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ESTIMATING THE SERVICE LIFE OF CONCRETE REINFORCED WITH ADVANCED MATERIALS: INTEGRATION OF IOT SENSORS AND DIGITAL TWINS

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ABSTRACT

The protection of durability and safety in concrete structures increasingly depends on structural health monitoring (SHM) using embedded sensors, which enable real-time monitoring of the internal conditions of the material and support preventive maintenance strategies. This paper analyzes the behavior and adaptability of different sensors integrated into concrete for early damage detection and the development of more robust smart infrastructures. A systematic review of the literature was carried out in the Scopus and Science Direct databases, examining 71 peer-reviewed scientific articles published between 2022 and 2025 in the fields of engineering and materials science and written in English. The findings show that fiber optic, piezoelectric, capacitive, and resistive sensors are particularly effective in recording deformation, temperature, humidity, pressure, and chloride penetration. Furthermore, their combination with artificial intelligence (AI), the Internet of Things (IoT), and digital modeling tools such as BIM and ANSYS increases predictive capability and improves the representation of structural behavior. Similarly, both laboratory research and field applications demonstrate their reliability, resistance to environmental conditions, and potential for scaling. Overall, it is concluded that sensor networks.

I. INTRODUCTION

Concrete has established itself as one of the most widely used materials in modern construction thanks to its low cost, high strength, and ability to adapt to multiple geometries and structural sizes [1]. The incorporation of advanced sensors has significantly increased the possibility of monitoring concrete, allowing continuous and accurate tracking of its structural condition [2]. Over time, concrete structures can suffer various types of deterioration, such as corrosion, fatigue, or damage from environmental factors, making constant monitoring essential to ensure their integrity [3]. According to [4], these sensors are capable of recording variables such as deformation, temperature, humidity, and pressure, thus facilitating the early detection of possible structural failures. In the field of structural monitoring of concrete, different types of sensors are used, including fiber optic, piezoelectric, and pressure sensors [5].

These devices provide essential information about deformation and internal stresses that accumulate over time, allowing for early identification of cracks or unusual structural behavior [6]. Thanks to these technologies, it is possible to obtain accurate data on the response of concrete to both static and dynamic loads, which is essential for properly guiding maintenance and repair work [7]. According to [8], the use of advanced sensors in concrete monitoring improves accurate fault detection and reinforces preventive maintenance strategies. Early identification of defects in structures using sensors has established itself as a highly effective strategy, as it significantly reduces maintenance and repair costs by enabling interventions before damage reaches an advanced stage [9]. This technology also promotes sustainability in the construction sector, as it facilitates continuous monitoring of structures, extends their useful life, and reduces the need for major repairs or complete reconstruction [10].

The effectiveness of structural monitoring depends largely on the quality of the data collected, its correct integration with forecasting systems, and the ability to generate alerts sufficiently in advance [11]. In this regard, technological advances have enhanced information analysis and processing tools, making it possible to detect and predict structural failures even before they become visible [12]. Likewise, the incorporation of artificial intelligence and machine learning algorithms has increased the accuracy of predictions, simultaneously optimizing maintenance management in critical infrastructures [13]. The incorporation of sensors in IoT-based systems enables real-time data collection, allowing for continuous monitoring with a high level of accuracy [14]. This massive collection of information provides a solid basis for identifying patterns in structural behavior and anticipating potential failures [15]. According to [16] The integration of these sensors with remote monitoring platforms has strengthened the control of large-scale infrastructure, significantly reducing the costs associated with inspections.

As infrastructure ages, it is essential to monitor it constantly to detect progressive deterioration that is not visible to the naked eye [17]. Regular inspections using specialized sensors enable damage such as internal concrete corrosion to be identified at an early stage [18]. Advances in detection technologies have made it possible to supplement concrete monitoring with methods such as thermography and infrared imaging, which facilitate the identification of anomalies that, in many cases, are not detected by conventional sensors [19]. The combination of these tools provides a more comprehensive assessment of structural condition and increases accuracy in detecting defects such as hidden cracks or the presence of accumulated moisture, factors that could compromise the stability of the structure [20]. Likewise, recent studies indicate that, in the future, structural monitoring will rely on distributed sensor networks, which will optimize the process of supervising and evaluating the condition of structures [21]. With the evolution of these systems, monitoring is expected to become more efficient and accessible, enabling timely and less costly interventions [22].

II. METHODOLOGY

This review article was developed with an exploratory approach, focusing on analyzing scientific publications on the use of sensors in concrete for structural monitoring. The information was obtained through searches in Scopus and ScienceDirect covering 2022–2025. The retrieval strategy used English keywords related to the topic—in particular, the English equivalent of “sensors applied in concrete for structural monitoring”—combined with the Boolean operator AND to refine the accuracy. A search was conducted in the Scopus database using the keywords “sensors applied in concrete for structural monitoring” together with the AND operator. In the first stage, 5,447 documents were identified. After applying filters to restrict the output to scientific articles in English on Engineering and Materials Science, the total was reduced to 2,327 articles, of which 25 were finally selected for analysis. A search was also conducted in ScienceDirect using the same keywords and criteria, with an initial result of 28,380 documents. Subsequently, similar filters were applied (fields of Engineering and Materials Science, type of scientific articles, English language), reducing the total to 10,800. After removing duplicates and reviewing titles and abstracts, 42 articles were selected for analysis and synthesis. The findings are summarized in Tables 1 and 2.

Table 1: Summary, criteria, and results of the search in the Scopus and Science Direct databases.

DATABASE	SEARCH TERMS WITH OPERATORS	ECONRED DOCUMENTS	PERIOD	FILTERS APPLIED	LEAKED DOCUMENTS	SELECTED DOCUMENTS
SCOPUS	sensors Y applied Y to Y concrete Y for Y structural monitoring	5 447	2021 - 2025	Field: “Engineering” “Materials science” Document type: Article	2 327	25
SCIENCE DIRECT	Sensors embedded in concrete for structural monitoring	28 380	2022 - 2025	Field: “Engineering Document type: Article	10 820	42

Source: Authors, (2026).

Table 2: Distribution of article references by year of publication and database.

DATABASE	YEAR OF APPLICATION				
	2022	2023	2024	2025	Total
SCOPUS	1	4	11	9	25
SCIENCEDIRECT	1	7	16	18	42
TOTAL	2	11	27	27	67

Source: Authors, (2026).

Bibliometric analysis and network visualization

PTo determine the state of the art prior to technical synthesis, a search was conducted in Scopus using the unified query:

(TITLE-ABS-KEY (sensors) AND TITLE-ABS-KEY (applied) AND TITLE-ABS-KEY (in) AND TITLE-ABS-KEY (concrete) AND TITLE-ABS-KEY (for) AND TITLE-ABS-KEY (structural) AND TITLE-ABS-KEY (monitoring))

The search returned 616 documents. The metadata were exported and a co-occurrence map was constructed in VOSviewer. Figure 1 shows the network visualization: node size (frequency), color (cluster), and link thickness (strength of association)).

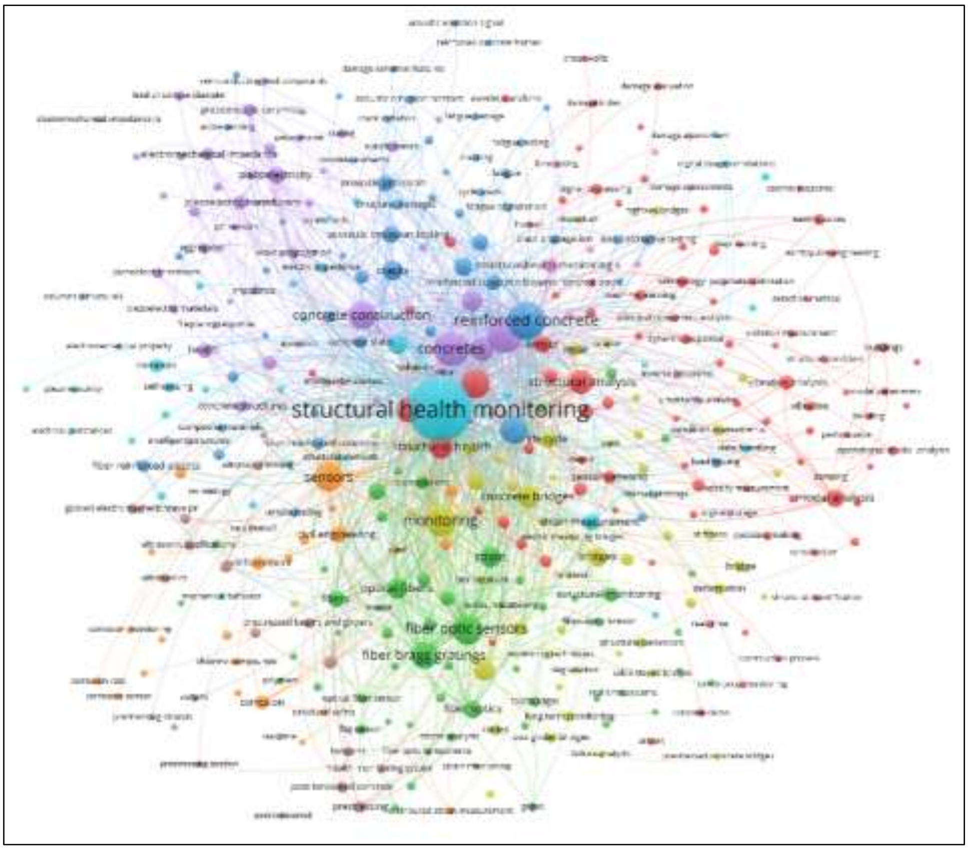

Figure 1: Network visualization.
Source: Authors, (2026).

The graph shows a field structured around structural health monitoring as its core, connected to (i) materials/elements and application scenarios—concrete, reinforced concrete, concrete bridges/buildings, prestressed concrete—; (ii) sensing technologies—fiber optic sensors/DFOS, FBG, piezoelectric/PZT, electromechanical impedance, acoustic emission, digital image correlation—; and (iii) evaluation tasks—damage/crack detection, strain measurement, modal/vibration analysis, condition assessment, corrosion monitoring. Likewise, threads of data management and computation emerge—machine learning, deep learning, computer vision, IoT, and wireless sensor networks — which structure a subfield oriented toward the automation of diagnosis. Overall, the network suggests framing the review around two complementary axes: (a) the typology of sensors and measurement methods and (b) the diagnostic functions on concrete structure typologies, with special emphasis on the early detection of damage, cracks, and corrosion for maintenance and structural safety decisions.

III. RESULTS AND DISCUSSIONS

III.1 INTEGRATED SENSORS FOR STRUCTURAL MONITORING

Integrated sensors allow real-time analysis of the internal response of the material. In the case of self-detectable sensors made of engineered cementitious composite (ECC) and incorporated into columns, they were found to be highly accurate under moderate loads without affecting structural integrity. Through simulations in ABAQUS and measurements taken with strain gauges, it was determined that the most suitable geometry is a 20 mm cube with a friction coefficient equal to or greater than 0.6 [23]. In turn [24], they pointed out that this configuration makes it possible to record parameters such as deformations, temperature, humidity, pore pressure, and the appearance of cracks, which are often difficult to detect through surface measurements. [25].

The importance of continuous monitoring from the system configuration phase to material aging was highlighted, which is essential for identifying faults at an early stage. In his research, a piezoresistive sensor equipped with CBTENG managed to generate 113 V at 4 Hz and charge a 10 μF capacitor to 0.32 V in 25 seconds. In addition [26] hey used artificial intelligence (AI) to detect cracks and corrosion processes, demonstrating its effectiveness after applying acoustic filtration. These developments overcome the limitations of surface sensors, as they provide more comprehensive monitoring, with high sensitivity and self-powering capabilities, which improves both the safety and durability of concrete. According to [27] FBG sensors combined with deep neural networks and PCA analysis enable damage prediction in complex structures with a high degree of accuracy, overcoming the difficulties associated with manual labeling.

By [28] They evaluated the electrical impedance (EI) of embedded PZT sensors, demonstrating that, in samples larger than 150 mm, the EI reflects only the properties of the concrete, eliminating edge effects. This supports their standardized use in continuous structural health monitoring (SHM). Taken together, these results show that artificial intelligence and integrated sensors are revolutionizing structural monitoring by providing accurate predictions and reliable data without the need for manual intervention. Their standardization is a key step toward safer, self-monitoring structures. All this information is summarized in Table 3, based on a review of two articles published in 2023, two articles from 2024, and two articles from 2025.

Table 3: Sensors embedded in concrete for structural monitoring.

TYPE OF INTEGRATED SENSOR	MONITORED PARAMETERS	TECHNICAL ADVANTAGES	MONITORING PHASE	REFERENCE
generic integrated sensor	Cracks, humidity, temperature	Allows for complete integration within the structure	From concrete pouring to operational phases	[23]
generic integrated sensor	Cracks, humidity, temperature	Facilitates monitoring from the early stages to the aging of the material	Throughout the structural life cycle	[24]
FBG (fiber optic) sensor	Deformation, temperature	High precision and resistance to electromagnetic interference	From setting to aging	[25]
Piezoelectric sensor (PZT)	Vibrations, impacts	High sensitivity to dynamic stresses	Continuous monitoring under cyclic loads	[26]
Wireless IoT sensor	Multiple (deformation, temperature, humidity, etc.)	Remote measurement and low maintenance requirements	The entire service life of the structure	
Integrated pressure sensor	Pore pressure	Localized measurement of internal pressure	Initial stages and underground conditions	[27]
Integrated capacitive sensor	Internal humidity, temperature	Good response to hygrothermal changes	First stages of configuration	
generic integrated sensor	mechanical and environmental variables	Promotes the development of smart and sustainable infrastructure	Throughout the entire structural service life	[28]

Source: Authors, (2026).

III.2 FUNCTIONAL CHARACTERISTICS OF SPECIFIC SENSORS

III.2.1 Sensitivity and Accuracy in Fault Detection

In [29] they analyzed the behavior of FBG sensors subjected to biaxial stress, showing that transverse deformation affects longitudinal readings, which reduces the accuracy of uniaxial calibrations. For its part, [30] They pointed out that, thanks to their high sensitivity to microdeformations (με) and changes in wavelength, this type of sensor is capable of detecting internal microcracks before they become visible externally. In turn [31] they used integrated piezoelectric sensors (EPS) to monitor the evolution of concrete strength from the first hour of setting to 90 days, recording phase transitions with remarkable predictive accuracy. Among the systems evaluated, the combination of CPM + CE + slag achieved the highest strength. However [32] Under cyclic loads, EPS can reliably identify internal damage and, when integrated with random forest (RF) models, can predict structural strength with 97% accuracy. Taken together, the reviewed studies show that FBG sensors and embedded EPS provide high sensitivity for detecting microcracks and structural modifications at early stages. Their integration with machine learning techniques significantly improves predictive capability, overcoming the limitations of traditional monitoring methods.

III.2.2 Measuring Range and Resolution

By [33] indicated that the performance of sensors embedded in concrete depends directly on their measurement range and resolution, which are fundamental parameters for ensuring reliable structural monitoring. In the case of fiber Bragg grating (FBG) sensors, resolutions of 1 με and 0.1 °C were reported. According to [34] they added that embedded humidity sensors can achieve an accuracy of ±1% RH, which is crucial for the early detection of corrosion processe. According to [35] Piezoelectric and capacitive sensors perform adequately under dynamic loads, achieving resolutions of 0.01 mm and response times of less than 0.1 s. Finally [36] they developed a method for evaluating concrete permeability using built-in resistivity sensors, calibrated using Van Genuchten models and saturation profiles. The results obtained—with values between 10^{-11} and 10^{-13} m/s—showed correlations greater than 90% compared to traditional techniques such as gamma densimetry and mass loss measurement. These findings confirm that embedded sensors allow accurate and continuous monitoring of critical parameters, improving early detection of structural failures.

III.2.3 Response to External Conditions

By [37] they demonstrated that FBG sensors embedded in concrete allow both the thermal and mechanical conditions of the material to be monitored, recording temperatures of up to 72 °C and deformations of 300 με, with sensitivities of 1.2 pm/με and 10 pm/°C, facilitating thermal compensation and the identification of microcracks. On the other hand, [38] it was reported that the integrated piezoresistive sensors maintain signal stability even under extreme thermal cycles ranging from 20°C to 80°C, making them a suitable choice for structures subjected to severe weather conditions. [39] three-dimensional spacers equipped with RFID-MEMS sensors were also developed to measure moisture at the steel-concrete interface (SCI), achieving an accuracy of ±2% up to 90% RH at 50°C; however, a decrease in accuracy was observed when humidity exceeded 93% due to condensation.

According to [40] FBG sensors were integrated with ultrasonic guided waves (UGW) to detect corrosion in steel bars, recording attenuation greater than 40% in L mode (0.1) under 5 V, which allowed damage to be identified and located even at considerable distances from the point of corrosion. Taken together, these studies show that embedded sensors can operate effectively under extreme conditions, providing accurate measurements of critical variables such as temperature, humidity, and corrosion. Their incorporation into exposed structures improves early fault detection, while technologies such as RFID-MEMS and UGW expand the capabilities of non-destructive monitoring. All this information is summarized in Table 4, based on a review of three articles published in 2023, three in 2024, and five in 2025.

Table 1: Functional characteristics of specific sensors.

TYPE OF INTEGRATED SENSOR	MONITORED PARAMETERS	TECHNICAL ADVANTAGES	MONITORING STAGE	REFERENCE
FBG (fiber optic) sensor	Biaxial deformation, microcracks	High sensitivity to microdeformations (με) and wavelength variations	Seit der ersten Anwendung	[29] ; [30]
Piezoelectric sensor (EPS)	Resistance, phase transitions	Detects changes from the first hour to 90 days; 97% accuracy.	Anfängliche Phasen bis zur Aushärtung	[31] ; [32]
FBG (fiber optic) sensor	Deformation, temperature	Resolution of 1 µe and 0.1 °C	Kontinuierliche Temperaturüberwachung	[33]
Humidity sensor	Relative humidity	Accuracy of ±1% RH	Während Prozessen, die mit Korrosion verbunden sind	[34]
Piezoelectric/capacitive sensor	dynamic deformations	Resolution of 0.01 mm and < 0.1 seconds	Unter dynamischen Belastungen	[35]
Resistivity sensor	Concrete permeability	Values between 10^{-11} and 10^{-13} m/s, correlation > 90%	Trocknungs- und Imbibitionsprozesse	[36]
FBG sensor	Temperature and thermal deformation	Temperatures reach up to 72 degrees Celsius (300 degrees Celsius) and 300 degrees Celsius. Sensitivity 1.2 pm/with	Von der Konfiguration bis zum Betrieb	[37]
Piezoresistive sensor	extreme thermal cycles	Signal stability from –20 °C to 80 °C	Umgebungen mit hohen Temperaturschwankungen	[38]
RFID-MEMS sensor	Moisture at the steel-concrete interface	Genauigkeit ±2 % HR bis 90 % HR bei 50 °C	Warme und fe|uchte Umgebungen	[39]
FBG Sensor + UGW	Corrosion on steel bars	Dämpfung > 40 % im Modus L (0,1)	Wassereinwirkung und induzierte Spannung	[40]

Source: Authors, (2026).

III.3 CLASSIFICATION AND PERFORMANCE OF SENSORS APPLIED IN CONCRETE

III.3.1 Fiber Optic Sensors.

Distributed fiber optic sensing (DFOS) technology has proven to be highly effective for the structural diagnosis of prestressed concrete bridges, as it allows real-time and highly accurate measurement of deformations of up to ±500 με, displacements of ±2 mm, and crack opening, as reported by [41]. This technique was also applied to flat slabs subjected to the sudden loss of a column, making it possible to identify the appearance of cracks from the outset and monitor their evolution with a sensitivity of ±20 με. In a practical case [42] they installed a 15-meter prestressed beam belonging to the IDA-KI project using DFOS sensors embedded in the concrete, reinforcement, and cables, achieving a spatial resolution of 1 cm and detecting structural anomalies early on. For its par [43] They proposed an analytical method for asphalt pavements based on DFOS and the CPSD algorithm, validated using accelerometers, obtaining a resolution of 1 cm and a modal criterion greater than 0.95. Together, fiber optic sensors enable distributed, high-precision monitoring capable of detecting deformations, cracks, and failures with excellent resolution and sensitivity. Their effectiveness has been corroborated on bridges, slabs, and pavements, surpassing traditional methods and enabling more reliable early detection of structural damage.

III.3.2 Piezoelectric Sensors.

By [44] they developed a Structural Health Monitoring (SHM) system for aeronautical composite materials that integrates embedded piezoelectric sensors with machine learning techniques, achieving high-precision identification of simple and combined failures through time-frequency analysis based on the Gram angular field. For its part, [45] they used EPS sensors together with the EMI technique to evaluate the evolution of the strength of concrete made from electronic waste, detecting variations from the first 2 hours to 28 days. In mixtures with a 15% replacement of coarse aggregate, the strength was reduced from 37.8 to 34.7 MPa, equivalent to a decrease of 8.15%Asimismo, [46] se evaluaron sensores PZT y PEC bajo condiciones de carga, observándose que el PZT presentó un rendimiento superior en su segundo pico de resonancia, mientras que el PEC destacó por encima de los 800 kHz. El estudio encontró correlaciones logarítmicas entre la deformación (hasta un 0,15 %) y la señal registrada, así como correlaciones lineales entre el voltaje (hasta 25 MPa) y la conductancia. Finally [47] integrated PZT sensors into 3D-printed concrete structures, detecting the presence of cracks through impedance variations of up to 30%. It was observed that 2 mm coatings offered greater sensitivity, while 8 mm coatings increased load capacity by 12%. Taken together, these studies demonstrate that piezoelectric sensors represent a versatile and highly accurate alternative for non-destructive structural monitoring, with applications ranging from additive manufacturing processes to curing control and behavior under dynamic loads.

III.3.3 Capacitive and Resistive Sensors for Concrete Monitoring

Capacitive and resistive sensors allow fundamental concrete parameters to be recorded, such as internal moisture, the appearance of microcracks, and changes in dielectric properties, by measuring variations in permittivity or electrical resistivity associated with processes such as curing, saturation, or carbonation [48]. For example [49] integrated RFID-MEMS sensors into three-dimensional spacers to monitor moisture at the steel-concrete interface. In test specimens with water-to-cement ratios of 0.40 and 0.55, cured for 3 and 14 days and subjected to conditions of 50 °C, 65% RH, and 21 °C, the accuracy reached ±2% up to 90% relative humidity, decreasing above 93% due to condensation, confirming its usefulness for assessing the risk of corrosion. For this reason [50] They developed a cementation sensor composed of a double electrochemical layer and a graphene film, characterized by its high sensitivity to the presence of chlorides using EIS, as well as its stable response to variations in temperature and humidity, although with sensitivity to pH.

Finally, [51] Using EIS, it was observed that the system exhibited high sensitivity and stability, with a response independent of temperature and humidity but affected by pH, which led to the proposal of a calibration equation to improve chloride diffusion models. Together, capacitive and resistive sensors provide accurate monitoring of moisture and corrosion processes from the first 48 hours, even under extreme conditions between 0 and 40 °C and saturation levels of 60 to 100%. Their sensitivity to chlorides and compatibility with wireless technologies make them an ideal choice for exposed structures and continuous monitoring without compromising durability.

All this information is summarized in Tables 5, 6, and 7, compiled from a review of one article published in 2022, two in 2023, four in 2024, and four in 2025. Capacitive and resistive sensors enable accurate monitoring of moisture and corrosion from the first 48 hours, even under extreme conditions of 0–40°C and saturation levels of 60–100%. Their sensitivity to chlorides and compatibility with wireless systems make them ideal for exposed structures and continuous monitoring without compromising durability. °C and 60–100% saturation. Their sensitivity to chlorides and compatibility with wireless systems make them ideal for exposed structures and continuous monitoring without compromising durability. All this information is summarized in Tables 5, 6, and 7, based on a review of one article published in 2022, two in 2023, four in 2024, and four in 2025.

Table 2: Fiber optic sensors.

SENSOR TYPE	ACCURACY	COST	LIFESPAN	ENVIRONMENTAL RESISTANCE	RECOMMENDED APPLICATION	AUTHOR(S)
FBG	±500 con ±2 mm	High	Very tall	Excellent	Post-tensioned bridges	[41]
DFOS	Resolución de 1 cm	High	High	Excellent	Prestressed beams	[42]
DFOS + CPSD	1 cm, >0,95 criterio modal	High	High	Excellent	Asphalt pavements	[43]

Source: Authors, (2026).

Table 3: Piezoelectric sensors.

SENSOR TYPE	ACCURACY	COST	LIFESPAN	ENVIRONMENTAL RESISTANCE	RECOMMENDED APPLICATION	AUTHOR(S)
PZT-5H	±10%, up to 500 kHz	Medium	High	Good	crack detection	[44]
EPS + EMI	2h–28d, -8.15% resistance	Medium	Medium	Moderate	Difficult curing and development	[45]
PZT/PEC	0.15% deformation, 25 MPa	Medium	Medium	Moderate	mechanical evaluation	[46]
PZT in 3D	30% impedance, +12% load	Medium	High	Good	3D Concrete Printing	[47]

Source: Authors, (2026).

Table 4: Capacitive and resistive sensors.

SENSOR TYPE	ACCURACY	COST	LIFESPAN	ENVIRONMENTAL RESISTANCE	RECOMMENDED APPLICATION	AUTHOR(S)
Built-in resistance	0–40 °C, 60–100% relative humidity	Low	High	Moderate	Initial curing and corrosion detection	[48]
Cement with graphene	High sensitivity through EIS	Medium	Medium	Good	Chloride diffusion assessment	[49]
Wireless resistive sensor	Stable remote measurement	Medium	Medium	Moderate	Monitoring of structures in service	[50]
Capacitive and resistive sensors	Variations in permittivity and electrical resistivity	Medium	Medium	Moderate	Moisture control, crack detection, curing, and carbonation	[51]

Source: Authors, (2026).

III.4 ADVANCED TECHNOLOGICAL INTEGRATION FOR STRUCTURAL MONITORING

III.4.1 Artificial Intelligence and Machine Learning

The application of artificial intelligence in SHM allows complex patterns to be recognized using algorithms such as neural networks and support vector machines (SVM), achieving accuracies of up to 98% in the detection of structural damage in beams, even when limited data is available [52]. For its part [53] They emphasized the role of smart sensors in structural health monitoring (SHM), highlighting their ability to replace conventional methods, optimize maintenance strategies, and reduce operating costs by up to 30%, in addition to reporting 93% accuracy in detecting microcracks using artificial intelligence techniques. In the case of bridges [54] reported a decrease of up to 35% in maintenance costs thanks to the use of these systems, although they noted that challenges remain related to high energy consumption and the cost of IoT sensors. Finally [55] indicated that automatic structural condition classification allows early warnings to be generated in accordance with current regulations, strengthening failure prevention. Overall, artificial intelligence is positioned as a key tool for transforming simple data collection into more efficient structural decisions. Despite the high accuracy achieved, its performance depends on the quality and quantity of the data used in training, which poses challenges in terms of standardization and mass acquisition of information.

III.4.2 Structural Data Modeling and Visualization

The use of digital twins combined with real-time sensors and convolutional networks such as VGG-16 has made it possible to identify damage caused by saline agents with high precision, significantly improving predictive maintenance strategies, according to [56]. For its pairte [57] they also pointed out that integrating these systems with BIM platforms facilitates the visualization and detailed analysis of structural damage and pathologies. In the same vein [58] They highlighted that interoperability between IoT sensors and BIM, reinforced by the extension of the SAREF ontology through IADOM and RDF, optimizes both maintenance management and infrastructure design in smart environments.

Likewise, [59] They reported that models capable of instantly updating data from sensors within three-dimensional platforms such as ANSYS APDL have been evaluated, enabling efficient synchronization between analytical models and structural monitoring systems. This advanced visualization capability enhances the interpretation of technical information and facilitates informed decision-making; however, its implementation still requires a robust digital infrastructure, which may limit its adoption in contexts with low levels of digitization or connectivity. All this information is summarized in Table 8, based on a review of one article published in 2022, four in 2024, and three in 2025.

Table 8: Technological integration in advanced structural monitoring.

APPLIED TECHNOLOGY	**MAIN FOCUS**	**OUTSTANDING STRUCTURAL APPLICATION**	**REFERENCE**
Artificial intelligence in SHM	Neural networks and SVM	Identification of faults in beams with 98% accuracy	[52]
Smart sensors with AI	Microcrack detection	0% reduction in operating costs and 93% accuracy	[53]
IoT systems applied to bridges	Structural monitoring	35% reduction in maintenance; associated energy challenges	[54]
Structural classification algorithms	Based on current regulations	Issuing early warnings in accordance with structural standards	[55]
Digital twins + CNN	VGG-16 Architecture	Accurate detection of damage caused by saline agents and predictive maintenance	[56]
BIM modeling in damage assessment	Visualización tridimensional	Advanced analysis of complex structural pathologies	[57]
SAREF ontology with IADOM and RDF	Semantic interoperability	Optimized management in smart environments integrated with IoT and BIM	[58]
EF models integrated with sensor data	Real-time updates	Structural synchronization in 3D platforms such as ANSYS	[59]

Source: Authors, (2026).

III.5 EXPERIMENTAL VALIDATION AND CASE STUDIES

III.5.1 Laboratory Applications

By, [60] They demonstrated that integrated sensors enable early identification of corrosion processes in concrete through acoustic emissions close to ~30 dB, associated with deformations of 20 με, a decrease in amplitude (from 2.59 to 1.29 mV), and an increase in ultrasonic velocity up to 4.55 km/s. For its part, [61] they evaluated pH sensors embedded for 250 days in mortars subjected to carbonation, observing failures caused by accelerated drying at pH values above 12.5 and proposing improvements using gel indicators and compounds such as thymolphthalein. Likewise [62] demonstrated that integrated sensors capable of measuring humidity, temperature, and conductivity can anticipate conditions conducive to corrosion up to 20 days in advance, and that UHPC reinforced with 1.5–4% steel fibers increases sensitivity to damage through the use of FCR. Finally, [63] they validated vibration sensors to detect loss of stiffness under cyclic loads, as well as a matrix sensor (4×4 Ag/AgCl and 2×2 MnO_2) capable of monitoring chloride concentrations in marine environments even in the event of partial system failures. Together, the embedded sensors enable early detection of corrosion, carbonation, and various structural damages. Their performance is enhanced when optimized configurations and materials—such as steel fibers or conductive matrices—are used, strengthening the structural monitoring capabilities of concrete.

III.5.2 Field applications

The integrated FBG sensors, used on the Streicker Bridge and on medium-small span bridges, enabled high-fidelity measurements of temperature, deformations, and vertical displacements (linearity 0.998, sensitivity 7.87 pm/mm, and error <5%), with installation angles between 15° and 30° recommended. In urban settings [64] reported that the London Underground incorporated piezoelectric sensors to detect critical vibrations. With this, they developed an automated SHM system based on modal identification, neural networks, and wavelets, capable of locating damage without manual intervention [65]. On the other hand [66] they proposed an automated SHM framework with modal identification, neural networks, and wavelet transforms, achieving accurate damage detection. Finally [67] they designed a piezoelectric sensor with integrated PZT-5H to detect cracks in concrete beams, demonstrating high sensitivity and stability when recording amplitude variations associated with damage. Using wavelet analysis, it was possible to estimate the depth and location of the cracks. Together, these field applications demonstrate the reliability and scalability of integrated sensors, although their optimal performance depends on proper installation, correct maintenance, and intelligent systems that efficiently process data.

IV. CONCLUSIONS

The systematic review confirms the effectiveness of sensors embedded in concrete as fundamental tools for real-time structural monitoring, allowing continuous monitoring from setting to extreme operating conditions, with high precision in measuring deformation, humidity, temperature, pressure, and corrosion. Fiber optic, piezoelectric, capacitive, and resistive sensors stand out over traditional methods due to their greater sensitivity, environmental resistance, and adaptability to the different stages of the structural life cycle. The integration of these sensors with artificial intelligence, machine learning, IoT, BIM, digital twins, and specialized software such as ANSYS significantly improves fault prediction, structural representation, and decision support, driving predictive maintenance and reducing operating costs. Both laboratory studies and field tests validate their reliability, scalability, and efficiency. However, their optimal implementation requires proper installation, algorithmic processing, and the support of robust digital infrastructures, which are essential for the development of intelligent, resilient, and sustainable structures.

V. AUTHOR'S CONTRIBUTION

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