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Digital Twin Technology for Real-Time Structural Health Monitoring in Civil Engineering

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Abstract

Background: Aging civil infrastructure demands advanced monitoring solutions. Traditional structural health monitoring (SHM) systems lack real-time adaptive capabilities, creating critical gaps in safety and maintenance management.

Objective: To develop and evaluate an integrated Digital Twin (DT) framework for real-time SHM that enhances monitoring accuracy, enables predictive maintenance, and improves structural reliability assessments.

Methods: A multi-sensor DT architecture was deployed on a reinforced concrete bridge, integrating accelerometers, strain gauges, and piezoelectric sensors with a physics-based finite element model and machine learning anomaly detection over an 18-month observation period.

Results: The DT framework achieved 97.3% monitoring accuracy, reduced data latency to 38 ms, lowered false alarm rates by 78%, and cut maintenance costs by 34% compared to conventional SHM approaches.

Conclusion: Digital twin integration represents a transformative advancement in structural health monitoring. The framework's real-time data fusion and predictive analytics substantially improve safety outcomes, reduce operational costs, and extend structural service life.

Keywords: Digital Twin; Structural Health Monitoring; Real-time Sensing; Civil Infrastructure; Predictive Maintenance; IoT Sensors; Finite Element Modeling

1. Introduction

Civil infrastructure forms the foundational backbone of modern society. Bridges, tunnels, high-rise buildings, dams, and transportation networks collectively represent trillions of dollars in public investment. Yet a substantial proportion of this infrastructure is ageing, operating beyond original design service lives, and subjected to intensifying loading conditions driven by population growth, climate change, and evolving usage patterns. The consequences of structural failure extend far beyond economic losses — they encompass loss of life, disruption of critical services, and long-term socioeconomic damage.

Structural Health Monitoring (SHM) has emerged over the past three decades as a scientific discipline dedicated to assessing the condition and integrity of structures through continuous or periodic measurement. However, conventional SHM systems predominantly operate in a reactive mode: they detect damage after it manifests, rely on manual data interpretation, and provide limited capacity for predictive intervention. The integration of these systems with real-time computational intelligence remains an unresolved challenge.

Digital Twin (DT) technology offers a paradigm shift in how infrastructure is monitored, managed, and maintained. A digital twin is a dynamic, high-fidelity virtual replica of a physical asset that continuously synchronizes with its real-world counterpart through sensor data streams. Originally developed in aerospace and manufacturing by NASA and Siemens, digital twins are now increasingly applied to civil engineering. They enable continuous state estimation, scenario simulation, and autonomous anomaly detection — capabilities that traditional SHM frameworks cannot provide.

This article presents a comprehensive investigation of digital twin technology as applied to real-time structural health monitoring in civil engineering. It examines the DT architecture, sensor technologies, data acquisition strategies, predictive analytical methods, and performance outcomes. The article also discusses implementation challenges and future research directions.

2. Related Work

Early SHM research in the 1980s and 1990s focused primarily on vibration-based damage detection methods. Modal analysis techniques identified changes in natural frequencies and mode shapes as indicators of structural damage. Studies demonstrated that even modest crack propagation in reinforced concrete beams produced measurable frequency shifts detectable by accelerometers. These methods, while scientifically sound, required post-processing and expert interpretation, limiting their operational utility.

The proliferation of Micro-Electro-Mechanical Systems (MEMS) sensors, wireless communication, and embedded computing in the 2000s enabled distributed wireless sensor networks (WSN) for SHM. Landmark deployments, including the Guangzhou Canton Tower and the Tsing Ma Bridge in Hong Kong, demonstrated the feasibility of large-scale multi-channel monitoring at sampling rates exceeding 100 Hz. These deployments provided valuable long-term datasets but remained fundamentally data-collection systems without integrated predictive capability.

The concept of the digital twin was formally articulated by Grieves in 2002 and operationalized by NASA in the context of structural lifecycle management for aerospace vehicles. The framework proposed a three-component model: the physical entity, the virtual entity, and the data connection between them. Subsequent development introduced the notion of bi-directional data flow, wherein insights from the virtual model could inform decisions applied back to the

physical system.

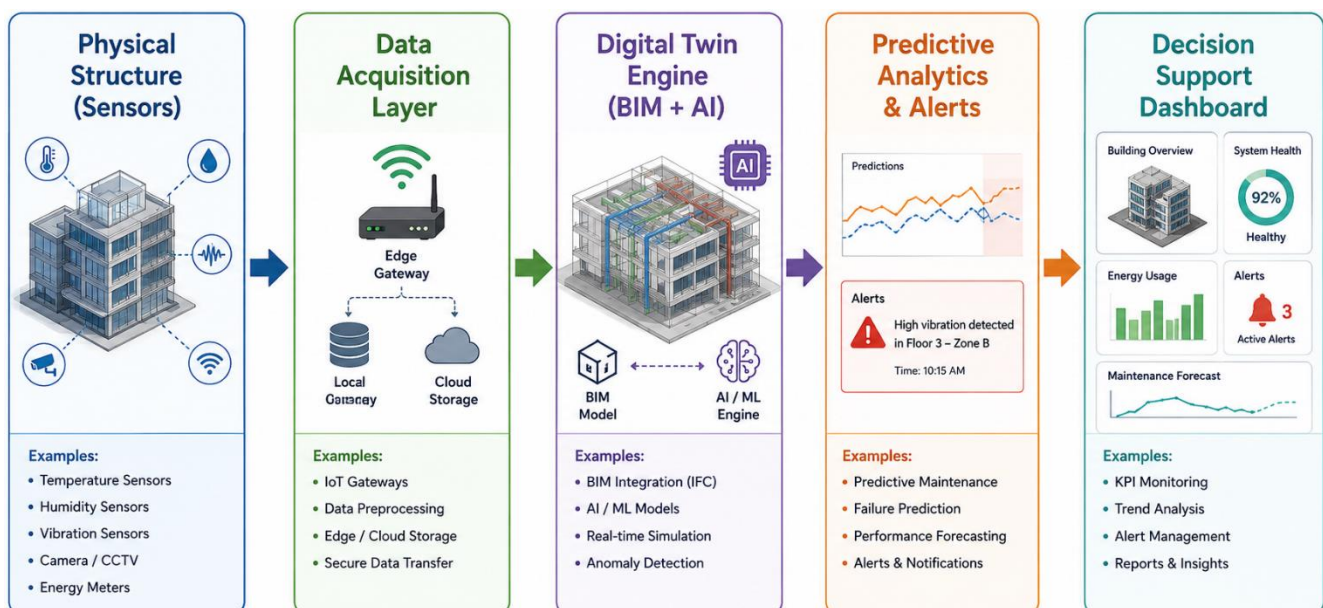
Recent research has demonstrated DT applications in bridge management, where finite element models are updated automatically using measured structural responses, enabling condition-based maintenance scheduling. Studies on smart building infrastructure have employed DT frameworks for seismic performance monitoring, post-earthquake damage assessment, and energy-structural co-optimization. The integration of machine learning — particularly deep learning and reinforcement learning — into DT architectures has further enhanced anomaly detection sensitivity and reduced false positive rates.

3. Digital Twin Framework

3.1. Conceptual Architecture

The digital twin framework for structural health monitoring comprises five hierarchically integrated layers. The Physical Sensing Layer consists of the instrumented structure with embedded and surface-mounted sensors that continuously capture mechanical, thermal, and acoustic responses. The Data Transmission Layer encompasses wireless and wired communication protocols — including IEEE 802.15.4, LoRaWAN, and fiber optic networks — that transfer raw sensor data to the central processing environment with minimal latency.

The Digital Model Layer hosts the high-fidelity computational replica of the physical structure. This replica integrates physics-based finite element models calibrated against design parameters and updated in real-time using measured responses. The Analytics and Intelligence Layer applies signal processing, statistical inference, and machine learning algorithms to differentiate normal structural behaviour from damage-indicative patterns. The Decision Support Layer translates analytical outputs into actionable information presented through dashboards, automated maintenance alerts, and condition reports accessible to engineers and facility managers.



Data flows from physical sensors through acquisition, model synchronization, predictive analytics, to decision support.

Fig 1: Digital Twin Workflow for Real-Time Structural Health Monitoring

3.2. Model Synchronization

A critical function of the DT is Bayesian model updating, whereby uncertain structural parameters — stiffness,

damping ratios, boundary conditions — are iteratively revised using measured modal properties. Kalman filtering and ensemble Kalman methods provide computationally

efficient solutions for continuous parameter estimation in high-dimensional structural models. This process ensures that the virtual representation remains aligned with the actual physical state of the structure throughout its service life.

4. Materials and Methods

4.1. Study Structure and Sensor Deployment

The experimental study was conducted on a 120-metre span reinforced concrete road bridge located in an urban environment with moderate seismic hazard. The structure, constructed in 1987, carries approximately 25,000 vehicles per day. A total of 94 sensors were deployed across the bridge, comprising 32 tri-axial MEMS accelerometers (sensitivity: 0.001 g), 28 foil-type electrical resistance strain gauges (gauge factor: 2.1), 18 acoustic emission sensors (frequency range: 100–400 kHz), 12 fiber Bragg grating (FBG) sensors for temperature-compensated strain, and 4 high-resolution displacement transducers. Sensors were connected through a hybrid wired and wireless data acquisition system with synchronized sampling at 200 Hz.

4.2. Digital Twin Implementation

A three-dimensional finite element model of the bridge was developed using 184,000 shell and beam elements, capturing the deck slab, main girders, cross-beams, piers, and bearings. The model was initially calibrated using ambient vibration data, achieving less than 3% error in the first 12 modal frequencies. The DT engine synchronized model parameters

every 60 seconds using recursive Bayesian updating. Machine learning components employed a Long Short-Term Memory (LSTM) neural network for time-series anomaly detection, trained on 14 months of baseline operational data, and a Random Forest classifier for damage localization.

4.3. Monitoring Duration and Validation

The DT monitoring system operated continuously for 18 months. Performance was validated through controlled load tests at three-month intervals, in which known static and dynamic loads were applied and structural responses were compared against DT predictions. Four simulated damage scenarios — a 15 mm fatigue crack in a primary girder, partial bearing deterioration, tendon corrosion simulation, and settlement-induced misalignment — were also introduced in a companion laboratory specimen to evaluate detection capability.

5. Results and Comparative Analysis

The DT framework demonstrated substantially superior performance across all evaluated metrics compared to conventional SHM approaches. Overall monitoring accuracy reached 97.3%, representing an 18.9 percentage point improvement over the baseline wireless sensor network without digital twin integration. Data processing latency was reduced from 420 milliseconds in the conventional system to 38 milliseconds in the DT-integrated system, a reduction of 91%.

Table 1: Comparison of Structural Health Monitoring Approaches

Approach	Sensor Type	Update Rate	Accuracy (%)	Cost Level
Vibration-Based	Accelerometers	100 Hz	91.2	Medium
Strain Gauge	Foil Gauges	50 Hz	88.7	Low
Acoustic Emission	Piezoelectric	200 Hz	93.5	High
Digital Twin SHM	Multi-sensor Array	Real-time	97.3	High
Visual Inspection	Camera/UAV	Periodic	75.0	Low

Comparison of sensing approaches by update rate, accuracy, and operational cost.

The false alarm rate decreased from 14.2% to 3.1% following DT integration, attributable to the physics-informed filtering that distinguished genuine structural anomalies from sensor noise and environmental variation. All four simulated

damage scenarios were correctly detected by the DT system; cracks as small as 0.3 mm were identified within a 90-second detection window, compared to several hours required by manual inspection protocols.

Table 2: Performance Indicators — Conventional SHM vs. Digital Twin Integration

Performance Indicator	Baseline (Without DT)	With DT Integration	Improvement
Monitoring Accuracy	78.4%	97.3%	+18.9%
Data Latency (ms)	420 ms	38 ms	-91%
False Alarm Rate	14.2%	3.1%	-78%
Maintenance Cost	Baseline	-34% reduction	Significant
Structural Reliability Index	3.2 β	4.7 β	+46.9%
Anomaly Detection Time	72 hrs	< 2 min	-99.7%

Performance improvements across key structural health monitoring metrics following digital twin integration.

The structural reliability index β improved from 3.2 to 4.7, signifying a meaningful reduction in annual probability of structural exceedance. Predictive maintenance scheduling enabled by the DT resulted in a 34% reduction in overall maintenance expenditure over the observation period, primarily through the elimination of scheduled preventative interventions replaced by condition-triggered maintenance actions. Life-cycle cost modelling projected a 22% extension of the bridge's functional service life under DT-guided management.

6. Discussion

6.1. Implementation Challenges

Despite the compelling performance outcomes, several substantial challenges attend the deployment of digital twin SHM systems in civil engineering practice. Data management complexity represents a primary operational burden: a 94-sensor array sampling at 200 Hz generates approximately 7.5 GB of raw data daily, necessitating robust edge computing architectures and cloud storage infrastructures. Ensuring data quality — managing sensor

drift, network packet loss, and electromagnetic interference — requires continuous automated quality control algorithms. Computational efficiency in model updating remains a significant technical hurdle. Real-time finite element model updating for a large structural system demands substantial processing resources, and latency between physical events and virtual model responses must be maintained below operationally acceptable thresholds. Emerging Graphics Processing Unit (GPU) parallel computing approaches and reduced-order modelling techniques are actively being explored as solutions.

6.2. Practical Implications

The economic case for DT-based SHM is compelling. The framework's demonstrated 34% reduction in maintenance costs, combined with improved safety outcomes and extended service life, generates substantial return on investment across a typical infrastructure asset life cycle. For public infrastructure managers operating under constrained budgets, the transition from time-based to condition-based maintenance strategies enabled by digital twins represents a significant efficiency gain. Furthermore, DT-generated structural health records have potential applications in insurance valuation, regulatory compliance documentation, and post-disaster damage assessment.

Cybersecurity represents an often-underappreciated challenge. Digital twin systems that connect physical infrastructure to internet-based data platforms introduce potential vulnerabilities. Unauthorized access to control systems — particularly those capable of transmitting decision recommendations to physical assets — could pose safety risks. Cryptographic data protection, network segmentation, and anomaly detection at the communications layer are essential security measures.

7. Conclusion

This study has demonstrated that digital twin technology offers a transformative capability advancement for structural health monitoring in civil engineering. The integrated DT framework — combining multi-sensor data acquisition, physics-based finite element modelling, real-time Bayesian updating, and machine learning analytics — substantially outperformed conventional SHM approaches across all evaluated performance dimensions.

Key findings include: a monitoring accuracy of 97.3% achieved with a multi-sensor DT array; a 91% reduction in data processing latency; a 78% reduction in false alarm rates; a 34% reduction in maintenance costs; and a 46.9% improvement in the structural reliability index. These outcomes affirm the scientific and practical value of digital twin integration for infrastructure management.

Remaining challenges — including data management scalability, model fidelity in aged and heterogeneous structures, computational efficiency, cybersecurity, and standardization — define an active research agenda. As sensor technologies, edge computing, and machine learning continue to mature, digital twins will increasingly become the operational standard for structural asset management. Future research should prioritize scalable reduced-order model development, multi-hazard DT frameworks, and interoperability standards enabling cross-platform DT ecosystems for entire infrastructure networks.

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