European Research Studies Journal
Volume XXVIII, Issue 4, 2025

pp. 242-260

Structural Health Monitoring of Corrosion in Reinforced Concrete: A Key Component for Smart Cities

Submitted 05/09/25, 1st revision 28/09/25, 2nd revision 17/10/25, accepted 12/11/25

Paweł Karol Frankowski[1], Piotr Majzner[2], Ryszard Ziętek[3], Wojciech Czapliński[4], Dominik Mech[5], Igor Stankiewicz[6], Joanna Wiśniewska[7], Sebastian Matysik[8]

Abstract:

Purpose: *The purpose of this study is to develop and validate a scientific framework for detecting and monitoring reinforcement corrosion in reinforced concrete structures through the integration of the Magnetic Force Induced Vibration Evaluation (M5) method, Artificial Intelligence (AI), and Internet of Things (IoT) technologies. The research aims to demonstrate that this approach can serve as a foundation for proactive and sustainable infrastructure management in smart cities.*

Design/Methodology/Approach: *The study employed a systematic literature review (SLR) following PRISMA standards to identify state-of-the-art methods for corrosion diagnostics in reinforced concrete. Based on the SLR results, the Magnetic Force Induced Vibration Evaluation (M5) method was selected and experimentally validated as a core component of a Structural Health Monitoring (SHM) system. The research combined AI-based Association Rules Analysis (ARA) for signal interpretation with IoT integration to enable real-time, non-destructive monitoring of corrosion processes.*

Findings: *Research shows that reinforcement corrosion in reinforced concrete (RC) structures is a major challenge for the construction industry, significantly hindering smart city development. One of the few effective methods for detecting corrosion in structural health monitoring (SHM) is the Magnetic Force Induced Vibration Evaluation (M5) method. The newly developed Association Rules Analysis (ARA) technique reveals that M5 frequency characteristics can indicate corrosion by damping specific resonant frequencies of the structure. Integrating M5-based SHM systems with the IoT can prevent structural failures and extend the lifespan of RC structures. This integration not only helps avoid construction disasters but also achieves cost savings, reduces material usage, and lowers CO2 emissions,*

[1]*West Pomeranian University of Technology in Szczecin, Faculty of Electrical Engineering, Poland, ORCID: 0000-0002-3652-1233, e-mail: frankowski@zut.edu.pl;*
[2]*Maritime University of Szczecin, Poland, ORCID: 0000-0002-7543-4263, e-mail: p.majzner@pm.szczecin.pl;*
[3]*The same as in 2, ORCID: 0000-0001-7034-7251, e-mail: r.zietek@pm.szczecin.pl;*
[4]*The same as in 2, ORCID: 0000-0002-9503-4742, e-mail: w.czaplinski@pm.szczecin.pl;*
[5]*The same as in 2, Student KN BIT, e-mail: 29956@s.pm.szczecin.pl;*
[6]*The same as in 2, Student KN BIT, e-mail: 30949@s.pm.szczecin.pl;*
[7]*University of Szczecin, Institute of Management, Poland, ORCID: 0000-0002-1607-8721, e-mail: joanna.wisniewska@usz.edu.pl;*
[8]*The same as in 7, Doctoral School, ORCID: 0009-0002-7264-0501, e-mail: sebastian.matysik@usz.edu.pl;*

fostering the growth of smart, sustainable cities.
Practical Implications: *The outcomes highlight opportunities to extend the service life of reinforced concrete structures, reduce inspection costs, and align infrastructure management with sustainability goals by lowering material consumption and emissions. Implementing these in smart city contexts could enable proactive maintenance and early warning systems, reducing costs and risks, and promoting sustainable urban development.*
Originality/Value: *The study introduces an innovative integration of modal analysis diagnostics, AI machine learning, and IoT communication to develop an advanced SHM system.*

Keywords: *Reinforced concrete, corrosion monitoring, non-destructive testing, structural health monitoring, IoT, M5 method.*

JEL codes: *L74, O18, Q55.*

Paper type: *Research article.*

Funding: *This research was funded by the National Science Centre (in Polish: NCN - Narodowe Centrum Nauki), program: Preludium, grant number 2021/41/N/ST7/02728 ("Smart support system for the Magnetic Force Induced Vibration Evaluation (M5) - an electromagnetic, non-destructive method designed for the evaluation of composite materials containing ferromagnetic and conductive elements").*

1. Introduction

Smart cities are a key focus of the European Union's agenda, supported by initiatives such as the Smart Cities Marketplace, which connects cities, industry, and researchers, providing technical and financial support. The EU Mission "100 Climate-Neutral and Smart Cities by 2030" aims to help cities reach climate neutrality. Collaboration is encouraged through the Smart Communities network, and digital tools such as Digital Twins are developed to address urban challenges.

These efforts combine policy, funding, technology, and citizen engagement to promote sustainable, innovative urban development. A significant obstacle to smart city development is the corrosion of reinforced concrete, which leads to numerous construction failures, substantial financial losses, and environmental damage (Correia, Marques, and Teixeira, 2022; Lytras and Serban, 2020; Balderacchi and Piacentini, 2024).

Corrosion of reinforcement in reinforced concrete (RC) structures remains a major challenge for the construction industry and the development of smart cities.

According to reports from the Federal Highway Administration and NACE International, approximately 30% of residential buildings already exhibit corrosion-related damage, with repair costs accounting for around 15% of total operating expenses for residential facilities.

Globally, the economic impact is immense, with annual losses estimated at $2.5 trillion – roughly 3.2% of the world's GDP (Koch *et al.,* 2016; Koch *et al.,* 2002; Chang, 2017; Frankowski *et al.,* 2021). Similar issues are prevalent in other developed countries, where the cost of RC corrosion typically ranges from 1% to 3% of GDP.

In the USA, this cost reaches $276 billion annually (3.1% of GDP) (NACE, 2025; Arndt and Jalinoos, 2009), in Switzerland just repair costs are estimated between $6.6 and $26.3 billion CAD per year (Giatec Scientific, 2025), and in Japan, expenses total around 1.02% of GDP, or 5,258 billion yen (Nurhadiyanto and Sianipar, 2024).

Beyond financial losses, corrosion leads to structural failures that can cause accidents and fatalities, while also accelerating resource depletion and contributing to increased greenhouse gas emissions. Notably, the built environment accounts for 39% of global CO_2 emissions (Crawford, 2022).

Constant structural health monitoring (SHM) is essential for RC structures in harsh environments like bridges. Reports from Reports Insights Consulting Pvt Ltd indicate that the smart bridges market is expected to grow at a CAGR of 18.5% from 2025 to 2033. The market's value is projected to reach $1.2 billion in 2025 and $4.85 billion by 2033.

Major drivers include the adoption of IoT-SHM systems, advances in sensor technology for non-destructive testing, and the integration of communication methods such as 5G, LoRaWAN, NB-IoT, and satellite links, along with rising demand for digital twin-based construction testing (Insights Consulting, 2024). Ignored corrosion in such structures can pose serious safety risks.

High-profile incidents like the Laval bridge collapse in Canada, which resulted in five deaths (Mitchell, Marchand, Croteau, and Cook, 2011), and the 2018 Genoa viaduct disaster in Italy, which caused 43 deaths and left 566 people homeless (Rymsza, 2021; Malerba, 2023), highlight the hazards to human life and raise public concern.

However, such accidents occur every year, even in highly developed countries. For example, the Carola Bridge failure in Dresden in 2024 (Marx *et al.,* 2025). That same year, an environmental incident also occurred: a Brazilian bridge collapsed, and as it fell into the river, tankers released tons of toxic substances into the environment (Almeida, Higor, and Wilson, 2024). These events are happening

worldwide, regardless of location, with seismic regions being especially vulnerable (Granata, 2024).

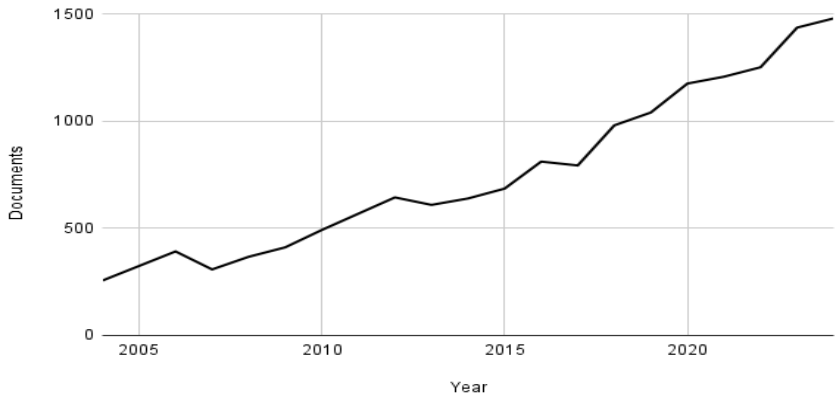
The demand for repairs and reconstruction increases material consumption and CO_2 emissions, which conflict with sustainability goals. Therefore, prevention and early detection of corrosion are essential to extend service life and minimize environmental impacts (Crawford, 2022).

Although reinforced concrete has been the main construction material for over a century, many structures built in recent decades still lack adequate corrosion protection, requiring extensive monitoring (Wegen, Polder, Breugel, 2012; Neville, 1995; Cappellesso et al., 2016). Interest in this issue has grown quickly, as shown by the increasing number of publications indexed in Scopus (query: "corrosion" AND ("reinforced concrete" OR "RC structures" OR "rebar" OR "concrete cover"), TITLE-ABS-KEY), which rose significantly between 2004 and 2024 (Figure 1) (Scopus, 2025).

Decisions about aging reinforced concrete (RC) infrastructure must be made within a limited timeframe to avoid costly shutdowns and failures, while also trying to extend the lifespan and reduce emissions. Routine inspections, like Schmidt hammer tests performed every five years, provide only indirect data and cannot directly detect rebar corrosion (Frankowski *et al.,* 2021). Using accurate, non-destructive testing (NDT) methods could save billions of dollars and many lives (Frankowski *et al.,* 2021; Arndt and Jalinoos, 2009).

Developing advanced diagnostic tools for reinforced concrete is therefore a global priority. Such solutions would improve durability, reduce material use, lower emissions, and support sustainable development and climate protection strategies.

Figure 1. *Publication Trends on Corrosion in Reinforced Concrete (Scopus Data 2004-2024)*

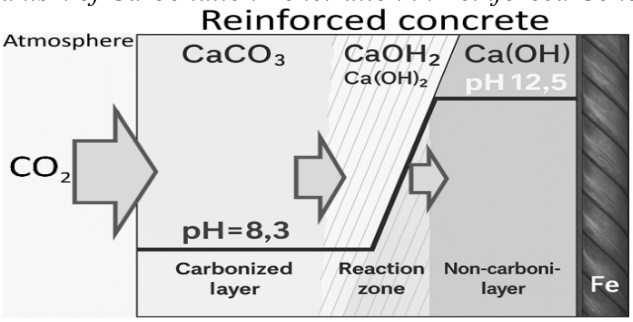


Source: *Own study.*

The carbonation of concrete plays a crucial role in the degradation of reinforced concrete, and understanding it is essential for developing effective prevention methods. Detecting early signs enables protective measures such as applying coatings or using more resistant materials (Frankowski *et al.,* 2021; Wegen *et al.,* 2012).

Carbonation occurs when atmospheric CO_2 penetrates concrete and reacts with calcium hydroxide ($Ca(OH)_2$), forming calcium carbonate ($CaCO_3$) and water. Similar reactions can involve other ions and acidic pollutants (Frankowski et al., 2021; Rimshin, Truntov, 2019). As this process advances, the pH of the concrete falls, reducing alkalinity and destroying the passive layer that shields the reinforcement bars from corrosion (Wegen *et al.,* 2012; Rimshin and Truntov, 2019). This loss of protection is illustrated in Figure 2.

Figure 2. *Mechanism of Carbonation Penetration in Reinforced Concrete Layers*



Source: *Own study.*

Typically, concrete cover provides high alkalinity that prevents chloride ions, sulfur oxides, and CO_2 from causing corrosion (Frankowski *et al.,* 2021; Wegen *et al.,* 2012). However, over time, carbonation reduces the pH and gradually weakens this protection. When the carbonation front reaches the steel reinforcement, moisture and pollutants can cause corrosion and rust formation (Wegen *et al.,* 2012; Neville, 1995). Environmental factors, such as air humidity, concrete composition, and pollutant levels, greatly influence carbonation rates, which tend to increase in these environments (Neville, 1995; Rimshin and Truntov, 2019).

Corrosion reduces the rebar's cross-sectional area, weakens its bonding, and lowers its load-bearing capacity, posing serious safety risks (Frankowski *et al.,* 2021; Wegen *et al.,* 2012). The formation of iron oxides (rust), which can be ten times the volume of steel, creates internal stresses that cause cracks and spalling. Even at this stage, danger is present.

There are known cases where falling concrete fragments have resulted in fatalities (Broomfield, 2007). However, the biggest threat is the exposure of reinforcement to water, which speeds up deterioration (the corrosion process) and further weakens the structure, ultimately leading to a disaster (Frankowski *et al.,* 2021; Neville, 1995).

2. Literature Review

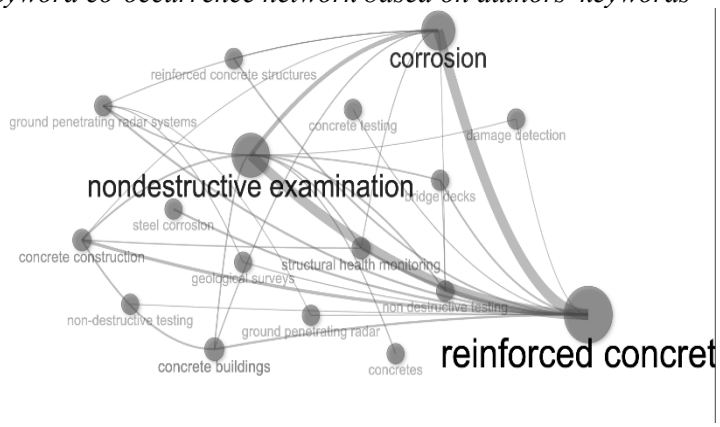
The systematic literature review (SLR) used EmbedSLR (Matysik, Wiśniewska, and Frankowski, 2025), a semantic tool for efficient article selection through natural language queries. Following PRISMA guidelines (PRISMA, 2025), the review retrieved 5,709 Scopus records on corrosion diagnostics in reinforced concrete (RC) using NDT in SHM systems.

To maintain thematic consistency, records were vectorized and ranked by cosine similarity (Frankowski, Wiśniewska, and Matysik, 2025; Matysik, Wiśniewska, and Frankowski, 2025). The final selection included 80 publications from 1998 to 2026, authored by 599 individuals across 40 sources, with an average citation count of 18.51 per document, indicating strong scientific relevance but minimal annual growth.

The review addressed three research questions: What are the main research directions and methods in non-destructive diagnostics of early reinforcement corrosion in concrete, and what is their potential for integration with SHM/IoT? The details of the SLR are presented in Frankowski and Matysik (2025).

The co-occurrence network shown in Figure 3 highlights three primary clusters: reinforced concrete, nondestructive examination, and corrosion. The strongest links involve structural health monitoring, rebar corrosion, ground-penetrating radar, and ultrasonic testing. The prevalence of durability-related terms suggests that research mainly concentrates on diagnosing reinforcement corrosion, whereas predictive modeling and IoT/ML integration are less studied.

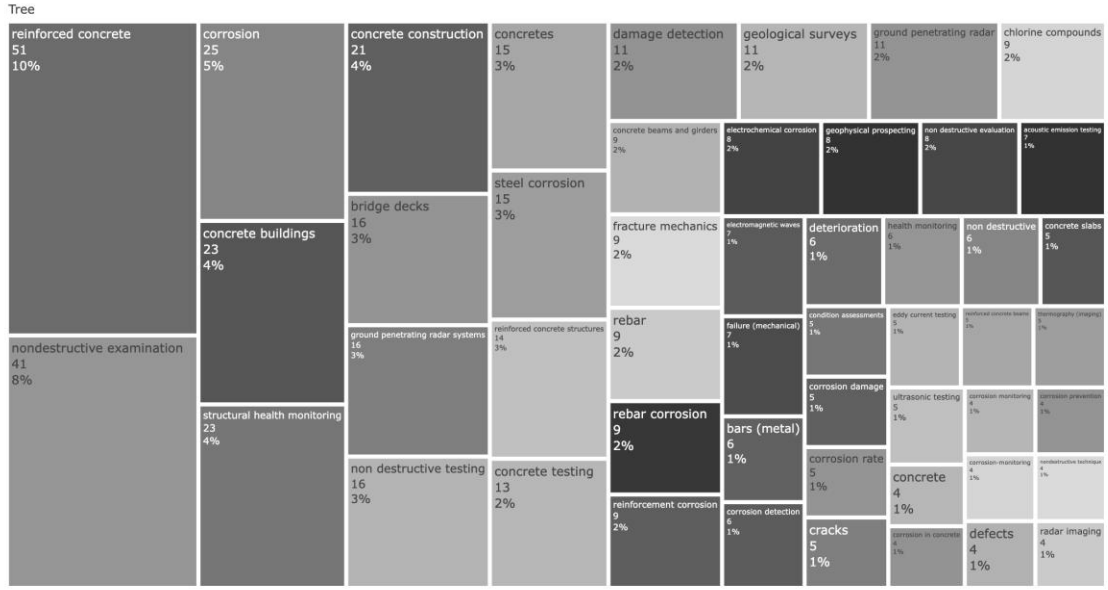
Figure 3. *Keyword co-occurrence network based on authors' keywords*



Source: *Own work using the Bibliometrix package in Studio R*

The treemap (Figure 4) of the 50 most common bigrams shows high diversity between NDT methods used to detect corrosion.

Figure 4. *Distribution of the most frequent bigrams in abstracts (N = 50)*



Source: *Own work using the Bibliometrix package in Studio R.*

Standard methods include Ground Penetrating Radar (GPR), Infrared Thermography (IRT), Acoustic Emission (AE), and Ultrasonic Testing (UT), with additional studies on resistivity, half-cell potential, Eddy Current Testing (ECT), and Modal Analysis (MA). Many approaches face limitations such as low resolution, damping, or shallow penetration depth. AE shows promise but depends on long-term monitoring and suffers from noise and attenuation issues. Within GPR research, advances such as matrix imaging and temperature compensation have been proposed. Electromagnetic innovations in ECT also show potential, though moisture and chloride calibration remain problematic (Frankowski and Matysik, 2025).

The systematic literature review (SLR) indicates that only two categories of methods are currently suitable for structural health monitoring (SHM) of reinforced concrete (RC) structures: Acoustic Emission (AE) techniques and modal analysis. However, their implementation remains scattered, mainly confined to small-scale smart city projects (Zhang *et al.,* 2024).

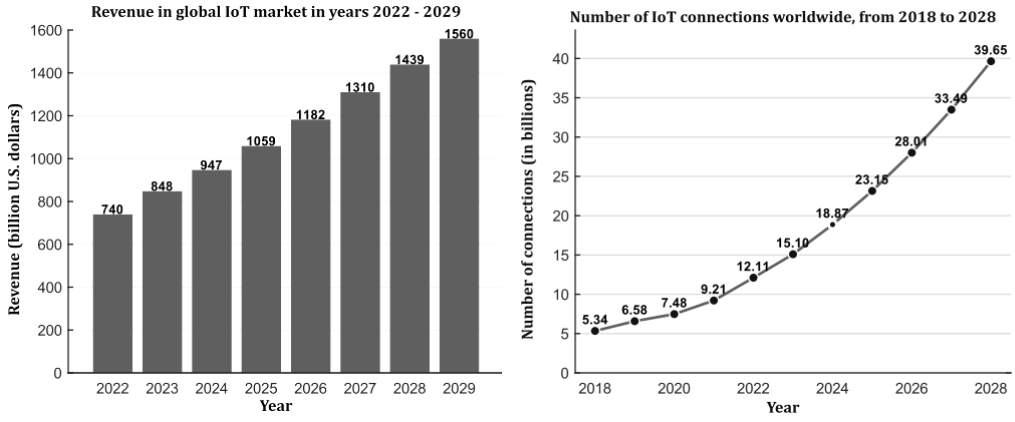
Among these methods, the M5 technique (which electromagnetically excites reinforcement bars and monitors eigen-vibrations) stands out for its ability to detect steel–concrete debonding through frequency shifts and damping. It performs well with AE systems and IoT nodes (Frankowski, Chady, and Zieliński, 2021) and demonstrates higher sensitivity to early-stage corrosion while being less affected by external noise compared to traditional AE methods.

IoT systems for Structural Health Monitoring mainly rely on Wireless Sensor Networks (WSN). Wireless networks provide greater scalability and flexibility compared to traditional wired systems, which is especially important for large engineering structures (Alonso, Barbarán, Chen, Díaz, Llopis, and Rubio, 2017; Gulati, Boddu, Kapila, Bangare, Chandnani, and Saravanan, 2021).

Moreover, deploying wireless systems is about 20% cheaper because they require less intrusion and eliminate the need for cabling, allowing for denser sensor placement and improving monitoring accuracy and damage detection (Silva, 2023; Abruzzese, Micheletti, Tiero, Cosentino, Forconi, Grizzi, Scarano, Vuth, and Abiuso, 2020; Maraveas and Bartzanas, 2021).

Statista Market Insights reported that since 2021, the global IoT market has grown at an average annual rate of 12% (CAGR), with revenues increasing by approximately $100 billion each year. This growth positions IoT as one of the industries expected to reach a valuation of over one trillion dollars by 2025. Additionally, the number of IoT connections is projected to double by 2028 (Statista, 2025), as shown in Figure 5.

Figure 5. *Growth of IoT 2022–2029: a) Global IoT revenue; b) IoT connections worldwide*



a) **b)**

Source: *Based on data from Statista Market Insights (AltIndex.com).*

3. Research Methodology

The research process consisted of three main stages: (1) conducting a systematic literature review (SLR) using the AI-based EmbedSLR tool to identify state-of-the-art methods in corrosion diagnostics; (2) selecting and adapting the M5 non-destructive testing method for detecting reinforcement corrosion; and (3) validating the M5 method through both laboratory and field experiments supported by AI-based Association Rules Analysis (ARA). The structure of these stages is

summarized in Table 1, which links each research phase to its objectives and applied methods.

Table 1. *Research stages, objectives, and applied methods*

Research Stage	**Objective**	**Methods and Tools Used**
Stage 1: Systematic Literature Review	Identify current approaches and research gaps in non-destructive testing of RC corrosion	EmbedSLR, PRISMA, bibliometric analysis
Stage 2: Method Development	Select and adapt the M5 electromagnetic method for corrosion monitoring	M5 excitation system, signal acquisition, frequency analysis
Stage 3: Experimental Validation	Verify method sensitivity and reliability on laboratory and field samples	ARA (Association Rules Analysis), frequency response analysis, IoT-SHM simulation

Source: *Own study.*

The review employed the AI-driven EmbedSLR method, which enables article selection based on natural language descriptions, thereby simplifying the systematic literature review (SLR) process (Matysik *et al.,* 2025). The tool is available for free (Matysik *et al.,* 2025). The process began with a broad Scopus search for NDT and corrosion, yielding 5,709 records.

The problem statement, expressed in natural language, was compared to each article's title and abstract using embeddings and cosine distance, which generated a relevance ranking. Both free and commercial embedding models are supported (Matysik *et al.,* 2025). Using this ranking, the researcher chooses a target set of publications, guided by the similarity matrix and bibliometric indicators.

This method combines embeddings with eleven bibliometric measures, allowing objective and efficient filtering while reducing subjective team bias. It facilitates quick identification and analysis of relevant articles. Systematic literature reviews are vital for contextualizing empirical research, assessing current knowledge, identifying gaps, and ensuring transparency in both theoretical and methodological foundations.

An SLR also reduces selection bias, clearly documents decision-making, and synthesizes findings to distinguish between confirmed evidence and areas of uncertainty or gaps. As a result, it offers strong conceptual frameworks and methodological options tailored to the research question (Linnenluecke, Marrone, and Singh, 2020; Chigbu, Atiku, and Du Plessis, 2023).

The conducted SLR shows that the M5 method is optimal for an SHM system designed to detect corrosion in reinforced concrete structures. This modal analysis technique relies on resonance frequencies, which act as unique identifiers, similar to

fingerprints or iris patterns.

Changes such as defects, deterioration, or material modifications affect these frequencies in characteristic ways. While this study specifically focuses on debonding caused by rusted rebars in reinforced concrete, vibration analysis can also identify various other failures. The proposed M5 system is intended for corrosion monitoring but can be expanded into a comprehensive RC diagnostics tool. It may operate in two modes: an active version for scheduled inspections and a passive IoT-SHM network for continuous monitoring.

The process begins with the control computer, which generates the excitation signal and sends it to the excitation subsystem. This subsystem creates an alternating magnetic field with a sweeping frequency that penetrates the RC sample and excites vibrations in the embedded rebars (Frankowski *et al.,* 2021; Chady, Frankowski, Waszczuk, and Zieliński, 2018).

Vibrations are generated directly in the rebar using an electromagnet and then transmitted via magnetic coupling to a surface-mounted magnet, which is mechanically connected to a seismic accelerometer. The accelerometer converts these vibrations into electrical signals, which are then sent back to the control computer for analysis. This closed-loop system ensures accurate detection of frequency shifts caused by corrosion or debonding.

By avoiding the strong damping effect of mechanical waves in concrete, the M5 method allows for direct and precise rebar assessment at standard cover depths (2–5 cm) without requiring prior knowledge of the structure's dynamics (Frankowski *et al.,* 2021; Chady *et al.,* 2018).

To identify the connections between corrosion appearance and changes in resonance frequencies (frequency characteristics), the authors developed an AI method called association rule analysis (ARA). ARA is a machine learning technique designed for signal analysis, especially in detecting corrosion in RC structures. ARA is available in two versions: one processes RAW signals (Frankowski, Alforque, and Chady, 2025), and the other operates on the derivative of the signal (Frankowski, Majzner, Mąka, and Chady, 2025). The method examines the frequency of specific changes in resonance frequencies that occur when corrosion is present, as described by equation (1).

$$\mathrm{conf}(A \rightarrow B) = \frac{\mathrm{supp}\,(A \cup B)}{\mathrm{supp}\,(A)} \approx P(B|A) \tag{1}$$

In equation (1), BODY (A) represents the progression of corrosion in rebars within an RC structure, while HEAD (B) indicates a change in a specific frequency in the frequency characteristic. Confidence is a parameter that quantifies the probability that the entire rule applies, given the presence of BODY.

Another important aspect of SHM systems is communication. Recent advances in RF transceivers and SHM platforms enable real-time transmission of vibration data from distributed accelerometers. This supports quick operational modal analysis of in-service structures and efficient large-scale data management (Whelan *et al.,* 2010; Scuro, Sciammarella, Lamonaca, Olivito, and Carni, 2018).

An M5-based SHM network employs accelerometers installed near rebars to offer sensitive and cost-effective monitoring of reinforcement and the surrounding concrete. For reinforcement evaluation, electromagnetic excitation can be used; for concrete assessment, mechanical excitation is applied.

The system can also operate passively without any excitation (Frankowski and Matysik, 2025). Sensors are recommended to be installed during construction, with grid arrangements enhancing corrosion detection. Long-term frequency monitoring can identify even minor changes, thereby improving accuracy and sensitivity (Frankowski *et al.,* 2021; Chady *et al.,* 2018).

4. Research Results and Discussion

The main benefit of integrating the Internet of Things (IoT) into Structural Health Monitoring (SHM) is its synergy with Building Information Modeling (BIM), which enables the development of a Digital Twin (DT). This integration transforms the static BIM model into a dynamic DT, especially during post-construction phases like operation and maintenance. DTs are virtual replicas that continuously synchronize with real-time data from IoT/SHM sensors, supporting predictive maintenance through advanced simulations (Shishehgarkhaneh, Keivani, Moehler, Jelodari and Laleh, 2022).

For example, in bridge monitoring, DTs use sensor data and machine learning algorithms to model structural behavior, plan maintenance, and reduce costs, potentially decreasing annual maintenance expenses by up to 38% (Venkatesh, Nimitha, Vishali, Sravanthi, and Suryanarayan, 2024). BIM and Heritage BIM (HBIM) supply essential as-built information, while IoT provides real-time updates.

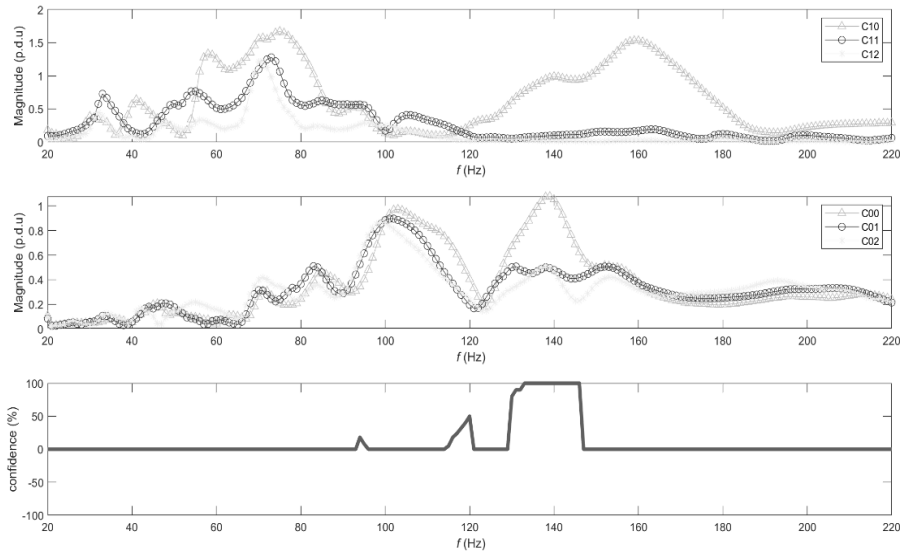
Ultimately, the Digital Twin combines BIM, IoT, and Artificial Intelligence (AI) for proactive asset management and better maintenance (Preethichandra, Suntharavadivel, Kalutara, Piyathilaka and Izhar, 2023).

Based on the systematic literature review (Frankowski and Matysik, 2025), the M5 method is a suitable option for structural health monitoring (SHM) systems. During the experiments, two types of samples were tested: laboratory-prepared samples with simulated corrosion (C00, C01, C02) and field samples from a disassembled bridge slab in Świerkocin on the Warta River in Poland (C10, C11, C12). The study examined association rules directly related to corrosion by analyzing the frequency characteristics of samples C00-C01 and C10-C11, which indicate the start of

corrosion, and C01-C02 and C11–C12, which show its progression (Frankowski *et al.,* 2021; Chady *et al.,* 2018).

The analysis initially focused on ACO decomposition attributes (Frankowski, Chady, 2023), allowing for a quantitative assessment of how corrosion affects Amplitude (A), Correlation (C), or Offset (O) in frequency characteristics. Previous studies confirm that these three parameters effectively describe the signal (Frankowski and Chady, 2023). Testing was performed within the 20–220 Hz range, where strong resonances were observed. Corrosion had minimal influence on offset, with amplitude differences only appearing when other parameters also changed. Examples of the results are shown in Figure 6.

Figure 6. *The effect of varying parameters on the signal can be seen in two cases: specimens with a larger and more diverse concrete cover (30–50 mm) and specimens with nearly identical, thinner covers of about 20 mm.*



Source: *Own study.*

Correlation analysis revealed weaker similarities between corroded (C01, C11) and debonded (C02, C12) samples, but more substantial similarities within groups that only vary in corrosion levels (C00, C01, C02). These differences are influenced by other structural factors, such as size, cover thickness, or rebar class, in the corroded and debonded series. Therefore, ARA analysis was employed, as it allows the detection of frequencies affected by corrosion. The identified frequencies were consistent across both laboratory and field samples.

Figure 5 demonstrates that even small variations in concrete cover thickness can

significantly impact correlation and amplitude, emphasizing the importance of precise cover measurements in tested samples. This highlights a key advantage of SHM over traditional periodic inspections. The confidence graph indicates that corrosion substantially affects frequencies between 130 and 146Hz, a pattern consistently observed across all tested cases.

However, since many factors influence frequency characteristics, previous experiments have shown that detecting corrosion in unknown samples is challenging because external influences can mask corrosion signals (Frankowski and Matysik, 2025). This underscores the importance of SHM in quickly and accurately identifying early-stage corrosion.

The data obtained with M5 is sent to the control room using the Wireless Sensor Networks (WSN) architecture of the proposed SHM system, which consists of five main layers: Physical, Data Link, Network, Transport, and Application. Additionally, WSNs incorporate three cross-layer planes that are vital for energy management.

- Power Management Plane: Maximizes battery life by managing module activity and energy-saving strategies.
- Mobility Management Plane: Monitors node movement and signal levels, which are important for detecting structural changes.
- Task Management Plane: Determines which nodes are active or in sleep mode to minimize energy consumption while ensuring monitoring quality (Davis and Chang, 2012; Kocakulak and Butun, 2017).

A key component of IoT-SHM systems is Edge Computing, which handles data processing at sensor nodes to reduce transmission load and conserve energy (Alonso *et al.,* 2017; Hidalgo-Fort, 2024).

For instance, the Random Decrement Technique (RDT) enables efficient vibration analysis without transmitting raw data, significantly extending node autonomy from approximately 638 days to over 10 years during low-frequency monitoring (Hidalgo-Fort, 2024; Lopez-Martin, Castellano, Zivanovic, Iriarte, and Carlosena, 2025).

This prolongs the operational lifespan of wind farms with a cost-effective, energy-independent IoT-based structural health monitoring system. More advanced data integration and analysis are typically conducted at higher levels, such as in the cloud or dedicated processing centers (Tai, Hameed Sultan, Grzejda, Shahar, 2025).

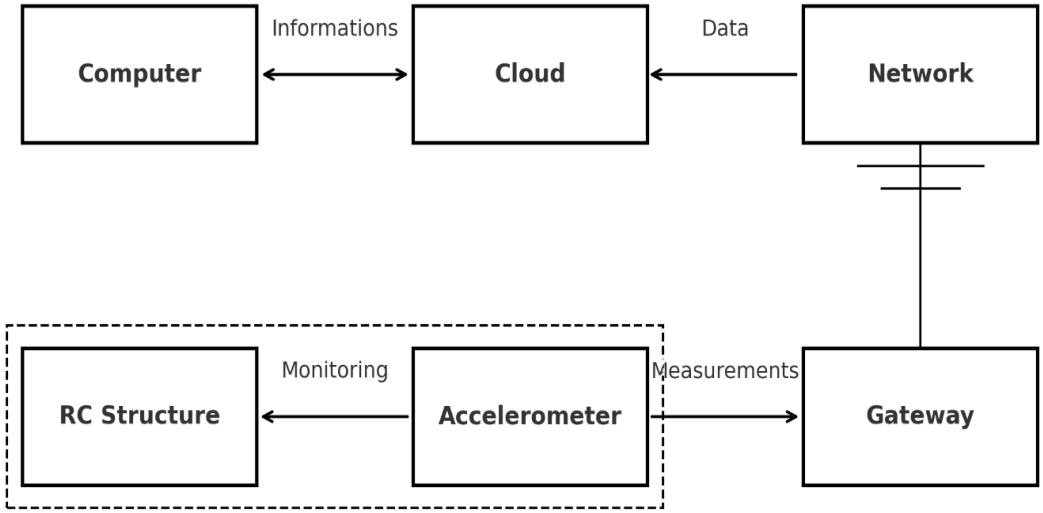
Among WSN communication technologies, LPWAN (Low-Power Wide Area Networks) is essential, offering long-range communication with minimal power consumption. Notable standards include:

- NB-IoT: Uses cellular networks for reliable data transfer without requiring

additional gateways, making it simple to connect with cloud platforms.

- LoRaWAN: Uses Chirp Spread Spectrum modulation for long-range communication in unlicensed bands, perfect for monitoring large structures in areas with limited cellular coverage.
- LPWAN solutions increasingly replace Older WPAN alternatives like ZigBee due to their superior range and battery life (Alonso *et al.,* 2017).
- The block diagram of the M5-SHM system is presented in Figure 7.

Figure 7. *Block diagram of the M5 IoT-SHM system.*



Source: *Own study.*

Early detection of corrosion in reinforced concrete (RC) structures is vital for developing smart cities. By allowing timely intervention before major damage happens, this proactive strategy reduces maintenance costs, extends infrastructure lifespan, and improves safety for residents. It also promotes sustainable urban growth by lowering resource use and avoiding costly emergency repairs.

Assessing corrosion in RC structures is critical and urgent. Existing non-destructive testing (NDT) techniques do not currently offer a straightforward, rapid, and reliable method for measuring corrosion levels. The M5 method offers a pioneering solution with significant potential for broad application. This innovative technique promotes sustainable infrastructure by minimizing destructive inspections and prolonging the lifespan of concrete structures.

Integrating the M5 method with structural health monitoring (SHM) systems improves its effectiveness. Using electromagnetic excitation enables a detailed assessment of rebars, while mechanical excitation provides insights into the condition of the concrete itself. Additionally, the M5 method can operate passively by detecting frequency shifts that signal structural issues. This capability enables proactive maintenance, ultimately reducing environmental impact and promoting a

more resilient built environment.

5. Conclusions, Proposals, Recommendations

The SLR identified a clear research gap in non-invasive, sensitive diagnostics for early reinforcement corrosion in concrete. Among new methods, the M5 approach is especially promising for NDT and SHM in Smart City environments. When miniaturized and connected via IoT, M5 can enable proactive risk alerts and enhance infrastructure maintenance, contributing to the development of resilient and sustainable cities.

The results show that M5 could become a key technique for SHM of reinforced concrete, enhancing traditional modal analysis by directly addressing rebar corrosion. This not only confirms existing knowledge about how defect-related resonance frequency changes but also demonstrates its versatility in detecting early deterioration. By reducing the need for resource-heavy repairs and prolonging service life, M5 promotes sustainable infrastructure management.

Nevertheless, these findings are still preliminary. More laboratory testing and real-world use are needed to verify their reliability. Combining SHM systems with IoT is a key step toward smart, adaptable monitoring, making urban structures safer and more durable in the digital age.

Future research should concentrate on controlled laboratory studies that verify the sensitivity of the M5 method to different corrosion stages. At the same time, pilot applications on actual structures are necessary to prove its practicality in real-world conditions.

Integrating M5-based SHM with IoT platforms is highly recommended to enable continuous, real-time monitoring in Smart Cities. Collaboration among engineers, material scientists, and digital infrastructure experts will be crucial to accelerate the method’s standardization and adoption.

The research achieved its primary scientific goal of defining and testing an integrated AI- and IoT-supported methodology for the non-destructive monitoring of corrosion in reinforced concrete. This framework can guide future studies aiming to standardize SHM systems for smart city applications.

AI note: Translation from the national language, Perplexity, and ChatGPT. Language proofreading was done with Grammarly.

References:

Abruzzese, D., Micheletti, A., Tiero, A., Cosentino, M., Forconi, D., Grizzi, G., Scarano, G., Vuth, S., and Abiuso, P. 2020. IoT sensors for modern structural health monitoring:

A new frontier. Procedia Structural Integrity, 25, 378-385. https://doi.org/10.1016/j.prostr.2020.07.086.

Almeida, H.F., Higor, F.A., Wilson, F. 2024. Responsabilidade civil e justiça ambiental no caso da contaminação química do Rio Tocantins após o colapso da ponte rodoviária. Humanidades and Inovação 11.9, 65-75.

Alonso, L., Barbarán, J., Chen, J., Díaz, M., Llopis, L., Rubio, B. 2017. Middleware and communication technologies for structural health monitoring of critical infrastructures: A survey. Computer Standards and Interfaces, 56, 83-100. https://doi.org/10.1016/j.csi.2017.09.007.

Arndt, R., Jalinoos, F. 2009. NDE for corrosion detection in reinforced concrete structures – a benchmark approach. NDTCE'09, Non-Destructive Testing in Civil Engineering. Nantes, France, June 30th-July 3rd.

Balderacchi, C., Piacentini, A. 2024. The path towards sustainable development in Europe: SDGs, EU institutions, and smart cities. Journal of European Integration, 1-7. https://doi.org/10.1080/07036337.2024.2423463.

Broomfield, J.P. 2007. Corrosion of Steel in Concrete: Understanding, Investigation and Repair. EandFN Spain, London, Great Britain, 277 p.

Cappellesso, V.G., dos Santos Petry, N., Dal Molin, D.C.C., et al. 2016. Use of crystalline waterproofing to reduce capillary porosity in concrete. J Build Rehabil, p. 9. DOI: 10.1007/s41024-016-0012-7.

Chady, T., Frankowski, P., Waszczuk, P., Zieliński, A. 2018. Evaluation of reinforced concrete structures using the electromagnetic method. AIP Conference Proceedings, 1949, 040004. https://doi.org/10.1063/1.5031538.

Chang. P. 2017. CPC SOURCE - DOD Facilities and Infrastructure Corrosion Costs. s.l. : (D, CPO) (OUSD (ATandL)). https://www.wbdg.org/ffc/dod/cpc-source/dod-facilities-infrastructure-corrosion-costs.

Chigbu, U.E., Atiku, S.O., Du Plessis, C.C. 2023. The Science of Literature Reviews: Searching, Identifying, selecting, and Synthesising. Publications, 11(1), 2. https://doi.org/10.3390/publications11010002.

Correia, D., Marques, J.L., Teixeira, L. 2022. The State-of-the-Art of Smart Cities in the European Union. Smart Cities, 5(4), 1776-1810. https://doi.org/10.3390/smartcities5040089.

Crawford, R.H. 2022. Greenhouse gas emissions of global construction industries. IOP Conference Series Materials Science and Engineering, 1218(1), 012047. https://doi.org/10.1088/1757-899x/1218/1/012047.

Davis, A. 2012. A survey of Wireless Sensor network Architectures. International Journal of Computer Science and Engineering Survey, 3(6), 1-22. https://doi.org/10.5121/ijcses.2012.3601.

Frankowski, P.K., Alforque, M.J., Chady, T. 2025. AI Identification of Key Frequency Response Patterns for Nondestructive Corrosion Assessment in Reinforced Concrete Structures Using Electromagnetic Methods. International Conference on Power, Energy and Innovations (ICPEI 2025), October 15-17, Pataya City, Thailand.

Frankowski, P.K., Chady, T. 2023. Evaluation of Reinforced Concrete Structures with Magnetic Method and ACO (Amplitude-Correlation-Offset) Decomposition. Materials, 16(16), 5589. https://doi.org/10.3390/ma16165589.

Frankowski, P.K., Chady, T., Zieliński, A. 2021. Magnetic force induced vibration evaluation (M5) method for frequency analysis of rebar-debonding in reinforced concrete. Measurement, 182, 109655. https://doi.org/10.1016/j.measurement.2021.109655.

Frankowski, P.K., Majzner, P., Mąka, M., Chady, T. 2025. Enhancing the Identification of Corrosion in Reinforced Concrete Structures Using Association Rules Analysis and the Non-Destructive M5 Method. 33rd International Conference on Information Systems Development (ISD 2025), 03-05 Sep. Belgrade, Serbia.

Frankowski, P.K., Matysik, S. 2025. Integrating Electromagnetic NDT and IoT for Enhanced Struc-tural Health Monitoring of Corrosion in Reinforced Concrete as a Key to Sustainable Smart Cities, Sustainability.

Frankowski, P.K., Wiśniewska, J., Matysik, S. 2025. A Comparative Analysis of Embedding Models and Traditional Methods for Publication Selection in Systematic Literature Reviews - A Case Study in Gamification Marketing. 33rd International Conference on Information Systems Development (ISD2025 Proceedings), 03-05 Sep. Belgrade, Serbia.

Frankowski, P.K., Wiśniewska, J., Matysik, S. 2025. Efficient Ai-Powered Decision-Making In Systematic Literature Reviews Using Multi-Embedding Models. Intelligent Management and Artificial Intelligence: Trends, Challenges, and Opportunities, Vol.2 Proceedings on 28th European Conference on Artificial Intelligence ECAI 2025 – InMan Workshop, Bologna, Italy, October 25-30. https://doi.org/10.18276/978-83-8419-053-1-25.

Giate Scientific. 2025. https://www.giatecscientific.com/education/understanding-concrete-corrosion.

Granata, M.F. 2024. Seismic retrofit of concrete buildings damaged by corrosion: a case study in southern Italy. Buildings, 14(4). 1064. https://doi.org/10.3390/buildings14041064.

Gulati, K., Boddu, R.S.K., Kapila, D., Bangare, S.L., Chandnani, N., Saravanan, G. 2021. A review paper on wireless sensor network techniques in Internet of Things (IoT). Materials Today Proceedings, 51, 161-165. https://doi.org/10.1016/j.matpr.2021.05.067.

Hidalgo-Fort, E., Blanco-Carmona, P., Muñoz-Chavero, F., Torralba, A., Castro-Triguero, R. 2024. Low- cost, low-power edge computing system for structural health monitoring in an IoT framework. Sensors, 24(15), 5078. https://doi.org/10.3390/s24155078.

Kocakulak, M., Butun, I. 2017. An overview of wireless sensor networks towards Internet of Things. 2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC), 1-6.

Koch, G.H., Brongers, M.P.H., Thompson, N.G., Virmani, Y.P., Payer, J.H. 2002. Corrosion Costs and Preventive Strategies in the United States. USA: McLean, VA: FHWA, FHWA-RD-01-156. https://www.nace.org/uploadedFiles/Publications/ccsupp.pdf.

Koch, G.H., Thompson, N.G., Moghissi, O., Payer, J.H., Varney, J. 2016. IMPACT (International Measures of Prevention, Application and Economics of Corrosion Technology), Report No. OAPUS310GKOCH, NACE International. Houston: TX.

Insights Consulting. 2024. Reports Insights Consulting Pvt Ltd. Smart Bridges Market Forecast 2025-2033.

Linnenluecke, M.K., Marrone, M., Singh, A.K. 2019. Conducting systematic literature reviews and bibliometric analyses. Australian Journal of Management, 45(2), 175-194. https://doi.org/10.1177/0312896219877678.

Lopez-Martin, A., Castellano, C., Zivanovic, M., Iriarte, X., Carlosena, A. 2025. Lifetime extension ofwind farms by a low-cost energy-autonomous IoT-based structural health monitoring system. In 23rd InternationalConference on Renewable Energies and Power Quality (ICREPQ'25), Tenerife, Spain, June 25-27. ISBN978-84-09-66511-2.

Lytras, M.D., Serban, A.C. 2020. E-Government Insights to Smart Cities Research: European Union (EU) study and the role of regulations. IEEE Access, 8, 65313-65326. https://doi.org/10.1109/access.2020.2982737.

Malerba, P.G. 2023. Bridge vulnerabilities and collapses: the Italian experience. Structure and Infrastructure Engineering, 20(7-8), 976-1001. https://doi.org/10.1080/15732479.2023.2277362.

Maraveas, C., Bartzanas, T. 2021. Sensors for structural health monitoring of agricultural structures. Sensors, 21(1), 314. https://doi.org/10.3390/s21010314.

Marx, S., Scheerer, S., Schacht, G., Fiedler, M., Ritter, R., Clages, L., Marzahn, G. 2025. Einsturz der Carolabrücke in Dresden Teil 1: Vom ambitionierten Entwurf bis zum tragischen Teileinsturz. Beton-und Stahlbetonbau, 120(7), 526-536.

Matysik, S., Wiśniewska, J., Frankowski, P.K. 2025. Artificial Intelligence for Personalized Rankings of Articles – Novel Embedding Method Supporting Decision-Making in Systematic Literature Review. Intelligent Management and Artificial Intelligence: Trends, Challenges, and Opportunities, Vol.2 Proceedings on 28th European Conference on Artificial Intelligence ECAI 2025 – InMan Workshop, Bologna, Italy, October 25-30. https://doi.org/10.18276/978-83-8419-053-1-24.

Matysik, S., Wiśniewska, J., Frankowski, P.K. 2025. EmbedSLR: An Open-Source Python Framework for Efficient Embedding-Based Screening and Bibliometric Validation in Systematic Literature Review. SoftwareX, Volume 32, 102416. https://doi.org/10.1016/j.softx.2025.102416.

Mitchell, D., Marchand, J., Croteau, P., Cook, W.D. 2011. Concorde Overpass collapse: structural aspects. Journal of Performance of Constructed Facilities, 25(6), 545-553. https://doi.org/10.1061/(asce)cf.1943-5509.0000183.

NACE. 2025. Corrosion Costs and Preventive Strategies in the United States, http://impact.nace.org/documents/ccsupp.pdf.

Nurhadiyanto, D., Sianipar, S. 2024. The effect of anode-cathode distance and time in the nickel electroplating process on coating thickness and corrosion rate of AISI 1020 steel. AIP Conference Proceedings, 3145, 020014. doi:10.1063/5.0214247.

Preethichandra, D.M.G., Suntharavadivel, T.G., Kalutara, P., Piyathilaka, L., Izhar, U. 2023. Influence of smart sensors on structural health monitoring systems and future asset management practices. Sensors, 23(19), 8279. https://doi.org/10.3390/s23198279.

PRISMA. 2025. Statement. www.prisma-statement.org.

Rymsza, J. 2021. Causes of the collapse of the Polcevera viaduct in Genoa, Italy. Applied Sciences, 11(17), 8098. https://doi.org/10.3390/app11178098.

Wegen, G., Polder, R.B., Breugel, K. 2012. Guideline for service life design of structural concrete - A performance-based approach with regard to chloride induced corrosion. Heron, 57, ISSN 0046-7316.

Neville, A.M. 1995. Properties of Concrete, 4th edition, Pearson Education Limited, London, ISBN: 978-0-273-75580-7.

Scopus. 2025. https://www.scival.com/benchmarking/analyse.

Shishehgarkhaneh, M.B., Keivani, A., Moehler, R.C., Jelodari, N., Laleh, S.R. 2022. Internet of Things (IoT), Building Information Modeling (BIM), and Digital Twin (DT) in construction industry: A review, bibliometric, and network analysis. Buildings, 12(10), 1503. https://doi.org/10.3390/buildings12101503.

Silva, C.F.B. 2023. Condition monitoring of railway infrastructures using drones (Master's thesis). Faculdade de Engenharia da Universidade do Porto.

Rimshin, V., Truntov, P. 2019. Determination of carbonation degree of existing reinforced concrete structures and their restoration. E3S Web of Conferences, 135,

03015. https://doi.org/10.1051/e3sconf/201913503015.

Scuro, C., Sciammarella, P.F., Lamonaca, F., Olivito, R.S., Carni, D.L. 2018. IoT for structural health monitoring. IEEE Instrumentation and Measurement Magazine, 21(6), 4-14. https://doi.org/10.1109/mim.2018.8573586.

Statista Market Insights. 2025. Global Internet of Things Market Growth and Revenue Projections

Tai, J.L., Hameed Sultan, M.T., Grzejda, R., Shahar, F.S. 2025. Remote non-destructive testing of portcranes: A review of vibration and acoustic sensors with IoT integration. Journal of Marine Science and Engineering, 13(7), 1338. https://doi.org/10.3390/jmse13071338.

Venkatesh, D., Nimitha, P., Vishali, M., Sravanthi, M., Suryanarayan, G. 2024. A Comprehensive Analysis of IoT-Driven Bridge Health Monitoring Systems for Structural Risk Mitigation. Journal of e-Science Letters, 5(1), 26-30. https://doi.org/10.51470/esl.2024.5.1.26.

Zhang, J., Peng, L., Wen, S., Huang, S. 2024. A review on concrete structural properties and damage evolution monitoring techniques. Sensors, 24(2). 620. https://doi.org/10.3390/s24020620.