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Modern Masonry Construction

The Fusion of Tradition, Technology, and Sustainability

Edited by Salih Yilmaz



Modern Masonry Construction - The Fusion of Tradition, Technology, and Sustainability

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Volume 16

Aims and Scope of the Series

Civil engineering is a traditional field of engineering from which most other branches of engineering have evolved. It comprises traditional sub-areas like transportation, structures, construction, geotechnics, water resources, and building materials. It also encompasses sustainability, risk, environment, and other concepts at its core. Historically, developments in civil engineering included traditional aspects of architecture and urban planning as well as practical applications from the construction industry. Most recently, many elements evolved from other fields of knowledge and topics like simulation, optimization, and decision science have been researched and applied to increase and evolve concepts and applications in this field. Civil engineering has evolved in the last years due to the demands of society in terms of the quality of its products, modern applications, official requirements, and cost and schedule restrictions. This series addresses real-life problems and applications of civil engineering and presents recent, cutting-edge research as well as traditional knowledge along with real-world examples of developments in the field.

Meet the Series Editor



Professor Assed N. Haddad is a Civil Engineer with a degree from the Federal University of Rio de Janeiro (UFRJ) earned in 1986, as well as a Juris Doctor degree from the Fluminense University Center earned in 1993, and a Master's degree in Civil Engineering from the Fluminense Federal University (UFF) obtained in 1992. He completed his Ph.D. in Production Engineering from COPPE / Federal University of Rio de Janeiro in 1996. Professor Haddad's academic pursuits have taken him to postdoctoral stays at the University of Florida, USA in 2006; at the Universitat Politècnica de Catalunya, Spain in 2010; and at the University of New South Wales Sydney, Australia in 2019. Currently, he serves as a Full Professor at the Federal University of Rio de Janeiro. He has held visiting professorships at various institutions including the University of Florida, Universitat Politècnica de Catalunya, Universitat Rovira i Virgili, and Western Sydney University. His research expertise encompasses Civil, Environmental, and Production Engineering, with a primary focus on the following topics: Construction Engineering and Management, Risk Management, and Life Cycle Assessment. He has been the recipient of research grants from the State of Rio de Janeiro, Brazil: CNE FAPERJ from 2019 to 2022 and from 2023 to 2025. Additionally, his research grants obtained from the Brazilian Government CNP since 2012 last to this date. Professor Haddad has been involved in several academic endeavors, being the Guest Editor of the International Journal of Construction Management; MDPI's Sustainability, Energies, and Infrastructures; Associate Editor at Frontiers in Built Environment / Sustainable Design and Construction; Guest Editor at Frontiers in Built Environment / Construction Management; and Academic Editor of the Journal of Engineering, Civil Engineering Section of Hindawi. He is currently a Professor of the Environmental Engineering Program at UFRJ and the Civil Engineering Program at UFF.

Meet the Volume Editor



Salih Yilmaz is a civil engineer and academic specializing in sustainable construction, seismic design, and the strengthening of structures against earthquakes. He currently works at the Institute for Construction and Environment, Eastern Switzerland University of Applied Sciences. With over 20 years of professional experience, Dr. Yilmaz has led and contributed to numerous research and praxis projects focusing on seismic performance assessment and retrofitting of structures, as well as the development of innovative methods and building materials. He has participated in several post-earthquake reconnaissance studies, which provided valuable insights into the real-world performance of buildings. These field experiences, together with subsequent projects on repair and strengthening, shaped his strong commitment to linking traditional knowledge with modern engineering solutions. He has published widely in leading journals, served as a reviewer and guest editor for international publications, and contributes actively to academic and professional networks in structural and earthquake engineering. Dr. Yilmaz is dedicated to advancing sustainable and resilient solutions for the built environment.

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Preface

It's been truly rewarding to put together this collection on *Modern Masonry Construction – The Fusion of Tradition, Technology, and Sustainability*. Throughout my career as a civil engineer, I have come to see that masonry, even though it is one of the oldest building methods out there, still sparks new questions and encourages fresh ideas. Back in 2014, I was visiting the University of Texas at Austin, and I remember my colleagues in Turkey looked at me like I was a bit off when I chose to focus on masonry materials.

At that time, it felt a little unusual to dedicate academic energy to something seen as so traditional. However, for me, masonry has always been relevant. It is an area that's constantly changing and resilient, which is why it has always been an important part of my work and studies. In my current role, we are even experimenting with 3D printing using earth-based materials, showing how an age-old traditional method can still be connected to emerging technologies. There is a famous saying primarily for literary works that "classics never go out of style", and I think masonry fits right into that idea: something that keeps its importance and continues to grow with each new challenge.

My understanding of masonry has also been shaped by studying how buildings perform after earthquakes. After several quakes in Turkey and an earthquake in L'Aquila, Italy, I was able to observe the actual strengths and weaknesses of masonry structures. These experiences were eye-opening: they exposed the flaws of poorly built walls and also showed the resilience of well-crafted traditional designs. Later on, through research and hands-on projects focused on repair and strengthening existing masonry, I learned that smart interventions can help buildings last longer, be safer, and still honor their heritage.

Over the years, I have observed the evolution of masonry to survive earthquakes, climate change, and fast urban growth. Each time, I was reminded that traditional techniques are not holding progress back—they actually have key roles in building a sustainable future. This book brings together different viewpoints, from traditional construction methods and recycled materials to high-tech diagnostic tools. Altogether, these chapters show masonry as a living, changing discipline: one that keeps inspiring, adapting, and linking our past with the future.

Honestly, what I enjoyed most about working on this book was the balance. On one side, the book includes chapters that look at traditional masonry from an architectural perspective, and on the other hand, some that focus on innovative engineering tools. Today, with sustainability more important than ever, I am particularly pleased to include sections on strengthening existing structures and creatively reusing waste materials in masonry production.

I would also like to express my greatest appreciation to everyone who contributed, reviewed, and helped to shape this book. I hope that the ideas and research presented in the book will inspire not only technical progress but also a renewed sense of responsibility for the built environment.

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Section 1

Traditional and Emerging Earthen and Masonry Techniques

Chapter 1

Rammed Earth Construction: From Tradition to a Sustainable Future

Dilek Eksi Akbulut and Rojda Naz Alibeyoglu

Abstract

While structures are necessary to meet housing needs, on the other hand, the construction industry consumes a great quantity of resources, creating a problem that is global in scale. Supplying the materials, processing them, and transporting them to the construction site create significant environmental problems. Therefore, to reduce waste, preserve resources, and increase energy efficiency, an ecodesign approach is now being considered. Earthen structures have played a significant role in the development of human civilization, both functionally and symbolically. These structures represent a crucial part of architectural heritage in terms of adaptability, cultural expression, and sustainability potential. As contemporary challenges such as climate change and urbanization intensify, the lessons offered by earthen construction techniques can illuminate future building methods and contribute to a more harmonious framework for the human-nature relationship. In this study, earth structure techniques used in building since the early ages and modern earthen techniques, like rammed earth structure, were analyzed. The rammed earth construction technique (RE), with its deep historical roots, holds a significant position among sustainable, eco-friendly, and cost-effective building methods. Traditional earthen construction techniques have contributed to cultural heritage preservation through local material use and community involvement, while modern approaches have integrated material innovations and technology. To promote sustainable building practices, it is essential to develop dedicated regulations for RE, enhance educational initiatives, and increase the visibility of successful projects. These measures will facilitate the wider acceptance and implementation of RE as a key solution for sustainable and resilient architecture.

Keywords: earthen structures, rammed earth construction, sustainable architecture, earth-based building material, sustainable building technologies

1. Introduction

Earthen structures have played a significant role throughout human history, serving as essential building materials for civilizations across different geographies. Constructed with materials such as adobe, rammed earth, and cob, these structures not only provided shelter but also reflected the cultural, social, and technological advancements of the societies that built them. The earliest applications of earthen

construction techniques are known to date back to the Neolithic period, when humans transitioned from a nomadic lifestyle to settled agricultural communities (**Figures 1** and **2**).

During this time, the need for permanent settlements necessitated structures that were resistant to natural conditions and provided safety for both humans and animals. Archaeological findings suggest that the earliest earthen structures were built using locally available and cost-effective materials such as mud and straw [3].

This practice not only contributed to the establishment of permanent settlements but also laid the foundation for more complex forms of social organization. For example, in Ancient Egypt, many monumental structures, including temples and tombs, were constructed using adobe bricks (**Figure 3**) [5]. Similarly, in the Near East, civilizations such as the Sumerians and Babylonians utilized earthen materials



Figure 1.
Building with Earth [1].



Figure 2.
Application in Iran [2].



Figure 3.
R.E Grave [4].

for multistory buildings, public structures, city walls, and irrigation systems, showcasing the diversity of architectural creativity and engineering knowledge [6].

Earthen structures often reflect the values, belief systems, and artistic expressions of the societies that built them. For instance, the intricate motifs and decorations found in adobe buildings in Mexico and the southwestern regions of the United States showcase the rich cultural heritage of the indigenous communities to which they belong [7]. The critical role these historical structures have played has profoundly influenced the social and economic dynamics of communities. In many cases, the construction of earthen buildings brings together collective labor and craftsmanship, strengthening social identity and solidarity [8].

Indeed, in many cultures, building with earth has served as more than just an architectural activity—it has functioned as a communal ritual that preserves cultural identity and heritage. It is estimated that approximately 10% of the structures on the UNESCO World Heritage List were built using earthen materials, highlighting their significance in global cultural heritage [9].

Durability and flexibility are key aspects that define the historical importance of earthen structures, yet they also remain among the most debated aspects of these buildings. While they are susceptible to environmental factors such as moisture and seismic activity, many earthen structures have proven to be relatively long-lasting. For example, constructions like the Great Wall of China, built using rammed earth techniques, demonstrate the resilience of traditional building methods, having stood the test of time for centuries [10]. However, with the acceleration of climate change and urbanization, the preservation of these structures is becoming increasingly challenging, necessitating modern restoration efforts [11].

Earthen buildings, as fundamental elements of human settlements in different geographic regions, exemplify the ability to adapt to local environments and the versatility of the material (**Figure 4**). In arid and semiarid climates, such as those found in North Africa and the Middle East, material availability and the need for thermal regulation have led to the prominence of traditional adobe and rammed earth structures. The Ksar d'Aït-Ben-Haddou in Morocco, for example, embodies cultural heritage while providing resilience against extreme temperature fluctuations [13–15].

In regions with a temperate climate, such as Europe and North America, earthen architecture is widely practiced as part of local building traditions, particularly in countries like Spain and Italy (**Figure 5**). In these areas, rammed earth and adobe



Figure 4.
Regions of the world with the presence and active use of earth structures [12].



Figure 5.
Old towns of Djenné [16].

construction techniques contribute to the preservation of local identity and cultural heritage, showcasing a rich architectural legacy [16–18].

In Asia, countries like China and India demonstrate the diversity of earthen construction techniques (**Figure 6**). In China, the Tulou, traditional rammed earth dwellings, symbolize communal living and social cohesion that have been sustained for centuries. Meanwhile, in India, cob and adobe construction methods provide cost-effective and sustainable housing solutions [19, 20].

During the nineteenth and twentieth centuries, as industrialization and urbanization accelerated, materials such as concrete and steel with high durability became dominant in the construction sector, significantly reducing the use of traditional earthen building techniques [21]. While these materials gained prominence in



Figure 6.
Bam ancient city [16].

modern urban planning due to their rapid production processes and suitability for large-scale structures, earthen construction techniques remained largely limited to rural areas [22]. However, in recent years, environmental sustainability concerns, carbon emission reduction targets, and the need to increase energy efficiency have brought about a significant transformation in building material selection [23]. Traditional earthen construction techniques have reemerged due to their low energy consumption, use of local materials, and natural insulation properties, and have begun to be considered within sustainable construction strategies [22].

Recent advancements in material science and engineering have enabled the development of innovative methods, such as stabilized earth blocks and reinforced earth applications. These innovations enhance the structural integrity and performance of earthen buildings, while research on seismic resistance provides valuable data for designing structures that are more resilient to natural disasters [7, 19]. These technological advancements not only facilitate the integration of traditional construction techniques into contemporary architectural discourse but also establish a dialog between the past and the present. Beyond traditional applications, earthen materials are increasingly being integrated into modern construction through innovations like 3D printing technology, offering practical solutions to contemporary challenges such as urbanization and environmental sustainability [19, 20]. Additionally, in regions prone to natural disasters such as earthquakes and floods, the use of stabilizers like lime or natural fibers enhances the seismic resilience of earthen structures, strengthening their resistance to environmental stresses [24, 25].

2. Earth structures in the context of sustainability

Today, sustainability and environmentally responsible approaches have brought earthen structures back into focus. The necessity to cope with resource scarcity and the effects of climate change has accelerated the search for alternatives to conventional materials such as concrete and steel. Earthen buildings stand out due to their low embodied energy, recyclability, and minimal carbon footprint, making them an attractive option for sustainable development [26]. Societies striving to combat climate change and the depletion of natural resources are re-evaluating the advantages of earthen structures, which use locally available materials such as clay, sand, and silt and require low embodied energy, thereby minimizing carbon emissions [25, 27, 28].

The environmental benefits of earthen structures stem from their production process, which does not require high temperatures and therefore consumes less energy. Particularly, compressed earth blocks (CEBs) are manufactured with significantly lower energy consumption compared to traditional fired bricks, reducing a building's carbon footprint over its lifecycle [28, 29]. Additionally, the use of locally sourced materials decreases emissions related to transportation and logistics, further supporting environmental sustainability [30–32]. In terms of thermal performance, the high thermal mass of earthen buildings effectively absorbs and stores heat, regulating indoor temperatures and reducing reliance on mechanical heating and cooling systems [33–35]. This, in turn, lowers energy consumption during a building's operational phase, further reducing carbon emissions and reinforcing the role of earthen architecture as a fundamental component of sustainable design.

The significance of earthen structures extends beyond environmental aspects, encompassing cultural and economic dimensions as well. Adobe and rammed earth construction techniques, as tangible representations of local cultural heritage and craftsmanship, contribute to cultural continuity and the preservation of social identity in the face of globalization and urbanization [36, 37]. Economically, the affordability and local availability of earthen materials help reduce construction costs, particularly in developing countries, support local economies, and encourage community participation in the building process [31, 38].

Moreover, the integration of modern construction technologies with earthen materials—such as the use of 3D printing techniques—enhances efficiency, precision, and design flexibility in construction processes [25, 28]. These technologies optimize material use, minimize waste, and enable the creation of complex geometries, thereby promoting new approaches that support both environmental and economic sustainability.

Earthen structures align with circular economy principles as they generate minimal environmental impact throughout their lifecycle, from production to operation, and are highly recyclable [39]. Additionally, the moisture-regulating and pollutant-reducing properties of earthen materials enhance indoor air quality, encouraging healthier building practices [33].

In conclusion, earthen structures play an essential role in sustainable construction by offering low embodied energy, local resource utilization, high thermal efficiency, technological adaptability, and cultural heritage preservation. These multidimensional advantages strengthen the relevance and applicability of earthen architecture in the construction sector's transition toward more sustainable solutions in response to environmental degradation.

3. Earth construction techniques

Earthen construction techniques have played a significant role in meeting the needs of different societies for centuries, adapting to various cultural and environmental contexts. These techniques include adobe, rammed earth, cob, and compressed earth blocks (CEBs), each offering unique characteristics and applications. The renewed interest in traditional methods is closely linked to the growing demand for sustainable housing solutions that minimize environmental impact. Firstly, adobe construction is one of the oldest and most widespread techniques, utilizing sun-dried bricks made from a mixture of clay, sand, and straw. Due to the abundance of local materials and its thermal mass benefits, adobe structures provide high energy

efficiency and require low production energy, making them an ideal alternative for eco-friendly construction practices [21, 40]. Additionally, the esthetic and cultural aspects of adobe buildings contribute to the preservation of local architectural styles and traditional ways of life. Meanwhile, rammed earth construction involves compacting a mixture of soil, gravel, and stabilizers to create durable walls. This method stands out for its strength and thermal efficiency while also demonstrating sufficient resistance to seismic forces, making it a low-carbon alternative in modern construction applications [7, 21, 23]. This characteristic supports the use of rammed earth in earthquake-prone regions, reinforcing its practicality in disaster-resilient construction.

The traditional cob technique, which involves hand-molding a mixture of clay, sand, straw, and water, allows for the creation of organic architectural forms while enhancing energy efficiency through its high thermal mass [21, 25]. Furthermore, the community-based nature of cob construction fosters social cohesion and local participation, strengthening collective engagement in the building process (**Figures 7**–**9**) [44].

In response to the demands of modern construction, compressed earth blocks (CEBs) have been developed as a sustainable alternative to traditional bricks. Produced by compressing a mixture of soil, sand, and stabilizers using modern manufacturing techniques, CEBs support environmental sustainability through low energy consumption and minimal waste production [45]. This innovative approach reflects the growing interest in sustainable building materials across both developing and developed countries. Adobe, rammed earth, cob, CEBs, and other earthen



Figure 7.
Peace in Africa [41].



Figure 8.
Djenne Mosque [42].



Figure 9.
Harran Houses [43].

construction techniques have emerged as pioneers of sustainable and eco-friendly construction, thanks to their low-carbon footprint, high energy efficiency, and potential for community involvement. When supported by modern technologies, these traditional approaches not only preserve cultural heritage but also provide flexible and innovative solutions to meet contemporary building demands.

3.1 Contemporary solutions

Modern adaptations in earthen construction techniques reflect the growing demand for sustainable building practices by maximizing efficiency and durability while minimizing environmental impact. The effective integration of these advancements is essential for optimizing the performance of earthen construction methods in contemporary applications. These adaptations primarily involve the incorporation of innovative materials, technologies, and methodologies that enhance the structural integrity of traditional techniques.

One of the key advancements is the use of stabilizers to improve the mechanical properties of earthen materials, addressing challenges related to water sensitivity and structural integrity. Lime, cement, and geopolymers enhance the strength and durability of earthen structures, while geopolymers derived from industrial by-products such as fly ash and ground granulated blast-furnace slag provide a sustainable alternative that reduces the carbon footprint associated with cement production [46].

Another innovation is the integration of 3D printing technology with earthen materials. This method enables the creation of complex geometries and customized designs, improving construction efficiency, reducing labor costs, and minimizing material waste. Additionally, utilizing locally sourced materials in 3D printing lowers transportation emissions, supports local economies, and provides rapid solutions for emergency housing needs [21, 23]. Among modern soil improvement techniques, microbially induced carbonate precipitation (MICP) has emerged as a key innovation. This biotechnological approach enhances soil stability and strength by leveraging natural microbial processes while reducing reliance on chemical stabilizers, thereby supporting environmental sustainability [44].

In contemporary construction projects, climate resilience has become a crucial criterion. The design of earthen structures to withstand floods, earthquakes, and other extreme weather events is increasingly emphasized. Research on the seismic performance of rammed earth and adobe structures plays a vital role in improving

structural durability and informing the development of design guidelines that enhance their resilience. The influence of circular economy principles has also underscored the importance of material reuse and recycling in earthen construction. For instance, recycled concrete or industrial by-products are now being incorporated into compressed earth block (CEB) production, reducing waste and enhancing resource efficiency through eco-friendly construction practices [45]. Furthermore, modern adaptations are revitalizing the cultural significance of earthen structures. The integration of local design elements and materials into modern sustainability standards helps to preserve architectural heritage while ensuring their relevance in contemporary construction practices. This approach fosters social continuity by safeguarding traditional building knowledge within modern urban development.

However, regulatory barriers, lack of awareness, and resistance to change sometimes hinder the widespread adoption of these innovative practices. Nevertheless, ongoing research and advocacy efforts are addressing these challenges by highlighting the benefits of earthen construction techniques. Additionally, educational programs for builders, architects, and policymakers play a critical role in advancing sustainability goals and overcoming institutional resistance [46, 47].

The modern adaptations of earthen construction techniques, including stabilization methods, 3D printing, and biotechnological innovations, alongside the integration of climate resilience and circular economy principles, are making significant contributions to the development of sustainable building solutions. These

Criterion	Traditional rammed earth techniques	Modern rammed earth techniques
Material use	Uses locally sourced natural materials such as clay, sand, and straw.	Incorporates stabilizers (lime, cement, biopolymers) and recycled materials.
Sustainability	Low-carbon emissions; environmentally friendly in material sourcing and transportation.	Aligned with circular economy principles, reducing waste and improving resource efficiency.
Thermal performance	High thermal mass helps regulate indoor temperatures and reduces energy demand.	Enhanced insulation and stabilization methods further improve thermal performance.
Cultural heritage	Contribution to the preservation of local cultures and architectural traditions.	Modern adaptations integrate cultural heritage while providing innovative solutions.
Cost	Low-cost, particularly suitable for developing regions.	Higher initial costs, but improves efficiency in the long-term.
Structural durability	Susceptible to water damage, erosion, and structural limitations, making it less suitable for high-rise buildings.	Stabilizers and technological integration enhance durability, making it suitable for multistory buildings.
Labor and time	Labor-intensive and requires skilled workers.	Technologies such as 3D printing reduce construction time and labor costs.
Environmental impact	Uses natural materials, making it eco-friendly, but vulnerable to water damage and erosion.	Chemical additives may have environmental implications but increase durability.
Climate adaptability	Limited resilience to climate change effects.	Improved resistance to floods, seismic activity, and other natural disasters.

Table 1.
Comparison of traditional and modern rammed earth construction techniques.

multidimensional advancements reinforce the continued relevance of traditional earthen structures, demonstrating their ability to adapt to modern demands while enhancing efficiency and durability (**Table 1**).

4. Rammed earth technique

The rammed earth technique, which has a deep-rooted history in traditional construction methods, has regained significance as an environmentally friendly, economical, and esthetically appealing option in today's sustainable building applications. This technique involves compacting layers of a mixture of sand, gravel, silt, and clay, often combined with stabilizers and additives in specific proportions, to create durable and naturally textured walls. Traditional earthen construction not only enables the efficient use of natural resources but also supports the preservation of local architectural heritage, aligning with environmental sustainability goals due to its low embodied energy requirements and minimal carbon footprint [23, 47].

One of the most notable advantages of rammed earth construction is the use of locally sourced materials, which reduces transportation costs and carbon emissions. Compared to conventional energy-intensive building materials such as concrete and steel, rammed earth emerges as an eco-friendly alternative [41, 42]. Additionally, the high thermal mass of earthen walls allows them to absorb and store heat, naturally regulating indoor temperatures. This property significantly reduces the need for mechanical heating and cooling systems, especially in climates with extreme temperature fluctuations [43, 48]. From an esthetic perspective, the natural colors and textures of earthen structures create a bridge between traditional architecture and modern design, enhancing both the cultural identity and visual appeal of buildings [39, 48].

In terms of durability, rammed earth walls can exhibit resistance to seismic forces, harsh weather conditions, and environmental factors such as erosion, provided that appropriate material selection, stabilizers, and proper construction techniques are implemented [48, 49]. However, certain challenges and limitations must be considered, including susceptibility to moisture, labor-intensive construction processes, restricted structural applications (particularly in high-rise buildings), and regulatory barriers [21, 23, 38–50].

The selection of the construction site plays a critical role in the application of the rammed earth construction technique. Before implementation, the site must be thoroughly analyzed and assessed. This process involves evaluating how the terrain is exposed to atmospheric conditions, such as rain and wind, as well as determining whether the land is situated in a flood-prone area, such as a riverbed. Such an assessment is a fundamental step to ensure the longevity and durability of rammed earth structures (**Figure 10**). To better understand how these advantages and disadvantages translate into practical applications, it is crucial to focus on the construction process itself (**Figure 11**). Site preparation marks the first step in rammed earth construction. The construction area is cleared of vegetation and debris, while the optimal composition of the soil mixture and its moisture content are determined through laboratory testing [28, 39].

Next, formwork systems are carefully designed and set up to achieve the desired wall thickness and height. These formworks are crucial for ensuring uniform compaction of the soil mixture and maintaining the structural integrity of the walls. The compaction process is typically carried out in layers ranging from 8 to 15 cm in thickness. Each layer is carefully compacted using mechanical tools

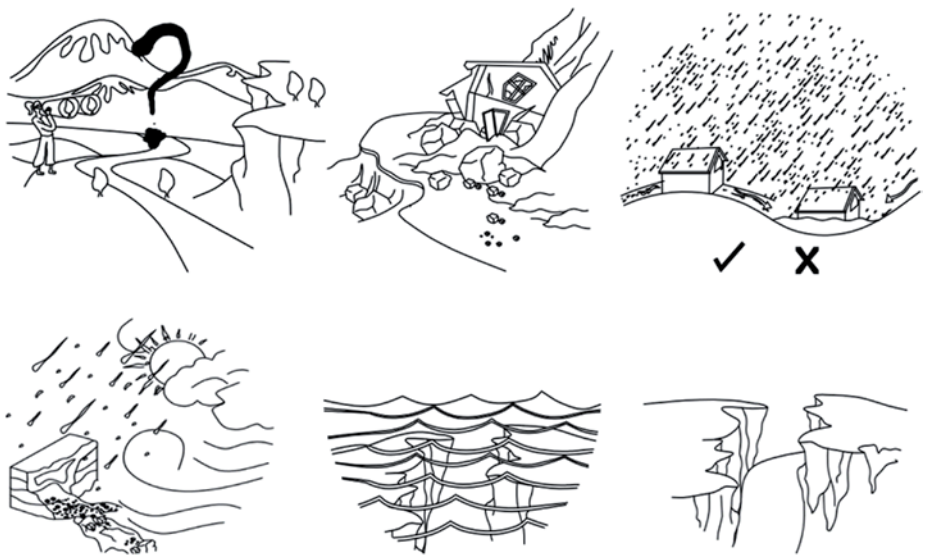


Figure 10.
The importance of site selection and key considerations in site [12].



Figure 11.
Field application stages of the rammed earth technique [12].

or hand-operated equipment, increasing the density and strength of the rammed earth wall (**Figure 12**).

This stage of construction plays a crucial role in determining the overall performance of the structure. Once the compaction process is completed, the structure enters the curing phase. During this phase, the rammed earth walls are left to dry for a specific period, depending on environmental conditions, allowing them to attain the necessary strength and durability. Finally, surface treatments are applied to enhance water resistance and improve the esthetic appearance of the structure (**Figure 13**) [40].

The rammed earth construction technique stands out among sustainable building practices due to its use of natural materials, low environmental impact, high thermal efficiency, and unique esthetic qualities. With the right material selection, proper stabilization techniques, and a carefully managed construction process, rammed earth walls have the potential to create long-lasting structures that are both environmentally and economically viable. The multifaceted advantages of this technique, particularly its efficient use of local resources and contribution to cultural heritage preservation, make it a valuable solution for the future of sustainable construction.

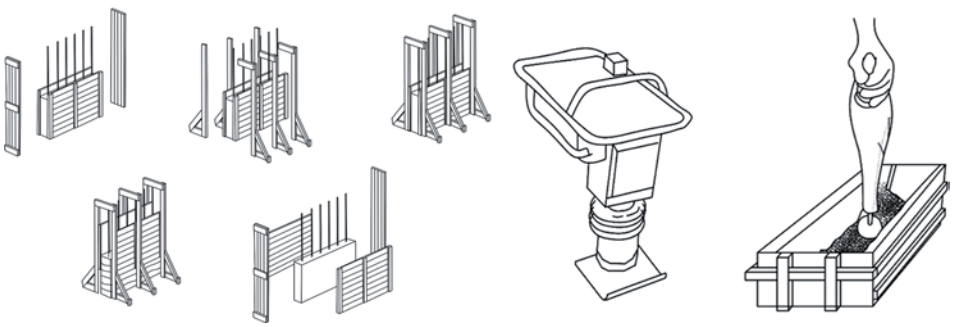


Figure 12.
Formwork installation and compaction process [12].

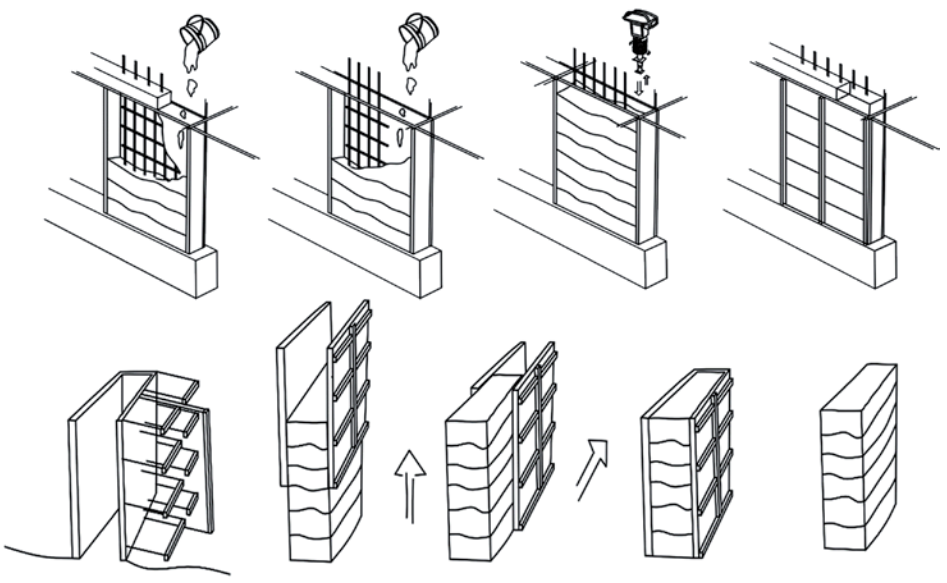


Figure 13.
Reinforcement procedures and formwork relocation [12].

4.1 Developments in rammed earth construction technique

The rammed earth construction technique is regaining prominence due to its alignment with modern construction criteria such as sustainability, energy efficiency, and durability. As technological innovations continue to emerge, traditional earthen construction benefits from advancements in material science, automation, and smart monitoring systems, significantly improving its performance and applicability.

In terms of modern material innovations, stabilizers such as cement, lime, and natural additives are now widely incorporated into rammed earth construction, enhancing the mechanical properties and durability of walls while increasing their resistance to moisture and erosion [49, 50]. Recently, alternative stabilizers, such as biopolymers and recycled materials, have been explored to improve environmental sustainability [51]. Furthermore, the use of nanomaterials such as nanosilica enhances

the compressive strength of rammed earth, allowing for the development of lighter and more efficient building systems [51].

A notable example of integrating modern advancements into rammed earth construction is the Telenor Headquarters in Islamabad (**Figures 14** and **15**). This project utilizes a combination of local soil and advanced stabilizers, selected specifically to adapt to the region's climate conditions while enhancing structural integrity. Additionally, the implementation of energy-efficient design principles has reduced heating and cooling demands, leading to lower operational costs for the building.

Advancements in construction techniques have been significantly influenced by the integration of robotics and automation systems into the rammed earth compaction process. Automated systems ensure consistent density and quality throughout the walls while reducing labor costs and construction time, thereby improving efficiency in the construction sector [51]. Additionally, 3D printing technology enables the creation of complex geometries and customized designs, which are difficult to achieve with traditional methods. This innovation minimizes material waste and aligns with sustainable construction practices [51, 52]. A successful application of this technology can be observed at the Göbeklitepe Visitor Center in Turkey (**Figure 16**). To preserve the historical site, the structural properties of the local soil were analyzed through digital simulations and 3D printer-assisted molds. These findings were used to improve ground stabilization and design a building form that aligns with the original architectural context of the archaeological site. As a result, a long-lasting structure



Figure 14.
Closer exterior view of the Telenor Headquarters in Islamabad, highlighting facade composition [40].



Figure 15.
General exterior view of the Telenor Headquarters in Islamabad [40].



Figure 16.
Göbeklitepe visitor center.

was achieved by integrating traditional earthen architecture with modern technological methods, ensuring harmony with the historical fabric.

Monitoring technologies play a crucial role in ensuring the long-term performance and safety of structures. IoT-based smart monitoring systems allow for the real-time tracking of key parameters such as moisture content, temperature, and structural integrity during the construction process and throughout the building's lifespan, enabling continuous assessment of rammed earth structures [49]. Additionally, nondestructive testing (NDT) methods, such as ultrasonic pulse velocity and rebound hammer tests, help examine structural quality without causing damage, ensuring that necessary maintenance measures can be taken in a timely manner [39, 53].

A notable example of how these technological approaches are integrated with traditional structures is the Tulou houses in China (**Figures 17** and **18**). Tulou dwellings, known for their multistory circular or oval forms, have historically combined rammed earth walls with wooden frameworks for structural stability. Today, some

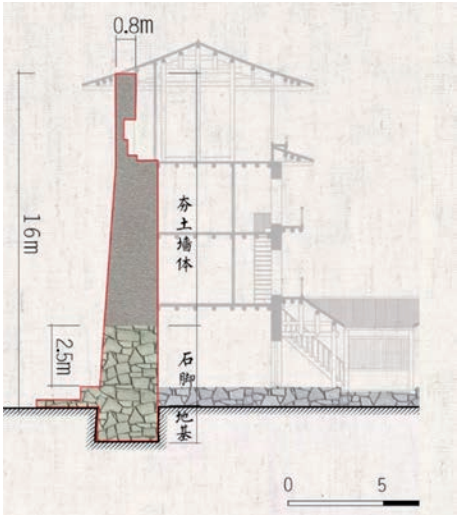


Figure 17.
Section view of a traditional Tulou dwelling [21].

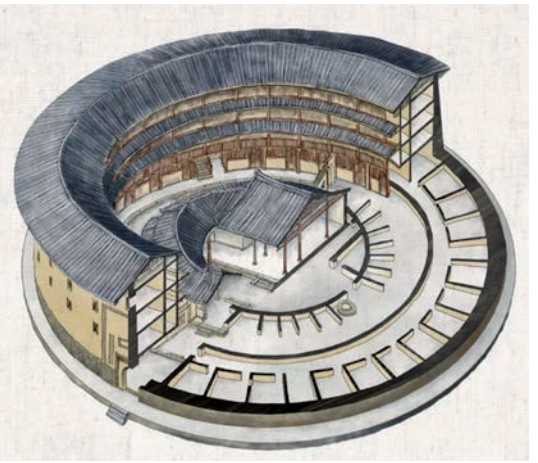


Figure 18.
3D sectional representation of a Tulou dwelling, highlighting internal spatial organization [21].

Tulou buildings are equipped with sensors and humidity control systems, aimed at preserving their historic fabric while improving living comfort. This fusion of cultural heritage preservation and modern monitoring technologies ensures the sustainability of these structures and extends their lifespan.

In the field of design optimization, parametric design tools provide architects and engineers with the ability to enhance the thermal performance, structural integrity, and esthetic qualities of rammed earth structures. These tools simulate various environmental conditions and material properties, supporting the development of more efficient, adaptable, and eco-friendly building solutions [22, 40]. A remarkable example of rammed earth architecture is the Ancient City of Shibam in Yemen, known for its high-rise earthen buildings. In Shibam, traditional construction



Figure 19.
City of Shibam [53].

techniques have enabled the creation of tall structures that adapt to hot climates, with high walls providing shade and narrow streets facilitating airflow, naturally cooling the urban environment (**Figure 19**). Today, modern parametric design principles are being applied in restoration and renovation projects, helping to preserve the city's architectural character while improving the durability and comfort conditions of its historic buildings.

Finally, Life Cycle Assessment (LCA) methodologies provide valuable data for evaluating the environmental impact of rammed earth structures. These studies reveal that, compared to conventional construction materials, rammed earth buildings exhibit lower carbon footprints and reduced embodied energy values, reinforcing their viability as a sustainable choice [31, 32, 35, 53]. As a result, rammed earth construction is emerging as a strong alternative in the building sector, where eco-friendly approaches are becoming increasingly significant.

In summary, technological advancements in rammed earth construction techniques—including material innovations, automated construction systems, smart monitoring, and design optimization—are transforming this ancient building method into a modern, sustainable, and environmentally friendly solution. As the construction industry continues to prioritize environmental responsibility and efficiency, rammed earth structures are expected to play an increasingly important role in the future.

4.2 Common sides of rammed earth in traditional and modern interpretation

Traditional and modern rammed earth (RE) construction techniques share key commonalities in terms of adaptability, sustainability, and efficiency, evolving to meet changing societal needs, technological advancements, and environmental considerations. Below, the similarities between the two approaches are examined based on various references.

First, both approaches prioritize the use of local materials. While traditional RE applications rely on natural soil, modern adaptations incorporate local stabilizers and additives to enhance performance [21, 50]. This localized approach helps reduce transportation costs and carbon emissions while ensuring that buildings harmonize with their surroundings. Environmental sustainability is a core principle in RE construction. Both traditional and modern techniques minimize environmental impact through low energy consumption, material recycling, and the use of industrial by-product stabilizers [50, 51]. Notably, the carbon emissions per kilogram of earthen building materials amount to only 15 kg, compared to 400 kg for concrete, 5320 kg for steel, and 22,000 kg for aluminum [22]. This highlights the significant role of RE in reducing the construction sector's carbon footprint. Thermal performance is another major advantage of both traditional and modern approaches. RE structures offer high thermal mass, which helps regulate indoor temperatures and reduces dependence on mechanical heating and cooling systems, improving energy efficiency in various climates [50, 53]. The core construction process of RE remains largely unchanged, whether traditional or modern. In both methods, soil and stabilizer mixtures are compacted in layers within formwork systems to achieve the desired density and structural integrity [54]. Modern technologies such as robotic systems and 3D printing enhance efficiency, but the fundamental principles remain consistent.

Both traditional and modern RE applications demonstrate comparable durability and longevity. Historical examples prove that earthen structures can endure for centuries, showcasing the technique's inherent resilience [46, 55]. Modern stabilizers and construction techniques further enhance durability, making RE adaptable to diverse environmental conditions [46, 54]. From an esthetic perspective, RE buildings offer

natural colors and textures, creating unique visual appeal. While traditional applications preserve local architectural heritage, modern projects integrate contemporary design elements, offering both esthetic and functional solutions [51, 56].

In terms of community involvement, both traditional and modern RE techniques share a common approach. Traditional methods often rely on local participation, reinforcing social cohesion, whereas modern projects encourage community engagement to strengthen social bonds [54, 55]. Finally, continuous research and development support both approaches. Studies on mechanical properties, thermal performance, and environmental impacts contribute to improving RE techniques and expanding their application areas [55, 56]. The commonalities between traditional and modern RE range from local material use and environmental sustainability to thermal efficiency, durability, and esthetic appeal. Both approaches offer significant advantages for sustainable construction, ensuring that RE structures continue to blend the legacy of the past with modern technological advancements, inspiring the eco-friendly buildings of the future.

4.3 Challenges and suggestions: Applicability of rammed earth

Rammed earth (RE) is an ancient building technique that has regained attention in recent years due to its sustainability and esthetic appeal. However, its applicability is influenced by legal regulations and construction standards, presenting both challenges and advancements. This discussion examines the current regulatory frameworks for RE construction, identifying existing barriers and recent developments in legislation.

Many countries have well-established regulations focusing on concrete and steel but lack comprehensive guidelines for RE construction [54]. While France and Spain have some regulations addressing RE structures, they are not as detailed or widespread as those for conventional materials. This regulatory gap presents a significant obstacle to the adoption of RE in modern construction projects. In regions prone to seismic activity, RE buildings require additional regulatory considerations. Recent studies emphasize the importance of reinforcement techniques and stabilizer use to enhance structural resilience against seismic forces [50, 53].

The growing global emphasis on sustainability has encouraged the development of environmental regulations promoting eco-friendly building materials. With its low embodied energy and minimal environmental impact, RE aligns well with these sustainability goals and is recognized as an environmentally friendly alternative [39, 56]. Quality control standards are crucial for ensuring the structural integrity and durability of RE buildings. However, compared to conventional materials, there is a lack of standardized guidelines, leading to variability in construction quality and hesitation among builders and engineers [54]. To address this issue, statistical quality control methods have been proposed [55].

Furthermore, heritage preservation regulations require the protection of historical RE structures. These regulations mandate that renovation and restoration processes adhere to specific conservation guidelines, ensuring that traditional RE techniques remain an integral part of modern construction practices [46, 53]. Public perception and acceptance also influence regulatory developments. Since RE is sometimes perceived as less durable than conventional materials, misconceptions about its strength and performance may lead to limited regulatory support [57]. Increasing the number of successful RE projects and educational initiatives can help bridge this gap, improving awareness among both the public and policymakers. Despite the regulatory gaps and technical challenges, ongoing updates in legislative frameworks and

improvements in building codes offer hope for broader acceptance of RE in modern construction. Moving forward, developing comprehensive and supportive regulations will play a pivotal role in expanding the use of rammed earth techniques, ensuring greater integration into sustainable and resilient construction practices.

5. Key results

Based on the analyses conducted and literature reviews within this study, the advantages of rammed earth construction techniques in terms of sustainability, durability, and integration with contemporary construction methods have been examined. The main findings are summarized below:

Sustainability: Rammed earth structures have 50–70% lower carbon emissions compared to concrete and steel structures. Since the production process does not require high temperatures, the embodied energy amount is also significantly lower. Analyses in the literature show that rammed earth structures have a lower carbon footprint compared to reinforced concrete structures and are compatible with circular economy principles [22, 23].

Durability and stabilization: While traditional rammed earth structures show sensitivity to water and erosion, it has been determined that mechanical strength increases by 30–40% when stabilization is provided with cement, lime, and natural fiber additives. This method is considered an important application for extending the structure's lifespan and developing resistance to environmental effects [45, 50].

Earthquake resistance: It has been found that rammed earth walls containing stabilizers show 1.5–2 times higher seismic resistance compared to traditional earthen structures. In regions with high earthquake risk, modern rammed earth walls integrated with steel or wooden supporting systems have been shown to provide higher structural integrity. Accordingly, the use of these building systems is recommended to minimize seismic risks [24, 27].

Energy efficiency: The high thermal mass of rammed earth structures stabilizes indoor temperature, reducing heating and cooling needs by 30–50%. Thermal optimization studies reveal that these structures significantly reduce indoor temperature fluctuations and decrease energy consumption [35, 49].

Economic and structural feasibility: Modern rammed earth building techniques reduce labor costs and shorten construction time thanks to prefabricated block production or mechanical compression systems. However, the use of stabilizers can increase material costs by 10–20%. This indicates that economic feasibility should be evaluated based on the project's scale and contextual requirements [51, 53].

These findings demonstrate how the rammed earth construction technique has been optimized in the transition from traditional methods to modern applications and can be considered as a potential alternative in sustainable building design.

6. Conclusion

The rammed earth construction technique (RE), with its deep historical roots, holds a significant position among sustainable, eco-friendly, and cost-effective building methods. Traditional earthen construction techniques have contributed to cultural heritage preservation through local material use and community involvement,

while modern approaches have integrated material innovations, 3D printing technology, and smart monitoring systems to adapt RE to contemporary architecture. Projects such as the Telenor Headquarters in Islamabad, the Göbeklitepe Visitor Center, the Tulou houses, and the Ancient City of Shibam demonstrate the successful application of RE across different geographical and cultural contexts, highlighting its potential for sustainable construction. These examples show how modern techniques can be harmonized with traditional practices, ensuring both cultural heritage preservation and environmental sustainability.

However, several challenges must be overcome for RE to be more widely adopted in the modern construction industry. In terms of scalability, rammed earth techniques can be effectively applied in small and medium-sized structures, but their applications in high-rise buildings remain limited due to structural constraints and additional reinforcement requirements. This building system is very limited use in dense urban areas where vertical construction is necessary. In buildings taller than four to five stories, rammed earth typically requires hybrid solutions with conventional support systems, which increases design and implementation complexity. From an economic perspective, although the use of local materials provides a cost advantage, the labor-intensive nature of traditional earth techniques can increase construction costs, especially in regions with high labor costs. The cost of stabilized rammed earth walls can be 15–25% higher than standard brick walls, as identified in this study. Additionally, the lack of specialized workforce in earth construction in many regions can lead to extended project durations and issues in technical application quality.

In terms of urban applicability, the rammed earth construction technique also presents implementation challenges. The space required for on-site material processing and the dependency on meteorological conditions are significant limiting factors in projects in city centers with limited construction space and strict time schedules. It has been determined that the construction process in dense urban areas can take 30–40% longer compared to conventional methods, which causes it to be less preferred, especially in commercial projects.

Regulatory barriers are also among the factors limiting the widespread use of rammed earth buildings. The absence of specific building regulations and standards for RE in most countries creates difficulties in project approval, insurance, and financing. The lack of comprehensive regulations for earth buildings in countries like Turkey makes the legal status of these structures ambiguous and limits their proliferation. To overcome these challenges, it is necessary to first develop specific regulations and standards covering structural requirements, material properties, and performance criteria. Especially in regions with seismic risk, it is important to establish regulatory frameworks that correctly model the behavior of earth structures and set out safe design principles. These standards should be designed with flexibility that can be adapted to local conditions and climate characteristics while ensuring structural safety.

Optimization of rammed earth technology performance is possible through research and development studies. It is recommended to focus on hybrid systems to increase structural strength and expand applicability to various building typologies. This study has shown that rammed earth walls integrated with steel or wooden supporting systems can both improve structural performance and extend the application area. Research on natural fiber-reinforced earth mixtures, nano-material enhanced stabilizers, and prefabrication techniques has the potential to contribute to the development of RE technique. The implementation of exemplary projects stands out as an effective methodology for increasing the visibility and acceptance of rammed earth

construction technique. The application of RE techniques in public buildings such as educational facilities, cultural centers, or visitor centers provides an opportunity to introduce the esthetic, environmental, and functional advantages of this construction method to wide audiences.

Technical education and knowledge transfer are of critical importance in the widespread adoption of rammed earth construction techniques. Developing comprehensive training programs for architects, engineers, and practitioners can provide a bridge between traditional knowledge and modern technological approaches. In addition, the documentation and publication of successful implementation examples can enrich the knowledge base in the sector.

In conclusion, while the rammed earth construction technique offers notable advantages as a sustainable and ecological building material, various challenges need to be systematically addressed for its widespread use. Through the development of regulatory frameworks, dissemination of technical education, promotion of research and innovation, creation of economic incentives, and implementation of successful exemplary projects, RE has the potential to move beyond niche applications to become an accepted solution for sustainable building practices in different contexts. The integration of traditional knowledge with modern technology can make significant contributions to creating a more sustainable, resilient, and culturally meaningful built environment.

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Chapter 2

Putuco as a Pre-Hispanic Construction Technology and Ch'ampa as Traditional Masonry Blocks

Yasmani Vitulas-Quille and Karina Reynoso-Machaca

Abstract

With the desire to know and revalue the mystical and traditional conception as part of our cultural identity, this study is presented on the myths and rites in the construction of traditional houses known as *Putucos*. Its purpose is to revive the ancestral knowledge. Although few of us know its existence, it should be emphasized that there are no studies on the subject, and it is necessary to awaken interest, discern, and recover ancestral knowledge by identifying the existence of hidden knowledge (empirical), transmitted from generation to generation and that is part of our cultural reserve for the future. The studies presented show the Andean cosmovision in the construction of rural dwellings, developing and describing the rites, myths, and customs in the construction of dwellings that resist the rough *Puno highlands* climate, which reflect the figure and sacred image of *Pachamama* as the guardian mother and benefactor of the future family, represented by the existence of empirical knowledge in construction and rituals for its protection. Additionally, to influence the understanding of ancestral knowledge with the use of traditional construction blocks called *Ch'ampa*, which are natural blocks extracted from virgin soil and transformed into construction material, promoting the interest of locals and strangers in the application of the so-called *Ethnoengineering*, which represents the existence of empirical knowledge in construction, which currently requires support in engineering and amazes us with its beauty and functionality, reflected in the durability of these constructions.

Keywords: ancestral, Putuco, Ch'ampa, ethnoengineering, traditional, masonry blocks, natural grass blocks, cultural identification

1. Introduction

For the revaluation of aspects of human culture, it is necessary to analyze the hidden ancestral knowledge, which despite time has been transmitted from generation to generation and from parents to children until today, becoming "Andean Traditional Knowledge" or "Ancestral Traditional Knowledge".

This knowledge was used in many areas of daily life, and in the case of this study we analyze the ancestral knowledge involved in ancestral constructions, which in the

area of the Puna highlands (Peru) are called *Putucos*, which are traditional houses that have a very particular architecture and engineering that is accompanied by rituals and/or mystical conceptions involved in the process of elaboration, These are part of our cultural identity and part of the cultural heritage, which is understood as the set of goods, both tangible and intangible, that are inherited from the past and are built in the present, associated with a certain identity [1–5], and which needs to be safeguarded through generations [1, 3].

The studies developed and presented in this article, try to clearly show the myths and rites present when building a traditional house called *Putucos* [6], detailing procedures that were learned from their ancestors and that have not been forgotten but rather valued within their Andean cosmovision, which need to be remembered and shared.

When we begin a discussion on the subject of the Andean indigenous peoples, with the help of scientific dissemination, an endless number of possibilities open up for us so as not to leave aside sociocultural and historical aspects, which leads us to reevaluate aspects of human culture itself. Our history itself has been observed during the oldest stages, from the so-called –Altiplanic civilization – to the new forms of assimilation of colonialism, and up to the present day, with confrontations between the Andean worldview and the Andean cosmovision. Aspects that have generated what we call social injustice, which in turn generates indifference and the oblivion of ancestral knowledge [6]. The link between social injustice and cognitive injustice will be one of the ideas that will find the most resistance in the university since it was historically the great agent of *epistemicide* committed against local, lay, indigenous, and popular knowledge in the name of modern science [7].

Consequently, to humanize science, this article aims to arouse the reader's interest, so that he/she can discern the knowledge called *Ethnoengineering* as vernacular empirical criteria and *Ethnoarchitecturing* based on the form as a milestone of the memory kept by the elders and transmitted from generation to generation through oral tradition. It should be remembered that traditional dwellings have designs that are decontextualized from the reality of the aborigines and generate changes in the indigenous tradition itself [8, 9].

Another important topic to discuss is the use of traditional building blocks called *Ch'ampa* [10], this type of vernacular material is composed of layers of soil extracted naturally, which includes a layer of vegetation, and thanks to the roots of these generate addition and/or internal reinforcement formed naturally, which is extracted moisture by drying in the sun and are cut into blocks and assembled as a lego by the way they are extracted, This material has demonstrated high-quality thanks to the studies carried out by Refs. [11, 12], in which reference is made to the constructive advantages and demonstrates its durability and consistency as well as structural stability, making the houses called *Putucos* last between 50 and 80 years, even houses with 150 years of antiquity have been reported.

2. Method

According to the conditions or principles that any proposal that helps the development of the research purpose must meet and comply with the conditions of exhaustive and excluding, the present study is nonintervention or observational study being of the qualitative exploratory research level, according to the planning of measurements it is a retrospective study with secondary data and according to the number of

measurements it is a longitudinal study, for the population of the case study, the constructions of the Aymara zone of the district of *Taraco* and *Huancané* were taken.

Self-built houses have been identified as part of the cultural heritage, as an expression of human creativity that results in a very particular construction called *Putuco*, which uses nature as a concept of eco-technology according to Refs. [10, 13], these methodologies that promote a harmonious relationship with the environment without neglecting the social and economic values of the stakeholders. According to Ref. [14], ecotechnologies or traditional ecological construction systems are "environmentally friendly construction technologies" that were created to restore the harmonious relationship between human beings and their habitat.

3. Putuco as a traditional dwelling

In this section, an analysis is made of the *Putuco*-type houses, their historical aspects of the origin of this name or denomination, the location of these architectural manifestations, construction criteria and materials used, in addition to the myths and customs related to their construction, which in addition to being empirical is also traditional, but has demonstrated durability over time, especially to the effects of humidity and extreme rainfall [12].

3.1 Putuco as a linguistic aspect

The chronicler *Felipe Huamán Poma de Ayala*, in his work "*El Primer Nueva Crónica y Buen Gobierno*", calls *Pucullo* to small funerary buildings of the highlands representing it as shown in **Figure 1**. The term *Putuco* is used by *Vicente Guerra Carreño* in his work *Kanchi, la Provincia de los Canchis a Través de su Historia*, using it to designate vaulted constructions of funerary character built with stone and mud [6].

Travelers and scholars reported in their writings and observations, presenting photographs and engravings, that *George Squier* in 1864 generated the first printed engraving of a *Putuco* that he called *Lawn House* as can be seen in **Figure 2**, also *Arnold Heim* in 1947, in his work called *Indigenous Building Techniques of Peru and Their Potential for Improvement to Better With Stand Earthquakes*, dedicates a brief chapter to the construction technology with *Ch'ampa* and mentions the *Putucos*.



Figure 1.
Graphical references of the Pucullo of Huamán Poma de Ayala.

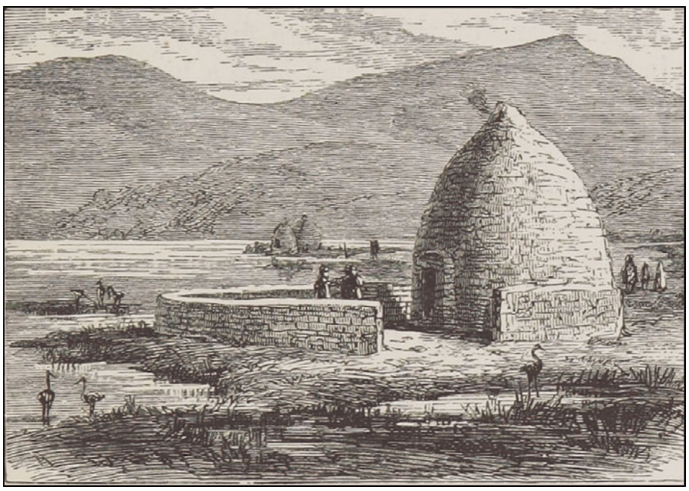


Figure 2.
Turf house near the mouth of the Rio Ramis (Engraving by George Squier, quoted by Javier Escalante Moscoso).



Figure 3.
Housing of the Chipaya culture, a name that comes from the Aymara word Ch'ipa, which means tangled straw, located near the Salar de Coipasa, on the banks of the Lauca River, 188 kilometers from the city of Oruro-Bolivia.

A variant of the *Putuco* term is *Putuku* or *Qullqa* as identification of habitation (see **Figure 3**), which refers to a circular deposit or silo in the Bolivian tradition [15, 16] of the tradition of the *Urus Chipaya* people.

3.1.1 Historical antecedents of the Putuco

Some archaeological evidence of similar buildings corresponds to the *Wankarani* culture (1000–1500 B.C. to 100–200 A.D.), extended to the northeast of Lake *Popo* (Bolivia), which developed constructions on earthen mounds (5–25 m); and in the *Tiahuanaco* culture (in Bolivia it is called *Tiwanaku*, 300–1200 A.D.), where stone foundations could be identified, as well as small ceramic representations as can be seen in **Figure 4**, an existing ceramic in the *Tiwanaku* museum [15].

Figure 5 shows the areas in South America, where these constructive characteristics are present, which curiously share climatic zones located in the climatic classification proposed by *Köpper-Geiger*, the same that coincides with areas known as the *Collas Lordships* of Puno in Peru and *Urus Chipaya* in Potosi from Bolivia.

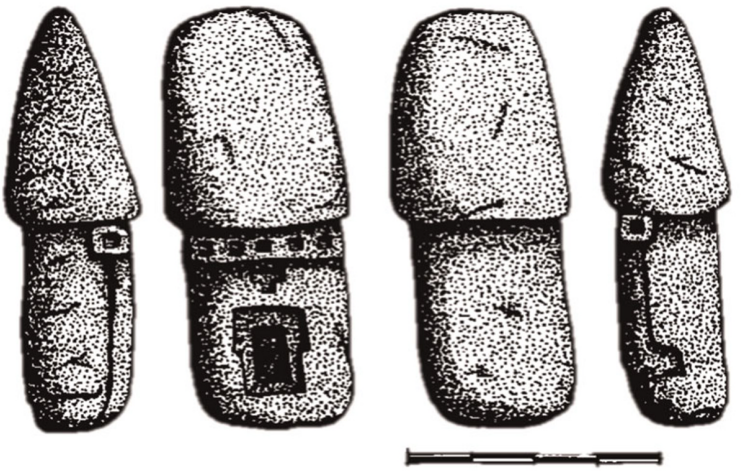


Figure 4.
Ceramics from a Tiahuanaco house (representation of a sample from the regional museum of Tiwanaku [15]).

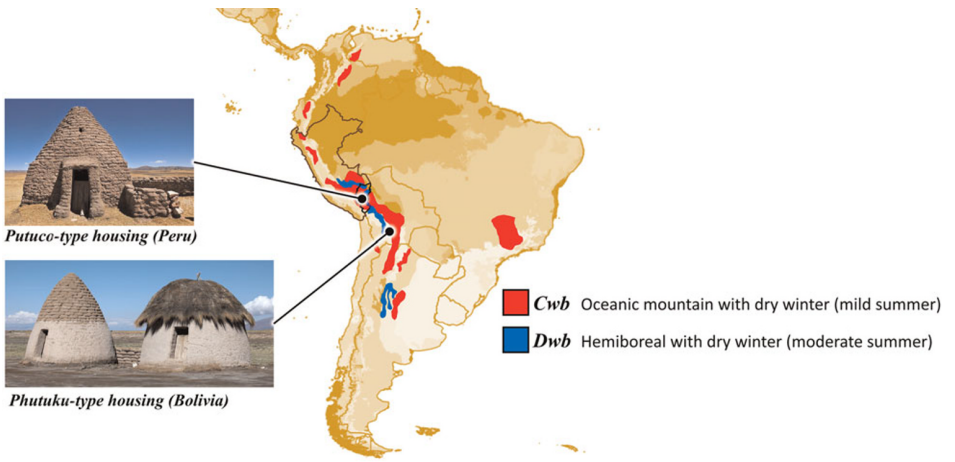


Figure 5.
South American zones with Cwb *and* Dwb *climatic characteristics, adapted to the Köpper-Geiger proposal [17].*

3.1.2 Traditional housing called Putuco

The *Putucos* considers an approach of Andean thought rather than Western thought, therefore, to understand it we can give it a singular concept and represent it as a mud cell, whose singular definition will give rise to a mini living organism that influences its growth, understanding and transformation, having a conceptual and integral model of architecture, urban and territorial context [18], as seen in **Figure 6**.

According to Ref. [19] a geometric pattern is a repetition in time and space and the figures below are the abstraction and visualization of this repeatable spatial process.

The *Putuco* has a square shape, which is very common, although rectangular shapes have been identified, its plants have a slight external curvature in the supporting walls, which are inclined at an angle between 75 and 80°, and the volumetric shape of the cover is a semi-curved conical shape with an angle of inclination between 50 and



Figure 6.
Putuco-type house in Taraco - Puno - Peru, you can see on a reference scale, the dimensions of the house, in addition to its construction form.

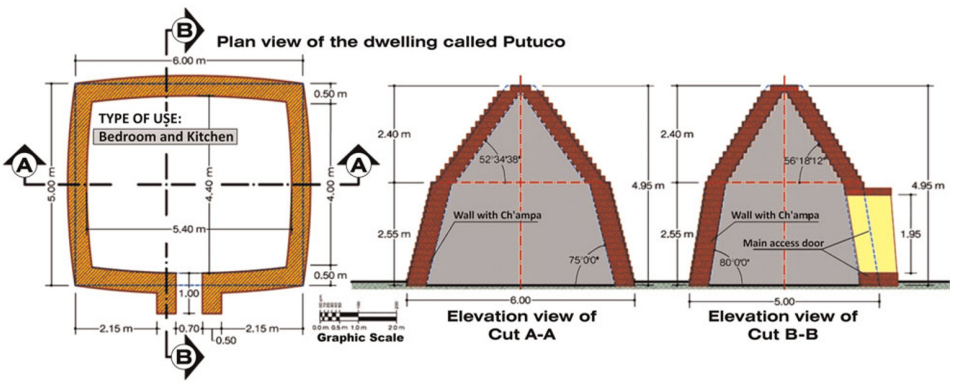


Figure 7.
Typical architectural detail and ideal interior dimensions.

60°, which cover 50% of the total height, and can reach a height of between 4 and 5 meters high. These dimensions are shown in **Figure 7**.

3.1.3 Distribution of the dwelling

The distribution of the environments in a typical home does not have many variations [20], but rather responds to the needs of each family group, and is organized in such a way that the customary rituals can be developed for each stage of communal and personal life as shown in **Figures 8** and **9**, where the table of forgiveness is located in the central courtyard of the house.

In the typical house chosen for analysis, the largest room is the kitchen and/or bedroom, which is in the shape of a *Putuco* and has quadrangular dimensions (length and width with similar dimensions; see **Figures 8** and **10**). At the same time, there are independent rooms for storage and/or warehouse, one in the shape of a *Putuco* and the others with more modern characteristics (covered with straw or calamine and rectangular in shape). In addition to having corrals for livestock (sheep pen), there are also protective fences for the house as a whole, with only one main access (see **Figures 8** and **9**).

The houses most used for cooking, sleeping, and food storage are preferably *Putucos* because they can better withstand the cold climates of the study area (months of June and July), as well as withstand rainfall efficiently, due to the construction material called *Ch'ampa*. The other houses have adobe as construction material.

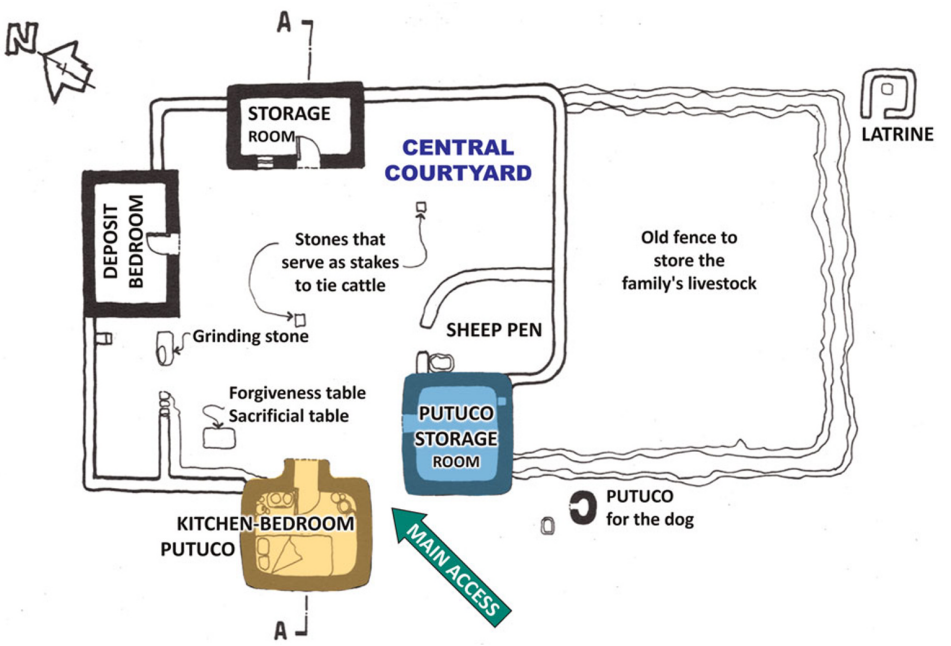


Figure 8.
Typical plan of a house in Taraco (Survey developed at the house of Mr. Paulo Chambi, by Architect Ferruccio Marussi Castellan).

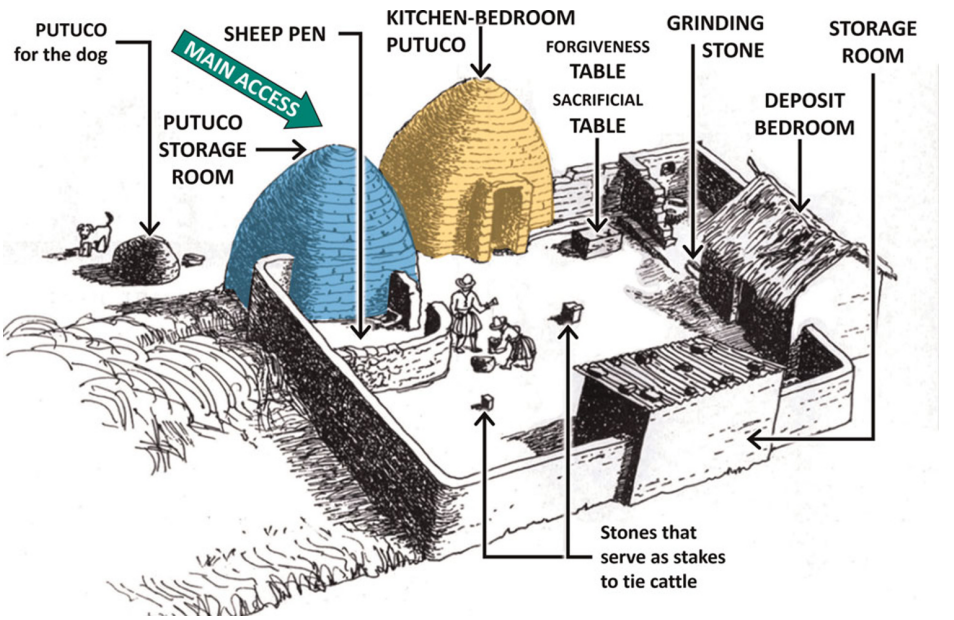


Figure 9.
Isometric view of the typical housing complex with traditional characteristics.

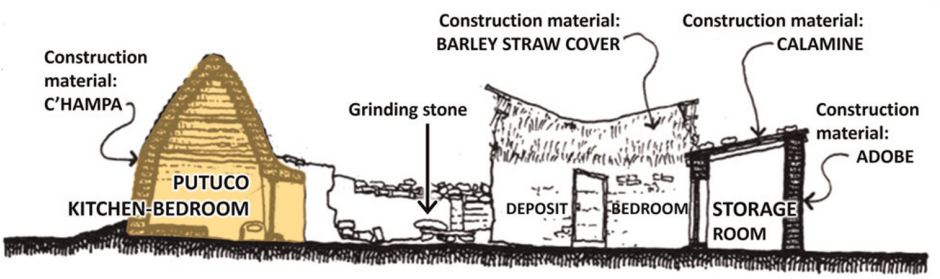


Figure 10.
View of the houses of Court A-A, the largest Putuco, and a calamine house can be seen.

Something that can be highlighted is the location of the table of forgiveness or table of sacrifice (see **Figure 9**), where the rituals are developed throughout the year. We can see that the table is very close to the bedroom, which facilitates the assembly of the ritual offering.

4. Rites and myths in the construction of Putuco-type homes

In ancient times, magical myths were necessary in many aspects of daily life, and in this aspect, it is associated with the construction process of traditional dwellings. This information is clear in Arriaga's writings: *At present, both the Quechua and the Aymara celebrate dedicatory ceremonies, in celebration of the different stages generally when the foundations of the houses are excavated and also many times when the structure is to be roofed* [21].

In most of the altiplano zones, the rituals go hand in hand with a *Yatiri* (a person knowledgeable in the celebration of ceremonial rituals, in addition to seeing the future, all with the help of coca leaves) to venerate the *Pachamama* (female divinity, protector and guardian par excellence, meaning Mother Earth) and the Apus (Andean deities represented by the highest and most imposing peaks, which are considered as protective entities of balance and life) in the different stages of the construction process of a house. This is why myths have been and are a substantial part of Andean culture, understood as the culture forged and developed in Peru before the Spanish invasion, as well as the culture that resists and recreates in new historical contexts. The myth was and is not only a way of facing life, as an essential conception to articulate its social, political, and economic relations [22], but also, by the very fact that myth relates the deeds of supernatural beings and the manifestation of their sacred powers, it becomes the exemplary model of all significant human activities [23].

For Bouysse-Cassagne and Harris [24], the *Pachamama* would be the meeting point between two worlds; on the one hand, it belongs to the Pacha above as the wife of the sun, and on the other hand, it participates in the fertilizing character of the devils. The aka Pacha refers to the world of humans or the ground where the living walk. In this sense, it is understood that *Pachamama* refers to the time and space of the double material-spiritual energy of femininity [25].

The main existing rituals in the *Putucos* construction process are:

- When extracting the Ch'ampas.
- Before choosing the land for the construction area.

- Before starting the construction of the *Putuco*.
- At the end of the work day.
- The final ritual inside the house is called *k'intu*.
- Ritualistic dance called *Achucallu*.

It should be mentioned that these rituals, as shown in **Figure 11**, due to Andean custom and tradition, oblige the villagers to build a *Putuco* in a single workday (a workday of 8–10 hours, some days even last up to 12 hours), that is, the *Putuco* is started at dawn or in the early hours of the morning and must be finished at dusk or even late at night. The work begins at dawn or in the early hours of the morning and must be finished at dusk or even late at night, and should not exceed one day's work, due to the strong belief that if this community work (with the help of neighbors and relatives) will bring good omens to the future family that will use this house. Moreover, when a new couple decides to start their marital life they must necessarily build their *Putuco* (this tradition is being lost), the construction only contemplates the stacking of building blocks but not the extraction of the same, considering that the building material called *Ch'ampa* is already extracted, stacked and previously dried for a period of approximately 20 days, a period in which it loses its natural humidity.

Each stage of the construction is accompanied by rituals divided into three phases, First Stage: 1. Before choosing the land and 2. Second Stage: 3. Before building the *Putuco*-type house and 4. At the end of the workday and in the afternoon. Third Stage: 5. Ritual of gratitude called *K'intu*, done inside the new *Putuco*, and 6. These stages are shown in **Figure 11** and are detailed below.

4.1 Ritual performed before the extraction of traditional masonry blocks

Before extracting the *Ch'ampas*, the master builder or *Pak'u*, generally the oldest of the work crew and knowledgeable of the traditions (see **Figure 12**), requests

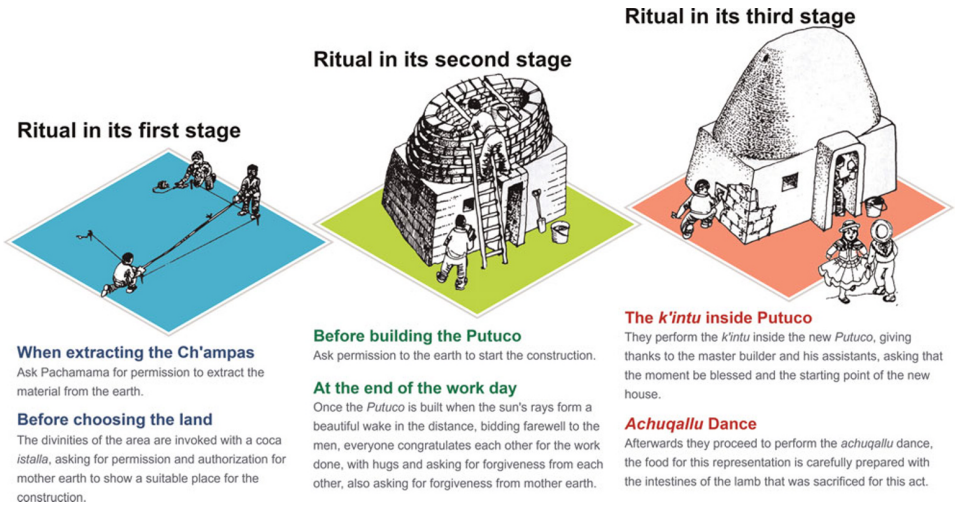


Figure 11.
Rituals and ceremonies during the construction process of a Putuco.



Figure 12.
Work tools for the extraction of the Ch'ampa and a chuspa (small bag) containing the offerings for the payment to the earth and a bottle of alcohol for the Challa, and then proceed with the extraction process of the traditional masonry blocks.



Figure 13.
Acknowledgment of the workers by the owners of the house, with portions of coca leaves that are chopped by the workers.

authorization from the *Pachamana*, to take its resources, to be used in the construction of a *Putuco*.

For this, they make use of the *k'intu*, complemented by the *challa* with alcohol, and also to visualize on the *Istalla* the will of Mother Earth, for this purpose they make use of the work tools such as the attachments for the respective payment, as can be seen in **Figure 10**. This ritual is done in the same extraction zone, the will of Mother Earth is interpreted to proceed with the programmed work.

Also, during the transfer of the *Ch'ampa* blocks to the area where the *Putuco* construction will be located, with the help of a donkey that can carry up to two blocks. The owner thanks the workers, offering them coca leaves as thanks for the work done, since the support is voluntary and reciprocal called *Ayni* or collaborative help between neighbors and relatives, as can be seen in **Figure 13**.

For their part, the women are engaged in preparing food for the workers, and the hostess (owner of the future house) thanks them by offering them coca leaves as thanks for the work done, since the support is voluntary as part of the *Ayni* or collaborative help, as can be seen in **Figure 13**.

4.2 Ritual performed to choose the construction zone

It is important to remember that language is fundamental for the reproduction of culture and for maintaining its own identity [4], and in this case, the study area uses Aymara to carry out the rituals, which are presented in the following lines.

Before choosing the land, the owners are in charge of spreading the coca leaf on a blanket or blanket, then the *Pak'u* takes command, who, using a specific language for this act, raises the coca leaves, invokes the deities of the area, while releasing the sheets to guess the expected answers, says (in the native Aymara language):

Jach'a achachila, wawamana machaqa uta utachasiñataki,
uraqiya uñacht'ayma. Uka uraqixa sumauja samaya;
umansa, thayansa, jani apañpachawxa.

————————x————————

Oh, great ancient supernatural gods, so that this your son may build his house,
show us a favorable place. This house is well-located;
in floods, in winds, do not snatch them away.

4.3 Ritual performed to start construction

Before starting the construction of *Putuco*, authorization must be requested from *Pachamama* to provide blessing and strength to the workers. First, identify the dimensions of the future *Putuco*, placing the base of the walls. This ritual is done with the help of an *Istalla*, coca leaves, wine, and alcohol, performing the *K'intu* and *Chuari* ritual as an offering to the land, in which all those who will support the work participate, in addition to the duels of the future home (see **Figure 14**).

An interesting aspect that can be noted is that the residents "*orient the door not towards the cardinal points but rather towards the intercardinal points*" [6], this is because, in their belief, the God sun, its rays should not shine directly on the door of the home.

4.4 Ritual performed at the end of construction

Once the *Putuco* is built, a procedure that usually ends in a work day (a day of work), and when the sun's rays form a beautiful trail in the distance, saying goodbye to the men (between 4:00 and 6:00 p.m., see **Figure 15**), the owner of the new home, accompanied by his relatives, with the presence of the father (the grandfather of the family), in addition to the workers, as a whole, congratulate each other for the work done, with hugs and asking forgiveness to each other, for the possible excesses produced, forgiveness to the earth, with joy and optimism, pronouncing the following:

Kuna llakitsa, perdont'apkita
Taqini perdont'apkita, Dios awkisjama.

————————x————————

From all evil and any pain, forgive us
Forgive us of all our bad actions, you who are our Father God.



Figure 14.
You can see the first lines for the construction of a home and you can also see the necessary additions to make the payment to the land.



Figure 15.
Completion of the house in the afternoon.

4.5 Ritual performed inside the new home

They also perform the myth of *k'intu*, for this the owner and all the participants gather inside the new *Putuco*, with hugs and giving thanks to the master builder and his assistants, in addition to the participants who participated in the construction, asking that May the moment be blessed and remembered as the starting point for the use of the new home, saying:

Suma urakipanaya, machaqa utaxa,
taq'paxa tukuchataxiwa.

———————x———————

May it be a good time, for our new house,
which was completely completed.

4.6 Festive ritual through the Achuqallu dance

Subsequently, the *achuqallu* dance is performed (between 8:00 and 10:00 p.m.), for this, the selected assistants enter the scene jokingly dressed in animal skins simulating ferocious condors, as they pass through flocks of sheep and llamas usually kidnap the smallest and most careless offspring with their terrible claws (this representation is a myth), directed by the eldest *chuqallu*; The food for this performance is carefully prepared with the intestines of the lamb that was sacrificed especially for this act. The *achuqallu* dance has countless copies and various verses that are sung by the participants of the small improvised party, and it can be seen that the songs have a relationship with the construction of the new home and the performance of the dance.

Achuqallu tatawa mantani, machaqa utawa utjasipana,
machaqa tapawa utijasipana.
Janiwa mulljasipxätati, achuqallu tatawa jayamarkata purini.

———————x———————

Mr. Achuqallu is entering, knowing that there is a new house,
knowing that there is a new nest.
Do not be afraid, Mr. Achuqallu has come from far away.

This couplet has a semantic content related to housing. Well, *Aymara* and/or *Quechua* are languages that in their expression await all the cultural value of a people, organized on limited occasions of a ceremony [26].

Another couplet used is:

Achuqallu tatawa purini, tata sitani mama sitani.
Qawkina machaqa istallaxa utji, qaukin ach'uwaña utji, winuxataki.

————————————x————————————

Mr. Achuqallu, Mr. and Mrs. Owner of the house, has arrived.
Where is the new island, where is the wine, to sprinkle.

Very fleetingly representing the need for the presence of the condor, which blesses and celebrates the construction, also requires wine to be able to sprinkled on the walls and in this way gives vital and sweet food to the earth, for its acceptance and future retribution for the well-being of the new family.

Once this act is over, in addition to sharing food, we proceed to give thanks; moving on to the conversation that is accompanied by alcohol and the *Chaqcha* (Procedure by which coca leaves are chewed, then discarded and repeated the procedure) of whole coca leaves, which can last until late at night.

5. Ch'ampa as a traditional building block

5.1 Extraction zones

The *Ch'ampa* or *T'epe* (native name) is used to build traditional pre-Hispanic dwellings called *Putukus* (Bolivia) [16] or *Putucos* (Peru) [18, 20], easily reaching 50 years of duration and even exceeding 80 years without collapse, being resistant to erosion [10].

For its extraction, the selected area should be identified well in advance and avoid using it as an agricultural area, reserving the land for at least 5 years (see **Figure 16**), in which wild plants called *Ch'iji* and *Quemello* sprout and thanks to their roots, the block of earth obtains its resistance properties [10].



Figure 16.
Extraction and stacking area for the drying process, the difference between a current extraction area and an old extraction area (3 years old), which is in the process of restoration and growth of wild vegetation called Ch'iji [10].

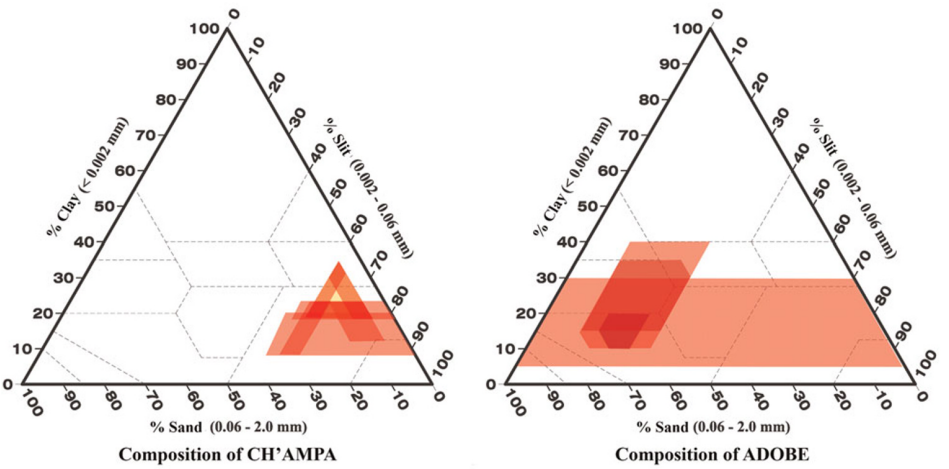


Figure 17.
Granulometric characteristics according to the NRCS Soil Triangle. In the case of Ch'ampa and Adobe [10].

5.2 Traditional masonry construction classified according to NRCS soil triangle

Based on the Natural Resource and Conservation Service (NRCS), USA soil classification shown in **Figure 17**, we can see the difference between the composition of *adobe* and *Ch'ampa*, the latter has a higher concentration of silt and little sand and clay, which is a characteristic of agricultural land where *Ch'iji* grows, This root strengthens the consistency of the masonry block, and when it loses humidity it consolidates in such a way that it becomes impermeable and very durable. In the case of *adobe*, its greater amount of sand makes it not very resistant to humidity. Therefore it is not a suitable material for construction in areas with a lot of rainfall [10].

5.3 Ch'ampa's capacity to resist humidity

Based on the laboratory tests and their results, it has been concluded that the traditional masonry block called *Ch'ampa* adequately withstands high levels of humidity compared to adobe, as shown in **Figure 18** (left), the houses called *Putuco* withstand flooding adequately, even though they are unoccupied during these periods. When the water level decreases, these houses continue to be used after a period of natural drying, but in the case of adobe houses they suffer serious structural failures as can be seen in **Figure 18** (left), being necessary to stabilize them with wooden props and once the water level decreases, it is even required to demolish them



Figure 18.
The stability of Putuco exposed to extreme flooding compared to adobe housing [12].

since they become uninhabitable, these results can be seen in the study [12]. Therefore, the existence of traditional knowledge is evident, but such constructive practices are not transmitted due to the entrance of the supposed modernity, and it should be objective the revaluation of this knowledge based on more detailed laboratory studies since there are no studies that are currently being interested in this subject. This academic platform is a way of disseminating sociocultural aspects of the villages of *Huancané*, *Taraco,* and *Samán* located in the high Andean zone of *Puno* in *Peru*.

6. Conclusions

The representation of the guardian mother as a protective being within ancestral and mystical knowledge is linked to the use of traditional housing, which brings to light deep roots and a close connection between nature—represented by Mother Earth—and man as a being that lives and subsists in the *Puno* highlands, a bond that generates a commitment from birth to take care of its environment, which cannot be broken and which integrates custom and knowledge, generating a transcendental importance of the rural home called *Putuco*, identifying it like a being that is alive.

Emphasizing the importance of rural housing, we can mention that the house is conceived as an extension of the land (*Pachamama*), which the Andean must permanently thank in his offerings because he lives off its fruits. These offerings or rituals do not constitute epidermal forms of superstition but express the deep feeling of the search for an alliance with the spirits of good and God [27].

It should also be mentioned that, within the Andean worldview, the traditional home called *Putuco* is built to form the union between a couple as a family nucleus that is being reborn and forming conjunction of union, which requires independence and, therefore, a new home, which is built in a single day of work, and from that moment on, it will be inhabited to raise its future children, always with the guardianship of *Pachamama* as a mother who provides well-being and protection from future adversities. Therefore, it is a very close custom between man and nature, since man does nothing without asking the permission of Mother Earth.

The soil composition according to the NRCS triangle of the U.S.D.A., shows us graphically the difference between *Ch'ampa* with *Adobe*, where it shows the highest silt content compared to clay and sand, but it should be considered that this classification lacks the root content that provides greater stability and flexibility to this traditional masonry block [10], which also does not need to be dosed as it is in its natural state, what should be evaluated is rather the extraction area that meets these conditions, which are shown in **Figure 5** shared by Peru, Bolivia, Argentina.

According to the laboratory findings [12] and the evidence from the study area, it was possible to verify the adequate stability and resistance of the blocks called *Ch'ampa*, since they adequately withstand floods (**Figure 18**), which is a characteristic that does not allow the use of other materials such as *Adobe*, It was also possible to verify that the arguments provided by the owners of the houses called *Putuco* are true, since they affirmed that they are up to 50 and 80 years old, using as reference the generations that used them, many of them remaining as living monuments of a tradition rarely revalued.

Therefore, the fusion between tradition and empirical technology results in a knowledge that can be called *Ethnoengineering*, which requires a line of research that has been promoted throughout many works, this one contributes from the *Aymara* and *Quechua* context of the high Andean cultures of Peru, this knowledge should be

rescued and used when building rural houses, which need high constructive efficiency and thermal comfort in its counterpart of low costs and sustainability at the time of construction. Considering also the transmission of customs of myths and rites at the time of construction, being palpable the close relationship between nature and man known as Andean cosmovision. The relationship between humans and *Pachamama* also raises ethical questions about how we should interact with our environment. It emphasizes the need for reconciliation with nature, promoting sustainable practices that respect its vital cycles.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 3

An Approach to Sustainable Construction Using PET Plastic Bottles Filled with C&D Waste Mortar

Ashwini B.T. and Srinidhi S.U.

Abstract

Technological advancements in the world have brought about several changes. In recent years, the production and commercialization of plastic have dramatically increased, resulting in environmental concerns, when plastic waste is improperly disposed of and mismanaged, bottles made from polyethylene terephthalate (PET), which are used to store drinking water and soft drinks, end up in the soil or water. This gives an opportunity to utilize these PET bottles as an alternate building material in the construction industry. In this research, we have used PET bottles filled with demolition waste as mortar and used as a brick for construction. Samples of brick and brick masonry prisms with PET bottle bricks were tested for compressive strength with demolition waste and cement mortar, compared with IS standards. The load and displacement curve showing a failure at 67.29 KN indicates that it is feasible to use construction and demolition waste-filled bricks for non-load bearing structures. The main goal of this research is to use plastic waste for low-cost sustainable construction.

Keywords: polyethylene terephthalate (PET), waste plastic bottles, eco-friendly construction, sustainable construction practices, alternate building material, construction demolition waste, plastic waste

1. Introduction

The usage of plastic is steadily on the rise, particularly in urban areas, as it is widely employed in various activities. However, the improper disposal of plastic by users has transformed it into a significant problem. Consequently, plastic has emerged as a worldwide pollutant, affecting our seas, oceans, and soil [1]. Polyethylene terephthalate, commonly known as PET, is a widely used form of plastic. It is primarily utilized in the manufacturing of PET bottles, which serve as water carriers for domestic use and hold significant commercial value.

The PET bottles are also utilized in the commercial storage and sale of various soft drinks. Typically, these bottles are designed for single use and are disposed of after they have served their purpose. Afterward, they are often recycled. However, due to

inadequate infrastructure in many major urban areas around the world, PET bottles are not properly recycled and instead end up in landfills or are burned in incinerators. The focus of this study is to explore the possibility of using waste PET bottles as a construction material, specifically as a substitute for bricks, to assess their viability for commercial purposes [2]. Few studies show that plastic waste can be used as decorative pavements [3], plastic-soil bricks [4, 5] or roof tile [6].

As urbanization progresses, the construction sector has given rise to a new type of waste known as construction and demolition (C&D) waste. This type of waste presents challenges for urban local authorities regarding its effective management and disposal, prompting research into the recycling of this waste as a sustainable method for construction.

In this research, the C&D waste is finely crushed and combined with 20% water to create demolition waste mortar. This mortar has been utilized to fill the empty space within the plastic bottle, enhancing its strength and rigidity.

2. Materials and methodology

The study focuses on a sustainable approach to construction practices. The use of waste PET bottles and C&D waste as mortar and filling material is the main concept of approach in this research.

2.1 Materials

The materials utilized for the research are outlined and detailed below:

2.1.1 Cement

The cement used for the comparative analysis is OPC 53 Grade cement referring IS code [7–9].

2.1.2 Demolition waste mortar

The rubble resulting from building demolitions was processed through IS Sieve of 4.75 mm, which was utilized as mortar and placed into bottles according to IS standards. This combination was then blended with 20% water to produce demolition waste mortar [10].

2.1.3 Brick

Conventional bricks composed of clay were utilized for a comparative analysis. The size of the bricks was 19 cm × 9 cm × 9 cm. The characteristics of the bricks were examined in accordance with the guidelines set forth by IS codes [7, 11].

2.1.4 Waste PET plastic bottles

The study involved collecting waste plastic bottles, cleaning and drying them. These bottles were then filled with demolition waste mortar to eliminate any empty spaces and make them more rigid. The prepared samples were tested alongside bricks to compare their properties [7, 11].

2.2 Methodology

The feasibility of utilizing the materials as low-cost and economical construction bricks was determined through an experimental analysis of the samples. Initially, the materials were tested to assess their properties in comparison to the recommended standards. Subsequently, the samples were divided into two categories: bricks and prisms. The compressive strength of the samples was then tested to evaluate their feasibility. Finally, the results were compared to draw a conclusion.

This demolition waste mortar is filled with the PET plastic bottle as normal brick, as shown in **Figure 1**; and PET plastic bottle bricks are bonded with demolition waste mortar to form Prism, as shown in **Figure 2**.



Figure 1.
Plastic bottles filled with demolition waste mortar.



Figure 2.
Prism formed by combination of waste plastic bottles.

3. Experimental program

The experimental phase of the study was initiated with material testing to validate the conformation of their properties with the recommended standards.

3.1 Test for properties of demolition waste

The material test results for the test on properties of demolition waste that was finely ground and sieved, passing though IS Sieve 4.75 mm is shown in **Table 1**.

3.2 Test for properties of demolition waste mortar

The mortar prepared by blending the finely ground demolition waste passed through IS Sieve 4.75 mm was mixed with 20% of water to convert it into a mortar. The material prepared was tested for its normal consistency, flow test and compressive strength, the results of which are shown in **Table 2**.

3.3 Test for properties of waste plastic bottle bricks

The waste PET bottles are filled with demolition mortar and these bottles are tested to replace bricks in the construction practices. Hence, some tests are conducted to validate its ability with the recommended standards for burnt clay bricks [1, 12]. The properties and their values of comparison are mentioned in **Table 3**.

Properties	Obtained value for demolition waste	Standard value as per IS code for fine aggregate
Specific gravity	2.6	2.5–3.0
Sieve analysis	Cc = 1	If Cc – 1 and 3, soil is well graded
Coefficient of curvature (Cc)	Cu = 6.25	If Cu > 4, gravels
Coefficient of uniformity (Cu)	Well graded sand	If Cu > 6, sand
Moisture content	9.82%	0–5%

Table 1.
Properties of demolition waste.

Properties	Conventional cement mortar	Demolition waste mortar	Standard value as per IS code
Normal consistency IS 2250 (1981)	32%	30%	28–32%
Flow table test IS 5512(1983)	32%	30%	26–33%
Compressive strength IS 4031 Part 6 (1988)	16 N/mm^2	14.5 N/mm^2	12–18 N/mm^2

Table 2.
Properties of normal cement mortar and demolition waste mortar.

Properties	Standard clay bricks	Waste PET plastic bottle bricks	Standard value as per IS code
Shape and size	22 cm × 10 cm × 7 cm	24 cm (L) × 8 cm (dia)	19 cm × 9 cm × 9 cm
Compressive strength	7.59 N/mm^2	3.83 N/mm^2	Not less than 7.5 N/mm^2
Water absorption	10.10%	0%	Not more than 20%

Table 3.
Properties of standard clay brick and PET plastic bottle brick.

4. Results and discussion

Figure 3 shows the compressive testing of PET plastic bottle brick with filled demolition waste mortar. The compressive strength of plastic bricks is carried out as per IS 1077:1992. The results are mentioned in **Table 4**.

The maximum compressive strength attained by plastic waste bottles is 5.33 N/mm^2, which is less as compared to standard brick [12–14].

Figure 4 shows that a Masonry or Brick Prism was constructed using plastic waste bricks of size 190 mm (L) × 90 mm (W) × 90 mm (T) with a mortar prepared from demolition waste as per IS: 2250-1981. Failure of PET plastic waste bottle prism was carried out as per IS 14278 (1995) and the results are mentioned in **Table 5**, and load-displacement curve was plotted as shown in **Figure 5**.

As the load increases, the displacement increases and then at a certain point, the masonry prism fails. This point is called Point of failure; as per **Figure 5**, the failure



Figure 3.
Plastic bottles filled as brick tested for compressive strength.

Specimen	Compressive strength N/mm^2
S1	3.33
S2	4.27
S3	3.9
S4	4.32
S5	5.24
S6	3.8
S7	4.24
S8	3.25
S9	5.33

Table 4.
Compressive strength of waste PET plastic bottle bricks.



Figure 4.
Plastic bottle prism filled and bonded with demolition waste mortar tested for compressive strength.

load is 67.29 KN, with maximum displacement of 3.6 mm. Which is probably less than that of the masonry prism as per IS code 3495: –1 to 4 (1992) [1, 13, 15].

5. Conclusion

The comparison of experimental work performed with the standard brick and plastic waste brick gives the following inferences.

Sl no	Load (KN)	Displacement (mm)	Sl no	Load (KN)	Displacement (mm)	Sl no	Load (KN)	Displacement (mm)
1	0	0	14	50.94	1.3	27	64.36	2.6
2	17.25	0.1	15	51.78	1.4	28	66.09	2.7
3	19.2	0.2	16	53.4	1.5	29	67.11	2.8
4	23.04	0.3	17	53.73	1.6	30	67.14	2.9
5	24.42	0.4	18	54.12	1.7	31	67.26	3
6	28.83	0.5	19	54.81	1.8	32	67.77	3.1
7	30.24	0.6	20	55.4	1.9	33	68.28	3.2
8	34.68	0.7	21	56.9	2	34	68.55	3.3
9	35.94	0.8	22	57.69	2.1	35	68.64	3.4
10	40.26	0.9	23	58.05	2.2	36	67.29	3.6
11	41.76	1	24	59.61	2.3	37	66.78	3.3
12	45.63	1.1	25	60.12	2.4	38	65.79	3.35
13	46.98	1.2	26	63.27	2.5			

Table 5.
Compressive strength of waste PET plastic bottle brick prism.

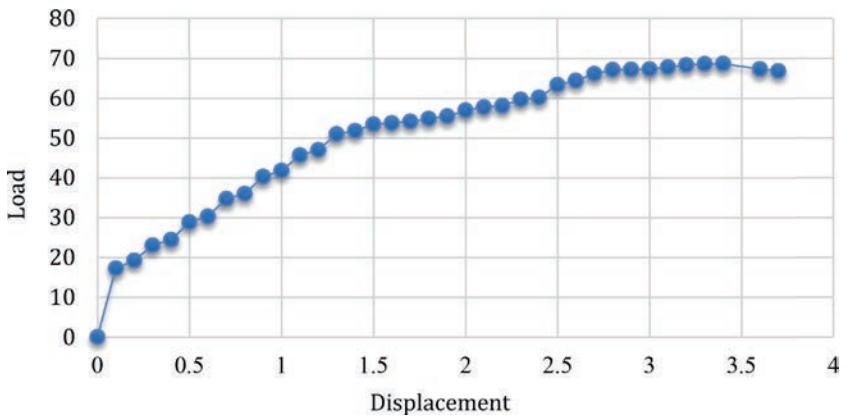


Figure 5.
Graph of load v/s displacement of compressive strength of PET plastic brick masonry.

1. The plastic waste brick is created by incorporating demolition of waste mortar, resulting in mortar properties that resemble those of standard cement mortar, thereby conforming to the specifications outlined in IS: 2250-1981.

2. The physical characteristics of plastic waste bricks differ significantly from those of conventional bricks.

3. The compressive strength of plastic waste bricks is lower across all samples when compared to conventional bricks as per IS: 3495-1 to 4 (1992).

4. The load and displacement curve indicates a failure load of 67.29 KN, with a maximum displacement of 3.6 mm. This value is likely lower than that of the masonry prism as specified in IS Code 3495: –1 to 4 (1992). Consequently, it may be suitable for use in non-load bearing structures.

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Section 2

Innovations and Diagnostics for Resilient Masonry

Chapter 4

Sustainable Strengthening of Masonry Structures Using Recycled Materials

Salih Yilmaz, Yavuz Yardim and Hasan Kaplan

Abstract

Many unreinforced masonry (URM) buildings in underdeveloped and developing countries remain highly vulnerable to seismic forces owing to poor construction practices, lack of seismic detailing, and limited access to modern retrofitting technologies. At the same time, end-of-life vehicle tires pose a growing global waste management problem as they are non-biodegradable and difficult to recycle. This study addresses both challenges through a sustainable and low-cost seismic retrofitting technique that repurposes waste tire strips as reinforcement for masonry walls, aligning with circular economy principles. Six full-scale 3D masonry wall models representing common rural building typologies were constructed and subjected to reversed cyclically imposed lateral sway to simulate earthquake action. The experimental program included unstrengthened, pre-damaged, retrofitted, and directly retrofitted 3D models, with strengthening applied either to wall surfaces alone or extended to corners. The results showed that tire-based retrofitting significantly improved the lateral strength (up to 28.4%) and displacement ductility (up to 52%), particularly when both the wall and corner regions were strengthened. The pre-damaged models also demonstrated a notable recovery in the structural performance after retrofitting. These findings suggest that tire-derived reinforcement is a promising solution for strengthening vulnerable masonry buildings in low-resource settings, offering both structural resilience and environmental benefits. Future research should focus on optimizing strengthening strategies and exploring the integration of other recycled or low-carbon materials to further enhance performance and long-term sustainability.

Keywords: seismic strengthening, masonry structures, recycled tire, circular economy, low-cost retrofitting

1. Introduction

Unreinforced masonry (URM) structures constitute a significant part of the global building stock, particularly in developing countries and seismically active regions. Typically built with hollow clay bricks or adobe, these structures are often self-constructed, non-engineered, and do not comply with modern seismic design codes [1–3]. Their popularity stems from their low cost and easy availability of materials,

making them a practical solution for rural and low-income housing, especially for single- and two-story buildings. However, their performance during earthquakes has historically been poor. Failures such as out-of-plane wall collapse and diagonal shear cracking have been widely reported (**Figure 1**) [4–7]. It is estimated that nearly one-third of the global population lives in vulnerable structures [4].

Previous earthquakes have repeatedly highlighted the risks associated with URM buildings. For instance, the Bingöl (2003) and Cameli (2007) earthquakes in Turkey have demonstrated the widespread vulnerability of these structures [3, 7]. More recently, the twin earthquakes in southeastern Turkey in February 2023 (Mw 7.7 and 7.6) caused the collapse of tens of thousands of masonry buildings, resulting in over 50,000 fatalities, particularly in rural areas where seismic detailing was largely absent [8]. Similarly, the 2024 Mandalay earthquake in Myanmar resulted in widespread failures in adobe and URM dwellings, mainly due to poor wall connections and insufficient lateral resistance [9]. These events underline the urgent need for effective and accessible retrofitting solutions, particularly for resource-constrained communities. However, post-earthquake surveys consistently show that technical and financial barriers make the large-scale strengthening of URM buildings extremely challenging [10, 11].

In parallel with these structural vulnerabilities, the global disposal of used vehicle tires is a growing environmental concern. Each year, approximately 1.5 billion tires reach the end of their service life, accumulating in landfills and unauthorized stockpiles, particularly in developing regions [12]. Tires are composed of complex, nonbiodegradable materials, including synthetic rubber, carbon black, steel, and chemical additives, which make recycling difficult and costly. When improperly managed, they pose serious environmental risks, such as fires, pollution, and proliferation of disease vectors [12]. Although reuse strategies, such as incorporating shredded tires into road sub-bases and concrete products, have been explored, their contribution to structural



Figure 1.
Masonry building damages in past earthquakes.

performance has been limited. This presents a promising opportunity to develop sustainable retrofitting techniques that integrate waste tire materials into masonry systems, thereby simultaneously addressing seismic resilience and environmental sustainability.

A wide range of retrofitting methods has been developed to improve the seismic performance of existing masonry structures. These techniques aim to increase the load-bearing capacity, control deformations, and reduce collapse risk while maintaining compatibility with historical architecture and ensuring cost efficiency, particularly for low-income regions [13, 14]. Strengthening approaches vary widely from traditional mortar-based systems to advanced composite materials, each with distinct advantages and limitations:

Fiber-Reinforced Polymers (FRP): Techniques such as externally bonded reinforcement (EBR) and near-surface mounted reinforcement (NSM) have shown strong improvements in the shear and flexural capacities of URM and reinforced concrete structures [14, 15].

Cementitious matrix composites: Basalt Fiber-Reinforced Cementitious Matrix (BFRCM) systems are gaining popularity owing to their compatibility with masonry, enhanced ductility, and moderate strength increases without compromising breathability [16].

Steel wire collaring: Wrapping masonry columns with steel wire along mortar joints has been used to improve the compressive strength and provide better confinement, particularly for slender elements [17].

Ferrocement strengthening: Applying a thin ferrocement layer (cement mortar reinforced with a fine wire mesh) can significantly enhance the strength and ductility of masonry panels. Recent studies have demonstrated its ability to restrain diagonal shear cracking and improve seismic resilience [18, 19].

Transversal tying and grout injection: In multi-leaf masonry walls, the use of GFRP ties across wythes and lime-based grout injections has proven effective in improving wall integrity and compressive resistance [20].

FRP tendons: In heritage restoration, post-tensioned FRP tendons have been employed to provide horizontal confinement in a reversible manner, adding strength without significantly altering the original structure [21].

Fabric-reinforced polymeric systems: For curved or irregular surfaces like arches and domes, flexible FRP strips and 2D composite grids have been successfully used to enhance both in-plane and out-of-plane behavior [22].

Modern composite-based retrofitting techniques are gaining popularity because of their high efficiency, adaptability, and good mechanical performance under seismic loading. They are often lightweight, minimally invasive, and compatible with various structural forms. However, applying these methods to heritage structures remains complex because the reversibility and preservation of cultural values are critical [23]. Choosing the right retrofitting strategy depends on the type of masonry, structural configuration, extent of degradation, and need to maintain the original architectural fabric [13, 24]. Recent research continues to seek strengthening solutions that are not only technically effective and durable, but also sustainable and sensitive to environmental and architectural requirements [25, 26].

Meanwhile, the construction sector remains a major contributor to global carbon emissions, resource depletion, and waste generation [27]. Sustainable construction practices aim to minimize these impacts by encouraging material reuse, reducing energy consumption, and reducing environmental degradation [28]. Studies have shown that using recycled materials in construction, including concrete systems, can offer both environmental and mechanical benefits [29, 30].

Integrating recycled materials into retrofitting strategies offers a promising pathway for achieving both the structural and environmental goals. Innovative methods, such as the use of post-tensioned tire rings and plastic meshes, have shown potential for improving the masonry performance under seismic conditions [31, 32]. However, many of these techniques remain experimental, and few address the broader need for low-cost, easily deployable solutions, particularly in rural and low-income areas, where vulnerability is greatest.

In response to these challenges, this study proposes an innovative and sustainable approach to masonry retrofitting by repurposing strips cut from discarded car tires as reinforcement. While existing retrofitting approaches, such as Fiber-Reinforced Polymers (FRP) and ferro-cement techniques, offer significant improvements in seismic performance, they often involve materials that are expensive, require specialized labor, or have substantial environmental footprints owing to production processes. In contrast, the proposed tire-strip strengthening technique differs distinctly by utilizing recycled waste materials (discarded vehicle tires), providing a highly sustainable and low-cost alternative. This method not only enhances seismic resilience through improved strength and ductility but also aligns directly with circular economy principles by repurposing problematic waste into structurally effective reinforcements. Moreover, unlike FRP or ferro-cement, tire-strip reinforcements do not require specialized manufacturing or installation expertise, making them particularly suitable for resource-limited settings.

To evaluate the effectiveness of the proposed method, six full-scale 3D masonry models were constructed and subjected to reversed cyclic lateral loading to simulate the seismic action. Both the unstrengthened and retrofitted configurations were tested, allowing for a detailed evaluation of the improvements in the lateral strength, deformation capacity, and crack resistance. The following sections describe the experimental program, observations, and findings.

2. Materials and methods

2.1 Experimental models

This study investigated the seismic performance of six full-scale three-dimensional (3D) unreinforced masonry (URM) wall models that were retrofitted using recycled tire strips. The models were designed to simulate typical rural construction practices in western Turkey, characterized by hollow clay bricks, cement-sand mortar joints, and minimal seismic detailing.

2.1.1 Geometry of the models

Two different geometric configurations were developed and labeled as Type A and Type B. Type A included a single large window opening per lateral wall, while Type B incorporated two smaller openings per wall, resulting in narrower masonry piers. These variations were intended to reflect different vulnerability profiles under lateral loading.

Each model had plan dimensions of 3600 × 2700 mm and a wall height of 2750 mm. The wall thickness was 250 mm, and an external plaster with a nominal

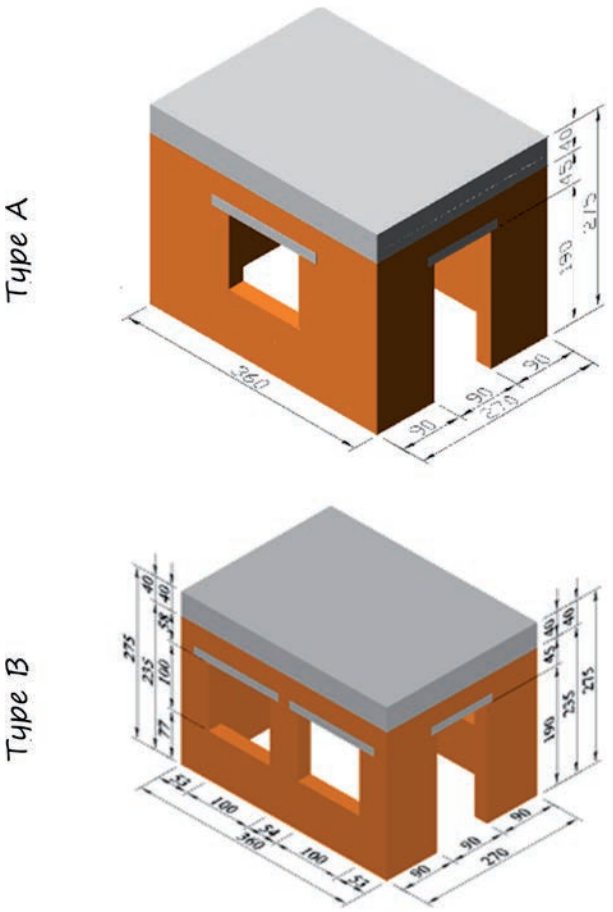


Figure 2.
Dimensions and configurations of Type A and Type B building models.

thickness of 25 mm was used to reflect the local construction norms (**Figure 2**). Care was taken during construction to minimize eccentricities or torsional irregularities.

The reinforcement layouts were varied across the test matrices. Tire strips were embedded in the wall surfaces either diagonally, around the openings, or at the corners to assess the effects of different configurations. **Figure 3** illustrates the typical reinforcement layout used, including the diagonal, horizontal, and vertical strip placements.

The reinforcement spacing was 15 or 30 cm, with closer spacing at the critical zones.

The two groups of models (Types A and B) were designated as follows:

- *Model A*: Reference model without retrofitting.
- *Model A-d-s*: Damaged under lateral loading, repaired, and strengthened.
- *Model A-s*: Strengthened only at walls.

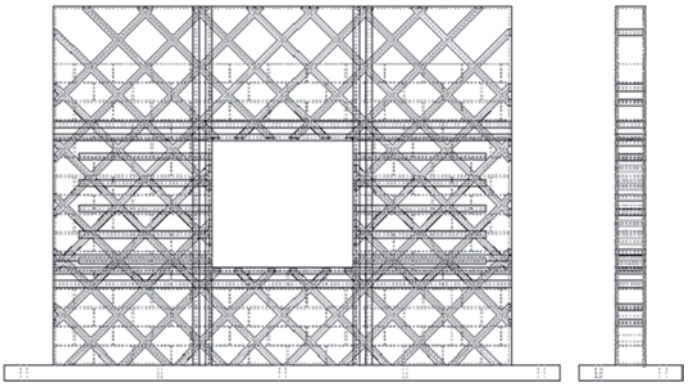


Figure 3.
A typical strip application schema with lateral, vertical, and diagonal strips.

- *Model A-s+*: Strengthened at both walls and corners.
- *Model B*: Reference model with two openings per wall.
- *Model B-s+*: Strengthened at walls and corners.

The configurations and strengthening types are presented in **Table 1**.

2.1.2 Material properties

Hollow clay bricks with vertical perforations were used in all models, which are representative of low-cost local construction. The brick had an average compressive strength of 4 MPa for the gros area of the brick when tested for compression. On the other hand, because of the composite action, mini test specimens made of 2 bricks had an average compressive strength of 1.6 MPa without plaster, and 1.5 MPa when plastered. A cement-sand mortar with a volumetric mix of 1:3 was used for all the joints. Tensile tests on the tire strips indicated an average tensile strength of 4.4 MPa and a modulus of elasticity of 150 MPa. The key material properties are presented in **Table 2**.

Model name	Pre damage	Wall strengthening	Corner strengthening	Model description
A	No	No	No	Reference Model A
A-d-s	Yes	Yes	No	Damaged and strengthened model
A-s	No	Yes	No	Strengthened model – wall-only
A-s+	No	Yes	Yes	Strengthened model – wall and corners
B	No	No	No	Reference Model B
B-s	No	Yes	Yes	Strengthened model – wall and corners

Table 1.
Properties of building models.

Material	Property	Value
Hollow clay brick	Gros compressive strength of brick	4.0 (gros area)
Block of two hollow clay bricks with bed joint	Compressive strength (composite)	1.4 MPa (gros area)
Cement-sand mortar	Mix ratio (by volume)	01:03
Tire strip	Width × thickness	25 × 7 mm
Tire strip	Tensile strength	4.4 MPa
Tire strip	Modulus of elasticity	150 MPa

Table 2.
Mechanical properties of the masonry and tire strip materials.

The strengthening material consisted of strips manually cut from discarded automobile tires (**Figure 4**). These strips were approximately 25 mm in width and 7 mm in thickness. The application involved creating shallow grooves on the wall surface by removing the plaster, fixing the strips using nails anchored into mortar joints, and covering the embedded strips with plaster or repair mortar.

Photographs taken during the construction stages of the models are shown in **Figure 5**.

2.2 Experimental setup and procedures

An experimental investigation was conducted at the Pamukkale University Earthquake and Construction Technologies Research Laboratory using a full-scale structural testing setup (**Figure 6**). The system consisted of a strong floor, reaction wall, 200 kN hydraulic actuator, hydraulic pump, and stiff steel loading beam. The loading beam was anchored to the top of each masonry wall to apply a constant axial load to simulate the vertical force generated by the upper floor or roof slab. The total vertical loading was maintained at 300 kN throughout the test using two hydraulic pumps and was applied prior to the initiation of lateral loading (**Figure 6**). The loads were applied to the slab using steel beams on the slab as line loads to allow a smooth transition to the walls of the model buildings.

Reversed cyclic lateral loads were imposed at the top of the wall via a horizontal actuator mounted perpendicular to the wall face. The actuator applied

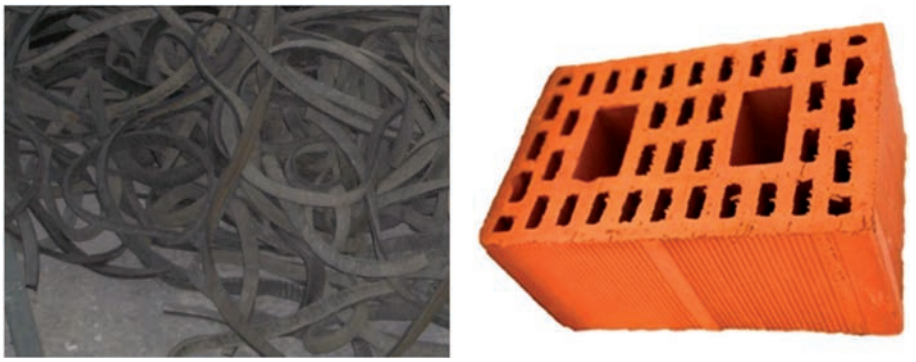


Figure 4.
Cut tire strips and hollow brick masonry units used in experiments.



Figure 5.
Construction of the models.

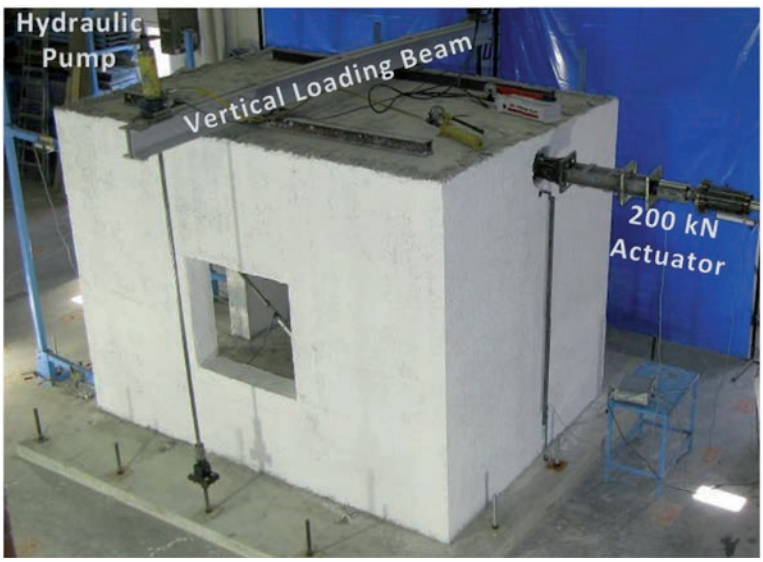


Figure 6.
Test set-up of specimens.

displacement-controlled loading in an incremental cyclic sequence, simulating in-plane earthquake-induced sway. Testing was continued until either significant strength degradation or visible failure patterns (e.g., cracking, corner separation, or local crushing) were observed.

To simulate realistic structural boundary conditions, the footings of all specimens were rigidly bolted to the strong laboratory floor, creating a fixed base condition. The top loading beam was laterally restrained to ensure only in-plane deformation, preventing out-of-plane translation or rotation during testing.

Instrumentation was designed to monitor both global behavior and local deformations. Load measurements were performed using load cells installed at key loading interfaces. Three primary load cells (LC1, LC2, and LC3) were used to monitor lateral and axial forces. Displacements were recorded using 14 LVDTs (D1 to D14) positioned to measure the following:

- In-plane wall deformation across diagonals and wall height,
- Base shear deformation,
- Vertical shortening, and
- Relative movement at critical connections.

The complete layout of the instrumentation, including the load cell and LVDT placement, is shown in **Figure 7**. This setup enabled the detailed capture of hysteretic behavior, energy dissipation, strength and stiffness degradation, and crack development under cyclic loading conditions.

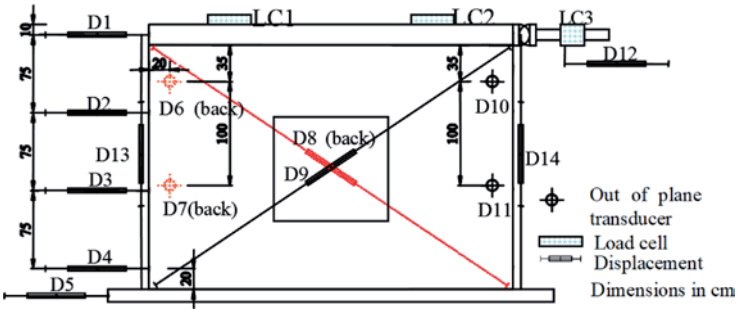


Figure 7.
Instrumentation of the test specimens.

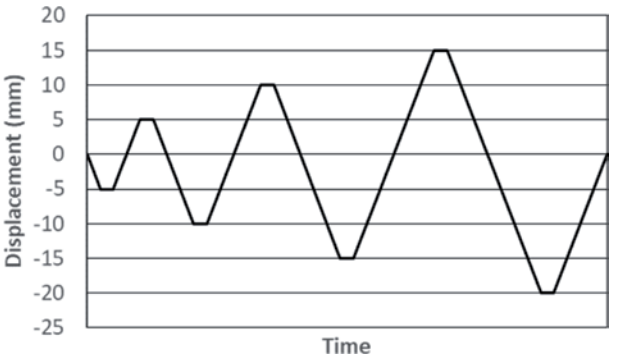


Figure 8.
Typical sway pattern applied during the experiments.

Detailed information on the reaction wall/strong floor system of the Pamukkale University Earthquake and Construction Technologies Research Laboratory is provided in the literature [33].

Typical sway patterns applied during the experiments are shown in **Figure 8**. A reversed cyclic induced displacement pattern is applied with a speed of 0.5 mm/s at the roof slab of the model.

3. Experimental results

3.1 Reference model a before and after strengthening

Model A was first tested under imposed lateral loads and then repaired and strengthened using old tire strips. The lateral load-displacement behaviors of the reference model and the damaged and strengthened specimens are shown in **Figure 9**.

The reference specimen (Model A) exhibited a maximum lateral load capacity of 174.0 kN at a displacement of 11.5 mm. Following pre-damage and subsequent wall strengthening, after the test, the same model was repaired and strengthened using the proposed method, which is named Model A-d-s. This model demonstrated an increased maximum capacity of 197.4 kN after repair and strengthening, corresponding to a 13.5% increase in strength compared to the undamaged reference model. However, despite prior damage, the displacement at significant capacity drop improved from 11.5 to 13.0 mm, indicating a 13% increase in displacement capacity.

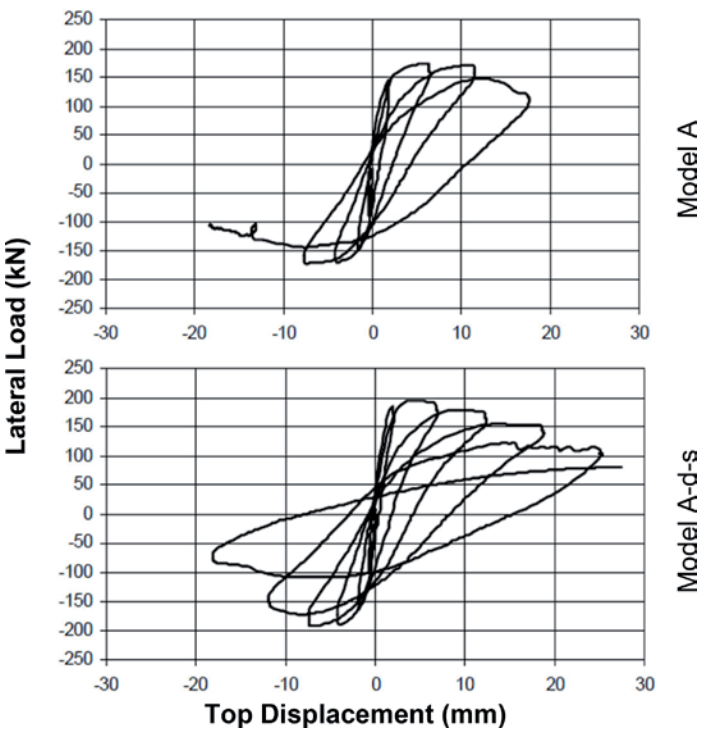


Figure 9.
Hysteresis behavior of Models A and A-d-s.

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Figure 10 illustrates the damage state of Model A at the end of the test, where pronounced diagonal shear cracks are visible, particularly at the orthogonal wall connection, which would cause out-of-plane failure in a real case.

Figure 11 shows the damage state of Model A-d-s after testing with a significant diagonal opening. No cracks were observed at the wall connections, indicating improved performance of the orthogonal connections.

3.2 Strengthened models with no prior damage: A-s and A-s+

The hysteresis behavior of the strengthened models constructed based on plan Type A is shown in **Figure 12**. Neither model was exposed to damage before strengthening. In



Figure 10.
Damage state of the Model A at the end of the test.



Figure 11.
Damage state of the Model A-d-s at the end of the test.

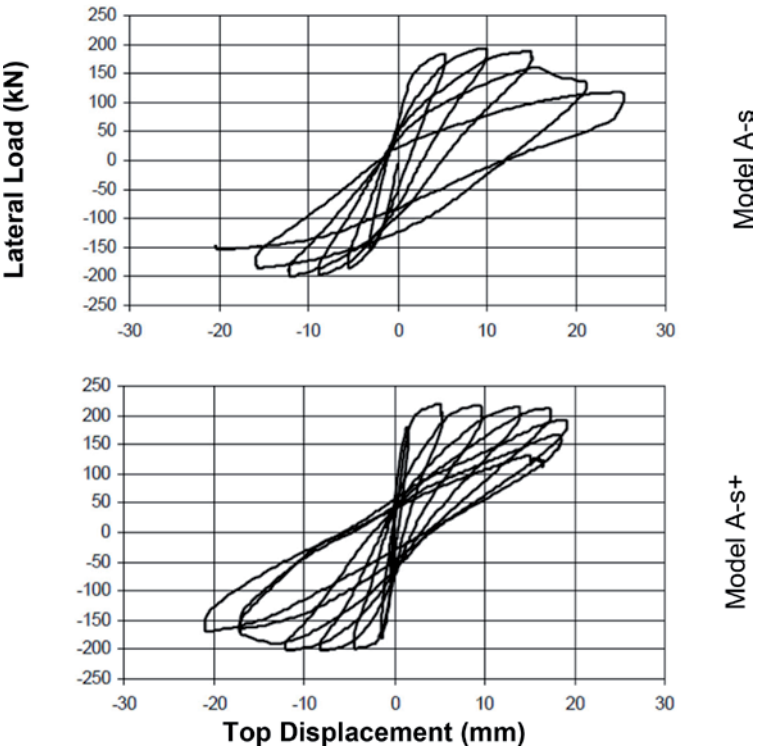


Figure 12.
Hysteresis behavior of models A-s and A-s+.

this context, Model A-s, which has the same configuration as Model A-d-s except having no prior damage before strengthening, achieved a maximum capacity of 192.2 kN, representing a 10.5% strength increase compared to Model A. This indicates a slightly lower strength compared to the damaged and strengthened models. Furthermore, its displacement at significant strength loss reached 15.4 mm, corresponding to a 34% increase in the ultimate displacement capacity relative to the reference model. Despite the lower strength level with respect to the damaged and strengthened model, A-s achieved a higher lateral displacement before a significant loss of capacity. Regardless, this outcome highlights the effectiveness of proactive wall strengthening measures, not only for enhancing strength but also for improving deformation capacity.

Figure 13 depicts diagonal cracking and the separation of the orthogonal wall connection in Models A-s, where wall-only reinforcement helped delay crack initiation. However, diagonal cracks still formed, causing separation at the wall junction.

Figure 14 presents a similar diagonal cracking of wall sections around window openings in Model A-s+, where corner strengthening significantly influenced the performance, with no cracks developing at the connection of walls at the corner. This also proves the effectiveness of strengthening the corners of masonry wall connections.

Model A-s+, which incorporated both wall and corner strengthening, exhibited the highest lateral load capacity of 223.4 kN, reflecting a 28.4% increase over the reference model. Notably, its displacement at a significant capacity drop was measured as 17.5 mm, corresponding to a 52% improvement in ductility compared to Model A. The incorporation of corner strengthening contributed significantly to both strength enhancement and post-peak deformation ability.



Figure 13.
Diagonal cracking at the walls and separation of orthogonal wall connection (A-s).

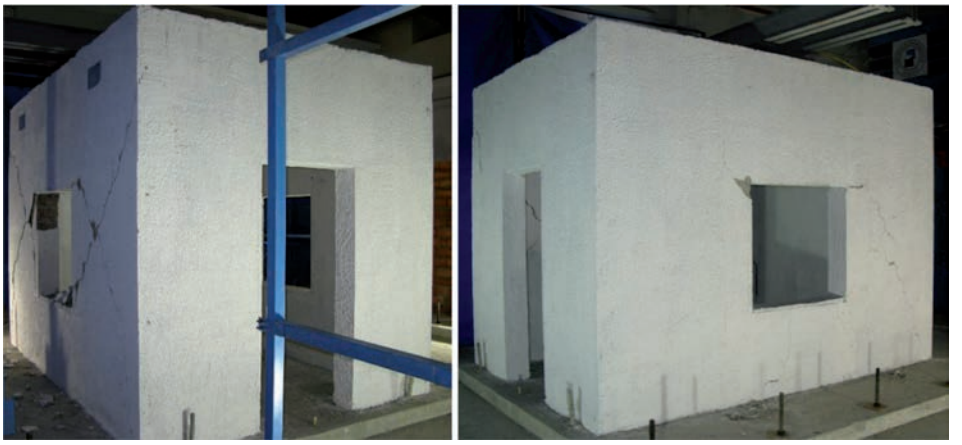


Figure 14.
Diagonal cracking at the walls and separation of orthogonal wall connection (A-s+).

In summary, all the strengthened models of the Type A specimens exhibited improved lateral strength and ductility compared with the unstrengthened reference specimen. The greatest improvements were observed in Model A-s+, emphasizing the critical role of comprehensive wall and corner reinforcement strategies in enhancing both load-carrying capacity and seismic resilience.

3.3 Reference model B and B-s+

The lateral load capacity, displacement behavior, and post-peak performance of Model B and its strengthened counterpart (Model B-s+) are shown in **Figure 15**. Model B, representing a reference specimen with a greater wall-opening ratio, exhibited distinct characteristics compared with Model A.

The reference specimen (Model B) achieved a maximum lateral load capacity of 89.6 kN at a displacement of 8.0 mm. Owing to the increased wall openings, the strength and displacement capacities were lower than those of Model A series specimens. The displacement at the point of significant strength degradation was recorded as 16.4 mm, demonstrating a moderate post-peak deformation capability.

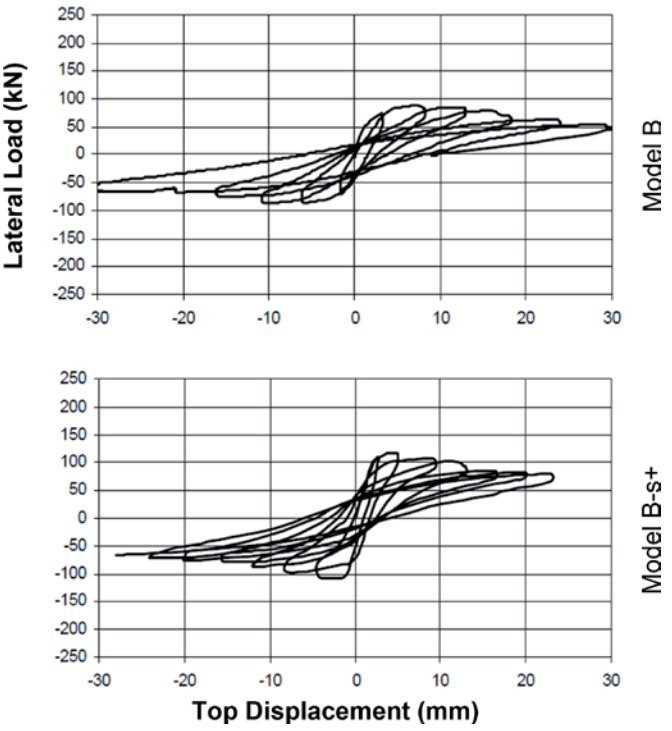


Figure 15.
Hysteresis behavior of Model B and B-s+.

After strengthening with the combined wall and corner enhancements, Model B-s + reached a maximum lateral load capacity of 109.1 kN, reflecting a 21.8% increase in strength compared with the reference model. However, the displacement at the maximum load decreased significantly to 4.3 mm, indicating stiffer behavior under lateral loading.

In terms of ductility, the displacement at significant capacity drop decreased from 16.4 mm in Model B to 7.6 mm in Model B-s+, corresponding to an approximate 54% reduction in post-peak deformation capacity. Although the strengthening measures effectively improved the lateral strength, they resulted in a notable reduction in displacement capacity. This trend is attributed to the increased initial stiffness and reduced deformation capacity introduced by the strengthening interventions, which are particularly critical for specimens with high wall-opening ratios.

The strengthening of Model B-s + successfully increased the lateral load-carrying capacity but at the expense of reduced ductility. For walls with larger openings, strengthening strategies should balance both the strength and deformation capacity to ensure optimal seismic performance.

Figure 16 shows the condition of Model B at the end of the test, with clear signs of severe cracking in the narrow wall sections between the wall openings, indicating the limits of its lateral load-bearing capacity.

Figure 17 shows the damage state of Model B-s + at the end of the testing, with the reinforced model showing similar crack propagation and significant deformation at the walls. It should also be noted that, in addition to the crack patterns, the residual capacities of the buildings are quite similar to each other.



Figure 16.
Model B at the end of the test.

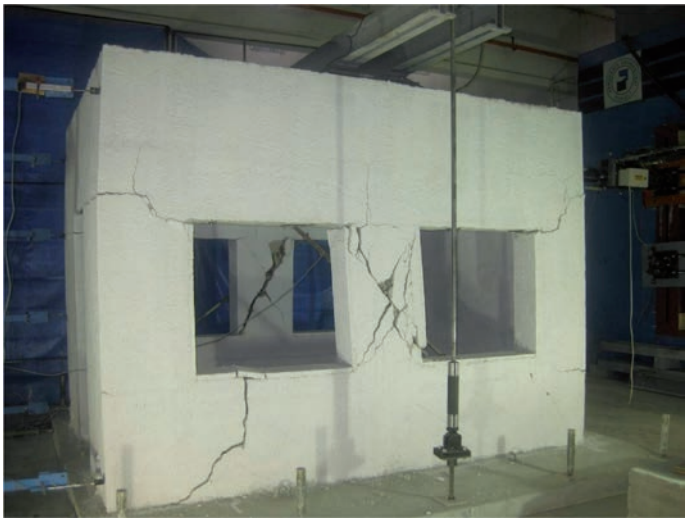


Figure 17.
Model B-s + at the end of the test.

4. Discussion of the test results

The experimental results demonstrated the effectiveness of the proposed tire strip retrofitting technique for masonry walls. A concise summary of the comparative improvements achieved by strengthening the tested specimens is provided in **Table 3**.

These results clearly highlight the structural advantages of the proposed strengthening method. Specifically, the greatest improvements were observed in the models with comprehensive strengthening, including the corners (Model A-s+), which achieved a 28.4% increase in strength and a remarkable 52% increase in ductility. This emphasizes the critical role that corner reinforcements play in resisting seismic forces.

Model	Maximum load (kN)	Strength change (%)	Displacement at peak (mm)	Ductility change (%)
A (reference)	174	—	11.5	—
A-d-s	197.4	13.5	13	13
A-s	192.2	10.5	15.4	34
A-s+	223.4	28.4	17.5	52
B (reference)	89.6	—	16.4	—
B-s+	109.1	21.8	7.6	–53.7*

Negative values indicate a reduction in ductility compared to the reference model.

Table 3.
Comparison of key performance metrics between reference and strengthened masonry wall models.

For previously damaged models (Model A-d-s), the method proved effective not only for preventive retrofitting but also for rehabilitating earthquake-damaged structures, showing a clear recovery in structural capacity.

However, the results from Model B-s + indicated a critical trade-off between increased strength and reduced ductility in highly perforated walls. This suggests that for buildings with significant wall openings, retrofitting strategies must be carefully balanced to ensure improvements in both strength and deformation capacities.

Overall, these findings support the use of tire-derived reinforcements as a sustainable and economically viable alternative to traditional seismic retrofitting approaches, particularly in low-income regions where conventional methods are economically or logistically challenging.

5. Conclusions

This study demonstrated the viability of using recycled tire strips as a sustainable and effective seismic retrofitting method for masonry walls. The key conclusions are as follows:

- Tire-strip reinforcements significantly enhance the lateral load capacity and ductility, particularly when corners and critical areas are included in the strengthening scheme.
- The greatest improvements in structural performance were observed in the models with both wall and corner reinforcements, highlighting the importance of comprehensive strengthening strategies.
- The proposed retrofitting technique proved effective in rehabilitating previously damaged masonry walls, indicating its suitability for post-earthquake recovery.
- A notable trade-off between strength increase and ductility reduction was identified in models with large openings, suggesting the need for careful optimization of strengthening strategies in such cases.

- The utilization of discarded automobile tires aligns with circular economy goals, providing a cost-effective and environmentally beneficial alternative suitable for resource-limited regions.

This study underscores the potential of recycled tire materials for sustainable seismic retrofitting, offering an affordable, accessible, and environmentally responsible solution.

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Chapter 5

Thermography Applied to Old Masonry Constructions

Rubén Rodríguez Elizalde

Abstract

Infrared thermography is a non-invasive technique widely used in architectural heritage conservation to analyze surface temperatures and identify material deterioration. This study presents the application of both terrestrial and aerial thermography for diagnosing structural pathologies in historical monuments. Thermographic imaging facilitates the detection of hidden elements, moisture infiltration, thermal bridges, and material heterogeneities without physical contact. The research examines case studies such as the Tower of Hercules and La Giralda, demonstrating the advantages of drone-mounted cameras for capturing hard-to-reach areas. Results confirm the effectiveness of thermography in recognizing material differences, moisture-induced damage, and the influence of environmental conditions on historical structures. The findings emphasize the importance of optimizing thermal camera parameters and selecting appropriate environmental conditions to enhance measurement accuracy. The study concludes that the combined use of terrestrial and aerial thermography provides valuable insights for preventive conservation strategies, contributing to the preservation of cultural heritage through non-destructive methods.

Keywords: thermography, heritage conservation, aerial inspection, infrared imaging, structural pathology

1. Introduction

Thermography is a recognition technique based on the detection of radiation emitted by objects, converting the captured information into images that provide highly valuable data regarding the surface temperature of the photographed bodies. Its significance is such that it has not only become a subject of detailed study in the field of heritage and historical constructions [1], but it is also currently regarded as a fundamental instrumental inspection technique in the field of monument conservation.

A conventional photographic camera, like the ones integrated into most modern smartphones, detects the visible light emitted by objects, capturing this visible light on a medium to produce photographs that can be easily perceived by the human eye. In other words, a photographic camera detects visible light and records it in a photograph. In contrast, a thermal camera detects infrared emissions: infrared radiation has a lower frequency than visible light, which makes it undetectable to the human eye. However, infrared radiation can be perceived organoleptically as heat. While the human eye is insensitive to the infrared radiation emitted by objects, the skin can

detect it. Therefore, a thermal camera captures the surface temperature of objects and records it in the form of a thermal image (or thermogram).

The reduction in camera costs over recent years, combined with their integration into drones as an additional component, has paved the way for a new, highly useful microtechnology that can be leveraged for the inspection of monuments and their constituent materials. For this reason, the following sections will analyze the potential applications of this technology in the context of heritage conservation.

2. Objectives

The objectives of the research included in this chapter are the following:

1. To analyze the potential of terrestrial and aerial thermography in the conservation of architectural heritage through non-invasive techniques.
2. To identify material damage and structural pathologies in historical constructions using thermal imaging technology.
3. To assess the effectiveness of infrared thermography in detecting hidden structural elements, moisture infiltration, and thermal anomalies.
4. To propose guidelines for the standardized application of thermography in preventive conservation practices for heritage structures.

3. Methodology

The methodology of this study follows a systematic approach to apply and evaluate terrestrial and aerial thermography in the context of architectural heritage conservation. The research was conducted in multiple historical monuments, utilizing thermal imaging techniques to identify material heterogeneities, moisture infiltration, and potential structural pathologies.

The study employs a descriptive and diagnostic research design to assess the thermal behavior of various heritage structures. The design integrates both qualitative observations and quantitative thermal measurements to identify patterns indicative of deterioration processes.

The methodology was applied to a series of historical monuments, including the Tower of Hercules, La Giralda, and the Cathedral of León. These case studies provided empirical evidence of thermography's effectiveness in detecting structural irregularities and evaluating material performance.

This methodological approach underscores the potential of terrestrial and aerial thermography as a non-invasive, reliable tool for the preservation of architectural heritage, offering critical insights into the thermal behavior and structural integrity of historical constructions.

4. Fundamentals of thermography

Conventional photographic cameras detect the visible light emitted by objects and are capable of capturing this visible light in a photograph. In contrast, thermal

cameras perform a similar task with infrared emissions. Infrared radiation has a lower frequency than visible light, which makes it undetectable to the human eye. However, infrared radiation can be perceived organoleptically as heat. While the human eye is insensitive to the infrared radiation emitted by an object, human skin can detect it. Thus, a thermal camera records the surface temperature of objects as a thermal image.

Depending on the camera model, some thermal cameras can detect temperature differences as small as a few hundredths of a degree. Thermography is an instrumental diagnostic and inspection technique of significant interest in the study of heritage materials [2]. It allows for the precise measurement of surface temperatures [3] without requiring physical contact with the object.

The primary characteristics of thermography are as follows [4]:

- It is non-invasive and operates remotely.
- It captures the observed object within an image, enabling temperature analysis.
- It allows for rapid visualization of stationary objects.
- The images provide information about temperature distribution, thermal patterns, behavior, and any existing anomalies.

Thermal images are commonly used to identify so-called 'hot spots'—points on an object where the temperature is higher, making them stand out in the thermal image or thermogram. For instance, the author of this study has employed thermography to locate buried structural metallic elements (**Figure 1**) or concealed utility pipelines (**Figure 2**). Infrared thermography is essential for accurately assessing the condition of building envelopes, as it facilitates the detection of thermal bridges, insulation

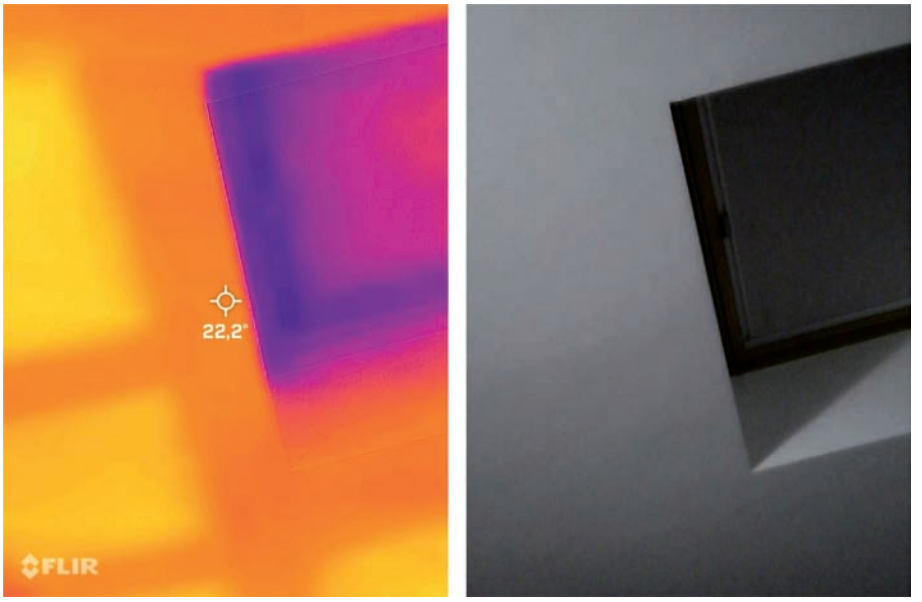


Figure 1.
Thermal analysis of an attic residence, illustrating the location of hidden beams, structural elements, and heat losses near the skylight (images by the author).

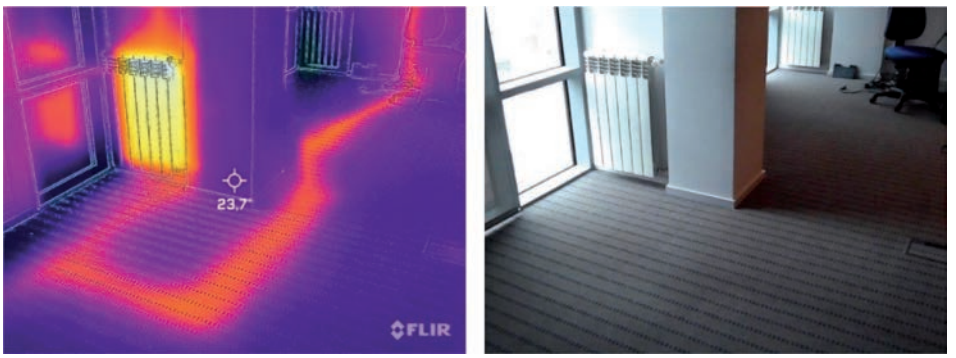


Figure 2.
Detection of an active heat conduction pipe supplying a radiator in an office building (images by the author).

defects, moisture intrusions, and other building pathologies [5]. This makes thermography particularly valuable for heritage inspection applications.

As mentioned in the introduction, thermography is a technique based on detecting the radiation emitted by objects and converting this information into images that reveal surface temperature data. Any object with a temperature above absolute zero (0 Kelvin = −273.15°C) emits infrared radiation (IR radiation). The human eye cannot perceive this radiation because it is insensitive to infrared wavelengths (**Figure 3**). However, the core component of a thermal camera—the infrared detector—is sensitive to this radiation. By analyzing the intensity of the infrared radiation, the detector determines the object's surface temperature and converts it into a thermal image that the human eye can interpret. This process is known as thermography.

To make infrared radiation visible, the detector captures the radiation, converts it into an electrical signal, and assigns each signal a specific color displayed on the thermal camera's screen. In simpler terms, a thermal camera translates infrared wavelengths into visible wavelengths, producing a color-coded image.

Contrary to popular belief, thermal cameras do not allow users to see inside objects; they only visualize surface temperature. However, if an internal object has a significantly different temperature, this temperature discrepancy may become visible in the thermal image (**Figures 1** and **2**).

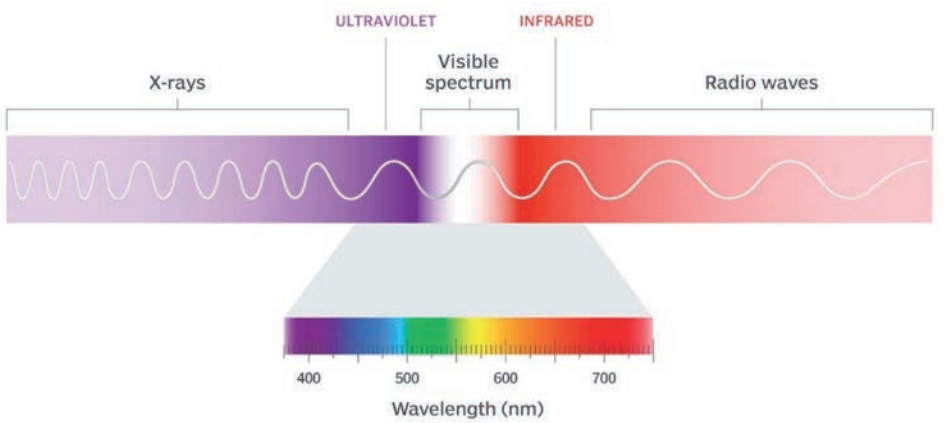


Figure 3.
Visible and invisible light (graphic by Scarpatti [6]).

The radiation detected by a thermal camera consists of three components: emitted, reflected, and transmitted radiation [7], originating from objects within the camera's field of view (**Figure 4**).

- Transmission (τ): Transmission refers to a material's ability to allow infrared radiation to pass through it. For instance, a thin plastic sheet exhibits high transmissivity. Consequently, if a thermal camera is used to measure the temperature of a plastic sheet placed in front of a building facade, the measurement will reflect the facade's temperature rather than that of the plastic. Most materials, however, do not transmit infrared radiation, meaning their transmissivity is close to zero and can be disregarded in practical applications.

- Emission (ε). Emission describes a material's capacity to emit infrared radiation and is expressed as a percentage. This property depends on the material's composition and surface characteristics. For example, the sun has an emissivity of 100%. Although this value is rarely encountered in everyday applications, materials like concrete exhibit high emissivity, with values around 93%. This indicates that 93% of the infrared radiation detected originates from the concrete itself.

- Reflection (ρ). Reflection represents the infrared radiation from the surrounding environment that bounces off the object's surface. For instance, if concrete has an emissivity of 93%, the remaining 7% corresponds to reflected radiation. Modern thermal cameras allow users to input both emissivity and reflected temperature values to enhance measurement accuracy.

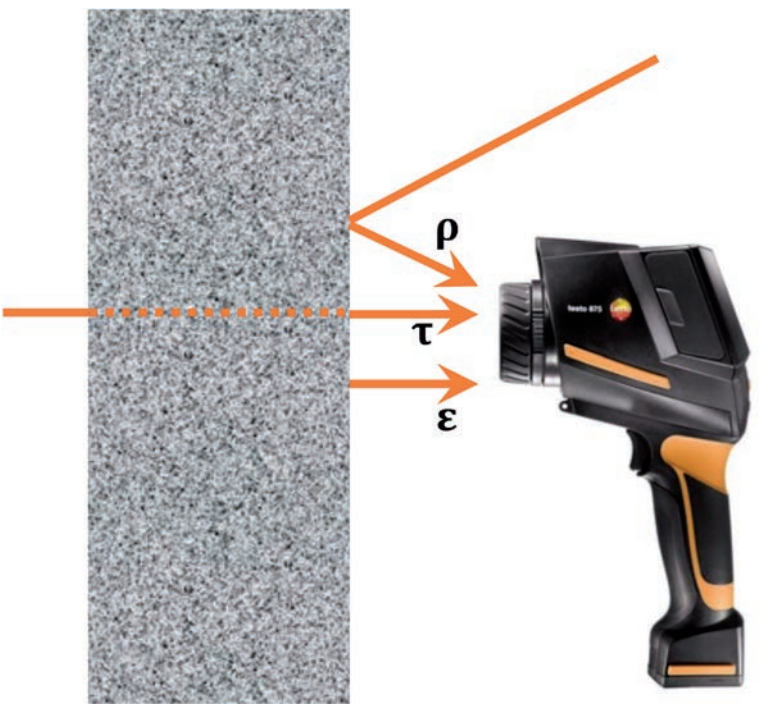


Figure 4.
Emitted (ε), reflected (ρ), and transmitted (τ) radiation recorded by a thermal camera (diagram by the author).

Thermal cameras generate images in which each pixel corresponds to a specific temperature value. These images typically employ pseudocolor scales, where cooler temperatures are represented in shades of blue and warmer temperatures in shades of red.

Infrared thermography, therefore, stands as a crucial, non-invasive tool for monitoring and analyzing the thermal behavior of historical structures, providing essential data for the diagnosis and conservation of heritage materials.

5. Terrestrial thermography applied to architectural heritage

Thermography can be employed as an instrumental technique for diagnosing and inspecting heritage materials of great interest. It can also aid in the characterization of materials of diverse origins when materials with distinct characteristics coexist within the same monument. For instance, the case of the Torre del Oro in Seville illustrates this application. In this structure, limestone blocks from different periods coexist with mortar in the lower part of the monument, presenting, depending on their age and exposure to external agents, a clearly distinguishable appearance to the naked eye (**Figure 5**), which is equally evident in the thermal image captured by the thermographic camera (**Figure 6**).

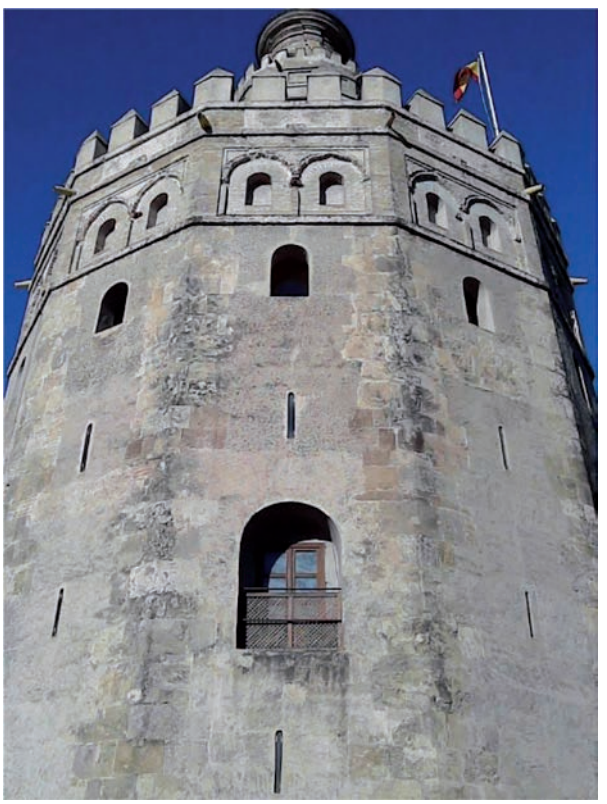


Figure 5.
Photographic image of the southern flank of the Torre del Oro in Seville, next to the Guadalquivir River (photo by the author).



Figure 6.
Thermogram of the image in **Figure 5**, *clearly showing the different materials used in construction (photo by the author).*

This distinction becomes even more pronounced when dealing with materials of markedly different nature. A clear example can be observed in the entrance door of Girona Cathedral (**Figure 7**), located on its western facade. Amidst the stone ornamentation made of limestone rock, the entrance door, being metallic, displays a stark contrast in the thermogram (**Figure 8**) due to the difference between the sedimentary rock of the facade and the metal of the door.

The Cathedral of León is globally renowned for its stained-glass windows. Beyond their decorative function, these tinted glasses were strategically placed to allow sunlight to illuminate the temple's interior. Consequently, the difference between the limestone of the walls and the glass of the windows is substantial in terms of transmission, emission, and reflection. From the outside, significant differences become apparent in both the photographic image (**Figure 9**) and the corresponding thermogram (**Figure 10**). Particularly interesting in this regard are the thermal readings captured around the edges of the windows.

Thus, the Torre del Oro exemplifies the utility of thermography in differentiating materials of varying ages. However, experience indicates that this observation cannot be universally applied. For instance, the enclosing walls of Palma de Mallorca Cathedral demonstrate this limitation. While a photographic camera can distinguish younger from older Marés sandstone blocks [8] due to differences in color and texture (**Figure 11**), the thermogram reveals this distinction with much less clarity (**Figure 12**). Conversely, in the granite blocks protecting the ancient Roman



Figure 7.
Photographic image of the entrance to Girona Cathedral on its western facade (photo by the author).

lighthouse of the Tower of Hercules (**Figure 13**) [9], the differentiation is more evident in the thermogram than in the photographic image (**Figure 14**) [10].

Another illustrative example can be found in the lower section of the eastern facade of La Giralda, the bell tower of Seville Cathedral. Despite its recent restoration [11], issues related to the brickwork, particularly moisture problems, persist. These issues are visible to the naked eye in the photograph (**Figure 15**) but become even clearer in the thermographic image, where areas affected by moisture are

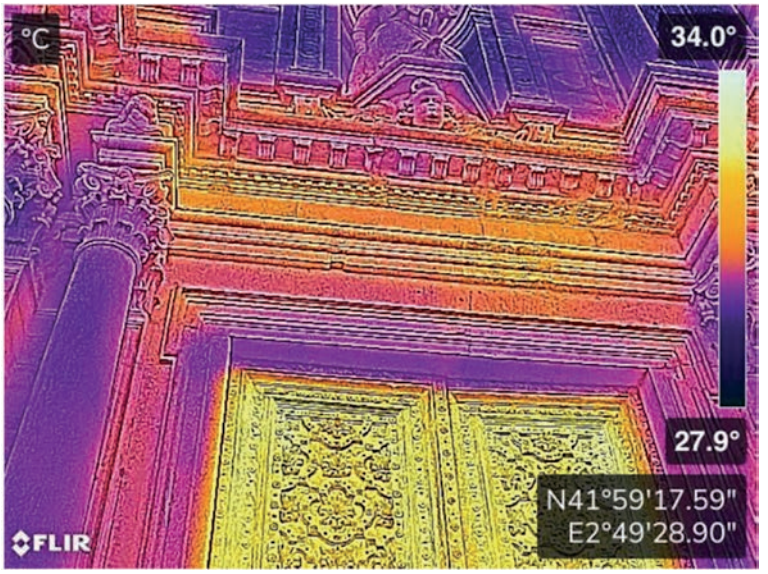


Figure 8.
Thermogram of the image in **Figure 7**, *illustrating the distinct materials (photo by the author).*



Figure 9.
Photographic image of the eastern apse of León Cathedral (photo by the author).

distinctly identifiable. Given the operational principles of thermography, it is logical to expect that moist areas would appear warmer than dry ones due to evaporative cooling (**Figure 16**). Nevertheless, this is not always the case, as thermal history can sometimes obscure useful signals, as observed in the lower rows of the bell tower of Valencia Cathedral, the Torre del Miguelete (**Figure 16**). Here, the varied degrees of moisture absorption, resulting from poorly executed restorations with



Figure 10.
Thermogram of the image in **Figure 9**, *highlighting the material differences (photo by the author).*



Figure 11.
Detail of the south façade wall of the Cathedral of Palma de Mallorca, where different ashlars from the Marés can be seen (photo by the author).

unsuitable materials [3], are accurately detected by the thermographic camera (**Figures 17** and **18**).

Similar phenomena can be observed in the stone blocks of Barcelona Cathedral's facade. The Montjuic sandstone [12] exhibits deterioration caused by the synergistic action of chemical and biological agents, notably the formation of black crusts (**Figure 19**), presumably linked to sulfur compounds from urban pollution [3]. This



Figure 12.
Thermogram of the image in **Figure 11***, highlighting the material differences (photo by the author).*



Figure 13.
Detail of the granite and mortar components of a section of the Tower of Hercules lighthouse (photo by the author).

phenomenon is unsurprising given the monument's central location in one of Europe's busiest cities. The restriction of traffic near the Cathedral is relatively recent, considering the building's age. Some of these lesions manifest distinctly in the corresponding thermogram (**Figure 20**).

When biological growth, such as plants, takes root in the joints between blocks, especially at angular points [3], their action exacerbates moisture issues, efflorescence, and runoff stains. These patterns are visible in both the photograph

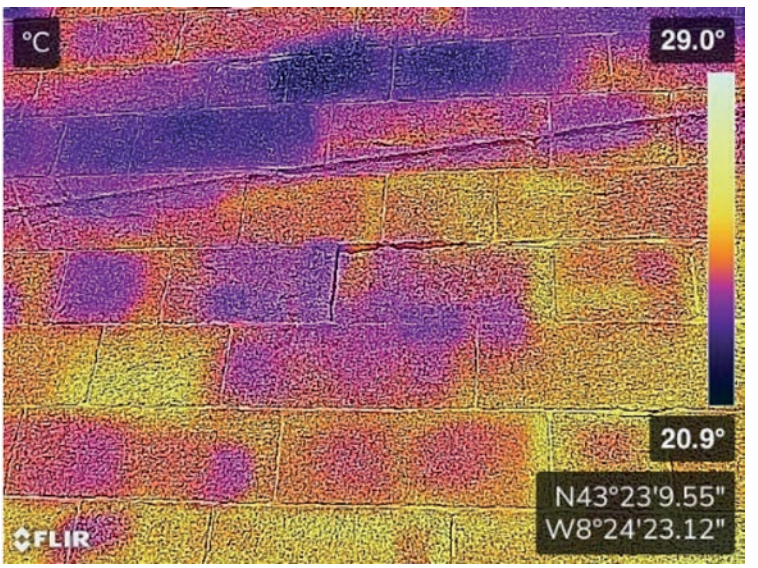


Figure 14.
Thermogram of the image in **Figure 13***, clearly differentiating the various blocks (photo by the author).*



Figure 15.
Photographic image of the lower eastern facade of La Giralda in Seville Cathedral, revealing moisture issues (photo by the author).

(**Figure 21**) and thermogram (**Figure 22**) of the western facade of Girona's Basilica of Sant Feliu [13].

The aforementioned examples underscore the utility of ground-based thermography in numerous heritage-related applications, predominantly associated with material durability.

Generally, these damages pertain to material durability rather than structural integrity, meaning they do not pose an immediate threat to the monument's stability but may lead to more severe damage if left unaddressed. Processes such as alveolization or sandstone disintegration can occur as a result [3]. The detection of efflorescence indicates ongoing chemical degradation and suggests the potential development of internal mechanical stresses due to salt crystallization.

In the context of heritage conservation, damage related to material durability stems from the interaction between the deteriorated material and the surrounding environmental conditions. In other words, material durability reflects a material's capacity to withstand environmental factors, including chemical, physical, and biological attacks or any other environmental process contributing to material deterioration.

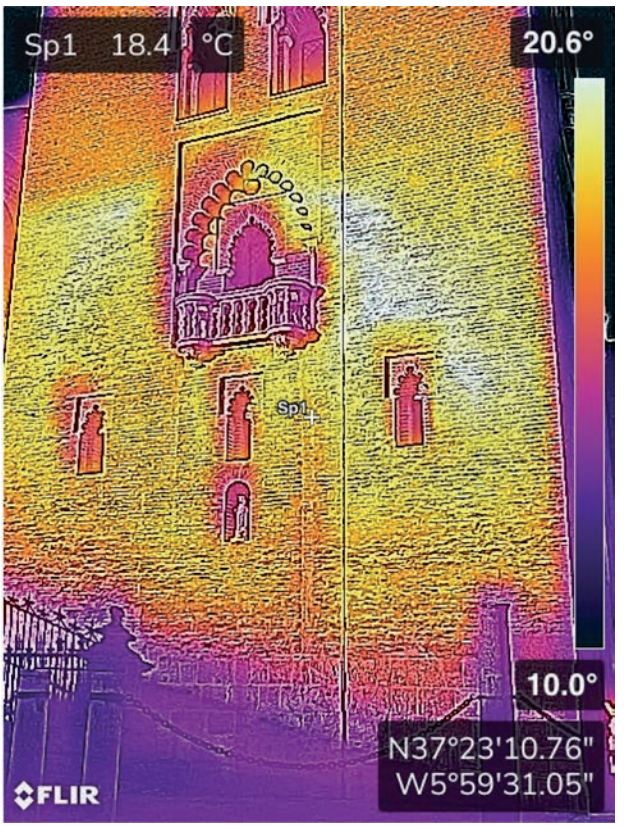


Figure 16.
Thermogram of the image in **Figure 15**, *showing varying moisture levels in the brickwork (photo by the author).*



Figure 17.
Detail of the southeast facade base of the Torre del Miguelete in Valencia Cathedral, showing diverse materials and varying deterioration states (photo by the author).

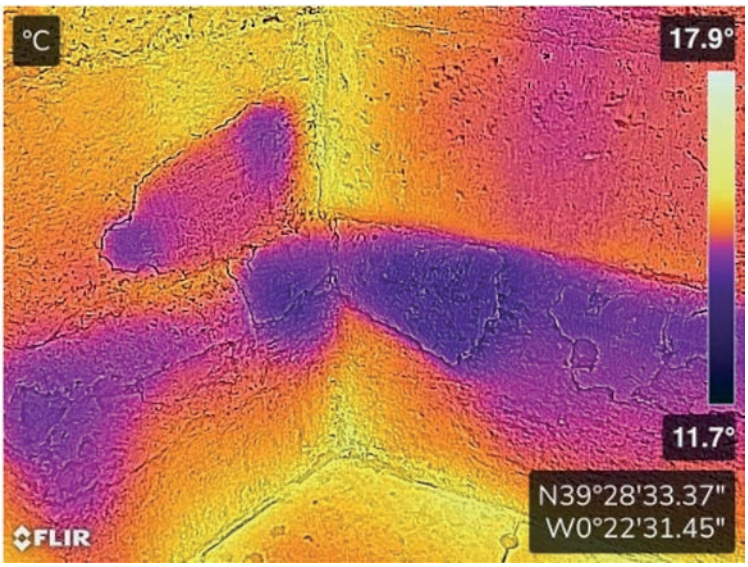


Figure 18.
Thermographic analysis of the materials from **Figure 17**, *revealing the differences captured by the camera (photo by the author).*



Figure 19.
Black crusts on the sandstone ashlars of the facade of the Cathedral of Barcelona (photo by the author).

6. Aerial thermography applied to architectural heritage

Thermal cameras provide information that cannot be obtained through other types of imaging. However, these cameras often face challenges in achieving optimal positioning for the desired perspective. In this context, drones, with their versatile maneuverability and positioning capabilities, can place thermal cameras in vantage points that are otherwise difficult to access.

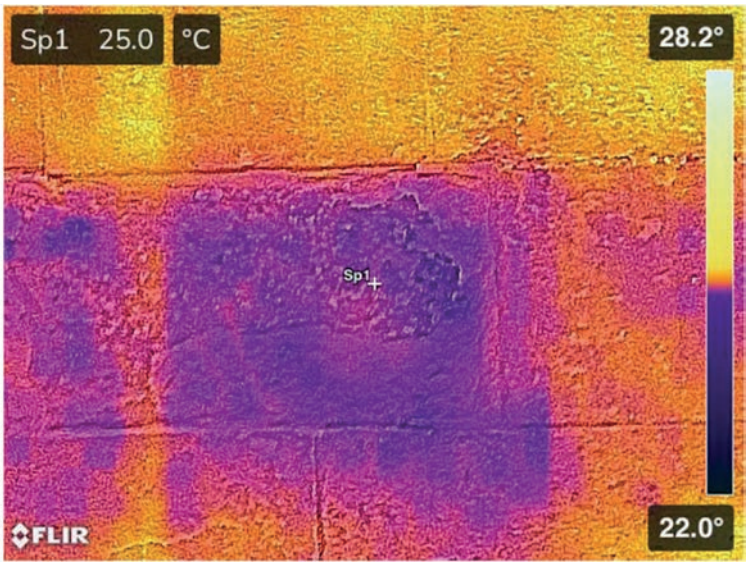


Figure 20.
Thermographic analysis of the ashlars in **Figure 19**, *reflecting the black crusts photographed (photo by the author).*



Figure 21.
Detail of the lower eastern facade of the Basilica of Sant Feliu, with visible vegetation growth (photo by the author).

Given the compact size and lightweight nature of modern thermal cameras, nearly any multirotor drone can now carry one. This advancement gave rise to aerial thermography: the fusion of thermographic imaging with drone piloting allows for the capture of thermal data from otherwise inaccessible viewpoints. For instance, for the accurate analysis of thermal anomalies, it is recommended that the thermal camera be positioned at an angle of 70 to 90° (**Figure 23**) relative to the surface under inspection

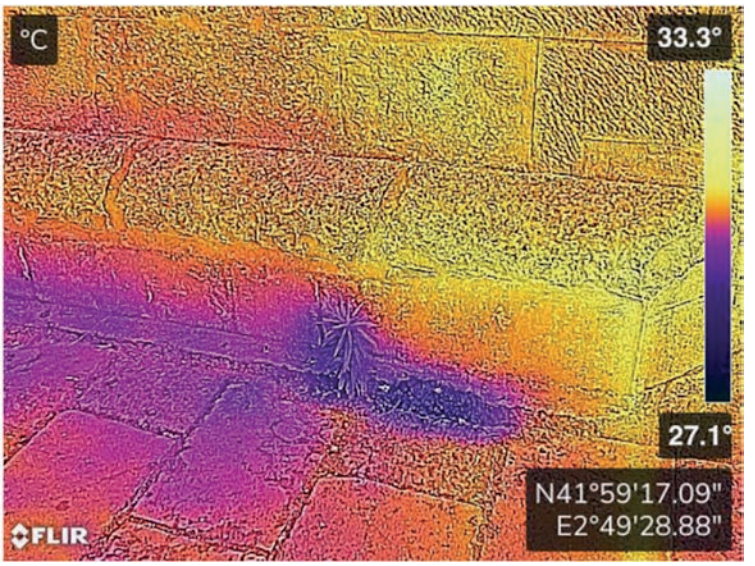


Figure 22.
Thermographic analysis of the image from **Figure 21***, showing the material differences detected by the camera (photo by the author).*

[14]. Achieving this with a handheld camera is challenging, whereas a drone-mounted thermal camera can accomplish it with ease [15].

The primary limiting factor during thermal measurements is often the meteorological conditions, as these can significantly impact measurement accuracy. As previously mentioned, thermal surveys should ideally be conducted during twilight—either at dawn or dusk—when temperature differences become more pronounced. During these periods, the varying heat dissipation of heterogeneous zones becomes evident, aiding in the identification of structural defects. Optimal conditions for measurements include an ambient temperature of approximately 25°C, solar radiation of 1000 Wm^{-2}, and some cloud cover to enhance thermal contrast. Unfortunately, these conditions are not always attainable.

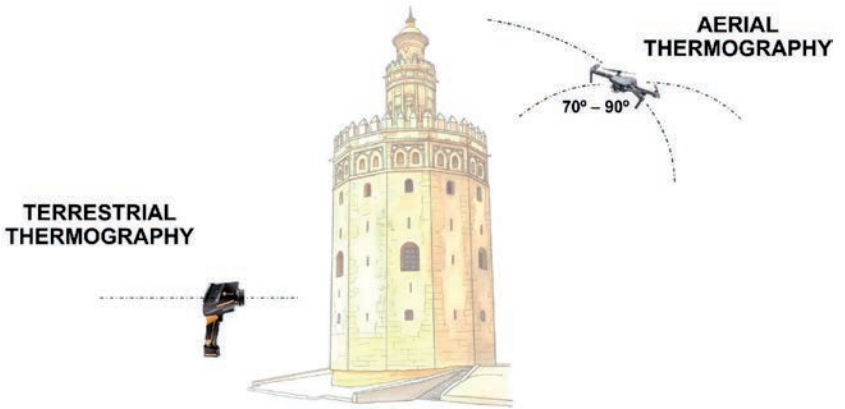


Figure 23.
Comparative analysis of the rigidity of terrestrial thermography and the flexibility of aerial thermography in a hypothetical thermographic inspection of the Torre del Oro (diagram by the author).

All objects with a surface temperature above absolute zero (0 K or − 273.15°C) emit electromagnetic energy in the infrared spectrum (0.75 to 100 μm). According to Stefan–Boltzmann's law [16], the infrared radiation emitted by an object increases with its temperature. This law applies to ideal black bodies—objects with an emissivity (ε) of approximately 100% [17]. Real objects, however, emit less radiation due to the partial reflection of incident infrared energy.

The total infrared radiation detected by a thermal camera (W) can be expressed as:

$$W = \tau\left[\varepsilon\,\sigma\left(T_s\right)^4 + \left(1-\varepsilon\right)W_{background}\right] + W_{atm}$$

where

- τ : atmospheric transmissivity.
- ε : emissivity of the object's surface.
- σ : Stefan–Boltzmann constant ($5.67 \times 10^{-8}\ \mathrm{Wm^{-2}\,K^{-4}}$).
- T_s : surface temperature of the object (K).
- $W_{background}$: background radiation from surrounding surfaces.
- W_{atm} : infrared radiation emitted by the atmosphere.

Modern thermographic software incorporates these corrections by default, enabling more accurate temperature measurements. Users must input values for surface emissivity, relative humidity, air temperature, distance to the object, and background temperature (**Figure 24**). The latter can be estimated by measuring the temperature of a crumpled aluminum foil piece placed between the camera and the object, assuming maximum emissivity (ε = 1.00) (**Figure 25**).

A noteworthy example is the main entrance of the western facade of the Monastery of San Lorenzo de El Escorial, whose fracturing has been meticulously studied [18]. Thermography proved highly useful in investigating whether this fracture, which has a structural explanation, could pose durability issues. To this end, terrestrial thermography was initially employed. However, despite conducting the thermographic inspection, the significant height of the lintel (over 6.00 m) prevented obtaining conclusive results due to the limited viewing angle.

For this reason, aerial thermography was employed: a drone was deployed to capture the corresponding thermogram, which clearly demonstrated the homogeneity of the lintel's constituent material and, consequently, the absence of durability-related damage associated with the existing fractures. The difference between the images obtained through aerial and terrestrial thermography is significant (**Figures 26** and **27**).

Another compelling example is the Tower of Hercules, previously mentioned in the context of terrestrial thermography (**Figures 13** and **14**). Given its height of 55 m [19], terrestrial thermography is evidently limited. Therefore, a drone was deployed to conduct the necessary reconnaissance operations and capture the required thermograms (**Figure 28**). The drone facilitated a detailed analysis of the neoclassical lantern atop the tower, where the most thermally significant points were identified



Figure 24.
Ground-level photograph of the lintel above the main entrance of the Monastery of El Escorial (photo by the author).

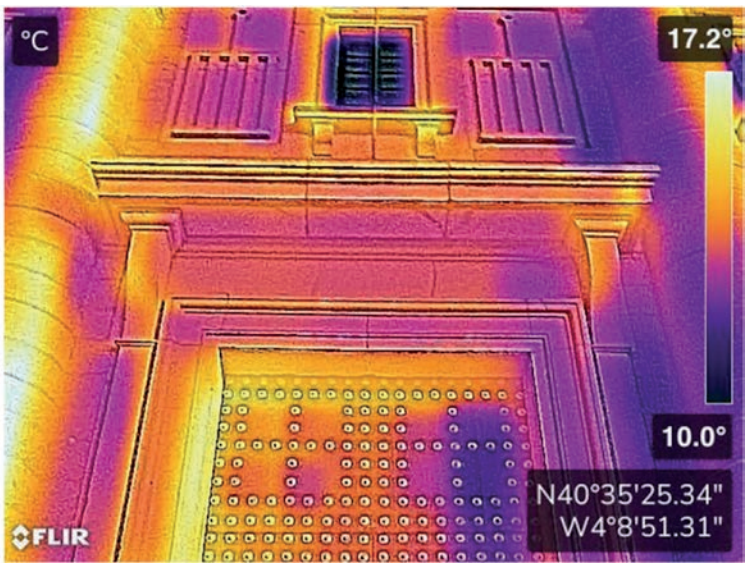


Figure 25.
Terrestrial thermogram corresponding to **Figure 24**, *showing the different materials used (photo by the author).*

(**Figures 29** and **30**). Additionally, a comprehensive examination of the facade was performed, with the drone positioned at various points to capture images from appropriate heights (**Figures 31–33**). The thermographic analysis confirmed the absence of significant anomalies, although minor irregularities were observed in some stone blocks, attributable to weathering effects on the granite (**Figure 32**). These irregularities are negligible and pose no durability concerns.



Figure 26.
Drone hovering in front of the lintel of the main entrance of the Monastery of El Escorial (photo by the author).

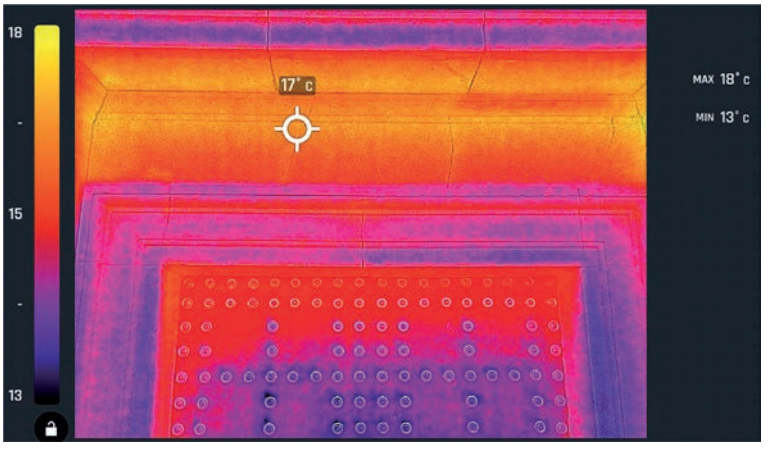


Figure 27.
Aerial thermogram, captured with a drone, of the lintel above the main entrance of the Monastery of El Escorial (photo by the author).

7. Conclusions

Thermography, as demonstrated in this study, is a powerful, non-invasive technique for the assessment and preservation of architectural heritage. The application of both terrestrial and aerial thermography has proven effective in identifying thermal anomalies associated with structural pathologies such as moisture infiltration, material heterogeneity, and hidden structural elements. The case studies presented, including the Tower of Hercules, La Giralda, and the Cathedral of León, highlight the method's capacity to provide detailed diagnostic information without physical contact.

Aerial thermography, facilitated by drone-mounted cameras, enables the inspection of hard-to-reach areas, offering new perspectives for heritage diagnostics. The technology's ability to detect thermal differences between materials of distinct compositions supports its usefulness in evaluating the state of historical facades and internal structures.

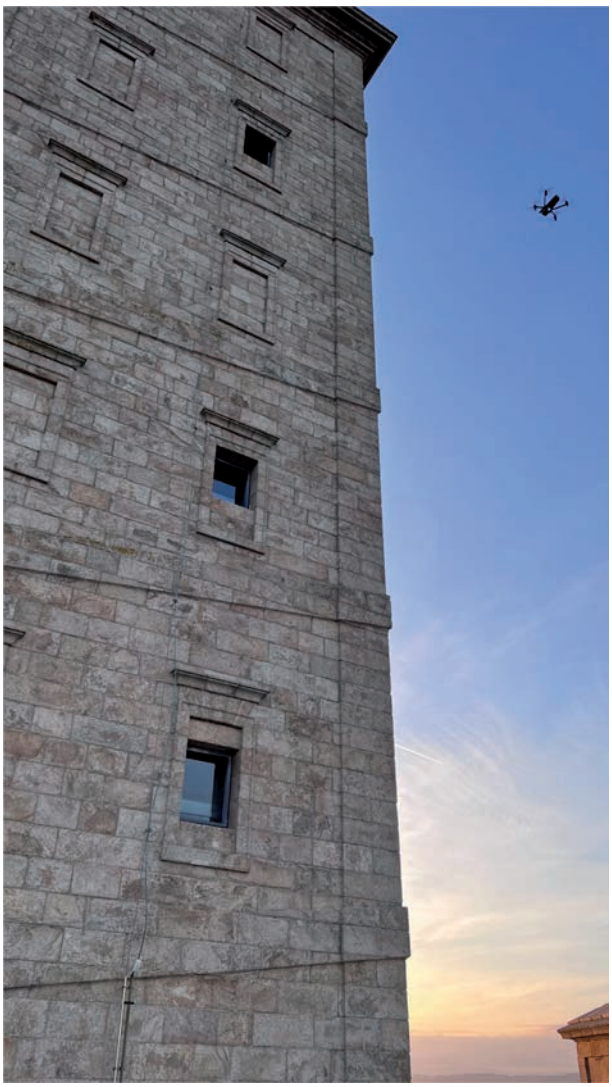


Figure 28.
Drone flying alongside the Tower of Hercules to capture photographs and thermograms (photo by the author).

Furthermore, the findings underscore the importance of selecting appropriate environmental conditions, such as measuring during twilight hours, to enhance thermal contrast and measurement accuracy. The research also confirms that material properties, including emissivity, transmissivity, and reflectivity, significantly influence the quality of thermographic data.

Thermography is a powerful, non-contact technique for obtaining temperature data from objects. Its applications are vast, given that all materials emit infrared radiation. Aerial thermographic inspection complements conventional heritage assessment by offering novel perspectives and the ability to access hard-to-reach areas.

This technology significantly enhances the speed and thoroughness of inspections, particularly when surveying large surfaces. Drone-based thermography reduces labor costs and ensures comprehensive coverage, minimizing the risk of overlooking critical areas.



Figure 29.
Junction between the original Roman section and the lantern added in the eighteenth century, highlighting the area with the highest recorded temperature (photo by the author).



Figure 30.
Thermogram analyzing the lantern atop the tower, marking the point of maximum temperature (photo by the author).

As a non-destructive diagnostic tool, thermography, when combined with *in-situ* observations, provides valuable insights into the thermal behavior of heritage structures. It facilitates the detection of patterns, anomalies, and potential structural pathologies within the building envelope.

The conducted surveys confirm the utility of aerial thermography for heritage applications. By capturing thermal data remotely, it is possible to assess the condition of historical elements without direct contact, preserving the integrity of the site. The technique's non-invasive nature and compatibility with other diagnostic methods underscore its potential as a standard practice in heritage conservation.

The information obtained through thermographic analysis aids in predicting future thermal anomalies, supporting preventive conservation strategies. Consequently, aerial thermography serves as a valuable tool for heritage professionals, providing insights that contribute to the ongoing preservation of historical structures.



Figure 31.
Thermogram captured by the drone to analyze the window of the first-level chamber on the northern facade, indicating the point of minimum temperature (photo by the author).

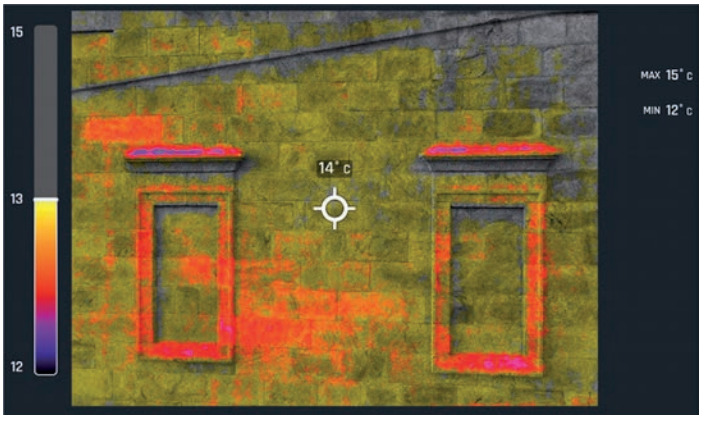


Figure 32.
Thermogram captured by the drone analyzing the opaque windows of the top level on the northern facade (photo by the author).

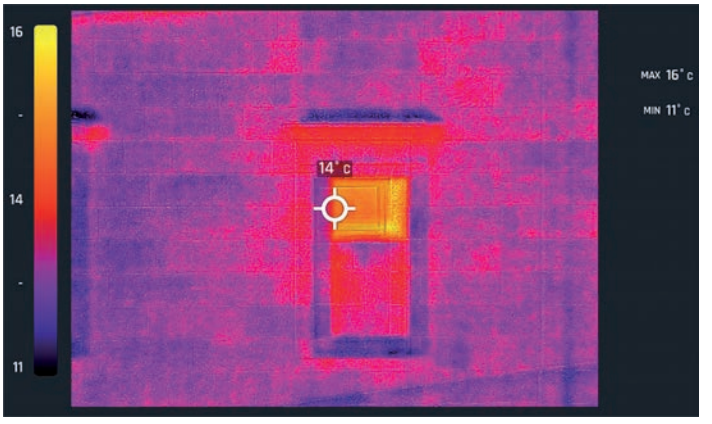


Figure 33.
Thermogram captured by the drone examining the highest window on the northern facade (photo by the author).

In conclusion, infrared thermography stands as a valuable tool for heritage conservation. Its integration into regular inspection protocols can contribute to the early detection of deterioration patterns, thereby supporting preventive conservation strategies and ensuring the long-term preservation of historical structures.

The experiences documented in this study are transferable to similar projects, demonstrating the versatility of drone-mounted thermal cameras in heritage contexts. As these technologies continue to evolve, their role in architectural diagnostics and cultural heritage conservation is expected to grow, offering innovative solutions for safeguarding our historical legacy.

Conflict of interest

The author declare no conflict of interest.

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