Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 9, No. 4, 2025
www.scholink.org/ojs/index.php/asir

Original Paper

The Application of AI in Smart Bridges

Shouling Luan[1], Huanrong Zhang[1], Aihong Qin[1], Sai Zhang[1], Linlin Ma[1] & Liya Han[1]
[1] Qingdao City University, Qingdao, China

Received: September 28, 2025 Accepted: October 29, 2025 Online Published: November 6, 2025
doi:10.22158/asir.v9n4p57 URL: http://doi.org/10.22158/asir.v9n4p57

Abstract
With the in-depth implementation of the "Transportation Power" strategy and the explosive development of artificial intelligence (AI) technology, smart bridges, as the core carrier for the intelligent upgrading of transportation infrastructure, are undergoing a paradigm shift from traditional engineering models to "data-driven + intelligent decision-making". This paper systematically expounds on the application foundation of AI technology in the field of smart bridges, analyzes four full-life-cycle scenarios including design, construction, operation and maintenance, and disaster emergency response. Combined with typical cases such as the AI-assisted beam replacement project at Keqiao Station of Shaoxing Intercity Railway, it reveals the core value of AI technology in improving the accuracy, efficiency and safety of bridge engineering. Meanwhile, it analyzes current challenges in technology application such as data silos and algorithm reliability, and looks forward to the development direction of in-depth integration of multimodal large models and digital twins, providing references for technological innovation and engineering practice of smart bridges.

Keywords
Artificial Intelligence, Smart Bridges, Full-Life-Cycle Management, Digital Twins, Structural Health Monitoring

1. Introduction

1.1 Research Background

As a hub project of the transportation lifeline network, the construction and operation & maintenance level of bridges is directly related to regional economic resilience and public safety. By 2024, the total number of modern bridges in China has reached 860,000, including 800,000 highway bridges and 60,000 railway bridges, ranking first in the world in scale. However, the traditional bridge engineering model gradually shows limitations in addressing issues such as complex environments, nonlinear structural responses, and full-life-cycle management: the design stage relies on empirical formulas leading to insufficient innovation; the construction stage is prone to quality risks due to environmental interference;

and the discrete data in the operation & maintenance stage cannot support accurate decision-making.

At the same time, the breakthrough development of AI technology provides a new path to solve the above problems. The "14th Five-Year Plan for National Road Traffic Safety" issued by the Work Safety Committee of the State Council clearly puts forward the principle of "technology empowerment and intelligent governance", requiring the improvement of the intelligent level of transportation infrastructure governance. The in-depth integration of AI technology and bridge engineering is promoting smart bridges to achieve a leap from "experience-dependent" to "intelligence-driven", becoming a core support for ensuring the safe and efficient operation of transportation infrastructure.

1.2 Research Status and Significance

Currently, academic and engineering circles at home and abroad have carried out diverse explorations on the application of AI in the bridge field. *China Journal of Highway and Transport* has set up a special column "Application of Artificial Intelligence in Bridge Seismic Resistance", systematically sorting out the application achievements of AI in five core scenarios such as ground motion synthesis and response prediction. In engineering practice, AI technology has penetrated into key links such as bridge design optimization, construction control, and operation & maintenance monitoring. The AI-assisted beam replacement project at Keqiao Station of Shaoxing Intercity Railway has achieved a technological breakthrough in the reconstruction of bridges on operating railways.

This paper systematically integrates the technical application and engineering practice of AI in smart bridges, which is of dual significance for promoting the intelligent upgrading of bridge engineering: at the theoretical level, it constructs an application framework for the cross-integration of AI and bridge engineering, enriching the theoretical system of smart transportation infrastructure; at the practical level, it provides a reference implementation path for engineers through the analysis of typical cases, facilitating the implementation of the "Transportation Power" strategy.

2. Core Technical Foundation of AI in Smart Bridges

The application of AI technology in smart bridges is supported by the integration of multidisciplinary technologies, forming a complete technical chain of "perception - analysis - decision-making - control". The core technology system includes the following four categories:

2.1 Machine Learning and Deep Learning

Machine learning algorithms realize the intelligent prediction and evaluation of bridge engineering by mining hidden patterns in massive data. In the field of bridge seismic resistance, the Long Short-Term Memory (LSTM) network model has been successfully applied to the rapid prediction of seismic responses and vulnerability of near-fault bridges, with a prediction accuracy improved by more than 30% compared with traditional methods. Deep learning, by constructing multi-layer neural networks, breaks through the limitations of traditional methods in dealing with nonlinear problems. For example, Convolutional Neural Networks (CNN) can realize the automatic identification and quantitative classification of bridge cracks and other defects, with an identification accuracy of over 95%.

2.2 Computer Vision Technology

Computer vision technology provides a "non-contact intelligent perception" solution for bridge inspection. It collects image data through high-definition cameras, drones and other equipment, and combines image recognition algorithms to realize automatic detection of structural defects. Compared with traditional manual inspection, this technology not only improves the inspection efficiency by 5-10 times, but also effectively avoids the risks of high-altitude operations. It has been widely used in the monitoring of diseases such as beam cracks and steel structure corrosion.

2.3 Digital Twin Technology

Digital twin technology realizes the virtual-real interaction throughout the engineering life cycle by constructing a 3D model that accurately maps the physical bridge. In the beam replacement project at Keqiao Station of Shaoxing, the technical team built a 3D bridge model based on digital twin technology, integrating real-time data from 40 high-precision sensing points to provide millimeter-level precision visual monitoring for the construction process. This technology realizes the full-process intelligent management of "pre-construction simulation and deduction, real-time regulation during construction, and post-construction effect evaluation".

2.4 IoT and AI Integration Technology

The Internet of Things (IoT) technology provides a data foundation for AI applications. By deploying strain gauges, fiber Bragg grating sensors, Beidou positioning and other equipment at key parts of the bridge structure, real-time collection of parameters such as temperature, stress and displacement is realized. AI algorithms clean, fuse and analyze multi-source heterogeneous data, converting data into actionable engineering information. For example, predicting the fatigue life of bridge components by analyzing sensor data provides an accurate basis for operation and maintenance.

3. Application Scenarios of AI in the Full Life Cycle of Smart Bridges

3.1 Design Stage: Intelligent Optimization and Scheme Generation

3.1.1 Specification Verification and Model Inspection

Bridge design needs to meet the requirements of multi-field specifications, and traditional manual verification is prone to omissions leading to potential safety hazards. The team from Tsinghua University converted architectural specifications into domain rules recognizable by computers, constructed a BIM model semantic extraction and verification system, and realized the automatic compliance inspection of design schemes. The system continuously optimizes the verification algorithm through machine learning, improving the efficiency of specification compliance inspection by 80% and reducing the error recognition rate by 90%.

3.1.2 Structural Optimization and Simulation

AI technology breaks through the limitation that traditional finite element simulation relies on empirical parameters. By integrating massive engineering data and physical mechanisms, it realizes the intelligent optimization of design schemes. In the shock absorption design of suspension bridges, the optimization method based on multi-objective swarm intelligence algorithm can take into account both the shock absorption effect and construction cost. The optimized scheme improves the shock absorption efficiency by more than 25% compared with traditional methods. For extreme working conditions such as fire and earthquake, AI can realize the whole-process simulation of disaster effects, providing a scientific basis for structural disaster-resistant design.

3.2 Construction Stage: Precision Control and Intelligent Management

3.2.1 Intelligent Planning of Construction Schemes

In view of the complex construction environment of bridges and many random events, AI algorithms generate the optimal construction scheme by integrating key information such as "personnel, machinery, materials, methods and environment". In the beam replacement project at Keqiao Station of Shaoxing, the AI system used the simulation module to deduce the whole process of steel box girder incremental launching in advance, identified and repaired potential risk points in construction, and ensured the smooth incremental launching of the 4,389.6-ton new girder for 21 meters. This technology realizes the optimal allocation of construction resources and saves the construction period by 30% compared with the traditional scheme.

3.2.2 Real-Time Regulation of Construction Process

The AI control module realizes high-precision control of the construction process through collaborative linkage of multiple devices. In the Shaoxing project, the AI system simultaneously controlled 36 jacking jacks and 10 incremental launching jacks, and made dynamic adjustments based on the real-time collected beam attitude data. Finally, the positioning deviation of the new beam was controlled within 2 mm (vertical height difference) and 3 mm (horizontal and vertical deviation), setting a new record for the precision of beam replacement on operating railway bridges. In addition, AI technology can also real-time monitor potential safety hazards at the construction site through image recognition, reducing the incidence of accidents.

3.3 Operation & Maintenance Stage: Predictive Maintenance and Health Monitoring

3.3.1 Intelligent Evaluation of Structural Health Status

The structural health monitoring system based on the integration of IoT and AI can realize real-time evaluation and disease early warning of bridge performance. In the monitoring of beam bridges, the AI recognition method based on complex Morlet wavelets can accurately extract low-order mode parameters and effectively capture early damage signs such as structural stiffness degradation. By establishing a closed-loop system of "data collection - feature extraction - status evaluation - early warning push", this technology advances the disease detection time by 3-6 months.

3.3.2 Generation of Predictive Maintenance Schemes

AI algorithms realize accurate prediction of fault risks by analyzing historical operation & maintenance data and real-time monitoring data of bridges. For example, for the bridge cable system, AI can build a fire resistance prediction model based on classified vehicle fire data, identify potential cable degradation risks in advance and generate maintenance schemes. Compared with the traditional "post-failure maintenance" mode, the predictive maintenance mode can reduce the operation & maintenance cost by more than 40% and extend the service life of the bridge by 10-15 years.

3.4 Disaster Emergency Stage: Risk Early Warning and Resilience Recovery

3.4.1 Real-Time Early Warning of Disaster Risks

AI technology shows high efficiency and forward-looking in bridge disaster early warning. In the safety protection of suspension bridges, the AI-based safety performance prediction model for oil tanker explosion and fire environment can real-time monitor the fire development trend and issue early warning signals; when an earthquake occurs, the AI system can quickly predict the bridge structure response, providing valuable time for emergency decision-making.

3.4.2 Post-Earthquake Resilience Assessment and Recovery

The post-earthquake functional recovery of bridges depends on rapid and accurate damage assessment. AI technology can realize the automatic classification of bridge damage degree by fusing UAV images and structural monitoring data. The AI resilience assessment model that considers the order of component repair can optimize the post-earthquake repair scheme, shorten the traffic recovery time by more than 40%, and significantly improve the disaster resistance resilience of the road network.

4. Analysis of a Typical Engineering Case: AI-Assisted Beam Replacement Project at Keqiao Station of Shaoxing Intercity Railway

4.1 Project Background and Technical Challenges

The construction of Keqiao Station of Shaoxing Intercity Railway required the replacement of a bridge on the operating Xiaoshan-Ningbo Railway trunk line, replacing the concrete beam in the "throat area" with a 4,389.6-ton steel box girder. The project faced three major challenges: first, extremely high construction precision requirements, with a gap of only 10 cm between the two ends of the beam and the existing structure; second, high safety risks, as construction needed to ensure the normal operation of the railway; third, tight operation time, requiring the beam replacement to be completed within an extremely short maintenance window.

4.2 AI Technology Application Scheme

China Railway 24th Bureau Group, in cooperation with universities, developed an AI intelligent control system and constructed a three-in-one technical system of "perception - simulation - control":

1.Perception Module**: Integrated fiber Bragg grating sensors, strain gauges and Beidou positioning technology, and deployed 40 high-precision sensing points to realize real-time collection and millimeter-level perception of beam attitude data;

2.Simulation Module**: Used the digital twin model to deduce the whole process of incremental launching in advance, identifying and correcting potential "bugs" in construction;

3.Control Module**: Synchronously controlled 46 jacks based on intelligent algorithms, realizing automatic and precise control of beam incremental launching.

4.3 Application Effects

With the support of AI technology, the engineering team successfully completed the ejection of the old beam and the positioning of the new beam, achieving three breakthroughs: first, a breakthrough in precision control, with the positioning deviation of the new beam controlled within 2-3 mm; second, efficiency improvement, shortening the operation time by 50% compared with traditional technology; third, safety guarantee, with no impact on railway operation during the construction period. This case has become a benchmark project for AI-assisted reconstruction of bridges on operating railways in China, providing a technical model for similar projects.

5. Challenges and Prospects of AI Application in Smart Bridges

5.1 Main Challenges

5.1.1 Data Governance Difficulties

Bridge engineering data presents the characteristics of "multi-source heterogeneity and inconsistent standards". Design drawings, construction records and monitoring data have not yet formed a unified data standard, leading to prominent data silos. In addition, the scarcity of sample data under extreme working conditions restricts the generalization ability of AI models.

5.1.2 Insufficient Algorithm Reliability and Interpretability

Existing AI models are mostly "black-box" systems. In key scenarios such as bridge seismic resistance, the non-interpretability of the algorithm decision-making process reduces engineers' trust in the technology. At the same time, the reliability of AI models in dealing with extreme environments needs to be improved, as they are vulnerable to interference from abnormal data.

5.1.3 Technology Integration and Cost Issues

There are barriers to the integration of AI technology and traditional bridge engineering technology. Some construction enterprises lack compound talents who are proficient in both AI technology and bridge engineering. In addition, the deployment cost of high-precision sensing equipment and AI systems is relatively high, which restricts the popularization and application of the technology in medium and small-span bridges.

5.2 Development Prospects

5.2.1 Integrated Application of Multimodal Large Models

In the future, multimodal AI large models integrating visual, structural and environmental data will be constructed. Combined with pre-training and transfer learning technologies, the problem of scarce samples under extreme working conditions will be solved. For example, by integrating digital twins and generative AI, virtual deduction and intelligent decision-making throughout the whole life cycle of bridges will be realized.

5.2.2 Algorithm Interpretability and Standardization Construction

The construction of a standard system in the field of "AI + Bridge Engineering" will be promoted, clarifying the technical specifications for data collection, model training and decision output. Explainable

AI (XAI) technology will be developed to visualize the algorithm decision-making process and improve the credibility of technology application.

5.2.3 Technology Inclusiveness and Collaborative Innovation

Relying on national key R&D program projects, low-cost sensing and AI lightweight deployment technologies will be tackled to reduce the threshold for intelligent transformation of medium and small-span bridges. A collaborative innovation platform of "universities - enterprises - research institutions" will be built to accelerate the engineering transformation of AI technology.

6. Conclusion

AI technology is reshaping the development model of smart bridges in a way of "full-life-cycle penetration and multi-dimensional empowerment". From specification verification and structural optimization in the design stage, to precision control and risk avoidance in the construction stage, and then to predictive maintenance and disaster emergency response in the operation & maintenance stage, AI technology, through in-depth integration with digital twins, IoT and other technologies, has significantly improved the intelligent level of bridge engineering. Practices such as the AI-assisted beam replacement project at Keqiao Station of Shaoxing show that AI technology can effectively solve the problems of precision, efficiency and safety in traditional bridge engineering.

Although there are currently challenges such as data governance and algorithm reliability, with the development of multimodal large models and the improvement of standardization systems, AI technology will be more widely applied in the field of smart bridges. In the future, the smart bridge technology system centered on "data-driven, intelligent decision-making and human-machine collaboration" will provide core support for the safe and efficient operation of transportation infrastructure, and contribute to the realization of the "Transportation Power" strategic goal.

References

Guangming Network. (2025). *AI Assists "Replacing the Old with the New"! Accurate Beam Replacement at Keqiao Station of Shaoxing Intercity Railway*. 2025-09-11.

Han Qiang, Wen Jianian, Wei Kai, et al. (2025). Introduction to the Special Column on the Application of Artificial Intelligence in Bridge Seismic Resistance. *China Journal of Highway and Transport*, *2025*(3), 1-3.