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Recent Advances in Structural Health Monitoring Technologies for Sustainable Civil Infrastructure Management

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ABSTRACT

The rapid development of modern civil infrastructure requires more accurate, continuous, and reliable structural condition monitoring systems capable of detecting damage at an early stage. Structural Health Monitoring (SHM) has emerged as a key approach for assessing structural integrity by integrating advanced sensor technologies, the Internet of Things (IoT), Wireless Sensor Networks (WSN), Artificial Intelligence (AI), Machine Learning, and Non-Destructive Testing (NDT) techniques. This study aims to review recent advances in Structural Health Monitoring technologies, identify enabling technologies, examine their applications in civil infrastructure, discuss implementation challenges, and explore future research directions. A Systematic Literature Review (SLR) was conducted by analyzing scientific publications published in 2023 and indexed in Google Scholar. The findings indicate that recent advances in smart sensing technologies, optimization algorithms, cloud computing, and AI-based data analytics have significantly improved the capability of SHM systems for real-time damage detection, structural diagnosis, and predictive maintenance. Nevertheless, several challenges remain, including data quality, system interoperability, cybersecurity, computational requirements, and implementation costs. Future SHM development is expected to focus on integrating intelligent digital technologies to support safer, more efficient, and sustainable infrastructure management.

Keywords: *Artificial Intelligence, Internet of Things, Machine Learning, Structural Health Monitoring, Systematic Literature Review.*

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1. | INTRODUCTION

The development of modern infrastructure that is increasingly complex demands a structural condition monitoring system that is able to ensure safety, reliability, and sustainability during the service life. Structures such as bridges, high-rise buildings, dams, tunnels, and other transportation infrastructure are degraded due to repeated loads, environmental influences, material aging, seismic activity, and extreme events. Conventional inspections conducted periodically often have limitations in detecting damage at an early stage, potentially increasing the risk of structural failure. Therefore, an approach that is able to monitor structural conditions in a sustainable, accurate, and data-based manner is needed to support decision-making in infrastructure maintenance and rehabilitation activities (Cantú, 2022; Gomez-Cabrera & Escamilla-Ambrosio, 2022).

Structural Health Monitoring (SHM) has developed into one of the main technologies in the field of structural engineering because it is able to provide information about the actual condition of a structure through the integration of sensors, data acquisition systems, digital communication, and intelligent analysis methods. SHM allows the process of identification, localization, and evaluation of damage to be carried out in real-time without disrupting the operation of the structure. Various sensor technologies such as accelerometers, strain gauges, piezoelectric sensors, fiber optic sensors, and Fiber Bragg Grating (FBG) have been widely applied to obtain continuous structural response data. The development of sensor technology provides significant improvements in measurement accuracy, data collection efficiency, and early detection capabilities of structural behavior changes (Huang et al., 2021; Chen et al., 2023).

Advances in digital technology have also accelerated the evolution of SHM through the application of Artificial Intelligence (AI), Machine Learning, Deep Learning, Internet of Things (IoT), Wireless Sensor Networks (WSN), and Cloud Computing. The integration of this technology allows the monitoring data to be processed automatically to recognize structural behavior patterns, detect anomalies, classify the extent of damage, and predict the condition of the structure in the future. Compared to conventional analysis methods, AI-based approaches are able to process large amounts of data with a higher level of accuracy, supporting the implementation of *predictive maintenance* and data-driven decision-making. In addition, the use of WSN and IoT allows the monitoring process to be carried out from different locations through wireless communication, thereby increasing the operational efficiency of SHM systems on various types of infrastructure (Cantú, 2022, Gomez-Cabrera & Escamilla-Ambrosio, 2022).

The application of SHM has developed in various infrastructure sectors, including bridges, high-rise buildings, tunnels, dams, offshore platforms, and transportation infrastructure. In bridge structures, SHM is used to monitor dynamic responses due to traffic, wind loads, and earthquake activity so that damage can be detected before it develops into structural failure. In high-rise buildings, this system helps evaluate the influence of earthquake loads and changes in building dynamic characteristics, while in maritime infrastructure, SHM is used to monitor corrosion, material fatigue, and deformation due to aggressive marine environments. The development of these applications shows that SHM has become an essential component in the management of modern infrastructure assets that prioritizes safety, maintenance cost efficiency, and operational sustainability (Ai et al., 2022; Chen et al., 2023).

Despite rapid development, the implementation of SHM still faces various challenges. Large volumes of data require efficient analysis methods, while data quality affected by environmental disturbances can lower the accuracy of damage identification. In addition, interoperability between devices, sensor energy consumption, cybersecurity in IoT-based systems, and high installation costs are still obstacles in the widespread implementation of SHM. On the other hand, the development of AI technology, cloud computing, intelligent sensors, and the Digital Twin concept opens up new opportunities to improve the system's ability to diagnose structural conditions automatically and adaptively. Therefore, a comprehensive study of the latest developments in SHM technology is needed to identify research trends, supporting technologies, implementation challenges, and future development directions. Based on these needs, this study uses the Systematic Literature Review (SLR) method to synthesize the latest scientific publications on the development of Structural Health Monitoring so that it can provide a comprehensive overview of technological advances and research opportunities in the field of structural engineering.

2. | RESEARCH METHOD

This study uses the Systematic Literature Review (SLR) method to identify, evaluate, and synthesize the latest developments in Structural Health Monitoring (SHM) technology published. The SLR approach was chosen because it is able to provide a systematic, transparent, and replicable study process in collecting and analyzing scientific evidence from various relevant studies. The research stage begins with the formulation of research objectives, namely identifying the development of SHM technology, evaluating the application of supporting technology, analyzing implementation challenges, and examining future research directions. Furthermore, a literature search process was carried out using Google Scholar as the main database with the keywords Structural Health Monitoring, Damage Detection, Smart Sensors, Wireless Sensor Networks, Internet of Things, Artificial Intelligence, Machine Learning, Deep Learning, Digital Twin, and Non-destructive testing. The search process is limited to scientific articles published throughout 2023 so that the study reflects the latest research developments.

Literature selection is carried out through the application of inclusion and exclusion criteria. The inclusion criteria include journal articles and international proceedings that discuss the development and implementation of SHM technology in various types of civil infrastructure, such as bridges, buildings, dams, tunnels, and offshore structures. Articles focusing on damage detection methods, sensor technology, artificial intelligence-based analysis, sensor placement optimization, and Internet of Things-based monitoring systems are also included in the scope of the study. On the other hand, articles that do not have full text, do not go through the peer review process, or are not directly related to SHM are excluded from the analysis process. Literature that meets all criteria is then analyzed using a descriptive-qualitative approach through a classification process based on the research theme, comparison of results between studies, identification of technology trends, evaluation of implementation challenges, and synthesis of key findings. The results of the synthesis are the basis for compiling a discussion on the latest developments in Structural Health Monitoring and its application prospects in supporting safer, more reliable, and sustainable infrastructure management.

3. | RESULTS AND DISCUSSION

The results of the literature review show that research on Structural Health Monitoring (SHM) is experiencing very rapid development in 2023, mainly driven by advances in sensor technology, digital communication systems, intelligent computing, and artificial intelligence-based data analysis. The paradigm shift from manual inspection methods to automated monitoring systems allows the process of evaluating structural conditions to be carried out continuously with a higher level of accuracy. This approach not only improves the ability to detect damage at an early stage, but also supports data-driven decision-making for infrastructure maintenance and rehabilitation activities. Various studies have shown that the application of SHM is able to improve the reliability of structures while reducing inspection and maintenance costs during the infrastructure lifecycle (Cantú, 2022; Ai et al., 2022;).

The development of sensor technology is one of the main factors that encourage the improvement of the performance of the SHM system. Different types of sensors such as accelerometers, strain gauges, piezoelectric sensors, Fiber Bragg Grating (FBG), as well as fiber-optic based sensors have been used to measure the response of structures to different types of loads (Janeliukstis & Mironovs, 2021). These sensors are able to continuously record changes in strain, deformation, vibration acceleration, temperature, and structural displacement so as to provide more accurate information about the actual condition of an infrastructure. Compared to visual inspection methods, the use of intelligent sensors is able to detect small changes in structural characteristics before they develop into more serious damage. In addition to having a high level of sensitivity, modern sensor technology also offers a smaller size, lower energy consumption, and resistance to extreme environmental conditions, making it ideal for application to bridges, high-rise buildings, dams, and offshore structures (Chen et al., 2023; Cantú, 2022).

The development of Wireless Sensor Networks (WSN) has also made a significant contribution to the implementation of modern SHM. WSN allows a number of sensors to be placed on various parts of the structure without the need for complex wiring installation, making the installation process more flexible and economical. The measurement data from each sensor can be transmitted wirelessly to the data processing center for real-time analysis (Amezquita-Sanchez et al., 2018). This approach is very useful for large-scale infrastructure such as long-span bridges, high-rise buildings, and transportation networks that have limited access. In addition to improving the efficiency of the monitoring process, the use of WSN also allows for the expansion of the monitoring area without increasing the complexity of the installation. However, some studies still report challenges related to sensor energy consumption, data communication stability, and transmission reliability under changing environmental conditions (Huang et al., 2021).

The advancement of Artificial Intelligence (AI) and Machine Learning has become one of the most significant developments in SHM research over the past few years (Azimi et al., 2020). Various machine learning algorithms are used to identify structural response patterns, classify damage rates, and predict structural conditions based on historical data and real-time monitoring data. Methods such as Artificial Neural Network, Support Vector Machine, Random Forest, and Deep Learning have shown high ability to improve the accuracy of damage detection compared to conventional statistical approaches. In addition, AI allows the analysis process to be carried out automatically so that the time required to identify damage can be significantly reduced. The implementation of this technology strongly supports the concept of predictive maintenance, which is a maintenance strategy that is carried out based on predicted structural conditions so that it can reduce operational costs while improving infrastructure safety (Gomez-Cabrera & Escamilla-Ambrosio, 2022; Cantú, 2022).

In addition to AI, the concept of the Internet of Things (IoT) is also an important part of the development of modern SHM. IoT integration allows sensors, data acquisition devices, and control centers to be interconnected through digital communication networks so that the monitoring process can be carried out from different locations in real-time. The monitoring data can be stored on a cloud computing platform (Cloud Computing) to facilitate the process of analysis, visualization, and decision-making. The combination of IoT with AI results in a SHM system that is able to automatically diagnose structural conditions, provide early warning of potential damage, and support the management of infrastructure assets more effectively. These developments show that SHM no longer functions only as a monitoring system, but has evolved into an intelligent platform capable of supporting data-driven decision-making in the management of modern infrastructure (Balzer & Schorn, 2022; Chen et al., 2023). The development of Digital Twin is one of the innovations that is increasingly adopted in the implementation of Structural Health Monitoring. A digital twin is a virtual representation of a physical structure that is dynamically updated using data obtained from sensors and monitoring systems in real-time. Through the integration of numerical models, field data, and computing technology, Digital Twin allows the actual condition of the structure to be accurately represented, facilitating the process of performance evaluation, simulation of various load scenarios, and prediction of the service life of the structure. Several studies have shown that the integration of Digital Twin with Artificial Intelligence algorithms is able to improve the accuracy of fault identification while supporting decision-making in condition-based maintenance planning. In addition to improving inspection efficiency, this technology also allows the evaluation process to be carried out in a continuous manner without disrupting infrastructure operations (Cantú, 2022; Ai et al., 2022;).

In addition to sensor-based monitoring, the Non-Destructive Testing (NDT) method remains an important part of modern SHM systems. Various techniques such as ultrasonic testing, infrared thermography, ground penetrating radar, acoustic emission, and laser scanning are used to obtain information about the internal condition of the structure without causing damage to the material. The development of NDT technology combined with the SHM system allows the validation process of monitoring results to be carried out more comprehensively, increasing the level of confidence in the results of damage identification. The combination of permanent sensors and non-destructive inspection methods provides a more effective approach to detecting cracks, corrosion, delamination, and material degradation in various types of civil structures. The integration of these two approaches also expands SHM's ability to monitor the condition of structures that have complex geometric characteristics and operational environments (Chen et al., 2023).

Literature review also shows that sensor placement optimization is one of the fastest-growing research topics. The number and location of sensors greatly affect the quality of the data obtained as well as the system's ability to identify damage. Improper placement of sensors can cause important information regarding the response of the structure to not be optimally recorded, while the use of too many sensors will increase installation and maintenance costs. Therefore, various optimization algorithms based on artificial intelligence and metaheuristic techniques began to be applied to determine the most efficient sensor configuration while maintaining a level of monitoring accuracy. This approach allows the SHM system to produce more representative information with more effective use of resources to support the implementation of large-scale infrastructure projects (Cantú, 2022)

Despite significant developments, the implementation of SHM still faces a number of technical and operational challenges. One of the main challenges is the management of the large amounts of data generated by the sensor network during the monitoring process. The data has various characteristics, both in terms of format, retrieval frequency, and quality, so it requires fast and reliable processing methods. In addition, environmental disturbances such as changes in temperature, humidity, traffic load, and external vibrations can affect the sensor's response, potentially producing *noise* in the data. Other challenges include limited data storage capacity, high computing requirements for Artificial Intelligence-based analysis, interoperability between devices from various manufacturers, and protection of data security on systems connected through the Internet of Things. Therefore, the development of communication standards, data preprocessing methods, and cybersecurity systems are important aspects in improving the reliability of SHM implementation in the future (Huang et al., 2021; Sajedi & Liang, 2022).

The synthesis of various studies shows that the direction of SHM development is no longer only focused on improving damage detection capabilities, but also on building a system that is smarter, adaptive, and able to support the management of infrastructure assets as a whole. The integration of Artificial Intelligence, Internet of Things, Cloud Computing, Big Data Analytics, and Digital Twin results in a monitoring ecosystem that is able to automatically analyze the condition of the structure, provide early warning of potential failures, and prepare maintenance recommendations based on the actual condition of the structure (Fuller et al., 2020). The approach supports the concept *of predictive maintenance*, which allows repair actions to be taken before the damage progresses to a more serious failure. In addition to improving the safety and reliability of the infrastructure, this strategy is also able to optimize maintenance costs during the life cycle of the structure, thus providing significant economic benefits for infrastructure managers (Cantú, 2022; Chen et al., 2023).

Overall, the results of the study show that Structural Health Monitoring research in 2023 is developing very rapidly with a main focus on the use of digital technology and artificial intelligence. The development of intelligent sensors, wireless communication networks, machine learning-based analysis methods, and Digital Twin integration have improved the system's ability to monitor the condition of structures in real-time with an increasingly high level of accuracy. While there are still challenges related to data quality, system interoperability, information security, and implementation costs, the growing innovations show that SHM will become a key component in the management of modern infrastructure. The next research is expected to focus on the development of more robust Artificial Intelligence algorithms, full integration of Digital Twin with field monitoring systems, improving energy efficiency in sensor networks, and drafting implementation standards that can be applied to various types of civil infrastructure to support the creation of smarter, more reliable, and sustainable monitoring systems.

4. | CONCLUSION

Structural Health Monitoring (SHM) has experienced significant advancements in recent years, driven by rapid developments in sensing technologies, data analytics, and computational methods. This systematic literature review highlights that modern SHM systems are increasingly shifting from traditional periodic inspection approaches toward continuous, real-time, and automated monitoring frameworks. The integration of advanced sensors such as fiber optic sensors, wireless sensor networks, and non-destructive evaluation tools has improved the accuracy and reliability of structural condition assessment.

In addition, the emergence of data-driven approaches, particularly machine learning and artificial intelligence, has enhanced damage detection, localization, and prediction capabilities. These techniques enable more efficient processing of large-scale monitoring data and support early warning systems for structural failure. However, challenges remain, including data quality issues, high implementation costs, limited standardization, and difficulties in integrating heterogeneous systems across different infrastructure types. While SHM technologies have made substantial progress, further research is needed to improve system robustness, scalability, and real-world applicability. Future developments are expected to focus on hybrid approaches that combine physics-based models with data-driven techniques, as well as the deployment of cost-effective, long-term monitoring systems for sustainable infrastructure management.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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