Current Status and Development Trends of Structural Health Monitoring for Ancient Chinese Buildings

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Abstract: Historical ancient buildings carry profound cultural heritage value. To better preserve this cultural heritage, structural health monitoring (SHM) of ancient buildings constitutes an essential preventive conservation measure. Currently, SHM technology for ancient buildings in China remains immature, relevant technical standards are incomplete, and a comprehensive SHM standard system for ancient buildings has yet to be established. To promote the advancement of SHM technology for ancient buildings in China, this paper systematically reviews the research progress, existing problems, relevant standards, and development prospects in this field. Firstly, the current status of monitoring during the renovation and reinforcement of ancient buildings is summarized. Secondly, an analysis is conducted on the monitoring methods and relevant standards associated with existing SHM technologies for ancient buildings. Finally, the development trajectory of SHM technology for ancient buildings is reviewed, and future development trends are projected, aiming to provide new insights and approaches for the advancement of ancient building SHM.

Keywords: Ancient Buildings; Structural Health Monitoring; Preventive Conservation; Non-Destructive Testing; Early Warning Threshold

1. Introduction

As precious legacies of human civilization, historical ancient buildings carry profound historical memories and cultural genes. In recent years, with the in-depth advancement of the Fourth National Cultural Relics Census, the review of all 767,000 cultural relics registered during the "Third National Cultural Relics Census" has been completed, and over 130,000 newly discovered cultural relics have been identified [1]. Concurrently, nearly 2,000 key national-level cultural relics protection and restoration projects have been vigorously promoted [1]. However, against the backdrop of rapid societal development and intensifying global climate crises, ancient buildings face increasingly prominent natural and anthropogenic risks. Issues such as structural aging, material degradation, and disaster-induced damage require urgent attention. In this context, intelligent sensing and monitoring technologies are progressively being applied to the conservation of ancient buildings. Nevertheless, existing monitoring efforts still exhibit deficiencies in scientific rigor and systematic approach, a lack of unified technical standards, inadequate specificity of monitoring indicators—hindering accurate reflection of the true condition of diverse cultural relics—as well as imperfect early warning mechanisms and weak foundational data accumulation [1-3].

Health monitoring technology for ancient buildings is a crucial means of assessing their structural condition. Domestic scholars have conducted extensive research on ancient building health monitoring, achieving significant progress in non-destructive testing, digital modeling, and ambient vibration monitoring. Shen Shu et al. proposed a sensor network architecture employing multi-dimensional information fusion technology to achieve automatic real-time condition monitoring of ancient buildings. This architecture comprises four layers: physical perception, network transmission, service analysis, and management decision-making. They designed technical solutions for each layer, established a database for ancient building health status, and proposed methods for in-depth analysis of ancient building health status using multi-source information fusion theory and predictive algorithms. This system has been applied in the actual monitoring of relevant ancient buildings [2]. However, persistent challenges remain in intelligent monitoring during ancient building restoration. Significant differences exist among ancient buildings of different regions and types concerning structural forms, material properties, and deterioration mechanisms. Existing monitoring schemes often lack targeted design, making it difficult to accurately capture key health indicators specific to a given structure. The processes of data acquisition, transmission, analysis, and early warning have yet to form a closed-loop system, with data silos being common, resulting in low overall utilization efficiency of monitoring information. Furthermore, the integration between monitoring technology application and the actual needs of ancient building conservation is insufficiently tight. Some advanced technologies face difficulties in widespread adoption during restoration projects due to operational complexity, high costs, or significant intervention with the heritage structure. There is an urgent need to establish an intelligent monitoring system that balances scientific rigor, practicality, and general applicability.

This paper aims to systematically review the current status, methodologies, and standard systems of health monitoring technology employed in the restoration and reinforcement of historical ancient buildings in China. It analyzes the monitoring characteristics and technical approaches relevant to various types of ancient building structures and summarizes the development history and future trends in this field. Through this literature review, it is anticipated to provide a clear technical roadmap for heritage conservation practitioners, offer reference bases for relevant standards-setting bodies, and promote the strategic transition of ancient building monitoring from "remedial restoration" to "preventive conservation." Concurrently, this paper seeks to enhance societal awareness regarding the scientific conservation of ancient buildings and contribute academic insights towards the inheritance and promotion of excellent traditional Chinese culture.

2. Current Status of Monitoring in the Restoration and Reinforcement of Ancient Buildings

2.1 Scale of Restoration and Number of Restored Ancient Buildings

The scale of conservation and restoration projects for ancient buildings in China is substantial, with continuous increases in investment efforts in recent years. Interim results from the Fourth National Cultural Relics Census indicate that the review of all 767,000 cultural relics registered during the "Third National Cultural Relics Census" has been completed, with over 130,000 newly discovered cultural relics identified [1]. Nationwide, there are over 42,000 immovable revolutionary cultural relics and more than 1.5 million movable revolutionary cultural relics/sets in state collections [1]. Regarding historical buildings, as of the present, China has designated 142 National Historic and Cultural Cities, 799 Chinese Historic and Cultural Towns and Villages, 8,155 Chinese Traditional Villages, and 1,274 Historic and Cultural Blocks. Furthermore, 67,200 historical buildings and 556,000 traditional buildings have been officially recognized, essentially forming a distinctive and diverse system for conserving urban and rural historical and cultural heritage.

Regarding restoration projects, the number of cultural heritage institutions has continued to increase (see Figure 1 and Figure 2). Figure 1 presents panel data illustrating the number of macro-level cultural and heritage institutions in China from 2010 to 2024, while Figure 2 shows panel data for other macro-level cultural heritage institutions in China from 1998 to 2024. Both figures reflect the growth trend in the scale of China's cultural heritage protection institutions. During the "14th Five-Year Plan" period, dedicated funds for cultural relics protection have been consistently allocated by financial authorities at all levels, facilitating the effective implementation of nearly 2,000 key national-level cultural relics protection and restoration projects and over 1,200 preventive conservation projects for museum collections [1]. Digital preservation efforts are also accelerating; by the end of 2024, digital archiving had been completed for 12,000 immovable cultural relics nationwide [1]. In terms of investment, special funds for cultural relics protection from central to local levels now cover multiple tiers, including National Key Cultural Relics Protection Units and city/county-level protected sites, leading to a comprehensive improvement in the state of cultural relics preservation.

Notably, the operational paradigm for ancient building restoration is undergoing a profound shift. The newly revised Cultural Relics Protection Law of the People's Republic of

China (effective 2025) incorporates the "principle of minimal intervention" into legal provisions for the first time [3], signifying a systemic transition in restoration philosophy from "passive repair" to "active prevention." The Notice on Strengthening the Full-Process Management of Cultural Relic Building Restoration Projects issued by the National Cultural Heritage Administration further standardizes restoration practices, reinforcing the principles of "preserving the original state of cultural relics" and "minimal intervention". These policy directions indicate that ancient building restoration has evolved from simple repairs towards systematic and scientific preventive conservation.

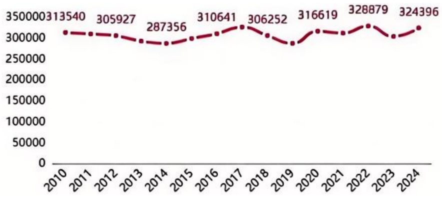


Figure 1. Time Series Chart of the Number of Cultural Heritage Institutions in China (2010-2024)

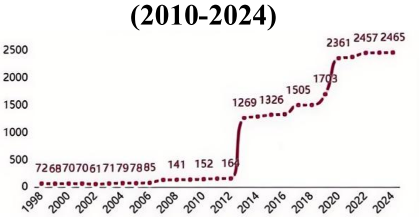


Figure 2. Time Series Chart of the Number of Other Macro-level Cultural Heritage Institutions in China (1998-2024)

2.2 Problems Encountered in Monitoring

The challenges confronting ancient building restoration monitoring are multifaceted. The core issues stem from the fundamental principles of "restoring the old as old" and "minimal intervention." The Cultural Relics Protection Law of the People's Republic of China, implemented on March 1, 2025, legally enshrines the "principle of minimal intervention" for the first time, emphasizing the maintenance of authenticity, integrity, and historical information with the least possible artificial interference while ensuring the safety of the cultural relics. These principal mandates that monitoring methods must be non-destructive or minimally destructive, prohibiting arbitrary drilling, sampling, or destructive testing common in modern building assessment [3]. However, many current high-precision detection techniques retain a degree of invasiveness or require direct contact with structural components, often facing stringent restrictions in ancient building conservation practice. Ling Ming, President of the China Academy of Cultural Heritage, noted that issues such as lack of research, excessive intervention, and improper maintenance exist in current cultural relic building restoration, necessitating joint responses at both institutional and technical specification levels [4].

Secondly, ancient building monitoring lacks a clearly defined threshold system, hindering quantitative health assessment. The cornerstone of modern SHM lies in establishing scientific early warning thresholds. However, due to material aging, structural degradation, and complex historical changes, the boundary between "healthy" and "deteriorated" states in ancient buildings is often ambiguous. Traditional monitoring relies heavily on empirical judgment, while the criteria for "health" vary significantly among buildings of different materials, structural types, and ages, rendering a universal quantitative model inapplicable. On the one hand, formulating specific indicator warning thresholds suffers from insufficient foundational data accumulation and weak research capacity, leading to imperfect early warning mechanisms and difficulty in issuing timely and effective risk alerts. On the other hand, existing monitoring indicator systems often fail to adequately consider the material characteristics, conservation status, and value attributes of different cultural relic types, resulting in insufficient precision and effectiveness. Research indicates that achieving precise quantification of monitoring and early warning indicators is a key technical challenge urgently requiring resolution in current ancient building safety monitoring.

Thirdly, some monitoring initiatives exhibit an over-reliance on technological equipment, leading not only to resource wastage but also diminishing the application value of traditional monitoring methods and empirical knowledge. Should technical equipment malfunction or conditions become unsuitable, monitoring efforts can be severely impacted. Finding synergy between advanced technologies like IoT sensors and digital twins, and traditional methods such as craftsman visual inspection and experiential judgment, is a critical issue facing the field of ancient building monitoring. Furthermore, monitoring gaps persist in some remote areas and lower-tier protected cultural relic sites, hindering the timely detection and early warning of potential risks to the heritage structure and its surrounding environment. President Ling Ming particularly emphasized the need to move away from the rudimentary "completion is the end" model in cultural relics protection and restoration, advocating for a research-oriented restoration concept to avoid an engineering-centric tendency [4]. The combined effect of these issues makes the practical implementation of monitoring during ancient building restoration exceedingly challenging, urgently requiring systematic technological breakthroughs and institutional improvements.

3. Health Monitoring Methods for Ancient Building Restoration

3.1 Traditional Monitoring Methods

Traditional methods for monitoring ancient buildings primarily rely on manual inspection, visual observation, hammer tapping for acoustic assessment, and conventional surveying instruments such as steel rulers, levels, and theodolites (see Figure 3). These methods have long played a foundational role in ancient building conservation, offering advantages like ease of operation, low cost, and minimal equipment requirements, while leveraging the intuitive judgment capabilities of experienced craftsmen and experts. However, their limitations are equally prominent: high subjectivity leading to variability in results; limited precision, insufficient for detecting minute deformations and early-stage damage; poor timeliness, unable to provide continuous, real-time condition tracking; and a lack of systematic data accumulation and analysis mechanisms, making it difficult to reveal the evolutionary patterns of structural deterioration. In the contemporary pursuit of increasingly refined and scientific cultural relics protection, these shortcomings of traditional methods are becoming ever more apparent.

Figure 3. Traditional Monitoring Instruments (from Left to Right: Level, Theodolite, Total Station)

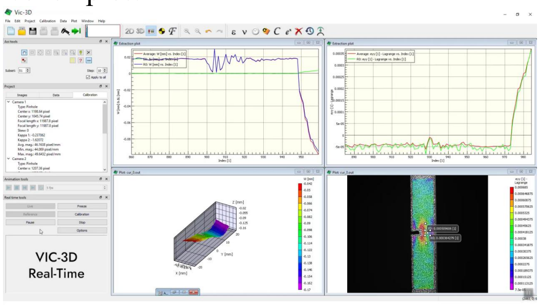
3.2 Non-Destructive Testing (NDT) Techniques

Non-destructive testing (NDT) techniques represent the most promising technological approach in the field of ancient building monitoring. Their core principle lies in accurately obtaining information on the internal condition of the structure and material properties without damaging the heritage object (see Figure 4). For instance, VIC-3D technology enables the collection of deformation data through remote photography, avoiding traditional contact-based operations like affixing strain gauges or installing displacement meters on precious wooden carvings or masonry surfaces, thereby effectively protecting the cultural relic itself (see Figure 4).

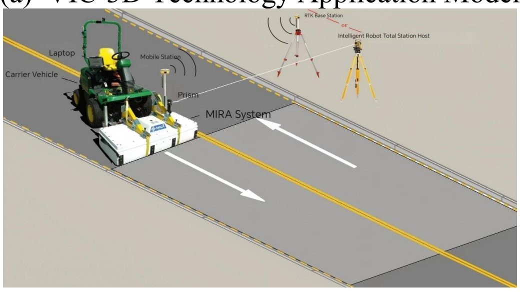
Beyond non-contact optical measurement techniques, ultrasonic testing demonstrates unique advantages in detecting internal defects within wooden components. Wood, a primary material in ancient buildings, is susceptible to insect infestation, decay, and moisture-induced changes due to long-term environmental exposure, forming internal voids and cracks that are invisible to the naked eye and severely threaten structural safety. Ultrasonic testing involves transmitting sound waves into wooden components; variations in wave propagation velocity and attenuation across regions of differing material density or integrity allow for the precise localization of internal defects regarding position, size, and severity, all without surface damage.

Scholars like Jiang Weile have systematically summarized NDT technology systems, noting that virtual reconstruction enables digital preservation and restoration of timber-frame ancient buildings, infrared thermography identifies defects like cracks and delamination based on material thermophysical property differences, terrestrial LiDAR can assess the structural safety status of historical buildings, and ultrasonic testing excels in detecting internal decay, voids, and cracks within wooden structures [5].

In recent years, Ground Penetrating Radar (GPR) technology has seen increasing application in monitoring masonry ancient buildings. By emitting high-frequency electromagnetic waves that penetrate structures like walls and foundations, GPR utilizes the distinct reflection characteristics of different media to clearly identify latent defects such as mortar joint deterioration, areas of inadequate masonry bonding, foundation voids, and subsidence. Its non-invasive nature minimally impacts the appearance and structural integrity of ancient buildings, making it particularly suitable for surveying large-scale immovable masonry cultural relics like the Great Wall and cave temples.

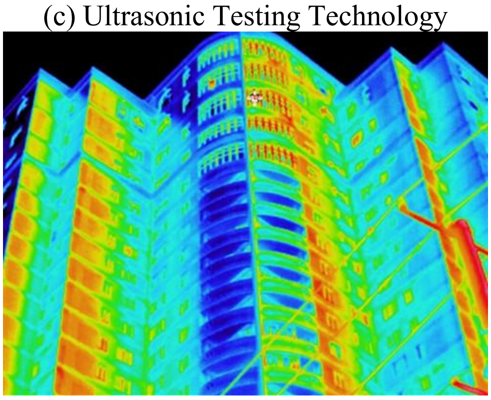


(a) VIC-3D Technology Application Model



(b) Ground Penetrating Radar Technology

(c) Ultrasonic Testing Technology



(d) Infrared Thermography Technology

Figure 4. Non-Destructive Testing Technology

Various NDT techniques possess distinct specializations. They can be applied individually based on material type or defect characteristics, or combined in a multi-technology approach to achieve mutual verification of detection results, significantly enhancing the accuracy of defect identification and performance assessment. This technical pathway adheres to the "minimal intervention" principle of cultural relics conservation while meeting the informational demands of structural health assessment. It effectively resolves the core conflict where traditional contact-based monitoring methods may damage the heritage object, providing a scientific basis for formulating precise restoration plans and avoiding the impairment of heritage value through ill-informed construction interventions.

3.3 Dynamic Characteristics Monitoring Technology

Dynamic characteristics monitoring technology is grounded in the principles of structural dynamics. By measuring the vibration response of ancient buildings under ambient or artificial excitation, it extracts dynamic parameters such as natural frequencies, damping ratios, and mode shapes, thereby enabling non-destructive assessment of overall structural stiffness, integrity, and damage state. In practical applications, this technique typically employs accelerometers, velocity sensors, or displacement sensors to capture structural vibration signals, processed by data acquisition units and signal analysis software (see Figure 5). For example, sensor arrays deployed at critical locations on an ancient building (e.g., beam frames, columns, roofs) can capture vibration time-history curves at various points. Modal analysis methods are then applied to identify the inherent dynamic characteristics of the structure. As structural dynamic parameters are closely related to physical properties (mass, stiffness, damping), damage in an ancient building manifest as stiffness changes, leading to decreased natural frequencies, increased damping ratios, or anomalies in mode shapes. Comparing changes in dynamic parameters over different periods effectively aids in determining the occurrence, progression, and potential location of structural damage, providing a crucial basis for structural health assessment and safety early warning. Compared to traditional static monitoring methods, dynamic characteristics monitoring better reflects the overall dynamic performance of the structure, making it particularly suitable for assessing the global stability and seismic performance of large, complex ancient building structures.

Figure 5. Various Sensor Elements

3.4 Environmental and Deformation Monitoring Technology

Environmental and deformation monitoring technology constitutes an integral component of the comprehensive SHM system for ancient buildings. It primarily focuses on the influence of external environmental factors on the structure and the structure's corresponding deformation responses. Environmental factors typically encompass temperature, humidity, sunlight exposure, precipitation, wind loads, atmospheric corrosive agents, and ground microtremors. Through systematic analysis of environmental factors affecting masonry ancient buildings, Shen Shu et al. categorized influencing factors into internal, chemical, physical, and biological types, selecting physical parameters like ambient temperature, ambient humidity, light intensity, PM2.5 concentration, CO_2 concentration, wind speed, wind direction, rainfall, and vibration as monitoring targets [2]. Deploying sensors such as thermo-hygrometers, rain gauges, anemometers, corrosive gas monitors, and microtremor sensors around and at key points of ancient buildings enables real-time collection of these environmental parameters. For instance, significant temperature fluctuations can induce thermal expansion and contraction in building materials, potentially causing cracks over time. Humidity variations can accelerate wood decay, stone weathering, and metal component corrosion. Deformation monitoring aims to precisely measure physical changes such as displacement, settlement, inclination, and crack width variation in ancient building structures under various internal and external influences. Common methods include periodic settlement and inclination surveys using total stations and levels, long-term monitoring of critical joint displacements and crack propagation using crack meters and displacement transducers, and increasingly employed real-time dynamic monitoring technologies like GPS or GNSS, which allow high-precision, automated continuous observation of overall three-dimensional displacements (see Figure 6). For components with unique forms or significant value, like pagoda finials, upturned eaves, or arches, techniques such as photogrammetry and 3D laser scanning are employed to acquire detailed surface deformation data. Comprehensive analysis integrating environmental parameters and deformation data can reveal intrinsic links between environmental actions and structural responses, assess the safety and durability of ancient buildings under environmental stressors, and provide a scientific basis for determining operational status and predicting deformation trends. For example, persistent differential settlement may indicate foundation issues, while progressive tilting in a specific direction might signal insufficient overall structural stability, necessitating timely intervention.

Figure 6. Various Environmental Monitoring Equipment

3.5 Digitalization and Intelligent Monitoring Technology

Intelligent monitoring technology and its digital support framework represent the frontier in contemporary ancient building conservation. The core involves the deep integration of technologies such as Building Information Modeling (BIM), Digital Twins, IoT sensors, Unmanned Aerial Vehicles (UAVs), and Computer Vision to construct an integrated intelligent monitoring system encompassing "sensing–transmission–analysis–early warning" (see Figure 7). Regarding BIM and IFC standard applications, Wang Yakang et al. proposed an IFC-based information extension model for monitoring deterioration in timber-frame ancient buildings. They classified deterioration information into nine types: cracks, decay, voids, inclination, settlement, leaning, loose tenon joints, deflection, and slippage. Based on the entity semantic definitions of "Accuracy" and attribute "Richness," they proposed an IFC standard extension method and established the

IFC-based deterioration monitoring information model. This provides essential data format support for real-time monitoring and visual management of monitoring systems for ancient timber structures [6]. Sun Xiaoyang et al., using the Nanjing Lishui Chenghuang Temple project as a case study, developed a digital and intelligent monitoring platform for the preventive conservation of ancient buildings based on Unity. The platform comprises four core modules: Homepage, 3D Model Display & Interaction, Real-time Termite Monitoring, and Patrol Records & Analysis. Through a 3D digital twin model, it offers users an intuitive means to view monitoring conditions across different parts of the ancient building, achieving digital monitoring and management [7]. Addressing the complexity and low predictability of fires in Tibetan ancient buildings, Huang Juan et al. designed an intelligent mobile monitoring system integrating ZigBee and the Android platform. This involved designing the ZigBee wireless sensor network, developing the Android client application, and implementing relevant middleware, with sensor-collected data uploaded to the client via GPRS [8]. Xiong Qian et al. proposed a fire monitoring method for the restoration phase of ancient buildings based on a YOLO-BP neural network. Using fire source temperature, distance between the fire source and combustibles, and wind speed as monitoring indicators, a BP neural network fire monitoring model was constructed. Training and testing yielded an accuracy of 93.9%, with an average response time of 16 seconds in fire scenarios [9]. Li Tianhao et al. established the first SHM Benchmark platform for ancient timber building structures globally, facilitating standardized validation and comparison of various monitoring methods through the synergy of physical models, numerical models, and a supporting website [10]. Liu Zichang et al. leveraged digital twin technology to achieve real-time mapping and dynamic updating between on-site monitoring data and virtual models, establishing an automated early warning mechanism triggered by thresholds [11]. At the perception level, self-developed low-power vision devices and UAV systems enable non-contact, high-precision monitoring of key indicators like displacement and cracks. At the analysis level, methods such as Convolutional Neural Networks (CNNs) and Variational Mode Decomposition (VMD) effectively enhance the depth of strain data mining and predictive capabilities. Compared to traditional methods reliant on manual inspection and empirical judgment, digital intelligent monitoring significantly improves real-time capability, accuracy, and data utilization efficiency, propelling the shift in ancient building conservation from "remedial restoration" towards "preventive conservation."

Figure 7. Architectural Structural BIM Modeling Rendering

3.6 Comparative Analysis with Traditional Methods

Compared to traditional methods, modern monitoring technologies achieve qualitative leaps across multiple dimensions. Regarding data acquisition, traditional methods largely depend on manual periodic inspections, which are not only time-consuming and labor-intensive but also susceptible to subjective experience, environmental conditions, and time constraints. This hinders the continuous, dynamic capture of the structural state of ancient buildings, often yielding only discrete, localized data points. In contrast, modern monitoring technologies, through the deployment of various sensors and intelligent sensing devices, enable real-time, continuous, and automated acquisition of mechanical responses, deformation characteristics at critical structural locations, and surrounding environmental parameters. The data coverage is broader and denser, providing massive, detailed raw data essential for comprehensively understanding the structural health status of ancient buildings. In terms of data analysis and interpretation, traditional methods rely primarily on technicians' empirical judgment of limited monitoring data. The analytical process is highly subjective, with limited capacity to extract latent patterns and early damage signals inherent in the data, making timely and accurate warnings difficult to ensure. Modern monitoring technologies integrate advanced techniques such as machine learning, deep learning, and digital twins. By constructing numerical models and training intelligent algorithms, they enable deep mining, intelligent analysis, and trend prediction from the vast amounts of collected data. This allows not only the precise identification of minute structural changes and early signs of damage but also data-driven automated early warning, significantly enhancing the intelligence level and decision-support capability of monitoring. Furthermore, concerning monitoring efficiency and cost-effectiveness, the traditional manual inspection model incurs high long-term labor costs and struggles to achieve all-weather, high-frequency monitoring. Although modern monitoring technologies involve relatively high initial equipment investment and system setup costs, once operational, they substantially reduce long-term labor maintenance costs and achieve efficient, continuous monitoring. The overall benefits become increasingly prominent over the monitoring lifecycle, especially for large-scale, significant, or inaccessible ancient building complexes, where the advantages are markedly more pronounced.

4. Standards Relevant to Health Monitoring in Ancient Building Restoration

As SHM technology for ancient buildings advances rapidly, the corresponding system of relevant standards and specifications is being developed and refined concurrently. These standards provide normative foundations for various aspects of ancient building monitoring work, encompassing monitoring system design, technical methodologies, data acquisition and processing, and safety early warning. Based on the structural typology of ancient buildings, the principal current standards can be categorized into those applicable to timber-frame ancient buildings and those for masonry ancient buildings, as detailed in Table 1.

Table 1. Relevant Standards for Health Monitoring in Ancient Building Renovation

Standard Number	Standard Name	Structural Type	Release Time	Scope of Application and Main Content
GB/T 50165-2020	Technical Standard for Maintenance and Strengthening of Ancient Timber Buildings	Timber Structures	2020-01-16	National standard. Covers project monitoring, structural appraisal and rating, seismic appraisal, etc. Appendices D and E specify requirements for deformation and temperature/humidity monitoring.
T/CECS 1392-2023	Standard for Design of Structural Monitoring System for Ancient Buildings	Timber Structures and Masonry Structures	2023-08-02	Association standard. Applicable to the design of monitoring systems for ancient timber and masonry structures. Comprises 7 chapters and 2 appendices, covering sensor subsystems, data acquisition and transmission, monitoring platforms, and safety early warning modules.
T/CSGPC 016-2023	Technical Specification for Health Monitoring of Cultural Relic Buildings	Comprehensive Structures	2023-12-12	Association standard, which specifies the basic requirements for health monitoring of cultural heritage buildings, monitoring methods (deformation, stress and strain, environment, biological diseases, soil quality), data collection and inspection, data processing and analysis, and technical reports
T/ZZ13 Q068-2024	Technical Specification for Intelligent Safety Monitoring of Cultural Relic Buildings	Comprehensive Structures	2024-11-12	Zhejiang Provincial Association standard. Addresses technical requirements for intelligent safety monitoring of cultural relic buildings.
DB14/T 3191-2024	Technical Code for Safety Appraisal of Timber Structures in Ancient Buildings	Timber Structures	2024-12-31	Shanxi Provincial local standard. Applicable to the safety appraisal of timber structural components within ancient buildings.
DBJ/T 13-502-2025	Technical Standard for Safety Monitoring of Ancient Buildings	Comprehensive Structures	2025-09-16	Fujian Provincial Engineering Construction local standard. Focuses on classified requirements for structural safety monitoring and environmental safety monitoring. Details monitoring methods for key indicators like settlement, inclination, cracking, and stress-strain, and establishes a three-tier early warning mechanism.

As evident from Table 1, China's standard system for ancient building monitoring is rapidly taking shape. Various regions, considering the unique characteristics and conservation needs of their local heritage buildings, have successively issued pertinent association and local standards. For instance, Zhejiang Province's T/ZZ13 Q068-2024 Technical Specification for Intelligent Safety Monitoring of Cultural Relic Buildings focuses on the technical requirements for intelligent safety monitoring, reflecting the emphasis on intelligent monitoring approaches. Shanxi Province's DB14/T 3191-2024 Technical Code for Safety Appraisal of Timber Structures in Ancient Buildings specifically addresses safety appraisal for timber structural components—a critical aspect of ancient building conservation—highlighting the specialized nature of timber structure preservation. Fujian Province's DBJ/T 13-502-2025 Technical Standard for Safety Monitoring of Ancient Buildings, as a local engineering construction standard, focuses on the classified requirements for structural and environmental safety monitoring, elaborates on monitoring methods for key indicators (settlement, inclination, crack, stress-strain), and establishes a three-tier early warning mechanism, offering more concrete and actionable guidance for practical monitoring implementation. The formulation and implementation of these standards, covering aspects of comprehensive monitoring, specific structure type (e.g., timber) monitoring, and intelligent monitoring, collectively drive the standardization and systematization of health monitoring work in ancient building restoration, providing robust technical support and reference for the conservation of ancient buildings of diverse types and geographic locations.

5. Prospects for Health Monitoring in Ancient Building Restoration

5.1 Development History

The evolution of health monitoring technology for ancient buildings can be broadly delineated into three phases.

Phase 1: Traditional empirical stage. The restoration and maintenance of ancient buildings primarily relied on the experiential judgment of craftsmen and traditional visual inspection methods. During this phase, craftsmen, drawing upon long-accumulated practical experience, assessed the preservation state and safety risks of ancient buildings by observing intuitive phenomena such as overall appearance, structural deformation, wood decay extent, and tile breakage. For example, assessing structural stability involved observing whether beam frames exhibited noticeable bending or tilting, whether columns showed signs of settlement or decay, and whether walls exhibited cracks or bulging. While this approach could identify relatively significant issues to some extent and offered simplicity and low cost, it lacked systematic rigor and scientific basis. It was highly subjective, making precise, quantitative assessment of internal damage, subtle deformations, and potential safety hazards challenging. The results depended heavily on the individual inspector's experience, leading to potential discrepancies in assessments by different craftsmen.

Phase 2: Initial intervention of monitoring technology. With the advancement of modern engineering inspection technologies, basic detection instruments began to be introduced into the field of ancient building conservation. Examples included ultrasonic flaw detectors for identifying internal voids and defects in timber, rebound hammers for auxiliary assessment of surface strength in masonry structures, and rebar scanners for locating reinforcing bars and assessing corrosion in concealed components. The introduction of these technologies partially compensated for the limitations of traditional empirical methods, enabling preliminary quantitative detection of certain physical and mechanical properties of ancient buildings and providing more objective data support for structural assessment. Compared to the previous phase, monitoring methods in this stage acquired a degree of scientific basis and objectivity, reducing some subjective influences and facilitating a transition from purely qualitative descriptions to semi-quantitative analysis of structural damage, thereby laying a foundation for more in-depth subsequent monitoring research.

Phase 3: Intelligent monitoring and preventive conservation stage. Entering the second decade of the 21st century, SHM for ancient buildings has experienced a qualitative leap. Foundational technologies like IoT sensors and wireless communication, coupled with mature data acquisition methods such as 3D laser scanning and UAV remote sensing, have enabled real-time, continuous, multi-parameter monitoring of ancient buildings. Cutting-edge technologies including Artificial Intelligence (AI), Digital Twins, and Distributed Fiber Optic Sensing have further enhanced the intelligence and precision of monitoring. Jiang Weile et al. highlighted the prominent advantages of Fiber Bragg Grating (FBG) sensors in monitoring timber-frame ancient buildings, noting their capability for multi-point cascaded multiplexing, high sensitivity, and multi-point monitoring, enabling real-time monitoring of strain and temperature at multiple critical points within timber structures [5]. The standard system has evolved from nonexistent to nascent and from fragmented to systematic, with the successive release of standards for structural monitoring system design, vibration control technology, and local safety monitoring technical standards. The monitoring philosophy has shifted from passive response—"repair upon discovering damage"—to active prevention—"preventing issues before they arise"—signifying that ancient building conservation has entered a new era of "preemptive preservation."

5.2 Development Trends

Several significant development trends are evident in the current field of ancient building health monitoring.

Firstly, multi-source heterogeneous data fusion will become a key direction for enhancing monitoring efficacy. Future monitoring systems will no longer be limited to information acquisition from a single sensor type. Instead, they will integrate diverse physical quantity data—structural vibration, strain, displacement, ambient temperature and humidity, light intensity, atmospheric pollutants—and combine this with multi-dimensional information such as historical restoration records, building material properties, and surrounding geological and hydrological conditions. Shen Shu et al. have already proposed methods for in-depth analysis of ancient building health status by integrating multi-source information fusion theory and predictive algorithms to support management decision-making [2]. Through big data analytics and AI algorithms, deep mining and correlative interpretation of this heterogeneous data will be achieved, enabling more comprehensive and accurate assessment of the structural health status of ancient buildings and revealing the potential mechanisms underlying deterioration processes.

Secondly, monitoring sensor devices will evolve towards higher precision, smaller dimensions, lower power consumption, and enhanced environmental adaptability. Miniaturized, intelligent sensors will allow for more discreet, longer-term monitoring without compromising the aesthetics or structural integrity of ancient buildings. For instance, the application of flexible or wearable sensors could enable precise sensing on complex curved surfaces or fragile components. Concurrently, advancements in communication technologies like Low-Power Wide-Area Networks (LPWAN) will effectively resolve data transmission challenges for monitoring ancient buildings in remote areas, ensuring stable network operation.

Thirdly, Digital Twin technology and immersive visualization will provide an integrated paradigm of data-driven dynamic monitoring–simulation prediction–immersive interaction for ancient building conservation. By constructing a digital twin that comprehensively maps the physical ancient building, it becomes possible not only to synchronize structural state data in real-time but also to simulate structural responses under various environmental conditions and load scenarios, thereby predicting potential risks. Sun Xiaoyang et al. noted the immense potential and value of digital technologies in the conservation and management of ancient buildings, highlighting that establishing a comprehensive and efficient digital monitoring and management system enables real-time monitoring of diverse building states and provides crucial decision support for managers [7]. Coupled with Virtual Reality (VR) and Augmented Reality (AR) technologies, managers can intuitively and immersively examine monitoring data, structural details, and the evolution of deterioration, providing robust support for restoration decision-making, emergency response, and public education.

Fourthly, intelligent early warning and autonomous decision-support systems based on algorithms like deep learning will achieve a leap from "passive monitoring" to "active early warning" and further to "intelligent decision-making." Leveraging deep learning algorithms, systems will be capable of real-time analysis of monitoring data, automatic identification of anomalous patterns, and proactive issuance of deterioration warnings. Xiong Qian et al.'s BP neural network-based fire monitoring model, which achieved error convergence after 14 iterations during training and attained 93.9% monitoring accuracy with an average response time of 16 seconds in fire scenarios, validates the applicability of intelligent algorithms in the field of ancient building monitoring [9]. More advanced systems could potentially integrate historical case data and expert knowledge to provide preliminary recommendations for restoration interventions and optimization directions for conservation plans, assisting managers in making rapid, scientifically informed decisions.

Finally, against the backdrop of collaborative development in world cultural heritage conservation, the internationalization and unification of standards and specifications for ancient building monitoring will accelerate. As conservation philosophies propagate globally and transnational collaborations increase, establishing a widely recognized set of international common specifications covering monitoring indicators, technical methods, data processing, and assessment criteria will enhance the comparability of monitoring data and the synergy of conservation efforts, fostering the collective advancement of global ancient building preservation.

6. Conclusion

Structural health monitoring of historical ancient buildings constitutes an interdisciplinary subject integrating engineering technology, heritage conservation theory, and cultural heritage studies. Its importance has become increasingly prominent with the deepening development of China's cultural heritage preservation endeavors. This paper has systematically reviewed the current status, methodologies, standards, and prospects of health monitoring in the restoration and reinforcement of ancient buildings in China, drawing the following primary conclusions:

(1) Regarding the current status: The scale of ancient building restoration and conservation projects in China continues to expand. During the "14th Five-Year Plan" period, nearly 2,000 key national-level cultural relics protection and restoration projects have been actively promoted, and digital archiving has been completed for 12,000 immovable cultural relics nationwide [1]. However, monitoring practice still confronts multiple challenges: the principles of "restoring the old as old" and "minimal intervention" impose stringent requirements for non-destructive or minimally destructive testing techniques; quantitative standards and early warning thresholds for health assessment of ancient buildings remain lacking; and instances of over-reliance on technological equipment, potentially diminishing the value of traditional expertise, persist in some regions.

(2) Regarding methodologies: A diverse technological system encompassing NDT, dynamic characteristics monitoring, environmental and deformation monitoring, and digitalization and intelligent monitoring has been established for ancient building health monitoring. Techniques such as ultrasonic timber testing, micro-drilling resistance measurement, stress wave detection, 3D laser scanning, fiber optic sensor networks, and AI-based crack identification each possess unique strengths and complement one another. In practice, a clear trend towards multi-technology fusion is emerging, driving the transformation of ancient building conservation from "remedial restoration" to "preventive conservation."

(3) Regarding standards: A preliminary standard framework covering maintenance and strengthening, inspection and appraisal, monitoring system design, and vibration control has been established for different types of ancient buildings, particularly timber and masonry structures. The release of national and association standards such as GB/T 50165-2020 and T/CECS 1392-2023, along with local standards from provinces like Fujian and Shanxi, signifies a move towards the standardization and systematization of ancient building monitoring practices.

(4) Regarding future prospects: SHM for ancient buildings will continue to evolve towards greater intelligence, refinement, and synergy. Intelligence focuses on the autonomous decision-making capacity of monitoring systems, achieving full-process automation from data collection to risk early warning through IoT sensor networks and deep learning algorithms.

(5) With the further penetration of technologies such as IoT, Big Data, and AI, monitoring systems will achieve end-to-end automation from data acquisition to intelligent early warning. For instance, real-time analysis of massive monitoring data using deep learning algorithms will enable precise identification of potential structural risks and proactive issuance of alerts, providing more scientific decision support for the preventive conservation of ancient buildings.

In summary, while the technical system for health monitoring in ancient building restoration has been preliminarily established, a gap remains before it can fully meet conservation demands. Future efforts should persistently focus on improving standard systems, fostering technological innovation and breakthroughs, cultivating and attracting talent, and ensuring robust funding mechanisms. It is anticipated that, in the not-too-distant future, every treasured historical ancient building will possess its own dedicated "health record," enabling it to endure even longer historical timescapes under the guardianship of science and wisdom, thereby preserving the brilliance of civilization for future generations.

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