Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 October 2022 doi:10.20944/preprints202210.0414.v1

Review

Embedded sensors for Structural Health Monitoring: methodologies and applications review

Pedro M. Ferreira [1], Miguel A. Machado [1,2,*], Marta S. Carvalho [1,2] and Catarina Vidal [1,2]

[1] UNIDEMI, Department of Mechanical and Industrial Engineering, NOVA School of Science and Technology, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal.
[2] Laboratório Associado de Sistemas Inteligentes, LASI, 4800-058 Guimarães, Portugal.
* Correspondence: miguel.m@fct.unl.pt

Abstract: Sensing Technology (ST) plays a key role in Structural Health Monitoring (SHM) systems. ST focuses on developing sensors, sensory systems or smart materials that monitor a wide variety of materials properties aiming to create smart structures and smart materials, using Embedded Sensors (ESs), and allowing continuous and permanent measurements of the structural integrity. The integration of ESs is limited to the processing technology to embed the sensor due to its high-temperature sensitivity and the possibility of damage during its insertion into the structure. In addition, the technological process selection is dependent on the base material composition, either metallic or composite parts. The selection of smart sensors or the technology underlying them is fundamental to the monitoring mode. This paper presents a critical review of the fundaments and applications of sensing technologies for SHM employing ESs, focusing on the actual developments and innovation of these, as well as analysing the challenges that these technologies present, to build a path that allows a connected world through distributed measurement systems.

Keywords: Embedded Sensors, Sensing Technology, Smart Materials, Structural Health Monitoring, Non-Destructive Evaluation

1. Introduction

The design, fabrication, construction and implementation of Embedded Sensors (ESs), smart materials and smart structures are currently one of the greatest challenges in engineering research, as well as innovation regarding sensors and sensor systems are essential for the development of smart structures technology [1]. In this sequence, Structural Health Monitoring (SHM) consists of monitoring structures and structural components in real-time and throughout their life cycle, including during their manufacturing process, without compromising structural integrity. The structural health should remain as specified during the design stage, although it can be changed due to normal ageing and use, by environmental action and accidental events. The concept of SHM can be tackled from a periodic monitoring perspective, through periodic maintenance actions, or continuous monitoring perspective, using Sensing Technology (ST), such as embedded sensors and smart materials. Fibre Optic Sensors (FOSs) and Piezoelectric Sensors (PSs) are some of the most widely used technologies for the development of this type of materials, although there are other technologies, such as Capacitive Methods, Electromagnetic Techniques, and materials with characteristics and/or properties that can be used for structural monitoring, such as Shape Memory Alloys (SMA), as it will be verified throughout this review.

Currently, continuous and real-time SHM are assisted with the classical Non-Destructive Testing (NDT) techniques, such as ultrasounds [2], X-ray [3], infrared thermography [4], holographic interferometry [5], eddy currents [6,7], terahertz [8], among others, which require highly specialized labour along with expensive procedures. Furthermore, periodic inspections, that are the most traditional form of structural monitoring, are unable to provide any information on accidents and failures that occur between two successive revisions. Consequently, there is a growing interest in the development of sensitive materials or structures that integrate sensors that provide real-time information about the material itself or its environment. The use of these sensitive materials offers a good opportunity to implement health monitoring systems that can operate throughout the component life cycle. The continuous monitoring of the material's integrity will result in its greater durability and reliability. ESs must satisfy a set of requirements, i.e., they must not damage the structure, they must achieve similar conventional NDT techniques sensitivity and be able to monitor a significant part of the structure [9].

ST has been in constant development, resulting in successful applications, but there are a set of challenges that motivate research and development in this area, such as new sensors that can find the exact location of the damage and its characteristics, or that can monitor structural resilience, for example. Moreover, it is essential to ensure a long life of ST, or in return to create sensors easily replaceable. Wireless sensor technology represents a step forward since the use of wired sensors causes many problems, including the increased cost of the application and the cost of labour, as well as reducing the reliability of data transmission [10]. With the development that is observed in nanotechnology, it is important to invest resources in sensors inspired by this area, thus guaranteeing the possibility of implementing sensory networks in topologies and variable structures. The implementation of these sensors turns into an increase in reliability in detecting structural damage. On the other hand, more sensors will generate more data, so it is necessary to develop models for data analysis and processing for storage, that is efficient at the same time [11,12].

Since ESs are developed and optimized for monitoring certain physical and mechanical properties in specific structures and performance under particular conditions, in this article an in-depth review is carried out about the state of the art of their development and innovation. The typologies of ESs that currently exist are presented, as well as the fundamentals and physical principles underlying this technology, and its applications. A comparison is made among ESs, highlighting their advantages and disadvantages, concluding in the exposure of the challenges that this technology presents for the near future.

1. Fundaments and techniques of SHM

The SHM systems are developed based on a set of elements that represent the essence of implementing these systems. First, a SHM system consists of a sensory network connected to the structure or structural component, a network that can consist of a set of integrated sensors and possibly also smart materials. This is the main difference when compared to conventional NDT techniques. The sensory network is essential for conducting automated and continuous inspections, but the high number of sensors running continuously generates a big amount of data that needs to be processed, and in many cases in real-time. Therefore, it is necessary to have optimized data processing facilities to ensure the instant analysis of structures or structural components, through the instantaneous acquisition of monitoring data. Finally, there are essential algorithms that analyse the stored data, with appropriate corrections for environmental factors, to predict the damage location and its characterization [13–15].

There are a set of monitoring techniques that are currently used in the widest applications, being these classified as Vibration-Based Techniques [16], FOSs [17], PSs [18], Electrical Resistance Techniques [19], Electromagnetic Techniques [9], Eddy Currents Techniques [20–22] and Capacitive Methods [19].

Vibration-Based Techniques, also known as modal analysis techniques, which is analysed the dynamic response of a structure or structural component when excited by a spectrum of frequencies, are the most widely used type for civil engineering applications [23,24], such as wooden and composite structures [19,25]. Additionally, these techniques can also be implemented for the analysis of structures subject to environmental factors [26], contact detection and force sensing[27].

The implementation of technology with FOSs consists of an instrument capable of transforming a certain physical or chemical parameter into information to be monitored, by varying parameters that define the optical wave, such as intensity, phase, wavelength, and polarization. Based on the type of parameters that are changed, different types of optical sensors have been developed, being the most used the Intensity-based sensors, the Phase-modulated optical fibre sensors or interferometers, and the Wavelength based sensors or Fibre Bragg Gratings (FBG) [9,28,29]. FOSs offer great potential for SHM applications. Its importance for structural integrity monitoring applications stems from factors such as long-life cycle, high-temperature resistance, flexibility, immunity to electromagnetic interference and reduced implementation costs [30,31]. In this sequence, its application becomes very versatile and can be used for monitoring buildings, bridges, highways, pipelines, tunnels, dams [31] and railways [32], or fire safety studies and structural fire applications [33], composite materials [34] or wooden structures [19].

Traditional non-destructive ultrasonic inspection techniques suffer from challenges such as acoustic coupling, structure accessibility, and low signal-to-noise ratio in highly attenuating materials. The use of embedded or attached PSs overcomes some of these difficulties as they remain permanently attached or embedded in the structure or structural component throughout its life cycle, including during its manufacturing process. So far, most inspections using ultrasonic emission techniques have focused on piezoelectric transducers. The most significant design techniques based on piezoelectric transducers can be classified into three classes, as their behaviour can be passive, active, or mixed. These main classes are acoustic, acoustic-ultrasonic emissions using piezoelectric transducers and electromechanical impedance. The latter is one of the most promising techniques for the development of SHM systems because it is very simple to implement and use low-cost, small, and lightweight PSs. It should be noted that PSs have a wide range of applications and can be implemented in metallic or composite structures [7,9,35–40].

The Electrical Resistance Techniques can use a particular material or structural component as sensitive material, i.e., this technique is based on the variation of the resistance of a given material. An example of the application of this technique is the carbon fibres reinforced polymers (CFRP) monitoring, since carbon fibres are electrical conductors incorporated in an insulating matrix. The measurement of global electrical resistance appears to be a valuable technique for monitoring fibre cracking in unidirectional arrangements, as well as the delamination process. Therefore, carbon sensors can be used for in-situ monitoring of the structural integrity of industrial composite components (primary structures), such as aircraft wings, helicopter blades, in real-time, and possibly with lower costs when compared to current composite structure inspection techniques. Nevertheless, much has yet to be done in this area [41–44].

Inspections by Eddy Currents are one of the NDT techniques that are based on the principle of electromagnetism. The electric current of a coil creates the primary magnetic field, that in the presence of conductive material, induces alternating electrical currents in the component. Consequently, these create a secondary magnetic field, contrary to the primary, which is measured using another coil. Induced currents circulate in planes perpendicular to the magnetic flux, usually parallel to coil winding [45]. Damage changes materials conductivity affecting eddy currents and modifying the secondary magnetic field. These techniques can be used to measure electrical conductivities and magnetic permeabilities, detect defects, detect and analyse corrosion in the material, and measure coating thicknesses [6,7,20,21,46].

Other techniques that make use of the component’s electrical properties are the Low-Frequency Electromagnetic Techniques, which monitor the integrity of a given component by measuring the electrical conductivity and dielectric signature of the components [42,43]; and Capacitive Methods, in which electrodes are placed on the outer surface of the sample and electric tension is applied between them, creating a condenser system, and capacity changes are indicative of internal properties (such as the materials nature or their humidity content) [9,19]. In addition, Continuous Wave Terahertz imaging was found to be especially interesting to image water infiltrations and composite materials that contain conductive wires [8]. Thermography techniques were also used to monitor the health of systems, such as the innovative variant of Active Transient Thermography known as Double Active Transient Thermography, which increased the temperature contrast for delamination defects at different depths and locations [4].

Currently, there is a very wide set of techniques that allow the accomplishment of effective and functional SHM systems. One of the main elements of SHM is the sensory network, which is a set of sensors placed strategically on the surface or inside of the structural component, or even smart materials with sensory characteristics, networked that allow a permanent monitorization of structural components or structures. ESs is a developing strand and in the last years, studies have been intensified because the challenges that ST imposes are incentives for the progression of science. Then it will be possible to know more about the applications and the challenges that ESs technology currently provides.

3. Sensors Technology

ST focuses on the development of sensors, sensory systems or smart materials that detect a wide variety of properties of the structural components. Today's technology already allows the monitorization and detection of stimuli that exist around us, using extremely accurate sensory systems, inexpensive to install and maintain, and energy-efficient [47]. Therefore, it is fair to say that sensors are vital components for creating value in existing technological processes and their industries.

Sensors are technological devices that allow quantifying the physical, chemical, or biological properties of the materials, converting them into signals measured by appropriate equipment, as illustrated in Figure 1**Error! Reference source not found.**, existing a wide variety of sensors available for any industrial application. In addition, for more demanding industrial applications, sensors can help to improve processes and offer significant protection of industrial equipment or components [1,31,32].

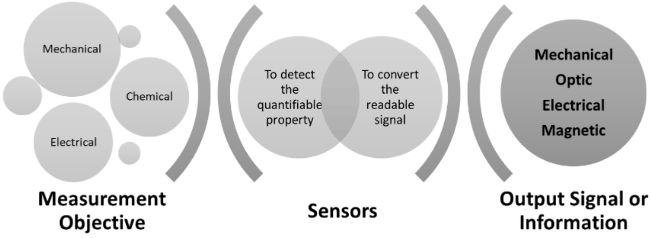


Figure 1. Sensor’s definition.

The existence of sensors in industry and structural components allows the possibility of detecting defects or damage and obtaining reports on structural integrity. Data from the implementation of sensors are processed and analysed by a set of instruments and algorithms of data analysis, and if any anomaly is identified, a set of prevention and monitoring actions is carried out to ensure the safety of industrial components [1,31,32].

With the constant evolution of ST and its recent developments, it is important to point out that sensors can be divided into Surface Sensors (SSs) and Embedded Sensors (ESs). The difference between them is depicted in Figure 2. The SSs are applied and coupled to the surface of components allowing life cycle monitoring. However, they were susceptible to damage from environmental factors or service conditions, including during the manufacturing process. The ESs are integrated into components that can result in smart materials or smart components, able to monitor themselves during their life cycle, and its manufacturing process.

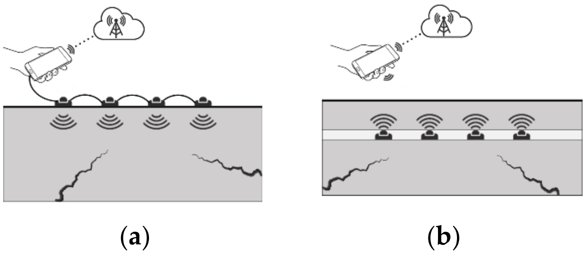


Figure 2. Implementation of monitoring sensors: (a) Surface sensors and (b) Embedded sensors.

ST can lead to two monitoring methodologies, i.e., depending on how sensors are implemented, these can lead to passive or active monitoring. Figure 3 illustrates the two possible approaches to monitor a component. In passive monitoring, the information for the analysis comes from the variation of the component physical properties being inspected, a variation that is caused by interactions that the component suffers throughout its life cycle. This type of monitoring requires that the components to be inspected have certain physical properties, such as piezoelectricity, pyroelectricity, thermoelectricity, among others [9,48–50].

In active monitoring, the information for analysis comes from the application of stimuli from an embedded actuator. The response captured caused by the stimulus is done by a set of sensors, embedded or on the surface. This type of monitoring requires that the components to be inspected have certain physical properties, such as piezo resistivity, pyro resistivity, thermoresistivity, among others [9,48–50].

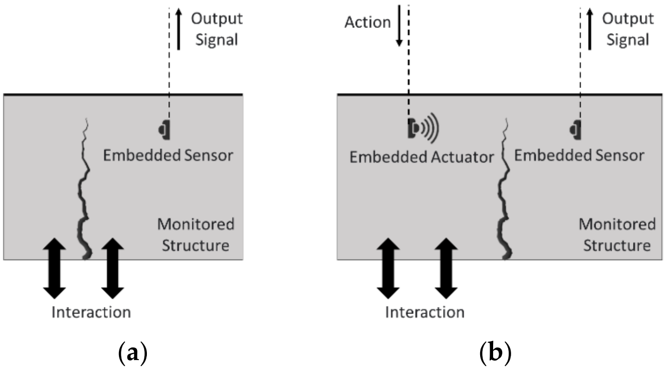


Figure 3. Component monitoring approaches with embedded sensors: (a) passive and (b) active monitoring.

SSs are the most conventional sensors used in structural integrity monitoring applications and are based on the transmission of electrical signals. However, they easily suffer electrical or magnetic interference, and due to this reason, in the last 20 years, intense developments in the field of FOSs were reached. FOSs provide a more beneficial alternative for SHM systems inspection and future smart structures, compared to traditional technologies.

Currently, the ESs are under intense development. Review studies, such as Wang *et al.* [51] and Janeliukstis *et al.* [52], have already been conducted. Wang *et al.* [51] investigated the incorporation of thin film piezoelectric sensors within aircraft composite components. This monitoring technology is quite versatile. However, other technologies may provide better results, as will be seen throughout this work. Moreover, the monitoring of metallic parts in aircrafts is very important, since it is the main material in these applications and is not included in this analysis. Relatively to the work of Janeliukstis *et al.* [52], a larger analysis was carried out, reviewing, and presenting the limitations of technologies for incorporating piezoelectric sensors and fibre optic sensors also in composite components.

This study, on the other hand, provides an overview of existing sensor technologies that can be embedded, as well as the processes and embedding techniques available, as well as the associated limitations, for metallic and composite components. With the progress of science, new mechanisms arise from the development of systems integrated into structural components, in addition to the advancement of smart materials, which is increasingly close to obtaining smart structural components. For this reason, it is presented a section exposing the recent research developed in the ESs field.

4. Embedded Sensors and Its Applications

ESs in structural components has been a topic of research in the last decades and has been showing themselves as a dominant technology. FOSs and PSs are among the most widely used technologies for the development of ESs, although there are other technologies. Throughout this section, an overview of the state of the art is presented, namely the technologies developed in the ESs area, their methodologies for sensors integration and their applications.

4.1. Fibre Optic Sensors

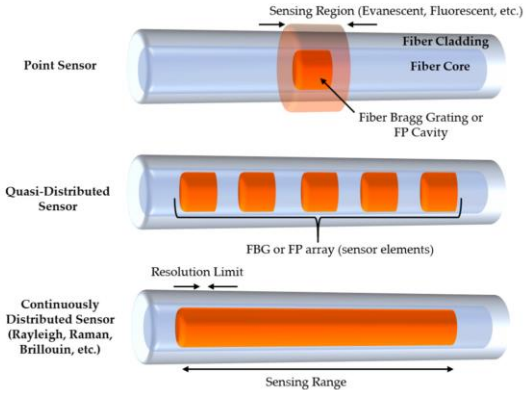
The FOSs have recently emerged as a promising technology to be incorporated into structures or structural components. With built-in sensors, it is possible to monitor structural parameters in critical locations that are not accessible for traditional sensors. In addition, these sensors can be used to validate or improve a project during the design stage or to obtain information about the performance and structural integrity of the in-service components.

FOSs are made of long-lasting materials (e.g., silica), which are resistant to corrosion and high tensile loads, with elongations up to 5%, leading to long life cycles. The resistance to high temperatures of these sensors, allow to measure temperatures from 200 to 800 °C, with a silica core, and up to 1500 °C with a sapphire core, being the measurement resolutions in the order of 0.1 °C. Another important feature is the flexibility that these sensors have because they can be applied to complex surfaces with difficult access, and can perform local or distributed measurements, which can range from 1 mm to tens of kilometres [31,53].

Each type of FOSs is based on a set of principles underlying the propagation of the optical wave and its physical properties. Although optical fibres are present at their base, FOSs can undergo geometrical (size and shape) and optical changes (refractive index and mode conversion) due to various environmental disturbances, while transmitting light from one place to another. These phenomena are unwanted, and thus, over the years such adverse influences have been attempted to minimize, to have smoother and more reliable transmitted signals. However, optical fibre has found its space in ST applications due to these optical changes that can be used to measure external stimuli. Developments in this area have shown that sensitive disturbances in temperature, voltage, rotation, electrical and magnetic currents can be converted or encoded into corresponding changes, such as amplitude (intensity), phase, frequency, wavelength, and polarization in the optical properties of transmitted light [26,31,54,55]. In Table 1 is presented a summary of the different types of FOSs, as well as the technologies implemented, the measurements they perform, the optical wave parameters that are influenced and an illustrative scheme of the technology [56–59].

Table 1. Types of optic fibre sensors (adapted from [31] and [59])

	Point Sensor	Quasi-Distributed Sensor	Distributed Sensor

Sensors	Fabry-Perot Cavity Fibre Bragg Grating Long gage sensor	Fibre Bragg Grating	Raman/ Rayleigh Brillouin
Measurands	Strain (displacement, pressure, temperature)	Strain (displacement, acceleration, pressure, relative fissure, inclination, etc.)	Temperature/ Strain
Modulation Method	Phase-modulated optical fibre sensors, or interferometers	Wavelength	Intensity
Schematic			

Many intensity-based sensors, as is the case of interferometric FOSs, are local sensors that allow measuring changes at specified locations in a structure. Interferometric FOSs are by far the most used local sensors because they offer the best sensitivity. This measuring technique is mainly based on the design of optical changes induced in light as it propagates along with the optical fibre. The light from a source is equally divided into two fibre-guided paths, one reference path and one analysis path. In the interferometric sensors are used two mirrors that are adjusted to mix the wave and form a "fringe pattern", which is directly related to the difference in the phase of optical waves caused by the two mirrors. The most common configurations of interferometric sensors are the FOSs Mach-Zehnder, Michelson and Fabry-Perot [31,56,60,61].

A Bragg grating is a permanent periodic modulation of the refractive index in the core of a single-mode optical fibre. The FBG sensor, which can be easily multiplexed to measure voltages in many locations, is a type of Quasi-distributed sensors, i.e., is a type of distributed Bragg reflector built into a short fibre optic segment, which reflects certain wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of fibre core, which generates a specific dielectric wavelength mirror. Any change in local voltage or temperature alters the core refraction index and the wave period, followed by changes in the wavelength of reflected light, which can be monitored. There are several important concerns in FBGs selection and associated monitoring systems. For example, the spectral overlap of the grating changes the adjacent desirable wavelength. On the other hand, side bands at measured wavelength, detector filter and incapable light source also introduce errors into the system [54,55,62,63].

The distributed FOSs are best suited for large structural applications since all fibre optic segments act as sensors, and therefore disturbances within various segments of the structure can be measured. This type of sensors is based on the modulation of light intensity, therefore fractures or local damage in a structure cause variation in light intensity. Two major distributed sensor methodologies are Optical Time Domain Reflectometry

(OTDR) and Brillouin dispersion. OTDR, Rayleigh and Fresnel dispersions are used to monitor structural disturbances. On the other hand, Brillouin dispersion shows the doppler change in the light frequency that is related to measurements. Distributed sensors have not found yet extensive use in civil structural applications due to their insufficient resolutions, detectable weak signals, and heavy demodulation systems. However, they can have a great potential in civil engineering due to their inherent distributive nature, if their obstacles are overcome [31,56,64].

Recently, there have been scientific reports about the inclusion of FOSs in composites and certain metallic components, particularly those having a low melting point. The techniques of inclusion of FOSs reported so far involve complex methodologies, so it is of scientific interest to look for some easier ways to incorporate the FOSs in these types of structures. Following this, sections 4.1.1 and 4.1.2 present a set of applications and methodologies that have been developed in recent years, to incorporate the sensors and ensure monitoring of the integrity of metal and composite structural components.

4.1.1. Applications for Composite Components

The components obtained with composite materials have great relevance in engineering applications, so they have become fundamental mechanisms for the control and monitoring of the component's integrity. When referring to the SHM mechanism of composite components, it includes real-time monitoring of manufacturing and curing process of composites, and in situ non-destructive evaluation of in-service structural components. So, it is difficult to perform using conventional NDT methods, arising then the possibility of using FOSs embedded in the composite component's matrix. The use of this type of sensors has a set of advantages due to their flexibility to easily form systems or sensory networks and originate smart materials, allowing continuous monitoring of the base material.

Currently, composite materials can be obtained through a wide range of products, such as metals, ceramics or even polymers. However, most applications of embedded FOSs focus on polymer matrix composites [65–72] [73] [74]. In the composite production phase, FOSs can be embedded in the matrix or between the laminates of the composite to monitor certain conditions, such as the composite stacking sequence, the resin flow during processing [65], the curing process of the laminates [73] or the misalignment of the fibres, which can lead to a significant reduction in the mechanical strength of the laminates [69]. In addition, embedded FOSs can be used to monitor residual strains and temperature profiles developed during fabrication [70]. During the post-production phase, these sensors allow simultaneous monitoring of strains and temperatures to which the component is subjected during its life cycle, and in special cases it can also be used to detect acoustic waves [74]. During the production process, misalignment, gap or overlaps of laminates or fibres may arise, and therefore such defects may endanger the component integrity when it is in service, and therefore the use of embedded FOSs ensures great control over the possible spread of defects during its life cycle [70].

In most applications of composite components monitoring, sensors such as Extrinsic Fabry-Perot Interferometer (EFPI) and FBG are implemented since these types of sensors can be easily distributed throughout a real structure with a single fibre. In addition, FBG sensors allows the identification of strains on dynamic requests and while, extrinsic Fabry-Perot interferometer allows the identification of transient events [74]. The EFPI and FBG sensors, are embedded in polymeric matrices and used to monitor in real-time and simultaneously the curing process of laminate composites, ensuring an effective damage detection during the manufacturing composites process [73]. Also, depending on the type of defect in terms of size and materials, three significant changes in the wavelength profiles of the FOSs sensors can be observed. These changes include the shape of wavelength profiles, changes in the length of corresponding waves and the wavelength profiles inclination during the cooling process at room temperature [69].

Considering the materials used to manufacture composites, and the manufacturing process, the type of fibre and the selected orientations strongly influence the temperature profiles obtained and the residual strains. In addition, FBG sensors can accurately determine the residual strains induced during the manufacturing and post-processing, as well as the thermal expansion behaviour of continuous fibre reinforced thermoplastic composites when manufactured by Fused Filament Fabrication [70].

Different applications can make use of this type of sensors. In Table 2 and Table 3 are presented an overview of the state of the art and the developments made about embedded sensors, also presenting the different types of FOSs used and the methodologies of integration of sensors for each of the applications developed.

Table 2. Overview of applications and methodology of integrating Fibre Bragg grating (FBG) Sensors for composite structural components

Autor	Methodology of Integrating Sensors	Measurements	Sensitivity	Applications
Kuang *et al.* [65] (2001)	Open Contact Moulding Processes	Strain	-	Carbon Fibre/Epoxy Laminate.
Keulen *et al.* [66] (2011)	Open Contact Moulding Processes	Strain	0.001 nm/mε	Composite Panel
Ramly *et al.* [67] (2012)	Resin Infusion Processes.	Strain	-	Sandwich Composite Panel
Bremer *et al.* [68] (2017)	Open Contact Moulding Processes	Strain and Crack	0.0033 mm/N	
Oromiehie *et al.* [69] (2018)	Automated Fibre Placement	Defects	-	Composite Components for the Aerospace Industry
Kousiatza *et al.* [70] (2019)	Fused Filament Fabrication.	Residual Strain	-	Complex Lightweight Structures
Mieloszyk *et al.* [71] (2021)	Open Contact Moulding Processes	Temperature and Strain	-	Marine Applications
Hurtado *et al.* [72] (2021)	Resin Transfer Moulding	Strain	up to 7500 $\mu\varepsilon$	Fibre-Reinforced Polymer Structure Failure

Table 3. Overview of applications and methodology of integrating both Fibre Bragg grating (FBG) Sensors and Extrinsic Fabry-Perot Interferometer (EFPI) for composite structural components

Autor	Methodology of Integrating Sensors	Measurements	Sensitivity	Applications
Leng *et al* [73] (2003)	Open Contact Moulding Processes	Strain	-	Carbon Fibre Reinforced Polymer
Oliveira *et al.* [74] (2008)	Compression Moulding Processes	Strain	2.6 $\mu\varepsilon$/N	Carbon Fibre Reinforced Polymer

Studies carried out for composite manufacturing monitoring with embedded FOSs, namely the Fibre Bragg grating, and the Extrinsic Fabry-Perot Interferometer (EFPI) have shown a capability and potential for certain applications in the future and serve as a basic knowledge for this goal. During the process of integrating FOSs into the polymer matrix, many authors [65–67] reported challenges with sensor fastening or FOSs breaks. These problems are critical and may lead to incorrect monitoring and consequently jeopardise the component integrity analysis, which requires the implementation of mechanisms or techniques to prevent such problems. To solve these issues, FOSs complemented with textile reinforcements have been implemented and studied by Bremer *et al.* [68] and Alwis *et al.* [75]. This textile reinforcement will take on its conventional counterparts, and civil infrastructure will be fully incorporated with sensors to ensure safety, comfort, and long-term durability.

Accordingly to Kuang *et al.* [65] and Ramly *et al.* [67], the composites manufacturing process can cause the appearance of residual strain in FOSs. Therefore, it is essential to perform a predicted analysis of the residual strain because these may lead to deviations from the results and influence the structural component monitoring. In this sequence, the signal obtained when FBG sensors are properly embedded and readable have a difference of minus 1 nm when compared to the signal obtained before FBG sensors were embedded in the composite matrix [67]. Therefore, the signal reduction obtained is not very significant when compared to the typical strain sensitivity of FBG sensors, which corresponds, for example, to 1.2 pm/με for the wavelength of 1550 nm, leading to the conclusion that incorporating FOSs is feasible and may be an alternative to conventional NDTs. Embedded optical fibre FBG sensors can also detect small delamination or disengagement between matrix and fibres via FBG spectrum change, allowing to predict a fibre-reinforced polymer beam structure failure [72].

Regarding the correlation between FBG sensors and EFPI, each has a preferred application, which is why these types of FOSs sensors are used simultaneously, complementing the monitoring, as shown in the works of Leng *et al.* [73] and Oliveira *et al.* [74]. For example, the curing process and bending tests can be monitored with the incorporation of these sensor types, being extremely advantageous, since, regardless of the loading type or life phase of the structural component, mixed and completed monitoring are guaranteed.

The main concepts related to the integration of FOSs into composite components are summarized in Figure 4. The Figure 4 depicts a schematic of an acquisition system used in this technology, and a summary of the advantages, limitations, and range of applications for the incorporation of FOSs into the composite components.

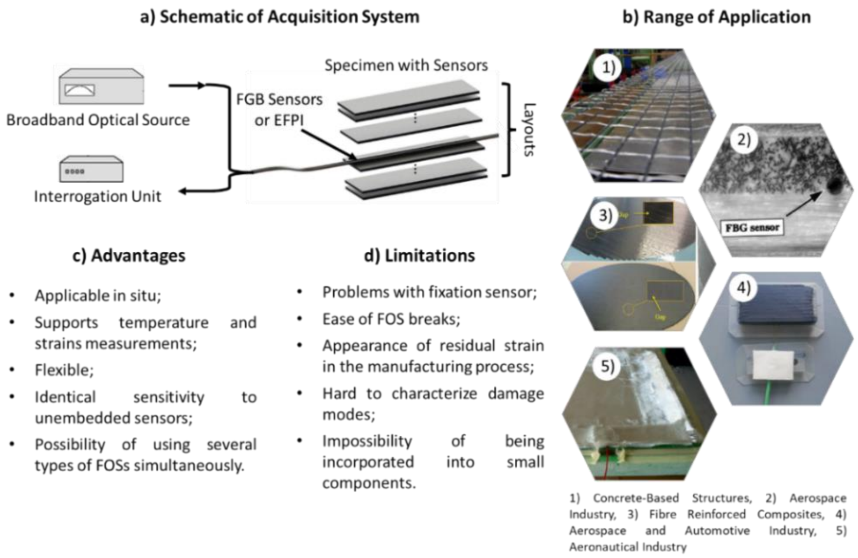


Figure 4. Fibre optic sensors embedded into composite components: a) schematic of an acquisition system, b) range of applications, c) advantages and d) limitations

4.1.2. Applications for Metal Components

The FOSs are attractive for in-situ structural monitoring, especially metallic structural components since sensors that use the optical properties provide less noisy monitoring, greater sensitivity, good accuracy, and high-temperature capacity.

Metals such as steel, nickel, iron, and titanium have high melting points. In this sense, metal processing technologies involving the melting of metals will lead to the destruction of FOSs, which is undesirable. Therefore, to avoid the damage of FOSs it is necessary to resort to a set of material processing technologies that does not involve the fusion of base metal, such as Shape Deposition Manufacturing, Layered Manufacturing, Laser Deposited, Ultrasonic Additive Manufacturing, Electron Beam Melting, Magnetron Sputtering and Electroplating.

Over the last few years and based on techniques of incorporation of FOSs, a set of systems has been developed that allows the monitoring of strains, temperature variations and cracking, using mainly FOSs of FBG type [76–85]. Xiao Chun Li *et al.* [76–79] is one of the main boosters in the development of methodologies capable of integrating sensors into metal components, using in this case, low-temperature processes, magnetron sputtering and electroplating.

FBG sensors incorporated into components manufactured, for example, with nickel and stainless steel provide high sensitivity, good accuracy, and high-temperature capacity for temperature measurements. Regarding sensitivity in temperature measurements, embedded FBG sensors have better results than those shown when sensors are not embedded [78] and an accuracy of about 2 °C [77].

For strain measurements, embedded sensors in metal produced high sensitivity, precision, and linearity, as well as the unembedded FBG sensors [78]. In addition, results obtained by Schomer *et al.* [81] showed that the embedded FBG sensors accurately track the strain for temperatures above 400 °C.

The different applications that can use of this type of sensors are presented in **Error! Reference source not found.** through an overview of the state of the art and the developments made regarding FOSs. The different types of FOSs used and the methodologies of integration of sensors for each of the applications developed for metallic components are also presented.

Table 4. Overview of applications and methodology of integrating Fibre Bragg grating Sensors in metal structural components

Autor	Methodology of Integrating Sensors	Measurements	Sensitivity	Applications
Li *et al.* [76] (2000)	Magnetron Sputtering and Electroplating	Temperature	0.0245 nm/°C	Nickel and Stainless-Steel Structures.
Li *et al.* [77] (2001)	Magnetron Sputtering and Electroplating	Temperature	0.021 nm/°C	Nickel and Stainless-Steel Structures
Li *et al.* [78] (2003)	Magnetron Sputtering and Electroplating	Strain Temperature	1.245×10^{-3} nm/$\mu\varepsilon$ 0.0334 nm/°C	Monitoring the Accumulation of Residual Strain
Li *et al.* [79] (2004)	Layered Manufacturing	Temperature	-	Turbine Blades and others Rotary Metal Tooling
Alemohammad *et al.* [80] (2011)	Magnetron Sputtering and Electroplating	Residual Stress Temperature	21 pm/°C.	Metal Cutting Tools
Schomer *et al.* [81] (2017)	Ultrasonic Additive Manufacturing	Temperature	-	High-Temperature Environments
Grandal *et al.* [82] (2018)	Laser Cladding Technology	Strain Temperature	29 pm/°C - 23 pm/°C. 0.9 pm/$\mu\varepsilon$ - 1 pm/$\mu\varepsilon$.	High-Temperature Environments

Jinachandran *et al.* [83] (2018)	Metal Packaging using Stainless Steel and Tin	Strain Temperature	0.4456 $\mu\varepsilon$/N 11.16 pm/℃	Iron Pipelines and other Ferromagnetic Components
Chilelli *et al.* [84] (2019)	Ultrasonic Additive Manufacturing	Cracks	Length of 0.286 ± 0.033 mm	Complex Systems
Hehr *et al.* [85] (2020)	Ultrasonic Additive Manufacturing	Residual Stress Temperature Delamination	-	Fibre-Routing Designs and Alloy Systems

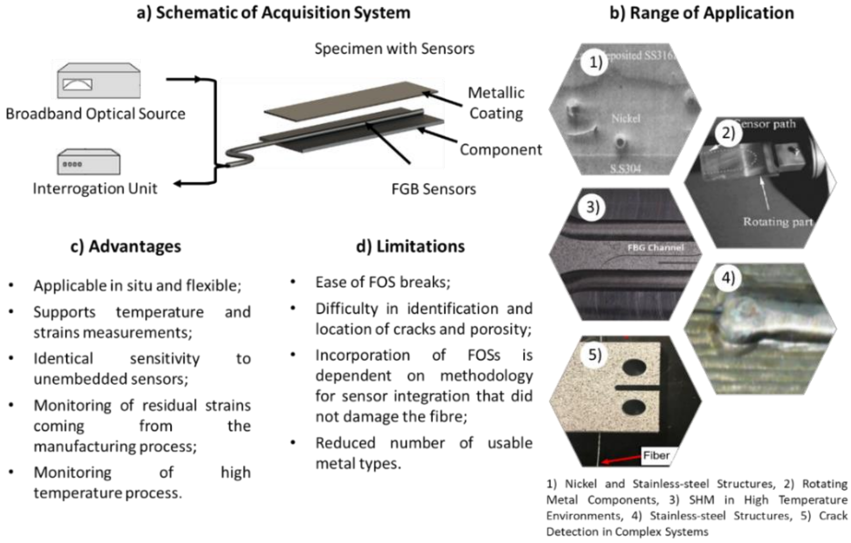
Xiao Chun Li *et al.* [76,79], have been contributed to the development of methodologies for the integration of FOSs into metal components, focusing mainly on structural components obtained in nickel and stainless steel, not covering the components fabricated from aluminium alloys, which is currently one of the main applications. The technology developed by these authors has shown very promising results, mainly due to the integration process of FOSs developed that leads to the temperature and strain measurements with satisfactory sensitivity when compared to the same unembedded sensors. Allowing monitoring of residual strain coming from the manufacturing process and high temperature but leaving aside the monitorization of cracks and porosity in structural components.

Alemohammad *et al.* [80] used a similar FOSs embedded process, incorporating the FOSs into a cutting tool and reporting results on the validation of this methodology when the component is subjected to thermal cycles, obtaining good and relevant results. However, it could also have focused on the analysis of strain cycles, since this type of application is subjected to very high stresses which can lead to the fracture of the cutting tool.

Schomer *et al.* [81], Chilelli *et al.* [84] and Hehr *et al.* [85] demonstrated the feasibility of integrating FOSs into metal matrices through UAM and monitoring temperature, cracks and residual stress, respectively, into structural components. This type of process also has great potential to monitor components present in environments subject to high temperatures, which does not happen with piezoelectric sensors as further forward will be analysed.

Grandal *et al.* [82] and Jinachandran *et al.* [83] implemented different methodologies to incorporate the FOSs with very promising results. The sensors present identical thermal and strain sensitivity when compared with the same unembedded sensors. These methodologies also ensure the durability, detachability, and reusability of monitoring equipment. However, the application range is still too small, requiring expansion for application with other metallic materials.

In Figure 5, it is possible to find a summary of the current state of the art, presenting a schematic of an acquisition system, a set of advantages, limitations, and a range of applications for the incorporation of FOSs into metal components.



c) Advantages

- Applicable in situ and flexible;
- Supports temperature and strains measurements;
- Identical sensitivity to unembedded sensors;
- Monitoring of residual strains coming from the manufacturing process;
- Monitoring of high temperature process.

d) Limitations

- Ease of FOS breaks;
- Difficulty in identification and location of cracks and porosity;
- Incorporation of FOSs is dependent on methodology for sensor integration that did not damage the fibre;
- Reduced number of usable metal types.

1) Nickel and Stainless-steel Structures, 2) Rotating Metal Components, 3) SHM in High Temperature Environments, 4) Stainless-steel Structures, 5) Crack Detection in Complex Systems

Figure 5. Fibre optic embedded sensors for metal components; a) schematic of an acquisition system, b) range of applications, c) advantages and d) limitations.

4.2. Piezoelectric Sensors

The piezoelectric effect was discovered in 1880 by the Curie brothers and was first used by Paul Langevin in the development of sounds, based on quartz crystal transducers, during the first World War. The development of piezoelectric ceramics, such as Lead Zirconate Titanate (PZT) and Barium Titanate, was revolutionary. Moreover, to have better properties than crystals after being polarized, they also offered flexible geometries and dimensions because they could be manufactured through sintering. Currently, piezoelectric ceramics of PZT type, in their various application, are the predominant ceramics in the market. In addition, other materials can also be found, such as PT ($PbTiO_3$) and PMN ($Pb (Mg_1/3 Nb_2/3) O_3$), used in devices that require special and very specific properties, such as high-temperature transducers. However, there are even more materials that have a piezoelectric effect, which can be classified into one of the following groups: piezoelectric ceramics, quartz crystals, piezoelectric composites, hydro soluble crystals, piezoelectric monocrystals, piezoelectric semiconductors or piezoelectric polymers [86,87].

The knowledge and electromechanical behaviour of these materials are fundamental for the industry, especially those that depend and focus on the ultrasound aspect. From the groups defined above, piezoelectric ceramics are the ones with greater flexibility of shape and properties, being widely used in the production of ultrasound equipment, NDT, and actuators [88].

Of all these possible applications, the possibility of developing technology that allows inspections of structural components, and periodic or continuous monitoring of structural integrity, through traditional or innovative NDT equipment, represents one of the most important applications. The most significant defect or damage inspection techniques based on piezoelectric transducers can be grouped into three classes, whereas their behaviour is passive, active, or mixed. These main classes are acoustic emissions, acoustic-ultrasonic emissions using piezoelectric transducers and electromechanical impedance [9].

The technique based on electromechanical impedance (EMI) is considered one of the most promising methods for the development of SHM systems. This technique is simple to implement and uses small and inexpensive piezoelectric sensors. However, practical problems have made it difficult to apply them to real-world structures, and the effects of temperature have been cited in the literature as critical problems [18,40].

Regarding non-destructive ultrasonic inspection techniques, there are problems in reproducibility of the acoustic coupling, accessibility to the structure and the weak signal-to-noise ratio in highly attenuating materials. The use of built-in or connected piezoelectric sensors overcomes some of these difficulties because they remain permanently connected to the structure and these sensors can be used to monitor the integrity of a given component, from its manufacturing phase to the end of its life cycle. At present, most works dealing with acoustic and ultrasonic processes have used piezoelectric transducers [9,86,87,89,90]

Recently there have been reports in the scientific community of the incorporation of piezoelectric sensors into composites and some metals. The techniques of piezoelectric sensors inclusion reported so far involve complex methodologies, so it is a scientific interest to look for some easier ways to incorporate piezoelectric sensors into metal or composite structures. Following this, in sections 0 and 0 are presented a set of applications and methodologies that have been developed in recent years, as a way to incorporate the sensors and ensure integrity monitoring of metal and composite structural components.

4.2.1. Applications for Composite Components

Interest in the concept of self-monitoring structural components has grown in recent years due to its potential to enable continuous monitoring of the next generation of smart structures [91–104]. Considering the studies developed, the applications of piezoelectric embedded sensors for composite components are mainly based on structures or components of reinforced concrete [91,96,98–102]. The development of structures or components of reinforced concrete, with PSs, incorporated to obtain smart structures is particularly suitable to be implemented in numerous strands, mainly in civil engineering, because PSs are characterized by being reliable and stable in the long term. Additionally, PSs embedded in reinforced concrete structures is a unique opportunity for SHM of civil structures due to their compatibility with new or existing infrastructures.

For this type of applications PSs based on PZT, disc or fibres, are usually used. In certain applications, a self-sensing structural material with piezoresistive characteristics, based on the addition of carbon nanotubes, can be obtained [96].

Sensors are usually attached to the reinforcing bars on key parts of reinforced concrete structures, which are susceptible to damage or difficult to access, such as bridge shoes, pavement connections or docks. In this applications, there are a set of parameters to be monitored, among them are internal strains [91]; effect of corrosion [98]; measurements of healthy and damaged steel bars in reinforced concrete beams [99]; strengths/behaviour evaluate by in-plane tensile, in-plane tension–tension fatigue, and short beam strength tests [92]; and deformations, strain, and damage [96].

The ability to monitor structural integrity is only possible if the use of ESs is successful, in this follow-up, studies have shown that the actuators and PSs are sensitive to the damage in concrete and steel reinforcement bars, however, the sensitivity of the transducers depends greatly on the frequency of the excitation selected. Thus, the use of these sensors to monitor, detect concrete fissures and analyse steel yield can be considered as a highly promising and non-destructive structural monitoring method [99].

Embedded piezoelectric sensors can also be used to monitor other types of composite materials, among these, are materials obtained by glass fibre/epoxy composite laminates. In addition, it is also possible to use the ESs to improve the internal stresses of the structural component. In this follow-up, the use of Piezoelectric Fibre Composite Sensors (PFCSs) has more advantages when compared to traditional PZT ESs, because the use of PFCSs leads to a 56% reduction in the concentration of longitudinal stresses and 38% in the concentration of transverse stresses when compared with the use of embedded sensors PZT ESs, although none of these types of sensors affects the fatigue behaviour of the base material [92].

For static and continuous monitoring, the techniques presented show great promises for the development of smart structural materials, materials that can be used to monitor the integrity of engineering systems, in civil, mechanical, or aerospace structures. Possible applications for structural components in civil infrastructure include the use of sensors integrated into columns, bridge beams and pillars, or the deployment of smart mortars and smart bricks for masonry structures; or structural components obtained by glass fibre/epoxy composite laminates [91,96].

This type of sensors is used to obtain different applications, so, in Table 5 and Table 6 is presented an overview of the state of the art and the developments made about ESs, also presenting the different types of PSs used and the methodologies of integration of sensors for each of the applications developed.

Table 5. Overview of applications and methodology of integrating Lead Zirconate Titanate (PZT) Piezoelectric Sensors into composite structural components

Autor	Methodology of Integrating Sensors	Measurements	Sensitivity	Applications
Wu *et al.* [91] (2006)	Mounted on Reinforced Concrete	Damages	1 to 15 × 10^{-3} V	Reinforced Concrete Structures
Konka *et al.* [92] (2011)	Open Contact Moulding Processes	Stress Ultimate Strength	-	Composite Structures
Tang *et al.* [97] (2011)	Vacuum Assisted Resin Transfer Moulding	Failure	-	Damage Prediction in Composites
Talakokula *et al.* [98] (2015)	Mounted on Reinforced Concrete	Corrosion	-	Reinforced Concrete Structures
Karayannis *et al.* [99] (2016)	Mounted on Reinforced Concrete	Admittance Signatures	-	Concrete Beams' Cracking
Gopalakrishnan *et al.* [100] (2019)	Mounted on Reinforced Concrete	Conductance Signatures	-	Reinforced Concrete Structures
Ahmadi *et al.* [101] (2021)	Mounted on Reinforced Concrete	Corrosion (Electro-Mechanical Impedance)	-	Reinforced Concrete Structures
Sha *et al.* [102] (2021)	Encapsulation with Concrete, Epoxy Resin and Curing Agent	Stress (Electromechanical Impedance)	-	Reinforced Concrete Structures
Huijer *et al.* [103] (2021)	Open Contact Moulding Processes	Degradation Failure (Acoustic Emissions)	-	Carbon Fibre-Reinforced Plastics
Gayakwad *et al.*[104] (2022)	Mounted on Concrete	Damage (Electromechanical Impedance)	-	Concrete Structures
Wu *et al.* [93] (2022)	Mounted on Reinforced Concrete	Strain	169 to 278 pC/$\mu\varepsilon$	Concrete Structures

Table 6. Overview of applications and methodology of integrating other piezoelectric sensors into composite structural components

Autor	Types of Sensors	Methodology of Integrating Sensors	Measurements	Applications
Lin *et al.* [94] (2001)	Thin Dielectric Film	Open Contact Moulding Process or Others	Damage Material Degradation	Metallic and Composite Structures

Takagi *et al.* [95] (2006)	Piezoelectric Fibres	Open Contact Moulding Process	Active Vibration	Carbon Fibre Reinforced Polymer Composites
Downey *et al.*[96] (2017)	Carbon Nanotubes	Mounted on Concrete	Damage Failure	SHM in Civil, Mechanical, and Aerospace Structures

Based on the studies presented in Table 5, the PSs are incorporated into reinforced concrete and on their reinforcement bars. In this application, the PSs has great applicability due to the ease of incorporating these sensors into the reinforced concrete matrix, since before drying the concrete, the cement mortar is easily handled. In addition, the production process of reinforced concrete structures is carried out at room temperature, which represents an advantage to incorporating PSs, because the use of PSs is limited by its Curie temperature, and in many applications is higher than room temperature.

Authors such as Wu *et al.* [91,93], Karayannis *et al.* [99], Gopalakrishnan *et al.* [100] and Sha *et al.* [102] have developed studies on structural components obtained in reinforced concrete, conducting experimental tests that simulate real applications, such as the debond and bending tests on reinforced concrete beams, and tensile tests on reinforcement bar. Both studies showed feasibility in identifying the presence of damage, such as concrete cracking, steel bar elongation, their location [99], and dynamic stress-sensing capability [102]. Downey *et al.* [96] also shown that the use of self-sensing structural material with piezoresistive characteristics, based on the addition of carbon nanotubes into a cementitious matrix can provide these monitoring. However, there is still great difficulty in sizing the damage and controlling the volume of collected data, since in this type of applications there is great potential to implement multi-sensing technology, that is, to incorporate numerous PSs into the reinforced concrete matrix. Despite the multi-sensing of the PZT-based sensors, by connecting them in series or parallel, this is a promising method to reduce the volume of data collected from the sensors to identify damage in a structure [100]. Environmental factors can permanently damage the integrity of a reinforced concrete structure through corrosion of concrete and reinforcing bars. The authors Talakokula *et al.* [98] and Ahmadi *et al.* [101] found that incorporating PSs into the concrete matrix or in strategic locations allows monitoring the corrosion process, acting preventively and controlling what is happening inside.

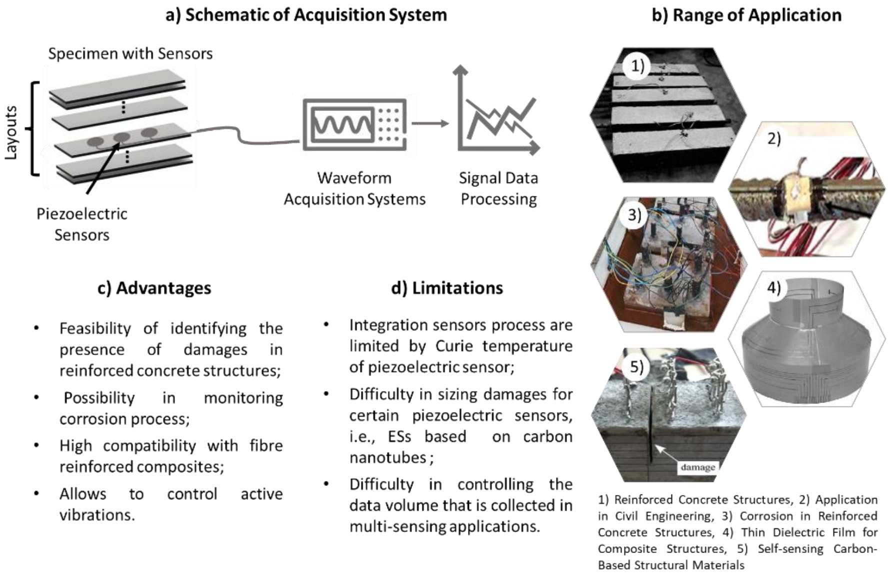
Regarding polymer matrix composites, there is a small range of manufacturing processes that allow the incorporation of PSs, due to the Curie temperature that limits the applicability of these sensors. Therefore, processes such as open contact moulding processes [92] and the vacuum assisted resin transfer moulding [97] are good alternatives since they allow PSs incorporation without disusing them. As for the PSs used, composite compatibility is one of the main conditions for good monitoring operation. In this sequence, according to Konka *et al.* [92], the conventional PZT sensors seem to have low compatibility with composites; hence the reduction in strength values is higher when compared to piezoelectric fibre composite sensors, which seem to have very high compatibility with composites. Hence a piezoelectric fibre composite sensor would be an ideal choice as an embedded sensor when compared with PZT sensors.

In addition to conventional PZT sensors, there is another type of ST that allows the monitoring of structural components and offers an alternative to conventional sensors. One of this type of technology is presented by Lin *et al.* [94], i.e., this author demonstrates that when combined with a sophisticated data acquisition system and diagnostic software, it can dramatically reduce inspection costs, allow for more frequent maintenance periods, and reduce the appearance of catastrophic structural failures.

Finally, Takagi *et al.* [95] demonstrated once again the versatility of PSs through the use of piezoelectric fibre with a metal core functions as a sensor or an actuator for effectively controlling active vibration.

doi:10.20944/preprints202210.0414.v1

The Figure 6 shows a schematic of an acquisition system used in this technology, and a review of the advantages, limitations, and range of applications for the incorporation of PSs into the composite components.



c) Advantages

- Feasibility of identifying the presence of damages in reinforced concrete structures;
- Possibility in monitoring corrosion process;
- High compatibility with fibre reinforced composites;
- Allows to control active vibrations.

d) Limitations

- Integration sensors process are limited by Curie temperature of piezoelectric sensor;
- Difficulty in sizing damages for certain piezoelectric sensors, i.e., ESs based on carbon nanotubes ;
- Difficulty in controlling the data volume that is collected in multi-sensing applications.

1) Reinforced Concrete Structures, 2) Application in Civil Engineering, 3) Corrosion in Reinforced Concrete Structures, 4) Thin Dielectric Film for Composite Structures, 5) Self-sensing Carbon-Based Structural Materials

Figure 6. Piezoelectric sensors embedded into composite components: a) a schematic of an acquisition system, b) range of applications, c) advantages and d) limitations

4.2.1. Applications for Metal Components

Currently, applications in metal components [94,105–109] use sensitively ceramic and polymeric piezoelectric sensors, more specifically PZT sensors [105] and Piezoelectric Polyvinylidene Fluoride (PVDF) sensors [109]. Traditional manufacturing approaches to incorporating active materials, such as piezoelectric materials, into metals can be problematic due to their high temperatures during production or the long curing times of the adhesives used to connect the sensor to the metal. To bridge the challenges that technological processes present, the scientific community has carried out a set of developments, among them, their focus on the development of a process of "stop and go", which consists of taking a break in the manufacturing process of a given component to allow the inclusion of PSs [105], or the inclusion of sensors through the joining of metal components in the solid-state, i.e., by ultrasonic additive manufacturing [109].

Based on the mechanisms that currently exist to incorporate PSs in metal components it was possible to obtain responses of about 3 V of maximum voltage, for pressure values not exceeding 40 MPa, and good behaviours when requested with different frequencies (i.e., 10 Hz, 15 Hz, 20 Hz and 25 Hz), for PZT piezoelectric sensors. For applications with PVDF sensors, studies were led to an average sensitivity of 9,4 mV $\mu\varepsilon^{-1}$, and the ability to detect strains.

The studies carried out so far proved the feasibility of manufacturing smart components with ESs. In addition, they can evaluate the component performance, leading to the possibility of manufacturing smart components that can have an impact in industries, such as the energy, aerospace, automotive and biomedical industries, or for applications such as air/fuel premix, pressure pipes and turbine blades [94,105,109].

Different applications can make use of this type of sensors, Table 7**Error! Reference source not found.** presents an overview of the state of the art and the developments made about embedded sensors, also presenting the different types of piezoelectric sensors used and the methodologies of integration of sensors for each of the applications developed.

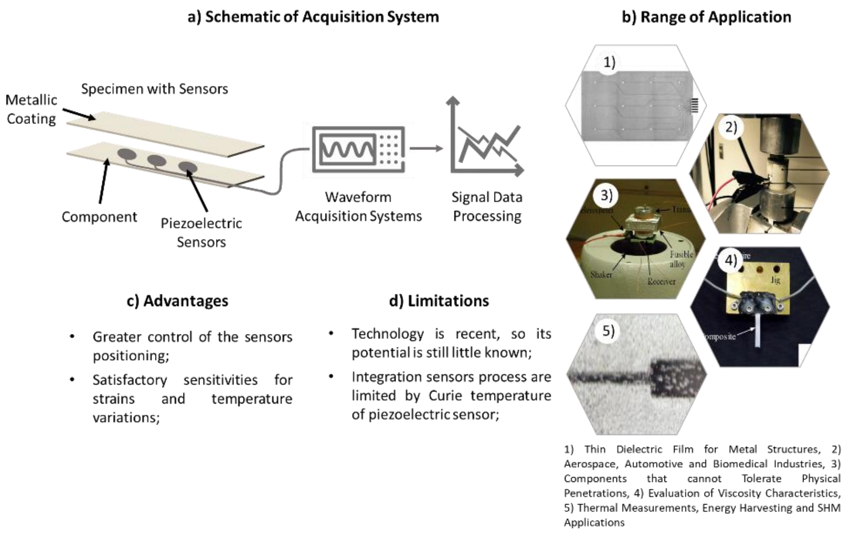
Table 7. Overview of applications and methodology of integrating different types of sensors such as Thin Dielectric Film, Lead Zirconate Titanate (PZT) Piezoelectric Sensors, Piezoelectric Ultrasonic Transducers and Piezoelectric polyvinylidene fluoride (PVDF) in metal structural components.

Autor	Methodology of Integrating Sensors	Measurements	Sensitivity	Applications
Lin *et al.* [94] (2001)	Open Contact Moulding Process or Others	Damage Material Degradation	-	Metallic and Composite Structures
Hossain *et al.* [105] (2016)	Electron Beam Melting	Stress	0.42 to 0.53 V/kN	Pressure Tubes and Turbine Blades
Tseng *et al.* [106] (2018)	Casting	Temperature	0.37 ℃/bit	Solid Metal Structural Component
Altammar *et al.* [107] (2018)	Sandwich Panel Manufacturing	Wave Propagation Analysis (Damage)	-	Laminate Structures
Yanaseko *et al.* [108] (2019)	Hot Pressing Process	Displacement	14.0 mV $/\mu m$	Evaluation of Viscosity Characteristics
Ramanathan *et al.* [109] (2021)	Ultrasonic Additive Manufacturing	Strain	9.4 mV $/\mu\varepsilon$	Functionalized Metal Structures

Based on the studies developed, the processes to incorporate PSs into metal matrices are based on the additive manufacturing process, allowing greater control of the sensors positioning and without damaging them.

The authors, whose studies are reported in Table 7, have shown that the use of PSs inside metal components allows monitoring external stimuli, such as strain and temperature variations, with satisfactory sensitivities. However, there are several factors that are fundamental to be studied to validate the applicability and versatility of this strand of ST. Regarding service factors, the possibility of monitoring, detecting, locating, and sizing possible damage or cracks is essential to ensure the integrity of structural components. About environmental factors, the action of corrosion can lead to irreparable consequences in the metal structure, as it is essential to study the possibility of PSs monitoring the corrosive actions that a metal structure is subjected to during its life cycle.

In Figure 7, it is possible to find a summary of the current state of the art, presenting a schematic of an acquisition system, a set of advantages, limitations, and a range of applications for the incorporation of PSs into the metal components.



- Greater control of the sensors positioning;
- Satisfactory sensitivities for strains and temperature variations;

- Technology is recent, so its potential is still little known;
- Integration sensors process are limited by Curie temperature of piezoelectric sensor;

1) Thin Dielectric Film for Metal Structures, 2) Aerospace, Automotive and Biomedical Industries, 3) Components that cannot Tolerate Physical Penetrations, 4) Evaluation of Viscosity Characteristics, 5) Thermal Measurements, Energy Harvesting and SHM Applications

Figure 7. Piezoelectric sensors embedded into metal components: a) schematic of an acquisition system, b) range of applications, c) advantages and d) limitations

4.3. Others Embedded Sensors

To this point, a set of applications that use sensors or sensory systems with optical properties (FOSs) or with piezoelectric properties have been analysed. Although most SHM applications are based on these two technologies, it is important to note that they are not the only ones, in this sense, throughout this section will be analysed other structural monitoring alternatives with ESs. These alternatives are monitoring technologies based on SHM techniques, such as Capacitive Methods, Electromagnetic Techniques (for example, Eddy Current), and materials with characteristics and properties that can be used for structural monitoring, such as Shape Memory Alloy (SMA).

Several studies have been developed using these SHM techniques to obtain self-monitored structural components, mainly for application in composites and metal components. Following this, sections 4.3.1 and 4.3.2 are presented with a set of applications and methodologies that have been developed in recent years, as a methodology to incorporate sensors and ensure integrity monitoring of metal and composite structural components.

4.3.1. Applications for Composite Components

In the last two decades, there has been significant growth in the development of multifunctional technologies to improve the materials' properties. Multifunctional technologies allow to obtain SHM systems to detect structural damage and strain sensing.

For applications obtained in composite materials, a set of SHM embedded techniques has been developed to incorporate the structural components [110–116]. Starting with SHM techniques that have Capacitive Methods in their base, the scientific community has developed technologies that allow the deformations monitoring that a particular component is subjected due to dynamic impacts, by including a pair of wires in adjacent layers to obtain a complex condenser. With the capacitance variation of this condenser, it is possible to monitor the deformations applied to the structural component [114]. In another approach, the authors developed a built-in monitoring sensor to monitor the water content inside reinforced concrete structures based on a passive and wireless condenser resonance circuit [110].

Regarding Electromagnetic Techniques based on SHM techniques, techniques have been developed to determine the humidity content and consequently the deterioration of reinforced concrete structures. To this end, smart sensors are incorporated into concrete structures for real-time monitoring. These sensors are microstrip patch antenna that generates a set of electromagnetic waves allowing the determination of humidity content in the structure [113].

For the development of SHM systems are also used materials that have interesting properties, as is the case of Shape Memory Alloys. SMA are metal alloys that, when deformed, return to the initial format if heated. These materials are generally lightweight, found in solid-state and present an alternative to mechanical actuators such as hydraulics, pneumatics, and motorized systems. These alloys have applications in robotics, automotive, aerospace, and biomedical. In addition, these materials can be incorporated within the traditional carbon fibre reinforced polymer composites, to increase the mechanical properties of composite panels and explore the intrinsic electrothermal properties. That is, with the variation of the electrical resistance and the internal resistance heating source provided by the SMA network, it is possible a rapid monitoring of the strains distribution and an in-situ visualization through thermographic images of damage [111].

The methodologies for integrating this type of sensors or materials are fundamentally based on a reinforced concrete structure, in the inclusion of sensors during the production phase and in polymer matrix composites, in the inclusion of these before the curing process. However, news approach to methodologies for obtaining smart sensors materials are beginning to emerge, such as the use of magnetron sputter deposition to deposit thin films on heat sensitive materials such as fibre-reinforced polymers, also known as composite materials [115].

The different applications that can make use of this type of sensors are presented in Table 8 through an overview of the state of the art and the developments made about ESs, also presenting the different types of ESs used and the integration methodologies of sensors for each of the applications developed.

Table 8. Overview of applications, type of embedded sensors used and methodology of integrating sensors for composite structural components

Autor	Types of Sensors	Methodology of Integrating Sensors	Measurements	Applications
Ong *et al.* [110] (2008)	Passive and Wireless Inductor-Capacitor Resonant Circuit	Mounted on Reinforced Concrete	Water Content	Real-Time Monitoring of Water Content in Structures
Pinto *et al.* [111] (2012)	Shape Memory NiTi Alloy	Open Contact Moulding Process	Strain Distribution Damage	Carbon Reinforced plastic Composites
Sebastian *et al.* [112] (2014)	Glass Fibre Coated with Carbon Nanotube	Open Contact Moulding Process	Strain	Carbon Reinforced plastic Composites
Teng *et al.* [113] (2019)	Microstrip Patch Antenna	Mounted on Reinforced Concrete	Moisture Content Deterioration	Reinforced Concrete Structures
Santiago *et al.* [114] (2020)	Capacitance System	Additive Manufacturing.	Deformation Impacts	Metal and Ceramic Lattices
Cougnom *et al.* [115] (2021)	Thin Films	Magnetron Sputtering Deposition and Open Contact Moulding Process	Heating Elements	Fabrication of Heating Elements.
Meoni *et al.* [116] (2021)	Carbon Nanotubes	Mounted on Reinforced Concrete	Strain	Reinforced Concrete Structures

In addition to fibre optic and piezoelectric ESs, many authors have been developed another type of ESs aiming monitoring other material properties and structures that are not possible with FOSs and PSs, such as Capacitive Methods. These methods allow moisture content monitoring of reinforced concrete structures [110], which is a huge advantage since excess moisture leads to the appearance of biological agents, cracks and delimitations. The monitoring of components with lattice structure is also a great challenge due to the difficulty of incorporating sensors, however, the use of Capacitive Methods allow overcoming this difficulty and consequently evaluate the internal efforts of this type of materials, as is detailed by Ong *et al.* [110]. However, this type of ESs have some limitations that can affect their performance, i.e., Capacitive Methods are much more sensitive to changes from environmental conditions, such as temperature and humidity variations, although, under certain conditions, this sensitivity can be easily changed. In addition, the measurement of capacitance or electrical resistance can be easily misinterpreted.

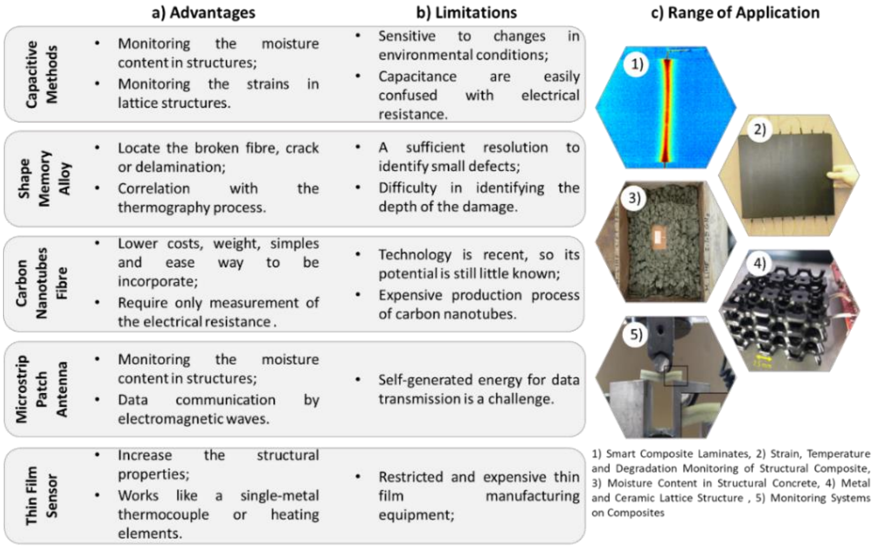
Other material properties can be used to inspect structural components. The use of SMA is another alternative and, according to Pinto *et al.* [111], it is possible to monitor, scale and locate the appearance of a broken fibre, crack or delamination in carbon reinforced plastic composites through thermography. At the same time, it allows monitoring of the stress-strain behaviour due to the thermo-mechanical behaviour of SMA. However, thermography does not have a sufficient resolution to identify small defects and has difficulties in quantifying damage depth [111].

The cost, weight, or physical size of the sensors restricts the total number that a structure can accommodate, and this is often complex systems and leads to high data for processing. In this sequence, the use of carbon nanotubes fibre sensors allows to lower costs, weight and ensures a simple and easy way to incorporate the fibres inside the composite [112]. Another advantage of this application is that the use of carbon nanotubes fibre sensors embedded in composites, requiring only a simple measurement of the electrical resistance to monitor the efforts that are applied in component [112]. Therefore, Meoni *et al.* [116] applied this typology of sensors inside of the reinforced concrete structures, leading to the development of a viable measurement technique. However, carbon nanotubes technology is recent, so its potential is still little known, and the production process of carbon nanotubes is relatively expensive.

A new breed of implanted nanocomposite sensor network was developed, for implementing in situ, ultrasound tomography driven SHM of carbon fibre–reinforced polymer (CFRP) laminates. Individual sensing units are formulated with graphene nanosheets using a spray deposition process, circuited with highly conductive carbon nanotube fibres as wires and then implanted into CFRP laminates to form a dense sensor network [117].Monitoring the moisture content inside concrete structure is one of the most critical factors to ensure structural integrity. However, much of the equipment or technologies used to measure moisture content are destructive and require additional drilling in the material to perform a measurement. In this sequence, Teng *et al.* [113] developed a microstrip patch antenna that presents a precise calibration, validated by a numerical model, reliable, easy to use and implemented inside the structure. However, self-generated energy for data transmission remains a challenge for these technologies, because the power supply typically has a longer service life than the structures where these types of sensors are integrated [113]. Wireless passive sensors can be a good solution to these problems. Radio Frequency Identification (RFID) passive sensors need no battery or maintenance so the sensors can be embedded in such structures as the wall, packaging or in clothing. A sensor's lifetime must then be the same as the lifetime of the structure in which it is embedded. Thus, the output from the sensor can be read through different materials [118,119]. RFID with sensing properties is predicted to become a key product of the next generation, because it could also be used in force measurements, since strain is proportional to force. [120]. The traditional RFID tag is typically used in power supply and data transfer [119]. One problem with the technology is the low-power output of the tag. Usually, RFID-based sensing has been limited to low-power consumption sensors such as temperature sensing [121]. In Suzuki *et al.* [119], a displacement sensor was developed using an external strain gauge and two tags, one providing power for the on-board electronics and strain gauge and the other tag for transferring of data. The sensor was tested in "real" conditions and reading of signals through many materials used in buildings was successfully performed.

Embedded sensors allow the addition of value or functionalities in structural components; however, they can compromise the structural properties of the host material. Therefore, the work developed by Cougnom *et al.* [115] presents an alternative that does not deteriorate the properties but rather guarantees an increase depending on the typology of the thin films deposited. Consequently, this composite material allows the fabrication of single-metal thermocouple thin and heating elements.

Therefore, in Figure 8 can be found the advantages, limitations, and range of applications for each of the technologies presented throughout this section. The advantages and limitations are related to the behaviour that the structure presents about the type of embedded sensor used.



	a) Advantages	b) Limitations
Capacitive Methods	• Monitoring the moisture content in structures; • Monitoring the strains in lattice structures.	• Sensitive to changes in environmental conditions; • Capacitance are easily confused with electrical resistance.
Shape Memory Alloy	• Locate the broken fibre, crack or delamination; • Correlation with the thermography process.	• A sufficient resolution to identify small defects; • Difficulty in identifying the depth of the damage.
Carbon Nanotubes Fibre	• Lower costs, weight, simples and ease way to be incorporate; • Require only measurement of the electrical resistance .	• Technology is recent, so its potential is still little known; • Expensive production process of carbon nanotubes.
Microstrip Patch Antenna	• Monitoring the moisture content in structures; • Data communication by electromagnetic waves.	• Self-generated energy for data transmission is a challenge.
Thin Film Sensor	• Increase the structural properties; • Works like a single-metal thermocouple or heating elements.	• Restricted and expensive thin film manufacturing equipment;

c) Range of Application

1) Smart Composite Laminates, 2) Strain, Temperature and Degradation Monitoring of Structural Composite, 3) Moisture Content in Structural Concrete, 4) Metal and Ceramic Lattice Structure , 5) Monitoring Systems on Composites

Figure 8. Others embedded sensors for composite components: a) advantages, b) limitations and c) range of applications

4.3.2. Applications for Metal Components

The monitoring by ESs of components manufactured with metallic materials is a more complex process when compared to the components obtained with composite materials [76,122–126]. In this sequence, technological processes such as laser-assisted metal deposition, low-temperature processes, magnetron sputtering and electroplating [76,123,126], ultrasonic metal welding [122,124], and a hybrid manufactured metal process with an in-situ process interruption [125] are used to incorporate sensors or materials that allow continuous monitoring.

Through the technological processes mentioned, there is the possibility of incorporating sensors or materials, such as thin-film [76,122] or shape memory alloys [124], to monitor the thermomechanical behaviour of structural components, and eddy current sensors [126], for studies of crack propagation and its evolution over time.

This type of sensors is implemented for applications, so, in Table 9 is presented an overview of the state of the art and the developments made about ESs, also presenting the different types of ESs used and the integration methodologies of sensors for each of the applications developed.

Table 9. Overview of applications, type of embedded sensors used and methodology of integrating sensors for metal structural components

Autor	Types of Sensors	Methodology of Integrating Sensors	Measurements	Applications

Li *et al.* [76] (2000)	Thin Film Thermo-Mechanical Sensor	Laser Assisted Metal Deposition	Strain	Nickel and Stainless-Steel Structures
Cheng *et al.* [122] (2007)	Thin-Film Thermocouple	Ultrasonic Metal Welding	Temperature	Nickel, Stainless-Steel and Titanium Alloy Tools
Zhang *et al.* [123] (2008)	Micro Ring Sensor	Laser Assisted Metal Deposition	Temperature	Monitoring of Manufacturing Processes
Hahnlen *et al.* [124] (2010)	Shape Memory NiTi Alloy	Ultrasonic Additive Manufacturing	Temperature	Monitoring of Manufacturing Processes
Juhasz *et al.* [125] (2020)	Passive Sensor Printed	Hybrid Manufactured Metal Structure	Strain	Metal Structural Components.
Sholl *et al.* [126] (2021)	Eddy Current Sensors	Laser Powder Bed Fusion.	Crack Propagation	Metal Structural Components.

Li *et al.* [76] and Cheng *et al.* [122] developed technologies for temperature monitoring in metal structural components through thin film thermo sensors but used different methodologies for sensors integration, i.e. the laser-assisted metal deposition and the ultrasonic metal welding, respectively. In the case of the application studied by Li *et al.* [76], it is notorious that there is a spread of strain values measures, which, according to the author, is due to the acquisition with limited resolution and the electrical noise generated during the amplification and transport of the signal. Therefore, it can be concluded that although the process of integration of thin film thermal sensors has been well achieved and present a response to external loads, the signal obtained is very noisy and have little resolution. Regarding the study accomplished by Cheng *et al.* [122], monitoring sensitivity identical to traditional thermocouples was obtained and provided strong evidence that the heat generated during ultrasonic welding may not be critical for structural integrity. In this sequence, this type of ESs is great potential to improve understanding of numerous other manufacturing processes by providing in situ monitoring with high spatial and temporal resolution in critical locations.

Still, in the context of temperature monitoring, Zhang *et al.* [123] developed a small sensor, i.e. a micro photonic sensor, which allowed to obtain data with a significantly improved spatial and temporal resolution, and with sensitivity higher than many applications with FOSs. As the operation of this sensor is based on optical properties, they present immunity to electromagnetic interference, and they are suitable for the operation and monitoring in processes with high operating electrical voltage and/or current, such as resistance welding, high voltage cable, etc. However, the challenges of incorporating this type of micro ring sensors arise from the fact that most metal structures have a hostile manufacturing environment, and the need to manufacture and incorporate the sensors before they are tested in an industrial environment.

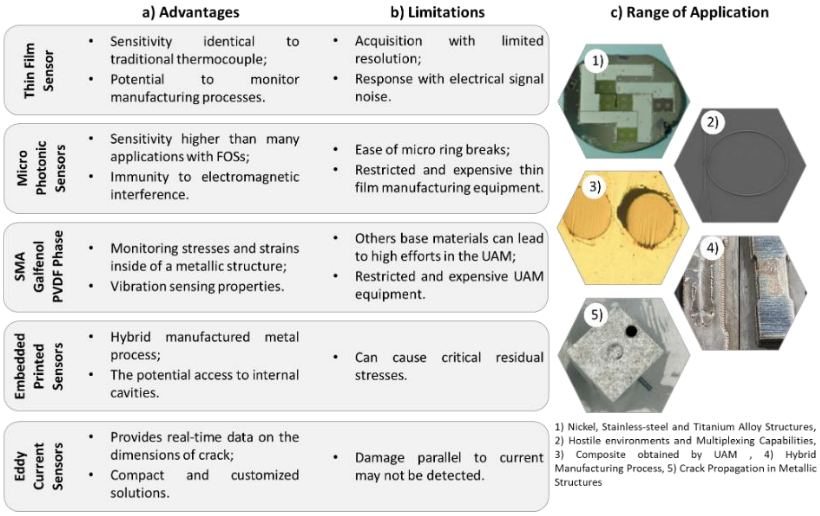
The Ultrasonic Additive Manufacturing process is one of the main methods that allow the incorporation of different materials into a metal matrix. Hahnlen *et al.* [124] demonstrated the possibility of obtaining aluminium alloy composites with shape memory NiTi, magneto strictive Galfenol, and electroactive PVDF phases. This allows to monitor properties, such as stresses and strains inside of a metallic structure, non-contact sensing of composite stress and strain utilizing the embedded magneto strictive material, and vibration sensing properties, respectively.

Juhasz *et al.* [125] described the implementation of an internal passive sensor printed on a hybrid manufactured metal structure during an in-situ process interruption. This hybrid process was combining the benefits of traditional manufacturing (machining) with additive manufacturing, resulting in more complex structures made of several materials, being this combination one of the main advantages of the hybrid processes. The greater benefit of the hybrid process is the potential access to internal cavities machined within an intermediate layer structure during manufacturing to place components.

doi:10.20944/preprints202210.0414.v1

Among the NDT technologies available, the Eddy Current technique has some advantages, such as robustness, no requirements for surface preparation, or the need for couplings [46]. In addition, they feature compact and suitable solutions to be incorporated into SHM applications [126]. According to Sholl *et al.* [126], it was possible to develop an application that provides real-time data on the dimensions of crack, allowing this type of sensor to be connected to a monitoring centre and consequently triggering a set of reparations or replacements according to the state of crack propagation. However, if a defect or planar crack does not cross or interfere with the current, this will not be found and may endanger the integrity of the component.

In Figure 9 can be found a review of the advantages, limitations, and range of applications for each of the technologies presented throughout this section. The advantages and limitations are related to the behaviour that the structure presents about the type of embedded sensor used.



	a) Advantages	b) Limitations
Thin Film Sensor	• Sensitivity identical to traditional thermocouple; • Potential to monitor manufacturing processes.	• Acquisition with limited resolution; • Response with electrical signal noise.
Micro Photonic Sensors	• Sensitivity higher than many applications with FOSs; • Immunity to electromagnetic interference.	• Ease of micro ring breaks; • Restricted and expensive thin film manufacturing equipment.
SMA Galfenol PVDF Phase	• Monitoring stresses and strains inside of a metallic structure; • Vibration sensing properties.	• Others base materials can lead to high efforts in the UAM; • Restricted and expensive UAM equipment.
Embedded Printed Sensors	• Hybrid manufactured metal process; • The potential access to internal cavities.	• Can cause critical residual stresses.
Eddy Current Sensors	• Provides real-time data on the dimensions of crack; • Compact and customized solutions.	• Damage parallel to current may not be detected.

1) Nickel, Stainless-steel and Titanium Alloy Structures, 2) Hostile environments and Multiplexing Capabilities, 3) Composite obtained by UAM , 4) Hybrid Manufacturing Process, 5) Crack Propagation in Metallic Structures

Figure 9. Others embedded sensors for metal components: a) advantages, b) limitations and c) range of applications

5. Methodology for Sensor Integration

Integrating sensors inside a given component is one of the major challenges in the development of self-monitored structures, since it is required to ensure the integrity of both, sensor and component. In this sequence, it is not straightforward how to integrate sensors into structural components, as they can consist of metals or polymers, or a set of materials, as is the case of composites. The ESs used is limited to the processing technology used to embed the sensor due to their usual high temperature sensitivity, and to the possibility of damage during incorporation process. In addition, the selection of the technological process depends on the base material composition.

Based on the applications and technologies analysed in the previous section, it can be concluded that there are appropriate technological processes set or methodology for incorporating sensors into structural components. Therefore, in sections 5.1.1 and 5.1.2, a set of technological processes for the manufacture and processing of composites and metallic materials are presented and analysed.

5.1. For Composite Components

Currently, it is possible to obtain enough types of composite materials, for this, a set of techniques of processing and manufacture of composite materials have been developed, that can be divided into several typologies. Among them exist open moulding (Figure 10 a)), resin infusion processes (Figure 10 b)) and high-volume moulding methods, such as automated fibre placement (Figure 10 c)), compression moulding (Figure 10 d)) [127–129] and spray deposition processes [117].

Based on existing technological processes for the manufacture of composite materials, there are already studies that have experimentally validated the use to embed sensors in composite materials. Therefore, FOSs and PSs are the main technologies used to be incorporated into composite materials, mainly, advanced composite materials and fibre/metal laminates, carbon fibre reinforced polymer laminates, sandwich composite panels and continuous fibre reinforced thermoplastic composites fabricated through the fused filament fabrication technique [65–71,73,74,91,92,94,95,97–102].

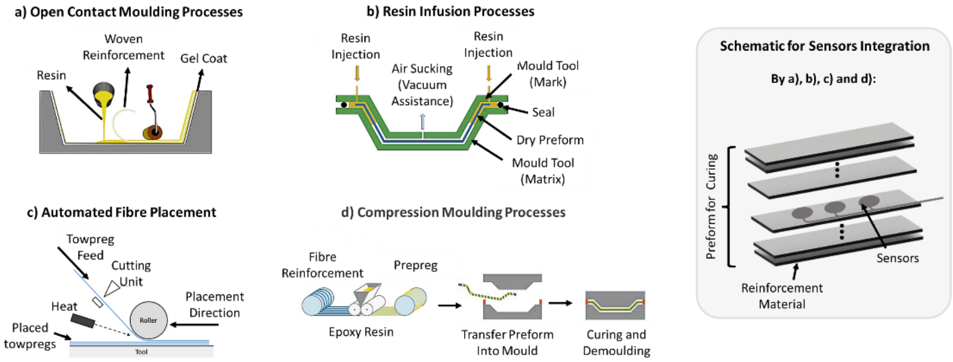


Figure 10. Methodology for sensor integration into composite components: a) open contact moulding processes, b) resin infusion processes, c) automated fibre placement and d) compression moulding processes.

5.2. For Metal Components

The metallic structures or structural components represent the large part of the applications in engineering, and therefore the methodologies of integrating sensors into these types of components are fundamental. However, most technological processes for the manufacture and processing of metallic materials may compromise the integrity of sensors or sensory components. In this sequence, it is essential to combine sensors physical limits with the manufacture or transformation technological process, so that it is possible to ensure the most efficient structural monitoring possible.

Currently, certain applications are already validated, i.e., the use of FOSs and PSs embedded in metal components are already possible through a set of manufacturing technologies with characteristics that allow the integrity of the sensors. These technologies are the Shape Deposition Manufacturing (Figure 11 a)), the Electron Beam Melting (Figure 11 b)), the Magnetron sputtering and Electroplating (Figure 11 c)), and the Ultrasonic Additive Manufacturing (Figure 11 d)). [76–85,105,106,108,109,122–126,130–133].

Sensor integration methodologies for metal components are mainly based on solid-state processing technologies, layered manufacturing or electroplating and laser deposited. This strand is still under development, however, there are already applications with sensors, integrated circuits or actuators incorporated within structural structures or components and fully functional.

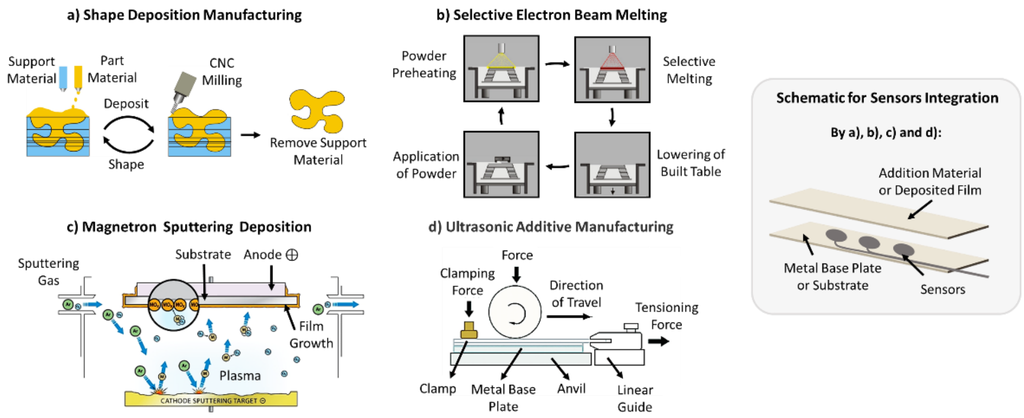


Figure 11. Methodology for sensor integration into composite components: a) open contact moulding processes, b) resin infusion processes, c) automated fibre placement and d) compression moulding processes.

6. Discussion and Challenges in Embedded Sensors

Generally, all sensors or monitoring systems present a set of challenges that must be overcome to ensure high structural reliability, such as the accurate detection of the damage. The use of wiring to connect sensors causes many problems, including the associated cost of its application, as well as the reduction in the reliability of data transmission [52,134–136].

The use of embedded FOSs is associated with a set of challenges. These are a result of the operational characteristics of the FOSs and the incorporation processes used. Regarding the incorporation of FOSs in composite components, the processes of fixing and handling FOSs are sometimes delicate situations and can lead to optical fibre breakdown, so it is important not only the insertion area of optical fibres, but also the protection the optical fibres to ensure that monitoring is not affected. Positioning the FOSs is also a challenge because the orientations of composite reinforcement fibres influence the spectrum response of the FOSs after fabrication, which can lead to insensitivity to crack propagation. As far as the curing process is concerned, this can lead to non-uniform strains causing noisy signals and impeding the monitoring of components. Mechanical degradation due to the poor mechanical properties at the sensor/composite material interface is a common issue in these applications, especially when it comes to soft and flexible composite structures. Given the soft nature of unconsolidated textile reinforcement fabrics, the mismatch between the sensor and the fabric is challenging issue from the perspectives of both, sensor measurement and fabric properties [137,138].

Embedding the FOSs in metallic components is a more challenging process, as one of the main challenges is to ensure that FOSs are not damaged during the incorporation phase, as some of the technological processes used require high pressures (as is the case of the UAM), and the FOSs are very fragile. In this sequence, although the FOSs remain functional at higher temperatures when compared to piezoelectric sensors, it is important to develop protection and reinforcement systems for FOSs to withstand temperatures above the melting point of metallic materials, to increase the range of applications. Regarding the fixation and handling process, the challenges are like those presented for composite components. The incorporation process of FOSs in metal components involve high operational costs, since the equipment used for processing the metal is quite expensive, being important to reduce these costs.

When referring to piezoelectric embedded sensors there are several challenges that are associated with their implementation. For smart composite structures, it is necessary to ensure electrical insulation, electrical shielding, or electromagnetic compatibility, as piezoelectric sensors are susceptible to electromagnetic interferences. Regarding the effect of temperature, it is essential to ensure thermal coupling, as piezoelectric sensors lose their piezoelectric properties when the curing temperatures of composites exceed the Curie temperature. In addition, the use of certain piezoelectric sensors leads to geometric disturbances, such as stress concentration at the sensor location and in its surrounding area, so it is necessary to optimize the sensors to be small and light. Finally, the use of embedded piezoelectric sensors requires a large, complicated, and power-consuming monitoring system due to each sensor requires a monitoring channel and an adequate number of wires to be connected. As well as heavy wiring for its operation, however, technological progress has been emerging for nanoscale wires manufacturing by printing or chemically deposition [139].

For applications in metallic materials structures, the challenges related to the characteristics of embedded piezoelectric sensors are identical to those related when applied to composite structures. However, concerning the embedding process of sensors, these are already distinct, since, in this segment, so far, the processes are mainly based on additive or solid-state manufacturing processes. Therefore, some challenges to overcome in the future are high costs associated with the equipment for the metal processing, and also extending to other processing technologies, e.g., processes that use the fusion of the base material.

FOSs and PSs are currently the main technologies to incorporate into structural components, although the micro and nanotechnology field has an interesting result ensuring the possibility of implementing sensory networks in variable structures and topologies. As a consequence, more sensors will generate more monitoring data, requiring the development of more efficient models for data analysis and processing [140,141]. In addition to FOSs and PSs, there are also other technologies, such as Capacitive Methods and Electromagnetic Techniques (for example, Eddy Current), and materials with characteristics and properties that can be used for structural monitoring, such as Shape Memory Alloy. These technologies generally use thin-film sensors, microstrips or nanotubes, and therefore may occur problems related to fixing thin film or electromagnetic interferences in microstrips.

According to the authors of this work, there are certainly numerous challenges to solve when it comes to embedding different types of sensors into structural components. However, one of the primary solutions to many of the challenges presented is the possibility to implement hybrid systems. Hybrid systems with FOSs and PSs, for example, as presented by Yu *et al.* [142], provide synergy for these types of applications.

Structures durability with embedded sensors is one of the main concerns, so researchers have also investigated the ESs to determine their effects on the mechanical behavior of a host structure. Warkentin and Crawley *et al.* [143] tested graphite/epoxy coupons with embedded integrated circuits on silicon chips showing a 15% decrease in ultimate strength of the host laminate with the embedded chips. Also, Crawley *et al.* found that the ultimate strength of a graphite/epoxy laminate was reduced by 20% when a piezoceramic was embedded in the composite. Chow *et al.* [144] performed an analytical study that showed interlaminar stresses were five times higher with the embedment of an inert rectangular implant in a graphite/epoxy laminate. They indicated the integrity of smart structures was affected due to the insertion of sensors/actuators [145].

Regard to FOSs incorporation, research indicates that there was no degradation in compressive strength when the optical fibers were placed parallel to reinforcing fibers, and there was no change in mechanical behavior due to embedded optical fibers [75,146,147].

The integration of sensors inside composite and metallic parts is still in the early stages of development, mainly for metal components. Thus, there is little literature available to compare their performance, structurally or in terms of efficiency and economy. Nevertheless, given the trend with new reinforcement techniques, combined with potential digital fabrication, it is possible to conclude that there is potential to incorporate sensors inside components without compromising the structural integrity of the components.

Monitoring metallic components is significantly more difficult than monitoring polymeric components when using the ESs presented, due to the sensor incorporation process. The incorporation of instrumentation or electronic sensors into structural components can sometimes endanger the component's integrity, and to lead problems associated with sensor fixation before embedding because glues and adhesives can be degraded under certain circumstances. Thus, according to the authors of this work, the application of metallic components manufactured of multifunctional materials and high sensorial properties materials will be the future of SHM.

SHM risk analysis is of the upmost value for companies, such as insurance companies, and the use of computational methods are gaining significant relevance. Chang *et al.* [148] explored the feasibility of integrating built-in piezoelectric-based diagnostic techniques with a progressive failure analysis to monitor damage in composite structures. Saravanos *et al.* [149] developed a coupled analysis of a layered composite structure with embedded piezoelectric sensors and actuators. Giurgiutiu *et al.* [38] investigated the use of finite element analysis to simulate various SHM methods with piezoelectric wafer sensors. A physics-based model incorporating PZT sensor measurement was developed by Ghoshal *et al.* [150] to study acoustic wave generation and propagation in plates. Kim *et al.* [151] developed a finite element-based methodology to model embedded sensors in delaminated composite structures with piezoelectric sensors. Their results showed that embedded sensors provide more information on delaminations than surface mounted systems. The strength of PZT piezoelectric sensors is usually significantly lower than that of their host structures. Yan *et al.* [152] developed a method for online detection of cracks in composite plates with embedded piezoelectric sensors using wavelet analysis. Butler *et al.* [153] investigated computational models focusing on PZT sensors, actuators and associated techniques for damage detection.

The capability and versatility of the mechanics model with the coupled quasi-static and free dynamic response of composite functioning in an active (applied voltages) or sensory (applied force/displacement) mode were critical for assessing risk analysis SHM. However, computational methods for evaluating embedded sensors in metallic parts are limited, thus researchers must focus on this area due to the extensive use of metal parts in SHM.7. Conclusions

Embedded Sensors currently represent one of the main fields of Sensing Technology, and therefore the scientific community has focused efforts on the development and optimization of a set of technologies that ensure continuous monitoring of structural integrity. SHM systems use a vast range of techniques, however, Fibre-Optic Sensors and Piezoelectric Sensors have proven that, through the right technological processes, can be incorporated into components or structures.

The selection of smart sensors or the technology underlying them is fundamental to the type of monitoring that is intended to be performed, i.e., each embedded sensor is developed and optimized to monitor certain physical and mechanical properties in specific structures and perform under specific conditions. Regardless of the type of embedded sensors or smart sensing technology, there are limitations of use related to the physical, chemical, and mechanical limits of each. In this sense, with the correct selection of embedded sensors and technological process for its integration it is possible to obtain structures or structural components that are reliable, and with a possibility of continuous monitoring that intends to be effective and accurate.

The review of studies developed in the embedded sensors in structural components showed that over the last 15 years, there was exponential growth, not only in terms of the technology progress but also in the development of new applications that use composite materials, essentially promoted by its increasing use in industrial applications. However, the development of applications with metallic components has suffered advances, these are still scarce and little industrialised, so it is crucial to allocate resources to boost the development of smart metallic systems.

Acknowledgements

The Authors acknowledge Fundação para a Ciência e a Tecnologia (FCT-MCTES) for its financial support via the project UIDB/00667/2020 (UNIDEMI). Pedro M. Ferreira also acknowledges FCT-MCTES for funding the PhD grant UI/BD/151055/2021.

Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

References

1. Spencer, B.F.; Ruiz-Sandoval, M.E.; Kurata, N. Smart sensing technology: Opportunities and challenges. *Struct. Control Heal. Monit.* **2004**, *11*, 349–368, doi:10.1002/stc.48.
2. Andreades, C.; Malfense Fierro, G.P.; Meo, M. A nonlinear ultrasonic SHM method for impact damage localisation in composite panels using a sparse array of piezoelectric PZT transducers. *Ultrasonics* **2020**, *108*, 106181, doi:10.1016/j.ultras.2020.106181.
3. Duarte, V.R.; Rodrigues, T.A.; MacHado, M.A.; Pragana, J.P.M.; Pombinha, P.; Coutinho, L.; Silva, C.M.A.; Miranda, R.M.; Goodwin, C.; Huber, D.E.; et al. Benchmarking of Nondestructive Testing for Additive Manufacturing. *3D Print. Addit. Manuf.* **2021**, *8*, 263–270, doi:10.1089/3dp.2020.0204.
4. Machado, M.A.; Silva, M.I.; Martins, A.P.; Carvalho, M.S.; Santos, T.G. Double active transient thermography. *NDT E Int.* **2022**, *125*, 102566, doi:10.1016/j.ndteint.2021.102566.
5. Santos, T.G.; Oliveira, J.P.; Machado, M.A.; Inácio, P.L.; Duarte, V.R.; Rodrigues, T.A.; Santos, R.A.; Simão, C.; Carvalho, M.; Martins, A.; et al. Reliability and NDT Methods. *Adv. Struct. Mater.* **2020**, *129*, 265–295, doi:10.1007/978-3-030-44522-5_8.
6. Machado MA, Rosado L, Pedrosa N, Miranda RM, Piedade M, S.T. Customized Eddy Current Probes for Pipe Inspection. *Stud Appl Electromagn Mech* **2017**, doi:10.3233/978-1-61499-767-2-283.
7. Machado, M.A.; Rosado, L.S.; Mendes, N.M.; Miranda, R.M.; Santos, T.G. Multisensor inspection of laser-brazed joints in the automotive industry. *Sensors* **2021**, *21*, 7335, doi:10.3390/s21217335.
8. Costa, F.B.; Machado, M.A.; Bonfait, G.J.; Vieira, P.; Santos, T.G. Continuous wave terahertz imaging for NDT: Fundamentals and experimental validation. *Meas. J. Int. Meas. Confed.* **2021**, *172*, 108904, doi:10.1016/j.measurement.2020.108904.
9. Balageas, D.; Fritzen, C.P.; Güemes, A. *Structural Health Monitoring*; John Wiley & Sons, 2010; Vol. 90; ISBN 9781905209019.
10. Fu, Y.; Peng, C.; Gomez, F.; Narazaki, Y.; Spencer, B.F. Sensor fault management techniques for wireless smart sensor networks in structural health monitoring. *Struct. Control Heal. Monit.* **2019**, *26*, e2362, doi:10.1002/stc.2362.
11. Ou, J.; Li, H. Structural health monitoring in the Mainland of China: Review and future trends. *Struct. Heal. Monit. 2009 From Syst. Integr. to Auton. Syst. - Proc. 7th Int. Work. Struct. Heal. Monit. IWSHM 2009* **2009**, *1*, 29–41.
12. Sony, S.; Laventure, S.; Sadhu, A. A literature review of next-generation smart sensing technology in structural health monitoring. *Struct. Control Heal. Monit.* **2019**, *26*, e2321, doi:10.1002/stc.2321.
13. Güemes, A.; Fernandez-Lopez, A.; Pozo, A.R.; Sierra-Pérez, J. Structural health monitoring for advanced composite structures: A review. *J. Compos. Sci.* **2020**, *4*, 1–16, doi:10.3390/jcs4010013.
14. Brownjohn, J.M.. Structural health monitoring of civil infrastructure. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2007**, *365*, 589–622, doi:10.1098/rsta.2006.1925.
15. Farrar, C.R.; Worden, K. An introduction to structural health monitoring. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2007**, *365*, 303–315, doi:10.1098/rsta.2006.1928.
16. Montalvão, D.; Maia, N.M.M.; Ribeiro, A.M.R. A review of vibration-based structural health monitoring with special emphasis on composite materials. *Shock Vib. Dig.* **2006**, *38*, 295–324, doi:10.1177/0583102406065898.
17. Giordano, M.; Nasser, J.S.; Zarrelli, M.; Cusano, A.; Cutolo, A. Fiber optic sensors in structural health monitoring. *Introd. To Optoelectron. Sensors, An* **2009**, *29*, 378–402, doi:10.1142/9789812834133_0017.

18. Qing, X.; Li, W.; Wang, Y.; Sun, H. Piezoelectric transducer-based structural health monitoring for aircraft applications. *Sensors (Switzerland)* **2019**, *19*, 545, doi:10.3390/s19030545.
19. Palma, P.; Steiger, R. Structural health monitoring of timber structures – Review of available methods and case studies. *Constr. Build. Mater.* **2020**, *248*, 118528, doi:10.1016/j.conbuildmat.2020.118528.
20. Machado, M.A.; Antin, K.N.; Rosado, L.S.; Vilaça, P.; Santos, T.G. High-speed inspection of delamination defects in unidirectional CFRP by non-contact eddy current testing. *Compos. Part B Eng.* **2021**, *224*, 109167, doi:10.1016/j.compositesb.2021.109167.
21. Antin, K.N.; Machado, M.A.; Santos, T.G.; Vilaça, P. Evaluation of Different Non-destructive Testing Methods to Detect Imperfections in Unidirectional Carbon Fiber Composite Ropes. *J. Nondestruct. Eval.* **2019**, *38*, 23, doi:10.1007/s10921-019-0564-y.
22. Machado, M.A.; Antin, K.N.; Rosado, L.S.; Vilaça, P.; Santos, T.G. Contactless high-speed eddy current inspection of unidirectional carbon fiber reinforced polymer. *Compos. Part B Eng.* **2019**, *168*, 226–235, doi:10.1016/j.compositesb.2018.12.021.
23. Brownjohn, J.M.W.; de Stefano, A.; Xu, Y.L.; Wenzel, H.; Aktan, A.E. Vibration-based monitoring of civil infrastructure: Challenges and successes. *J. Civ. Struct. Heal. Monit.* **2011**, *1*, 79–95, doi:10.1007/s13349-011-0009-5.
24. Humar, J.; Bagchi, A.; Xu, H. Performance of vibration-based techniques for the identification of structural damage. *Struct. Heal. Monit.* **2006**, *5*, 215–241, doi:10.1177/1475921706067738.
25. Montalvao, D. A Review of Vibration-based Structural Health Monitoring with Special Emphasis on Composite Materials. *Shock Vib. Dig.* **2006**, *38*, 295–324, doi:10.1177/0583102406065898.
26. Deraemaeker, A.; Reynders, E.; De Roeck, G.; Kullaa, J. Vibration-based structural health monitoring using output-only measurements under changing environment. *Mech. Syst. Signal Process.* **2008**, *22*, 34–56, doi:10.1016/j.ymssp.2007.07.004.
27. Sandykbayeva, D.; Kappassov, Z.; Orazbayev, B. VibroTouch: Active Tactile Sensor for Contact Detection and Force Sensing via Vibrations. *Sensors* **2022**, *22*, 6456, doi:10.3390/s22176456.
28. Luyckx, G.; Voet, E.; Lammens, N.; Degrieck, J. Strain Measurements of Composite Laminates with Embedded Fibre Bragg Gratings: Criticism and Opportunities for Research. *Sensors* **2010**, *11*, 384–408, doi:10.3390/s110100384.
29. Campanella, C.; Cuccovillo, A.; Campanella, C.; Yurt, A.; Passaro, V. Fibre Bragg Grating Based Strain Sensors: Review of Technology and Applications. *Sensors* **2018**, *18*, 3115, doi:10.3390/s18093115.
30. Fidanboylu, K.A.; Efendioglu, H.S. Fiber optic sensors and their applications. In Proceedings of the 5th International Advanced Technologies Symposium (IATS'09); 2009; Vol. 6, pp. 2–3.
31. Li, H.-N.N.; Li, D.S.; Song, G.B. Recent applications of fiber optic sensors to health monitoring in civil engineering. *Eng. Struct.* **2004**, *26*, 1647–1657, doi:10.1016/j.engstruct.2004.05.018.
32. Du, C.; Dutta, S.; Kurup, P.; Yu, T.; Wang, X. A review of railway infrastructure monitoring using fiber optic sensors. *Sensors Actuators, A Phys.* **2020**, *303*, 111728, doi:10.1016/j.sna.2019.111728.
33. Bao, Y.; Huang, Y.; Hoehler, M.S.; Chen, G. Review of fiber optic sensors for structural fire engineering. *Sensors (Switzerland)* **2019**, *19*, 877, doi:10.3390/s19040877.
34. Güemes, A.; Fernández-López, A.; Díaz-Maroto, P.F.; Lozano, A.; Sierra-Perez, J. Structural health monitoring in composite structures by fiber-optic sensors. *Sensors (Switzerland)* **2018**, *18*, 1094, doi:10.3390/s18041094.
35. Park, G.; Farrar, C.R.; Di Scalea, F.L.; Coccia, S. Performance assessment and validation of piezoelectric active-sensors in structural health monitoring. *Smart Mater. Struct.* **2006**, *15*, 1673–1683, doi:10.1088/0964-1726/15/6/020.
36. Na, W.S.; Baek, J. A review of the piezoelectric electromechanical impedance based structural health monitoring technique for engineering structures. *Sensors (Switzerland)* **2018**, *18*, 1307, doi:10.3390/s18051307.
37. Ha, S.K.; Keilers, C.; Chang, F.-K. Finite element analysis of composite structures containing distributed piezoceramic sensors and actuators. *AIAA J.* **1992**, *30*, 772–780, doi:10.2514/3.10984.

38. Giurgiutiu, V.; Zagrai, A.; Bao, J.J. Piezoelectric wafer embedded active sensors for aging aircraft structural health monitoring. *Struct. Heal. Monit.* **2002**, *1*, 41–61, doi:10.1177/147592170200100104.
39. Dong, B.; Li, Z. Cement-based piezoelectric ceramic smart composites. *Compos. Sci. Technol.* **2005**, *65*, 1363–1371, doi:10.1016/j.compscitech.2004.12.006.
40. Baptista, F.G.; Budoya, D.E.; de Almeida, V.A.D.; Ulson, J.A.C. An experimental study on the effect of temperature on piezoelectric sensors for impedance-based structural health monitoring. *Sensors (Switzerland)* **2014**, *14*, 1208–1227, doi:10.3390/s140101208.
41. Seppänen, A.; Karhunen, K.; Lehikoinen, A.; Kaipio, J.P.; Monteiro, P.J.M. Electrical resistance tomography imaging of concrete. *Concr. Repair, Rehabil. Retrofit. II - Proc. 2nd Int. Conf. Concr. Repair, Rehabil. Retrofit. ICCRRR* **2009**, *40*, 231–232, doi:10.1201/9781439828403.ch79.
42. Baltopoulos, A.; Polydorides, N.; Pambaguian, L.; Vavouliotis, A.; Kostopoulos, V. Damage identification in carbon fiber reinforced polymer plates using electrical resistance tomography mapping. *J. Compos. Mater.* **2013**, *47*, 3285–3301, doi:10.1177/0021998312464079.
43. Tallman, T.N.; Wang, K.W. Damage and strain identification in multifunctional materials via electrical impedance tomography with constrained sine wave solutions. *Struct. Heal. Monit.* **2016**, *15*, 235–244, doi:10.1177/1475921716635574.
44. Silva, D.D.S.; Sobrinho, J.M.B.; Souto, C.R.; Gomes, R.M. Application of electromechanical impedance technique in the monitoring of sigma phase embrittlement in duplex stainless steel. *Mater. Sci. Eng. A* **2020**, *788*, 139457, doi:10.1016/j.msea.2020.139457.
45. Machado, M.A.; Rosado, L.S.; Santos, T.G. Shaping Eddy Currents for Non-Destructive Testing Using Additive Manufactured Magnetic Substrates. *J. Nondestruct. Eval.* **2022**, *41*, 50, doi:10.1007/s10921-022-00882-1.
46. Machado, M.A.; Rosado, L.F.S.G.; Mendes, N.A.M.; Miranda, R.M.M.; dos Santos, T.J.G. New directions for inline inspection of automobile laser welds using non-destructive testing. *Int. J. Adv. Manuf. Technol.* **2022**, *118*, 1183–1195, doi:10.1007/s00170-021-08007-0.
47. Wilson, J.S. *Sensor Technology Handbook*; Elsevier, 2005; ISBN 9780750677295.
48. Saeedifar, M.; Mansvelder, J.; Mohammadi, R.; Zarouchas, D. Using passive and active acoustic methods for impact damage assessment of composite structures. *Compos. Struct.* **2019**, *226*, 111252, doi:10.1016/j.compstruct.2019.111252.
49. Liu, M.; Zeng, Z.; Xu, H.; Liao, Y.; Zhou, L.; Zhang, Z.; Su, Z. Applications of a nanocomposite-inspired in-situ broadband ultrasonic sensor to acousto-ultrasonics-based passive and active structural health monitoring. *Ultrasonics* **2017**, *78*, 166–174, doi:10.1016/j.ultras.2017.03.007.
50. Chandarana, N.; Soutis, C.; Gresil, M. Passive and active monitoring for defect detection and quantification in composites. In Proceedings of the Health Monitoring of Structural and Biological Systems XII; Kundu, T., Ed.; SPIE, 2018; Vol. 10600, p. 71.
51. Wang, Y.; Hu, S.; Xiong, T.; Huang, Y.; Qiu, L. Recent progress in aircraft smart skin for structural health monitoring. *Struct. Heal. Monit.* **2022**, *21*, 2453–2480, doi:10.1177/14759217211056831.
52. Janeliukstis, R.; Mironovs, D. Smart Composite Structures with Embedded Sensors for Load and Damage Monitoring – A Review. *Mech. Compos. Mater.* **2021**, *57*, 131–152, doi:10.1007/s11029-021-09941-6.
53. Leng, J.; Ecke, W. Opportunities of fiber optic sensors and their applications. In Proceedings of the Optics and Lasers in Engineering; 2009; Vol. 47, p. 1017.
54. Di Sante, R. Fibre optic sensors for structural health monitoring of aircraft composite structures: Recent advances and applications. *Sensors (Switzerland)* **2015**, *15*, 18666–18713, doi:10.3390/s150818666.
55. Lopez-Higuera, J.M.; Rodriguez Cobo, L.; Quintela Incera, A.; Cobo, A. Fiber Optic Sensors in Structural Health Monitoring. *J. Light. Technol.* **2011**, *29*, 587–608, doi:10.1109/JLT.2011.2106479.

56. Rajan, G. *Optical Fiber Sensors: Advanced Techniques and Applications*; Taylor & Francis, 2017;
57. Jackson, D.A.; Jones, J.D.C. Fibre Optic Sensors. *Opt. Acta Int. J. Opt.* **1986**, *33*, 1469–1503, doi:10.1080/713821914.
58. Amanzadeh, M.; Aminossadati, S.M.; Kizil, M.S.; Rakić, A.D. Recent developments in fibre optic shape sensing. *Measurement* **2018**, *128*, 119–137, doi:10.1016/j.measurement.2018.06.034.
59. Su, Y.D.; Preger, Y.; Burroughs, H.; Sun, C.; Ohodnicki, P.R. Fiber optic sensing technologies for battery management systems and energy storage applications. *Sensors (Switzerland)* **2021**, *21*, 1–36, doi:10.3390/s21041397.
60. Inaudi, D.; GLISIC Smartec, B.S. Overview of fibre optic sensing applications to structural health monitoring. **2008**.
61. Ou, R.; Luo, L.; Soga, K. Brillouin scattering spectrum-based crack measurement using distributed fiber optic sensing. *Struct. Heal. Monit.* **2021**, *0*, 147592172110309, doi:10.1177/14759217211030913.
62. Li, C.; Tang, J.; Cheng, C.; Cai, L.; Yang, M. FBG Arrays for Quasi-Distributed Sensing: A Review. *Photonic Sensors* **2021**, *11*, 91–108, doi:10.1007/s13320-021-0615-8.
63. Pei Luo; Dongsheng Zhang; Lixin Wang; Desheng Jiang Structural Damage Detection Based on a Fiber Bragg Grating Sensing Array and a Back Propagation Neural Network: An Experimental Study. *Struct. Heal. Monit.* **2010**, *9*, 5–11, doi:10.1177/1475921709349896.
64. Sieńko, R.; Zych, M.; Bednarski, Ł.; Howiacki, T. Strain and crack analysis within concrete members using distributed fibre optic sensors. *Struct. Heal. Monit.* **2019**, *18*, 1510–1526, doi:10.1177/1475921718804466.
65. Kuang, K.S.C.; Kenny, R.; Whelan, M.P.; Cantwell, W.J.; Chalker, P.R. Embedded fibre Bragg grating sensors in advanced composite materials. *Compos. Sci. Technol.* **2001**, *61*, 1379–1387, doi:10.1016/S0266-3538(01)00037-9.
66. Keulen, C.; Rocha, B.; Yildiz, M.; Suleman, A. Embedded fiber optic sensors for monitoring processing, quality and structural health of resin transfer molded components. In Proceedings of the Journal of Physics: Conference Series; 2011; Vol. 305, p. 12135.
67. Ramly, R.; Kuntjoro, W.; Rahman, M.K.A. Using embedded fiber bragg grating (FBG) sensors in smart aircraft structure materials. *Procedia Eng.* **2012**, *41*, 600–606, doi:10.1016/j.proeng.2012.07.218.
68. Bremer, K.; Weigand, F.; Zheng, Y.; Alwis, L.S.; Helbig, R.; Roth, B. Structural health monitoring using textile reinforcement structures with integrated optical fiber sensors. *Sensors (Switzerland)* **2017**, *17*, 345, doi:10.3390/s17020345.
69. Oromiehie, E.; Prusty, B.G.; Compston, P.; Rajan, G. Characterization of process-induced defects in automated fiber placement manufacturing of composites using fiber Bragg grating sensors. *Struct. Heal. Monit.* **2018**, *17*, 108–117, doi:10.1177/1475921716685935.
70. Kousiatza, C.; Tzetzis, D.; Karalekas, D. In-situ characterization of 3D printed continuous fiber reinforced composites: A methodological study using fiber Bragg grating sensors. *Compos. Sci. Technol.* **2019**, *174*, 134–141, doi:10.1016/j.compscitech.2019.02.008.
71. Mieloszyk, M.; Majewska, K.; Ostachowicz, W. Application of embedded fibre Bragg grating sensors for structural health monitoring of complex composite structures for marine applications. *Mar. Struct.* **2021**, *76*, 102903, doi:10.1016/j.marstruc.2020.102903.
72. Maldonado-Hurtado, D.; Madrigal, J.; Penades, A.; Ruiz, R.; Crespo, A.I.; Sales, S. Pultruded FRP Beams with Embedded Fibre Bragg Grating Optical Sensors for Strain Measurement and Failure Detection. *Sensors* **2021**, *21*, 7019, doi:10.3390/s21217019.
73. Leng, J.; Asundi, A. Structural health monitoring of smart composite materials by using EFPI and FBG sensors. *Sensors Actuators, A Phys.* **2003**, *103*, 330–340, doi:10.1016/S0924-4247(02)00429-6.
74. de Oliveira, R.; Ramos, C.A.; Marques, A.T. Health monitoring of composite structures by embedded FBG and interferometric Fabry-Pérot sensors. *Comput. Struct.* **2008**, *86*, 340–346, doi:10.1016/j.compstruc.2007.01.040.
75. Alwis, L.S.M.; Bremer, K.; Roth, B. Fiber Optic Sensors Embedded in Textile-Reinforced Concrete for Smart Structural Health

Monitoring: A Review. *Sensors* **2021**, *21*, 4948, doi:10.3390/s21154948.

76. Li, X.; Golnas, A.; Prinz, F.B. Shape deposition manufacturing of smart metallic structures with embedded sensors. In Proceedings of the Smart Structures and Materials 2000: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials; 2000; Vol. 3986, p. 160.
77. Li, X.C.; Prinz, F.; Seim, J. Thermal behavior of a metal embedded fiber Bragg grating sensor. *Smart Mater. Struct.* **2001**, *10*, 575–579, doi:10.1088/0964-1726/10/4/301.
78. Li, X.; Prinz, F. Metal embedded fiber Bragg grating sensors in layered manufacturing. *J. Manuf. Sci. Eng. Trans. ASME* **2003**, *125*, 577–585, doi:10.1115/1.1581889.
79. Li, X.; Prinz, F. Analytical and experimental study on noncontact sensing with embedded fiber-optic sensors in rotating metal parts. *J. Light. Technol.* **2004**, *22*, 1720–1727, doi:10.1109/JLT.2004.829231.
80. Alemohammad, H.; Toyserkani, E. Metal embedded optical fiber sensors: Laser-based layered manufacturing procedures. *J. Manuf. Sci. Eng. Trans. ASME* **2011**, *133*, doi:10.1115/1.4004203.
81. Schomer, J.J.; Dapino, M.J. High temperature characterization of fiber bragg grating sensors embedded into metallic structures through ultrasonic additive manufacturing. In Proceedings of the ASME 2017 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2017; 2017; Vol. 2, p. V002T05A003.
82. Grandal, T.; Zornoza, A.; Fraga, S.; Castro, G.; Sun, T.; Grattan, K.T.V. Laser Cladding-Based Metallic Embedding Technique for Fiber Optic Sensors. *J. Light. Technol.* **2018**, *36*, 1018–1025, doi:10.1109/JLT.2017.2748962.
83. Jinachandran, S.; Li, H.; Xi, J.; Prusty, B.G.; Semenova, Y.; Farrell, G.; Rajan, G. Fabrication and Characterization of a Magnetized Metal-Encapsulated FBG Sensor for Structural Health Monitoring. *IEEE Sens. J.* **2018**, *18*, 8739–8746, doi:10.1109/JSEN.2018.2866803.
84. Chilelli, S.K.; Schomer, J.J.; Dapino, M.J. Detection of crack initiation and growth using fiber bragg grating sensors embedded into metal structures through ultrasonic additive manufacturing. *Sensors (Switzerland)* **2019**, *19*, 4917, doi:10.3390/s19224917.
85. Hehr, A.; Norfolk, M.; Kominsky, D.; Boulanger, A.; Davis, M.; Boulware, P. Smart build-plate for metal additive manufacturing processes. *Sensors (Switzerland)* **2020**, *20*, 360, doi:10.3390/s20020360.
86. Gallego-Juarez, J.A. Piezoelectric ceramics and ultrasonic transducers. *J. Phys. E.* **1989**, *22*, 804–816, doi:10.1088/0022-3735/22/10/001.
87. Cady, W.G. *Piezoelectricity: Volume Two: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals*; Courier Dover Publications, 2018;
88. Chong, K.P.; Carino, N.J.; Washer, G. Health monitoring of civil infrastructures. *Smart Mater. Struct.* **2003**, *12*, 483–493, doi:10.1088/0964-1726/12/3/320.
89. Tressler, J.F.; Alkoy, S.; Newnham, R.E. Piezoelectric sensors and sensor materials. *J. Electroceramics* **1998**, *2*, 257–272, doi:10.1023/A:1009926623551.
90. Horchidan, N.; Ciomaga, C.E.; Frunza, R.C.; Capiani, C.; Galassi, C.; Mitoseriu, L. A comparative study of hard/soft PZT-based ceramic composites. *Ceram. Int.* **2016**, *42*, 9125–9132, doi:10.1016/j.ceramint.2016.02.179.
91. Wu, F.; Chang, F.K. Debond detection using embedded piezoelectric elements for reinforced concrete structures - Part II: Analysis and algorithm. *Struct. Heal. Monit.* **2006**, *5*, 17–28, doi:10.1177/1475921706057979.
92. Konka, H.P.; Wahab, M.A.; Lian, K. The effects of embedded piezoelectric fiber composite sensors on the structural integrity of glass-fiber-epoxy composite laminate. *Smart Mater. Struct.* **2012**, *21*, 15016, doi:10.1088/0964-1726/21/1/015016.
93. Wu, C.; Xiang, H.; Jiang, S.; Ma, S. Stress Monitoring of Concrete via Uniaxial Piezoelectric Sensor. *Sensors* **2022**, *22*, 4041, doi:10.3390/s22114041.
94. Lin, M.; Qing, X.; Kumar, A.; Beard, S.J. SMART Layer and SMART Suitcase for structural health monitoring applications. In Proceedings of the Smart Structures and Materials 2001: Industrial and Commercial Applications of Smart Structures

Technologies; McGowan, A.-M.R., Ed.; 2001; Vol. 4332, pp. 98–106.

95. Takagi, K.; Sato, H.; Saigo, M. Vibration control of a smart structure embedded with metal-core piezoelectric fibers. *Adv. Compos. Mater. Off. J. Japan Soc. Compos. Mater.* **2006**, *15*, 403–417, doi:10.1163/156855106778835195.
96. Downey, A.; Garcia-Macias, E.; D'Alessandro, A.; Laflamme, S.; Castro-Triguero, R.; Ubertini, F. Continuous and embedded solutions for SHM of concrete structures using changing electrical potential in self-sensing cement-based composites. In Proceedings of the Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, and Civil Infrastructure 2017; 2017; Vol. 10169, p. 101691G.
97. Tang, H.Y.; Winkelmann, C.; Lestari, W.; La Saponara, V. Composite structural health monitoring through use of embedded PZT sensors. *J. Intell. Mater. Syst. Struct.* **2011**, *22*, 739–755, doi:10.1177/1045389X11406303.
98. Talakokula, V.; Bhalla, S. Reinforcement corrosion assessment capability of surface bonded and embedded piezo sensors for reinforced concrete structures. *J. Intell. Mater. Syst. Struct.* **2015**, *26*, 2304–2313, doi:10.1177/1045389X14554133.
99. Karayannis, C.G.; Chalioris, C.E.; Angeli, G.M.; Papadopoulos, N.A.; Favvata, M.J.; Providakis, C.P. Experimental damage evaluation of reinforced concrete steel bars using piezoelectric sensors. *Constr. Build. Mater.* **2016**, *105*, 227–244, doi:10.1016/j.conbuildmat.2015.12.019.
100. Balamonica, K.; Jothi Saravanan, T.; Bharathi Priya, C.; Gopalakrishnan, N. Piezoelectric sensor–based damage progression in concrete through serial/parallel multi-sensing technique. *Struct. Heal. Monit.* **2020**, *19*, 339–356, doi:10.1177/1475921719845153.
101. Ahmadi, J.; Feirahi, M.H.; Farahmand-Tabar, S.; Keshvari Fard, A.H. A novel approach for non-destructive EMI-based corrosion monitoring of concrete-embedded reinforcements using multi-orientation piezoelectric sensors. *Constr. Build. Mater.* **2021**, *273*, 121689, doi:10.1016/j.conbuildmat.2020.121689.
102. Sha, F.; Xu, D.; Cheng, X.; Huang, S. Mechanical Sensing Properties of Embedded Smart Piezoelectric Sensor for Structural Health Monitoring of Concrete. *Res. Nondestruct. Eval.* **2021**, *32*, 88–112, doi:10.1080/09349847.2021.1887418.
103. Huijer, A.; Kassapoglou, C.; Pahlavan, L. Acoustic Emission Monitoring of Carbon Fibre Reinforced Composites with Embedded Sensors for In-Situ Damage Identification. *Sensors* **2021**, *21*, 6926, doi:10.3390/s21206926.
104. Gayakwad, H.; Thiyagarajan, J.S. Structural Damage Detection through EMI and Wave Propagation Techniques Using Embedded PZT Smart Sensing Units. *Sensors* **2022**, *22*, 2296, doi:10.3390/s22062296.
105. Hossain, M.S.; Gonzalez, J.A.; Hernandez, R.M.; Morton, P.; Mireles, J.; Choudhuri, A.; Lin, Y.; Wicker, R.B. Smart parts fabrication using powder bed fusion additive manufacturing technologies. *Solid Free. Fabr. 2017 Proc. 28th Annu. Int. Solid Free. Fabr. Symp. - An Addit. Manuf. Conf. SFF 2017* **2020**, *10*, 2467–2480.
106. Tseng, V.F.-G.; Bedair, S.S.; Lazarus, N. Acoustic Power Transfer and Communication With a Wireless Sensor Embedded Within Metal. *IEEE Sens. J.* **2018**, *18*, 5550–5558, doi:10.1109/JSEN.2018.2839558.
107. Altammar, H.; Dhingra, A.; Salowitz, N. Ultrasonic Sensing and Actuation in Laminate Structures Using Bondline-Embedded d35 Piezoelectric Sensors. *Sensors* **2018**, *18*, 3885, doi:10.3390/s18113885.
108. Yanaseko, T.; Sato, H.; Kuboki, I.; Mossi, K.; Asanuma, H. Vibration Viscosity Sensor for Engine Oil Monitoring Using Metal Matrix Piezoelectric Composite. *Materials (Basel).* **2019**, *12*, 3415, doi:10.3390/ma12203415.
109. Ramanathan, A.K.; Gingerich, M.B.; Headings, L.M.; Dapino, M.J. Metal structures embedded with piezoelectric PVDF sensors using ultrasonic additive manufacturing. *Manuf. Lett.* **2021**, doi:10.1016/j.mfglet.2021.08.001.
110. You, Z.; Mills-Beale, J.; Pereles, B.D.; Ong, K.G. A Wireless, Passive Embedded Sensor for Real-Time Monitoring of Water Content in Civil Engineering Materials. *IEEE Sens. J.* **2008**, *8*, 2053–2058, doi:10.1109/JSEN.2008.2007681.
111. Pinto, F.; Ciampa, F.; Meo, M.; Polimeno, U. Multifunctional SMArt composite material for in situ NDT/SHM and de-icing. *Smart Mater. Struct.* **2012**, *21*, 105010, doi:10.1088/0964-1726/21/10/105010.
112. Sebastian, J.; Schehl, N.; Bouchard, M.; Boehle, M.; Li, L.; Lagounov, A.; Lafdi, K. Health monitoring of structural composites

with embedded carbon nanotube coated glass fiber sensors. *Carbon N. Y.* **2014**, *66*, 191–200, doi:10.1016/j.carbon.2013.08.058.

113. Teng, K.H.; Kot, P.; Muradov, M.; Shaw, A.; Hashim, K.; Gkantou, M.; Al-Shamma'a, A. Embedded smart antenna for non-destructive testing and evaluation (NDT&E) of moisture content and deterioration in concrete. *Sensors (Switzerland)* **2019**, *19*, 547, doi:10.3390/s19030547.
114. Carradero Santiago, C.; Randall-Posey, C.; Popa, A.A.; Duggen, L.; Vuksanovich, B.; Cortes, P.; MacDonald, E. 3D Printed Elastomeric Lattices with Embedded Deformation Sensing. *IEEE Access* **2020**, *8*, 41394–41402, doi:10.1109/ACCESS.2020.2973664.
115. Cougnon, F.; Kersemans, M.; Van Paepegem, W.; Depla, D. Sputter deposited metal layers embedded in composites—from fundamentals to applications. *Coatings* **2021**, *11*, 1–17, doi:10.3390/coatings11020190.
116. Meoni, A.; D'Alessandro, A.; Mancinelli, M.; Ubertini, F. A Multichannel Strain Measurement Technique for Nanomodified Smart Cement-Based Sensors in Reinforced Concrete Structures. *Sensors* **2021**, *21*, 5633, doi:10.3390/s21165633.
117. Yang, J.; Su, Y.; Liao, Y.; Zhou, P.; Xu, L.; Su, Z. Ultrasound tomography for health monitoring of carbon fibre–reinforced polymers using implanted nanocomposite sensor networks and enhanced reconstruction algorithm for the probabilistic inspection of damage imaging. *Struct. Heal. Monit.* **2022**, *21*, 1110–1122, doi:10.1177/14759217211023930.
118. Loh, K.J.; Lynch, J.P.; Kotov, N.A. Passive wireless sensing using SWNT-based multifunctional thin film patches. *Int. J. Appl. Electromagn. Mech.* **2008**, *28*, 87–94, doi:10.3233/JAE-2008-961.
119. Ikemoto, Y.; Suzuki, S.; Okamoto, H.; Murakami, H.; Lin, X.; Itoh, H.; Asama, H. Force sensor system for structural health monitoring using passive RFID tags for structural health monitoring. In Proceedings of the PORTABLE-POLYTRONIC 2008 - 2nd IEEE International Interdisciplinary Conference on Portable Information Devices and the 2008 7th IEEE Conference on Polymers and Adhesives in Microelectronics and Photonics; IEEE, 2008; pp. 1–6.
120. Gao, J.; Sidén, J.; Nilsson, H.-E. Printed Temperature Sensors for Passive RFID Tags. **2010**, 835–838.
121. Merilampi, S.; Björninen, T.; Ukkonen, L.; Ruuskanen, P.; Sydänheimo, L. Embedded wireless strain sensors based on printed RFID tag. *Sens. Rev.* **2011**, *31*, 32–40, doi:10.1108/02602281111099062/FULL/XML.
122. Cheng, X.; Datta, A.; Choi, H.; Zhang, X.; Li, X. Study on embedding and integration of microsensors into metal structures for manufacturing applications. *J. Manuf. Sci. Eng. Trans. ASME* **2007**, *129*, 416–424, doi:10.1115/1.2515456.
123. Zhang, X.; Jiang, H.; Li, X. Design, fabrication, and characterization of metal embedded microphotonic sensors. *J. Manuf. Sci. Eng. Trans. ASME* **2008**, *130*, 0311041–0311047, doi:10.1115/1.2917356.
124. Hahnlen, R.; Dapino, M.J. Active metal-matrix composites with embedded smart materials by ultrasonic additive manufacturing. In Proceedings of the Industrial and Commercial Applications of Smart Structures Technologies 2010; 2010; Vol. 7645, p. 76450O.
125. Juhasz, M.; Tiedemann, R.; Dumstorff, G.; Walker, J.; Plessis, A. Du; Conner, B.; Lang, W.; MacDonald, E. Hybrid directed energy deposition for fabricating metal structures with embedded sensors. *Addit. Manuf.* **2020**, *35*, 101397, doi:10.1016/j.addma.2020.101397.
126. Stoll, P.; Gasparin, E.; Spierings, A.; Wegener, K. Embedding eddy current sensors into LPBF components for structural health monitoring. *Prog. Addit. Manuf.* **2021**, *6*, 445–453, doi:10.1007/s40964-021-00204-3.
127. Nagavally, R.R. Composite materials-history, types, fabrication techniques, advantages, and applications. *Int J Mech Prod Eng* **2017**, *5*, 82–87.
128. Chung, D.D.L. *Composite materials: science and applications*; Springer Science & Business Media, 2010;
129. Gay, D.; Hoa, S. V *Composite materials: design and applications*; CRC press, 2007;
130. Merz, R.; Ramaswami; Terk, K.; Weiss, M. Shape Deposition Manufacturing. In Proceedings of the The Solid Freeform Fabrication Symposium; 1994; pp. 1–7.
131. Kelly, P.J.; Arnell, R.D. Magnetron sputtering: A review of recent developments and applications. *Vacuum* **2000**, *56*, 159–172,

doi:10.1016/S0042-207X(99)00189-X.

132. Friel, R.J.; Harris, R.A. Ultrasonic additive manufacturing A hybrid production process for novel functional products. *Procedia CIRP* **2013**, *6*, 35–40, doi:10.1016/j.procir.2013.03.004.

133. Körner, C. Additive manufacturing of metallic components by selective electron beam melting - A review. *Int. Mater. Rev.* **2016**, *61*, 361–377, doi:10.1080/09506608.2016.1176289.

134. Measures, R.M. Smart composite structures with embedded sensors. *Compos. Eng.* **1992**, *2*, 597–618, doi:10.1016/0961-9526(92)90045-8.

135. Rocha, H.; Semprimoschnig, C.; Nunes, J.P. Sensors for process and structural health monitoring of aerospace composites: A review. *Eng. Struct.* **2021**, *237*, 112231, doi:10.1016/j.engstruct.2021.112231.

136. Hassani, S.; Mousavi, M.; Gandomi, A.H. Structural health monitoring in composite structures: A comprehensive review. *Sensors* **2022**, *22*, 153, doi:10.3390/s22010153.

137. Kinet, D.; Mé Gret, P.; Goossen, K.W.; Qiu, L.; Heider, D.; Caucheteur, C. Fiber Bragg grating sensors toward structural health monitoring in composite materials: Challenges and solutions. *mdpi.com* **2014**, *14*, 7394–7419, doi:10.3390/s140407394.

138. Montazerian, H.; Rashidi, A.; Milani, A.S.; Hoorfar, M.; Montazerian, H.; Rashidi, A.; Milani, A.S. Integrated Sensors in Advanced Composites : A Critical Review. *Crit. Rev. Solid State Mater. Sci.* **2020**, *45*, 187–238, doi:10.1080/10408436.2019.1588705.

139. Yang, Y.; Duan, S.; Zhao, H. Advances in constructing silver nanowire-based conductive pathways for flexible and stretchable electronics. *Nanoscale* **2022**, *14*, 11484–11511, doi:10.1039/D2NR02475F.

140. Chopra, I. Review of state of art of smart structures and integrated systems. *AIAA J.* **2002**, *40*, 2145–2187, doi:10.2514/2.1561.

141. Sun, M.; Staszewski, W.J.; Swamy, R.N. Smart sensing technologies for structural health monitoring of civil engineering structures. *Adv. Civ. Eng.* **2010**, *2010*, doi:10.1155/2010/724962.

142. Yu, Y.; Liu, X.; Yan, J.; Wang, Y.; Qing, X. Real-Time Life-Cycle Monitoring of Composite Structures Using Piezoelectric-Fiber Hybrid Sensor Network. *Sensors* **2021**, *21*, 8213, doi:10.3390/s21248213.

143. Crawley, E.F.; de Luis, J. Use of piezoelectric actuators as elements of intelligent structures. *AIAA J.* **1987**, *25*, 1373–1385, doi:10.2514/3.9792.

144. CHOW, W.; GRAVES, M. Stress analysis of a rectangular implant in laminated composites using 2-D and 3-D finite elements. In Proceedings of the 33rd Structures, Structural Dynamics and Materials Conference; American Institute of Aeronautics and Astronautics: Reston, Virigina, 1992.

145. Yocum, M.; Abramovich, H.; Grunwald, A.; Mall, S. Fully reversed electromechanical fatigue behavior of composite laminate with embedded piezoelectric actuator/sensor. *Smart Mater. Struct.* **2003**, *12*, 556–564, doi:10.1088/0964-1726/12/4/307.

146. Mendez, A.; Morse, T.F.; Mendez, F. Applications Of Embedded Optical Fiber Sensors In Reinforced Concrete Buildings And Structures. In Proceedings of the Fiber Optic Smart Structures and Skins II; Udd, E., Ed.; SPIE, 1990; Vol. 1170, p. 60.

147. Bremer, K.; Alwis, L.S.M.; Zheng, Y.; Weigand, F.; Kuhne, M.; Helbig, R.; Roth, B. Durability of Functionalized Carbon Structures with Optical Fiber Sensors in a Highly Alkaline Concrete Environment. *Appl. Sci.* **2019**, *9*, 2476, doi:10.3390/app9122476.

148. Chang, F.-K.; Markmiller, J.F.C.; Ihn, J.-B.; Cheng, K.Y. A Potential Link from Damage Diagnostics to Health Prognostics of Composites through Built-in Sensors. *J. Vib. Acoust.* **2007**, *129*, 718–729, doi:10.1115/1.2730530.

149. Saravanos, D.A.; Heyliger, P.R. Coupled Layerwise Analysis of Composite Beams with Embedded Piezoelectric Sensors and Actuators. *J. Intell. Mater. Syst. Struct.* **1995**, *6*, 350–363, doi:10.1177/1045389X9500600306.

150. Ghoshal, A.; Martin, W.N.; Schulz, M.J.; Prosser, W.H.; Chattopadhyay, A. Simulation of Asymmetric Lamb Waves for Sensing and Actuation in Plates. *Shock Vib.* **2005**, *12*, 243–271, doi:10.1155/2005/684653.

151. Kim, H.S.; Ghoshal, A.; Chattopadhyay, A.; Prosser, W.H. Development of Embedded Sensor Models in Composite

Laminates for Structural Health Monitoring. *J. Reinf. Plast. Compos.* **2004**, *23*, 1207–1240, doi:10.1177/0731684404039703.

152. Yan, Y.J.; Yam, L.H. Online detection of crack damage in composite plates using embedded piezoelectric actuators/sensors and wavelet analysis. *Compos. Struct.* **2002**, *58*, 29–38, doi:10.1016/S0263-8223(02)00043-0.
153. Butler, S.; Gurvich, M.; Ghoshal, A.; Welsh, G.; Attridge, P.; Winston, H.; Urban, M.; Bordick, N. Effect of embedded sensors on interlaminar damage in composite structures. *J. Intell. Mater. Syst. Struct.* **2011**, *22*, 1857–1868, doi:10.1177/1045389X11414225.