Tailored Embeddable Sensor-Actuator Layers for CFRP Aerospace Structures

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Abstract. The increasing structural integration of fibre-reinforced composites and the growing demand for more electrical and intelligent structural components are one of the future markets for aerospace and aviation industry to master growing economic and ecological challenges.

Fibre-reinforced composites offer the opportunity to embed sensor and actuator networks in the material, which is of particular relevance for example for structural health monitoring (SHM) applications. In order to maintain the structural integrity and necessary safety margins of the carbon fibre-reinforced plastic (CFRP) components, the elements (e.g. sensors, conducting paths, carrier layer, etc.) which will be integrated will have to be selected by extensive experimental characterization. To realize this, a methodology has been developed to embed tailored functional layers, assembled with piezo ceramic elements, into structural components made of CFRP. Due to the high sensitivity, high temperature stability, commercially availability as well as the variable small element sizes of the piezo ceramic elements, they are predestined for the integration into CFRP.

The resulting smart structures provide both, sensoric and actoric functionalities. Thus, the developed Tailored Embeddable Sensor-Actuator Layers (TEmSAL) are particularly characterized by „off-the-shelf" manufacturing, cost-efficiency, a high automation capability, tailored sensing capabilities for customized applications and parts, and a low impact on mechanical CFRP properties. The presented investigations show the aspects of the characterization and manufacturing strategy on specimen level, the resulting structural properties of the CFRP material and sensor as well as actuator performance. Additionally, TEmSAL CFRP engine components will be covered as an outlook for further investigations and applications.

Keywords: function integration, piezo ceramic module, active composite structures, screen printing conductive paths, impact localisation, structural health monitoring

1 Introduction

Sensor and actuator networks are of rising interest for aerospace applications. An embedding in carbon fibre-reinforced plastic (CFRP) components offers the possibility for in-situ structural health monitoring (SHM) of the component, by detecting structural response changes like eigenfrequency shifts or varying damping behaviour due to damage or fatigue [1], [2]. Additionally, these systems can be used for the detection of external disturbances during operation time, like dynamic and high dynamic loading scenarios caused by tool drop, hail, stone, ice and bird impact or foreign object damage (FOD). With such information one can either adapt or individually plan the service and maintenance interval as well as gather more realistic field data for the design and analysis process of future components. This results in a better understanding of the material behaviour and consequently in improved material damage, failure and deterioration models.

The high specific mechanical properties of epoxy resin based thermoset CFRP result in a broad applicability for high performance structural components. However, the integration of electric components are one of the biggest challenges due to the inherent electrical conductivity of the CFRP material.

In this study a method is presented to design and manufacture sensor and actuator networks, which are adaptable to the needs of the component and their functional intention. One key electric element for this purpose are piezo ceramic elements. They are predestined for an embedded SHM system and impact detection due to their high sensitivity, high temperature stability, relatively low price, high availability, adaptable size and their simultaneous utilization as sensor and as actuator, see Table 1.

Table 1 Advantages of piezo ceramic elements

Advantages	**Disadvantages**
+ High sensitivity → high output and low noise voltage even for small deformations	- Bridle ceramic material (but also available as flexible PVDF polymer foil)
+ Can be used as sensor and actuator elements	- Solderability sometimes difficult
+ Relatively cheap	- Stress over xx MPa lead to depolarisation
+ Needs not necessarily a conductive connection to signals paths (high fault tolerance contacting)	- Voltage measurement equipment needs protection circuitry for high piezo loads (up to kV)
+ High temperature capabilities	
+ Available as very thin elements	

2 Material and specimen preparation

2.1 Manufacturing and sensor positioning

Starting point for the development of the Tailored Embeddable Sensor-Actuator Layers (TEmSAL) for CFRP structures is the integration and experimental investigation of so called “thermoplastic composite compatible piezo ceramic modules (TPM)” [3-6] within a prepreg (Hexel HexPly 8552) panel specimen (Fig. 1c) of 12 plies ($[0/90]_{6S}$).

TPMs are thin (0.2 mm) piezo ceramic modules with a quadratic (10 mm) shape, enclosed in a polyamide matrix with special designed electrode structure, mostly used in glass thermoplastic material (Fig. 1a). To electrically insulate the TPMs within the CFRP panel the copper contacts of the TPMs as well as the attached soldering terminal were wrapped in polyimide (PI) tape. Within the plate specimen 16 TPMs (Fig. 1b) were placed between two very thin glass fleeces (30 g/m^2). The electric contacts of the TPMs in the middle of the plate (#6, #7, #10 and #11) were extended with enamelled copper wire to the left and right edges of the plate. This TPM layer was then positioned between ply 10 and 11 of the prepreg plate specimen. To ensure the accessibility of the soldering terminals after the

consolidation process, the prepreg was cut out according to the position of the soldering terminals of each sensor.
After the consolidation process at 180°C and 7 bar pressure for 180 min. within a vacuum press, the positioning of the individual TPMs was checked with a computed tomography (CT) scan (Fig. 1c) and the insulation polyimide tape of the soldering terminal was removed to contact the sensors to the measuring system.

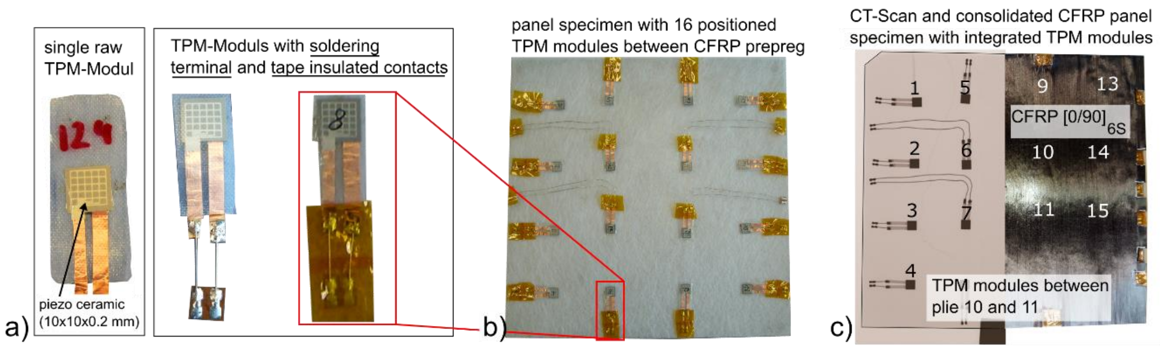

Fig. 1 a) Raw TPM with simplified contacting (soldering terminal) and isolation (polyimide tape), b) placement of 16 TPM on a 12 layer CFRP prepreg ($[0/90]_{6S}$) on additional glass fleece, c) consolidated CFRP prepreg plate specimen with integrated TPMs and additional computed tomography scan to check sensor position

2.2 Impact detection and test results

To examine the dynamic sensor capabilities of the piezo ceramic elements, impact tests with a modal hammer (Fig. 2a) were performed. In Fig. 2b an exemplary test result of a direct impact on TPM #2 of around 18 N with the corresponding sensor excitations of eight TPMs is shown. The voltage signals of the eight TPMs were recorded simultaneously with a sampling rate of 2 MS/s (mega samples per second).
On account of the high sensitivity of the TPM a voltage peak of around 7 V is gained. Due to mechanical wave propagation a delayed excitation of the other seven sensors can be observed. This results show the capabilities of the used piezo elements for detecting the impact location as well as the intensity of an impact event.

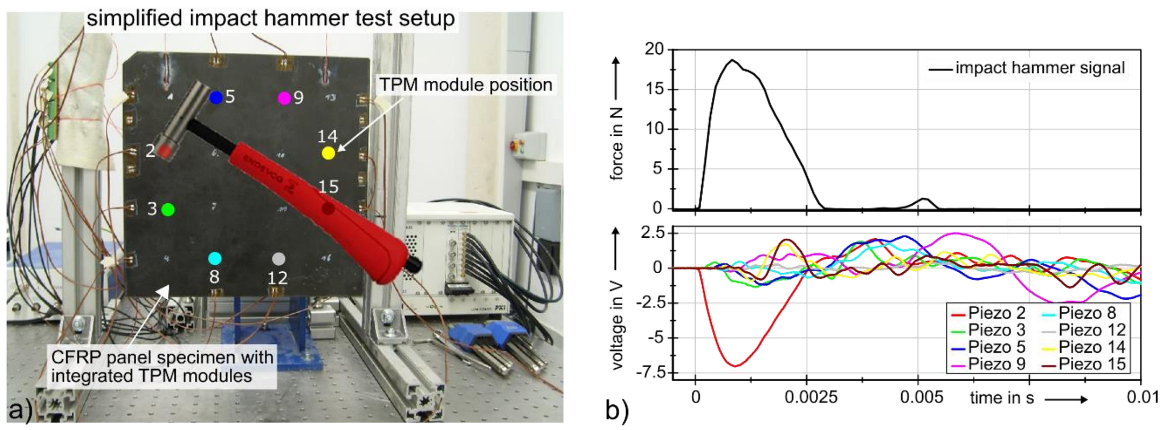

Fig. 2 a) Test setup for the impact detection experiment with a modal hammer, b) comparative diagram with the modal hammer force time signal and the voltage time response of the integrated TPMs

2.3 Structural health monitoring and test results

The ability to use integrated piezo ceramic elements either as sensor or as actuator are an essential advantage for their use in structural health monitoring systems. After detecting e.g. an impact event, a modal analysis with the same piezo elements as an excitation source can be performed in order to determine shifts in the eigenfrequency of the structural component, indicating delaminations. An alternative possibility for detecting changes in the integrity of the component is the analysis of the mechanical waves and their propagation und reflection behaviour. [7-10]
In Fig. 3a the test setup for actuator capability investigations is shown. TPM #1 is excited once with a rectangular voltage pulse of 250 V and a frequency of 0.2 Hz. To visualize the propagating mechanical waves (Fig. 3a top and bottom), induced by TPM #1, a scanning laser vibrometer is used. Fig. 3b shows the sensoric voltage response of the marked eight TPMs induced by the propagating wave. By comparing the response signals of the TPMs after an external loading event with a reference state it is possible to identify structural changes.

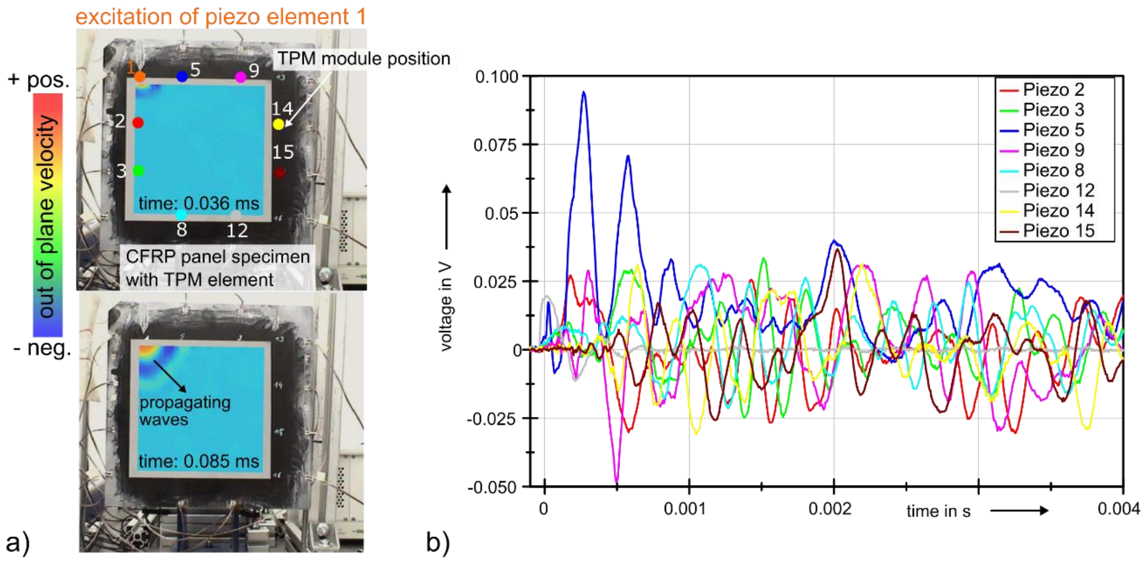

Fig. 3 a) Test setup for the structural health monitoring system, excitation of TPM #1 with half sine and corresponding wave propagation and out of plane velocity recorded with a laser vibrometer, b) voltage time response of the integrated TPMs after excitation of TPM #1

Within the impact detection and SHM tests setups the concept for the sensoric and actoric usage of the chosen piezo element has been demonstrated. However, the complicated handling of the individual TPMs, such as the addition of soldering terminals, the positioning of enamelled copper wires, the insulation of the individual modules and the TPM material (polyamide), which is unfavorable for epoxy resin-based prepreg systems, requires further development of the methodology. Furthermore, the danger of blurring of the sensors (incorrect positioning) during the manufacturing process leads to the consideration of a designated sensor-actuator layer.

3 Tailored Embeddable Sensor-Actuator Layers (TEmSAL)

The basic idea is the development of a highly adaptable to arbitrary geometry and measurement requirements. Also, it should have the capability of an automatable manufacturing process and off-the-shelf usage. The interlaminar properties of the composite component should not be weakened. The most important demands are on the one hand the electrical insulation of the layer so that it can be used in any CFRP material. On the other hand such tailored sensor-actuator layers (TEmSAL) must not affect the mechanical properties of the structural component itself, specifically the interlaminar properties should not be reduced.

3.1 TEmSAL carrier material - polymer foil characterisation

To identify suitable polymer carrier foils for TEmSAL to be used in epoxy resin based CFRP components, one of the most important design criteria are the interlaminar material properties under mode I (tension) and mode II (shear) as an indication of delamination resistance. Table 2 shows an excerpt from the experimental investigations of different polymer foils under mode I (double cantilever beam – DCB – experiment) and mode II (end loaded split – ELS – experiment) loading conditions.

The reference material configuration is a 30 ply unidirectional ($[0]_{30}$) epoxy CFRP prepreg (Hexel HexPly 8552). In the mid surface of the CFRP prepreg different polymer foils were embedded to replicate a full-surface TEmSAL. Polyamide (PA) as well as polyimide (PI), which is a widely used foil for flexible circuit boards, was characterized. Especially the energy release rate under shear loading G_{IIC} (mode II) was significantly higher than the pure CFRP reference. Under tension loading (mode I) the energy release rate G_{IC} for the pure polymer foils were partially much lower.

The most promising configuration for the TEmSAL is a combination of 2 PI. In order to connect the two PI foils an adhesive agent (AA) – Nolax cox 391 – is used. This increases the energy release rates G_{IC} (+109 %) and G_{IIC} (+346%) significantly and improves the delamination resistance substantially compared to the CFRP reference.

Table 2 Exemplary test results from the experimental investigations of different polymer foils under mode I and mode II load for the TEmSAL selection process

Configuration (CFRP material: Hexcel HexPly 8552)	**DCB experiment - mode I load** Energy release rate G_{IC} in kJ/m²	**ELS experiment - mode II load** Energy release rate G_{IIC} in kJ/m²
Pure CFRP prepreg **$[0]_{30}$**	0.280 ± 0.035 (reference)	0.73 ± 0.08 (reference)
CFRP prepreg with 100µm polyamide (PA) foil **$[0]_{15}$/PA/$[0]_{15}$**	0.052 ± 0.036 (-81.4 %)	2.16 ± 2.41 (+195.8 %)
CFRP prepreg with 125µm polyimide (PI) foil **$[0]_{15}$/PI/$[0]_{15}$**	0.192 ± 0.032 (-31.4 %)	2.78 ± 0.62 (+280.0 %)
CFRP prepreg with 2x125µm polyimide (PI) foils and 100µm adhesive agent* (AA) foil in between PI **$[0]_{15}$/PI/AA/PI/$[0]_{15}$**	**0.579 ± 0.035 (+109.7 %)**	**2.53 ± 1.46 (+346.5 %)**

*adhesive agent Nolax cox 391

In order to create a fully functional and insulated TEmSAL, two covering foils are required to position the electrical contacting surface to the piezo ceramic element and to build the conducting paths for the electrical signal. Therefore the presented combination of 2 PI polymer foils with an additional adhesive agent foil will be further investigated in detail.

3.2 Designing and manufacturing of TEmSAL

Flexible circuit boards made of PI foils, deposited and etched copper conducting paths are widely used in the electronic industry and was also a starting point for integrated sensor systems for structural composite components [11], [12]. Due to their limited size, very high price and more extensive use of chemicals (acid) an alternative process for adding conductive paths onto surfaces was chosen. By using epoxy based conductive ink, the screen printing is a very promising technology for this kind of application. One of its advantages (Table 3) is the wide industry usage with the subsequent availability and high automation capability and a fast and cheap manufacturing process. Additionally, a straight forward conductive layout design process is available, using standard CAD and vector drawing programs only.

Table 3 Advantages and disadvantages of conductive screen printing

Advantages	Disadvantages
+ Highly automatable, cheap, fast and widely used process	- no soldering possible, however wires could be bonded to conductive adhesive or soldered onto a hollow copper rivet (Fig. 5a)
+ Printing even with simple tools	
+ Printable on nearly any surface and size	
+ For printing no harming chemicals (acid) needed	
+ Easy designing process of electrical paths with standard CAD and vector programs	

A PI cover foil for 16 piezo ceramic elements was designed for the development of the manufacturing process. In Fig. 4a the workflow from designing the conductive paths and contacting surfaces in a standard CAD program (#1), over creating the vectorised screen print templates (#2) for the screen print mask (#3) to a one side printed PI cover foil (#4) is presented. Alternatively, a fully automated roll to roll screen print processing machine can be used, Fig. 4b which is necessary for a series production of the TEmSAL PI cover foils.

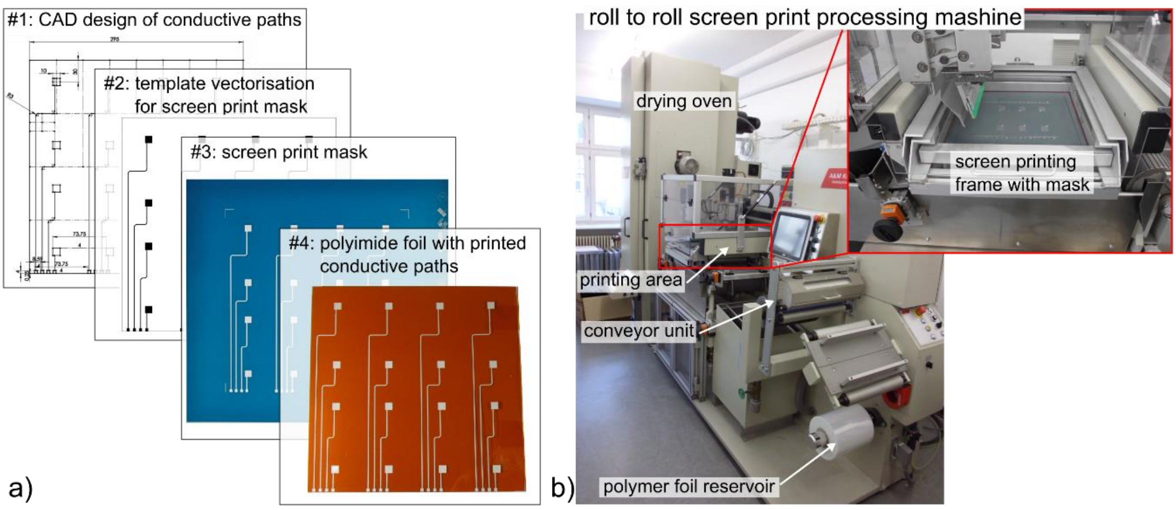

Fig. 4 a) Workflow from designing to finished conductive layout of an exemplary TEmSAL, b) roll to roll screen printing processing machine for the automated manufacturing of conductive PI cover foils for TEmSAL

In order to manufacture fully functional off-the-shelf TEmSALs (Fig. 5b) additional steps need to be done. In Fig. 5a one can see two PI cover foils with the screen printed conducting and contacting paths. On the left side the AA agent layer is placed on top of the PI cover foil. Depending on the number of measuring points, the AA layer must to be cut out on the position of the piezo contacting surface. At these points the piezo ceramic elements are fixated with additional epoxy resin. In order to be able to solder electrical wires to the screen printed conductive wire connection points, hollow copper rivets are placed. After soldering the electrical wires to the connection points, the right PI cover foil is flipped over. The package is then placed in a vacuum bag and heat treated at 180°C to activate the AA layer and consolidate the TEmSAL. Fig. 5b shows a fully functionised TEmSAL with eight piezo ceramic elements and electrical wiring.

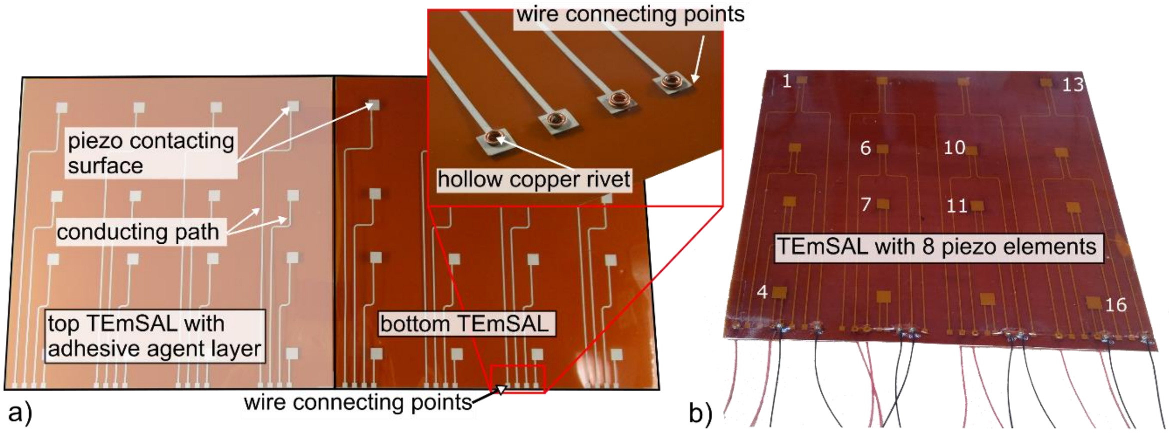

Fig. 5 a) PI cover foil with adhesive agent (left) and inserted hollow copper rivet as wire connecting points (right) before consolidation process of a TEmSAL, b) functionised TEmSAL with eight piezo elements and soldered contact wires

Consequently, the TEmSAL is positioned between ply 14 and 15 of a CFRP panel prepreg specimen $[0/90]_{8S}$ (Fig. 6a). To verify the correct positioning of the individual piezo ceramic elements a CT scan is performed (Fig. 6b). The flexibility and the small piezoelectric elements used, the integration of TEmSAL also allows an adaption to complex shaped geometries.

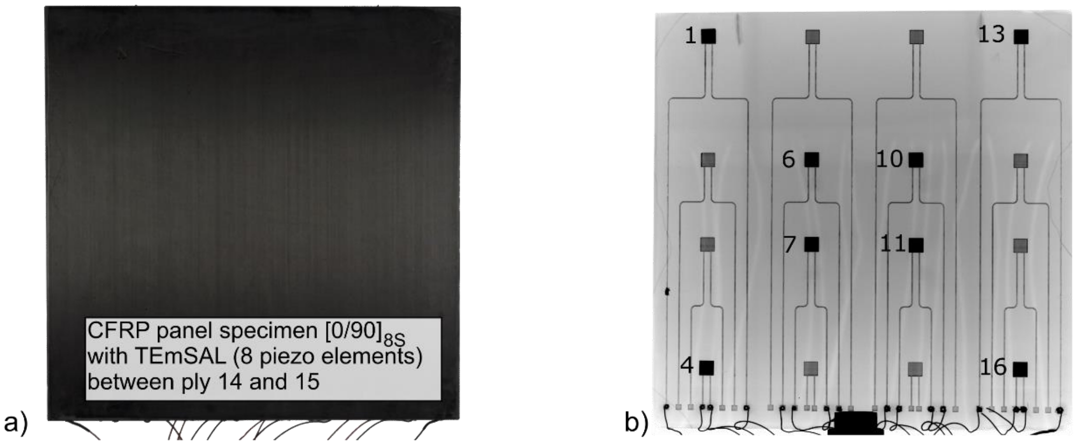

Fig. 6 a) CFRP panel specimen $[0/90]_{8S}$ with integrated TEmSAL, b) CT scan of the same panel specimen to check correct positioning of the eight integrated piezo elements

4 Structural application

To explore the potential of the developed technology on component level, the integration of the TEmSAL into a generic fan blade like structure (Fig. 7a) is presented. Due to its axially tapered (Fig. 7b, cut 1) and curved cross section (Fig. 7b, cut 2) this geometry is a suitable starting point for the validation of structural sensing and actuator capabilities. To measure the time signal of the induced piezo voltage during impact events as well as the oscillation behaviour and eigenfrequencies, the piezo ceramic elements are positioned as shown in Fig. 7c. Furthermore a modal analysis of the generic fan blade could be done in advance.

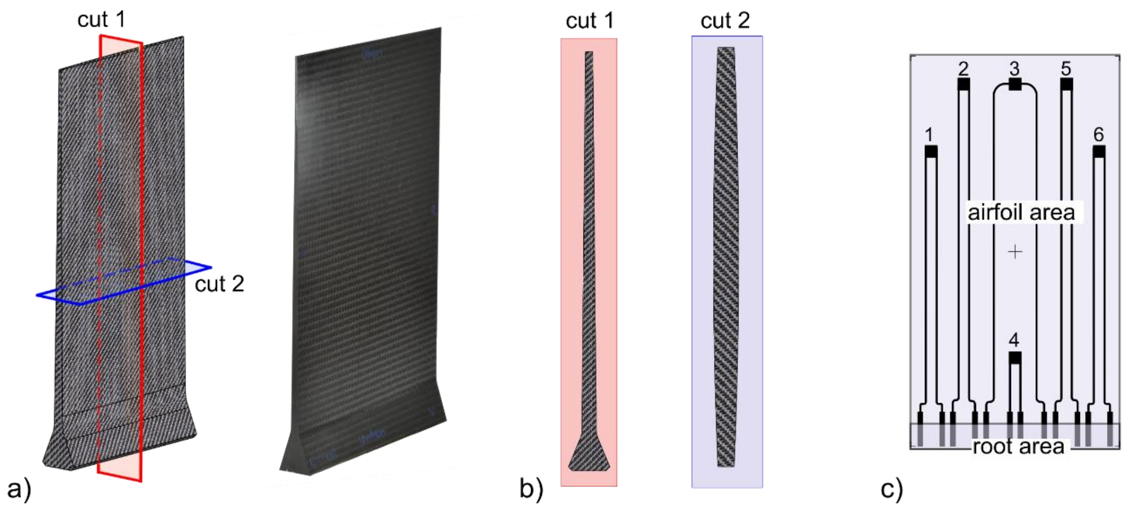

Fig. 7 a) CAD design (left) and manufacturing example (right) of a generic fan blade specimen with integrated TEmSAL, b) cross sectional cuts of the generic blade, c) sensor layer design and positioning of the piezo elements within the generic fan blade specimen

To ensure functionality of the integrated TEmSAL an impact hammer setup as well as a test setup for the SHM configuration analogously to the setups in Fig. 2 and Fig. 3 were performed. In Fig. 8a the manufactured generic blade specimen with the corresponding piezo element positons (with overlaid CT-scan), the location of the impact hammer (red circle) and the active excited piezo element #2 (orange) for the SHM test are shown.

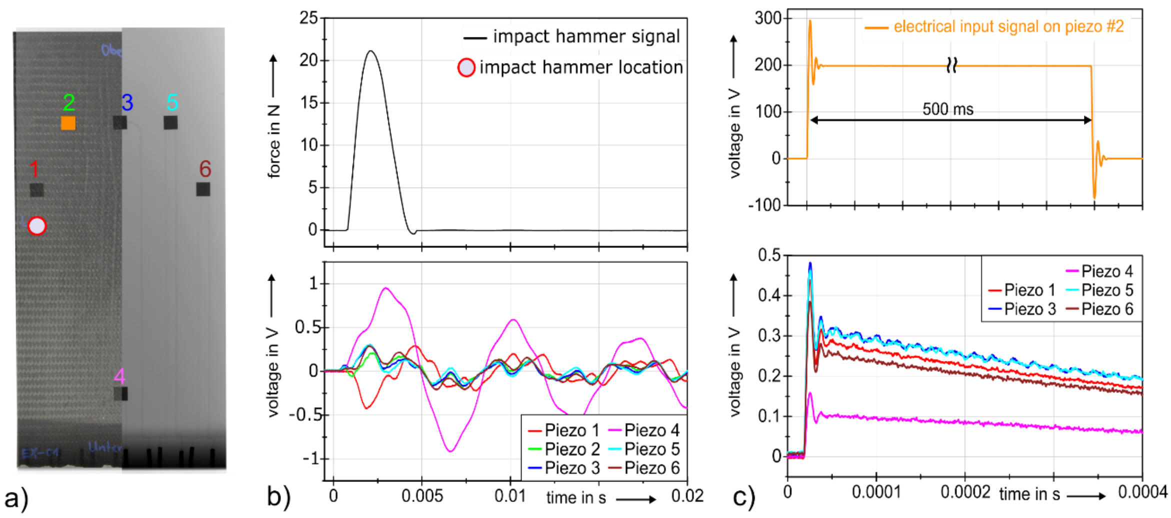

Fig. 8 a) Manufactured generic blade specimen with overlaid CT-scan to check correct piezo element positioning; location of the impact hammer (red circle) and excited piezo element #2 (orange) for the SHM test, b) force and piezo voltage time signals of the impact hammer test, c) voltage input signal of excited piezo element #2 and corresponding response of the other piezo elements

In Fig. 8b the induced impact of approx. 20 N results in a very high quality low noise response (4 MS/s sampling rate) of the integrated piezo elements. With this setup an eigenfrequency analysis can be performed to check on the one hand the manufacturing quality of the blade and on the other hand set a reference for a pre and post impact comparison to evaluate structural damage and failure.
In Fig. 8c an exemplary SHM test is presented. A voltage pulse with a nominal amplitude of 200 V and 500 ms duration is send to piezo element #2 and the corresponding voltage over time response (4 MS/s sampling rate) of the other piezo elements are plotted. This could also be repeated with the excitation of the remaining sensors in order to do an in-situ structural health comparison of the blade after an impact event.

5 Conclusions

In the presented study a methodology for designing and manufacturing embedded sensor-actuator layers for CFRP aerospace components has been developed. With Tailored Embeddable Sensor-Actuator Layers (TEmSAL) the sensor network can be individually customized for the loading and geometrical requirements of the respective component. It also features off-the-shelf capabilities for series production purposes.
It has been shown that the used PI carrier foil in combination with the adhesive agent has not only a negligible influence on the layer interface properties, but rather strengthens it and prevents delaminations. A proof of concept has been performed using impact tests to investigate sensing capabilities and excitation by the embedded piezo ceramic elements using laser vibrometer for SHM capabilities. Subsequently, the applicability of the developed concept for aerospace applications has been demonstrated by using TEmSAL in a generic fan blade like structure. Both sensor and actuator capabilities where examined. In a next step, soft body impact experiments at 120 m/s will be performed to explore TEmSAL capabilities under extreme loading conditions.

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