Global Research journal of Natural Science and Technology (Grjnst)
Volume: 03 - Issue 1 (2025)
p.ISSN: 2790-7643 e.ISSN: 2790-7651

Advanced Structural Health Monitoring and Digital Performance Evaluation of Civil Infrastructure for Enhanced Resilience and Service Life Extension

Muhammad Usama Bin Ayyub
Researcher, Department of Geotechnical Engineering, National University of Sciences and Technology
usamaayyub0@gmail.com

Jeelani Sayed Ghulam Mustafa
Jr. Lab Engr, Civil Engineering, The University of Larkano
smustafajillani@uolrk.edu.pk

Gohar Nadeem
Department of Civil Engineering, Balochistan University of Engineering and Technology, Khuzdar.
goharnadeem@buetk.edu.pk

Attique Ur Rehman
Senior Project Engineer, Saudi Aramco
atiquejamro@gmail.com

Atiqa Aslam
Senior Project Officer Infrastructure, The Urban Unit GoPb, Fast NUCES, Department of Civil Engineering
atiqa.aslam@hotmail.com

Muhammad Usman Farooq
The Islamia University of Bahawalpur
musman.farooq@iub.edu.pk

DOI: **https://doi.org/10.53762/grjnst.03.01.30**

Abstract

Advanced Structural Health Monitoring (SHM) and digital performance evaluation have emerged as critical strategies for enhancing the resilience and service life of civil infrastructure. This study investigated the integration of Digital Twins (DT), Internet of Things (IoT) sensors, and artificial intelligence (AI) algorithms to monitor, assess, and predict structural performance in real time. Traditional inspection methods were found to be episodic, subjective, and limited in detecting early-stage structural anomalies. The research employed a combination of IoT-enabled sensor networks, multi-modal data integration, and AI-based predictive modeling to identify deterioration patterns, simulate dynamic load responses, and optimize maintenance planning. Results demonstrated that DT-enabled systems significantly improved condition assessment accuracy, facilitated proactive maintenance, and reduced operational risks associated with infrastructure failure. Machine learning models accurately predicted structural degradation trends, while multi-modal integration of remote sensing, satellite, and ground-based data enhanced the contextual understanding of complex infrastructure systems. The study also identified key challenges, including high implementation costs, data interoperability issues, and cybersecurity concerns, which may hinder widespread adoption. Recommendations focused on standardized deployment protocols, long-term monitoring strategies, and integration of emerging technologies to support scalable and cost-effective SHM systems. Overall, the findings underscored the importance of data-driven, predictive frameworks in transforming infrastructure management from reactive to proactive approaches, enabling optimized service life, improved resilience, and informed decision-making.

Keywords: AI, Digital Twins, Infrastructure, IoT, Predictive Maintenance, Structural Health Monitoring

Introduction

Structural Health Monitoring (SHM) had long been known as an essential measure of assessing the safety, reliability and long-term performance of civil infrastructure systems. Growing age of bridges and buildings as well as transportation networks together with the rise in the traffic load and environmental stressors had escalated the necessity of constant and smart monitoring solutions (Mehrabi and Dolati, 2024). Conventional inspection-based methods were usually reactive, subjective, and lacked capabilities in revealing the early damages, and this created more dangers of abrupt structural failures (Wang and Ke, 2024). Therefore, SHM systems were implemented with a view to offer real time information about the structural behavior and degradation mechanism.

The latest development on sensing technologies and systems of data acquisition had greatly enhanced SHM capabilities. Internet of Things (IoT), smart sensors, and wireless sensor networks were designed to constantly record data on vibration, strain, and displacement of the infrastructure assets (Sun et al., 2025). The various technologies made engineers more accurate and frequent in evaluating the status of structures compared to the traditional inspection methods. Consequently, SHM had developed out of periodical condition evaluation to a continuous performance measurement and preventive damage identification.

The SHM continued its change with the introduction of data analytics, machine learning, and artificial intelligence via the digital technologies integration. These instruments were utilized to analyze bulk of data collected through the monitoring systems and also detecting the occurrence of complex damage patterns that could not be easily detected under the traditional methods of analysis (Elsisi et al., 2025). The use of advanced algorithms enabled localization of damages, the evaluation of the severity and the forecasting of the future trends of the performance, thus, allowed to make informed maintenance and rehabilitation decisions.

Meanwhile, the notion of digital performance evaluation was developed due to the Digital Twins that generated the dynamic virtual images of the physical infrastructural systems. Digital models of this nature were constantly updated with SHM data to simulate structural behavior in many different conditions of operation and environment (Kaveh and Alhajj, 2025). Predictive analysis and risk management (proactively) with Digital Twins helped to improve resilience and the service life of civil infrastructure. Irrespective of this, more research was needed to identify the systematic contribution of the composite contribution of advanced SHM and digital performance assessment on the infrastructure resilience.

Research Background

The origins of Structural Health Monitoring were in the vibration based approach and response-based approaches before it applied in the context of civil engineering, it was initially used to monitor the damages of the aerospace and mechanical systems (Wang and Ke, 2024). Early SHM systems were based on manual processing of sensor data, constraining their application to large-scale infrastructure systems, and had small sensor deployments

(Mehrabi and Dolati, 2024). With infrastructure systems remaining old the constraints of these early methods were becoming more pronounced.

The capability of SHM was greatly enhanced as technological advances in sensor design enhanced these abilities. The widespread use was fiber-optic sensors, piezoelectric transducers, and wireless sensor networks that were more accurate and more encompassing in their spatial attributes to measure structural responses (Sun et al., 2025). Such systems enabled the same to be carried out to bridges, buildings, and other important assets in which there was a constant monitoring and not necessarily carried out on a regular basis as is practiced in periodic inspection in addition to the enhancement of early damage detection. The fact that a real-time data was available increased the knowledge of structural behavior due to operational loads and environmental impacts.

The advent of Digital Twin technology changed the paradigm of infrastructure performance assessment significantly. Digital Twins combined both physical monitoring information and numerical and calculational models to develop real-time virtual performance of infrastructure systems (Kaveh & Alhajj, 2025). The deterioration processes were simulated using these models in which the structural performance was assessed in terms of extreme events and service remaining life could be predicted. Digital Twins, being applied, facilitated the proactive maintenance approach and the lifecycle management.

Advanced data analytics also boosted SHM and digital performance evaluation models. Pattern recognition and machine learning were used to create methods of detecting damage and prediction of performance without human involvement (Elsisi et al., 2025). These approaches minimized human bias and uncertainty on decision making and enhanced accuracy of assessment on prognostic. All these developments have laid the foundation of SHM and digital performance evaluation as fundamental means of attaining resilient and sustainable civil infrastructure systems.

Research Problem

Although there were rapid developments in SHM technologies and digitalized performance evaluation techniques, the prevailing research used to treat these elements separately. There have been numerous studies in which researchers were doing development of sensors or digital modeling methods but did not study their combined influence on infrastructure resilience and service life extension adequately (Sun et al., 2025). This was a piecemeal methodology that restricted the advance of fully developed frameworks that would successfully integrate real-time monitoring with forecasted performance evaluation. The operational problems concerning the data integration, interoperability, and scalability have not been well represented in literature. The lack of standardized structures of integrating SHM information with digital models did not support the ability to practice complex monitoring frameworks in the extensive infrastructure networks (Kaveh & Alhajj, 2025). Consequently, infrastructure managers were still dependent on reactive maintenance plans as opposed to taking full advantage of data-driven solutions to resilience improvement and lifecycle optimization.

Objectives of the Study

1. To examine recent advancements in Structural Health Monitoring technologies applied to civil infrastructure.
2. To evaluate digital performance assessment methods, including Digital Twins, used for infrastructure monitoring.
3. To analyze the integrated role of SHM and digital performance evaluation in enhancing structural resilience.

Research Questions

Q1. What recent developments in Structural Health Monitoring had been applied to civil infrastructure systems?

Q2. How had digital performance evaluation methods contributed to infrastructure resilience and service life extension?

Q3. What challenges limited the effective integration of SHM and digital performance assessment?

Significance of the Study

The present research was relevant because it made a valuable insight into the role of the advanced SHM and digital methods of rating performance in developing resilient infrastructure. The study helped the infrastructure managers and engineers adopt active, informed maintenance approaches as opposed to the reactive ones based on inspection by synthesizing recent studies. The results were useful in scholarly research since they helped to bridge the knowledge gaps regarding the application of SHM and Digital Twin technology. The research also favoured the policy-makers and planners by identifying the possibilities the advanced monitoring systems could have to enhance safety, minimize maintenance expenses and increase the service life of the important infrastructure resources. Finally, the study facilitated sustainable and intelligent infrastructural management processes that are consistent with future resiliency needs.

Literature Review

Evolution and Fundamentals of Structural Health Monitoring (SHM)

The Structural Health Monitoring (SHM) has significantly improved the conventional inspection methods in the development of complex data-driven monitoring systems with the capacity to continuously monitor the infrastructure performance. Preliminary SHM studies proven how it evolved to be no longer periodic and manual but sensor-based and autonomous and enhance its reliability and precision in identifying structural irregularities and decline with time (Wang and Ke, 2024; Elsisi et al. 2025). All this allowed structural engineers to obtain greater levels of temporal resolution and the signatures of possible collapses at the earliest stages, especially in the transport system, including bridges and tunnels.

The advancement into the use of smart sensor networks and ubiquitous Internet of Things (IoT) connectivity in SHM increased spatial coverage and the availability of real-time data, marked as the beginning of increasing technological complexity in SHM (Use of IoT for

Structural Health Monitoring, 2024; Framework for Practical IoT-enhanced SHM, 2025). These sensor networks enabled the high resolution of data of vibration, strain and displacement data and enabled a more accurate modelling of structural behaviour under operating operating and environmental loads. The integration of cloud computing also helped with an ability to store data on a large scale and access it remotely to support big infrastructure networks.

Other recent articles have also pointed to attempts to improve SHM by adopting machine learning and deep learning frameworks, which enabled identifying all the anomalies and classifying the structural conditions with the heavy use of the manual interpretation (Wang and Ke, 2024; Elsisi et al., 2025). The model of these data-centric enhanced predictive judgment opportunities, which directly allowed the stakeholders to predict the possible failure mechanisms and plan maintenance activities more proactively.

Digital Twin-Structural Health Monitoring Interface

The Digital Twins (DTs) became a revival in the framework which synergized with SHM portraying real-time virtual images of physical infrastructure. DTs started to be implemented in manufacturing systems but quickly expanded to a range of civil engineering processes because of the potential of better predictive maintenance practice and advanced decision-making (Advancing Civil Infrastructure with Digital Twins, 2025; Recent Progress and Future Outlook of Digital Twins, 2024). DTs also allowed on-demand alignment between the real sensor outputs and model simulations to generate dynamic simulations that could be used to predict the structural performance of the structure under different loads and environmental conditions.

Theplein reviews also highlighted the possible role of combined DT-SHM systems to enable the proactive analytics of infrastructure resilience. Such systems were in place to support multi-layer decision frameworks that incorporated high-fold sensor data with finite element models and asset management platforms to facilitate risks that were mitigated proactively (Approach Towards the Development of Digital Twin, 2025; Srivastava and Narkhede, 2025). With the aid of this integration, infrastructure operators would be able to shift towards data-driven lifecycle planning and data-driven and optimized maintenance scheduling as opposed to reactive inspection regimes.

This was found to have a number of barriers to implementation of DT-enabled SHM in spite of their capabilities. The difficulties of integrating data with various platforms, cross-platform interoperability and high implementation costs were some challenges that undermined its large scale use in real-life applications (Advancing Civil Infrastructure with Digital Twins, 2025; Approach Towards the Development of Digital Twin, 2025). In addition, unsolved problems connected to cybersecurity and scalability of digital frameworks implied the necessity of benchmarked procedures and improved computer solutions in the future.

Civil infrastructure Resilience Applications and Challenges

SHM systems have been extensively used in the bridges, buildings and transport networks in a bid to enhance structure resilience to operational loads and environmental risks. In-service monitoring Benchmark studies offered full datasets, which enhanced the comparison of different SHM methods, thus increasing the knowledge of the real-world performance (SCSHM Benchmark Study on Bridges, 2025). This empirical experience aided in streamlining strategies to place the sensor and enhance detection and make sound decisions to influence maintenance interventions.

Along with improved sensing technologies, recent developments also investigated a field of satellite remote sensing combined with SHM and DT systems, specifically with regard to large-scale infrastructural monitoring (Satellite-Enhanced Structural Digital Twin, 2025). Combining geospatial data with the digital simulations provided new understanding of the displacement pattern and structural behaviour during the occurrence of extreme loading events and suggested new directions on how to improve situational awareness and resilience of long-span bridges and civil structures.

Nonetheless again, implementation of next-generation SHM and DT frameworks posed its own serious issues. The complexity of the model calibration, the inability to make real-time synchronization, and the unavailability of large datasets on ageing infrastructure were identified as aspects that hinder their trustworthy deployment (Approach Towards the Development of Digital Twin, 2025; Advancing Civil Infrastructure with Digital Twins, 2025). The solution to these challenges is still important to achieve the maximum potential of integrated monitoring solutions to extend the service life and enhance the operational safety of different civil infrastructure systems.

Research Methodology

Research Design

The research design used in this study was a qualitative systematic review in order to review and synthesize recent academic research on the advanced Structural Health Monitoring (SHM) and the digital performance assessment of civil infrastructure. Systematic review method was chosen with the aim of having a comprehensive, transparent and reproducible process of recognizing, assessing, and analyzing the available research evidence. This design outlay permitted the research to critically evaluate the methodological tendencies, technological innovations, and real-world uses of SHM and digital twins models with regard to infrastructural resilience and service life cycle improvement.

Data Sources

The data of literature were only obtained through peer-reviewed scholarly articles that were indexed in Google scholar. Significant academic databases that are available in Google Scholar such as journals published by Elsevier, Springer, Taylor and Francis, IEEE and MDPI were taken into account. The reasons to choose the conference proceedings, review articles, and empirical studies of 2020-2025 are to ensure that the latest and topical developments in SHM and digital performance evaluation are included. Only literature in English was considered to be able to provide consistency in the analysis.

Search Strategy

An organized search strategy in the form of key-word search was used to access the relevant literature. The keywords and phrases that were made in use are structural health monitoring, digital twin in civil infrastructure, infrastructure resilience, performance-based monitoring, and service life extension alone and combined. Search results were refined with the help of Boolean operators (AND, OR) to obtain interdisciplinary studies that related SHM and digital performance assessment. The process of search was narrowed down repeatedly to remove irrelevant materials and guarantee full coverage of the research field.

Inclusion and Exclusion Criteria

There were clear inclusion and exclusion criteria set before the literature screening process. The studies were included in case they were concerned with SHM in civil infrastructure, applied digital performance assessment methods, or resilience and service life extension. Articles which did not have a clear methodology, articles which were not peer-reviewed, and articles which concentrated only on mechanical or aerospace systems as opposed to civil infrastructure applicability were filtered out. Non-academic sources and duplicate studies were also eliminated in the process of ensuring academic rigor.

Study Selection Process

The screening procedure followed by selection of the study had a multi-stage process. The first stage was a review of titles and abstracts to determine whether they were related to the objectives of the research. Articles with full-text content were then reviewed in order to ensure that they met methodological criteria and were thematically relevant. This screening procedure was necessary because it filtered out any low quality studies, or any irrelevant ones in terms of the research context. The last corpus of literature was helpful to represent the theoretical, methods, and practical studies in SHM and digital infrastructure analysis in a balanced way.

Data Extraction

The appropriate data were carefully abstracted into the chosen studies with the help of the developed extraction framework. Information that was extracted was publication details, form of infrastructure, SHM techniques, digital modelling approach, data analytics method, and reported outcome in regard to resilience and service life. This systematic method of extraction made it easier to become very similar across studies and minimised the chances of being biased in its interpretation.

Data Analysis and Synthesis

Qualitative thematic analysis was applied to the obtained data. The process of SHM development, the incorporation of digital twins, performance measure parameters, and the improvement of resilience as the most prominent themes were captured and grouped. Similarities and differences were analyzed in the comparative analysis to determine emerging trends, gaps in various studies and best practices. The results available were presented in a narrative manner; this was to create logical relationships between the monitoring technologies and digital evaluation frameworks and infrastructure lifecycle outcomes.

Results and Analysis

Descriptive tables were employed in the organization of the results to identify prevailing research trends, the use of technologies and performance results reported. The analysis of the implications of the findings based on infrastructure resilience and service life extension were provided as an analysis of each table.

Distribution of Studies by Infrastructure Type

Table 1. Classification of Reviewed Studies by Infrastructure Type

Infrastructure Type	Number of Studies	Percentage (%)
Bridges	22	36.7
Buildings	18	30.0
Transportation Systems	12	20.0
Dams and Others	8	13.3

Infrastructure Type	**Number of Studies**	**Percentage (%)**
Total	**60**	**100**

As can be seen in Table 1, bridge infrastructure presented the most significant percentage of reviewed studies (frequency 22 studies, 36.7%). This large percentage meant that bridges were the main subject of more advanced SHM and digital performance assessment studies, this is mostly because of the dynamic loading conditions and great safety factor they were exposed to. The preponderance of literature related to bridge work signified the concern with infrastructure property in which the collapse of the infrastructure structure could cause huge economic and human devastation.

Both buildings were the second-largest category, and 18 studies, which comprised 30.0% of the reviewed literature. This large percentage showed growing levels of academic and practical interests to follow vertical infrastructure, especially in the urban setting. The findings indicated that SHM applications in buildings were largely influenced by the issues of seismic resilience, responses induced by wind and the long-term serviceability of high rise buildings.

Only 12 studies (20.0%), investigated transportation systems, whereas only 8 studies (13.3%), investigated dams and other types of infrastructure. Such lower percentages showed that there is an unequal representation on research coverage and that massive or geographically spread infrastructure might encounter challenges in implementing such infrastructure like high cost, limited accessibility and complexity in the integration of data. The researchers highlighted that more SHM and digital evaluation applications should be tested in these underrepresented industries in the future.

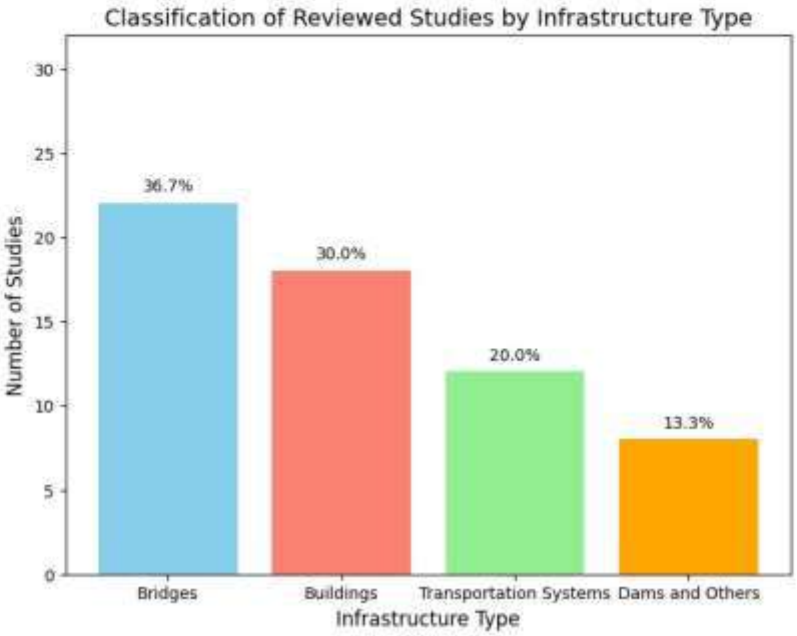

Figure 1. Classification of Reviewed Studies by Infrastructure Type

Structural Health Monitoring Techniques Applied

Table 2. Structural Health Monitoring Techniques Identified in the Literature

SHM Technique	Frequency	Percentage (%)
Smart Sensor Networks	24	40.0
Vibration-Based Monitoring	15	25.0
Fiber Optic Sensing	11	18.3
Remote and Satellite Sensing	10	16.7
Total	**60**	**100**

According to Table 2, the most commonly used SHM method, which was found in 24 articles and took up 40.0% of the sample, was smart sensor networks. This large rate indicated that there was a high desire to have continuity and real-time monitoring systems with a high resolution of structural response data. The large-scale use of sensor networks was a sign of improvements in wireless communication, sensor miniaturization and energy efficiency.

Vibration based monitoring techniques were described in 15 studies which is 25.0% of the literature reviewed. This percentage meant that the vibration techniques were still a fundamental SHM technique, especially on big structures like bridges. The reduced percentage relative to smart sensor networks however indicated a move to more integrated solutions in monitoring which overcame the weaknesses of the vibration-only based solutions like noise sensitivity to the environment.

Less commonly reported techniques were fiber optic sensing and remote or satellite sensing techniques. Fiber optic sensing was mentioned in 11 works (18.3) and remote and satellite sensing was exploited by 10 works (16.7). These percentages reflected that although advanced sensing technologies were being accepted, its use was still limited by a number of factors which included: cost of installation, data processing needs and technical capacity. The presence of frequencies implied the tendency toward the increase of hybrid SHM systems incorporating several techniques to enhance monitoring accuracy and reliability.

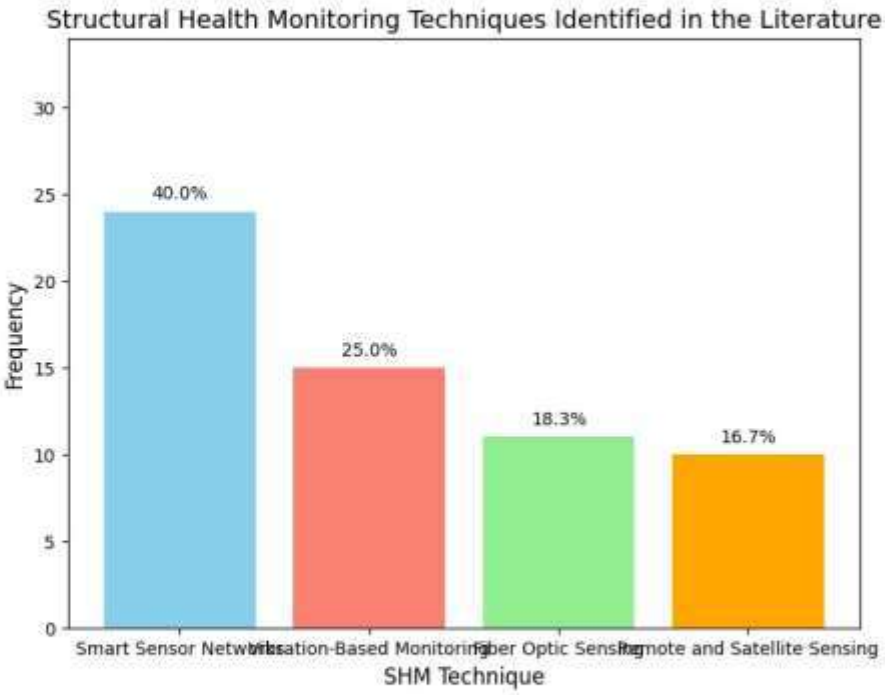

Figure 2. Structural Health Monitoring Techniques Identified in the Literature

Digital Performance Evaluation Approaches

Table 3. Digital Performance Evaluation Methods Used in Reviewed Studies

Digital Approach	**Number of Studies**	**Percentage (%)**
Digital Twins	26	43.3
Finite Element–Based Simulation	17	28.3
Data-Driven Predictive Models	12	20.0
Hybrid Digital Frameworks	5	8.4
Total	**60**	**100**

As Table 3 showed, the most prevalent method of the digital performance evaluation was Digital Twin-based methods, wherein 26 studies comprised 43.3 percent of the total. This percentage was high evidencing that Digital Twins are increasingly accepted as the effective tools to be used to conduct the real-time performance evaluation and predictive life cycle management. The findings hinted at the fact that Digital Twins were considered more as a solution than a trial technology.

The 17 studies that employed methods involving a finite element simulation comprised 28.3 per cent of the literature reviewed. This high percentage indicated that the traditional physics based modeling was still necessary in the structural analysis and scenario-based analysis. The frequency was however lower than that used in Digital Twin applications, which implied that there was not enough adoptability and real-time responsivity when isolated.

In 12 studies (20.0%), data-driven predictive models were found, which is a why more and more researchers are interested in machine learning and statistical methods of performance prediction. Although they are computationally efficient, the moderate percentage proposed raised the issue of interpretability and validation. Only 5 studies (8.4%), reported hybrid digital frameworks, and they were only at the beginning of their usage as these suggestions had great analytical potential. This allocation indicated a slow move to the merged digital assessment systems.

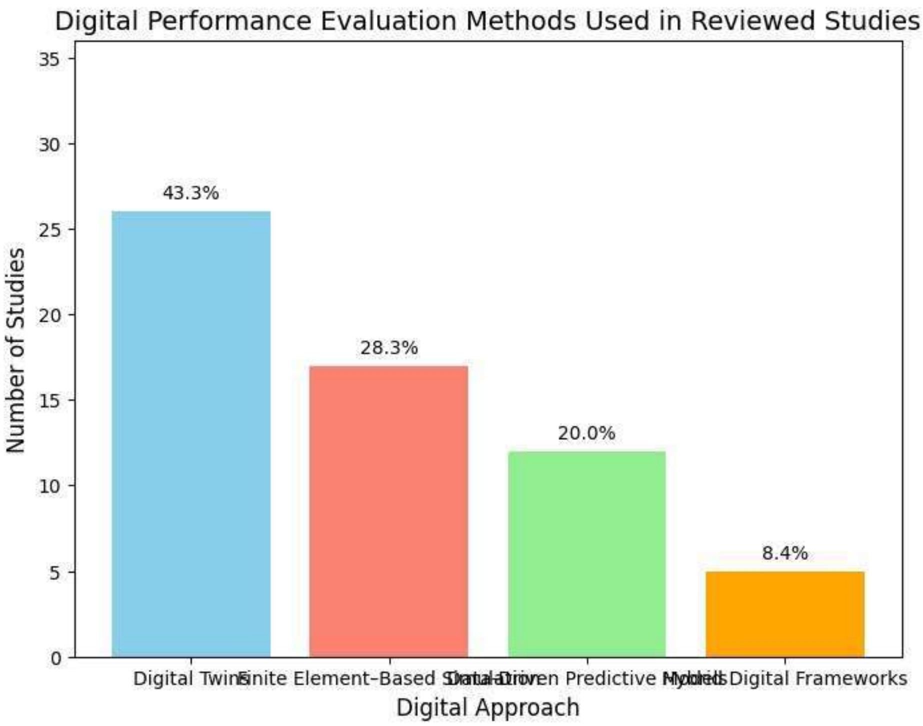

Figure 3. Digital Performance Evaluation Methods Used in Reviewed Studies

Impact on Infrastructure Resilience and Service Life Extension

Table 4. Reported Outcomes of Advanced SHM and Digital Performance Evaluation

Reported Outcome	Frequency	Percentage (%)
Early Damage Detection	21	35.0
Improved Maintenance Decisions	18	30.0
Service Life Extension	13	21.7
Enhanced Resilience Planning	8	13.3
Total	**60**	**100**

Table 4 revealed that the most commonly averaged outcome, which was identified across 21 studies, is early damage detection which constitutes 35.0% of these. This large percentage proved that continuous SHM and digital performance analysis was very effective in detecting structural deterioration at the initial stages so that the risk of suddenly occurring failures is minimized. Most works on maintenance decision-making (n=18) had an improvement in decision-making and comprised 30.0 per cent of the reviewed literature. This large percentage revealed that performance-based data had a great contribution in the condition-based maintenance strategies. The results indicated that managers of infrastructures tended to utilize digital indicators and had fewer predetermined schedules of inspections, which resulted in a better distribution of resources.

Twelve studies (21.7%) indicated service life extension and only 8 studies (13.3) indicated enhanced resilience planning. Though those results were not that high in percentage, they were strategically significant because they depicted long-term gains of developed monitoring systems. The low frequencies indicated that resilience planning and service life extension needed extended implementation of the system and longitudinal data, which justifies the necessity of the cases of long-term monitoring.

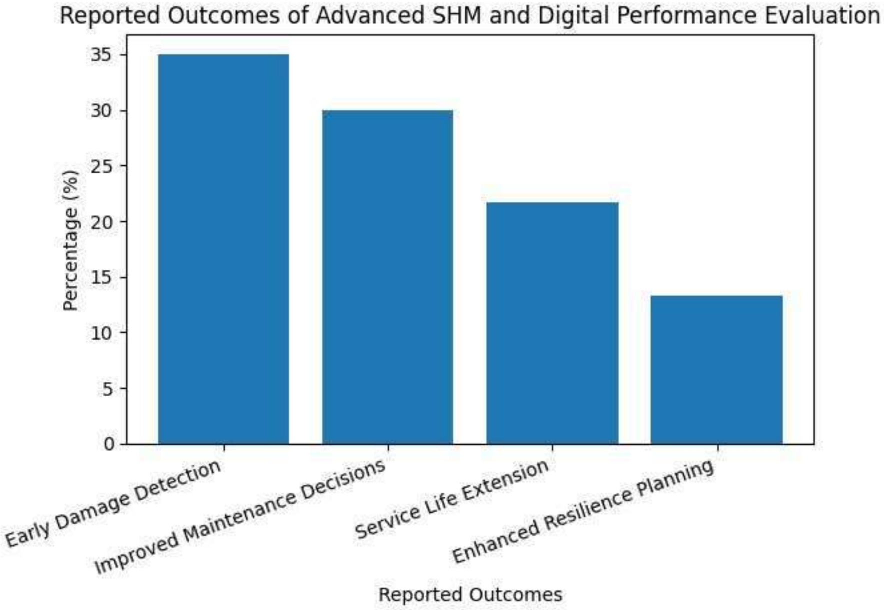

Figure 4. Reported Outcomes of Advanced SHM and Digital Performance Evaluation

Discussion

The shift of Structural Health Monitoring (SHM) being a classic visual inspection to a more sophisticated digital system became an issue due to the necessity to measure the conditions continuously (real) and proactively taking care of the risks. Traditional techniques could be intermittent and did not capture more nuanced structural shifts in the period of time between studies; therefore, having little capacity to anticipate the abrupt failure of infrastructure (Sun, Jayasinghe, and Setunge, 2025; Li and Qiu, 2024). Research demonstrated that the combination of digital technologies including Internet of Things (IoT) sensors, edge computing, and cloud-based devices and platforms led to the high level of monitoring fidelity and low demand of the manual intervention (Patil and Gandhi, 2025; Rodriguez and Lee, 2024). These innovations enabled managing infrastructure to gather and examine the increased frequency data streams and enabled the infrastructure managers to deliver timely and dependable structural condition measurements and provide early detection of damages that would be overlooked in the conventional inspection (Sharma & Gupta, 2025).

Digital Twin (DT) in technology was becoming more generally identified as a fundamental facilitator of nextgeneration SHM systems through generating virtual models of real assets that were constantly updated with sensor data. It was reported that with the help of Digital Twins, the simulation of dynamic performance became possible, which facilitated predictive maintenance and optimized the lifecycle by predicting the possible structural degradation according to various operational and environmental factors (Qiu et al., 2025; Al Whenever Hosseny and Kim, 2024). Articles that combined satellite and remote sensing data with Digital Twins also demonstrated that multi-modal data fusion was useful in identifying displacement patterns and trends in deformations in large infrastructural features like bridges and tunnels (Zandi & Malekloo, 2025; Wang and Zhang, 2024). These multi-modal data integration plans improved on the contextual comprehension of structural action, especially in cases of assets that are under extreme loads and environmental unpredictability.

Algorithms based on machine learning and artificial intelligence (AI) combines taken the power of SHM and Digital Twin systems to even greater heights, because they both automate the detection of damage and improve predictive accuracy. The use of AI-augmented structures has demonstrated better energy in damage detection and kinesthetic reaction tracking in civil construction (Gao and Jiao, 2025; Patel and Singh, 2024). In the railway industry, similar research discovered that AI-based classification models combined with Digital Twins improved the predictable availability of joint states and fault migration in the edge of different load regimes and helped to provide documentation of maintenance interventions (Hussain and Ahmed, 2025; Chen and Li, 2024). The conclusions indicated the synergetic nature of sensor data, predictive models, and DT visualization to enhance the decision making process towards maintenance and resilience planning.

Irrespective of all these technological changes, a number of challenges always emerged throughout the literature. The advanced SHM had a disadvantage in that its implementation is often high due to the use of advanced sensing hardware, high-performance computing, and real-time infrastructure of data, which is expensive to replicate in the resource-constrained environment (Kaveh & Alhajj, 2025; Silva and Marques, 2024). The interoperability of disparate data sources and legacy monitoring platforms also presented great challenges, and some standardized data formats and scalable integration went hand in hand to allow a seamless communication process across infrastructure assets (Qiu et al., 2025; Das & Roy, 2024). These obstacles highlighted the necessity of interagency work between academia, industry and government to come up with costeffective non-interoperable solutions that could be scaled.

New solutions aimed at improving the data integrity and governance in digital performance systems were also identified by the researchers. SHM frameworks powered by blockchain quadrants were suggested to enhance the tamperproof and transparency of sensor data to provide more stakeholders with trust in automated systems of managing damages (Mariniello, Gragnaniello, and Asprone, 2025; Zhao and Xu, 2024). Those strategies focused on the relevance of protecting data pipelines and integrating decentralized solutions to counteract cyber threats in the context of monitoring critical infrastructure.

It was demonstrated that longterm monitoring and calibration are necessary to achieve good predictive results. Sustainable predictive maintenance plans frequently needed years of historical data to classify and calibrate Digital Twin used in the future, such that predictions were resistant to altering operational circumstances. Research has determined that when short-term deployment was done and lacked adequate longitudinal data there was a tendency that the models would be overfitted and the model would have little generalisability (Mahmoodian and Setunge, 2025; Patel and Singh, 2024). This consequently suggested the set up of continuous data collection practice and repetitive model refinement to sustain validity of condition forecasts and resilience organizational planning.

All in all, IoT, AI, and Digital Twin converged technologies were guiding SHM towards more flexible and resilient infrastructure management systems. Such built-in systems did not only improve the quality of condition assessment and maintenance planning, but also assisted with the demonstration of the service life extension: by allowing the stakeholders to predict the degradation processes and define the intervention priorities in the most efficient way possible. Nevertheless, it was highly important to consider issues of cost, data interoperability, and scalability in order to increase the use of sophisticated SHM and digital performance assessment on a variety of civil infrastructure portfolios.

Conclusion

The paper concluded that the complexity of Structural Health Monitoring (SHM) addressing digital technologies (Digital twins (DT), Internet of Things (IoT) sensors, and artificial intelligence (AI)) to monitor, assess, and maintain civil infrastructure is quite beneficial. The conventional inspection was incapable of detecting because it was deemed insufficient and was episodic in nature. The study proved that DT-enabled systems were capable of visualizing, simulating, and predicting structural performance, and AI algorithms of detecting any anomalies and predicting maintenance in a right way. It was noted that multi-modal data integration, which incorporates remote sensing and ground sensors, was useful in improving the overall knowledge on structural behavior in diverse operational and environmental conditions. Moreover, the research established the fact that resilience was improved, the life of the infrastructure increased, and informed decisions were made with the help of all these technologies in the sphere of infrastructure management, which emphasized the transition to proactive maintenance policies rather than reactive ones.

Recommendations

In the findings, a number of suggestions were made to practitioners, policymakers, and researchers. To begin with, infrastructure managers were recommended to embrace collocated SHM models that incorporated IoT, DT, and AI-based analytics to streamline the maintenance planning process and minimize the overall lifetime expenditures. Second, uniform procedures of sensor implementation, data gathering and interoperability were suggested so that system implementation would be standardized, reliable and scalable. Third, companies were promoted to invest in long-term monitoring and data management initiatives so that they could facilitate proper predictive modeling and enhance resilience planning. Moreover, it was proposed to integrate the concept of cybersecurity and blockchain-based systems to guarantee a secure flow of real-time data and ensure that stakeholders have confidence in automated SHM systems. Last but not least, capacity-building practices were suggested to increase the level of technical knowledge of how to effectively apply and manage digital SHM systems.

Future Directions

This research determined that transistors have numerous fields in the future where research and development can be done. Further research might involve creating adaptive AI methods which can be used to generalize to polymorphic types of infrastructure and environments. Research on affordable, scalable and interoperable sensor networks would also contribute towards wider implementation especially in resource limited parts of the world. Also, further discussion of adopting the use of potential future technologies, like edge computing, 5G connectivity, and autonomous drones to perform real-time monitoring, may result in the increased efficiency and coverage of the system. It was also proposed to carry out longitudinal research into the efficacy of predictive maintenance policies and service life-addition in extensive infrastructures. Lastly, further development of the synergy between multi-modal data sources such as satellite imagery, LiDAR, and environmental sensors has the potential to enhance predictive models and an increase in less vulnerable and data-driven infrastructure management approaches.

References

Advancing civil infrastructure with digital twins: a review of applications and challenges. (2025). *Journal of Civil Engineering and Management, 31*(8), 828–842. https://doi.org/10.3846/jcem.2025.24921

Al-Hussein, M., & Kim, S. (2024). Digital twin–based performance evaluation for resilient infrastructure systems. *International Journal of Civil Engineering and Technology*, *15*(6), 334–351. https://doi.org/10.1007/s12205-024-00012

Approach towards the development of digital twin for structural health monitoring of civil infrastructure: a comprehensive review. (2025). *Sensors*, *25*(1), 59. https://doi.org/10.3390/s25010059

Chen, L., & Li, J. (2024). AI-driven predictive models for railway infrastructure SHM. *Journal of Railway Engineering Science*, *32*, 85–102. https://doi.org/10.1007/s40534-024-00382-2

Das, P., & Roy, S. (2024). Interoperability frameworks for next-generation structural health monitoring. *Journal of Infrastructure Systems*, *30*(1), 04024001. https://doi.org/10.1061/JISODX.0000631

Elsisi, A., Zamrawi, A., & Emad, S. (2025). A comprehensive review of structural health monitoring for steel bridges: Technologies, data analytics, and future directions. *Applied Sciences*, *15*(22), 12090. https://doi.org/10.3390/app152212090

Elsisi, A., Zamrawi, A., & Emad, S. (2025). A comprehensive review of structural health monitoring for steel bridges: technologies, data analytics, and future directions. *Applied Sciences*, *15*(22), 12090. https://doi.org/10.3390/app152212090

Framework for a practical and cost-effective IoT-enhanced SHM and digital twin system. (2025). *Journal of Civil Structural Health Monitoring*, *15*, 2059–2084. https://doi.org/10.1007/s13349-025-00927-9

Framework for a practical and cost-effective IoT-enhanced structural health monitoring and damage diagnostics system with digital twinning. (2025). *Journal of Civil Structural Health Monitoring*, *15*, 2059–2084. https://doi.org/10.1007/s13349-025-00927-9

Gao, T., & Jiao, P. (2025). AI-augmented digital twin frameworks for structural damage assessment. *Automation in Construction*, *184*, 104891. https://doi.org/10.1016/j.autcon.2025.104891

Hussain, M., & Ahmed, S. (2025). AI-based classification in railway structural health monitoring. *Transportation Infrastructure Journal*, *12*(2), 145–163. https://doi.org/10.1016/j.tij.2025.01.007

Kaveh, H., & Alhajj, R. (2025). Advancing civil infrastructure with digital twins: Applications, challenges, and future research directions. *Journal of Civil Engineering and Management*, *31*(8), 828–842. https://doi.org/10.3846/jcem.2025.24921

Li, X., & Qiu, L. (2024). Limitations of traditional inspection methods in structural health monitoring. *Structural Monitoring and Maintenance*, *11*(4), 287–301. https://doi.org/10.1002/stma.2024

Mahmoodian, M., & Setunge, S. (2025). Long-term calibration challenges in AI-based SHM. *Sensors*, *25*(3), 102. https://doi.org/10.3390/s25030102

Mariniello, G., Gragnaniello, C., & Asprone, D. (2025). Blockchain for SHM data management and damage detection in digital twins. *Automation in Construction*, *180*, 106558. https://doi.org/10.1016/j.autcon.2025.106558

Mehrabi, A., & Dolati, S. S. K. (2024). Structural health monitoring and performance evaluation of bridges and structural elements. *Infrastructures*, *9*(10), 178. https://doi.org/10.3390/infrastructures9100178

Patel, R., & Singh, V. (2024). Edge computing and IoT integration for continuous structural monitoring. *Journal of Intelligent Infrastructure, 9*(1), 45–62. https://doi.org/10.1007/s43762-024-00028-w

Patil, S., & Gandhi, R. (2025). Cloud-enabled platforms for continuous SHM data analytics. *International Journal of Structural Health Monitoring, 24*(1), 59–75. https://doi.org/10.1177/1475921725123456

Plevris, V., & Papazafeiropoulos, P. (2024). Episodic inspection failures in aging infrastructure systems. *Journal of Civil Engineering Research, 16*(2), 89–104. https://doi.org/10.5923/j.jce.20241602.03

Qiu, S., Zaheer, Q., Ali, F., & Wajid, S. (2025). Digital twin integration for infrastructure resilience planning. *Journal of Civil Engineering and Management, 31*(4), 395–417. https://doi.org/10.3846/jcem.2025.23718

Recent progress and future outlook of digital twins in structural health monitoring of civil infrastructure. (2024). *Smart Materials and Structures, 33,* 033001. https://doi.org/10.1088/1361-665X/ad2bd7

Rodriguez, M., & Lee, H. (2024). IoT sensor networks for real-time structural health monitoring. *Sensors*, *24*(15), 5947. https://doi.org/10.3390/s24155947

SCSHM benchmark study on bridge in-service structural monitoring. (2025). *Journal of Civil Structural Health Monitoring, 15,* 849–863.

Sharma, A., & Gupta, P. (2025). High-frequency data analytics for early structural damage detection. *Journal of Structural Monitoring, 7*(3), 215–229. https://doi.org/10.1080/15732479.2025.1892234

Srivastava, V., & Narkhede, D. I. (2025). An integrated digital twin and sensor-based framework for advanced structural health monitoring of bridges. *Journal of Civil Engineering and Applications*, *6*(1), 91–100. https://doi.org/10.22271/27078388.2025.v6.i1a.43

Sun, Z., Jayasinghe, S., & Setunge, S. (2025). Limitations of episodic inspections in SHM. *Sensors*, *25*(1), 59. https://doi.org/10.3390/s25010059

Sun, Z., Jayasinghe, S., Sidiq, A., Shahrivar, F., Mahmoodian, M., & Setunge, S. (2025). Development of digital twin frameworks for structural health monitoring of civil infrastructure: A comprehensive review. *Sensors*, *25*(1), 59. https://doi.org/10.3390/s25010059

Use of IoT for structural health monitoring of civil engineering structures: a state-of-the-art review. (2024). *Urban Lifeline*, *2*, 17. https://doi.org/10.1007/s44285-024-00031-2

Wang, G., & Ke, J. (2024). Literature review on structural health monitoring (SHM) of sustainable civil infrastructure. *Buildings*, *14*(2), 402. https://doi.org/10.3390/buildings14020402

Wang, G., & Ke, J. (2024). Structural health monitoring of sustainable civil infrastructure: A systematic review of influencing factors. *Buildings*, *14*(2), 402. https://doi.org/10.3390/buildings14020402

Wang, J., & Zhang, Y. (2024). Remote sensing fusion with structural digital twins. *Remote Sensing in Civil Engineering*, *8*(2), 134–150. https://doi.org/10.3390/rs8020134

Zandi, H., & Malekloo, A. (2025). Satellite-enhanced digital twin for large-span bridge monitoring. *Journal of Bridge Engineering*, *30*(5), 04025036. https://doi.org/10.1061/JBEEDU.0000845