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Orginal Article

Investigating the problems of historical buildings in relation to earthquakes and researching some of their retrofitting methods

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Abstract: Historical buildings are valuable cultural heritage sites that showcase diverse architectural typologies worldwide. However, these structures are highly susceptible to natural disasters, particularly earthquakes, which present unpredictable risks beyond human control. The primary objective of this research is to investigate the seismic behaviour of historical buildings and examine methods for their strengthening and preservation. This study analyses the seismic behaviour of various materials, including stone, brick, and mortar, in historical buildings and explores modern retrofitting methods, such as the use of nanotechnology and advanced material reinforcement. The findings indicate that employing advanced techniques can significantly enhance the seismic resistance of these structures. Finally, recommendations for future research and the application of innovative methods in the seismic retrofitting of historical buildings are provided. The study adopts an analytical-interpretive approach, emphasising minimal intervention and reversibility in preserving these invaluable structures.

Keywords: seismic retrofitting, historical buildings, earthquake retrofitting, earthquake, seismic protection

1. Introduction

Historical buildings are irreplaceable treasures that reflect the cultural, architectural, and historical identity of societies. Their preservation is essential for maintaining heritage continuity and ensuring that future generations can connect with their past. However, these structures, often built using materials such as brick, stone, and clay, are inherently vulnerable to natural disasters, particularly earthquakes, due to their age, material degradation, and the absence of modern engineering considerations during their construction.

Numerous studies have examined the structural and seismic behaviour of historical buildings, highlighting the challenges posed by their traditional materials and construction techniques. For instance, Szostak and Trochonowicz [1] emphasised the complexity of working with historic materials in reinforced concrete structures, stressing the importance of appropriate calculation algorithms. Rinaldis et al. [2] provided insights into the dynamic responses and seismic vulnerabilities of historical structures in Italy, offering methodologies to mitigate these weaknesses. Christov et al. [3] detailed advanced technologies for safeguarding historical buildings in Bulgaria, focusing on tailored retrofitting strategies. Similarly, Nappi [4] discussed the integration of modern technologies in cultural heritage preservation, underscoring the balance between innovation and tradition in seismic retrofitting.

A comprehensive understanding of the vulnerabilities of cultural heritage requires multidisciplinary studies, encompassing fields such as architecture, art history, earth sciences, and earthquake engineering. Such vulnerability analyses must include a clear identification of structural systems, an assessment of dynamic characteristics, and an understanding of the mechanical properties of the materials used in their construction.

Despite these advances, preserving the cultural values, authenticity, and identity of these structures presents significant challenges. The core principle of reversibility, ensuring minimal intervention while maintaining structural integrity and aesthetic authenticity, often complicates the implementation of modern seismic retrofitting techniques. Methods for seismic strengthening must be non-invasive, reversible, and effective, safeguarding both the cultural and structural integrity of these buildings.

This research builds upon existing studies to analyse the seismic behaviour of historical buildings and propose practical retrofitting strategies that balance modern engineering demands with conservation principles. A multidisciplinary approach is adopted, integrating insights from architectural conservation, structural engineering, and materials science. Key focuses include understanding the dynamic behaviour of traditional materials, assessing failure modes, and evaluating retrofitting methods with minimal intervention and maximum reversibility.

By situating this study within the broader discourse on historical preservation and seismic retrofitting, we address the critical gap between safeguarding cultural heritage and ensuring structural safety. This work builds on foundational methodologies and case studies, such as seismic isolation in heritage structures [5,6] and retrofitting examples using nanotechnology and fibre-reinforced polymers [7,8], to offer both theoretical insights and practical recommendations for advancing seismic retrofitting practices in historical buildings.

2. Methodology

This research employs logical reasoning and theoretical discussions on seismic retrofitting in conjunction with protection principles, presenting a range of approaches, interventions, strategies, and solutions, from the most fundamental to the most advanced. Therefore, the study is theoretical in nature and focuses on seismic retrofitting and strengthening historical structures through an analytical-interpretive approach, ensuring better alignment with preventive protection. A key feature of this research is the interaction and juxtaposition of perspectives between the science of historical structure protection and seismic retrofitting knowledge in the application of strategies and solutions.

The methodology consists of the following key steps:

- Evaluating various modern retrofitting techniques, including the use of nanotechnology and advanced material reinforcement.
- Conducting case studies of successfully retrofitted buildings to identify effective strategies and best practices.
- Providing recommendations for future research to further enhance the seismic resilience of historical buildings, with a focus on minimal intervention and reversibility.

3. Structural characteristics of historical buildings

To assess traditional structures against earthquake forces, the characteristics of historical buildings must be evaluated along three axes: the types and mechanical properties of the materials, the types of structural elements and forms, and the dynamic properties and behaviour of historical buildings during earthquakes.

3.1. Mechanical properties of materials

Mudbrick, clay, brick, stone, wood, and mortar are the primary materials used in historical buildings. Depending on the location and period of construction, various combinations of these materials have been employed. For instance, in some regions, lime-based mortars and layered masonry systems were introduced to enhance structural integrity [9]. These techniques provided benefits such as improved cohesion and ductility, which are less common in purely mudbrick or stone constructions.

However, the mechanical properties of traditional materials are significantly inferior to those of modern materials like concrete and steel. As a result, the primary vulnerability of historical buildings to earthquakes lies in the low strength of their constituent materials. Additionally, ageing and cumulative damage over time further reduce the expected strength and performance of these materials. Furthermore, most traditional materials exhibit brittle failure under load, increasing their susceptibility to seismic events [10].

3.2. Types of structural elements and forms

- Stone Buildings: A significant characteristic of stone buildings, which also represents a major weakness in the face of earthquakes, is their heavy weight. This weight increases the lateral forces acting on the structure during seismic events. However, in some regions, advanced techniques such as the use of lime mortar or layered masonry systems have been employed. For example, the three-layer midis masonry used in certain Armenian structures enhances bonding and structural integrity, reducing vulnerability to seismic forces, particularly out-of-plane movements.
- Mudbrick (Adobe) Buildings: The predominant structural system in mudbrick buildings consists of load-bearing walls and various types of vaulted and domed roofs. In some cases, flat wooden beam roofs are also utilised. The primary weakness of mudbrick buildings in earthquakes is the very low strength of the bricks and the lack of cohesion between structural elements. Regional techniques, such as adding straw or fibrous materials to the mud mixture, can slightly improve tensile strength, but the overall seismic resistance remains low.

- Brick Buildings: Brick buildings generally exhibit better resistance to earthquakes compared to mudbrick and stone structures due to the improved strength of the material and the potential use of bonding techniques. In some historical examples, tensile elements have been incorporated to enhance cohesion and integrity under dynamic loads. These features make brick structures moderately more resilient, though they still share some vulnerabilities, such as cracking at openings or domes under seismic forces [3,4,9,10].

3.3. Dynamic characteristics and behaviour of historical buildings during earthquakes

Based on observations from earthquakes, the collapse of historical buildings, particularly those constructed with mudbrick and brick, can be attributed to three main factors:

- Material Brittleness and Weak Bonding: Mudbrick and brick are brittle materials with very low tensile strength and ductility. The connections between units are typically weak, relying on cohesion provided by mortar or clay, which degrades over time and under cyclic loads. During strong earthquakes, the lack of ductility and poor bonding lead to the rapid deterioration of cohesion, both locally and globally within the structure, resulting in widespread cracking and collapse.
- Structural Mass and Inertial Forces: The significant mass of historical buildings generates large inertial forces during seismic events, which can exceed the capacity of the materials and structural systems to resist. However, in regions employing advanced masonry systems, such as the three-layer midis masonry found in Armenian churches, this challenge is partially mitigated. The midis system utilises a combination of heavy outer layers with lighter, less dense inner cores, reducing the overall seismic mass. Additionally, the cohesive properties of lime-based mortars improve energy dissipation and reduce stress concentrations during seismic movements.
- Modes of Failure: Common failure modes in historical structures include wall separation, out-of-plane bending, corner cracking around openings, and cracking in domes, particularly at their support zones. These failures result from the combination of weak material properties, insufficient connections between structural elements, and high inertial forces, which together lead to a progressive loss of structural integrity under seismic loading [3,4,9-11].

4. Seismic weaknesses in historical buildings

These types of buildings exhibit poor performance due to structural weaknesses against seismic loads. In such structures, seismic loads are transferred through the roof to the interior and exterior walls and then to the ground. The most common weakness in these buildings is the absence or inadequacy of bond beams under load-bearing walls. This not only prevents the proper transfer of loads to the foundation and ground but also causes walls to separate and slide during an earthquake [11].

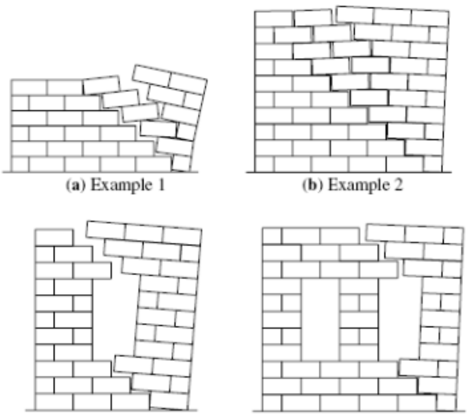
Another major weakness of adobe buildings is the low strength of their materials against seismic loads and environmental conditions, as well as their high weight. These materials lack sufficient compressive and tensile strength and are highly susceptible to moisture and water absorption. The lack of tensile and compressive strength reduces the ductility and rigidity of adobe structures. Moreover, the high water absorption of adobe over time leads to waterlogging, expansion, and contraction, resulting in cracking and eventual collapse [12].

Another structural issue is the lack of connections between perimeter and interior walls, the absence of unity among load-bearing walls, and the lack of proper wall-to-ceiling connections or adequate load distribution paths due to weak coherence between ceilings and vertical walls [10]. Improper lateral load distribution between vertical walls, particularly in structures with flexible roofs, can compromise structural stability. Properly connecting walls to each other and to the floor and ceiling levels can significantly enhance the seismic performance of adobe structures.

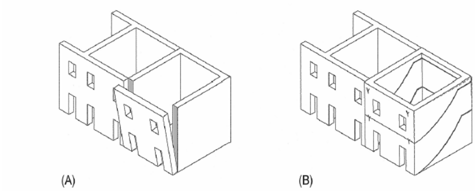
Wall thickness has a direct correlation with the shear and flexural resistance of adobe walls against seismic loads [13]. Thicker walls provide greater resistance, delaying failure both within and outside the plane.

The weaknesses of historical structures also include the excessive weight of ceilings and the insufficient length of roof supports [14]. During an earthquake, an increase in building mass leads to higher seismic forces being absorbed. If the structure lacks adequate resistance, ductility, stiffness, and energy absorption capacity, its performance will be significantly compromised. Additionally, an excessive length of roof supports can cause the roof to slide off the walls and collapse more quickly. Other structural deficiencies include the absence of diagonal bracing in ceilings, the effects of torsion in rigid roof conditions (following ceiling bracing), the lack of vertical ties, and the absence of horizontal ties. Examples of these weaknesses are illustrated in Fig. 1.

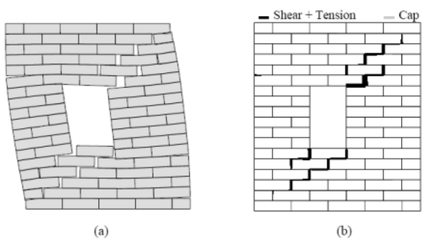
In adobe buildings, excessive height and length, combined with insufficient wall bracing, can lead to buckling, particularly in structures with embedded openings [15]. Plan irregularities and a lack of symmetry in wall distribution are also significant weaknesses in adobe structures [16]. Consequently, historical adobe buildings generally exhibit inadequate seismic performance and are at high risk of severe damage. However, it is worth noting that these considerations are general, and in some earthquakes, certain historical adobe buildings have demonstrated good resistance.



Failure modes of walls subjected to vertical and horizontal loading.



Failure modes of buildings without ties (a) and with ties anchoring the façade to lateral walls.



Micro-modelling of masonry shear walls – results of the analysis at a lateral displacement of 2.0 mm: (a) deformed mesh; (b) damage.

Fig. 1. Failure modes in masonry construction. *Source*: [11]

Finally, the low quality of mortars, poor construction and installation practices, as well as violations of design and construction standards, have all contributed to the low seismic resistance of these buildings [17].

5. Key elements in preparing a seismic retrofitting plan for a historical building

Preparing a seismic retrofitting plan involves various activities that can generally be categorised into three key areas:

- Determining the Building's Specifications and Current Condition (Documentation): This phase requires a thorough investigation and study of various aspects, including the building's history, climate, geography, architecture, and structural characteristics. Additionally, it involves understanding the building's environmental context, as well as its economic and social implications.
- Pathology: At this stage, the gathered information and data are analysed to identify the factors that have contributed to the building's deterioration over time. These factors may include ageing, previous alterations, material degradation, and damage from past seismic events. A detailed assessment of the building's current condition, with a focus on load-bearing walls, foundations, and other key structural components, is essential in identifying weak points that could lead to structural failure during an earthquake.

Equally important is the analysis of the properties and condition of primary building materials (e.g., stone, brick, mortar). This may involve laboratory testing to assess the strength and durability of these materials, particularly under seismic forces.

A comprehensive evaluation of existing damage, such as cracks, settlements, or deformations, is necessary to understand how these issues may affect the building's seismic resistance. Advanced modelling techniques, including dynamic simulations, are also employed to predict the building's behaviour under various seismic scenarios. These simulations assist in identifying the most effective retrofitting solutions.

Modelling and detailed analysis of these structures require accurate simulation of material behaviour, which is particularly challenging for historical brick buildings. One essential method for understanding the seismic performance of historical structures is the Risk-UE methodology (Lagomarsino, 2006; Milutinovic and Trendafiloski, 2003). This procedure for assessing seismic vulnerability is based on the vulnerability index method developed in Italy from 1976 onwards. It analyses key parameters that define a specific building typology, allowing for the establishment of a damage index – a coefficient representing the building's intrinsic capacity to resist seismic forces [18].

- Final Presentation: In this phase, executable plans that include all structural and non-structural details are prepared. These plans present solutions and methods for seismic retrofitting while adhering to conservation principles essential for historical buildings. It is important to note that the selection of each method and its implementation may vary depending on the significance and specific characteristics of different structures.

Based on experimental studies, earthquake analyses, international experiences, and vibration tests on specific laboratory models, a comprehensive methodology has been developed for the seismic assessment of existing structures. This methodology consists of several stages: 1) gathering general information and design documentation for the building; 2) verifying the accuracy of this data; 3) conducting on-site inspections to assess the structure's technical condition and the quality of its building materials; 4) evaluating the dynamic characteristics of the soil; 5) preparing a design model of the building; 6) determining the maximum potential accelerations in various parts of the structure and assessing the actual physical, mechanical, and dynamic properties of the load-bearing elements; 7) calculating the ratio of actual to required load-bearing capacity, ensuring that this ratio is at least 1 to confirm the building's seismic resistance [17].

While this methodology was originally developed for reinforced concrete buildings, its general framework can be adapted for historical buildings, although certain specific challenges may arise. For instance, special attention must be given to the materials, construction techniques, and potential physical deterioration in historical structures. Additionally, in projects involving historical buildings, it is important to estimate the actual load-bearing capacity, particularly in cases where information on structural components is incomplete. Assessing the physical deterioration of buildings is a highly complex yet essential task for ensuring their seismic resilience.

6. Principles and strategies for seismic retrofitting of historical buildings

The principles and strategies for the seismic retrofitting of historical buildings are not significantly different from those applied to other structures. However, factors such as the cultural and historical value of these buildings, the deterioration and damage of many structural elements, and, most importantly, the need to preserve their overall integrity, as well as their exterior and interior façades without excessive alteration, impose significant constraints.

The use of modern materials in restoration is not permitted if traditional, ethnically specific methods – including traditional materials, processes, and forms – can meet the necessary requirements. However, for buildings that cannot be repaired using traditional means, modern techniques incorporating contemporary materials, technology, and forms may be adopted, provided they align with conservation criteria [19].

As a result, retrofitting methods must be safe, non-destructive, effective, and reversible. Despite their higher costs, the application of modern technologies is justified for such buildings.

The primary strategies for the seismic retrofitting of historical buildings include: enhancing the load-bearing capacity of structural elements, creating a cohesive and appropriate structural configuration, reducing vertical loads on the structure, implementing seismic isolation systems, employing energy absorption systems, and utilising active control systems. Each of these strategies comprises various methods, selected based on the specific conditions and requirements of each building. The details of each strategy will be explained in the following sections.

6.1. Increasing the load-bearing capacity of structural components

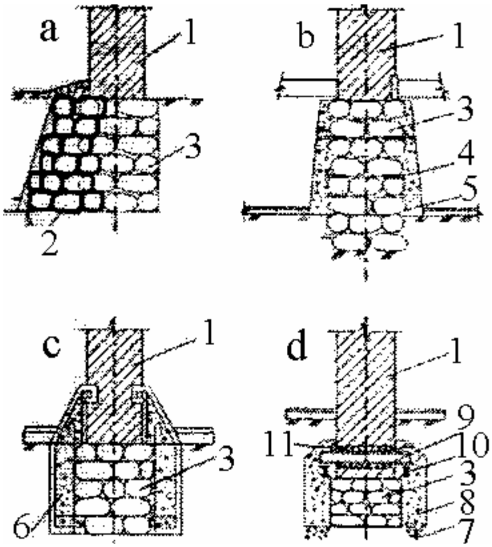
The materials and components used in historical buildings generally have low load-bearing capacity in terms of compression, tension, shear, and flexural resistance. Additionally, these materials are often brittle and fragile, lacking significant deformability. As a result, they are not highly effective in dissipating dynamic energy during seismic events.

To enhance the load-bearing capacity and deformability of structural components, several methods can be employed:

6.1.1. Increasing cross-sectional dimensions

There are various approaches to achieving this:

- The foundation level should be reinforced with new materials.
- Steel rebars can be used to improve the connection between new and existing materials.
- Concrete coating can be applied to foundation walls. To ensure better adhesion between the concrete and the existing materials, rebars can be placed horizontally between the stone joints in the foundation section, with their ends anchored in the concrete cover.



1 - Masonry
2 - New masonry, connected to the existing structure
3 - Old masonry
4 - Anchors
5 - Concrete enclosure
6 - Reinforced concrete enclosure
7 - Sand bed
8 - Concrete addition
9 - Bearing beam
10 - Distributing beam
11 - Thickened concrete

a - Enlargement of the masonry base using stone masonry
b, d – Enlargement using a concrete enclosure
c - Enlargement using a reinforced concrete enclosure

Fig. 2. Methods for strengthening the foundations. *Source*: [3]

Some methods for strengthening masonry foundations are illustrated in Fig. 2. The objective of this approach is to reach stronger soil at a deeper level and to reduce stresses at the soil-foundation contact surface. This is achieved by enlarging the foundations.

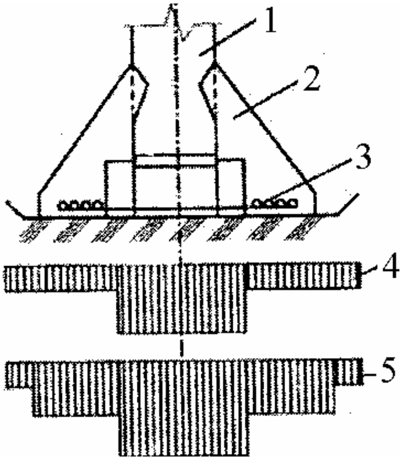
Case (a): The masonry base is enlarged using stone masonry. The foundation's basic plane is extended with new stone masonry on one side. To improve the connection, steel anchors with diameters of 12 to 16 mm (class A3) can be inserted into the horizontal joints at intervals of 50–60 cm. Cement-lime mortar is used to ensure a secure bond.

Case (b): The existing masonry foundations are strengthened by adding concrete enclosures. Steel anchors can be inserted into the horizontal joints of the masonry to resist the horizontal forces generated at the interface between the masonry and the concrete enclosure.

Case (c): This method is similar to case (b), but the concrete enclosure is further reinforced with transverse and longitudinal reinforcement to enhance its load-bearing capacity.

Case (d): For structures subjected to heavier loads, the existing masonry foundations are strengthened using concrete enclosures reinforced with horizontal bearing steel beams placed at intervals of 1.5-2.0 m. These beams help distribute concentrated loads longitudinally between embedded longitudinal beams within the concrete enclosure. Additionally, transverse beams pass through holes bored into the existing foundations, which are approximately 50 cm in diameter. Once the cross beams are installed, the holes are filled with concrete [3].

A simplified diagram illustrating the stress distribution in the subsoil before and after the application of additional loading is presented in Fig. 3.



1 - Existing foundation
2 - Base enlargement
3 - Reinforcement
4 - Simplified diagram of compression loads before enlargement
5 - Simplified diagram of compression loads after enlargement and additional loading on the foundation

Fig. 3. Simplified scheme of the increased loading under the foundations. *Source*: [3]

6.1.2. Reinforcing components

One of the critical weaknesses of masonry materials is their minimal resistance to tensile stresses. This inherent limitation results in brittle behaviour and a high susceptibility to cracking. Therefore, one of the key methods for strengthening historical buildings, and masonry structures in general, involves the use of auxiliary materials that can compensate for this weakness and withstand tensile stresses where they are most likely to occur. Materials capable of resisting tensile forces include wood, steel, and certain types of polymers [4].

Historically, wood has been widely used in historical buildings as a tensile element. However, its major drawbacks include limited durability and susceptibility to decay, termites, fire, and other damaging factors. With the advent of steel, it has been utilised in various forms, such as profiles, cables, tendons, and most notably, steel meshes for the reinforcement of historical buildings. Steel meshes remain widely used for the confinement of masonry materials. However, steel has two significant disadvantages: susceptibility to corrosion and high density, which increases the structural mass and, consequently, the seismic loads on the structure.

A highly effective material in structural reinforcement is fibre-reinforced polymers (FRPs). These materials consist of high-strength fibres that enhance the structural capacity of building components in shear, bending, and compression, reduce damage from explosions, improve seismic resistance, and control the propagation of existing cracks. FRPs offer a high strength-to-weight ratio and excellent corrosion resistance. They also possess favourable electrical, magnetic, and thermal properties, are lightweight, highly durable under various environmental conditions, and are recyclable. The fibres used in FRPs can be made of carbon (CFRP), glass (GFRP), or aramid (AFRP). The tensile strength of these fibres along their length is several times greater than that of steel [7].

However, this material also has certain disadvantages, some of which can be partially mitigated. These include a relatively low modulus of elasticity, limited long-term resistance to high temperatures, and the phenomenon of plastic ageing. The modulus of elasticity of FRP material is approximately twice that of wood, yet it is ten times lower than that of steel. As a result, FRP-based reinforcements may exhibit issues such as insufficient stiffness and easy deformation. To address this, high-modulus fibres can be incorporated into the reinforcement composition to enhance its structural rigidity. Another drawback of FRP is its inability to maintain strength at high temperatures over extended periods. These materials are generally used at temperatures below 100°C, although FRP fibres retain remarkable strength at temperatures above 60°C. By incorporating heat-resistant resins, FRP can function at temperatures as high as 200–300°C. However, in the context of strengthening masonry buildings, this limitation is usually not a significant concern. A major issue with FRP is plastic ageing, which occurs when the material deteriorates under exposure to ultraviolet (UV) radiation, wind, sand, rain, snow, chemicals, and mechanical stress. Over time, these factors reduce the material's performance and durability. Additionally, the high cost of FRP remains a disadvantage in retrofitting projects [7].

In Italy, fibre-reinforced polymer (FRP) has been extensively utilised for the seismic retrofitting of historical buildings, including churches. One notable example is the retrofitting of the SS. Rosario Church bell tower in Finale Emilia, which was severely damaged by the Emilia-Romagna earthquakes.

For the SS. Rosario Church, researchers employed a simplified modelling technique known as the "Equivalent Frame" method to assess seismic vulnerability and design appropriate retrofitting interventions. They determined that replacing piers and spandrels with an equivalent frame of non-linear beams was an effective solution. The application of FRP reinforcements enhanced the structure’s strength and flexibility, significantly improving its seismic performance [20].

The church’s bell tower presented a unique challenge due to its isolation and its complex interaction with neighbouring structures. The interventions involved wrapping critical sections of the masonry with FRP to increase its ductility and strength. This method proved highly effective in both isolated and integrated structural scenarios, demonstrating the versatility of FRP in the seismic retrofitting of historical masonry buildings [20].

Overall, the use of FRP in seismic retrofitting has yielded promising results, significantly enhancing the structural integrity and resilience of historical buildings. These techniques ensure both the preservation of cultural heritage and improved resistance to future seismic events.

6.1.3. Pre-stressing

The pre-stressing method is a technique used for the repair and reinforcement of damaged structures, particularly in areas where tensile stresses have caused cracking in building materials and components. This method involves placing tendons in specific regions (either embedded within structural elements or externally), anchoring their ends, and applying tension to them. This process induces compressive stresses in the structural elements, which helps control crack widening and eliminates tensile stresses in targeted areas, thereby enhancing the load-bearing capacity of the structure.

The repair and strengthening process includes the following key steps:

- Installation of External Tendons: High-strength steel tendons are installed externally along critical sections of the structure. These tendons are strategically placed to address areas experiencing significant tensile stresses.
- Application of Tension: The tendons are tensioned and anchored at their ends, inducing compressive stresses within the structural elements. This process counteracts the tensile forces responsible for cracking over time.
- Mitigation of Cracks: The compressive stresses introduced by pre-stressing tendons effectively reduce the width of existing cracks and prevent new cracks from forming, thereby enhancing the durability of the building [21,22].

The selection of the appropriate technique and materials depends on each case study and the purpose of the intervention. Pre-stressing of masonry structures is not a recent retrofitting technique, as it has been observed in ancient masonry buildings in Italy. Early interventions included pre-stressing applications in the Roman Colosseum in the early 19th century, where internal walls were connected perpendicularly to the external ring (Fig. 4).

Figure 5 illustrates several types of metal rods, along with their anchors and tensioners made from the same material. To generate the pre-stressing effect, the metal tie was traditionally heated, causing the material to expand. As the tie cooled and returned to its normal temperature, it contracted, producing shortening forces that generated active pre-stressing within the masonry.

The main disadvantages of these old metal bars include their heavy weight and susceptibility to corrosion, which reduces their strength and damages the masonry due to the volumetric changes of the corroded bars. Additionally, difficulties in creating a strong connection between the bars and the excessive concentration of stresses induced by the anchorage can lead to masonry crushing. Another drawback was the lack of control or monitoring of the pre-stressing force, which changed over the years due to temperature fluctuations, corrosion, and relaxation caused by masonry deformation (creep) [21-24].

Fig. 4. Roman Colosseum. *Source*: [21]

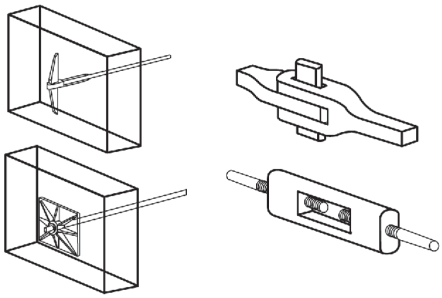


Fig. 5. Metal bars with their anchorages and tensioners. *Source*: [21]

6-1-4. Injection

One of the methods for repairing and reinforcing cracked masonry components or filling gaps and voids between different parts is grout injection, using materials such as expanding cements or various resins. In this approach, the injected material fills the cavities and pores between the masonry components, leading to a more uniform distribution of stresses. This, in turn, increases the load-bearing capacity. Moreover, combining this method with other reinforcement techniques can yield more effective results.

The grout injection technique played a pivotal role in the restoration of the St. Francis of Assisi Church in Lima, Peru. This historic church, built in the 17th century, had suffered extensive cracking and voids in its masonry components due to seismic activity and the natural ageing of materials. In this restoration project, a combination of expanding cement and resin injections was used to fill cracks and voids within the masonry. The injected materials filled the cavities and pores between the masonry units, leading to a more uniform distribution of stresses across the structure. This method not only increased the load-bearing capacity of the church's walls but also improved the overall stability of the building. Additionally, the injection technique was complemented by other reinforcement methods, such as the installation of steel ties and anchors, further enhancing the church's structural integrity [25].

In addition to repairing and strengthening cracked masonry or filling voids between different structural components, the injection method can also be used to strengthen and consolidate soil for specific projects.

For cohesionless soils, if the masonry foundations are in good condition, their load capacity can be increased through silicatization, which involves the injection of cement mortar and water glass. For cohesive soils, an electrochemical method can be implemented to enhance their load-bearing capacity [3].

Grouting is a widely used technique, primarily applied for soil stabilisation and filling cracks or voids in concrete structures. However, it remains a complex and challenging process. Due to the varied performance requirements across different applications and the diversity of grouting methods and design strategies, it is essential to understand how the components of grout – such as cement, aggregates, supplementary cementitious materials, and chemical additives – affect its performance and sustainability. Key factors influencing grouting effectiveness include injectability, consistency, rheology, and the resulting material properties, along with mechanical strength and the long-term efficiency and functionality of the grouting application. Over time, all cement-based materials are prone to deterioration, which may compromise durability and service life, potentially leading to safety concerns. This often necessitates costly maintenance or rehabilitation efforts, with the total lifecycle cost of a structure sometimes surpassing its initial construction expenses [26].

To address these challenges, researchers have introduced self-healing cementitious materials, which offer a promising solution by extending the longevity of structures and reducing their environmental footprint throughout their lifecycle. Numerous studies have demonstrated the effectiveness of self-healing mechanisms in concrete and mortar. However, the application of this technology in grouts has been relatively limited. In this context, a comprehensive review of cementitious grouts by Suelen da Rocha Gomes et al. provides an in-depth examination of cement-based grouts, exploring their composition, characteristics, application techniques, and the factors influencing their performance. The review also highlights self-healing technologies adapted for grouts and identifies critical research gaps that must be addressed to fully leverage the advantages of self-healing grouts in structural and infrastructure applications. It is also important to note the risks associated with grouting techniques, including excessive fluidity, bleeding, liquefaction, and loss of strength, which can pose challenges or uncertainties in the effectiveness and durability of this method [25,26].

6.2. Establishing a coherent and proportionate configuration

The regularity of a structure in plan and elevation, the geometric proportions of structural elements, and the coherence between different structural components are crucial factors influencing a building's load-bearing capacity and seismic resistance. However, in many historical buildings, these principles are often violated according to modern engineering sciences, such as structural dynamics. To address these deficiencies, the following methods can be employed:

6.2.1. Eliminating or reducing irregularities in elevation or plan

Irregularities in buildings can manifest in various ways. For instance, a significant discrepancy between the centre of mass and the centre of rigidity can induce torsional modes in the dynamic behaviour of the structure, which can be particularly destructive for historical buildings [10]. This issue is particularly evident in buildings with large porticos, where modifications to stiffness, centre of gravity, and force distribution can help mitigate the problem. Hidden braces, tie-beams, coils, and tensile elements can be incorporated to enhance structural coherence and improve resistance to dynamic loads.

Another example is structures composed of sections with differing vibration periods, such as mosques with very tall minarets attached to relatively short courtyards, which exhibit highly unfavourable seismic behaviour. One method to address this issue is the implementation of a separation joint between the two distinct sections of the structure. However, this solution requires extensive studies and the incorporation of safety measures to ensure its effectiveness [3,4,9,10].

6.2.2. Correcting geometric proportions of elements

In some buildings, disproportionate dimensions of openings, such as excessively long or tall windows and doors, or inadequate wall dimensions, can lead to undesirable seismic behaviour. This issue can be rectified through methods such as increasing the dimensions and cross-section of structural components, as discussed in section 6.1.1.

6.3. Creating support structures

If the structure itself is unable to withstand or transfer incoming loads, the load-bearing capacity of a historical building can be enhanced by introducing new elements or auxiliary structural systems. One common method involves tying together different parts of the building using tension elements. This technique can be applied at the foundation level to connect and stabilise the piles, as well as at the ceiling level and in areas where walls or other components are joined.

A notable example of creating support structures to enhance the load-bearing capacity of a historical building can be seen in the restoration and reinforcement of the Basilica di San Francesco in Assisi, Italy. The basilica suffered severe damage from earthquakes, particularly in 1997. To preserve the structure and improve its load-bearing capacity, engineers implemented several auxiliary structural systems. One of the key interventions was the introduction of tension elements to connect different parts of the building. At the foundation level, steel ties were installed to connect and stabilise the piles, ensuring a more uniform distribution of loads and enhancing overall structural integrity. Additionally, at the ceiling level, tension rods were used to connect the walls and prevent them from spreading apart. These measures were critical in preserving the basilica’s historical and architectural significance while significantly improving its ability to withstand future seismic events [27].

6.4. Reduction of vertical loads on structures

Increasing vertical loads can not only damage many structural elements in historical buildings but also increase the overall mass of the structure, consequently amplifying the inertial forces generated during earthquakes. To reduce the load and mass of a building, several methods can be employed, such as lightening the roof and decreasing additional loads at different levels of the structure. For instance, removing heavy objects or structural components from upper levels and controlling additional loads by limiting visitor access or reducing foot traffic in vulnerable areas are effective management strategies.

A notable example of the importance of reducing vertical loads can be seen in the Leaning Tower of Pisa, Italy. The tower began tilting soon after its construction in the 12th century due to unstable foundation soil and has undergone several interventions to prevent further tilting and potential collapse. One significant restoration project focused on reducing vertical loads to enhance stability. Engineers implemented various measures, including removing heavy bells from the upper levels and installing a lightweight lead counterweight at the base. These actions decreased the overall mass of the tower, reducing the seismic inertial forces acting on the structure. Additionally, to further stabilise the tower, soil extraction was carried out beneath the north side of the foundation. This innovative technique slightly reduced the tilt and helped redistribute vertical loads more evenly across the foundation, thereby enhancing structural stability without adding extra weight [27,28].

6.5. The use of nanotechnology materials

One of the key factors influencing the durability of traditional materials is moisture. The surfaces of clay structures exposed to moisture require reinforcement and repair using materials that reduce water permeability and absorption. Nanotechnology has made significant advancements in this field; however, reversibility must be a fundamental consideration in strengthening research. If nanomaterials do not conflict with the principle of reversibility, they can be effectively integrated into conservation strategies.

Currently, extensive research is being conducted to expand the applications of nanotechnology while also addressing its environmental impact. One of the most prominent uses of nanomaterials in historical buildings is enhancing the insulation properties and mechanical strength of adobe and brick structures.

For instance, research investigating the effect of nano-montmorillonite clay particles on historical adobe walls utilised FE-SEM, AFM, porosity tests, hydraulic conductivity analysis, and compressive strength measurements. Images obtained from FE-SEM and AFM tests showed that, using a spray-based method, nano-montmorillonite clay particles penetrated the empty spaces within the adobe, filling pores, reducing cavity diameters, and forming a uniform layer on the surface. The optimal application involved spraying a 1% solution of nano-montmorillonite clay particles twice, which resulted in: a 44% increase in compressive strength compared to non-sprayed samples; a 14% reduction in hydraulic conductivity, improving moisture resistance; increased structural integrity due to cavity filling and void reduction. In all sprayed samples, the compressive strength increased due to the reduction in voids and the filling of cavities [8].

This study demonstrates that the use of nano-montmorillonite clay particles with a spray-based technique is an innovative and effective method for protecting and restoring historic adobe buildings. Furthermore, this method can be applied to preserve and strengthen other soil-based materials, bricks, and rammed earth walls.

6.6. Implementation of a seismic isolation system

Seismic isolation systems have been effectively utilised in structures since the 1970s, ensuring structural performance after major earthquakes and safeguarding structural integrity. The primary objective of a seismic isolation system is to decouple the structure from ground motion, thereby mitigating the destructive effects of earthquakes through energy dissipation [5]. The implementation of a seismic isolation system is designed to reduce the transfer of dynamic energy from an earthquake to a building. This is achieved by significantly increasing the structure's dominant vibration period, which in turn reduces the amount of seismic energy transferred. Seismic isolators, characterised by low horizontal stiffness and appropriate damping, facilitate this process. These isolators are typically made of elastomeric materials reinforced with steel plates, enhancing their vertical load capacity [29-32]. Seismic isolation design methods strategically position isolation devices between the foundation and the building to reduce ground motion transmission and safeguard the structure from potential damage [33].

However, implementing seismic isolators in complex historical buildings poses a challenge due to their varied and often unknown dynamic characteristics. Each historical structure requires a carefully selected and tailored isolation system. For base isolation applications, a comprehensive foundation beneath the building is typically required, making the construction process complex and delicate.

Seismic isolation functions by decoupling the movement of the superstructure from that of the ground. This is achieved through seismic devices with low horizontal stiffness, leading to an elongation of the structure's fundamental natural period. This significantly reduces seismic demands in terms of lateral accelerations, while increasing lateral displacements. As a result, damage to the superstructure is minimised or even eliminated due to the considerable reduction in interstorey drifts and floor shear forces. Seismic isolation can be a more effective approach compared to dissipative bracing systems, which increase a structure's stiffness and strength by incorporating additional elements [34].

It is well established that the dynamic behaviour of an isolated building is highly dependent on the characteristics of the isolation devices. These devices serve to re-centre the building during horizontal oscillations while simultaneously dissipating kinetic energy. A variety of isolation devices can be employed, including elastomeric bearings, sliding bearings, and hybrid systems [34].

- Elastomeric Bearings: Composed of layers of rubber and steel plates, these bearings offer horizontal flexibility while maintaining vertical stiffness. Common types include high-damping rubber bearings (HDRBs) and lead rubber bearings (LRBs), which provide both energy dissipation and restoring force.
- Sliding Bearings: Allow movement in all directions through sliding interfaces, thereby reducing shear forces. Friction pendulum bearings (FPBs) are a popular type, utilising a concave sliding surface to lengthen the building's natural period.
- Hybrid Systems: These systems combine features of both elastomeric and sliding bearings, optimising the benefits of each type [29-32].

Seismic isolation is a remarkable concept with deep historical roots and has long been applied in the retrofitting of historic structures. Several notable examples from ancient times to the present day demonstrate its effectiveness.

Research on the Temple of Artemis at Ephesus suggests that its foundations consisted of a continuous stone slab, separated from a thin layer of marshland by a mixture of clay, charcoal, and ashes [6]. Modern interpretations indicate that this configuration functioned as an early form of base isolation.

The Walls of Troy, dating back to 1500 B.C., were discovered by Blegen to be founded on a compact 'cushion of earth', which separated the foundation from the underlying rock. Similarly, in Paestum, Italy, the foundations of three Doric temples, including the Temple of Athena (6th century B.C.), rested on a sand layer that isolated the foundation from the soil [5,29,30,32].

In Peru, the Santa Catalina Monastery, located approximately 1,000 kilometres south of Lima, was constructed on a 1-metre-thick sand layer, serving as a natural isolating foundation. This design has allowed the monastery to settle without sustaining damage, even during severe earthquakes. The walls of Cuzco, believed to have been built using a similar technique, have also shown remarkable resilience during seismic events [32].

A comparable method was employed by Frank Lloyd Wright in the construction of the Imperial Hotel in Tokyo. The hotel's foundations were set on a compacted soil layer approximately 2 metres deep, atop a 20-metre-thick stratum of muddy silt. Completed in 1921, this "cushion" is thought to have contributed to the hotel's survival during the 1923 Tokyo earthquake, which caused widespread destruction of other buildings [32].

In 1965, following the 1963 Skopje earthquake, the Pestalozzi School was rebuilt with seismic isolation. The isolation devices, provided by Swiss engineers, were made entirely of rubber, resulting in high vertical deformability. These original rubber bearings were recently replaced with new high-damping rubber bearings to improve performance (Fig. 6).

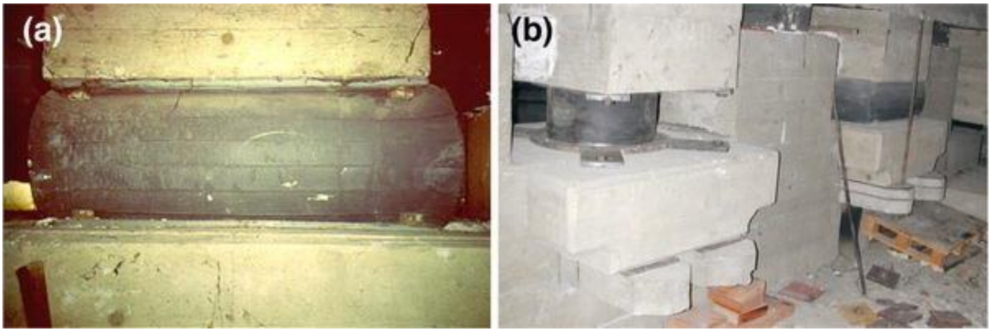


Fig. 6. (a) Original LDRB and (b) new HDRB in the Pestalozzi School. *Source*: [32]

The Italian architect Francesco Milizia, in his 1781 architectural treatise, addressed earthquake-resistant design in Chapter IX. He advocated for the construction of tightly interconnected timber structures, stipulating that their height should not exceed their width. Instead of anchoring the building to the ground, he proposed placing it freely on a stone platform. According to Milizia, such a structure would shake during an earthquake but never topple, as he reasoned, "this house is like a tree trunk" [5].

A prominent example of seismic retrofitting is San Francisco City Hall, which was reconstructed following the destruction of the original building in the 1906 earthquake. This five-storey structure, characterised by a steel framework and masonry walls providing lateral support, suffered extensive damage during the earthquake. The retrofitting process involved the implementation of a seismic isolation system, along with the addition of concrete shear walls. Initially, the foundations were reinforced with new beams, and a new deck was constructed above the isolation layer. Subsequently, structural elements were braced, and the tops of the foundations were cut to accommodate lead-rubber bearings beneath each column, with hydraulic jacks temporarily supporting the structure during this phase [32].

One of the most notable advancements in base isolation was introduced by the English physician J.A. Calantarients, who filed for a U.S. patent in 1909. His innovative construction technique, which relied on sliding foundations, gained significant recognition. He proposed constructing the superstructure on a "free joint" – a layer composed of talc, fine sand, or mica – to create a lubricated surface, allowing the building to shift or slide during seismic events [5].

Seismic isolation techniques have been in use for over a century, with continuous advancements. One notable application was at the Law and Justice Center in California, which incorporated high-damping natural rubber bearings [35].

In another case study, a base-isolated masonry building representative of the neo-Renaissance period in Europe was analysed. The structure is a three-storey unreinforced masonry building, located in a region with moderate seismic activity and a designated ground acceleration level. A base isolation system using natural rubber bearings (NRBs) was selected and incorporated into the mathematical model of the studied building. The structure was modelled using a macroelement frame approach, which employed a failure mode interaction surface to simulate the nonlinear behaviour of masonry elements under seismic forces. This method utilised a combined plastic hinge model to account for the interaction between flexural, shear, and diagonal failure modes, while also considering the influence of vertical (axial) loads on the masonry elements. The results of a comparative pushover analysis indicated that the implementation of a base isolation system significantly reduces seismic damage in such buildings. Additionally, the installation of a base isolation layer requires minimal alterations to the existing structure, as the system is typically installed at the foundation level [36].

Calculations suggest that base seismic isolation can be approximately five times more effective than traditional methods, offering lower costs and shorter implementation times. The "Melkumyan Seismic Technologies" company has developed a programme aimed at reducing seismic risks in buildings constructed in Armenia before 1994, by applying seismic isolation technologies at their base [17].

With these considerations, all structures protected by seismic isolation in areas affected by strong earthquakes have exhibited excellent performance, sustaining no damage. However, the presence of a structural health monitoring (SHM) system in these buildings can provide valuable data on their actual behaviour during different earthquakes.

6.7. Utilisation of energy absorption systems

These systems come in various types, including viscoelastic, elastoplastic, viscoelastic, and electromagnetic. Energy dissipation systems absorb a significant portion of dynamic energy, preventing damage to structural components. One type of energy-absorbing system operates using shape memory alloys (SMA). Shape memory alloys are metals that exhibit unique properties – their flexibility is comparable to that of rubber. When subjected to significant deformations, these materials can return to their original shape when heated. One particularly corrosion-resistant alloy used for this purpose is nickel-titanium (NiTi) [37-39].

6.8. Usage of active control systems

This system consists of actuators that interact simultaneously with sensors and controllers embedded within the structure and are managed by a central processor. The system monitors environmental stimuli, such as wind or earthquakes, and gathers data on forces and deformations within the structure using sensors and the central processing unit.

Upon detecting external forces and deformations, the system generates counteracting forces in a very short time through its actuator systems, effectively neutralising the effects of these environmental forces. As a result, the structure experiences significantly fewer deformations and forces over time during seismic or environmental disturbances. Several buildings in the United States, Japan, and China have been constructed using this active control system, providing enhanced protection against seismic activity [4,40]. However, for historical buildings, research in this field is still ongoing.

7. Conclusions

Preserving and restoring historical monuments is a fundamental responsibility, as they represent invaluable cultural heritage. Earthquake experiences have demonstrated that neglecting these structures can lead to irreparable damage, highlighting the increasing urgency of studying seismic behaviour, retrofitting techniques, and strengthening methods for these buildings.

However, preserving the cultural values, authenticity, and identity of these structures presents significant challenges in restoration methods. The core principle of reversibility, which ensures minimal intervention while maintaining structural integrity and aesthetic authenticity, often complicates the implementation of modern seismic retrofitting techniques. Therefore, methods for seismic strengthening must be non-invasive, reversible, and effective, safeguarding both the cultural and structural integrity of these buildings.

Looking ahead, it is essential to explore further avenues of research, particularly focusing on the adaptation of advanced technologies, such as active control systems, energy dissipaters, and seismic isolators, to historical buildings. The integration of such systems, despite their higher cost, is crucial for enhancing seismic resilience without compromising historical value. Future studies should aim to: refine these systems for broader application; assess their long-term effectiveness; explore new materials and techniques that balance modern safety standards with the preservation of cultural heritage; in conclusion, while seismic isolation systems have demonstrated their potential, further research is required to fully understand their feasibility and applicability in historical buildings. This continued research is critical for the future of seismic retrofitting and the preservation of cultural heritage.

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