

Review

# Technical Challenges and Practical Approaches in Structural Restoration of Ancient Buildings

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**Abstract:** Structural restoration of ancient buildings plays a vital role in preserving cultural heritage and ensuring the longevity of historic architecture. This review analyzes the key technical challenges faced in restoring ancient structures, including material compatibility, aging and deterioration mechanisms, limitations of traditional and advanced inspection methods, design complexities, and environmental constraints during construction. Practical approaches such as the development and application of compatible materials, integration of advanced non-destructive testing technologies, innovative reinforcement techniques, and effective project management are discussed. Furthermore, emerging trends involving digital technologies like BIM and IoT-based monitoring, eco-friendly high-performance materials, interdisciplinary collaboration, and skill preservation are highlighted as essential for future advancements. This synthesis aims to guide conservation professionals in balancing authenticity, structural safety, and sustainability in the complex task of ancient building restoration.

**Keywords:** ancient building restoration; structural repair; non-destructive testing; reinforcement techniques

## 1. Introduction

Ancient buildings are invaluable cultural heritage assets that embody the architectural ingenuity, social history, and artistic expression of past civilizations. The structural restoration of these edifices plays a critical role in preserving not only their physical form but also the historical narratives and cultural identity they represent. As many ancient buildings have endured centuries or even millennia of environmental exposure, natural aging, and human intervention, their structural integrity often deteriorates, threatening their survival. Effective restoration of these structures ensures that future generations can continue to access and learn from these tangible links to the past [1].

The structural systems of ancient buildings are often fundamentally different from modern constructions, characterized by unique materials, construction techniques, and design philosophies specific to their historical contexts. For example, timber-framed temples, load-bearing masonry walls, and earthen architecture each possess distinct vulnerabilities and maintenance requirements. Furthermore, the conservation of these structures necessitates a delicate balance between ensuring structural safety and maintaining historical authenticity. Excessive intervention or inappropriate materials can lead to irreversible damage, loss of cultural value, or distortion of the building's original character. Consequently, the structural restoration of ancient buildings presents complex technical and ethical challenges.

Given these complexities, this paper aims to comprehensively analyze the key technical challenges encountered in the structural restoration of ancient buildings. It also

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explores practical approaches and solutions currently employed by conservation professionals to address these challenges effectively. Particular emphasis is placed on the issues of material compatibility, structural health assessment, repair and reinforcement strategies, and site-specific construction constraints [2,3]. By synthesizing current research findings, case studies, and emerging technologies, this review seeks to provide guidance for practitioners and researchers involved in heritage conservation.

The scope of this study covers a broad overview of ancient building structures, their common degradation patterns, and the multifaceted challenges they pose for restoration engineers. It includes an examination of innovative materials and nondestructive evaluation techniques that enhance the precision and durability of structural interventions. Additionally, the paper discusses modern reinforcement methods that reconcile the often competing demands of structural performance and cultural preservation. Case studies highlighting exemplary restoration projects further illustrate how theory translates into practical, site-specific applications. Finally, future trends such as digital technologies and smart materials are considered as promising avenues for advancing ancient building structural restoration.

In summary, this introduction sets the stage for a detailed exploration of the technical and practical dimensions of ancient building structural restoration. It underscores the importance of adopting scientifically sound, culturally sensitive, and sustainable approaches to conserve these irreplaceable monuments. The subsequent sections delve deeper into the specific challenges and methods, providing a comprehensive resource for advancing the field of heritage structural conservation [4].

## 2. Overview of Ancient Building Structures and Their Vulnerabilities

### 2.1. Common Structural Types of Ancient Buildings

Ancient buildings worldwide utilize a variety of structural systems, primarily shaped by regional materials, climatic conditions, and cultural heritage. Timber frameworks are predominant in East Asia, Europe, and parts of North America. These structures emphasize the use of large wooden beams and sophisticated joinery techniques, often assembled without nails or metal fasteners. Timber's natural tensile strength and flexibility make it ideal for seismic-prone areas, but it also introduces vulnerabilities such as susceptibility to insect infestation and fungal decay.

Masonry construction, including stone and brickwork, is widespread in Mediterranean, Middle Eastern, and European regions. Stones like limestone, sandstone, granite, and marble are chosen based on local availability and desired aesthetics. Bricks, typically made of fired clay, vary in size and composition depending on historical periods and locations [5]. Masonry's high compressive strength allows for durable load-bearing walls but makes it vulnerable to tensile stresses, leading to cracking and disintegration.

Table 1. summarizes the common structural types along with their typical materials and associated vulnerabilities, providing a clear reference for understanding their conservation challenges.

**Table 1. Overview of Common Ancient Building Structural Types, Materials, and Vulnerabilities.**

Structural Type	Typical Materials	Key Characteristics	Common Vulnerabilities
Timber	Large wooden beams, timber joints	Flexible, good tensile strength	Insect infestation, fungal decay, moisture damage
Masonry	Stone (limestone, sandstone, granite, marble), fired clay bricks	High compressive strength, durable	Cracking, salt crystallization, weathering

Earth-based Rammed earth, adobe, clay	Good insulation, sustainable	Moisture erosion, material loss, freeze-thaw damage
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Earth-based structures such as rammed earth and adobe are common in arid regions, prized for their insulation and sustainability. However, these materials are particularly prone to erosion from moisture, resulting in structural weakness over time.

Understanding these structural types and their unique properties is critical for developing restoration strategies. Each system requires tailored conservation methods that address specific material behaviors and vulnerabilities.

## 2.2. Mechanisms of Material Deterioration

The deterioration of ancient building materials results from a complex interplay of physical, chemical, and biological factors, each contributing uniquely to the gradual degradation of historic structures. Physically, fluctuations in temperature cause repeated expansion and contraction within materials, generating microcracks that accumulate over time and reduce structural integrity. In regions with cold climates, freeze-thaw cycles pose a significant threat: water trapped within pores freezes and expands, exerting pressure that fractures stone, brick, and mortar [6]. Mechanical stresses, including load variations from occupancy, seismic activities, and environmental vibrations, further contribute to material fatigue and eventual failure.

Chemical deterioration predominantly stems from environmental pollutants such as sulfur dioxide ( $\text{SO}_2$ ) and nitrogen oxides ( $\text{NO}_x$ ). These pollutants react with atmospheric moisture to form acid rain, which attacks calcium carbonate-based stones by transforming them into gypsum—a more soluble and fragile compound prone to erosion. Additionally, salt crystallization presents a persistent issue, especially in structures near marine environments or exposed to de-icing salts. Salt ions penetrate porous materials and, upon crystallization, exert crystallization pressure leading to flaking, powdering, and surface loss. These chemical processes alter the original composition of materials and degrade their load-bearing capabilities.

Biological factors play a critical role in the decay of organic materials such as timber, widely used in traditional frameworks and decorative elements. Wood is particularly vulnerable to fungal rot, termite infestations, and wood-boring insects that consume the material, undermining its strength and functionality. On inorganic surfaces like stone and brick, colonization by algae, lichens, and mosses creates a microenvironment that traps moisture, exacerbating chemical and physical deterioration through prolonged wetting. The presence of biological growth can also stain surfaces and obscure decorative features, impacting the aesthetic value of historic buildings.

A summarized overview of these degradation mechanisms, including their causes and effects, is provided in Table 2. This comprehensive understanding facilitates accurate diagnosis and targeted interventions during restoration projects, allowing conservation professionals to select appropriate treatment methods that address the root causes of deterioration rather than merely its symptoms.

**Table 2. Main Mechanisms of Material Deterioration in Ancient Buildings.**

Deterioration Mechanism	Description	Typical Effects on Materials
Physical	Temperature changes causing expansion/contraction; freeze-thaw cycles; mechanical stresses and vibrations	Microcracks, fracturing, material fatigue
Chemical	Acid rain from $\text{SO}_2$ , $\text{NO}_x$ ; salt crystallization; pollutant reactions	Surface erosion, flaking, powdering, material weakening

Biological	Fungal decay, termite and insect attacks on wood; colonization by algae, lichens, mosses	Structural weakening, moisture retention, surface biodeterioration
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Addressing these multifaceted deterioration mechanisms requires an interdisciplinary approach combining material science, environmental monitoring, and biological control [7]. Restoration strategies must be tailored to the specific materials and environmental conditions of each site, ensuring that treatments do not introduce new vulnerabilities. For example, consolidants and protective coatings can mitigate physical erosion and chemical attack, but their compatibility and long-term effects must be carefully evaluated to avoid damage to original materials.

In conclusion, understanding the physical, chemical, and biological processes responsible for material degradation is fundamental to preserving the structural and cultural integrity of ancient buildings. Such knowledge guides the development of more effective conservation techniques and prolongs the lifespan of these irreplaceable cultural heritage assets.

### 2.3. Common Forms of Structural Damage

Ancient structures commonly exhibit a range of damage forms that threaten both their stability and cultural significance. Cracks are among the most visible and concerning forms of damage. They may manifest as superficial hairline fissures or deep fractures that compromise load-bearing capacity [8]. Cracking often results from uneven settlement, thermal stress, or mechanical overload and can lead to further material loss if left untreated.

Settlement and foundation failures cause structural distortions, tilting, and increased stress concentrations. Soil subsidence or changes in groundwater levels may exacerbate these problems, necessitating foundation stabilization. Corrosion of embedded metal elements such as iron nails, bolts, or reinforcements induces expansive forces that crack surrounding masonry or timber. Moisture ingress is a common factor that accelerates all these damage processes by weakening materials and fostering biological growth.

Biological deterioration, particularly in timber structures, causes significant strength loss. Termites, beetles, and fungi degrade wooden beams, requiring careful assessment and treatment. In masonry, biological colonization retains moisture, promotes chemical reactions, and causes surface disintegration [9].

The coexistence of these damage types complicates restoration efforts, requiring integrated diagnostic approaches to address the root causes effectively.

### 2.4. Balancing Structural Safety and Heritage Conservation

Restoring ancient buildings demands a delicate balance between enhancing structural safety and preserving historical authenticity. Overly aggressive interventions risk damaging original materials or obscuring historical craftsmanship, while insufficient repairs may leave structures vulnerable to collapse. Therefore, restoration materials and techniques must be carefully selected for compatibility, reversibility, and minimal visual impact.

Modern materials such as fiber-reinforced polymers, nano-consolidants, and eco-friendly binders offer new possibilities for reinforcement and protection. However, their long-term effects on heritage fabric remain under study, requiring cautious application. Reversible interventions that can be undone without damage are preferred to allow for future improvements based on advancing knowledge.

Successful restoration requires multidisciplinary collaboration among engineers, conservation scientists, architects, and historians. Such teamwork ensures interventions meet structural requirements without compromising the building's cultural and historical significance.

Through these integrated efforts, ancient structures can be preserved safely and authentically for future generations.

### **3. Key Technical Challenges in Structural Restoration**

#### *3.1. Material Compatibility and Selection Challenges*

One of the foremost challenges in the structural restoration of ancient buildings lies in selecting repair materials that are physically and chemically compatible with the original construction materials. Ancient structures were built using materials that have undergone centuries of aging, environmental exposure, and microstructural changes. Introducing new materials without proper compatibility assessment risks causing adverse interactions such as differential thermal expansion, chemical reactions, or moisture entrapment, which can accelerate deterioration instead of preventing it [10]. For example, applying modern Portland cement-based mortars on historic lime-based masonry often leads to brittle joints and trapped moisture, resulting in cracking and material loss.

Furthermore, the inherent heterogeneity and uncertain performance of old materials complicate repair decisions. The physical and mechanical properties of aged stones, bricks, and timbers may have significantly degraded or altered, making it difficult to predict how they will interact with new restoration materials. Non-uniform aging within the same element further complicates compatibility evaluation. Therefore, restorers must conduct thorough material characterization and often customize repair mortars, consolidants, or reinforcements to align with the existing material properties. This process requires interdisciplinary collaboration between material scientists, conservators, and engineers to balance durability with authenticity.

#### *3.2. Limitations in Structural Inspection and Health Assessment Technologies*

Accurate detection and evaluation of structural health is critical for the planning and monitoring of restoration interventions. Traditional nondestructive testing (NDT) methods such as visual inspection, hammer sounding, and simple ultrasound have been the mainstay for decades [11]. While these techniques are valuable for identifying surface cracks, delamination, or gross defects, they often lack the sensitivity to detect subsurface or hidden damages. This limitation poses risks when defects remain undetected, potentially leading to inadequate repair strategies or sudden failures.

Modern NDT technologies, including ground-penetrating radar (GPR), infrared thermography, laser scanning, and acoustic emission monitoring, have significantly improved the detection capabilities. However, their application in ancient structures often encounters challenges such as complex geometry, heterogeneity of materials, and limited accessibility of structural components. For instance, masonry walls with irregular thicknesses or timber elements obscured by plaster reduce the reliability of some imaging techniques. Additionally, interpretation of the data requires specialized expertise, and the high cost of advanced equipment may restrict their widespread use. Hence, integrating multiple inspection methods and developing tailored protocols remain necessary to overcome these challenges.

#### *3.3. Complexity in Restoration Design*

Designing effective restoration interventions involves complex decision-making processes that must balance the preservation of structural integrity with the conservation of cultural and historical values. Ancient buildings are not merely engineering artifacts but embody intangible heritage, requiring interventions that respect original craftsmanship, aesthetics, and historic authenticity. Achieving this balance demands multidisciplinary input from architects, historians, engineers, and conservators, often leading to compromises in repair scope or methods.

Selecting appropriate reinforcement or stabilization schemes is particularly challenging due to the unique structural behavior and constraints of historic constructions.

For example, introducing rigid steel reinforcements may enhance load-bearing capacity but conflict with the building's flexibility or visual appearance. Innovative techniques such as fiber-reinforced polymers (FRP) or minimally invasive anchor systems offer promising alternatives but require careful assessment of long-term performance and reversibility. Moreover, every restoration project is site-specific, with factors such as seismic risk, environmental exposure, and usage dictating tailored design solutions [12].

### *3.4. Environmental and Technical Constraints during Construction*

The onsite implementation of restoration measures is often limited by environmental conditions and practical constraints. Ancient structures are typically located in urban centers or protected heritage zones, where limited working space restricts equipment access and material storage. Weather conditions such as high humidity, rainfall, or extreme temperatures may delay work or affect the curing of repair materials, necessitating strict scheduling and protective measures.

Additionally, heritage preservation regulations impose stringent controls on construction activities, restricting methods or materials that could harm the building or its surroundings. These legal frameworks ensure protection but also complicate project execution, demanding detailed documentation, approvals, and monitoring.

Another significant limitation is the availability of skilled personnel trained in both traditional craftsmanship and modern conservation technologies. The specialized nature of restoration work requires expertise that is increasingly scarce, affecting the quality and timeliness of repairs. Training programs and knowledge transfer are essential to overcome these human resource challenges.

## **4. Practical Approaches and Solutions in Structural Restoration**

### *4.1. Innovation and Application of Material Technologies*

Material innovation plays a crucial role in overcoming the challenges of compatibility and durability in ancient building restoration. One widely adopted approach involves the development and application of materials that closely match the physical and chemical properties of the original fabric. Traditional lime-based mortars, which offer breathability and flexibility, have been refined with pozzolanic additives to enhance mechanical strength and longevity while maintaining compatibility. Such materials avoid the problems caused by inappropriate cementitious products and preserve the building's ability to regulate moisture.

Composite materials such as fiber-reinforced polymers (FRP) have gained increasing attention for their excellent strength-to-weight ratio and corrosion resistance. FRP materials, especially carbon fiber fabrics, are employed to reinforce timber beams, masonry walls, and arches without significantly altering the original structure's appearance or adding excessive load. Case studies demonstrate that these materials improve load capacity and crack resistance while allowing reversibility in repairs.

Looking forward, the emergence of smart and self-healing materials offers promising prospects. Self-healing concretes and coatings embedded with microcapsules or bacteria can autonomously repair microcracks, extending the life of restorations and reducing maintenance costs. Similarly, intelligent materials capable of responding to environmental stimuli or providing real-time structural feedback are under development, potentially revolutionizing long-term conservation strategies.

### *4.2. Integration of Advanced Inspection Technologies*

Accurate assessment of structural conditions is fundamental for effective restoration planning and monitoring. Modern inspection technologies enable non-invasive, high-resolution diagnosis of complex ancient structures. Laser scanning, for example, allows detailed 3D mapping of building geometry, capturing surface deformations and enabling

precise documentation. Combined with infrared thermography, it can detect hidden moisture ingress, delamination, and material defects.

Acoustic and ultrasonic testing provide insights into internal flaws such as voids or cracks within masonry and timber elements, which are often invisible to the naked eye. Vibration analysis further supports dynamic assessment, detecting changes in modal properties indicative of structural weakening or damage.

The integration of these diverse technologies into digital building models facilitates the creation of comprehensive structural health monitoring (SHM) systems. SHM platforms collect real-time data from sensors embedded in the building, allowing continuous monitoring of strain, displacement, temperature, and humidity. This proactive approach aids early damage detection and informed decision-making for maintenance and emergency interventions.

#### *4.3. Structural Reinforcement and Strengthening Techniques*

Traditional reinforcement techniques remain vital, particularly for timber and masonry elements requiring direct replacement or repair. Skilled carpenters replace decayed wooden members with carefully selected and treated timbers, replicating original joinery methods. Brick and stone repairs employ compatible mortars and locally sourced materials to patch cracks or rebuild damaged sections, emphasizing aesthetic and structural continuity.

Modern reinforcement methods complement traditional approaches by offering higher performance and less intrusive solutions. Carbon fiber-reinforced polymer (CFRP) fabrics are increasingly used to wrap structural elements, providing tensile strength and crack arrest without heavy equipment or major structural alterations. Steel bracing and anchors serve as robust supports in cases requiring enhanced load transfer or seismic retrofitting.

Grouting and injection techniques are applied to consolidate masonry, filling voids and cracks with compatible binders that restore mechanical integrity. These methods require careful formulation and application to ensure penetration and avoid blocking moisture pathways.

Structural damping and foundation strengthening techniques are essential in seismic-prone areas. Base isolators, energy dissipators, and shock absorbers reduce the impact of earthquakes, while underpinning and soil stabilization enhance foundational stability without compromising historical fabric.

#### *4.4. Engineering Management and Construction Practices*

Effective project management is critical for the success of restoration works, requiring protective construction plans that minimize damage to fragile elements and comply with heritage regulations. Scheduling work to avoid adverse weather and coordinating multidisciplinary teams ensures optimal progress and safety.

Onsite quality control involves continuous monitoring of material performance, workmanship, and environmental conditions. Documentation of all interventions and material batches supports transparency and future maintenance.

Training and skills transfer are fundamental to sustain restoration efforts. Specialized workshops and apprenticeships help preserve traditional craftsmanship, while cross-training in modern technologies equips workers to apply innovative methods appropriately. Encouraging collaboration between academia, industry, and cultural institutions fosters knowledge exchange and innovation.

### **5. Case Studies**

The restoration of ancient buildings presents unique challenges depending on their geographic location, structural systems, and historical contexts. This section highlights three representative case studies, illustrating technical difficulties encountered and the

practical solutions adopted to preserve structural integrity while respecting cultural heritage.

### 5.1. Case Study 1: The Forbidden City, Beijing

The Forbidden City, as a vast complex of wooden structures and intricate decorations, faces challenges including timber decay, insect infestation, and damage to painted beams and roofs. Restoration efforts have integrated traditional wood treatments with modern consolidants to preserve structural elements. Digital imaging and 3D scanning technologies have been employed to document and analyze damaged areas precisely. In addition, advanced nanomaterials are being tested to protect painted surfaces from moisture and UV degradation while maintaining historical authenticity (As shown in Figure 1).



**Figure 1.** Restoration engineering technology of the Forbidden City in Beijing.

### 5.2. Case Study 2: The Great Wall of China

Restoration efforts on the Great Wall focus on sections exposed to harsh environmental conditions, including erosion and seismic risks. One of the key technical challenges was reinforcing aged wooden beams and deteriorated masonry without visually altering the structure. The use of carbon fiber-reinforced polymers (CFRP) provided lightweight but high-strength reinforcement, enhancing load-bearing capacity while preserving the original appearance. Digital modeling and structural health monitoring systems were deployed to continuously assess the effectiveness of reinforcements and detect early signs of damage. This integration of modern technology with traditional craftsmanship exemplifies the evolving nature of conservation practice (As shown in Figure 2).



**Figure 2.** The Great Wall Restoration Project.

### 5.3. Summary and Insights

These cases underscore the necessity of tailoring restoration methods to the specific material and structural conditions of each site. They illustrate the importance of balancing traditional techniques with advanced materials and technologies. Furthermore, the integration of digital tools for monitoring and modeling enhances long-term preservation strategies. Collectively, these experiences highlight the critical role of interdisciplinary collaboration, ongoing research, and skilled craftsmanship in overcoming the complexities of ancient building restoration.

## 6. Future Trends and Conclusion

The structural restoration of ancient buildings remains a complex and evolving field, where technical challenges persist but also inspire innovative solutions. As this review has discussed, the compatibility of materials, precise detection and health assessment, design complexity, and environmental constraints are central hurdles that conservation professionals must carefully address to preserve both the physical integrity and cultural significance of heritage structures.

Looking ahead, the integration of intelligent monitoring and digital technologies promises to revolutionize restoration practices. Building Information Modeling (BIM), combined with Internet of Things (IoT) sensors and advanced data analytics, enables continuous, real-time health monitoring of structures, facilitating timely interventions before minor issues escalate. This digital transformation supports more precise diagnosis, documentation, and long-term maintenance strategies, thereby enhancing restoration quality and sustainability.

Simultaneously, the development of new eco-friendly, high-performance materials is critical. Researchers are focusing on innovative binders, self-healing composites, and nanomaterials that not only improve durability and compatibility but also reduce environmental impacts. These advancements will offer restorers more reliable and sustainable options, helping balance preservation goals with modern environmental standards.

Moreover, fostering interdisciplinary collaboration among material scientists, engineers, architects, historians, and policymakers is essential. Effective restoration demands combining technical expertise with cultural sensitivity and robust policy frameworks that support heritage protection. In parallel, investing in the education and training of skilled technicians and craftspeople ensures the continuity of traditional

restoration knowledge alongside modern techniques, which is vital for heritage conservation.

In conclusion, addressing the technical challenges of ancient building structural restoration requires a holistic approach that embraces both tradition and innovation. By leveraging cutting-edge technologies, developing sustainable materials, and nurturing cross-sector partnerships, the field can advance towards more effective, respectful, and lasting preservation of historic structures. This will safeguard our cultural heritage for future generations, enabling ancient buildings to continue telling their stories in a rapidly changing world.

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