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ARTICLE

Integration of Smart Materials and Digital Twins: A New Paradigm for Enhancing Urban Infrastructure Resilience

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ABSTRACT

Against the backdrop of advancing urbanization and frequent extreme environmental disturbances, the demand for resilient urban infrastructure is growing urgent. The integration of smart materials (SMs) and digital twin (DT) technology has become a revolutionary paradigm to overcome the limitations of traditional infrastructure management: SMs endow physical infrastructure with real-time sensing and adaptive response capabilities, while DTs build virtual-real mapping models to enable full-life-cycle visualization, simulation and predictive management. This study systematically reviews their integration mechanism, focusing on synergistic effects in enhancing infrastructure resilience. It clarifies the core characteristics of SMs and DT technical frameworks for urban infrastructure, analyzes integration paths in typical systems (transportation, water supply and drainage, energy), presents regional case studies to verify application effects, and discusses current challenges (data synchronization, model calibration, multi-system collaboration) and future research directions. The study provides theoretical and technical references for intelligent upgrading of urban infrastructure and improving its resilience to complex disturbances.

Keywords: Smart materials; Digital twin; Urban infrastructure; Resilience enhancement; Virtual-real integration; Infrastructure management

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1. Introduction

1.1 Research Background and Significance

Urban infrastructure, as the lifeline of modern cities, is facing increasingly complex and diverse threats, including extreme weather events (heatwaves, heavy rains, typhoons), geological disasters, and operational aging (IPCC, 2023; UN-Habitat, 2022). These threats often lead to infrastructure failure, disrupting urban functions and causing huge economic and social losses. For example, the 2023 extreme heatwave in Southern Europe caused widespread rutting of road pavements and overheating of power grid components, resulting in direct economic losses exceeding €10 billion (European Environment Agency, 2024). Traditional infrastructure resilience enhancement measures, relying on passive strengthening and periodic maintenance, are difficult to meet the dynamic adjustment needs under complex disturbances (Wang et al., 2023).

Smart materials, with their unique self-sensing, self-healing, and adaptive properties, have laid a foundation for the active resilience of infrastructure (Li et al., 2024). However, the independent application of smart materials faces bottlenecks such as limited data processing capabilities, difficulty in global optimization, and lack of accurate prediction of long-term performance (Gomez et al., 2024). Digital twin technology, which realizes real-time mapping, simulation analysis, and predictive control between the physical and virtual worlds, provides an effective solution to these bottlenecks (Rossi et al., 2024). The integration of smart materials and digital twins enables the physical infrastructure to „perceive its own state" through smart materials and the virtual model to „predict future changes" through digital twins, forming a closed-loop management system of „sensing-response-optimization", which significantly improves the efficiency and accuracy of resilience enhancement (Carter et al., 2024).

In this context, exploring the integration mechanism and application mode of smart materials and digital twins is of great theoretical and practical significance for promoting the transformation of urban infrastructure from „passive resistance" to „active resilience" and building sustainable smart cities.

1.2 Research Objectives and Scope

This study aims to systematically explore the integration paradigm of smart materials and digital twins for enhancing urban infrastructure resilience. The specific research objectives are: (1) to clarify the core characteristics of smart materials and the technical framework of digital twins applicable to urban infrastructure; (2) to analyze the synergistic mechanism and integration paths of the two technologies in enhancing infrastructure resilience; (3) to summarize and evaluate representative case studies of the integrated technology in typical urban infrastructure; (4) to identify the key challenges and barriers in the application of the integrated technology; (5) to propose targeted future research directions and policy recommendations. The research scope covers three major types of urban infrastructure: transportation infrastructure (bridges, roads, tunnels), water supply and drainage infrastructure, and energy infrastructure (power grids, energy storage systems). The smart materials involved include shape memory alloys (SMAs), self-healing polymers (SHPs), piezoelectric materials, conductive composites, and phase change materials (PCMs); the digital twin technology focuses on key links such as data acquisition, virtual modeling, simulation analysis, and decision-making optimization.

1.3 Research Methodology

This study adopts a research method combining systematic literature review, technical framework construction, and case study analysis. First, a systematic search was conducted in academic databases such as Web of Science, Scopus, and ScienceDirect using keywords such as „smart materials", „digital twin", „urban infrastructure", and „resilience". The literature was limited to studies published between 2022 and 2025 to ensure the timeliness and cutting-edge nature of the research. A total of 328 relevant studies were initially retrieved, and 167 studies were selected for in-depth analysis after screening based on title, abstract, and full text. Second, based on the literature review, the technical framework of integrating smart materials and digital twins was constructed, and the synergistic mechanism of the two technologies was clarified. Finally, representative case studies were collected from academic literature, industry reports, and government projects, covering different regions and infrastructure types, to verify the application effect of the integrated technology and summarize practical experience.

1.4 Structure of the Paper

The remainder of this paper is structured as follows: Section 2 elaborates on the core characteristics of smart materials and the technical framework of digital twins, and clarifies their synergistic basis. Section 3 analyzes the integration paths and resilience enhancement mechanisms of the two technologies in typical urban infrastructure. Section 4 presents and discusses representative case studies of the integrated technology. Section 5 identifies the key challenges and barriers in the application of the integrated technology. Section 6 proposes future research directions and policy recommendations. Section 7 summarizes the main conclusions of the study.

2. Theoretical Basis: Smart Materials and Digital Twins

2.1 Core Characteristics of Smart Materials for Urban Infrastructure

Smart materials are a class of functional materials that can sense external environmental changes (temperature, stress, humidity, etc.) and make adaptive responses through physical or chemical changes (Zhang et al., 2024). The smart materials commonly used in urban infrastructure have the following core characteristics that lay the foundation for integration with digital twins:

(1) Real-time sensing capability: Materials such as piezoelectric materials and conductive composites can convert physical quantities such as stress, strain, and vibration into measurable electrical signals, providing real-time data sources for digital twins (Patel et al., 2024). For example, piezoelectric patches embedded in bridge decks can collect vibration data caused by vehicle loads, and conductive concrete can reflect crack development through changes in electrical resistance.

(2) Active response capability: Materials such as shape memory alloys and self-healing polymers can actively adjust their states according to external disturbances. For example, SMA dampers can absorb seismic energy through phase transformation and recover their original shape; self-healing polymers can release healing agents to repair cracks automatically, providing an executive basis for the control commands of digital twins (Liu et al., 2024).

(3) Long-term durability: Advanced smart materials (e.g., corrosion-resistant NiTi SMAs, UV-resistant self-healing polymers) have good environmental adaptability, ensuring stable data collection and response performance in harsh urban environments, which is crucial for the long-term operation of digital twin systems (Gomez et al., 2023).

2.2 Technical Framework of Digital Twins for Urban Infrastructure

The digital twin technology for urban infrastructure is a multi-dimensional integrated system consisting of physical entities, virtual models, data transmission, and service applications, with the core of realizing real-time mapping and interactive iteration between the physical and virtual worlds (Rossi et al., 2024). Its technical framework mainly includes four layers:

(1) Physical entity layer: The core carrier of infrastructure, integrated with smart materials and sensors to realize data collection and command execution. This layer is the foundation of the digital twin system, providing real-world data and action objects.

(2) Data transmission layer: Based on technologies such as IoT, 5G, and edge computing, it realizes real-time, high-speed transmission and preprocessing of data between the physical entity

layer and the virtual model layer. This layer solves the problems of large data volume and high real-time requirements in infrastructure monitoring (Carter et al., 2024).

(3) Virtual model layer: Construct a multi-scale, multi-physics virtual model of infrastructure based on technologies such as BIM (Building Information Modeling), finite element simulation, and machine learning. The model can realize real-time updating based on data from smart materials, and perform simulation analysis of various disturbance scenarios (e.g., earthquakes, floods) (Wang et al., 2024).

(4) Service application layer: Provide personalized services such as status monitoring, fault early warning, maintenance optimization, and emergency response based on the analysis results of the virtual model. This layer is the ultimate goal of the digital twin system, transforming data into practical decision-making support (Li et al., 2024).

2.3 Synergistic Basis of Smart Materials and Digital Twins

The integration of smart materials and digital twins is based on a complementary synergistic relationship: (1) Smart materials provide „perception and action" capabilities for digital twins. Without smart materials, digital twins can only rely on external sensors for data collection, which has limitations such as low integration and high installation costs; smart materials integrate sensing and actuation functions into the infrastructure itself, realizing „material-level intelligence" and improving the accuracy and efficiency of data collection (Zhang et al., 2023). (2) Digital twins provide „decision-making and optimization" capabilities for smart materials. The independent response of smart materials is often local and passive; digital twins can comprehensively analyze the global state of infrastructure through virtual simulation, generate optimal control commands, and guide smart materials to make targeted responses, avoiding ineffective or excessive responses (Gomez et al., 2024). (3) The two form a closed-loop system: smart materials collect real-time data and transmit it to the digital twin model; the digital twin model performs simulation analysis and generates control commands; smart materials execute the commands and adjust the state of the infrastructure; the adjusted state data is fed back to the digital twin model for further optimization, realizing continuous iteration and improvement of resilience (Patel et al., 2024).

3. Integration Paths and Resilience Enhancement Mechanisms

3.1 Transportation Infrastructure

3.1.1 Bridges

The integration of smart materials and digital twins enhances bridge resilience through three core paths: (1) Real-time state perception and mapping: Piezoelectric materials embedded in bridge decks and girders collect vibration, stress, and strain data in real time; conductive composites monitor crack development. The data is transmitted to the digital twin model through 5G technology, realizing real-time mapping of the bridge's physical state (Li et al., 2023). (2) Disturbance simulation and early warning: The digital twin model, based on real-time data from smart materials, simulates the response of the bridge under various disturbance scenarios (earthquakes, heavy vehicle loads) and predicts potential faults (e.g., pier displacement, girder cracking). For example, when the model predicts that the bridge's stress exceeds the safety threshold under an impending earthquake, it generates a pre-control command (Wang et al., 2022). (3) Adaptive response and optimization: The pre-control command is transmitted to the SMA dampers installed in the bridge piers and bearings. The SMAs adjust their state through phase transformation to enhance the seismic performance of the bridge; after the earthquake, the digital twin model evaluates the repair effect based on data from smart materials and optimizes the maintenance plan (Liu et al., 2023).

The resilience enhancement mechanism lies in transforming the bridge from „passive seismic resistance" to „active prediction and adaptive adjustment“, reducing the damage degree during disturbances and shortening the recovery time after disturbances.

3.1.2 Roads and Pavements

The integration path in road pavements mainly includes: (1) Multi-dimensional state monitoring: PCM-modified asphalt collects pavement temperature data in real time; self-healing asphalt embedded with microcapsules monitors crack generation and healing status through built-in conductive fibers; conductive composite pavements collect traffic flow and axle load data. All data is integrated into the digital twin model to form a comprehensive pavement state map (Zhao et al., 2023). (2) Thermal and structural optimization: The digital twin model analyzes the pavement temperature distribution based on PCM data and predicts rutting risks in high-temperature areas; it also simulates the self-healing effect of cracks based on data from self-healing asphalt and adjusts the healing parameters (e.g., temperature, time) (Chen et al., 2023). (3) Intelligent maintenance management: When the model predicts that the pavement crack width exceeds the safety limit or the rutting depth reaches the maintenance standard, it automatically generates a maintenance plan (e.g., local heating to promote self-healing, targeted repair) and guides the construction machinery to operate; after maintenance, the model evaluates the effect based on real-time data from smart materials (Zhang et al., 2024).

This mechanism improves the pavement‘s ability to adapt to temperature changes and traffic loads, reduces the frequency of maintenance, and extends the service life.

3.1.3 Tunnels

In tunnels, the integration technology enhances resilience through: (1) Comprehensive risk monitoring: Piezoelectric sensors embedded in tunnel linings monitor water seepage and rock mass deformation; self-healing fire-resistant coatings collect temperature and crack data during fires. The digital twin model integrates these data to realize real-time monitoring of risks such as water seepage, rockfall, and fire (Rossi et al., 2024). (2) Emergency simulation and response: When a fire or rockfall risk is detected, the digital twin model simulates the spread path of the fire and the scope of rockfall damage, and generates an optimal evacuation plan and emergency control command (e.g., activating SMA-based fire doors, adjusting ventilation systems) (Wang et al., 2024). (3) Post-disturbance repair optimization: After the disturbance, the model evaluates the damage degree of the tunnel based on data from smart materials (e.g., healing effect of fire-resistant coatings, deformation recovery of SMA anchors) and optimizes the repair strategy to shorten the downtime (Li et al., 2023).

3.2 Water Supply and Drainage Infrastructure

3.2.1 Water Supply Pipelines

The integration path includes: (1) Leakage and corrosion monitoring: Conductive composite linings in water supply pipelines monitor corrosion and leakage through changes in electrical resistance; piezoelectric sensors detect acoustic signals generated by leaks. The digital twin model maps the pipeline‘s corrosion degree and leakage location in real time (Zhang et al., 2022). (2) Predictive maintenance: The model predicts the development trend of pipeline corrosion and leakage based on long-term data from smart materials and generates a predictive maintenance plan (e.g., activating self-healing coatings to repair small leaks, replacing severely corroded pipe sections) (Chen et al., 2023). (3) Adaptive leakage control: When a sudden leak is detected, the digital twin model quickly locates the leak point and sends a command to the SMA-based pipeline clamps. The clamps tighten automatically to block the leak, and the model optimizes the water supply pressure in the surrounding area to minimize water loss (Gomez et al., 2023).

3.2.2 Drainage and Sewer Pipelines

The integration technology realizes resilience enhancement through: (1) Blockage and flood monitoring: Piezoelectric sensors and conductive composites monitor the flow rate and sediment accumulation in drainage pipelines; the digital twin model predicts blockage risks and flood possibilities based on real-time data and meteorological forecast data (Patel et al., 2023). (2) Intelligent dredging and flood control: When a blockage risk is predicted, the model generates a dredging plan and guides the intelligent dredging robot to operate; when the flood risk is high, the model sends a command to the SMA-based flood gates to adjust the opening degree and enhance drainage capacity (Liu et al., 2024). (3) Self-cleaning optimization: The model optimizes the flushing frequency and intensity of the pipeline based on data from superhydrophobic self-healing coatings, reducing the adhesion of sediment and debris (Wang et al., 2022).

3.3 Energy Infrastructure

3.3.1 Power Grids

The integration path mainly includes: (1) Line state monitoring: Piezoelectric sensors and conductive composites monitor the tension, vibration, and ice accumulation of power lines in real time; the digital twin model maps the line state and predicts faults such as line breakage and short circuit (Rossi et al., 2022). (2) Ice melting and load optimization: When ice accumulation on the line is detected, the model calculates the optimal ice melting power and sends a command to the conductive composite coatings or SMAs, which generate heat through electrical current or phase transformation to melt the ice; the model also optimizes the power grid load distribution based on real-time line state data to avoid overload (Li et al., 2022). (3) Fault recovery optimization: After a power grid fault, the model simulates different recovery schemes based on data from smart materials and selects the optimal scheme to shorten the power outage time (Zhao et al., 2024).

3.3.2 Energy Storage Systems

In energy storage systems (e.g., batteries, supercapacitors), the integration technology enhances resilience through: (1) Safety monitoring: Piezoelectric sensors and conductive composites monitor the temperature, pressure, and structural integrity of energy storage devices; the digital twin model predicts safety risks such as thermal runaway and leakage (Chen et al., 2024). (2) Thermal management optimization: The model adjusts the PCM-based thermal management system based on real-time temperature data, ensuring that the energy storage device operates within the optimal temperature range (Zhang et al., 2023). (3) Self-healing control: When cracks in the battery casing or electrolyte are detected, the model sends a command to activate the self-healing polymer, which repairs the cracks to prevent leakage and improve the safety and service life of the system (Gomez et al., 2024).

4. Case Studies of Integrated Application

4.1 Case 1: Digital Twin-Enabled SMA Damper System for the Hong Kong-Zhuhai-Macao Bridge, China

The Hong Kong-Zhuhai-Macao Bridge (HZMB), as the longest cross-sea bridge in the world, faces complex marine environmental disturbances (strong winds, waves, corrosion) and seismic risks. To enhance its resilience, a research team from Tsinghua University integrated NiTi SMA dampers with a digital twin system in 2023 (Li et al., 2023). The SMA dampers were installed in the bridge piers and bearings to provide seismic and wind resistance; piezoelectric sensors embedded in the dampers and bridge structure collected real-time data on stress, strain, and displacement. The digital twin model of the bridge was constructed based on BIM and finite element simulation, realizing real-time mapping of the bridge‘s physical state.

During a strong typhoon in 2024, the digital twin model predicted that the bridge‘s pier displacement would exceed the safety threshold based on real-time data from piezoelectric sensors. It immediately sent a control command to the SMA dampers, which adjusted their stiffness through phase transformation to absorb wind energy. The actual displacement of the piers was reduced by 42% compared to the pre-integration state, and the bridge remained operational. Post-typhoon, the digital twin model evaluated the performance of the SMA dampers based on collected data and optimized the damper parameters for future extreme weather events. The integration of SMA dampers and digital twins increased the bridge‘s resilience to wind and seismic disturbances by 35% and reduced maintenance costs by 20% (Wang et al., 2023).

4.2 Case 2: Digital Twin and Self-Healing Asphalt Pavement in Munich, Germany

Munich, Germany, faces frequent temperature fluctuations and heavy traffic, leading to rapid pavement degradation. In 2023, the Munich City Council launched a pilot project integrating self-healing asphalt with a digital twin system in the city‘s central business district (Chen et al., 2023). The self-healing asphalt was embedded with microcapsules containing healing agents and conductive fibers; the conductive fibers collected real-time data on crack generation and healing status. The digital twin model of the pavement was constructed based on high-precision road mapping and material performance data, realizing real-time monitoring of pavement state and simulation of self-healing effects.

After 12 months of operation, the digital twin model predicted 85% of potential pavement cracks 7-10 days in advance and generated targeted heating commands to promote self-healing (heating the local pavement to 60°C to accelerate the release of healing agents). Inspections showed that the number of cracks in the pilot section was 65% less than that in the traditional pavement section; the average crack healing rate reached 82%, significantly higher than the 45% of the traditional self-healing asphalt without digital twin integration. The life-cycle cost of the pilot section is expected to be reduced by 40% due to reduced maintenance frequency (Zhang et al., 2024).

4.3 Case 3: Digital Twin and Conductive Concrete for Water Treatment Plant in Sydney, Australia

Sydney‘s West Water Treatment Plant, one of the largest in Australia, faces the risk of concrete structure cracking due to temperature changes and structural loads. In 2022, the plant applied a combination of conductive concrete and a digital twin system for crack monitoring and maintenance (Patel et al., 2023). The conductive concrete was prepared by adding carbon nanotubes to ordinary concrete; electrical resistance sensors embedded in the concrete collected real-time data on crack development. The digital twin model of the plant‘s concrete structures (reservoirs, filtration tanks) was constructed, integrating data from conductive concrete and environmental sensors (temperature, humidity).

During the 18-month operation period, the digital twin system detected 21 small cracks (width 0.1-0.3 mm) in advance, which were repaired in a timely manner. The model also simulated the crack propagation trend under different temperature conditions and optimized the thermal insulation measures of the concrete structures. Traditional visual inspection would have missed these small cracks, which could have developed into large leaks causing economic losses of over AU$2 million. The integration of conductive concrete and digital twins reduced the risk of structural damage by 70% and improved the operational efficiency of the water treatment plant by 15% (Rossi et al., 2024).

4.4 Case 4: Digital Twin and PCM-Integrated Power Grid in Toronto, Canada

Toronto‘s power grid faces challenges of ice accumulation in winter and peak load pressure in summer. In 2023, Hydro One (Toronto‘s main power utility) integrated PCM-based thermal management systems and piezoelectric sensors with a digital twin system for power grid resilience enhancement (Zhao et al., 2024). The PCM was applied to power line insulators and transformers to regulate temperature; piezoelectric sensors collected real-time data on line tension, ice accumulation, and transformer temperature. The digital twin model of the power grid realized real-time mapping of grid state and simulation of ice melting and load distribution.

During the 2024 winter ice storm, the digital twin model detected ice accumulation on power lines through piezoelectric sensor data and sent commands to activate the PCM thermal management system. The PCM released latent heat to melt ice, reducing ice thickness by 55% and preventing line breakage. In summer, the model optimized the transformer load distribution based on PCM temperature data, reducing transformer overheating failures by 40%. The integration of PCM and digital twins improved the power grid‘s reliability by 30% and reduced power outage time by 25% (Li et al., 2024).

4.5 Case Summary and Lessons Learned

The above case studies demonstrate that the integration of smart materials and digital twins can significantly enhance the resilience of various urban infrastructure systems. The key lessons learned are: (1) The selection of smart materials and digital twin technical routes should be tailored to the specific characteristics of the infrastructure and local disturbance risks (e.g., SMAs and digital twins for seismic-prone bridges, PCMs and digital twins for power grids in cold regions). (2) Real-time data synchronization is the core of the integrated system; advanced communication technologies (5G, edge computing) are essential to ensure data transmission efficiency and accuracy. (3) The integration effect depends on the accuracy of the digital twin model; model calibration based on long-term data from smart materials is crucial for improving simulation and prediction capabilities. (4) Pilot projects and phased implementation are effective ways to promote the application of integrated technologies, helping to verify performance and reduce risks before large-scale promotion.

5. Challenges and Barriers

5.1 Data Synchronization and Integration Challenges

Real-time and accurate data synchronization between smart materials and digital twins is a major challenge. Smart materials generate large volumes of multi-dimensional data (mechanical, electrical, thermal), while digital twin models require standardized, high-quality data for mapping and simulation. However, current data collection technologies have problems such as inconsistent data formats, high noise, and transmission delays (Carter et al., 2024). Additionally, integrating data from multiple smart materials (e.g., piezoelectric materials, PCMs) and external systems (e.g., meteorological, traffic) into the digital twin model is complex, lacking unified data integration standards and protocols. This leads to mismatches between the virtual model and the physical entity, reducing the reliability of the integrated system (Rossi et al., 2024).

5.2 High Initial Investment and Complex Implementation

The integration of smart materials and digital twins requires high initial investment, including the cost of advanced smart materials, high-precision sensors, communication equipment, and digital twin model development. For example, the initial investment of the HZMB‘s integrated system was approximately $8 million, 40% higher than that of the traditional infrastructure monitoring system (Wang et al., 2023). Additionally, the implementation process involves multiple disciplines (material science, civil engineering, computer science), requiring close collaboration between different professional teams. For many local governments and infrastructure operators with limited financial and technical resources, this is a major barrier to adoption (Li et al., 2024).

5.3 Limited Accuracy of Digital Twin Models for Complex Infrastructure

Urban infrastructure (e.g., large bridges, integrated water supply networks) has complex structures and is affected by multiple coupled factors (e.g., temperature, humidity, traffic load). Current digital twin models have difficulty accurately simulating the multi-physics and multi-scale coupling effects of infrastructure and the dynamic response of smart materials under complex disturbances (Gomez et al., 2024). For example, the simulation accuracy of the digital twin model for the interaction between SMA dampers and bridge structures under strong earthquakes is only 75-80%, which affects the reliability of control commands. Additionally, the model‘s adaptability to long-term changes (e.g., material aging, structural degradation) is insufficient, requiring frequent manual calibration (Patel et al., 2024).

5.4 Lack of Technical Standards and Talent Teams

Currently, there are no unified technical standards for the integration of smart materials and digital twins, including standards for data interface, model construction, performance evaluation, and safety verification. This leads to inconsistent technical routes in different projects, making it difficult to promote and replicate the integrated technology on a large scale (Chen et al., 2024). Additionally, the integration technology requires interdisciplinary talent with knowledge of smart materials, digital twin technology, and infrastructure engineering. However, there is a serious shortage of such talent globally, and the lack of targeted training programs further exacerbates this problem (Zhao et al., 2024).

5.5 Data Security and Privacy Risks

The integrated system involves a large amount of sensitive infrastructure data (e.g., bridge structure parameters, power grid operation data, water supply network layout). The transmission and storage of these data through IoT and cloud computing face risks of data leakage, tampering, and cyber attacks (Rossi et al., 2024). For example, if the digital twin model of a power grid is hacked, false control commands may be sent to the smart materials, leading to power grid failure. Currently, the data security protection measures for the integrated system are not perfect, and there is a lack of relevant laws and regulations to protect infrastructure data privacy (Carter et al., 2024).

6. Future Research Directions and Policy Recommendations

6.1 Future Research Directions

6.1.1 Development of High-Performance Smart Materials for Digital Twin Integration

Future research should focus on developing smart materials with higher sensing accuracy, faster response speed, and better compatibility with digital twin systems. For example, developing multi-functional smart materials that integrate sensing, actuation, and data transmission functions to reduce the complexity of data collection; improving the durability and environmental adaptability of smart materials to ensure stable performance in harsh urban environments. Additionally, research on material digitalization models should be strengthened to accurately describe the dynamic behavior of smart materials in digital twin models (Zhang et al., 2024).

6.1.2 Optimization of Digital Twin Model Accuracy and Adaptability

Research should focus on improving the accuracy of digital twin models for complex infrastructure systems. This includes developing multi-physics, multi-scale coupling simulation algorithms to accurately simulate the interaction between smart materials and infrastructure; integrating machine learning and artificial intelligence technologies to realize automatic model calibration and adaptive update based on real-time data from smart materials. Additionally, research on digital twin models for integrated multi-infrastructure systems (e.g., transportation-water-energy) should be carried out to improve the overall resilience of urban infrastructure (Liu et al., 2024).

6.1.3 Establishment of Standardized Data Integration and Transmission Protocols

Developing unified data interface standards and transmission protocols for the integration of smart materials and digital twins is essential. This includes formulating standardized data formats for different types of smart materials (piezoelectric, conductive, PCMs) to realize seamless integration of multi-source data; developing high-reliability, low-latency data transmission technologies (e.g., 6G, quantum communication) to ensure real-time and secure data transmission between physical entities and virtual models. Additionally, research on edge computing and fog computing technologies should be strengthened to solve the problem of large data volume and high real-time requirements (Gomez et al., 2024).

6.1.4 Enhancement of Data Security and Privacy Protection

Future research should focus on developing advanced data security protection technologies for the integrated system. This includes applying encryption technologies (e.g., homomorphic encryption, blockchain) to protect data during transmission and storage; developing intrusion detection and anti-tampering technologies to prevent cyber attacks on the digital twin model and smart materials. Additionally, research on data privacy protection laws and regulations for urban infrastructure should be carried out to clarify the scope of data collection and usage rights (Rossi et al., 2024).

6.1.5 Exploration of Multi-Scale and Multi-System Integrated Applications

Research should explore the application of the integrated technology at different scales (material, component, system, urban) and in integrated multi-infrastructure systems. For example, applying the integrated technology to the whole life cycle of infrastructure (design, construction, operation, maintenance, demolition); exploring the synergistic effect of the integrated technology in transportation, water supply, and energy systems to improve the overall resilience of the city. Additionally, research on the application of the integrated technology in emerging urban infrastructure (e.g., autonomous vehicle roads, smart grids) should be carried out (Patel et al., 2024).

6.2 Policy Recommendations

6.2.1 Development of Unified Technical Standards and Specifications

Governments and international organizations should take the lead in formulating unified technical standards and specifications for the integration of smart materials and digital twins. This includes standards for smart material performance evaluation, digital twin model construction, data interface, and safety verification. The participation of industry, academia, and research institutions should be encouraged to ensure the practicality of the standards. Additionally, the standards should be regularly updated to keep up with the latest technological developments (Li et al., 2024).

6.2.2 Provision of Financial Incentives and Support

Governments should provide financial incentives to promote the adoption of the integrated technology. This includes providing subsidies and tax breaks for infrastructure projects adopting the integrated technology; establishing special funds to support research and development of key technologies (e.g., high-performance smart materials, digital twin models). Additionally, public-private partnerships (PPPs) should be encouraged to share the investment and operation risks of the integrated technology projects (Zhao et al., 2024).

6.2.3 Strengthening Interdisciplinary Talent Training

Governments and educational institutions should strengthen the training of interdisciplinary talent in smart materials and digital twins. This includes adjusting university curricula to integrate courses on smart materials, digital twin technology, and infrastructure engineering; establishing professional training programs for existing engineering and technical personnel to improve their ability to apply the integrated technology. Additionally, international talent exchange and cooperation should be promoted to attract global outstanding talent in related fields (Chen et al., 2024).

6.2.4 Improvement of Data Security and Privacy Protection Laws

Governments should formulate and improve laws and regulations on data security and privacy protection for urban infrastructure. This includes clarifying the responsibilities and obligations of infrastructure operators in data collection, transmission, and storage; establishing a data security supervision mechanism to investigate and punish illegal acts such as data leakage and tampering. Additionally, cross-border data flow regulations should be formulated to ensure the security of global infrastructure data (Gomez et al., 2023).

6.2.5 Promotion of Pilot Projects and Experience Sharing

Governments should select representative urban infrastructure projects to carry out pilot applications of the integrated technology. The pilot projects should focus on verifying the technical feasibility, economic benefits, and resilience enhancement effect of the integrated technology. Additionally, experience sharing platforms should be established to promote the successful experience of pilot projects. International cooperation should be encouraged to share research results and application experience of the integrated technology globally (Wang et al., 2023).

7. Conclusion

This study systematically explores the integration paradigm of smart materials and digital twins for enhancing urban infrastructure resilience. The main findings are as follows: (1) Smart materials provide real-time sensing and active response capabilities for physical infrastructure, while digital twins realize virtual-real mapping and predictive optimization, forming a complementary synergistic relationship. (2) The integration of the two technologies enhances infrastructure resilience through multiple paths such as real-time state monitoring, disturbance simulation and early warning, and adaptive response and optimization, which has been verified in typical infrastructure systems such as transportation, water supply and drainage, and energy. (3) Representative case studies from different regions demonstrate that the integrated technology can significantly improve infrastructure resilience, reduce maintenance costs, and extend service life. (4) The widespread application of the integrated technology is hindered by challenges such as data synchronization, high initial investment, limited model accuracy, lack of technical standards, and data security risks. (5) Future research should focus on developing high-performance smart materials, optimizing digital twin models, establishing standardized data protocols, enhancing data security, and exploring multi-scale and multi-system applications; policy recommendations include formulating technical standards, providing financial incentives, strengthening talent training, improving data security laws, and promoting pilot projects.

This study contributes to the existing literature by constructing the integration framework of smart materials and digital twins for urban infrastructure resilience enhancement and clarifying their synergistic mechanism. The findings provide a theoretical and technical reference for urban planners, engineers, and policymakers to promote the intelligent upgrading of urban infrastructure. Future research should focus on solving the key technical challenges of the integrated technology and carrying out more in-depth case studies to verify its long-term performance and application effect in complex urban environments.

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