in nanomodified adhesively-bonded composite joints using inkjet-printed interdigital sensors. Composite Structures 211:557–563. https://doi.org/10.1016/j.compstruct.2019.01.008

32. Kim HS, Kang JS, Park JS et al. (2009) Inkjet printed electronics for multifunctional composite structure. Composites Science and Technology 69:1256–1264. https://doi.org/10.1016/j.compscitech.2009.02.034

33. Bekas DG, Hou Y, Liu Y et al. (2019) 3D printing to enable multifunctionality in polymer-based composites: A review. Composites Part B: Engineering 179:107540. https://doi.org/10.1016/j.compositesb.2019.107540