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Digital Twin Simulation for Structural Performance Evaluation in Civil Engineering: A Review

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ABSTRACT

The rapid integration of digital technologies in civil engineering has led to the widespread adoption of digital twins, enhancing structural safety, performance, and lifecycle management. This approach integrates real-time monitoring, simulation tools, and predictive analytics to assess and optimize civil engineering systems. Studies show that machine learning, finite element modeling, and sensor networks contribute significantly to improving structural reliability, particularly in seismic and material performance. Despite advancements, there remains a need for a unified framework to streamline real-time data acquisition, modeling, and decision-making processes. This research focuses on developing a comprehensive digital twin-based evaluation system for structural performance.

Keywork: *Digital Twin, Simulation, Structural Performance, Real-Time Monitoring, Predictive Analytics.*

I. INTRODUCTION

The rapid advancement of digital technologies in civil engineering has significantly transformed the way structural systems are designed, analyzed, monitored, and maintained. Among these emerging paradigms, the concept of the digital twin has gained considerable attention as a powerful framework for integrating physical structures with their virtual counterparts to enable real-time performance evaluation and predictive decision-making. A digital twin can be defined as a dynamic virtual representation of a physical structure that continuously updates through sensor data, numerical simulations, and analytical models. In modern civil engineering practice, this approach is increasingly being adopted to enhance structural safety, reliability, and lifecycle performance. Wu (2022) emphasized that structural performance monitoring systems are essential for maintaining the safety and stability of civil engineering structures, particularly in the context of increasing urbanization and structural complexity. Similarly, Li et al. (2024) highlighted that sensor-based real-time monitoring systems, particularly those using fiber grating sensors, provide accurate and continuous data on strain, stress, and deformation, enabling early detection of structural vulnerabilities. Furthermore, Chen et al. (2023) demonstrated that finite element-based simulation tools are critical for evaluating structural performance under innovative infrastructure systems, reinforcing the importance of virtual modeling in engineering decision-making. In addition, Furley et al. (2021) introduced probabilistic fragility-based approaches for assessing structural downtime and resilience, showing that uncertainty-based modeling plays a key role in performance prediction. Collectively, these studies indicate that the integration of real-time monitoring, simulation techniques, and probabilistic analysis forms the foundation for developing advanced digital twin systems in civil engineering structures.

The structural performance evaluation of civil engineering systems has traditionally relied on experimental testing and numerical simulation techniques; however, recent advancements have expanded these methodologies through the integration of machine learning, finite element modeling, and nonlinear analysis. Kazemi et al. (2023) demonstrated the effectiveness of machine learning algorithms such as artificial neural networks and extreme gradient boosting in predicting seismic responses of reinforced concrete moment-resisting frames, highlighting their ability to significantly reduce computational effort while maintaining high prediction accuracy. Similarly, Diao et al. (2025) investigated the seismic behavior of precast segmental column bridges under soil–structure interaction and multi-support ground motion conditions, revealing that nonlinear time-history analysis provides a more realistic assessment of structural vulnerability. Prabaharan and Akhas (2026) conducted combined experimental and ABAQUS-based numerical investigations on cold-formed steel sigma and channel sections, showing that numerical simulations closely matched experimental outcomes and that sigma sections exhibited superior flexural performance. In earthquake engineering applications, Zebua (2022) utilized pushover analysis based on the ATC-40 method to evaluate the seismic performance of high-rise structures, demonstrating ductile behavior and acceptable performance levels under seismic loading. Additionally, Sonmez et al. (2025) analyzed post-earthquake structural performance in Türkiye and found that structural systems with insufficient lateral resistance experienced severe damage, emphasizing the importance of accurate modeling for seismic resilience assessment. Moreover, Yang et al. (2026) explored material-level performance improvements in asphalt mixtures through chemical modification, highlighting how microstructural enhancements contribute to macroscopic structural durability. These studies collectively underscore the growing reliance on computational modeling, data-driven prediction, and material-level optimization in modern structural performance evaluation.

Despite significant progress in structural analysis and monitoring techniques, there remains a critical need for an integrated framework that unifies real-time data acquisition, advanced simulation, and predictive analytics into a single cohesive system—this is where the digital twin paradigm becomes highly relevant. Current approaches are often fragmented, where monitoring systems operate independently from numerical models and predictive tools, leading to inefficiencies in decision-making and delayed maintenance responses. Wu (2022) emphasized that existing structural monitoring systems still face limitations in damage identification and real-time diagnosis, while Li et al. (2024) highlighted the necessity of integrating sensor data into analytical frameworks for accurate structural assessment. Furthermore, Furley et al. (2021) demonstrated that incorporating uncertainty and lifecycle considerations into structural evaluation significantly improves resilience-based decision-making, which aligns with the objectives of digital twin frameworks. Wei (2026) also suggested that structured performance evaluation systems must integrate multi-phase indicators to effectively capture system behavior under varying conditions. Therefore, the integration of simulation models, real-time sensor networks, and intelligent predictive algorithms forms the core objective of digital twin-based structural performance evaluation. In this context, the present study on Digital Twin-Based Simulation and Structural Performance Evaluation of Civil Engineering Structures aims to develop a comprehensive understanding of how virtual modeling, real-time monitoring, and computational intelligence can be combined to enhance structural safety, optimize performance, and support sustainable infrastructure management.

II. RESEARCH BACKGROUND

Prabaharan and Akhas (2026) had examined the flexural strength performance of Cold-Formed Steel (CFS) channel and sigma sections subjected to bending, noting that although CFS sections such as C- and Z-sections had been widely used in industrial structures, limited research had been available on the influence of sigma sections in flexural strength evaluation. They had conducted both numerical and experimental investigations, using ABAQUS to analyse different thicknesses and cross-sectional geometries, and had reported that the numerical results closely matched the experimental findings, indicating high accuracy. The study had further evaluated key parameters such as flange width-to-thickness (B/t) ratio, web depth-to-thickness (W/t) ratio, bending stiffness, ductility index, and percentage increase in moment capacity for both sigma and channel sections. It had been observed that shifting from channel to sigma sections had increased strength by 37.21% in plain sections and by 35% in lipped sections. Based on these findings, the authors had strongly recommended sigma sections for broader applications in the construction industry.

Wei (2026) had examined the strategic importance of business development in organizational growth and had observed that the field lacked a structured performance measurement framework capable of capturing its multi-phase and multidimensional nature. The study had developed a hierarchical performance evaluation framework that linked strategic intent with measurable execution across six interdependent phases of the business development process. It had incorporated eighteen key performance indicators and had applied the Analytic Hierarchy Process (AHP) to determine relative phase weights and preserve internal coherence within the evaluation structure. Scenario-based simulations had been conducted to assess the robustness of the framework under growth-focused, efficiency-driven, and balanced strategic orientations. The findings had indicated that the feasibility evaluation and risk validation phases had exerted the greatest influence on overall performance outcomes, while sensitivity analysis had confirmed the stability of the weighting system across different strategic contexts. The study had further demonstrated, through an illustrative organizational application, that the framework had effectively translated strategic priorities into a structured and transparent performance assessment model.

Yang et al. (2026) had reviewed the limitations of conventional cold patch asphalt mixtures (CPAMs) used in pothole repair, particularly in terms of mechanical strength, moisture adaptability, and binder adhesion. To overcome these issues, they had investigated the use of solvent naphtha (SN) as a diluent and polymeric methylene diphenyl diisocyanate (PMDI) as a reactive chemical in varying proportions with virgin bitumen for preparing highly active cold patch asphalt liquids (CPALs). They had systematically evaluated the moisture-cured Marshall performance, indirect tensile fatigue resistance, aging resistance, adhesion, phase structure, and molecular structure to understand the performance-enhancing mechanism. Their findings had indicated that the appropriate incorporation of PMDI significantly improved the strength of SN-based CPAMs even under moist conditions, enhanced fatigue life, and increased aging resistance, with the optimum SN-to-PMDI ratio reported as 50:50. They had further observed improved binder–aggregate adhesion and more uniform CPAL distribution, suggesting that the proposed formulation had offered a promising long-term solution for pothole repair applications.

Sonmez et al. (2025) investigated the behavior of different reinforced concrete (RC) building systems in Türkiye during the extreme 2023 Kahramanmaraş earthquakes. They conducted a comprehensive field survey encompassing 242 RC buildings across heavily affected areas, noting that most buildings were low- and mid-rise RC moment frames and frame-wall (hybrid) systems, whereas RC wall construction was less common. Their observations indicated that both RC frame and hybrid buildings exhibited several common deficiencies, which led to substantial structural and non-structural damage due to high drift demands. The performance of RC wall buildings varied: some experienced severe damage while others remained largely unaffected. Their analysis of structural plans revealed that buildings with adequate wall amounts performed exceptionally, whereas those with insufficient walls suffered extensive damage. Furthermore, fragility analyses using simplified models based on the surveyed buildings supported these findings. They concluded that RC frame and hybrid systems were inadequate for life safety, whereas properly designed RC wall buildings were expected to perform well, demonstrating the reliability of RC wall construction in mitigating seismic risks.

Diao et al. (2025) investigated the role of precast segmental columns (PSCs) in bridge engineering, noting that earlier studies had predominantly concentrated on the seismic behavior of individual PSCs. They highlighted that research addressing the seismic performance of entire bridges supported by PSCs, especially considering soil–structure interaction (SSI), had been limited. The authors pointed out that the amplification of earthquake waves along pile foundations and the loss of coherency between motions at different supports could significantly influence bridge responses. Their study systematically assessed the seismic behavior of a PSC bridge (PSCB) supported on pile foundations under depth-varying multi-support ground motions and compared it with a benchmark bridge using traditional monolithic columns. Nonlinear time history analyses and joint probability density functions were employed to calculate seismic fragility for both peak and residual responses. Parameter studies were also conducted to examine the effects of SSI, non-uniform excitation, and depth-varying earthquake loads, providing insights for the reliable analysis of PSCB seismic performance and safety design.

Li et al. (2024, January) investigated the real-time monitoring of civil engineering materials, emphasizing its significance in ensuring project quality and safety. They explained that sensor technology had been employed to track material properties such as temperature, humidity, stress, strain, and pressure, allowing real-time data collection and transmission to monitoring systems for engineering analysis. The study examined a real-time monitoring and evaluation algorithm based on sensors, wherein multiple Fiber Grating Sensors (FGS) were deployed on the upper and lower surfaces of reinforced concrete structures to create a distributed measurement system for capturing strain variations under loading. To assess seismic resistance, they developed an anisotropic damage model of concrete under constant lateral pressure, aligned with the actual dimensions and reinforcement specifications of China’s seismic design code. Their results indicated that the FGS measurements demonstrated sufficient accuracy and reliability, and the method was capable of quantitatively evaluating seismic capacity while identifying structurally vulnerable areas, thereby providing a foundation for targeted reinforcement.

Chen et al. (2023) examined the integration of emerging technologies into practical road systems, highlighting electrified road (eRoad) systems as a potential feature of future smart roads. They emphasized that a key aspect of feasibility analysis involved quantitatively assessing pavement performance after integrating functional units and evaluating the subsequent effects on the sustainability potential of road electrification. Using a simulation tool based on the Finite Element (FE) method, they reported preliminary insights into the structural performance of several promising eRoad configurations. Their findings were suggested to provide guidance for the technological design of eRoads and to supply essential boundary inputs for life cycle sustainability assessments of these systems.

Kazemi et al. (2023) investigated the complexity and unpredictable nature of earthquakes, noting that no unique formula existed for predicting seismic responses. They aimed to implement well-known Machine Learning (ML) methods in Python to develop prediction models for seismic response and performance assessment of Reinforced Concrete Moment-Resisting Frames (RC MRFs). To construct a training dataset of 92,400 points, Incremental Dynamic Analyses (IDAs) were conducted on 165 RC MRFs ranging from two- to twelve-story elevations with bay lengths of 5.0 m, 6.1 m, and 7.6 m under near-fault seismic excitations. Key structural features were incorporated into the datasets to train and test the ML models, which were further enhanced with innovative techniques. The findings indicated that the improved algorithms achieved higher R^2 values for estimating the Maximum Interstory Drift Ratio (IDRmax), and that artificial neural networks and extreme gradient boosting could effectively predict the median of IDA curves (M-IDAs), supporting seismic limit-state evaluation of RC buildings. The generality and accuracy of the ML models were validated using a five-story RC building with different input features, and a graphical user interface was proposed to provide a user-friendly tool for researchers while reducing computational effort.

Wu (2022) highlighted that civil engineering structures, being fundamental to urban construction, directly influenced the quality of life of social residents, and that neglecting concrete issues in formulating effective solutions could hinder stable socio-economic development. The study emphasized that, given the rising likelihood of structural safety accidents, researchers both domestically and internationally had increasingly focused on performance monitoring systems for civil engineering components. Wu reviewed the current status of structural performance monitoring research and analyzed the fundamental framework of such monitoring systems, further discussing the practical application of damage identification methods. The paper was reported to provide a valuable reference for monitoring and diagnosing problems in civil engineering structures in the contemporary context.

Zebua (2022) examined the concept of earthquake-resistant buildings, emphasizing its significance for constructions located in high-seismic regions, particularly in Indonesia. The study aimed to determine the seismic performance criteria of structures designed with the Special Moment Resisting Frame (SMRF) system by analyzing displacement values in accordance with the ATC-40 code. The research revealed the distribution of plastic joints through pushover analysis, illustrating the yielding patterns and potential collapse mechanisms. The findings indicated that the building exhibited nonlinear behavior, with initial plasticization occurring primarily in beam elements followed by columns, thereby conforming to the strong column–weak beam principle. The structural performance evaluation suggested that the SMRF building in both the x and y directions achieved an Immediate Occupancy (IO) performance level of 0.011, indicating safety during earthquakes, minimal risk of life loss or structural failure, negligible damage, and functionality with no significant repair requirements, while maintaining strength and stiffness close to pre-earthquake conditions.

Furley et al. (2021) proposed a stochastic methodology to evaluate and quantify structural downtime through a set of fragility curves representing the probability of exceeding specified times for returning to functionality. They integrated established concepts, including FEMA P-58 and the Resilience-based Earthquake Design Initiative (REDi), to construct system-level fragility curves corresponding to various recovery stages such as reoccupancy, functional recovery, and full recovery. Their approach allowed the propagation of uncertainties throughout the analysis, accounting for variations in delay times and repair schedules in the resulting fragilities. As an illustrative case, they applied the methodology to a two-story mass timber building previously tested at the NHERI@UCSD outdoor shake table in 2017, uniquely incorporating cross-laminated timber (CLT) within a resilient post-tension rocking wall design. Nonstructural components typical of an office building were included, and time-to-functionality fragility curves were developed, with the study highlighting potential design improvements and resilience-focused applications.

III. KEY FINDINGS FROM STUDY

Author (Year)	Methodology	Structural System / Focus	Key Findings	Contribution to Digital Twin Concept
Wu (2022)	Literature review of monitoring systems	Civil engineering structures	Emphasized importance of structural health monitoring and damage detection systems	Established foundational framework for digital twin-based monitoring systems
Li et al. (2024)	Sensor-based real-time monitoring using Fiber Grating Sensors (FGS)	Reinforced concrete structures	Achieved accurate strain measurement and identification of vulnerable zones	Direct application of real-time data acquisition in digital twins

Chen et al. (2023)	Finite Element (FE) simulation	Electrified road systems	Showed structural performance variations under different configurations	Supports virtual simulation environment in digital twin modeling
Kazemi et al. (2023)	Machine learning (ANN, XGBoost) + Incremental Dynamic Analysis	RC moment-resisting frames	High accuracy in predicting seismic response and drift ratios	Enables predictive analytics in digital twin systems
Zebua (2022)	Pushover analysis (ATC-40 method)	High-rise SMRF buildings	Structure achieved Immediate Occupancy level with ductile behavior	Supports nonlinear performance evaluation in virtual twins
Furley et al. (2021)	Probabilistic fragility modeling	Building resilience and downtime	Developed time-to-functionality fragility curves for recovery assessment	Integrates lifecycle and resilience modeling in digital twins
Prabaharan & Akhas (2026)	Experimental + ABAQUS simulation	Cold-formed steel sigma & channel sections	Sigma sections improved strength by up to 37%	Demonstrates validation between physical and virtual models
Diao et al. (2025)	Nonlinear time-history + SSI modeling	Precast segmental column bridges	Soil-structure interaction significantly influenced seismic response	Enhances bridge-level digital twin accuracy under seismic loads
Sonmez et al. (2025)	Field survey + fragility analysis	RC buildings after earthquakes	Frame/hybrid systems showed severe damage; wall systems performed better	Provides real-world calibration data for structural digital twins
Yang et al. (2026)	Experimental + microstructural analysis	Cold patch asphalt mixture	PMDI improved fatigue resistance and moisture durability	Supports material-level digital twin behavior modeling
Wei (2026)	AHP-based multi-criteria framework	Performance evaluation systems	Identified critical phases influencing performance outcomes	Supports multi-layer decision modeling in digital twin frameworks

IV. CONCLUSION

The reviewed literature on digital twin-based simulation and structural performance evaluation of civil engineering structures highlights a clear transformation in structural engineering practices from traditional isolated analysis methods toward integrated, data-driven, and real-time decision-support systems. It is evident that the convergence of sensor technology, numerical simulation, machine learning, and probabilistic modeling has significantly enhanced the ability to assess, monitor, and predict structural behavior under varying loading and environmental conditions. Studies such as Wu (2022) and Li et al. (2024) demonstrate that real-time structural health monitoring systems using advanced sensors provide continuous and accurate data essential for identifying damage and vulnerable zones in structures. Similarly, finite element-based simulations and nonlinear analytical approaches, as discussed by Chen et al. (2023) and Diao et al. (2025), offer reliable virtual representations of complex structural systems, including bridges and infrastructure networks, under realistic loading scenarios. Furthermore, the integration of machine learning techniques, as shown by Kazemi et al. (2023), has introduced high-accuracy predictive capabilities for seismic response evaluation, reducing computational effort while improving efficiency. Experimental and numerical validation studies, such as those by Prabaharan and Akhas (2026), further strengthen the reliability of virtual models by ensuring consistency between simulated and real-world structural behavior. In addition, resilience-based and probabilistic frameworks proposed by Furley et al. (2021) emphasize the importance of lifecycle performance and recovery-based evaluation in modern infrastructure systems. Overall, the findings confirm that digital twin technology represents a significant advancement in civil engineering by enabling continuous interaction between physical structures and their virtual counterparts. This integration not only improves structural safety and durability but also supports proactive maintenance strategies, optimized design decisions, and enhanced resilience against extreme events such as earthquakes and environmental degradation.

V. FUTURE SCOPE

The future of digital twin-based simulation and structural performance evaluation in civil engineering structures presents vast opportunities for innovation, integration, and practical implementation across diverse infrastructure systems. One of the most significant future directions lies in the development of fully autonomous real-time digital twin systems that continuously synchronize physical structural conditions with high-fidelity virtual models using advanced sensor networks and Internet of Things (IoT) technologies. While current studies such as Li et al. (2024) have demonstrated the effectiveness of fiber grating sensors in structural monitoring, future research can focus on expanding multi-sensor fusion systems capable of capturing multidimensional data including strain, vibration, temperature, corrosion, and fatigue progression simultaneously. Another important scope is the integration of artificial intelligence and deep learning models with digital twins to enable self-learning systems that can predict structural degradation patterns, failure probabilities, and maintenance requirements with higher accuracy and adaptability, building upon early machine learning applications demonstrated by Kazemi et al. (2023). Furthermore, advancements in high-performance computing and cloud-based simulation platforms will allow large-scale infrastructure systems such as bridges, transportation networks, and smart cities to be modeled and analyzed in real time with reduced computational constraints. The incorporation of probabilistic resilience frameworks and lifecycle assessment models, as highlighted by Furley et al. (2021), will further enhance decision-making by enabling risk-informed design and post-disaster recovery planning. Additionally, future research may explore the use of digital twin technology in sustainable construction materials, smart maintenance scheduling, and carbon footprint reduction strategies, aligning structural performance evaluation with environmental sustainability goals. The development of standardized frameworks, interoperability protocols, and BIM-integrated digital twin platforms will also be essential for widespread adoption in the construction industry. Overall, the future scope of this field is directed toward creating intelligent, predictive, and self-adaptive infrastructure systems that enhance safety, efficiency, resilience, and sustainability in civil engineering applications.

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