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Seismic Response of Masonry and Heritage Structures: Conservation Strategies, Retrofitting Techniques, and Vulnerability

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ABSTRACT

The seismic safety of masonry and heritage structures is of paramount importance in earthquake-prone regions, where these buildings serve as both historical artifacts and functional spaces. Constructed using traditional techniques and regionally sourced materials, they typically lack the ductility, reinforcement, and design standards needed to endure seismic events. Their vulnerability is further amplified by material aging, construction irregularities, and inadequate maintenance over time.

This review paper provides a comprehensive analysis of their seismic behaviour through the lens of vulnerability assessment methods, innovative retrofitting technologies, and conservation strategies that align with international heritage preservation guidelines. Emphasis is placed on balancing the need for structural safety with the imperative to retain cultural and architectural integrity.

Real-world case studies from countries such as Italy, Nepal, and Portugal illustrate the practical application and challenges of seismic retrofitting in heritage contexts. Additionally, the paper identifies current research gaps and future directions, including the development of eco-friendly materials, integration of AI and smart monitoring systems, and the advancement of performance-based seismic design. This study aims to guide engineers, architects, and policymakers in developing sustainable, context-sensitive approaches to protect heritage masonry structures from seismic hazards.

Keywords: Seismic vulnerability, heritage structures, retrofitting, conservation, masonry buildings, seismic resilience, historical preservation, traditional construction, structural assessment, earthquake engineering, performance-based design, cultural heritage, adaptive reuse, vulnerability assessment, structural reinforcement

1. Introduction

Advancing Toward Intelligent and Resilient Infrastructure Systems

Masonry and heritage structures are not merely buildings; they represent irreplaceable cultural, historical, and architectural legacies that serve as profound symbols of identity and continuity within communities. These structures—ranging from ancient temples and churches to traditional homes and civic edifices—were constructed using techniques and materials that reflect the architectural ingenuity and craftsmanship of their time. Many of these buildings embody the cultural history and collective memory of past generations, making their preservation essential not only for the protection of human life and property but also for safeguarding the invaluable cultural heritage they represent.

However, in regions prone to seismic activity, these structures face significant risks. Built long before the advent of modern reinforcement techniques and seismic design principles, they often lack the necessary features to withstand the forces generated by earthquakes. As a result, many masonry and heritage buildings are especially vulnerable, with potential for catastrophic damage or complete collapse during seismic events. The loss of these structures can result in the irreversible erasure of historical narratives and architectural heritage that cannot be easily restored.

Given the importance of these buildings, preserving them has become a priority in the face of seismic threats. Seismic retrofitting and conservation strategies are at the forefront of efforts to enhance the resilience of these structures while maintaining their historical authenticity. The challenge, however, lies in balancing the need to improve structural performance with the imperative of preserving the aesthetic, historical, and cultural integrity of these buildings. This delicate balance requires interdisciplinary approaches that draw on the expertise of engineers, architects, historians, and conservationists.

This paper aims to provide a comprehensive review of current practices in the seismic vulnerability assessment, retrofitting technologies, and conservation approaches tailored to masonry and heritage structures. The review highlights the most effective strategies for mitigating seismic risk, with a particular focus on the integration of modern technologies that can provide structural reinforcement without compromising the buildings' architectural value. By synthesizing recent advancements and best practices in the field, this study offers practical recommendations to guide engineers, conservationists, and policymakers in their efforts to protect cultural heritage and ensure the seismic safety of these irreplaceable structures.

2. Literature Review

- **Early Empirical Approaches:**
  - Initial research focused on post-earthquake damage observation, especially in regions with frequent seismic activity.
  - Giovinazzi (2005) introduced empirical methods based on historical data, useful for rapid, region-specific assessments.
  - These methods, while accessible and cost-effective, lacked predictive capability and could not be generalized across different geographies.
- **Development of Analytical Modelling:**
  - The evolution of computational tools enabled more detailed structural analysis.
  - **Macro-Modelling:**
    - Introduced by Lourenço et al. (2007), this method simplifies structures into equivalent frame models.
    - Best suited for system-wide behaviour analysis with moderate accuracy.
  - **Micro-Modelling:**
    - Advanced by Addessi & Sacco (2001), it uses finite element analysis to simulate brick-by-brick interactions.
    - Offers high accuracy and detail but requires significant computational resources and expertise.
- **Material Innovations for Retrofitting:**
  - **Fiber-Reinforced Polymers (FRP):** Demonstrated by Triantafillou (1998) to enhance strength without affecting historical appearance.
  - **Textile-Reinforced Mortars (TRM):** Explored by Papanicolaou et al. (2008) for improved flexibility and compatibility with masonry.
  - **Emerging Technologies:**
    - Nikolaidis et al. (2023) examined 3D printing for custom retrofitting solutions.
    - Dogariu et al. (2020) highlighted nanomaterials for strength and durability improvements.
- **Conservation-Oriented Frameworks:**
  - Guidelines such as ICOMOS Charters and Preservation Brief 41 emphasize minimal intervention and material compatibility.
  - Performance-Based Seismic Design (PBSD) enables tailored interventions based on expected performance levels under seismic loads.
- **Identified Research Gaps:**
  - Lack of standardized global tools for vulnerability assessment.
  - Inadequate regional databases for historical construction materials.
  - Limited integration of smart monitoring systems and AI-based damage prediction models.

3. Classification of Masonry and Heritage Structures

Masonry and heritage structures are a diverse category of buildings that exhibit a wide range of construction materials and techniques, often reflective of the historical and cultural context in which they were built. The materials used in these structures are typically chosen based on local availability, environmental conditions, and the specific function of the building. The most common types of materials used in heritage structures include:

3.1 Stone Masonry:

Stone masonry is one of the oldest and most enduring construction techniques, frequently found in castles, churches, fortifications, and other monumental structures. It is characterized using stone blocks, which can vary in size and shape. The durability and strength of stone masonry have made it a preferred material for structures that require long-lasting stability and resistance to natural elements. However, the heavy weight of stone can create challenges for seismic performance, as it tends to be brittle and lacks the flexibility needed to withstand dynamic loads. Additionally, the mortar joints between the stones can be weak and prone to deterioration over time, further compromising the structure’s seismic resilience.

3.2 Brick Masonry:

Brick masonry is another widely used material, particularly in temples, houses, and public buildings. Bricks offer more uniformity, and a lighter structure compared to stone, which can improve seismic performance to some extent. However, brick masonry can still exhibit weak bonding between bricks, especially in older buildings where mortar may have degraded over time. The relatively low tensile strength of bricks and the absence of significant ductility often make these structures susceptible to cracking and collapse under seismic forces, particularly if the buildings are not properly retrofitted.

3.3 Adobe and Rammed Earth:

Adobe and rammed earth are traditional building materials that have been widely used in older structures, particularly in regions with limited access to stone or brick. These materials are often found in rural or historical buildings, including homes, churches, and fortifications. Adobe is made from sun-dried mud bricks, while rammed earth involves compacting earth into formwork to create solid walls. While both materials are environmentally sustainable and offer good thermal performance, they are highly susceptible to seismic damage due to their brittle nature and low tensile strength. The lack of reinforcement and the tendency of adobe and rammed earth to crumble under dynamic loads make them particularly vulnerable in earthquake-prone areas.

3.4 Timber-Masonry Composite:

Timber-masonry composite structures combine the flexibility of timber with the stability of masonry, offering a unique solution for buildings in earthquake-prone regions. These composite structures are often found in traditional homes and buildings that require both seismic resilience and thermal insulation. The timber components provide ductility and flexibility, which can help dissipate seismic forces, while the masonry elements contribute to the building’s overall stability. However, the interaction between timber and masonry can sometimes result in complex structural behaviour, and the effectiveness of these systems largely depends on the quality of connections and the condition of the materials used.

3.5 Seismic Implications:

While each of these materials has distinct advantages, they also present specific challenges when it comes to seismic performance. Heritage structures often feature weak mortar joints, lack of ductility, and irregular geometric configurations, all of which can significantly influence their ability to withstand dynamic loads. The combination of these factors makes many heritage structures prone to failure during seismic events, especially if they have not been retrofitted to modern standards. Understanding the characteristics of these materials is essential for developing appropriate strategies for strengthening and retrofitting heritage buildings, ensuring that they can resist seismic forces while preserving their historical and architectural integrity.

Table 1: Classification Summary of Masonry and Heritage Structures

Structure Type	Materials	Seismic Behavior	Advantages	Disadvantages
Stone Masonry	Irregular stone blocks, lime mortar	Brittle, low ductility, prone to collapse	High durability, historical value	Heavy, weak joints, low seismic resistance
Brick Masonry	Fired clay bricks, lime/cement mortar	Moderate ductility, weak tension capacity	Uniform, relatively lighter	Weak bonding, mortar degradation
Adobe/Rammed Earth	Mud, straw, earth	Very brittle, extremely vulnerable	Sustainable, thermal insulation	Crumbles under seismic loads, low strength
Timber-Masonry Composite	Wood frames with infill masonry	Better seismic performance due to flexibility	Good energy dissipation	Complex interaction between timber and masonry

4. Seismic Vulnerability Assessment

A comprehensive seismic vulnerability assessment is crucial to understanding the potential risk posed to masonry and heritage structures during seismic events. By evaluating the structural weaknesses, it helps inform decisions regarding retrofitting, risk management, and resource allocation. Various assessment methods, each with its own advantages and limitations, have been developed. These methods vary in scope, accuracy, and applicability based on the available data, resources, and the level of detail required. The most common techniques include:

4.1 Rapid Visual Screening (RVS):

Rapid Visual Screening (RVS) is one of the most widely employed methods for preliminary vulnerability assessments, especially in urban areas. It involves on-site visual inspection by trained engineers, based on a predefined set of criteria, such as structural characteristics, material properties, and previous damage. This approach allows for the rapid screening of many structures at a low cost, making it ideal for initial evaluations and prioritizing structures that may require more detailed analysis.

However, RVS has limitations. Its primary drawback is its lower accuracy due to the lack of in-depth structural analysis. It is often based on qualitative assessment rather than quantitative data, meaning it can overlook critical structural details or fail to identify hidden vulnerabilities. As a result, RVS should be considered as a preliminary tool rather than a definitive evaluation method.

4.2 Analytical Modelling:

- **Macro-Modelling**: In macro-modelling, the building or structure is simplified into an equivalent frame model, representing the overall seismic behaviour of the system. This approach allows for quicker and more general assessments of the building's performance under seismic loads. Macro-modelling is particularly effective for evaluating the behaviour of large-scale structural systems and is widely used in the early stages of seismic vulnerability studies.

While it is more accurate than RVS, macro-modelling has limitations. It may overlook localized failure mechanisms or ignore detailed material and connection behaviours that can be crucial for understanding the specific seismic risk of a structure. Despite these limitations, macro-modelling remains an effective and widely used approach for generalized vulnerability assessments.

- **Micro-Modelling**: Micro-modelling, often based on finite element methods (FEM), takes a more detailed approach by simulating complex interactions between the building components and the forces acting upon them. This technique allows for a granular analysis of individual structural elements, predicting localized damage and failure under seismic loads. Micro-modelling offers high accuracy, enabling the assessment of intricate details such as wall openings, connections, and material behaviour.

However, micro-modelling comes with its own set of challenges. It requires substantial computational resources, including advanced software and hardware, as well as highly detailed material data (e.g., stiffness, strength, and ductility properties). Additionally, the process is time-consuming and requires significant expertise in both structural engineering and computational methods.

Table 2: Conceptual comparison between macro-modelling and micro-modelling approaches in seismic analysis of masonry structures.

Aspect	**Macro-Modelling**	**Micro-Modelling**
Representation	Simplified frames or equivalent walls	Individual bricks and mortar joints
Detail Level	Low to moderate	Very high (element-by-element)
Computation	Fast, less resource-intensive	Requires high computing power
Application	General vulnerability assessment	Localized failure simulation
Software Examples	SAP2000, ETABS	ABAQUS, DIANA, ANSYS

4.3 Empirical Methods:

Empirical methods rely on observed damage patterns from past seismic events, typically combined with historical earthquake data. This approach is particularly valuable in regions that have experienced frequent seismic activity, as it draws on real-world experience and empirical damage records to estimate the vulnerability of similar structures. These methods are useful for providing a rapid and localized understanding of vulnerability, especially in areas where direct structural inspections or advanced modelling are not feasible.

However, the major limitation of empirical methods is their dependence on local data, which may not be applicable to different geographic locations or structural contexts. Furthermore, they rely heavily on historical data, which may not account for evolving seismic hazard profiles, changes in construction practices, or the aging of materials. As such, empirical methods are often used in conjunction with other assessment techniques to provide a more comprehensive vulnerability evaluation.

The following table summarizes the comparative features of these methods:

Table 3: Comparison of Vulnerability Assessment Methods

Method	**Accuracy**	**Cost**	**Time Requirement**	**Application Scope**	**Citation**
Rapid Visual Screening	Moderate	Low	Short	Urban screening	FEMA P-154 (2015)
Macro-modelling	High	Moderate	Moderate	General analysis	Lourenço et al. (2007)
Micro-modelling	Very High	High	Long	Detailed analysis	Addessi & Sacco (2001)

Empirical Methods	Variable	Low	Short	Region-specific evaluation	Giovinazzi (2005)

Each method offers unique benefits and trade-offs, and often a combination of these approaches provides the most comprehensive understanding of structural vulnerability.

5. Retrofitting Techniques

Retrofitting heritage structures presents a unique challenge, as it requires balancing the imperative of enhancing structural safety with the need to preserve the aesthetic, historical, and cultural significance of the building. A diverse range of retrofitting techniques—ranging from traditional methods to cutting-edge innovations—are employed to achieve this delicate equilibrium. The most widely used techniques include:

5.1 Traditional Methods:

- **Grout Injection**: This technique involves injecting grout into the mortar joints to strengthen the masonry without altering the structure's outward appearance. It improves the bond between the masonry units, enhancing the overall stability of the structure while maintaining its historical integrity.
- **Steel Ties**: Steel ties are used to reinforce and connect different parts of a building's masonry, effectively improving its overall stability and helping to distribute seismic forces across the structure. These ties can be discreetly incorporated to minimize impact on the building's aesthetics.
- **Wooden Diaphragms**: Typically employed in timber-framed buildings, wooden diaphragms serve to improve lateral stability, helping the structure resist horizontal seismic forces. These systems are particularly useful for preserving the original timber elements while enhancing performance.

5.2 Modern Methods:

- **Fiber-Reinforced Polymer (FRP) Wrapping**: A widely recognized non-invasive technique, FRP wrapping involves applying a composite wrap around masonry walls to increase their strength and ductility. This method significantly improves the structure's seismic resilience without compromising the historical appearance of the building.
- **Textile-Reinforced Mortar (TRM)**: This innovative technique utilizes textile reinforcements combined with mortar to enhance the strength and flexibility of masonry. TRM provides excellent reinforcement, offering improved durability and seismic performance without altering the building's original features, making it a valuable tool for preserving historical authenticity.

5.3 Emerging Approaches:

- **Shape Memory Alloys**: These materials can return to their original shape after deformation, offering self-healing capabilities. This property makes shape memory alloys particularly beneficial in retrofitting heritage structures, as they can help the building recover from minor seismic damage without the need for extensive repairs.
- **Smart Materials**: Smart materials integrate embedded sensors within the structure, enabling real-time monitoring of seismic activity. These materials can adapt their behaviour based on detected changes, providing dynamic performance enhancements during seismic events. The integration of smart materials offers a promising avenue for improving the resilience of heritage buildings.
- **3D Printing-Based Retrofitting**: Utilizing additive manufacturing technologies, 3D printing enables the creation of customized reinforcement elements that perfectly match the original structure. This technique holds immense promise for precise retrofitting, especially in areas where traditional methods are challenging. However, practical issues such as material compatibility, cost, and the complexity of on-site implementation remain significant barriers to its widespread use (Nikolaidis et al., 2023).
- **Nanomaterials**: The incorporation of nanomaterials, such as nano-silica and carbon nanotubes, into repair mortars has shown considerable potential in enhancing the mechanical properties and long-term durability of masonry. While these materials promise increased strength, sustainability, and durability, challenges such as their high cost, the need for further research on their long-term behaviour, and standardization in application remain critical obstacles to their widespread use (Dogariu et al., 2020).

Table 4: Comparison of Retrofitting Techniques

Technique	Historical Compatibility	Invasiveness	Effectiveness	Cost	Sustainability	Citation
Grout Injection	High	Low	Moderate	Low	Moderate	Binda et al. (2003)
Steel Ties	Moderate	Moderate	High	Moderate	Moderate	Magenes & Calvi (1997)
FRP Wrapping	Low	Low	High	High	Low	Triantafillou (1998)

TRM	High	Low	High	Moderate	High	Papanicolaou et al. (2008)
Shape Memory Alloys	Moderate	Low	High	High	Moderate	Dolce et al. (2000)
3D Printing Retrofitting	High	Low	High	High	High	Nikolaidis et al. (2023)
Nanomaterials	High	Low	Very High	Moderate	High	Dogariu et al. (2020)

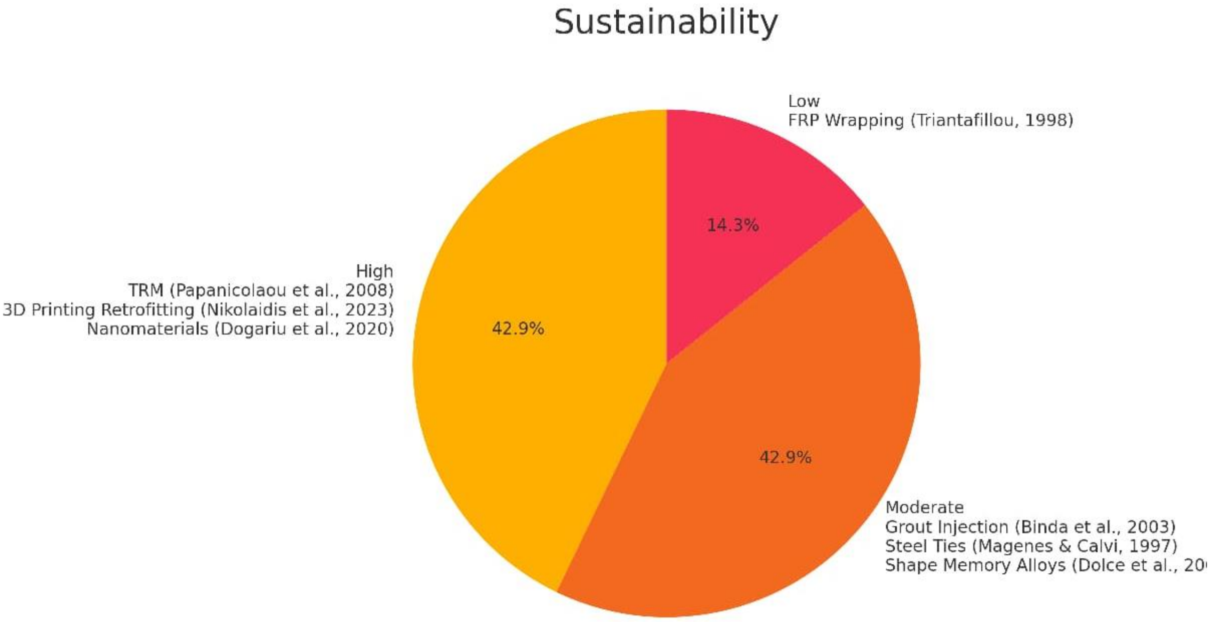

Figure 1: Sustainability of Retrofitting Techniques

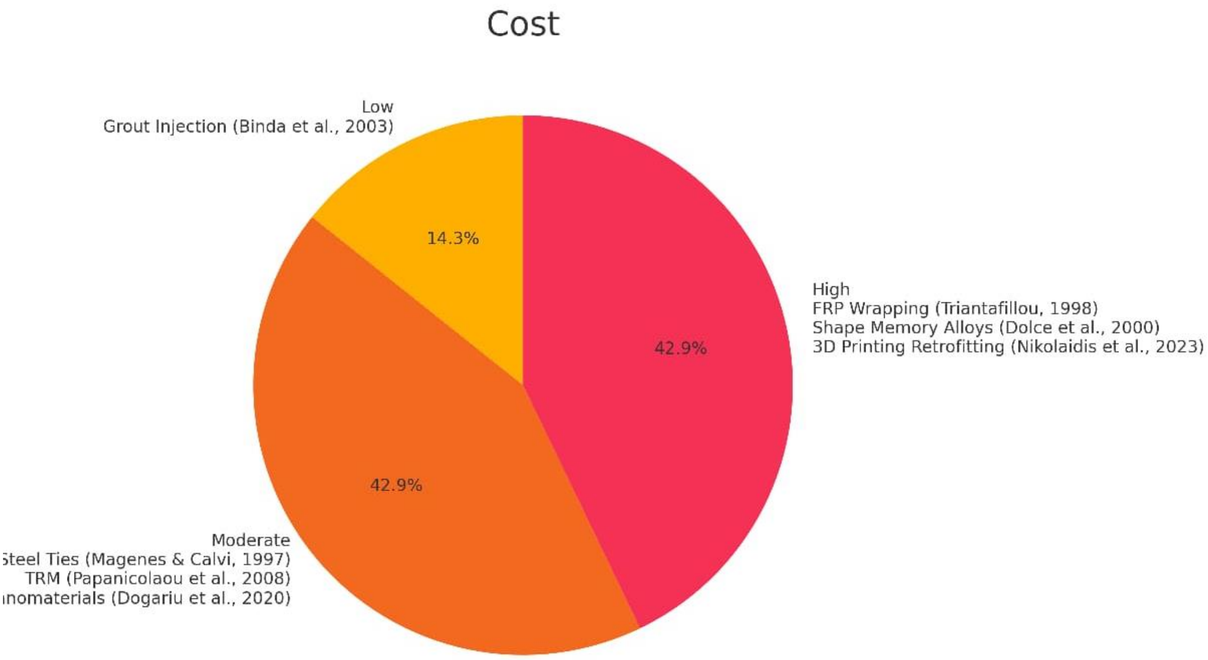

Figure 2: Cost Comparison of Retrofitting Techniques

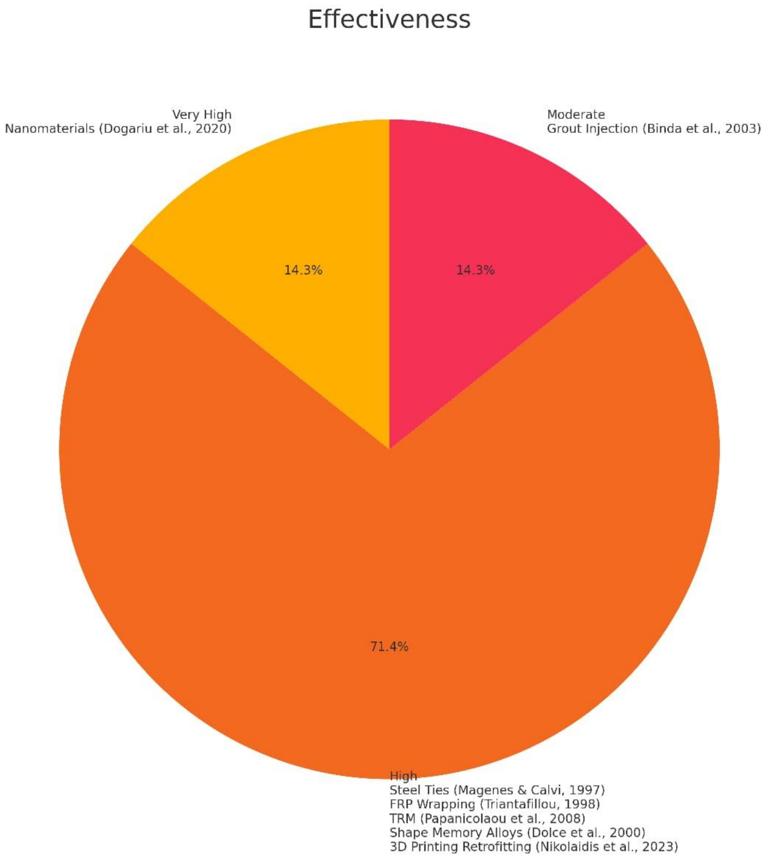

Figure 3: Effectiveness of Retrofitting Methods

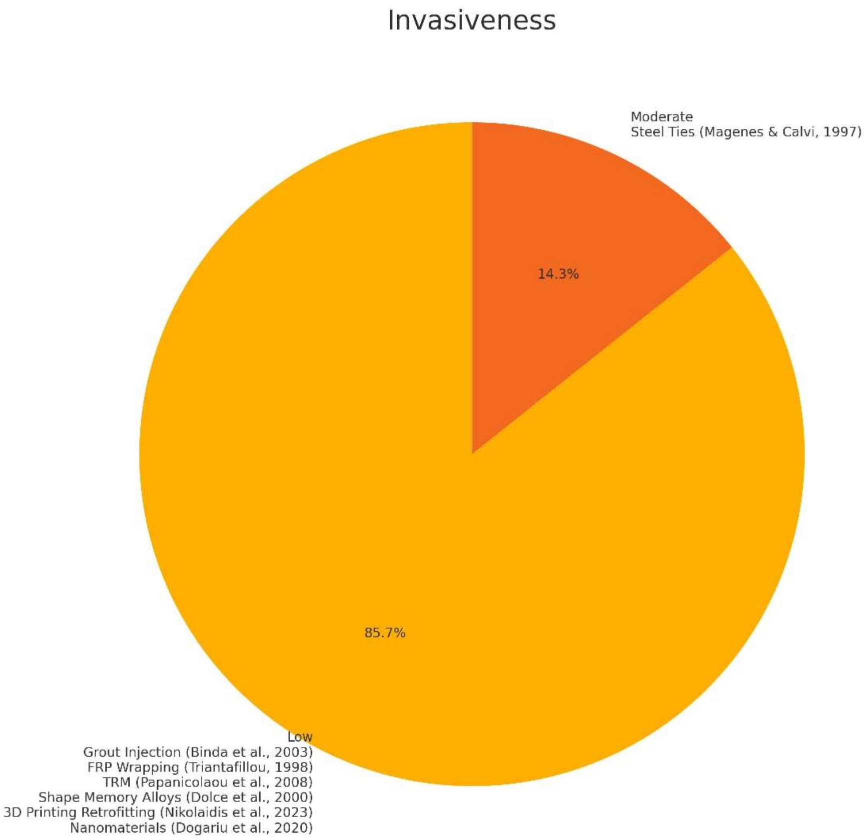

Figure 4: Invasiveness of Selected Retrofitting Approaches

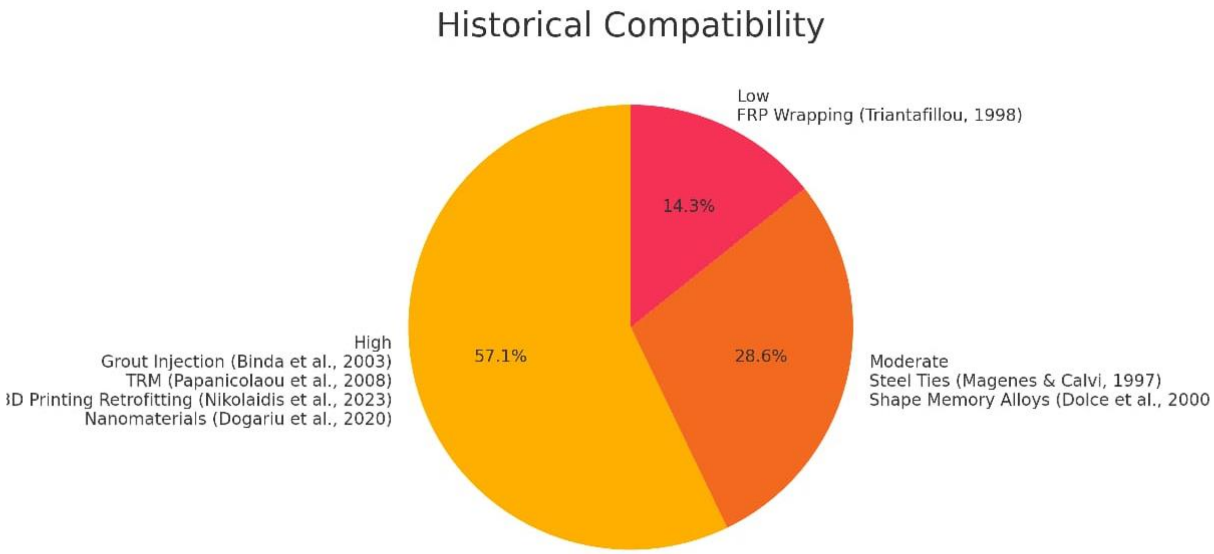

Figure 5: Historical Compatibility of Retrofitting Solutions

6. Conservation Strategies

The conservation of heritage structures is a complex and nuanced process that seeks to preserve their historical, cultural, and architectural significance while ensuring they are resilient to seismic events. The key principles that guide these efforts include:

- **ICOMOS Charters and UNESCO Recommendations**: These global frameworks advocate for minimal intervention in the conservation of heritage structures, emphasizing the importance of preserving the authenticity of historical buildings. The use of reversible techniques is strongly encouraged to allow for future interventions without compromising the original fabric of the structure. These guidelines underscore the delicate balance between maintaining historical value and addressing the demands of modern safety standards.
- **Preservation Brief 41 (U.S. National Park Service)**: This publication provides a comprehensive set of guidelines for the seismic rehabilitation of historic buildings, with an emphasis on maintaining their aesthetic and cultural value. It recommends a tailored approach to retrofitting, where interventions are designed to reinforce the structure's seismic resilience without altering its historical appearance or diminishing its heritage significance.
- **Performance-Based Seismic Design (PBSD)**: PBSD offers a modern framework for adapting seismic design principles to heritage buildings. This approach focuses on assessing the performance of a building under seismic loads, allowing for the implementation of targeted interventions that improve safety while preserving the building's original form and function. By considering both the structural and non-structural elements of a building, PBSD provides a comprehensive solution for heritage conservation in seismic zones.

A major challenge in conservation is achieving a balance between structural integrity and the preservation of aesthetic and historical authenticity. Each intervention must be carefully planned, considering not only the engineering needs but also the significance of the building in its cultural and historical context. This process requires close interdisciplinary collaboration among engineers, conservationists, historians, and architects to ensure that both safety and heritage are preserved. Effective conservation strategies must prioritize long-term sustainability, adaptive reuse, and minimal disruption to the building's original fabric.

Table 5: Conservation Guidelines Comparison

Guideline / Framework	Principle	Key Focus	Application in Seismic Context
ICOMOS Charters	Minimal intervention, authenticity	Reversibility, material compatibility	Encourages non-invasive retrofitting
UNESCO Recommendations	Heritage value preservation	Universal protection standards	Balances safety and cultural significance
Preservation Brief 41 (NPS, USA)	Visual integrity and performance	Historical aesthetics	Focuses on compatible retrofitting strategies

Performance-Based Seismic Design	Functionality after earthquakes	Quantifiable safety targets	Enables precise, tailored retrofitting approaches

7. Case Studies

The preservation and retrofitting of heritage masonry structures have been exemplified in several countries, where diverse approaches have been implemented to balance seismic safety with architectural and cultural integrity:

- **Italy – L'Aquila (2009 Earthquake)**: Following the devastating earthquake in L'Aquila, a range of post-earthquake interventions were employed to enhance seismic resilience. These included strengthening diaphragm action and improving the anchorage of masonry elements, which led to a significant reduction in seismic vulnerability. Despite these advancements, a key challenge was integrating modern materials and technologies into centuries-old structures while maintaining their historical authenticity. The intervention strategies were carefully designed to preserve the architectural heritage while addressing the pressing need for seismic safety.
- **Nepal – Gorkha Earthquake (2015)**: The aftermath of the Gorkha earthquake prompted urgent retrofitting efforts, particularly for temples and other historical religious structures. Steel bands were employed to reinforce masonry, and lime-based mortars were used to maintain compatibility with traditional construction materials. These interventions successfully preserved the visual and cultural integrity of the buildings. However, the retrofitting process faced significant constraints, particularly the scarcity of skilled artisans familiar with traditional methods. The challenges of training and retaining local expertise remain a concern, but these efforts demonstrated a valuable synthesis of modern engineering and traditional craftsmanship.
- **Portugal – Seismic Retrofit of Churches and Historical Buildings**: In Portugal, a mixed approach combining traditional and modern retrofitting techniques was applied to churches and other historic structures. The strategy included the use of advanced materials like fiber-reinforced polymers alongside conventional restoration methods such as masonry reinforcement and re-pointing. This balance allowed for an improved seismic performance while respecting the original aesthetics and construction techniques. The integration of both old and new methods ensured the preservation of the cultural heritage while making the buildings more resilient to future earthquakes.

These case studies highlight the challenges and successes in the retrofitting of heritage masonry structures. Each example underscores the importance of context-specific strategies that respect both engineering principles and cultural preservation. The ongoing dialogue between tradition and innovation is crucial for the long-term sustainability and safety of heritage buildings in seismic regions.

Table 6: Case Study Summary: Seismic Retrofitting of Heritage Buildings

Country	Structure Type	Techniques Used	Outcome	Citation
Italy	Churches, palaces	Diaphragm enhancement, wall anchorage	Reduced vulnerability	CNR-DT212/2013
Nepal	Temples	Steel bands, lime mortar	Preserved appearance, improved safety	D'Ayala & Fodde (2008)
Portugal	Churches, buildings	FRP wrapping, traditional mortars	Balanced preservation and performance	LNEC Report (2012)

8. Research Gaps and Future Directions

While significant strides have been made in the seismic assessment and retrofitting of heritage masonry structures, several challenges continue to impede progress and demand attention in future research:

- **Lack of Region-Specific Data**: There is an urgent need for comprehensive, region-specific data on materials, construction techniques, and seismic hazards. This will help refine vulnerability models and ensure retrofitting interventions are tailored to local conditions.
- **Standardization of Vulnerability Assessment Tools**: Current methodologies for assessing seismic vulnerability lack uniformity, leading to inconsistencies in evaluation and intervention strategies. Developing standardized, universally accepted tools for seismic vulnerability assessment is crucial for improving the accuracy and reliability of assessments across diverse heritage structures.
- **Sustainable, Eco-Friendly Retrofitting Materials**: As environmental concerns gain prominence, there is a growing need for retrofitting materials that are both effective in enhancing seismic performance and environmentally sustainable. Future research should focus on developing and testing green materials that do not compromise on structural safety and preservation goals.
- **Integration of Nanomaterials and 3D Printing**: The integration of nanomaterials and 3D printing technologies offers exciting possibilities for the preservation and retrofitting of heritage structures. Nanomaterials can enhance the mechanical properties of existing masonry, while 3D printing

can facilitate the creation of custom components for repairs, improving precision, reducing labor costs, and expediting the process, particularly in remote or resource-limited settings.

- **Artificial Intelligence (AI) for Damage Prediction and Monitoring**: AI holds significant promise in advancing seismic retrofitting practices. Machine learning algorithms could be used to predict damage patterns more accurately, optimize retrofitting strategies, and enable real-time structural health monitoring. By integrating sensor networks and data-driven models, AI could offer continuous insights into the condition of heritage buildings, allowing for proactive maintenance and more informed decision-making.

The incorporation of emerging technologies such as AI, nanomaterials, and 3D printing represents a transformative leap forward in the field of seismic retrofitting. AI-driven tools could revolutionize damage prediction and post-event analysis, while 3D printing can provide a rapid, cost-effective means of creating bespoke retrofitting components. As these technologies mature, they could significantly enhance the efficiency, precision, and sustainability of seismic retrofitting for heritage masonry structures, ensuring their resilience against future seismic events without compromising their historical value.

9. Conclusion

The seismic vulnerability of masonry and heritage structures represents a critical challenge at the intersection of structural engineering, architectural conservation, and cultural preservation. These structures, often built without modern seismic considerations, are highly susceptible to earthquake-induced damage due to material brittleness, lack of reinforcement, and irregular geometries. Given their historical, cultural, and social significance, any intervention must carefully balance the goals of life safety, structural resilience, and preservation of authenticity.

This review has synthesized a broad spectrum of assessment techniques and retrofitting strategies, ranging from traditional methods like grout injection and steel ties to advanced technologies including textile-reinforced mortars, nanomaterials, and 3D-printed components. Analytical tools such as macro- and micro-modelling, along with empirical and rapid visual screening approaches, provide engineers and conservationists with a multi-tiered framework for vulnerability evaluation. Furthermore, the application of international guidelines—such as those from ICOMOS, UNESCO, and the U.S. National Park Service—emphasizes the importance of reversibility, minimal intervention, and contextual compatibility in seismic conservation efforts.

Real-world case studies from Italy, Nepal, and Portugal demonstrate that successful retrofitting of heritage structures is achievable through interdisciplinary collaboration, community engagement, and a deep understanding of local materials and techniques. However, the journey forward demands increased investment in region-specific research, standardization of assessment tools, and the scalable application of emerging technologies like AI-driven monitoring systems and eco-friendly retrofitting materials.

In conclusion, safeguarding masonry and heritage structures from seismic hazards is not merely a technical task—it is a cultural imperative. By combining scientific innovation with heritage sensitivity, stakeholders can ensure that these irreplaceable monuments continue to withstand the tests of time and nature, preserving both structural integrity and historical legacy for future generations.

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