Chapter 24

An Integrated AR-FEM-AI System for Real-time Structural Simulations and X-ray Visualisation of Heritage and Ageing Buildings

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Abstract

Heritage and ageing structures are increasingly vulnerable to deterioration, environmental loads, and long-term material fatigue. Conventional structural monitoring techniques, such as embedded sensing systems or invasive sampling, often face practical, financial, or ethical constraints, particularly in conservation contexts. In response, this research proposes an integrated, non-contact framework that combines Augmented Reality (AR), Finite Element Modelling (FEM), and Artificial Intelligence (AI) to enable early-stage structural assessment and immersive visualisation. The framework is currently under development and is being applied to representative case studies of Chinese heritage architecture, including timber pagodas and masonry towers. Within this system, FEM provides simulated structural responses under various loading scenarios. AI models are trained on these outputs to deliver rapid, predictive analysis, and AR interfaces project these insights onto physical structures through intuitive, layered visualizations. This approach aims to support conservation workflows by facilitating preliminary diagnostics without physical intervention, while also enhancing educational and public engagement with built heritage. Although still in progress, the framework is conceived to be scalable and adaptable across diverse structural typologies and regional contexts, offering a novel pathway toward sustainable, data-informed heritage management.

Keywords: *Artificial Intelligence, Augmented Reality, FEM, Predictive Simulation, Structural Health Monitoring, Heritage, Ageing and Existing Structures, Digital Twin*

Introduction and Background

Heritage structures, from Gothic cathedrals in Europe to timber pagodas in China, embody centuries of cultural and technological achievement. Yet they face accelerating risks from ageing, climate change, urbanisation, and inadequate maintenance[1]. Modern urban buildings, though constructed with advanced materials, also develop vulnerabilities over time, highlighting the need for advanced monitoring strategies to ensure resilience and safety[2]. Traditional diagnostic methods such as strain

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[1]Rossi, Michela, and Dionysios Bournas. "Structural Health Monitoring and Management of Cultural Heritage Structures: A State-of-The-Art Review." *Applied Sciences* 13, no. 11 (January 1, 2023): 6450. https://doi.org/10.3390/app13116450.

[2]Fikret Necati Catbas et al., "Extended Reality (XR) for Condition Assessment of Civil Engineering Structures: A Literature Review," *Sensors (Basel, Switzerland)* 22, no. 23 (December 6, 2022): 9560, https://doi.org/10.3390/s22239560.

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gauges, embedded sensors, and destructive sampling are often invasive, expensive, and limited in scope. For heritage sites protected under conservation laws, such approaches are frequently unacceptable, while large-scale or retrofitted buildings demand real-time solutions that surpass the capabilities of manual inspection[3].

Recent advances in digital technology present opportunities to transform structural monitoring through the integration of computational modelling and immersive visualisation (Figure **1**). Augmented Reality (AR) offers interactive ways to engage with heritage, but current applications tend to emphasise appearance rather than performance[4]. The Finite Element Method (FEM) remains the benchmark for high-fidelity simulation of stresses, deformations, and dynamic responses, yet its computational demands hinder real-time use[5]. Artificial Intelligence (AI), particularly machine learning, provides a bridge by learning from FEM datasets and sensor inputs to generate predictive surrogates capable of rapid, scalable analysis[6].

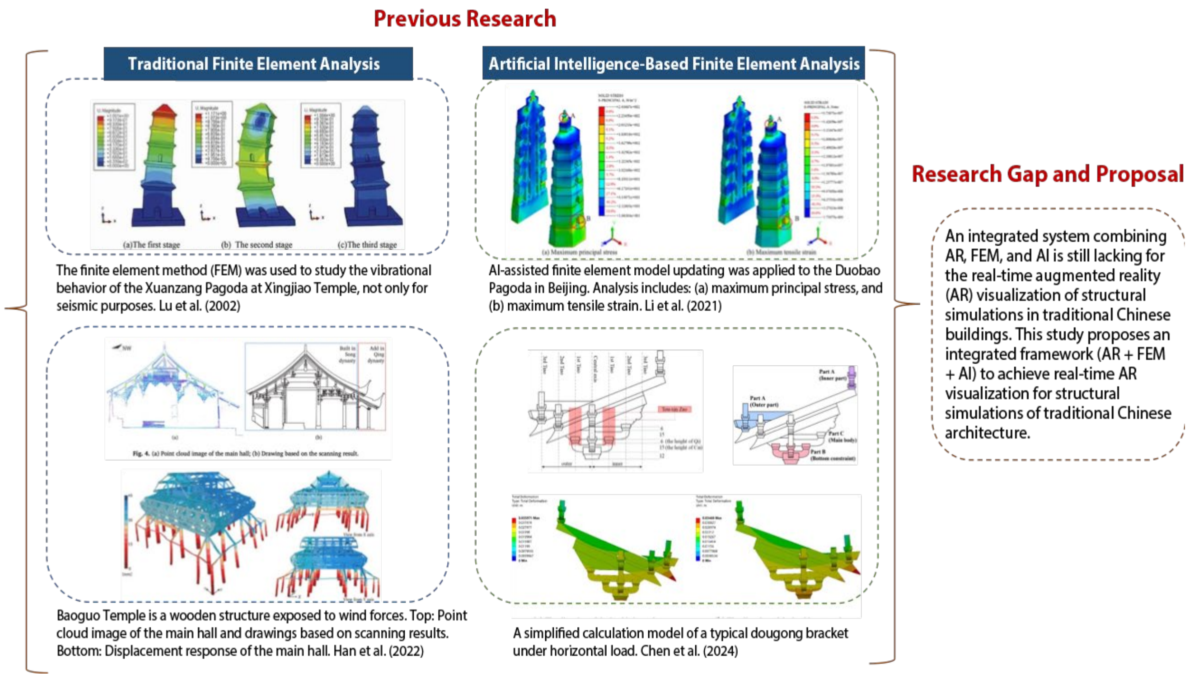

Figure 1: Previous studies and simulations of Chinese heritage structures.

Heritage buildings present particular challenges due to their material variability, aged timber, stone, or rammed earth often resist standardised characterisation, and conservation restrictions that limit

[3]Mariella De Fino, Rosella Alessia Galantucci, and Fabio Fatiguso, "Condition Assessment of Heritage Buildings via Photogrammetry: A Scoping Review from the Perspective of Decision Makers," *Heritage* 6, no. 11 (October 30, 2023): 7031–67, https://doi.org/10.3390/heritage6110367.

[4]Yingwen Yu et al., "How Digital Technologies Have Been Applied for Architectural Heritage Risk Management: A Systemic Literature Review from 2014 to 2024" 13, no. 1 (February 28, 2025), https://doi.org/10.1038/s40494-025-01558-5.

[5]Vagelis Plevris and George Papazafeiropoulos, "AI in Structural Health Monitoring for Infrastructure Maintenance and Safety," *Infrastructures* 9, no. 12 (December 7, 2024): 225–25, https://doi.org/10.3390/infrastructures9120225.

[6]Plevris and Papazafeiropoulos, "AI in Structural Health Monitoring for Infrastructure Maintenance and Safety," 225–25.

invasive intervention[7]. Environmental stressors such as seismic activity, moisture infiltration, and wind further accelerate deterioration. Comparable problems are evident in ageing modern structures, where concrete fatigue, steel corrosion, and incompatibility between old and new systems complicate maintenance[8]. These factors underscore the urgent need for non-invasive yet accurate monitoring frameworks.

This research proposes a novel integration of AR, FEM, and AI into a single system for real-time, predictive structural analysis and immersive X-ray visualisation. The framework is being designed initially for testing on Chinese heritage buildings such as the Xuanmiao Guan Temple (Suzhou), the Yingxian Wooden Pagoda (Yingxian), and the Tiger Hill Pagoda (Suzhou) (Figure **2**), chosen for their material diversity, architectural form, structural typology, and cultural significance (Figure **3**). While rooted in Chinese case studies, the system is inherently adaptable to diverse global typologies of heritage and ageing buildings, offering a contribution to conservation, education, and structural resilience[9].

Figure 2: Selected Chinese heritage structures for pilot study and implementation of the AR-FEM-AI system.

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[7]Jingyi Wang and Safial Aqbar Zakaria, "Design Application and Evolution of 3D Visualization Technology in Architectural Heritage Conservation: A CiteSpace-Based Knowledge Mapping and Systematic Review (2005–2024)," *Buildings* 15, no. 11 (May 28, 2025): 1854, https://doi.org/10.3390/buildings15111854.

[8]Doga Bitik, "Climate- Responsive HBIM for Sustainable Preservation: A Case Study of Villa Ottolini Tovaglieri - Environmental Impact and Preservation Strategies," *Polimi.it*, June 23, 2024, https://hdl.handle.net/10589/223026.

[9]Gian Piero Lignola et al., "Validated and Optimized Strategies for Preserving Historical Heritage towards Natural and Anthropic Risks: Insights from the DETECT-AGING Project," *Buildings* 15, no. 5 (February 22, 2025): 693, https://doi.org/10.3390/buildings15050693.

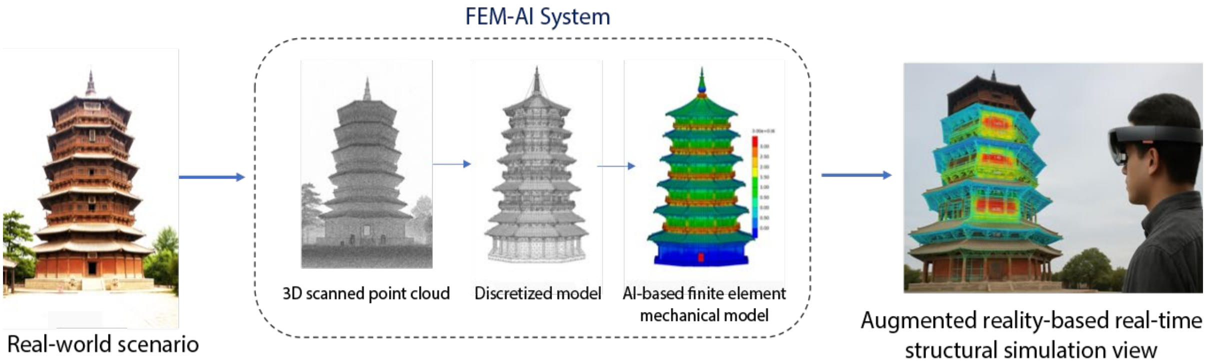

Figure 3: Conceptual workflow of the AI-FEM-AR system.

Aims and Objectives

This research aims to develop and validate a unified AR-FEM-AI system to support preliminary structural health scanning and immersive visualisation of historical buildings (Figure **3**). Intended as a first-response tool, the system offers hands-off, data-driven insights that help identify potential structural issues early, guiding conservation professionals toward areas requiring detailed analysis. It also serves as an educational and engagement platform for educators and the public. Key objectives include:

a. **Developing an AR platform** that overlays real-time indicators, such as stress, deformation, and risk zones, onto heritage structures for rapid visual assessment.
b. **Conducting FEM simulations** on representative Chinese heritage buildings to generate foundational datasets for AI training.
c. **Designing AI models** that learn from FEM outputs and sensor inputs to provide fast, adaptive predictions suitable for early-stage evaluations.
d. **Validating the integrated system** through pilot applications at selected heritage sites, assessing its effectiveness as a diagnostic tool and its broader impact on conservation workflows, education, and public engagement.

Methodology

The methodology follows an iterative, four-step workflow currently in progress—starting from digital capture and progressing through simulation, AI training, and AR-based visualisation. Each phase is interconnected, supporting the development of a responsive, data-informed tool for early-stage structural health assessment (Figure **4**).

Step 1: Digital Twin Construction

Tools: High-resolution 3D scanning, photogrammetry, archival research

The process begins with the creation of accurate digital twins of heritage structures. These models are being developed using high-resolution scanning technologies that capture both geometric form and surface texture. Archival documents and historical references are used to estimate hidden structural components and material properties. The resulting models serve not only as visual replicas but also as data-rich foundations for structural analysis.

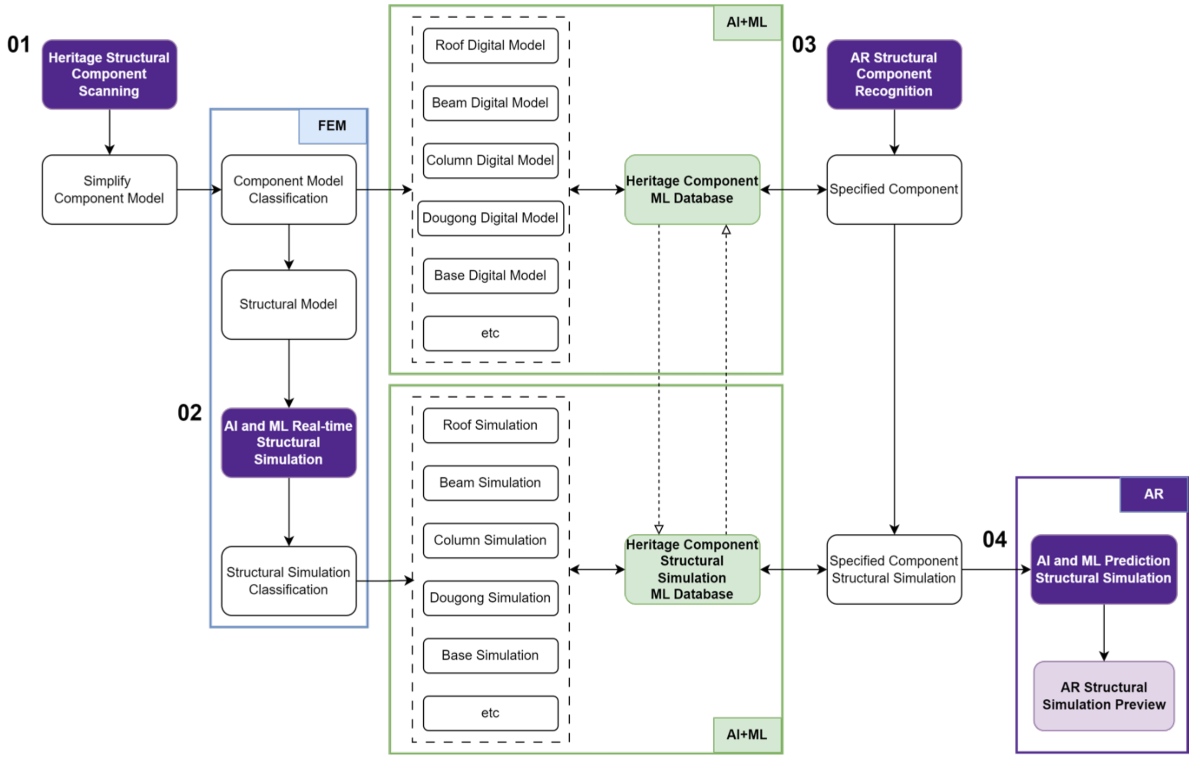

Figure 4: Methodological workflow for developing the AI-FEM-AR system.

Step 2: Structural Simulation via FEM

Tools: Finite Element Modelling software (e.g., ANSYS, Abaqus, Karamba3D)

These digital twins are currently being analysed through Finite Element Modelling (FEM). Simulations emphasise different structural behaviours depending on the material and typology, such as timber anisotropy in wooden pagodas, nonlinear cracking in masonry, or corrosion in reinforced concrete. FEM outputs include predicted stress distributions, displacements, modal frequencies, and failure zones. However, their high computational demands limit their use in real-time applications.

Step 3: AI Surrogate Model Training

Tools: Machine learning libraries (e.g., TensorFlow, PyTorch), neural network models

To overcome FEM's computational constraints, AI surrogate models are being developed. Convolutional and recurrent neural networks are trained on FEM-generated datasets to learn how input parameters (e.g., load conditions, boundary constraints) relate to structural responses. Once adequately trained, these AI models are expected to deliver near-instantaneous predictions, enabling rapid assessments in the field.

Step 4: Immersive AR Visualisation

Tools: AR hardware (e.g., Microsoft HoloLens, AR-enabled tablets)

The final step involves integrating the trained AI predictions into an AR platform, which is under development. This interface will overlay real-time structural insights, such as stress paths and deformation zones, onto physical buildings. Engineers, conservators, and even the public will be able to interact directly with the structure, gaining insights through visual overlays without physical contact.

Expected and Preliminary Results

The integrated system is designed as an early-stage diagnostic tool for structural health monitoring—offering conservation teams a first-look assessment that can inform expert decision-making and guide more advanced investigations. Rather than replacing high-fidelity FEM analysis, it serves as a rapid, non-invasive scanning approach to flag potential structural issues and prioritise areas for deeper study. The prototype allows engineers to navigate heritage sites while viewing projected overlays of stress patterns and deformation directly on structural elements. For conservators, this transforms preliminary inspections into interactive, data-informed processes. The system also enhances public engagement by enabling tourists and students to explore the hidden structural dynamics of historic architecture.

The Yingxian Wooden Pagoda's roof frame is currently being used as the first pilot case (Figure **5**). The team is preparing 3D scanning to generate a refined FEM model, while experimenting with various Dougong bracket types. Roof structures across all tiers are being processed for machine learning training. These efforts will lay the foundation for the next development phase of the AR-FEM-AI platform.

Discussion: Potential, Limitations, and Future Work

This research aimed to develop a unified AR-FEM-AI system for early-stage structural health monitoring and visualisation of heritage buildings. By combining the analytical precision of FEM, the responsiveness of AI, and the accessibility of AR, the system aims to offer a hands-off alternative to traditional methods, supporting rapid, first-pass assessments to guide expert analysis.

Initial applications to Chinese timber and reinforced-concrete structures are showing promise. Ongoing and future work focuses on expanding compatibility to include stone masonry, steel, and hybrid typologies to improve the generalizability of AI models. Integration with IoT-based sensors is being explored to enable real-time updates, while a hybrid feedback loop combining simulated and measured data is expected to enhance prediction accuracy. Planned VR extensions will support remote collaboration and broaden applications in conservation, education, and disaster risk management.

However, certain limitations are already evident. AI performance depends on the quality of FEM training data, which is often constrained by undocumented materials and limited access to physical testing. AR deployment may face spatial misalignment, lag, or environmental interference in field conditions. Current development efforts focus on adaptive learning for incomplete data, transfer learning across similar structures, and lightweight AR interfaces.

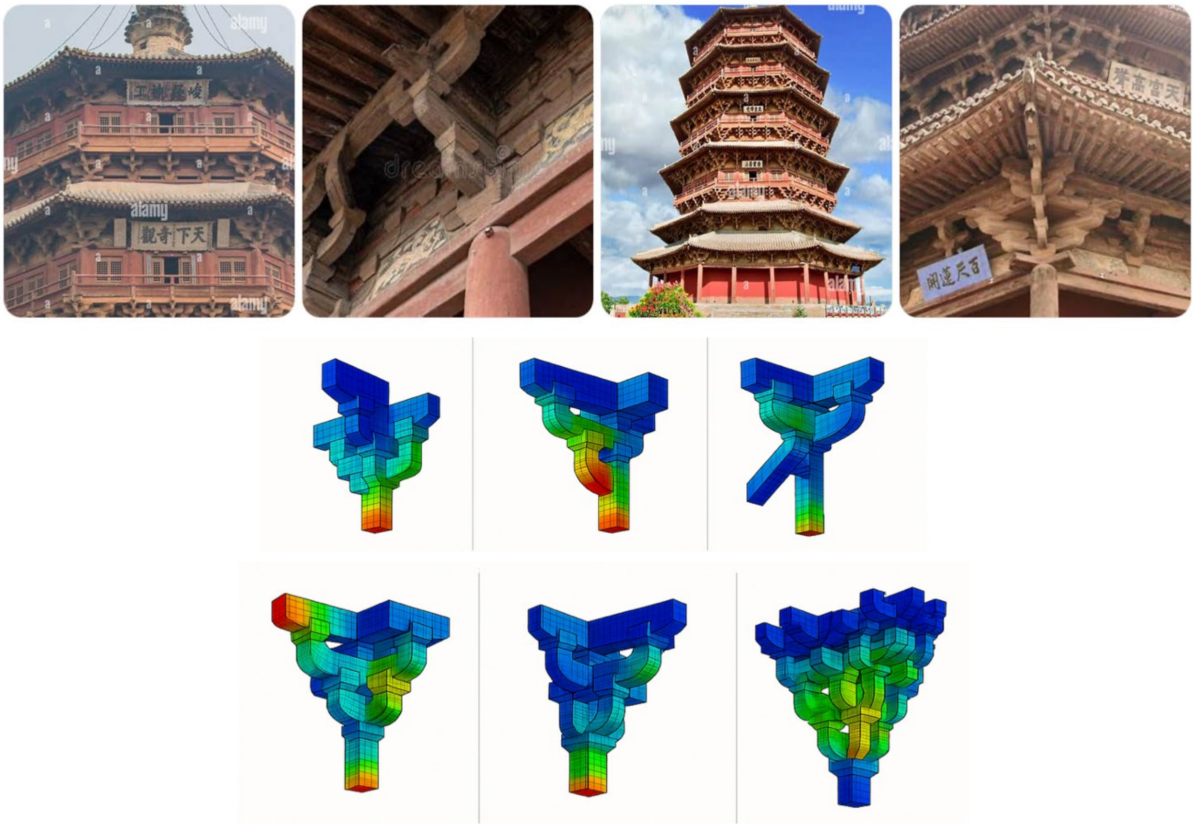

Figure 5: Top – Different Douging typologies of Yingxian Wooden Pagoda; Bottom – FEM structural simulations of all dissimilar Dougong bracket types.

Beyond technical goals, the platform aims to foster public engagement by revealing hidden structural narratives. As development progresses, it has the potential to evolve into a scalable tool for sustainable heritage conservation, bridging technology and cultural preservation.

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