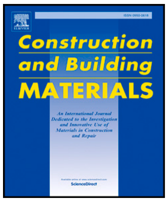
Construction and Building Materials 442 (2024) 137380

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Review

Assessment, repair, and retrofitting of masonry structures: A comprehensive review

Ayoub Keshmiry [a], Sahar Hassani [b,*], Ulrike Dackermann [b], Jianchun Li [c]

[a] Faculty of Civil Engineering, Shahrood University of Technology, Shahrood, Iran
[b] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW, Australia
[c] School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW, 2007, Australia

ARTICLE INFO

Keywords:
Masonry structures
Repair and strengthening
Retrofitting
Damage detection
Machine learning
Structural health monitoring

ABSTRACT

In the history of our civilization, masonry structures date back thousands of years. Considering the different types, geometries, and arrangements of masonry components, as well as the mortar properties, defining "masonry" precisely is challenging. Construction of masonry structures relies on layering single components and binding them using mortar or crafting them with stones without mortar. Despite many advantages, masonry structures remain one of the most vulnerable construction types. Many of these structures have not been designed to withstand seismic loads. Generally, their structural systems have been designed primarily to withstand gravity loads. Consequently, moderate earthquakes can cause extensive damage and destroy entire cities. Therefore, the assessment, repair, and retrofitting of these structures is vital to society's well-being. First, this study describes masonry structures and their mechanical and structural characteristics. Next, methods for detecting and classifying common types of damage are presented. Subsequently, a comprehensive review of assessment, repair, and retrofitting methods for masonry structures is provided. Machine learning (ML) techniques have proven to be exceptional tools for providing accurate and reliable information. In this paper, descriptions and recent advances in ML techniques for the assessment, repair, and retrofitting of masonry structures are presented. These models can be utilized for several predictive applications, such as determining possible damage scenarios in heritage buildings, assessing seismic vulnerability, detecting superficial surface damage, and selecting mortar compositions for optimal mechanical properties. Furthermore, structural health monitoring (SHM) methods applicable to masonry structures are discussed. The study concludes with case studies, and an extensive discussion of existing methods, challenges, and recommendations for future work.

Contents

---

[*] Corresponding author.
E-mail address: sahar.hassani@unsw.edu.au (S. Hassani).

https://doi.org/10.1016/j.conbuildmat.2024.137380
Received 29 August 2023; Received in revised form 25 June 2024; Accepted 5 July 2024

1. Introduction

Masonry structures, among the oldest man-made constructions still in use, have seen evolving construction techniques over time. Various types of stones, bricks, and blocks have been stacked, with or without mortar, in the construction of these structures. Throughout history, there have been numerous changes in masonry materials, methods, and applications [1,2]. The progress of masonry construction was shaped by various factors, encompassing regional economic conditions, cultural influences, the availability of equipment and labor, and accessibility to materials. In ancient times, individuals employed materials like wattle and daub, bark, skins, and turf to construct shelters for their safety. Over time, more sophisticated structures made of clay, wood, and stone emerged as advancements from simpler construction methods. The choice of building materials has significantly contributed to the overall development of human civilization [3,4]. The cast-iron beams and columns of the 19th century led to the development of structural masonry. The development of skyscrapers following the turn of the century reduced the need for large masonry piers at ground level [5]. With the introduction of guidelines for the design of reinforced concrete (RC) structures in the early 20th century, masonry declined in popularity as a structural material. As RC emerged as a strong, durable, adaptive, and affordable material, several developed countries gradually reduced masonry from structural applications [6]. Over the past few decades, reinforced masonry has evolved as a cost-effective and dependable construction material, particularly in earthquake-prone regions, owing to its favorable cost–benefit analysis. A diverse range of structures, such as hotels, residential housing, offices, commercial buildings, educational institutions, and warehouses, have been successfully constructed using reinforced masonry [7–9]. Recommended construction techniques involve utilizing two-cell blocks filled with grout, reinforced concrete, horizontal bond beams, and vertical tie beams. Additionally, confined masonry practices are frequently adopted in developing countries, as the modifications from unreinforced masonry construction are relatively minimal. By embedding small sections of reinforced concrete both vertically and horizontally within the masonry, the shear and flexural strengths can be improved. These techniques offer a greater level of ductility and enhanced energy dissipation [10,11].

Preserving historic masonry structures, whether they are celebrated monuments or local vernacular buildings, is crucial for safeguarding cultural heritage. Heritage serves as the vibrant memory of a country's history and development and, therefore, should be conserved to the fullest extent possible. Considerable expertise has been gained in the restoration and rehabilitation of damaged masonry buildings over the past decades. Instances of wartime destruction have prompted the reconstruction of monuments and historic centers, as seen in the restoration of Warsaw's center, for example. Post-World War II, certain restoration efforts were carried out following prolonged periods of neglect and inadequate maintenance [12,13]. Prevention and rehabilitation can only be successfully accomplished when an accurate evaluation of the damaged state of a structure has been conducted [14]. Therefore, it becomes evident that a comprehensive comprehension of the mechanical and structural dynamics, assessment techniques, as well as repair and retrofitting methods for masonry structures is indispensable to guarantee the success of any maintenance program. The following section offers an overview of the mechanical behavior of masonry structures.

Various types of masonry exhibit a weakness in tensile strength, a characteristic that played a pivotal role in the design of ancient constructions. Investigating ancient structures poses substantial challenges due to the diverse range of materials used, variability within a structure, and the complexity involved in replicating these characteristics in reconstructed specimens. Consequently, the majority of empirical research in the past decade has concentrated on exploring the design implications of brick and block masonry [15,16]. Essentially, masonry can be broadly classified into unreinforced and reinforced categories. A reinforced masonry structure exhibits a tensile strength comparable to that of a reinforced concrete structure. As a result, conventional methods for designing and analyzing reinforced concrete structures are applicable in such cases, as the relevance of nonlinear constitutive behavior and orthotropic behavior diminishes. In contrast, unreinforced materials tend to display nonlinear constitutive behavior due to their limited tensile strength. The results from seismic analyses and assessments of existing structures corroborate this observation [8,17,18]. Abbass et al. [19] showed that graphene/polyurethane nanocomposite coatings can enhance the mechanical performance and environmental resistance of natural fibers for masonry retrofitting. They reported a 120% and 163% increase in tensile strength and elastic modulus, respectively. Brinkmann and Wiehle [20] aimed at developing a practical approach to assess the impact of different material moisture contents on the mechanical properties of unstabilized earth masonry. Their findings indicated a linear correlation between compressive strength and elasticity modulus with relative humidity. In contrast, changes in temperature under constant relative humidity showed no significant impact. The following section will delve into the mechanical behavior of masonry structures.

As a material experiences ongoing deterioration, its resistance to load–deformation diminishes, resulting in material softening. The occurrence of progressive internal cracks and the accumulation of damage within quasi-brittle materials are common factors leading to failure in such materials. Masonry materials, including bricks, ceramics, concrete, mortar, and stone, often demonstrate this characteristic. The heterogeneity of the material, arising from various phases and defects within the mortar matrix, is attributed to this behavior [21]. Several factors contribute to the formation of microcracks in masonry materials. In bricks, microcracks arise from the shrinkage that occurs during the burning process. In mortar, microcracks are present before loading due to curing shrinkage and the presence of aggregates. Stones often contain inclusions and microcracks as well. The deformation of the material can lead to the progressive growth of cracks, influenced by factors such as changes in strength and stiffness [22]. Microcracks start as stable; however, their growth becomes more pronounced with increasing loads. At peak load, there is an acceleration in crack formation, resulting in the emergence of macro-cracks, which are less stable compared to microcracks. Consequently, a decrease in load becomes necessary to prevent uncontrolled growth. The characteristics of masonry are significantly influenced by the properties of its individual components [23].

Masonry structures commonly exhibit their greatest vulnerability at the junctions where the masonry components connect to the mortar. A notable feature of masonry behavior is its nonlinear response, particularly at these joints [24]. The behavior is notably influenced by the interface between the mortar and the unit. The failure of this interface is governed by two distinct fracture modes:

1. Mode I is related to tensile failure, and
2. Mode II is related to shear failure.

Masonry structures are particularly susceptible to earthquake loads, often experiencing significant structural failures even in moderate seismic events. The collapses of masonry structures contribute significantly to economic losses and pose a threat to human lives. Consequently, implementing seismic retrofitting techniques becomes crucial for enhancing the safety and integrity of masonry structures [25,26]. Fig. 1 presents the distribution of URM buildings and the number of all buildings (in millions) in European countries. For further information, Pagani et al. [27] illustrated the seismic hazard map of European and Middle-Eastern countries.

Various repair and retrofitting methods have been proposed as an alternative to demolishing aged masonry structures. These methods can be applied to masonry constructions to recover and increase their strength and ductility [29,30]. Preserving the structure and ensuring successful rehabilitation necessitate the control of damage and comprehensive assessments before any intervention. Monitoring the effectiveness of repair techniques during and after the repair process is also crucial for a successful outcome.

The period from 2000 to 2023 witnessed a significant increase in research emphasis on evaluating masonry structures, as evident in the findings from Scopus. However, other crucial aspects of masonry maintenance programs, namely repair and strengthening, have not received comparable attention from the research community. Fig. 2 shows a graphical presentation of the research trend during in this field, categorized by “Masonry Repair”, “Masonry Retrofitting”, “Masonry Assessment”, “Masonry Monitoring”, and “Masonry Strengthening”. The presentation illustrates an overview of the research interest in the related topics over the years.

Furthermore, Fig. 3 provides a detailed breakdown on these research topics, which revealed more in-depth development on each specific aspect of masonry maintenance distributed throughout the studied period. The analysis of these figures highlights the growing interest in assessing masonry structures while also indicating the need for more attention to be directed toward research on repair and strengthening methods. Overall, these findings contribute valuable insights into the research landscape concerning masonry maintenance, aiming to drive future research and development efforts in the field.

2. Assessment of masonry structures

The seismic vulnerability of masonry buildings in various regions has been a subject of considerable research interest, especially following significant earthquake events. Understanding the performance of such structures during seismic events is crucial for assessing their resilience and informing retrofitting strategies to mitigate potential damage. Table 1 presents a summary of key findings from selected studies focusing on seismic performance evaluations of masonry structures following earthquake events in different geographical locations.

Structural evaluation is a systematic process that involves assessing structures in terms of their current strength, and performance, and predicting their future reliability. Masonry structures require regular inspections to ensure their structural safety and mitigate the risk of collapse. This section presents a general classification of damage levels in masonry structures 2.1, along with an overview of testing strategies 2.2 and monitoring approaches for these structures 2.3.

2.1. Classification of damage levels in masonry structures

Damage can be defined as changes in the geometric characteristics or material of a structure, affecting its current and future performance. Various types of damage have been observed in masonry structures resulting from different events. The inadequate tensile strength of these structures has been attributed as the most influential factor in the occurrence of damage. The seismically vulnerable characteristics of masonry structures include [35,36]:

- an insufficient level of integrity between the load-bearing components,
- weak wall connections, which cause the failure of box action,
- extensive unsymmetrical openings resulting in the inability to resist lateral loads,
- cantilever wall behavior in long unsupported walls,
- soft-story effects, and
- reduction in load-carrying capacity due to the delamination of walls.

The European Macroseismic Scale (EMS-98) offers a standardized method for assessing damage in masonry structures following earthquakes or other seismic events. It categorizes damage severity into five grades. Each grade is linked to specific types and the extent of observable damage. Beginning with Grade 1, characterized by negligible to slight damage, there is typically no structural compromise, with only minor non-structural issues such as hairline cracks in a few walls or the occasional fall of small plaster pieces. Advancing to Grade 2, damage becomes more pronounced, with cracks appearing in numerous walls and larger pieces of plaster falling. Chimneys may experience partial collapse. Grade 3 signifies substantial to heavy damage, with extensive cracks in most walls, roof tiles detaching, and chimneys fracturing at the roof line. Structural elements like partitions and gable walls may fail. Grade 4 marks very heavy damage, featuring serious wall failure and partial structural collapse of roofs and floors. Finally, Grade 5 represents utter destruction, with total or near-total collapse, indicative of very heavy structural damage [37].

Table 2 presents impairment types in masonry structures.

Cracking is the most common damage type in masonry structures. The classification of cracks in masonry structures based on crack severity is presented in Table 3 [43,44].

Based on research conducted on earthquakes-damaged masonry structures, the following summarizes the related findings [45,46]:

1. Non-load-bearing panels tend to fail more frequently than load-bearing panels,
2. generally, element failures tend to be progressive,
3. with the failure of an element, the failure risk of adjacent components increases,

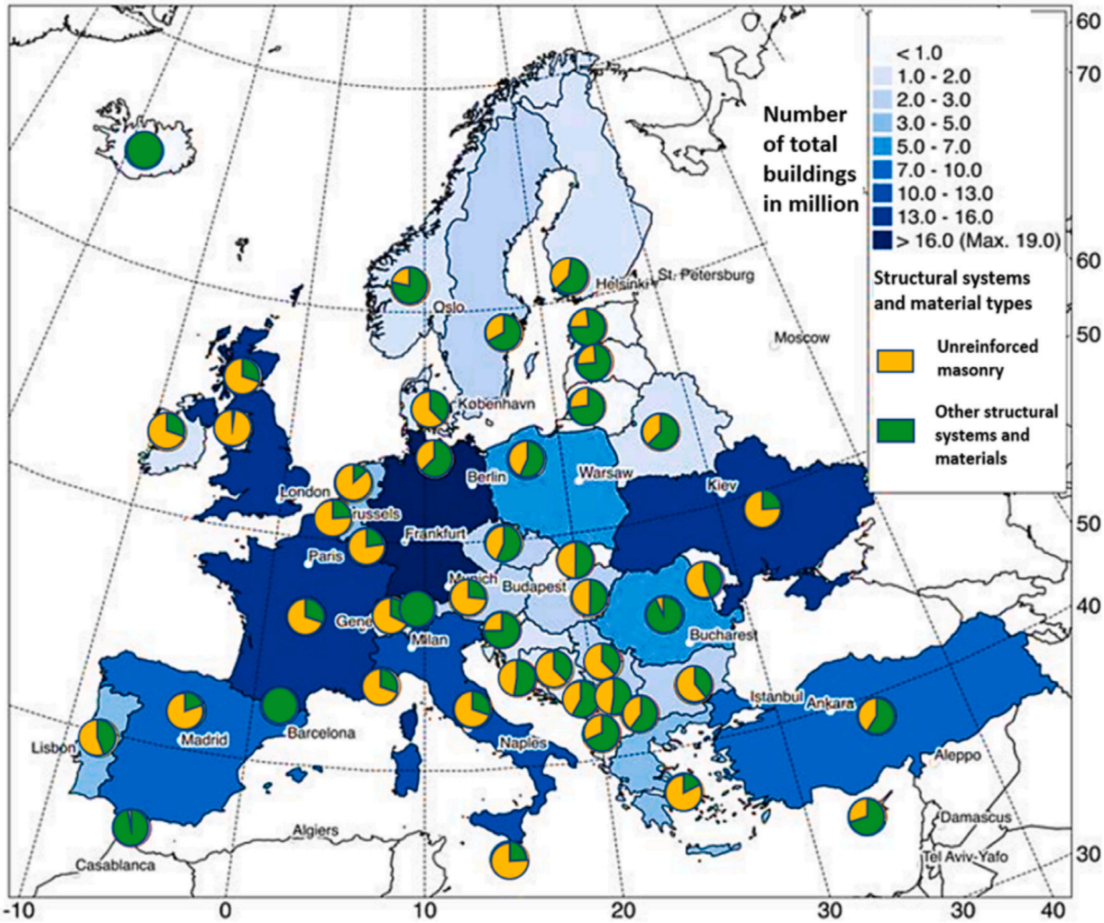


Fig. 1. Distribution of URM buildings and the number of all buildings (in millions) in European countries [28].

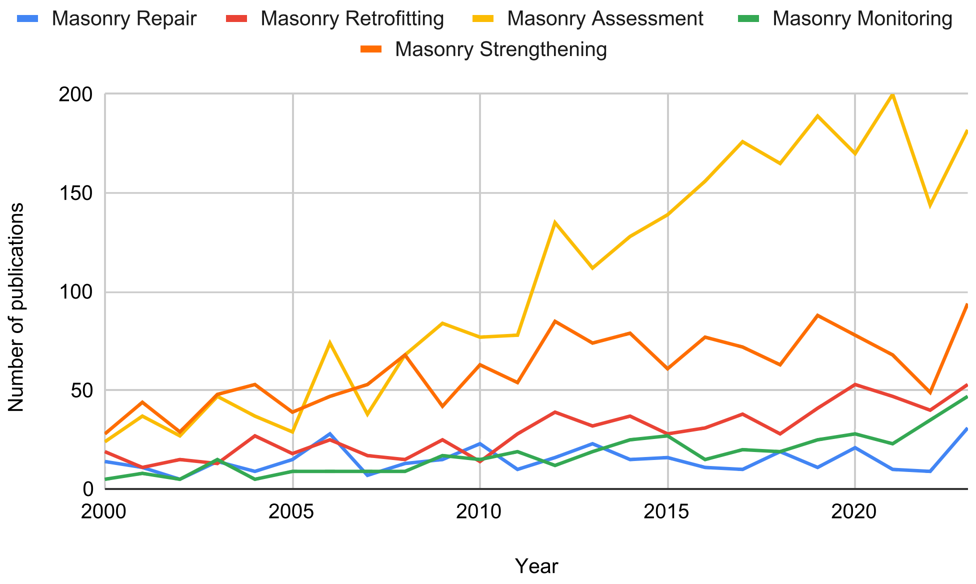


Fig. 2. Publication trend from 2000 to 2023 including the words “Masonry Repair”, “Masonry Retrofitting”, “Masonry Assessment”, “Masonry Monitoring”, and “Masonry Strengthening” in the title.

4. in the case that two corners fail, any panel between them is unrestrained and improbable to remain stable, and
5. corners have a greater probability of failure than mid-wall elements.

2.2. *Testing strategies for masonry structures*

This subsection presents testing strategies for masonry structures, including visual inspections (Section 2.2.1), non-destructive testing

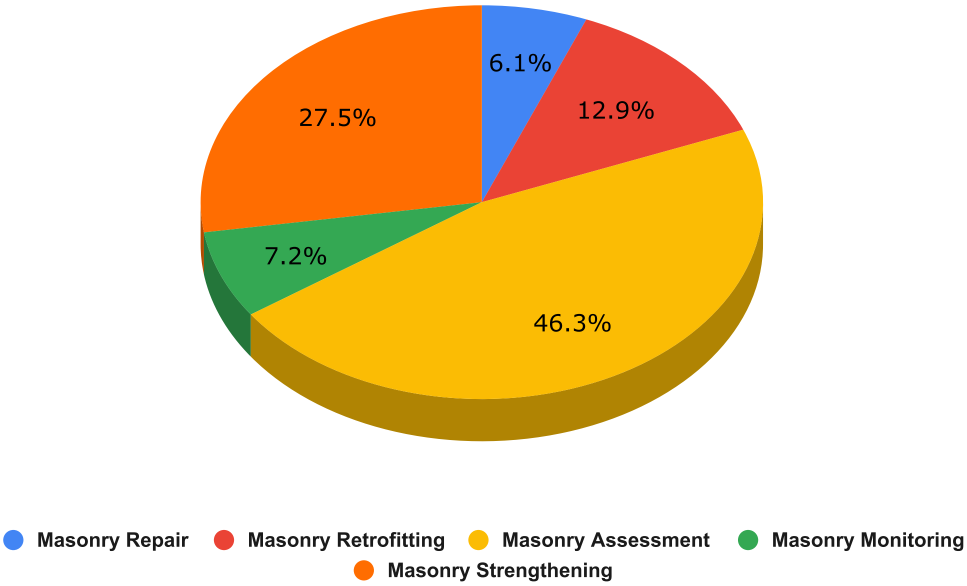


Fig. 3. Breakdown of various maintenance issues studied for masonry structures.

Table 1
Basic conclusions on masonry structure performance in selected earthquakes.

Ref	Earthquake	Location	Basic conclusions
[31]	Emilia, 20 May 2012	Italy	The majority of older masonry buildings were constructed using fired clay bricks, and their seismic performance, despite being primarily designed for vertical loads, was generally satisfactory during the earthquakes, which had peak ground accelerations (PGA) of 0.25–0.3 g. The seismic design became mandatory in the area only in 2003, resulting in modern masonry buildings, especially those incorporating seismic design and proper detailing, showing significantly better performance compared to older structures. The paper presented examples illustrating the superior performance of seismically designed modern masonry buildings compared to their older counterparts.
[32]	Zagreb, 22 March 2020	Croatia	This paper highlighted the seismic vulnerability of historical buildings in Zagreb, Croatia. The conclusions suggested that no single analysis method adequately addresses all failure modes, recommending a combination of nonlinear static or dynamic analysis and out-of-plane analysis.
[33]	Kahramanmaraş, 6 February 2023	Türkiye	The most common failure mechanisms observed are out-of-plane behavior and corner failure, often triggered by inadequate connections, low material strength, and poor workmanship. In-plane failures result from irregular door and window openings, and many buildings lack sufficient lintel bands for seismic performance. The study concluded with an examination of strengthening methods for masonry structures with light to moderate damage, along with recommendations.
[34]	Christchurch, 4 September 2010	New Zealand	Common failure types included parapet and chimney failures, out-of-plane facade wall failure, and in-plane damage. Water ingress was identified as a significant contributor to mortar deterioration. Laboratory tests on mortar samples from damaged buildings showed low compressive strengths, consistent with on-site observations. Preliminary case studies highlighted various failure modes in URM buildings. Retrofitted URM buildings generally fared well, with minimal damage observed, though parapet and chimney collapses were noted due to insufficient lateral support. Case studies were retrofitted using different methods, such as steel and concrete moment frames, steel brace frames, and surface-bonded FRP materials.

(NDT) and minor destructive testing (MDT) (Section 2.2.2), as well as destructive laboratory testing (Section 2.2.3).

2.2.1. *Visual inspections*

Visual inspection serves as a straightforward, non-destructive evaluation technique for masonry structures. It enables a rapid assessment of structural issues, aiding in the selection of suitable remedial measures. Additionally, visual inspection assists in planning diagnostic measures, and maintenance operations, validating the accuracy of design drawings, and identifying the degradation of materials and structural components [47].

A drone, also known as an Unmanned Aerial Vehicle (UAV), is an aircraft that operates without a human pilot on board. Drones

Table 2
Typical damages in masonry structures.

Impairment	Common cause(s)	EMS-98 grade	Potentially affecting structural performance	Ref
Cracking	• Settlement • Ground deformations • Poor mortar preparation	1 to 4	✓	[38,39]
Moisture Penetration	• Highly permeable material • Humid environment • Freezing and thawing	1	✓	[40]
Bond Failure	• Adhesion lose within materials	2 to 4	✓	[41]
Displacement	• Inadequate anchors for lateral support • Corrosion of steel elements • Freezing and thawing	2 to 4	✓	[42]

Table 3
General classification of damage levels due to cracks in masonry structures.

Damage level	Description	Potential consequences
Negligible damage	Structures with hairline cracks (crack-width less than 0.1 mm) and differential settlement less than 3 cm fall under this damage class. The angular rotation of negligible crack damage is less than 1/300.	Dam- ages are non-structural. In a few cases, small pieces of plaster fall.
Slight damages	In this category, structures undergo a maximum crack width of 3 mm and a differential settlement of 4 to 5 cm. The angular rotation varies between 1/140 and 1/175.	Moderate non-structural damages are present in the masonry system. Cracks are apparent in most of the walls, as well as the crumbling of larger plaster pieces.
Moderate damage	The width of the cracks in this category varies from 5 to 15 mm. The differential settlement is between 5 and 8 cm, and the angular rotation changes from 1/175 to 1/120.	Most of the walls undergo extensive cracks. The structural damages are of moderate severity, whereas the non-structural damages are substantial. Additionally, failure of the non-structural components has been reported in some cases.
Severe damage	In severe damages, the angular rotation varies from 1/120 to 1/70, and the differential settlement is between 8 and 13 cm. Extensive cracks with 15 to 25 mm width are present.	Partial failure

represent an emerging technology with diverse potential applications in civil engineering. Visual inspection often presents challenges, especially when accessing inspection locations is difficult, poses safety risks for inspectors, or urgent reactive inspections are economically impractical. Introducing advanced technologies like drones in this context can bring substantial benefits. Drones offer advantages such as high speed, safety for workers, cost-effectiveness, instant data sharing with multiple stakeholders, and the ability to navigate through automated flights. Utilizing drones for visual inspection serves as the initial phase of a comprehensive survey campaign, allowing for the planning of further diagnostic investigations [48,49].

2.2.2. *Non-destructive testing (NDT) and minor destructive testing (MDT)*

NDT and MDT techniques enable the assessment of the in-situ condition, geometry, and engineering properties of existing masonry structures using minimal to no intrusion. A general overview of commonly used NDT and MDT methods for masonry structure assessment is presented in the following.

- **Flat Jack Testing:** An important aspect of evaluating existing masonry structures is estimating the level of compressive stress on the walls and pillars. In engineering practice, a combination of loads on a structure is commonly used to estimate compressive stress. Such calculations are usually subject to large margins of error due to the lack of accurate documentation of existing masonry structures. The flat-jack method is a practical MDT for assessing the stress state in masonry structures. Using this method, compressive stress levels are evaluated directly from in-situ testing [50–55].
- **Flat Jacks-Shear Compression Test (FJ-SCT):** The FJ-SCT method was developed utilizing flat jacks to apply horizontal loads. This approach greatly reduces the impact of the test, making the testing technique applicable to a wide range of existing buildings [56].
- **Impact Echo Testing:** Impact-echo testing is an NDT method based on multiple reflections of an acoustical wave between the test surface and an interface between materials with different mechanical impedances. An impact load is applied to the structure, and a receiver records the vibrations that result from the impact. A time domain waveform is produced as a result [57,58].
- **Ground-Penetrating Radar (GPR):** GPR is an NDT method that can provide information about internal damage, foundation conditions, embedded material thicknesses, and moisture zones [59,60].
- **Thermography:** Thermography is an NDT method for masonry wall evaluation. It has been shown to be practical for crack detection and localization in masonry walls [61–63].
- **Ultrasonic Pulse Velocity:** Ultrasonic Pulse Velocity (UPV) is an NDT technique widely used in laboratory-based investigations and on-site material characterization and damage assessment. It involves the transmission of high-frequency sound waves above 20 kHz through the tested structure in order to measure the velocity of the wave passing through the material [64,65].
- **Impulse Radar Testing:** The purpose of this NDT test is to detect subsurface delamination. It can also be used to detect internal cracks and voids. The impulse radar testing method can provide accurate images of the internal condition of elements and can be used for large surface areas [66].

- **Borescope Method:** The borescope method is commonly used to examine small voids or inaccessible areas. It can provide information regarding the depth of the outer layer of materials and may be used to examine the mortar between bricks or natural stones [67].
- **Operational Modal Analysis (OMA):** OMA, also known as in-operation modal analysis, output-only modal analysis, and ambient modal identification, is a technique employed to determine the modal parameters of a structure. This approach involves collecting vibration data while the structure is in its operational state. OMA proves particularly useful in situations where the structure is too large to be effectively excited artificially or when a complete system shutdown is not feasible. In OMA, modal parameters are identified based on ambient forces or forces generated by cyclic loads acting on the structure as the excitation source. As these excitations are not precisely known, OMA relies solely on measurable response data. Various algorithms are utilized to extract modal parameters, ensuring a comprehensive analysis [68,69]. The insights gained from OMA can contribute to more informed decision-making in maintenance, retrofitting, and seismic risk mitigation, ensuring the longevity and safety of masonry structures in diverse operational conditions [70].
- **Sonic Testing:** The sonic pulse velocity method is a non-destructive technique employed to diagnose existing masonry structures and assess the efficacy of interventions. Valluzzi et al. [71] presented a comparative study on the reliability of sonic pulse velocity as a non-destructive method for diagnosing in-situ masonry structures. The findings offered valuable guidance for optimizing sonic wave transmission tests in pre-existing masonry constructions. Focusing on seismic-vulnerable historic urban cores in southern Europe, Ortega et al. [72] determined that both flat-jack and sonic pulse velocity tests are effective for estimating the elastic properties of existing masonry. Their study offers a comprehensive dataset and insights into challenges associated with on-site testing. Sajid et al. [73] studied the construction industry in southern Asia and discussed the transition from burnt clay bricks to concrete masonry units.

2.2.3. Laboratory testing

Laboratory testing of masonry structures is conducted for different objectives as described in the following. Various test setups have been employed to characterize the tensile behavior of the unit-mortar interface [74,75]. These experiments include:

- bond-wrench flexural testing,
- three-point flexural testing,
- four-point flexural testing,
- tension testing,
- splitting test, and
- compression test of cylindrical samples core.

Furthermore, Frumento et al. [76], Stepinac et al. [77], Tomić et al. [78], Beyer and Dazio [79], and Bosiljkov et al. [80] provided valuable information about laboratory testing methods for masonry structures.

Establishing a uniform distribution of stress in masonry joints is crucial to meet their designed shear strength. However, due to equilibrium constraints, the joints experience non-uniform normal stresses, posing a challenge to achieving this objective. The composite material exhibits anisotropic behavior, influenced by the relationship between the loading direction and the material axes. Specifically, this involves the directions parallel and normal to the bed joints [81]. Determining the constitutive behavior of masonry under biaxial stress conditions is challenging solely based on its response to uniaxial loading. To address this, a biaxial strength envelope has been established by examining the effects of biaxial stress up to the peak stress. This characterization cannot be accurately described in terms of principal stresses due to the anisotropy of masonry [82,83]. The biaxial strength envelope of masonry can be defined in the following two ways:

1. The primary stresses, along with the angle of rotation between these principal stresses and the material axes and
2. the complete stress vector within a defined set of material axes.

Performing compressive strength tests is a straightforward and convenient method that offers valuable insights into the overall condition of the tested materials. However, correlating tensile strength with compressive strength poses challenges due to variations in factors like manufacturing processes, shapes, and materials [84]. Prior to the recent introduction of numerical techniques for masonry structures, the only relevant structural material property was considered to be the compressive strength in the direction perpendicular to bed joints. The stacked bond prism, a frequently used test, was employed to determine this uniaxial compressive strength. However, the impact of this type of sample on the strength of masonry remains unclear. It has been noted that the difference in elastic properties between mortar and unit serves as a precursor to compression failure. Additionally, uniaxial compression of masonry induces compression/biaxial tension and triaxial compression in the unit and the mortar, respectively [85,86]. The load-bearing capacity is notably affected by the resistance to compressive loads along the bed joints. Nevertheless, conventional masonry displays anisotropic characteristics, particularly in the reduced longitudinal compressive strength of its units caused by detrimental perforations [87].

Choosing the most effective testing method for masonry structures depends on various factors, including the structure's value, available budget, location, type of structure, available equipment and expertise, and the current condition of the structures. Despite these limitations, there is no universally recognized best testing strategy, as the effectiveness of methods varies from one structure to another.

2.3. Monitoring of masonry structures

SHM entails the ongoing and automated monitoring of structures through regularly sampled structural responses and operational environment measurements collected from an array of sensors. These measurements are then analyzed to assess the current condition and predict the future performance of a structure. [64,88]. Monitored data is additionally utilized for evaluating the condition, offering timely and dependable insights into the structural integrity following occurrences like earthquakes or blast loading [89]. Fig. 4 illustrates the different levels of SHM.

Over time, diverse SHM methodologies have been formulated, taking into account various forms of recorded data, including measurements of vibration or static responses [90,91]. From these structural responses, damage signatures are extracted, such as modal strain energy, precursor transformation, modal flexibility-based deflection, and curvature, Kolmogorov–Smirnov (KS) statistical test distance, and model residual errors [92]. In recent times, artificial intelligence, including neural networks and machine-learning-based algorithms, is being utilized to assess damage signatures for the final detection of damage [93]. Demonstrations have shown that SHM technology can offer substantial economic and life-safety benefits. However, due to the intricate nature of the problem, along with structural and environmental uncertainties, the practical application of SHM in the real world remains challenging and requires continuous research. Challenges in SHM include limited data from existing structures, financial constraints, a diverse range of systems, and the impact of environmental and operational conditions (EOCs) [94,95]. The presence of EOCs can have a considerable impact on the dependability and resilience of damage assessment technologies, potentially restricting their effectiveness. However, the performance of these technologies can be enhanced by employing more sophisticated SHM and NDT methodologies capable of adapting to varying EOCs [64]. Keshmiry et al. [96] delivered a comprehensive overview of the impact of EOCs on SHM and NDT systems. They discussed recent advancements in sophisticated sensing technology, signal processing, and analysis methods designed to mitigate the interference caused by

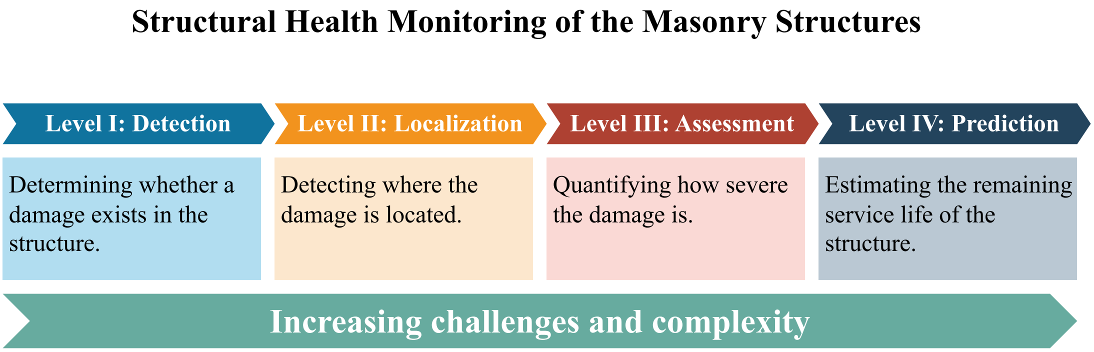


Fig. 4. SHM of the masonry systems.

EOC variations. Cavalagli et al. [97] summarized the results of the continuous dynamic monitoring of two iconic cultural heritage towers constructed from masonry. They emphasized that, even with a limited number of permanently installed accelerometers on-site, the detection of damage under varying EOCs can be successfully achieved with the assistance of statistical process control tools, even when lacking specific information on environmental conditions. Utilizing statistical tools such as Hotelling's T-squared distribution can contribute to the preventive conservation of heritage structures. Anwar and Abd Elwaly [98] employed modal displacement, modal curvature, and modal strain energy functions as indicators to identify cracks in masonry structures. They determined that all suggested metrics were appropriate for detecting damage. Their approach demonstrated effectiveness, particularly in scenarios involving multiple or inclined cracks. The utilization of curvature functions for identification proved more efficient than displacement functions when considering an equal number of monitoring points and crack severity. Nonetheless, accurately acquiring curvature information posed challenges for intricate structures with limited data. Notably, the accuracy of detection results improved as crack dimensions increased. Sansoni et al. [99] introduced an analytical approach utilizing the Simplified Lateral Mechanism Analysis (SLaMA) method to conduct seismic vulnerability assessments on URM structures. The methodology involves a structural discretization into an equivalent frame, considering pier, spandrel, and joint elements. It encompasses the following steps: (i) establishing moment–rotation capacity curves for each pier-spandrel subassembly, (ii) evaluating the strength hierarchy within each subassembly, and (iii) computing the structural capacity curve based on the anticipated failure mechanism. Validation of the proposed SLaMA-URM method was performed on a one-story URM substructure subjected to lateral cyclic loading, demonstrating its efficacy for seismic assessments of URM buildings. Rozsas et al. [100] proposed an automated Siamese convolutional neural networks (SCNN) approach to predict similarities in crack patterns which demonstrate a strong correlation with assessments conducted by structural engineers. Their results indicate that SCNNs can generalize well to unseen cases without compromising their performance. While the analysis was limited to synthetic images, the results are promising, demonstrating the general applicability of the approach. Table 5 presents recent research on the application of SHM to masonry structures.

Table 4 presents recent research on the application of SHM to masonry structures.

2.4. Artificial intelligence for masonry assessment

The application of AI in structural engineering has gained increasing attention in recent years [108]. According to recent research, AI offers superior efficiency and precision compared to traditional approaches. The exploration of AI for predicting the strength characteristics of masonry structures presents a promising avenue for future investigations. Numerous scholars have delved into the utilization of ML in assessing masonry structures.[109,110]. Loverdos and Sarhosis [111] aimed to address challenges related to the documentation of individual masonry units and cracks in structures by leveraging computer vision and convolutional neural networks (CNN). Notably, they introduced a novel approach, implementing a dynamic workflow that automatically detects masonry units and cracks. This automated process contributes to the creation of a comprehensive geometric digital twin. The resultant dataset comprises spatial coordinates and geometric entities that accurately depict the masonry structure, enabling a better understanding of the object for documentation and structural assessment purposes. This seamless integration across architectural, structural, and structural analysis models signifies a significant step towards utilizing engineering for the development of smarter, safer, and more sustainable future infrastructures. The innovative approach presented by Asjodi and Dolatshahi [112] introduced a new method for assessing the post-earthquake damage conditions of URM walls through the utilization of visual damage features. The authors utilized Tree-based ML regression models to establish a 3D fragility surface. This proposed methodology serves as a dependable foundation for conducting risk assessments of unreinforced masonry walls and has proven effective in generating comprehensive multi-variable 3D fragility surfaces. Table 5 presents applications of ML in masonry structures.

2.5. Smart materials

In recent years, there has been a notable emergence of innovative materials known as smart materials, which offer advantages across various industries compared to their traditional counterparts. These materials are also referred to as intelligent, adaptive, or active materials. The key distinction between smart materials and conventional ones, widely utilized for centuries, particularly in construction, lies in their capacity to react to changes in the environment and associated loads. Environmental loads encompass factors such as mechanical strain, alterations in magnetic or electrical fields, temperature variations, pH levels, light exposure, and moisture conditions [123]. Smart materials are categorized based on the nature of the loading they respond to and the corresponding reactions they exhibit. Examples include shape memory alloys [124], magnetostrictive materials [125], piezoelectric materials [126], and electrochromic materials [127].

Changes in the strain field occur when cracks initiate within a masonry structure, presenting an opportunity for utilizing strain-based SHM systems to detect damage. For this purpose, strain-sensing piezoresistive clay bricks, known as Smart bricks, can be employed [128]. Originally introduced by Downey et al. [129], smart bricks are characterized as piezoresistive burned clay bricks with inherent self-sensing capabilities, relying on observed variations in electrical resistance when subjected to external forces. Although conventional clay bricks can meet these criteria and serve as piezoresistive sensors, the incorporation of fire-resisting metals, carbon-based particles, and other additives can

Table 4
Recent studies on SHM of masonry structures.

Ref	Technique	Model	Description
[101]	Dynamic-based SHM	Church	The paper introduced a dynamic-based SHM strategy, implemented for the Saint Torcato church in Guimarães, Portugal. The church faces notable structural issues arising from soil settlements.
[102]	Based on the integration of traditional sensors consisting of crackmeters, servo-inclinometers, cable extension sensors, etc.	Heritage building	In this research, a comprehensive SHM system was created and utilized for a historical masonry building undergoing restoration. The structure underwent several structural alterations during the monitoring process.
[103]	Radar interferometry	Historic masonry bell tower	The suggested method utilized the identification of modal parameters to characterize the mechanical properties of the structure, including mass, damping, and stiffness matrices. This was achieved through OMA, utilizing measurements obtained from an experimental approach employing radar interferometry.
[104]	Static-based SHM	Medieval heritage and Church	This paper introduced a comprehensive automated data analysis method designed for full integration into static-based SHM systems. The approach employs dynamic linear regression models to effectively mitigate the impact of environmental variations on the analysis results.
[105]	Internet of Things (IoT)	Historical and cultural heritage	The paper provided an overview of IoT applications for SHM in masonry structures.
[106]	Wireless sensing	Historic masonry tower	This article examined a surveillance system consisting of micro-electro-mechanical sensors interconnected via a wireless network.
[107]	Capacitive Stress Sensors (CSS)	General masonry	The use of a low-cost CSS was investigated to detect the compression state level in mortar joints of masonry structures.

Table 5
Some of the studies on the applications of machine learning in masonry structures.

Ref	Objective	Model	Description
[113]	Defect surveying	Masonry wall	This paper introduced an approach for overseeing the condition of ashlar masonry walls in historical structures by employing reality capture techniques and data processing, which includes the utilization of ML.
[114]	Predicting compressive strength	Museum	ML techniques were evaluated as alternative techniques for predicting the compressive strength of masonry structures.
[115]	Period estimation	Masonry infilled RC frames	This study explored the applications of ML techniques in period estimation.
[116]	Deriving generalized temperature-dependent material models for concrete masonry units(CMU)	General masonry	A technique was introduced for developing comprehensive material models for Concrete Masonry Units (CMUs) that account for temperature variations. This approach utilized statistical, Bayesian methods, and ML.
[117]	Strength predictions of eco-friendly masonry units	General masonry	Artificial neural networks and statistical linear regression analysis were used to obtain more accurate properties to predict the compressive strength of alkali-activated soil.
[118]	Damage intensity assessment	Masonry buildings	This paper presented the results of comparative studies on the implementation of ML techniques for damage severity assessment of masonry buildings.
[119–121]	Seismic risk estimation	Masonry buildings	In this research, an analysis of 543 masonry buildings was conducted to identify the primary building characteristics influencing the seismic risk results. A new, efficient, and precise method for seismic evaluation was introduced.
[122]	Documentation of aging masonry infrastructure	Masonry infrastructure	This study sought to enhance the efficiency of documenting and evaluating aging masonry infrastructures by employing image-based methods and ML.

enhance their electro-mechanical characteristics. This approach surpasses the capabilities of ordinary distributed sensors, as Smart bricks seamlessly integrate into the structure [130].

In recent years, self-sensing structural masonry materials, such as smart bricks, have been proposed for SHM systems. When exposed to external loads, a smart brick changes its electrical resistance. It is both electrically and piezo-resistively conducting. Smart bricks are manufactured by mixing normal clay bricks with conductive or semi-conductive impurities. Such inclusions, however, must be able to endure the high firing temperatures that the brick is subjected to throughout the production process, for instance, titanium dioxide (titania) and micro- or microfibers made of certain metals that resist oxidation at high-temperature [128,131,132]. In contrast to vibration-based monitoring systems, static parameter-based techniques using smart bricks benefit from the capacity to discover local defects, even if they are not severe enough to affect dynamic responses [133]. Piezoresistive clay bricks are a type of smart brick with embedded electronics that can modify their electrical properties as their strain condition changes. This function may be used to analyze stress in critical parts of a brick wall and capture variations in loading patterns that signify structural deterioration, such as during an earthquake. The smart brick concept can surpass prior monitoring tools because it can deliver both high-fidelity measurements (the brick is deployed to capture brick strains) and long-term dependability (the sensor replicates the structural material's durability). At the same time, electrodes may be concealed by positioning them on the interior sides of the bricks. To assess the impact of installing smart bricks into a wall, Downey et al. [129] constructed a reduced-scale brick wall sample consisting of 35 bricks placed five bricks in width and seven in height layered with cement mortar roughly 0.5 cm thick horizontally and vertically. The wall was built with fine-grained Geolite mineral mortar and a semi-rapid setting. Meoni et al. [134] tested the strain sensing and damage detection capabilities of smart bricks in a masonry wall. The experiment used a hydraulic press and a shake table to simulate earthquake events and compared the strain data from the smart bricks before and after each event. The experiment also used a 3D FEM model to validate the results. The authors concluded that smart bricks can detect and locate seismic-induced damage in URM structures by revealing permanent changes in the structural characteristics.

An SHM system can further developed to a self-diagnosing system capable of detecting the presence of a fault or damage following a severe event such as an earthquake [131]. In this branch of SHM, the building material itself may be used for strain monitoring, resulting in a self-sensing structural material. Self-sensing structural materials have the potential to self-diagnose civil buildings, providing important information for structural retrofitting decisions [129,135].

Smart concrete technology entails integrating electrically conductive micron- or nano-sized inclusions within the concrete matrix to instil smart strain and damage-detecting capabilities. Carbon-based inclusions, for instance, carbon fibers, nanotubes, or carbon black, are especially common for this use, while metallic fibers and nickel powder can also be used [129,131].

3. Repair and retrofitting of masonry structures

Repair and retrofitting measures of masonry structures aim at mitigating the risks associated with natural disasters and the degradation of structures over time. These measures can further improve the load resistance and service life of the structures. Different objectives drive repairs and retrofitting efforts, such as eliminating structural problems or distress resulting from unusual loading and exposure conditions, inadequate design, and construction practices. Rectifying design or construction inaccuracies and increasing the strength of structural members are further aims of repair and retrofitting measures [136, 137].

Repair methods can be classified into the following three categories based on the repair impact [138–140]:

1. Surface repair methods are cosmetic repairs that improve the appearance of structures and restore the non-structural properties and environmental protection of damaged components, such as repointing and pinning.
2. Structural repairs intend to restore the structural properties of components, including injections of cracks and structural repointing.
3. Structural strengthening involves repairing or replacing structural elements to increase their load capacity and strength. Rather than adding new components, like bands, overlays, etc., the main objective is to retrofit the damaged structural components.

3.1. Surface repair methods

The objective of surface repair methods is to address any damage or deterioration present on the surface of unreinforced masonry walls by employing strengthening and repair techniques. Surface treatment methods are typically utilized for aged masonry buildings. Well-established surface treatment techniques are shotcrete, bamboo, and fiber-reinforced polymer (FRP), which are described in more detail below.

3.1.1. Shotcrete

Retrofitting with shotcrete significantly enhances the ultimate load of walls in terms of shear and flexural capacities, preventing future cracking and improving inelastic deformation capacity. Engineered Cementitious Composite (ECC) is a suitable material for seismic strengthening of Unreinforced Masonry (URM) walls, as shown by Lin et al. [141]. The study indicates diminishing returns with increasing ECC thickness for externally bonded shotcrete reinforcement on masonry wallets. However, ECC shotcrete effectively enhances in-plane strength and pseudo-ductility, with a 220% increase in average pseudo-ductility compared to as-built walls.

In another study, Lin et al. [142] employed ECC shotcrete and near-surface mounted steel bars for seismic strengthening of URM walls, significantly improving out-of-plane capacity. The researchers proposed a seismic design methodology based on conventional procedures to predict increased out-of-plane strength due to ECC intervention. Ghezelbash et al. [143] conducted shake table tests on a URM building, demonstrating effective bond and crack prevention by shotcrete, though concentrated cracks were observed at perpendicular wall connections.

Static cyclic tests by ElGawady et al. [144] revealed shotcrete retrofitting increased lateral strength by a factor of approximately 3.6, with double-sided retrofitting exhibiting more ductile failure. Shabdin et al. [145] explored the efficiency of traditional shotcrete for URM walls, finding it created stiff panels, prevented cracks, and increased strength, energy dissipation, and stiffness. However, in long-length walls, the failure mode shifted from shear sliding to rocking.

Rezaee et al. [146] investigated shotcrete retrofitting for seismic rehabilitation, finding it significantly increased lateral resistance and cyclic dissipated energy. Shotcrete-retrofitted specimens exhibited enhanced lateral strength and gradual post-peak strength deterioration. Huang et al. [147] combined experiments and simulations, showing that thicker sprayed mortar layers improved compression strength in URM retrofitting, contributing to elastic modulus improvement, but over-thin layers reduced the elastic phase range. Double-sided spraying had a significant impact on elastic modulus but not on ultimate strength.

3.1.2. Bamboo-band

Retrofitting masonry buildings with bamboo-band mesh significantly increases their seismic capacity. External reinforcement is provided by bamboo, which is used both vertically and horizontally in this retrofitting system. It was reported that the retrofitted masonry building by this method could withstand over twice the amount of input energy in comparison to a non-retrofitted sample. However, bamboo meshes cannot be adequately protected by the bricks surrounding them. This technique has several advantages, including its low cost and operational simplicity that eliminates the need for specialized labor [29]. The URM wallets were enhanced by incorporating bamboo fiber textile and affixing them onto the wall surfaces through the application of short bamboo fiber-reinforced geopolymer mortar, as documented by Libre et al. [148]. The study revealed that wallets reinforced on one side and both sides with textile exhibited an average increase in shear strength of approximately 24% and 35%, respectively. Additionally, the analysis of failure modes indicated that the typical failure in URM was characterized by running bond failure, whereas strengthened URM exhibited a columnar failure. These findings have potential implications for the development of textile-reinforced geopolymer mortar systems aimed at fortifying URM walls.

3.1.3. Fiber-reinforced polymer (FRP)

FRP, comprising a polymer matrix reinforced with fibers, is utilized to strengthen unreinforced masonry walls both in-plane and out-of-plane. Studies by Estevan et al. [149] indicate substantial improvements in strength using epoxy-bonded carbon FRP, particularly under static cyclic loading. However, cases of debonding were noted at lateral loads exceeding 50% of ultimate resistance, limiting its application on historical buildings. Mazzotti et al. [150] focused on GFRP sheets bonding with single clay bricks, emphasizing the relationship between bond strength and brick mechanical properties. They observed a stronger shear capability in the initial bonded section, leading to a softening branch in force–elongation diagrams. Analytical models proposed by Carozzi et al. [151] explained load transfer mechanisms between FRP reinforcements and masonry, incorporating bond length and width effects. Ghiassi et al. [152] studied debonding mechanisms in repaired FRP-strengthened masonry components, assessing the effectiveness of repair methods. Al-Jaberi et al. [153] demonstrated the effectiveness of FRP external bonding in enhancing the flexural capacity of reinforced masonry walls. Croce [154] introduced an innovative repair technique using composite fabric in mortar joints for historical structures, achieving stabilization and cohesion. While Dezfouli et al. [155] showed shotcrete reinforcement improves strength and ductility, it comes with drawbacks, making FRP plates a suitable alternative for seismic retrofitting due to their strength, low weight, corrosion resistance, and ease of implementation.

3.1.4. Textile reinforced mortar (TRM)

The growing requirement to enhance the structural performance of buildings and structures has been addressed through the introduction of newly developed TRM composites. This demand is particularly crucial for unreinforced masonry structures. In contrast to FRP, TRM incorporates high-strength fibers into an inorganic matrix. As a result, the matrix, usually consisting of cementitious mortar, provides compatibility with substrates, cost-effectiveness, superior performance at elevated temperatures, improved permeability, and reversibility. With these benefits, it is not surprising that TRM has garnered significant popularity for strengthening masonry structures [156]. Garmendia et al. [157] examined the performance of a strengthening system using basalt textile-reinforced mortar (BTRM) when applied to stone masonry arches. The study evaluated the suitability of three different analytical approaches for design purposes. The researchers established the main constitutive laws through testing both the primary materials and the BTRM composite. To determine the most appropriate analytical approach for design, a comparison between experimental and analytical results was carried out. In a similar vein, Papanicolaou et al. [158] investigated the use of TRM to improve the load-carrying capacity and deformability of unreinforced masonry walls subjected to cyclic out-of-plane loading. The study compared the effectiveness of TRM overlays with overlays or near-surface mounted (NSM) reinforcement of FRP. The results demonstrated that TRM jacketing significantly enhances the strength and deformability of the structure. In contrast to epoxy-resin-based FRP, TRM generally exhibits superior effectiveness in terms of both strength and deformability. Although NSM strips provide lower strength, they offer improved deformability through controlled debonding. The overall conclusion of the study is that TRMs show great promise as a solution for structurally enhancing masonry structures under out-of-plane loading.

Recent studies on the surface treatment of masonry structures are summarized in Table 6.

3.2. Structural repair techniques

This subsection delves into the details of various structural repair techniques tailored specifically for masonry structures. It focuses on methods and materials designed to address the unique challenges associated with masonry, such as mortar deterioration, brick or stone cracking, and structural instability. The subsection will explore common repair techniques like repointing, grouting, and reinforcement with materials such as helical ties or fiber-reinforced polymers in depth. It aims to provide insights into the application, benefits, and considerations associated with each technique for masonry repair. By examining these techniques closely, the subsection offers a thorough understanding of their role in ensuring the safety, reliability, and longevity of masonry structural components.

3.2.1. Stitching and grout/epoxy injection

The grout injection repair method is one of the most commonly used techniques in strengthening masonry structures. Typically, the method is employed for restoring the bond in the cracks of masonry structures. The advantageous factors of utilizing this technique include affordability, easy accessibility of the repair material, and operation simplicity. Additionally, the architectural aspect of the structure is not affected by grout injection rehabilitation. However, the method suffers from a significant disadvantage in terms of shrinkage [173–175].

3.3. Re-pointing

Generally, repointing has been used as a retrofitting technique, particularly on historic masonry structures. In this method, the mortar joints are washed, removed, cleaned, and a new mortar is replaced. The replacement mortar should be consistent with the properties of the masonry units, i.e. similar in mechanical properties and durability, and also resistant to mechanisms of deterioration. Steel bars are applied in the grout matrix across the joint cracks, which minimizes surface preparation and preserved aesthetics. Advantages include its low cost and ease of implementation [176–178].

3.4. Post-tensioning

Over the past decade, there have been significant advancements in the field of post-tensioning of masonry structures. There has been a substantial increase in the utilization of this method to strengthen existing structures and new constructions. In addition to increasing the ductility and strength of structures, post-tensioning reduces cracking deflection under service loads. Furthermore, the appearance of the structures is not altered by this technique. Nevertheless, the method has some drawbacks, such as its relatively high cost and the potential for causing shrinkage of the masonry. Moreover, post-tensioning elements are exposed to corrosion, and external straps and connections may affect the architectural aspects of the building [179,180].

3.5. Center core

The center core technique is an advanced non-destructive approach for strengthening unreinforced masonry structures, which allows for the strengthening process to be carried out without evacuating the structure. This method preserves the architectural aspect of a building while allowing external intervention. However, its major drawbacks are the requirement of highly skilled labor, high-tech equipment, and stringent quality supervision. Furthermore, the technique typically leads to areas with variable stiffness and strength characteristics [29,181].

3.6. Confinement

In this technique, the tying of columns is employed to confine and strengthen a masonry structure at its corners, junctions, and boundaries of openings. This approach enhances the in-plane deformability and energy dissipation of the structure. Additionally, in-plane shear strength, ductility, and flexural strength are enhanced through this method [182–184]. The research conducted by Gul et al. [185] investigated enhancements in seismic characteristics of self-interlocking mortarless masonry through the implementation of corner confinement. The evaluation

Table 6
Recent studies on surface treatment.

Ref	Technique	Model	Description
[159]	FRP composites	General	This report provided a summary of research investigations and practical implementations related to the reinforcement of masonry using FRP composites.
[160]	Water repellents, consolidants, and combinations of the both	School building	A study was undertaken to assess the origin of a leak and the possible efficacy of four potential surface treatments aimed at sealing or consolidating bricks.
[161]	Composite grid reinforced mortar	Masonry walls	This research examined how the structural characteristics of masonry walls without reinforcement were affected when enhanced with layers of mortar reinforced with composite grids.
[162]	Bamboo band, FRP, and shotcrete	Masonry brick walls	This research investigated techniques for enhancing the seismic resilience of masonry brick walls, discussing their benefits, disadvantages, and constraints.
[163]	Hydrophobization	Historic masonry	In this study, the scientists examined and assessed the impact of different water repellents commonly employed in commercial applications on the hydration mechanism of Roman cement mortars.
[164]	Fiber-reinforced lime-based mortars	Ancient masonry	This investigation examined the physical–mechanical characteristics and microstructure of lime-based hydraulic mortars reinforced with fibers, aiming to formulate binding substances for the preservation of historical structures. The results were contrasted with those of a hydraulic lime-based mortar devoid of any additives.
[165]	Basalt fiber reinforced natural hydraulic lime mortars	Typical masonry	This research examined the physical and mechanical characteristics as well as the microstructure of mortars composed of hydraulic lime reinforced with basalt fibers.
[166]	FRP	Brick masonry	The effect of mechanical surface treatment on the bond durability was investigated.
[167]	Silane/siloxane blend liquid & cream and acrylic & stearate-based liquids	Brick masonry	This article examined the results obtained through a set of benchmark tests designed to assess hydrophobicity, water absorption, and water vapor transmission in compliance with established codes. The purpose was to evaluate the impact of waterproofing on the hygric behavior alteration in brick masonry.
[168]	FRP	General	This paper presented a study on the characterization of the bond behavior using innovative surface treatment techniques.
[169]	Shotcrete	Masonry infill walls	The study investigated the performance of masonry walls retrofitted with shotcrete applied either in front of or behind the wall facing the explosion source.
[170]	Shotcrete	U-shaped masonry walls	This experimental study focused on examining the effects of reinforcing U-shaped masonry walls using polypropylene fiber dry-mix shotcrete.
[171]	TRM	URM walls	This work experimentally investigated the application of a novel system that combines TRM with thermal insulating materials for the structural, including seismic, and energy retrofitting of masonry walls.
[172]	TRM	Masonry panel	This article experimentally investigated the use of three types of TRMs (steel, carbon, and basalt textiles) embedded in cement mortar matrices as shear reinforcement for masonry panels.

encompassed various seismic parameters, such as lateral load-carrying capacity, energy dissipation, displacement ductility, structural stiffness, response modification factor, and performance levels. The findings from the experiments indicated that introducing corner confinement to dry stacked masonry significantly increased the ultimate lateral load and drift capacity by 64% and 288%, respectively. Sheikh [186] reported the effect of openings (windows) on the earthquake-resistant behavior of confined masonry structures. The researcher concluded that the window should be placed as far from the center location of the wall panel as possible. Placing windows closer to the center can otherwise affect the diagonal strut action of the masonry wall panel and hence reduce its seismic performance. Al-Jaberi and Myers [187] investigated the efficiency of using different types of advanced composite in confining masonry columns. According to the results, all types of advanced composites provided a significant increase in the ultimate strength capacity. The behavior of the masonry columns was found to be significantly influenced by the type of fabric used. Cascardi et al. [188] analyzed and reported the results of experiments conducted on masonry columns confined with Fiber-Reinforced Cementitious matrices (FRCM) under a centered compression test. The primary objective of their study was to assess the influence of the inorganic matrix in determining the efficacy of FRCM confinement. Koutas and Bournas [189] explored the confinement of masonry columns using jackets made of TRM to improve their axial load-bearing capacity and deformability. Based on the findings, the authors reported that TRM jacketing showed promise as an effective solution for confining masonry columns.

3.7. L-shaped reinforcement

Using L-shaped reinforcement can improve the strength of an unreinforced masonry structure by strengthening its junction, the most vulnerable part of a masonry wall. Steel bars are used in alternate layers for L-shaped reinforcement to strengthen the junction. The L-shaped composite material strengthening system offers high flexural strength and shear strength, leading to improved strength and stiffness in the in-plane direction. However, it was reported that this technique can lead to corrosion [30,190].

Table 7 describes recent studies on repair and strengthening methods.

Table 7
Recent studies on repair strengthening techniques of masonry structures.

Ref	Technique	Model	Description
[191]	Repointing	Fair-faced masonry structures and historic buildings	This study provided an overview of diagonal compression tests carried out on masonry elements that were reinforced through structural repointing, as documented in the existing literature.
[192]	L-Shaped Reinforcing	Masonry structures with Openings	The seismic behavior of masonry structures with openings was investigated.
[193]	Post-tensioning	Arch footbridges and anti-funicular structures	This paper reported the potential of masonry structures as a primary load-bearing material when combined with post-tensioning.
[194]	Grout Injection	Traditional masonry walls	The main objective of this article was to experimentally and numerically study the improvements introduced by the grout injection strengthening technique.
[195]	Confinement	Confined masonry	In this research, a simplified macro-element model, utilizing smeared crack and total stress–strain models, was employed to analyze a prototype structure of CM in a benchmark setting.
[196]	Center-core	Unreinforced masonry walls	The in-plane nonlinear behavior of two full-scale unreinforced masonry wall specimens, retrofitted with three and five reinforced cores were tested under experimental cyclic loading.

3.8. Comparison of various repair and retrofitting techniques for masonry structures

The selection of the most effective repair and retrofitting method for masonry structures is influenced by various factors, including the structure’s value, budget, location, type, equipment, and expertise. Although the limitations discussed above are significant, the most optimal strategy for repairing and retrofitting a masonry structure is structure-dependent. This section provides a comparison table, including the advantages and disadvantages of various repair and retrofitting methods for masonry structures. Moreover, related references to further studies are cited in Table 8.

4. Case studies

Case studies provide valuable learning experiences. In the case of masonry structures, applying an ineffective assessment, repair, or retrofitting technique can result in irreversible damage to cultural and historical heritage. Learning from case studies mitigates such risks. Hence, the following section presents several case studies on real-life examples of repair and strengthening applications for masonry structures.

4.1. Madonna del Carmine Historical Church [217]

The Madonna del Carmine Church, constructed in the 18th century, is a masonry edifice featuring irregular stone walls connected at the corners. The building includes a system of non-load-bearing decorative vaults and a relatively recent wooden roof. The façade, rising to a height of approximately 24 m, exhibits an arched design with walls of varying thickness along its height. The floor plan encompasses a single hall with three apses, and the presbytery is elevated above the nave floor. The layout is an elongated and irregular octagon, with three semi-cylindrical volumes attached, of lesser height than the central body—two along the transverse axis and one at the longitudinal axis endpoint. A prolonged pavilion vault, octagonal in shape, covers the central nave, while the side apses are topped with vaulted ceilings and linked to the central body through arch structures.

4.1.1. Point cloud survey, MDT, and NDTs

The intricate architectural design of the church poses challenges for accurate manual surveys. To overcome this, a photogrammetric survey was conducted, yielding precise 3-dimensional geometry of the building. Subsequently, this data was employed to generate detailed drawings and structural models with high precision. Fig. 5 illustrates the survey stations and presents the final 3D view of the Point Cloud Model (PCM), achieved through the utilization of Autodesk Recap Pro software.

Various NDT and MDTs were conducted to assess the quality of the masonry, in addition to visual inspections. The primary examinations included both single and double flat jacket tests (FJ), pulse velocity tests (PS), and endoscopies (PE). In order to reconstruct the composition and assess potential deterioration mechanisms, some masonry cores were extracted, and mortars from the joints were analyzed. Fig. 6 provides a visual representation of the test locations.

4.2. Hocailyas school building [218]

Hocailyas Secondary School is located in western Türkiye, covering an area of 340 m^2 (Fig. 7).

This structure features a load-bearing masonry framework. The outer walls, constructed in a rectangular fashion, incorporate a combination of irregularly arranged stone and blended brick. Independent of the outer walls, intermediate partition walls were erected using load-bearing elements composed of adobe-filled timber and adobe-filling material. Both the inner and outer walls of this masonry construction were crafted using limestone and solid brick, bound together with lime mortar. The interior walls underwent plastering with a cement-based substance, followed by a whitewash finish. Topping the building is a hipped roof adorned with Marseille tiles. Positioned on level ground, the structure comprises rectangular ground and first stories. The floor structure of these levels consists of plank coating on timber beams. Notably, there are no adjacent structures nearby, as the building stands on its own foundation. All facades received a coating of cement-added mortar, with the ground story exhibiting a cut stone appearance and the first story displaying an alternating pattern of masonry brick and stone. The exterior walls, originally constructed with a combination of stone and brick using lime mortar, were subsequently plastered with cement-added mortar.

4.2.1. Laser scanning

To gain a comprehensive understanding of the structure and identify both exterior perspectives and inappropriate alterations, the three-dimensional laser scanning technique was utilized. The integrated GPS receiver within the laser scanner facilitated the alignment of individual scans during post-processing. The resultant images, generated through

Table 8
Advantages and disadvantages of various repair and retrofitting techniques.

Technique	Advantages	Drawbacks	ref(s)
FRP	• Enhanced resistance • Simple operation • Increased ductility	• High-cost • High electric conductivity	[197,198]
Shotcrete	• High deformation • High stability e • High ultimate load	• Potential for rebound and dust generation • High mass	[199,200]
Bamboo	• Sustainability • High strength • High input energy	• High disturbance • Affects architecture	[201,202]
Stitching and grout injection	• Simple operation • Preservation of architectural aesthetics • Minimal cost	• High degradation • High shrinkage • Irreversible action	[203,204]
Re-pointing	• Minimal cost • Low deformation	• Lead corrosion	[205,206]
Post tensioning	• Increased ductility • Easy application Reduced cracking	• Costly • Shrinkage and creep • Corrosion • Anchorage problem	[207,208]
Confinement	• High energy • Improved ductility • Increased flexural strength	• Labor intensive • Significant disruption • High cost	[209,210]
Center core	• Safe resistance • Preservation of original appearance	• High cost • High technology requirements	[196,211]
L-Shaped Reinforcement	• High resistance • High strength	Corrosion	[192,212]
Steel bars	• Improved structural behavior	• Loss of historical material • Risk of corrosion	[213,214]
3D Tying System	• Increased ductility • High energy dissipation	• Risk of corrosion	[138,215]
Box action	• Enhanced lateral load resistance • Improved In-Plane Capacity of Walls	• Increased design complexity • Potential architectural design restrictions	[216]

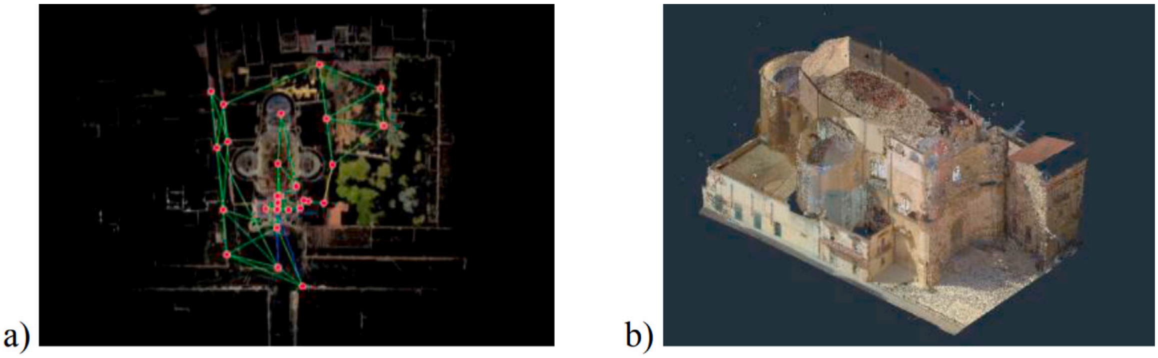


Fig. 5. Photogrammetric survey stations (a) and PCM view (b), [217].

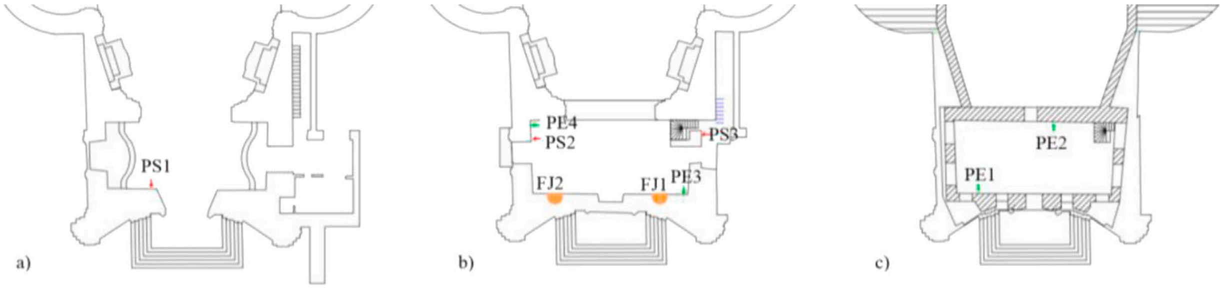


Fig. 6. Positions of the flat jacket (FJ) tests, pulse velocity (PS) and endoscopies (PE), [217].

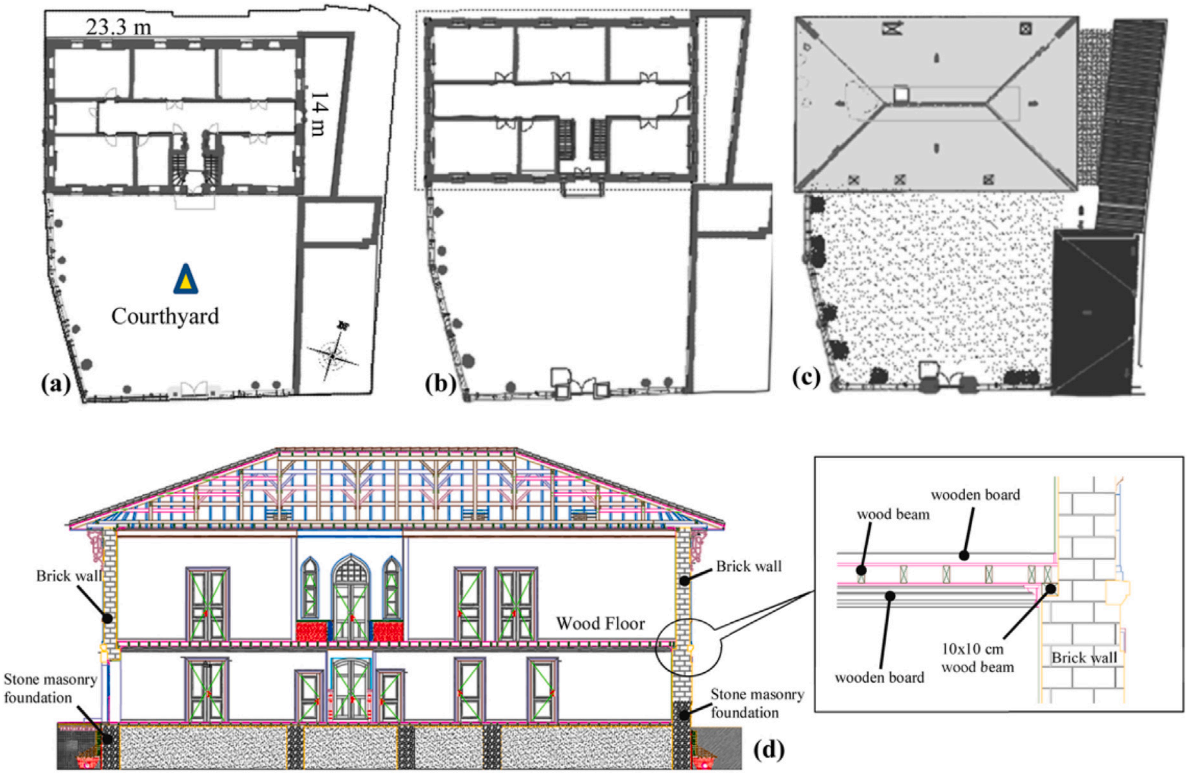


Fig. 7. Floor plans, top and side view of the Hocailyas secondary school. (a) Ground floor, (b) first floor, (c) top view (plot dimensions: 26.1 m × 35.3 m), and (d) side view and cross-sectional structural details of the building [218].

this methodology, are depicted in Fig. 8. Noteworthy findings include surface pollution on the facades, erosion of limestone material, and the presence of mixed bricks on unplastered walls. Additionally, the building exhibited signs of degradation and deformations caused by moisture. Notable interventions encompassed cement mortar applications on lower levels and the incorporation of various elements such as electrical wiring, lighting fixtures, and security cameras. Specifically, the primary degradation observed on the northern facade involved the pergola roof of the cafe and the teacher's lodge, significantly disrupting the facade's aesthetic and rendering it obscured.

This section is followed by two tables of case studies. Table 9 presents several case studies on the assessment of masonry structures. This table includes various information on the case studies, such as year, location, objective, etc. Table 10 presents the same information on the repair and retrofitting of masonry structures.

Fig. 9 illustrates the distribution of the case studies reviewed in Tables 10 and 9.

The assessment and repair of masonry structures represent critical efforts in preserving cultural heritage and ensuring structural safety, particularly in earthquake-prone regions. A comprehensive review of recent case studies in the above tables reveals a multifaceted approach employed by researchers. In terms of geographical focus, Italy and Türkiye emerge as key hubs for both assessment and repair/retrofitting initiatives. This concentration could be attributed to the rich historical heritage and susceptibility to seismic events in these regions. Additionally, notable contributions from countries such as Greece, Spain, and the United Kingdom underscore the global significance of masonry structure preservation endeavors. Objectives vary across case studies, with seismic assessment and evaluation being predominant, followed by investigations into damaged conditions and vulnerability assessments. Dynamic identification, NDT, and structural vulnerability assessment also feature prominently, reflecting the diverse challenges addressed by the community. Structurally, towers and churches are frequently assessed, highlighting their historical significance and vulnerability to seismic activity. Additionally, mosques and institutional buildings are common targets for repair and retrofitting, emphasizing the need to safeguard various types of masonry structures. A wide array of methodologies is employed in these endeavors, ranging from nonlinear FEA and seismic performance evaluation to laboratory testing and NDT techniques such as GPR and thermography. The integration of traditional techniques with modern technologies like wireless sensing and machine learning underscores the multidisciplinary approach applied by researchers. These efforts contribute to the preservation of cultural heritage and the enhancement of structural resilience in the face of seismic hazards.

5. Future trends

The following section provides an overview of future trends in assessment, repair, and retrofitting methods for masonry structures and explores potential advancements and innovations that may shape the field in the coming years. It highlights emerging technologies, methodologies, and approaches that could revolutionize the way masonry structures are assessed, repaired, and retrofitted, leading to improved performance, durability, and sustainability.

1. Non-Destructive Testing (NDT): The development of more advanced NDT techniques such as ground-penetrating radar (GPR), terahertz imaging, and enhanced ultrasonic techniques have the potential to provide more accurate and detailed information about the internal condition of masonry structures. GPR utilizes electromagnetic waves to image subsurface objects and can identify defects such as voids, cracks, or reinforcement placement. Terahertz imaging utilizes terahertz waves to detect hidden moisture and delamination within the masonry. Advanced ultrasonic techniques involve the use of high-frequency sound waves to evaluate the quality and integrity of masonry. These advancements in NDT can significantly enhance the assessment process, increase the reliability of data, and support targeted repairs and retrofitting strategies.

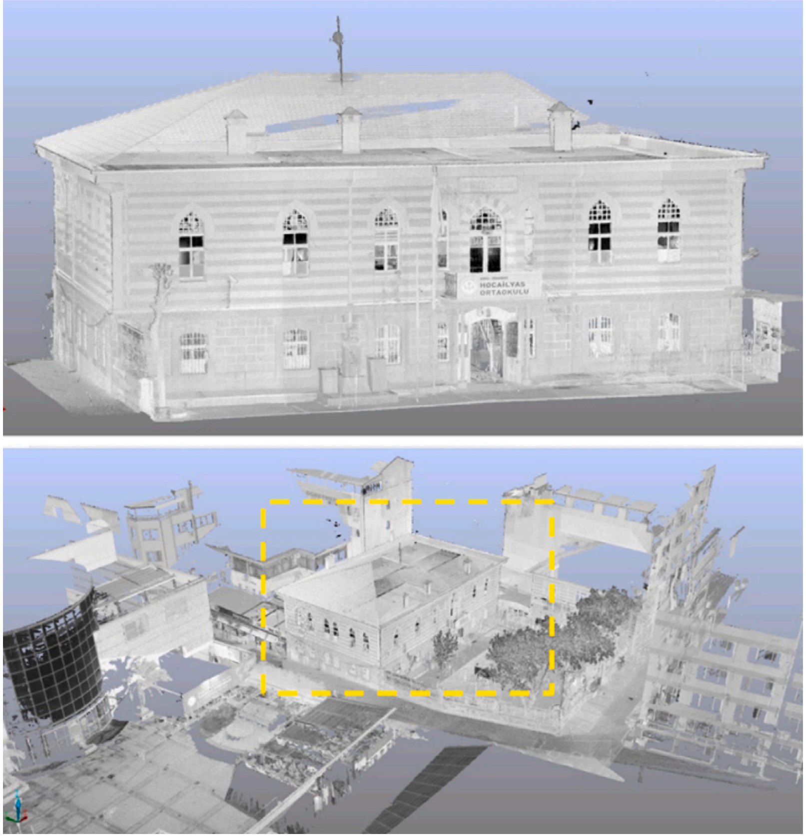


Fig. 8. 3D laser views of the building, [218].

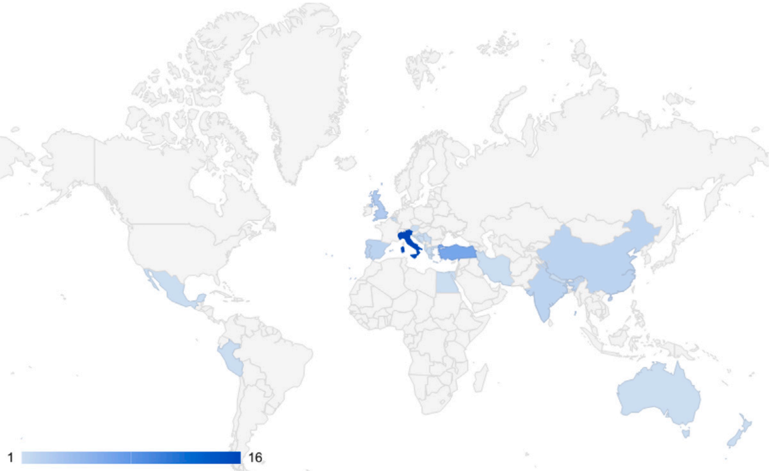


Fig. 9. Distribution map of the case studies reviewed in Tables 10 and 9.

2. Unmanned Aerial Vehicles (UAVs): The utilization of UAVs equipped with thermal imaging cameras, LiDAR sensors, or photogrammetry techniques for conducting visual inspections of masonry structures is currently an active field of research. UAVs provide safe and efficient means of accessing difficult-to-reach areas, reducing the need for manual inspections. Thermal imaging cameras can detect variations in surface temperatures, helping identify areas of potential moisture intrusion or insulation problems. LiDAR sensors capture detailed 3D point cloud data, enabling precise measurements of the structure and identifying surface deformations or cracks. Photogrammetry techniques use high-resolution images to create accurate 3D models of the masonry, aiding in condition assessment and visualization of defects. The use of UAVs in masonry inspection can significantly improve efficiency, lower costs, and provide valuable data for targeted repair and retrofitting solutions.
3. SHM systems: The integration of SHM systems using sensors, data acquisition systems, and advanced data analysis techniques to continuously monitor the structural behavior of masonry structures presents another future opportunity to prolong the life of historic structures. These systems provide real-time data including vibration, strain, and environmental measurements. By monitoring the structural health over time, SHM systems can detect changes, identify potential damage or deterioration, and provide early warnings of structural issues. This enables

Table 9
Recent case studies on assessment of masonry structures.

Ref	Year	Location	Objective	Structure	Method	Description
[70]	2010	Portugal	SHM	Tower and church	Operational modal analysis	This research aimed to investigate the early-stage assessment of damage in masonry structures using vibration signatures as an integral component of an SHM procedure, with the objective of safeguarding historical constructions.
[219]	2010	India	Seismic assessment	Tower	Parametric analysis considering Tensile strength and fracture energy, damping, mass and stiffness proportional damping.	This paper described the numerical seismic assessment of the Qutb Minar in Delhi, India.
[220]	2012	Iran	Investigating lateral performance and load carrying capacity	Vault with adobe piers	Nonlinear FE analysis and experimental tests	This research examined how a historic brick vault, supported by adobe piers, behaves structurally and resists lateral forces when retrofitted with Carbon Fiber Reinforced Polymer (CFRP).
[221]	2012	Austria	Seismic assessment	Building	Rapid visual screening	The study focused on evaluating structure-relevant parameters and assessing the human and economic impact of earthquake-induced damage. By classifying buildings into vulnerability classes, the research provided insights for emergency planning and identifies critical objects susceptible to seismic loading.
[222]	2013	Italy	Analysis and repair	Building	Vulnus method	This research conducted a preliminary investigation of a group of buildings located in the historical city center of L'Aquila, which suffered damage from the earthquake that occurred in April 2009.
[223]	2014	Spain	Evaluation	Building column	GPR	This work presented the study of one column by using GPR combined with seismic tomography, under laboratory conditions.
[224]	2015	Italy	Dynamic identification	Bell tower	MEMS-based acquisition system	This paper reported the results of dynamic tests performed on a bell tower.
[225]	2016	Türkiye	Seismic performance evaluation	Tower	Multiple	This paper primarily explores fundamental principles essential for conducting a performance-based seismic assessment of historical structures.
[226]	2017	Greece	Seismic and restoration assessment	Church	Multiple	This study presented a new stochastic computational framework for seismic and restoration assessment of masonry structural systems.
[227]	2018	Australia	Vulnerability assessment for mine blast-induced vibrations	Building	Parametric analysis	This paper presented a method to assess the vulnerability of heritage masonry buildings to mine blast-induced vibrations. The approach offers valuable insights for both structural and blast engineers in understanding the effects of blasting on heritage structures.
[228]	2019	Italy	Integrating NDT, thermography, and numerical modeling for damage assessment	City hall building	Multiple techniques	The aim of this work was to illustrate the importance of integrating documentation, NDT, and numerical modeling for damage assessment of heritage structures.
[229]	2020	Italy	Testing shear characteristics	Building	Flat jack testing	This paper presented the evaluation of the seismic behavior of existing buildings.
[230]	2020	Italy	Continuous SHM	Tower	Wireless sensing	This article examined a surveillance system comprising micro-electro-mechanical sensors linked via a wireless network.
[231]	2020	Türkiye	Restoration	University building	Thermography and laboratory testing	This paper presented a detailed description of the restoration works, which were based on the original geometric and material properties.
[114]	2020	India	Evaluation	Museum	ML techniques and laboratory testing	This research investigated the suitability of three machine learning approaches as alternative means for forecasting the compressive strength of masonry structures.
[232]	2021	Türkiye	Seismic assessment	Mosque	Multiple techniques	This study conducted a seismic evaluation of a restored mosque located in Bigali Castle, which was originally constructed in the early 1800s.
[233]	2021	Italy	Seismic vulnerability assessment	Urban center	Multiple	This study demonstrated the implementation of three widely recognized methodologies in assessing the medieval city of Campi Alto di Norcia in Valnerina, Italy, which was affected by the earthquakes on August 24 and October 30, 2016.
[234]	2021	Peru	Assessment	Dwellings	In-situ survey and laboratory testing	The paper summarized an in-depth survey to collect structural data on buildings in Cusco. This data was used to create an empirical model for seismic vulnerability assessment, adapted from one used in Italian historic centers.
[235]	2021	Mexico	Assessment	Building	Displacement ductility demand spectra (DDDS) comparison for both earthquake ground motions records and artificial acceleration records	This study calculated DDDS to assess seismic vulnerability in masonry structures of different heights. It examines earthquake ground motions and artificial acceleration records across various base shear capacities, with particular attention to linking observed damage with structural irregularities.
[236]	2022	Romania	Assessment	Building	In-situ PEST (the Romanian acronym for Method of Assessing the Technical Condition)	This paper introduced a revised PEST method for building condition assessment, aligning with national norms. It aimed to enhance assessment consistency, aiding inspectors in evaluating damages and establishing degradation classes for structural and non-structural components.
[217]	2023	Italy	Modal characterization and NDT	Church	MDT, NDT, FE analyze	This study outlined the practical investigations conducted on a historic church, placing significant emphasis on the examination of its exterior frontage.
[237]	2023	Italy	Structural assessment	Building	Normative references, NDT, and MDT	This paper aimed to contribute to the discussion of the experimental campaigns on cultural heritage buildings.
[238]	2023	Europe	Evaluation	Church	Laboratory testing	This study examined the masonry cloister vault of a historic structure to gather information on the distinctive deformation features exhibited by the aged masonry.
[239]	2023	Croatia	Resistance evaluation	Museum building	Flat-jack test	The paper explored reliability approaches for evaluating the resistance of a cultural heritage building, using data from standards and flat-jack tests.

Table 10
Recent case studies on repair and retrofitting of masonry structures.

Ref	Year	Location	Objective	Structure	Method	Description
[240]	2011	Portugal	Seismic rehabilitation	Building	Multiple techniques	This research paper conducted a comparison analysis of various seismic retrofitting methods applied to simulate an already constructed masonry building.
[241]	2011	Belgium	Characterization of repair mortars	Church, castle ruins, abbey	A systematic approach	Historic mortars and repair mortars were analyzed in terms of a chemical, mineralogical, and physical point of view.
[242]	2012	United Kingdom	Repair	Natural stone	Plastic repair	The objective of this paper was to explore the perceptions surrounding the appropriateness of various materials for use in a repair.
[243]	2013	Türkiye	Strengthening	Mosque	externally bonded textile-reinforced mortar (TRM)	This work described the strengthening process of a historical Mosque with externally bonded TRM.
[244]	2014	United Kingdom	Strengthening	Cross vaults	Reinforcing mesh	This article discussed the enhancement of masonry cross vaults that have suffered from geometric instability.
[245]	2014	Italy	Pre-qualification of repair mortars	Sacro Monte di Varallo Special Natural Reserve	Multiple techniques	A novel laboratory method for the pre-approval assessment of repair mortars was elucidated.
[246]	2017	Italy	Seismic vulnerability assessment and retrofitting	Building	Multiple techniques	In this paper, the usability check and the seismic vulnerability appraisement and repairing of a masonry building were reported and discussed.
[247]	2018	United Kingdom	Repair and maintenance	Palace	TLS	This study introduced a novel algorithm designed for the automated segmentation of individual masonry units and mortar regions within digitized rubble stone constructions. The algorithm utilizes geometrical and color data obtained through TLS devices.
[248]	2019	Italy	Retrofitting	University hall	Buckling restrained braces and pre-tensioned steel ribbons	This work summarized the theoretical conception and underlying design philosophy of the seismic retrofitting of the case study.
[249]	2019	Türkiye	Seismic retrofitting	Mosque	Multiple techniques	In this study, the seismic performance of a historical mosque was assessed both before and after retrofitting.
[12]	2020	Bosnia	Reconstruction	Multiple	Reconstruction and anastylosis	This paper discussed the challenges and justification of the reconstruction of built heritage in Bosnia.
[250]	2020	Italy	Seismic assessment, repair, and strengthening	Tower	Multiple techniques	This paper provided a comprehensive examination, encompassing on-site diagnostic investigations, seismic assessment, and non-invasive strengthening, of an ancient masonry tower located in Torre Orsaia, Southern Italy.
[251]	2020	Spain	Retrofitting	U-shaped masonry structure	TRM and Laboratory testing	This paper presented the experimental results obtained from tests on a U-shaped masonry building.
[252]	2020	China	Restoration	Relic	Sticky-rice lime binders	In this research, an extensive characterization was conducted on a series of sticky-rice lime binders obtained from thirteen ancient masonry relics originating from three regions spanning the 16th to 19th centuries.
[253]	2021	Nepal	Performance evaluation of strengthening options	Institutional buildings	Multiple techniques	This study presented a new integrated strengthening option for masonry building.
[254]	2022	Italy	Multi-objective	Building	Multiple techniques	In this paper, the seismic vulnerability appraisement, together with repairing and consolidation operations, of a masonry building with cultural and artistic value were reported and discussed.
[26]	2023	Serbia	Seismic Retrofitting	Building	RC jackets along the facade	This study showcased a case study involving an URM building that suffered damage during the 2010 Kraljevo earthquake and was subsequently subjected to retrofitting.
[255]	2023	Türkiye	Seismic performance evaluation and strengthening	Building	FE analyses and textile reinforced mortar	This paper presented a seismic assessment of a reconstruction project involving a historic masonry building constructed in 1866, which was subsequently demolished in the 1940s.
[256]	2023	Italy	Retrofitting	Multiple churches	Multiple techniques	This paper offered a comprehensive review critically analyzing the primary interventions implemented in the churches of Central Italy to mitigate seismic vulnerability and assess their overall effectiveness.
[218]	2023	Türkiye	Seismic performance assessment and retrofitting	School building	Multiple techniques	This study elucidated every phase involved in the restoration of a masonry building, encompassing the assessment of its seismic performance following restoration. Subsequently, a seismic retrofitting proposal was formulated in alignment with the findings.
[257]	2023	Romania	Rehabilitation and restoration	Opera house	Laboratory testing, thermography, surface treatment, grout injection	This paper aimed to address the subject of the deficiencies faced by the materials that make up the facade of the historic masonry building.
[258]	2023	China	Repair	Building	Mechanical physical methods and chemical injection methods	This paper described a study of two methods currently in use for repairing damp-proof layers in such buildings in Shanghai, China.
[259]	2023	Italy	Strengthening	Building	Multiple techniques	This research aimed at investigating the effectiveness of a minimally invasive strengthening technique used to repair a full-scale two-story building.
[260]	2023	New Zealand	Retrofitting	Building	Shotcrete, post-tensioning, and Plywood diaphragms with tie rods	This study examined the potential of integrating deep energy retrofit with seismic strengthening in historic buildings, particularly focusing on unreinforced masonry structures in Aotearoa New Zealand.
[261]	2022	Albania	Retrofitting	Stone masonry tower	Digital surveying, NDT, and nonlinear structural analysis	This paper presented the seismic retrofit of the Ottoman fortress of Gjirokastra. Through comprehensive inspection and analysis, including non-destructive tests and finite element analysis, effective strengthening solutions were determined.
[262]	2018	Egypt	Retrofitting	Building	Timber bracing system	This research focused on analyzing the installation of a straightforward and sturdy timber bracing system above timber boards and beneath flooring layers of timber flat roofs. The aim was to enhance the seismic behavior and stability of historical load-bearing masonry buildings in Cairo.

proactive maintenance and repair strategies based on actual performance data, optimizing the lifespan and resilience of masonry structures. The implementation of SHM systems can enhance safety, reduce maintenance costs, and facilitate informed decision-making for repair and retrofitting interventions.
4. Advanced repair techniques: The adoption of advanced repair techniques such as 3D printing of masonry elements, fiber-reinforced polymers (FRPs), and smart materials. 3D printing of masonry elements allows for precise fabrication and customization of complex shapes, enabling efficient and cost-effective repairs. FRPs, such as carbon or glass fiber composites, offer high strength-to-weight ratios and corrosion resistance, making them suitable for reinforcing masonry structures. Smart materials, such as shape-memory alloys or self-healing concrete, have the ability to sense and respond to changes in their environment, improving the durability and functionality of repaired masonry. These advanced repair techniques enhance efficiency, durability, and sustainability while minimizing disruption to the structure. By embracing these innovative methods, the repair and retrofitting of masonry structures can be carried out more effectively and with improved long-term performance.
5. Sustainable retrofitting solutions: The integration of eco-friendly and energy-efficient solutions in masonry structure retrofitting approaches can improve their environmental performance, enhance energy efficiency, and contribute to overall sustainability goals. This includes the use of renewable energy systems, green roofs, and innovative insulation materials. Renewable energy systems such as solar panels or wind turbines can be integrated into masonry structures to reduce energy consumption and promote sustainability. Green roofs, consisting of vegetation layers, provide thermal insulation, stormwater management, and biodiversity benefits. Innovative insulation materials, such as aerogels or vacuum-insulated panels, offer improved thermal performance with reduced thickness, minimizing energy losses.
6. Smart materials: Smart materials can serve as advanced functional components and essential elements for imparting intelligent functions to structures. Technologies employing smart materials prove beneficial for both new and existing constructions. However, additional research is needed to refine the design guidelines of these systems. The establishment of codes, standards, and practices is integral for the continued advancement in this field.
7. Digital Twin technology: The development and implementation of digital twin technology to masonry structures enables the real-time monitoring, analysis, and simulation of the structural behavior, facilitating data-driven decision-making for maintenance, repair, and retrofitting. By continuously collecting data from sensors and monitoring systems, digital twins can create virtual replicas of physical masonry structures. Digital twins provide insights into the performance, degradation, and structural response to various load and environmental conditions. This enables proactive maintenance planning, predictive modeling, and optimization of repair and retrofitting strategies. By integrating digital twin technology, stakeholders can simulate different scenarios, test interventions, and evaluate the long-term effects on the masonry structure. This technology has the potential to revolutionize the assessment, repair, and retrofitting processes, improving the efficiency, resilience, and lifecycle management of masonry structures.

By discussing these future trends, this section aimed to provide insights into the potential directions for research and development in the field of masonry structure assessment, repair, and retrofitting. It emphasized the importance of staying updated with emerging technologies and methodologies to ensure the continued improvement and resilience of masonry structures.

6. Conclusion and discussion

In conclusion, this review has underscored the multifaceted challenges and opportunities in the assessment, repair, and retrofitting of masonry structures. While we have emphasized the critical importance of addressing seismic vulnerability, structural dynamics, architectural integrity, and economic feasibility, there remains a pressing need to translate these insights into practical solutions. Moving forward, it is essential to bridge existing gaps in knowledge and technology by prioritizing research and development efforts that focus on sustainable, efficient, and cost-effective retrofitting methods. One avenue for exploration is the integration of emerging technologies, such as smart materials and systems, which hold promise for revolutionizing maintenance practices and enhancing long-term structural performance. Moreover, given the escalating threats posed by climate change, there is an urgent call to explore retrofitting strategies aimed at bolstering resilience against environmental stressors, particularly in vulnerable regions and developing countries. This entails not only adapting existing structures but also designing future-proof solutions that can withstand the challenges of a changing climate. By continuously advancing assessment, repair, and retrofitting techniques for masonry structures, we can not only ensure public safety and preserve cultural heritage but also build a more resilient infrastructure capable of meeting the demands of the future.

Below, we provide a summary of the current state and offer recommendations for future directions in the assessment, repair, and retrofitting of masonry structures.

1. The majority of human fatalities during earthquakes are attributed to the failure of unreinforced masonry walls. Hence, methods with a high potential to enhance the out-of-plain behavior of structures should be considered for retrofitting.
2. The high mass of URM structures is a significant characteristic that must be considered. Hence, retrofitting methods that introduce low additional mass are preferable in order to minimize the impact on the overall structural dynamics.
3. Harsh environmental conditions can lead to the degradation of appearance and the loss of architectural value in historical masonry structures. Therefore, it is critical to implement suitable repair and retrofitting methods to safeguard against these effects and preserve the architectural integrity of the structures.
4. To determine the most effective intervention technique, it is important to assess the seismic vulnerability and potential collapse mechanisms of structures resulting from constructive and technological deficiencies. A detailed assessment of seismic retrofit upgrades on a case-by-case basis can determine the most appropriate solution, taking into account factors such as cost and complexity.
5. The architectural or historical value of a building must be considered. In historically important structures, it might not be feasible to employ surface treatment methods, and other treatments such as injection, center core, or base isolation techniques must be utilized.
6. To implement low-cost methods that are not sufficiently suitable poses not only a risk to the structure but only an economic risk. Consequently, it is essential to also conduct a study on the economics of retrofitting.
7. While low-cost or low-technology approaches may not consistently deliver optimal efficiency, certain methods, such as bamboo-band retrofitting techniques, have proven to exhibit satisfactory performance.
8. The utilization of post-tensioning methods is discouraged, even for historical buildings, in rural areas due to the substandard quality of mortar and bricks.

9. The advancement of smart materials and systems, such as smart brick technology, is a growing research area with significant potential. Beyond enhancing safety, these technologies also offer the advantage of significantly reducing maintenance costs, by replacing vulnerable components before they may cause damage to other structural components. Accordingly, investigating the application of intelligent materials and systems is a promising direction for future studies in masonry structures.
10. Climate change and its effects on civil infrastructure have become a pressing concern in the research community. URM structures are particularly vulnerable and developing countries have experienced substantial economic losses as a result. Hence, retrofitting URMs to mitigate the effects of climate change is a critical area for future studies.

CRediT authorship contribution statement

Ayoub Keshmiry: Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sahar Hassani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Data curation, Conceptualization. **Ulrike Dackermann:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Jianchun Li:** Writing – review & editing, Visualization, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

This review paper is based on an analysis of previously published studies and publicly available data. No new data were generated specifically for this study.

References

[217] F. Faleschini, K. Toska, F. Andreose, G. Gobbi, G. Feltrin, M.A. Zanini, C. Pellegrino, D. De Domenico, G. Ricciardi, Modal characterization and NDTs of a historical church in Noto, Procedia Struct. Integr. 44 (2023) 2114–2121.

[218] T. Cosgun, O. Ceylan, M.M. Nasery, Ö. Güler, B. Sayin, O. Uzdil, C. Akcay, Seismic performance assessment and retrofitting proposal for a historic masonry school building (Bursa, Türkiye), Case Stud. Construct. Mater. (2023) e02087.

[1] P.B. Lourenço, Computations on historic masonry structures, Prog. Struct. Eng. Mater. 4 (3) (2002) 301–319.

[2] P.B. Lourenço, Masonry structures, overview, in: Encyclopedia of Earthquake Engineering, 2014, pp. 1–9.

[3] S. Huerta, The analysis of masonry architecture: A historical approach: To the memory of professor Henry J. Cowan, Archit. Sci. Rev. 51 (4) (2008) 297–328.

[4] G. Magenes, Masonry building design in seismic areas: Recent experiences and prospects from a European standpoint, in: 1st European Conference on Earthquake Engineering and Seismology, 2006, pp. 1–22.

[5] T. Leslie, Built like bridges: Iron, steel, and rivets in the nineteenth-century skyscraper, J. Soc. Archit. Historians 69 (2) (2010) 234–261.

[6] P.K. Mehta, R.W. Burrows, Building durable structures in the 21st century, Concrete Int. 23 (3) (2001) 57–63.

[7] R.E. Klingner, Masonry Structural Design, McGraw-Hill Education, 2017.

[8] L. Biolzi, S. Cattaneo, P. Crespi, M. Scamardo, N. Vafa, Diagonal compression cyclic testing of unreinforced and reinforced masonry walls, Constr. Build. Mater. 363 (2023) 129839.

[9] G. Magenes, A. Penna, Seismic design and assessment of masonry buildings in europe: recent research and code development issues, in: Proceedings of the 9th Australasian Masonry Conference, vol. 15, Australian Masonry Conference, Auckland Queenstown, New Zealand, 2011, p. 18.

[10] A.W. Hendry, B.P. Sinha, S. Davies, Design of Masonry Structures, CRC Press, 2017.

[11] N. Ranjan, S. Banerjee, S. Nayak, S. Das, Efficacy of waste plastic towards enhancement of shear and flexure carrying capacity of masonry structures, J. Clean. Prod. 365 (2022) 132669.

[12] L. Kudumovic, The experience of post-war reconstruction: The case of built heritage in Bosnia, Open House Int. 45 (3) (2020) 231–248.

[13] M. Penića, G. Svetlana, V. Murgul, Revitalization of historic buildings as an approach to preserve cultural and historical heritage, Procedia Eng. 117 (2015) 883–890.

[14] G. Castellazzi, A.M. D'Altri, S. de Miranda, F. Ubertini, An innovative numerical modeling strategy for the structural analysis of historical monumental buildings, Eng. Struct. 132 (2017) 229–248.

[15] J. Scacco, B. Ghiassi, G. Milani, P.B. Lourenço, A fast modeling approach for numerical analysis of unreinforced and FRCM reinforced masonry walls under out-of-plane loading, Composites B 180 (2020) 107553.

[16] A. Borri, M. Corradi, G. Castori, A. De Maria, A method for the analysis and classification of historic masonry, Bull. Earthq. Eng. 13 (2015) 2647–2665.

[17] P.B. Lourenço, N. Mendes, L.F. Ramos, D.V. Oliveira, Analysis of masonry structures without box behavior, Int. J. Archit. Herit. 5 (4–5) (2011) 369–382.

[18] A. Soleymani, M.A. Najafgholipour, A. Johari, S. Jowkar, In-plane shear strengthening of traditional unreinforced masonry walls with near surface mounted GFRP bars, Constr. Build. Mater. 367 (2023) 130362.

[19] A. Abbass, M.C. Paiva, D.V. Oliveira, P.B. Lourenço, R. Fangueiro, Graphene/polyurethane nanocomposite coatings–enhancing the mechanical properties and environmental resistance of natural fibers for masonry retrofitting, Composites A 166 (2023) 107379.

[20] M. Brinkmann, P. Wiehle, Correlation between relative humidity and the strength and deformation characteristics of unstabilised earth masonry, Constr. Build. Mater. 366 (2023) 130048.

[21] M. Indirli, L.A. S. Kouris, A. Formisano, R.P. Borg, F.M. Mazzolani, Seismic damage assessment of unreinforced masonry structures after the Abruzzo 2009 earthquake: The case study of the historical centers of L'Aquila and Castelvecchio Subequo, Int. J. Archit. Herit. 7 (5) (2013) 536–578.

[22] G.H. Nalon, J.C.L. Ribeiro, L.G. Pedroti, R.M. da Silva, E.N.D. de Araújo, R.F. Santos, G.E.S. de Lima, Review of recent progress on the compressive behavior of masonry prisms, Constr. Build. Mater. 320 (2022) 126181.

[23] V. Sarhosis, J.V. Lemos, K. Bagi, G. Milani, Recent advances on the mechanics of masonry structures, J. Eng. Mech. 148 (6) (2022) 02022002.

[24] S. Cattari, B. Calderoni, I. Caliò, G. Camata, S. de Miranda, G. Magenes, G. Milani, A. Saetta, Nonlinear modeling of the seismic response of masonry structures: Critical review and open issues towards engineering practice, Bull. Earthq. Eng. 20 (4) (2022) 1939–1997.

[25] C. Filippou, N. Kyriakides, C. Chrysostomou, Numerical study of the seismic retrofitting of masonry-infilled RC frames with openings using TRM, Earthq. Eng. Struct. Dyn. 52 (3) (2023) 776–805.

[26] P. Blagojević, S. Brzev, R. Cvetković, Seismic retrofitting of mid-rise unreinforced masonry residential buildings after the 2010 Kraljevo, Serbia earthquake: A case study, Buildings 13 (3) (2023) 597.

[27] M. Pagani, J. Garcia-Pelaez, R. Gee, K. Johnson, V. Poggi, R. Styron, G. Weatherill, M. Simionato, D. Viganò, L. Danciu, et al., Global Earthquake Model (GEM) Seismic Hazard Map (version 2018.1–December 2018), DOI: 10.13117, Technical Report, GEM-GLOBAL-SEISMIC-HAZARD-MAP-2018.1, 2018.

[28] A. Shabani, M. Kioumarsi, M. Zucconi, State of the art of simplified analytical methods for seismic vulnerability assessment of unreinforced masonry buildings, Eng. Struct. 239 (2021) 112280.

[29] C. Wang, V. Sarhosis, N. Nikitas, Strengthening/retrofitting techniques on unreinforced masonry structure/element subjected to seismic loads: A literature review, Open Construct. Build. Technol. J. 12 (1) (2018) 251–268.

[30] F. Yavartanoo, T.H.-K. Kang, Retrofitting of unreinforced masonry structures and considerations for heritage-sensitive constructions, J. Build. Eng. 49 (2022) 103993.

[31] A. Penna, P. Morandi, M. Rota, C.F. Manzini, F. Da Porto, G. Magenes, Performance of masonry buildings during the Emilia 2012 earthquake, Bull. Earthq. Eng. 12 (2014) 2255–2273.

[32] M. Uroš, M. Demšić, M. Šavor Novak, J. Atalić, M. Baniček, R. Jevtić Rundek, I. Duvnjak, J. Košćak, A. Pilipović, S. Prevolnik, Damage evaluation and seismic assessment of a typical historical unreinforced masonry building in the Zagreb 2020 earthquake: A case study—Part I, Buildings 14 (2) (2024) 474.

[33] Ö. Mercimek, Seismic failure modes of masonry structures exposed to Kahramanmaraş earthquakes (Mw 7.7 and 7.6) on February 6, 2023, Eng. Fail. Anal. 151 (2023) 107422.

[34] D. Dizhur, N. Ismail, C. Knox, R. Lumantarna, J.M. Ingham, Performance of unreinforced and retrofitted masonry buildings during the 2010 Darfield earthquake, Bull. New Zealand Soc. Earthq. Eng. 43 (4) (2010) 321–339.

[35] P.G. Asteris, A. Moropoulou, A.D. Skentou, M. Apostolopoulou, A. Mohebkhah, L. Cavaleri, H. Rodrigues, H. Varum, Stochastic vulnerability assessment of masonry structures: concepts, modeling and restoration aspects, Appl. Sci. 9 (2) (2019) 243.

[36] F. Clementi, V. Gazzani, M. Poiani, S. Lenci, Assessment of seismic behaviour of heritage masonry buildings using numerical modelling, J. Build. Eng. 8 (2016) 29–47.

[37] G. Grünthal, European macroseismic scale 1998 : EMS-98, 1998, URL: https://api.semanticscholar.org/CorpusID:128026981.

[38] R. Latifi, M. Hadzima-Nyarko, D. Radu, R. Rouhi, A brief overview on crack patterns, repair and strengthening of historical masonry structures, Materials 16 (5) (2023) 1882.

[39] C. Alessandri, M. Garutti, V. Mallardo, G. Milani, Crack patterns induced by foundation settlements: Integrated analysis on a renaissance masonry palace in Italy, Int. J. Archit. Herit. 9 (2) (2015) 111–129.

[40] M. Solla, S. Lagüela, B. Riveiro, H. Lorenzo, Non-destructive testing for the analysis of moisture in the masonry arch bridge of Lubians (Spain), Struct. Control Health Monit. 20 (11) (2013) 1366–1376.

[41] M.A. Aiello, S. Sciolti, Bond analysis of masonry structures strengthened with CFRP sheets, Construct. Build. Mater. 20 (1–2) (2006) 90–100.

[42] G. Guerrini, S. Kallioras, S. Bracchi, F. Graziotti, A. Penna, Displacement demand for nonlinear static analyses of masonry structures: Critical review and improved formulations, Buildings 11 (3) (2021) 118.

[43] S. Okada, N. Takai, Classifications of structural types and damage patterns of buildings for earthquake field investigation, in: Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, vol. 30, 2000.

[44] M. Stepinac, P.B. Lourenço, J. Atalić, T. Kišiček, M. Uroš, M. Baniček, M.Š. Novak, Damage classification of residential buildings in historical downtown after the ML5. 5 earthquake in Zagreb, Croatia in 2020, Int. J. Disaster Risk Reduction 56 (2021) 102140.

[45] G. Vlachakis, E. Vlachaki, P.B. Lourenço, Learning from failure: Damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece), Eng. Fail. Anal. 117 (2020) 104803.

[46] A. Afreen, A. Ahmed, K. Moin, Effect of near-field earthquake on masonry structure, Asian J. Civ. Eng. 22 (2021) 895–910.

[47] A. Borri, M. Corradi, A. De Maria, R. Sisti, Calibration of a visual method for the analysis of the mechanical properties of historic masonry, Procedia Struct. Integr. 11 (2018) 418–427.

[48] N. Cavalagli, M. Gioffrè, S. Grassi, V. Gusella, C. Pepi, G.M. Volpi, On the accuracy of UAV photogrammetric survey for the evaluation of historic masonry structural damages, Procedia Struct. Integr. 29 (2020) 165–174.

[49] N. Hallermann, G. Morgenthal, Unmanned Aerial Vehicles (UAV) for the assessment of existing structures, in: IABSE Symposium Report, vol. 101, (no. 14) International Association for Bridge and Structural Engineering, 2013, pp. 1–8.

[50] D. Łątka, P. Matysek, The estimation of compressive stress level in brick masonry using the flat-Jack method, Procedia Eng. 193 (2017) 266–272, http://dx.doi.org/10.1016/j.proeng.2017.06.213, URL: https://www.sciencedirect.com/science/article/pii/S1877705817327698, International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures.

[51] D. Łątka, P. Matysek, The estimation of compressive stress level in brick masonry using the flat-Jack method, Procedia Eng. 193 (2017) 266–272.

[52] L. La Mendola, E. Lo Giudice, G. Minafò, Experimental calibration of flat Jacks for in-situ testing of masonry, Int. J. Archit. Herit. 13 (5) (2019) 619–629.

[53] M. Stepinac, L. Lulić, D. Damjanović, I. Duvnjak, M. Bartolac, P.B. Lourenço, Experimental evaluation of unreinforced brick masonry mechanical properties by the flat-Jack method–an extensive campaign in Croatia, Int. J. Archit. Herit. (2023) 1–18.

[54] L. Lulić, M. Stepinac, M. Bartolac, P.B. Lourenço, Review of the flat-Jack method and lessons from extensive post-earthquake research campaign in Croatia, Constr. Build. Mater. 384 (2023) 131407.

[55] F.F. Pinho, R.J. Serra, A.F. Saraiva, V.J. Lúcio, Performance of single and double flat Jacks in stone masonry lab tests, J. Build. Eng. 42 (2021) 102465.

[56] D. Foppoli, A. Armanasco, Laboratory and in situ calibrations of new flat Jack method for assessing masonry shear characteristics, in: Structural Analysis of Historical Constructions: An Interdisciplinary Approach, Springer, 2019, pp. 513–522.

[57] A. Garbacz, T. Piotrowski, L. Courard, L. Kwaśniewski, On the evaluation of interface quality in concrete repair system by means of impact-echo signal analysis, Constr. Build. Mater. 134 (2017) 311–323.

[58] Y.-L. Liu, J.-J. Shi, J.-Q. Huang, G.-S. Wei, Z.-X. Wu, Grouting defect detection of lapped bar connections based on impact-echo method, Shock Vib. 2019 (2019) 1–14.

[59] Ground-penetrating radar for the structural evaluation of masonry bridges: Results and interpretational tools, Constr. Build. Mater. 29 (2012) 458–465, http://dx.doi.org/10.1016/j.conbuildmat.2011.10.001, URL: https://www.sciencedirect.com/science/article/pii/S0950061811005502.

[60] A. Alani, F. Tosti, K. Banks, L. Bianchini Ciampoli, A. Benedetto, Non-destructive assessment of a historic masonry arch bridge using ground penetrating radar and 3D laser scanner, 2017.

[61] G.M. Carlomagno, C. Meola, Comparison between thermographic techniques for frescoes NDT, NDT & E Int. 35 (8) (2002) 559–565.

[62] C. Meola, R. Di Maio, N. Roberti, G.M. Carlomagno, Application of infrared thermography and geophysical methods for defect detection in architectural structures, Eng. Fail. Anal. 12 (6) (2005) 875–892.

[63] C. Meola, Infrared thermography of masonry structures, Infrared Phys. Technol. 49 (3) (2007) 228–233.

[64] S. Hassani, U. Dackermann, A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring, Sensors 23 (4) (2023) URL: https://www.mdpi.com/1424-8220/23/4/2204.

[65] S. Noor-E-Khuda, F. Albermani, Mechanical properties of clay masonry units: Destructive and ultrasonic testing, Constr. Build. Mater. 219 (2019) 111–120.

[66] C. Colla, D. McCann, M. Forde, Radar testing of masonry arch bridges with soil backfill, in: Arch Bridges, CRC Press, 2020, pp. 253–261.

[67] E.C. Oikonomopoulou, V.A. Palieraki, V.S. Nikolopoulou, E. Vintzileou, Application of non-destructive techniques for the investigation of old masonry structures, in: Protection of Historical Constructions: Proceedings of PROHITECH 2021 4, Springer, 2022, pp. 34–45.

[68] R. Brincker, C. Ventura, Introduction to Operational Modal Analysis, John Wiley & Sons, 2015.

[69] E. Reynders, System identification methods for (operational) modal analysis: Review and comparison, Arch. Comput. Methods Eng. 19 (2012) 51–124.

[70] L.F. Ramos, L. Marques, P.B. Lourenço, G. De Roeck, A. Campos-Costa, J. Roque, Monitoring historical masonry structures with operational modal analysis: Two case studies, Mech. Syst. Signal Process. 24 (5) (2010) 1291–1305.

[71] M.R. Valluzzi, E. Cescatti, G. Cardani, L. Cantini, L. Zanzi, C. Colla, F. Casarin, Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls, Constr. Build. Mater. 192 (2018) 272–286.

[72] J. Ortega, M. Stepinac, L. Lulić, M.N. García, S. Saloustros, C. Aranha, F. Greco, Correlation between sonic pulse velocity and flat-Jack tests for the estimation of the elastic properties of unreinforced brick masonry: Case studies from Croatia, Case Stud. Construct. Mater. 19 (2023) e02467.

[73] S.H. Sajid, S.M. Ali, N.J. Carino, S. Saeed, H.U. Sajid, L. Chouinard, Strength estimation of concrete masonry units using stress-wave methods, Constr. Build. Mater. 163 (2018) 518–528.

[74] M. Barnaure, M. Cincu, Testing methods for the assessment of material properties in historical masonry structures: A review, in: IOP Conference Series: Materials Science and Engineering, vol. 789, (no. 1) IOP Publishing, 2020, 012003.

[75] L. Pelà, S. Saloustros, P. Roca, Cylindrical samples of brick masonry with aerial lime mortar under compression: Experimental and numerical study, Constr. Build. Mater. 227 (2019) 116782.

[76] S. Frumento, G. Magenes, P. Morandi, G.M. Calvi, Interpretation of Experimental Shear Tests on Clay Brick Masonry Walls and Evaluation of Q-Factors for Seismic Design, Iuss Press Pavia, 2009.

[77] M. Stepinac, T. Kisicek, T. Renić, I. Hafner, C. Bedon, Methods for the assessment of critical properties in existing masonry structures under seismic loads—The ARES project, Appl. Sci. 10 (5) (2020) 1576.

[78] I. Tomić, A. Penna, M. DeJong, C. Butenweg, A. Correia, P.X. Candeias, I. Senaldi, G. Guerrini, D. Malomo, B. Wilding, et al., Shake-table testing of a stone masonry building aggregate: overview of blind prediction study, Bull. Earthq. Eng. (2023) 1–43.

[79] K. Beyer, A. Dazio, Quasi-static cyclic tests on masonry spandrels, Earthq. Spectra 28 (3) (2012) 907–929.

[80] V.Z. Bosiljkov, Y.Z. Totoev, J.M. Nichols, Shear modulus and stiffness of brickwork masonry: An experimental perspective, Struct. Eng. Mech. 20 (1) (2005) 21–44.

[81] J.V. Lemos, Discrete element modeling of masonry structures, Int. J. Archit. Herit. 1 (2) (2007) 190–213.

[82] P. Gkournelos, T. Triantafillou, D. Bournas, Seismic upgrading of existing masonry structures: A state-of-the-art review, Soil Dyn. Earthq. Eng. 161 (2022) 107428.

[83] E. Çaktı, Ö. Saygılı, J.V. Lemos, C.S. Oliveira, Discrete element modeling of a scaled masonry structure and its validation, Eng. Struct. 126 (2016) 224–236.

[84] A. Gregori, M. Mercuri, M. Angiolilli, M. Pathirage, Simulating defects in brick masonry panels subjected to compressive loads, Eng. Struct. 263 (2022) 114333.

[85] S. Singh, P. Munjal, Bond strength and compressive stress-strain characteristics of brick masonry, J. Build. Eng. 9 (2017) 10–16.

[86] A. Iannuzzo, A. Dell'Endice, T. Van Mele, P. Block, Numerical limit analysis-based modelling of masonry structures subjected to large displacements, Comput. Struct. 242 (2021) 106372.

[87] J.K. Bhaskar, D. Bhunia, J. Karthik, A. Samadhiya, A state-of-the-art review on the evolution of performance of masonry infill walls under lateral loadings, Asian J. Civ. Eng. 23 (7) (2022) 973–1028.

[88] S. Hassani, M. Mousavi, A.H. Gandomi, Structural health monitoring in composite structures: A comprehensive review, Sensors 22 (1) (2021) 153.

[89] V.R. Gharehbaghi, E. Noroozinejad Farsangi, M. Noori, T. Yang, S. Li, A. Nguyen, C. Málaga-Chuquitaype, P. Gardoni, S. Mirjalili, A critical review on structural health monitoring: Definitions, methods, and perspectives, Arch. Comput. Methods Eng. (2021) 1–27.

[90] Y. Yang, Y. Zhang, X. Tan, Review on vibration-based structural health monitoring techniques and technical codes, Symmetry 13 (11) (2021) 1998.

[91] M. Rossi, D. Bournas, Structural health monitoring and management of cultural heritage structures: A state-of-the-art review, Appl. Sci. 13 (11) (2023) 6450.

[92] K. Roy, B. Bhattacharya, S. Ray-Chaudhuri, ARX model-based damage sensitive features for structural damage localization using output-only measurements, J. Sound Vib. 349 (2015) 99–122.

[93] A. Keshmiry, S. Hassani, U. Dackermann, AI-based structural health monitoring systems, in: Artificial Intelligence Applications for Sustainable Construction, Elsevier, 2024, pp. 151–170.

[94] R. Tarantini, A. Cardoni, S. Marasco, J. Merlin, E. Pribaz, G. Rupolo, M. Domaneschi, G.P. Cimellaro, Dynamic characterisation and seismic vulnerability assessment of existing masonry port structures, in: Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures: 17th World Conference on Seismic Isolation, 17WCSI, Springer, 2023, pp. 1032–1042.

[95] A. Saisi, C. Gentile, A. Ruccolo, Continuous monitoring of a challenging heritage tower in Monza, Italy, J. Civ. Struct. Health Monit. 8 (1) (2018) 77–90.

[96] A. Keshmiry, S. Hassani, M. Mousavi, U. Dackermann, Effects of environmental and operational conditions on structural health monitoring and non-destructive testing: A systematic review, Buildings 13 (4) (2023) 918.

[97] N. Cavalagli, G. Comanducci, C. Gentile, M. Guidobaldi, A. Saisi, F. Ubertini, Detecting earthquake-induced damage in historic masonry towers using continuously monitored dynamic response-only data, Procedia Eng. 199 (2017) 3416–3421.

[98] A. Anwar, A. Abd Elwaly, Modal displacement vs curvature functions as damage identifier for masonry structures, Alex. Eng. J. 68 (2023) 527–538.

[99] C. Sansoni, L.C. da Silva, R. Marques, S. Pampanin, P.B. Lourenço, SLaMA-URM method for the seismic vulnerability assessment of UnReinforced masonry structures: Formulation and validation for a substructure, J. Build. Eng. 63 (2023) 105487.

[100] A. Rozsas, A. Slobbe, W. Huizinga, M. Kruithof, K. Ajithkumar Pillai, K. Kleijn, G. Giardina, Siamese convolutional neural networks to quantify crack pattern similarity in masonry facades, Int. J. Archit. Herit. 17 (1) (2023) 147–169.

[101] L.F. Ramos, R. Aguilar, P.B. Lourenço, S. Moreira, Dynamic structural health monitoring of Saint Torcato church, Mech. Syst. Signal Process. 35 (1–2) (2013) 1–15.

[102] H. Blanco, Y. Boffill, I. Lombillo, L. Villegas, An integrated structural health monitoring system for determining local/global responses of historic masonry buildings, Struct. Control Health Monit. 25 (8) (2018) e2196.

[103] A. Castellano, A. Fraddosio, F. Martorano, G. Mininno, F. Paparella, M.D. Piccioni, Structural health monitoring of a historic masonry bell tower by radar interferometric measurements, in: 2018 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems, EESMS, IEEE, 2018, pp. 1–6.

[104] N. Makoond, L. Pelà, C. Molins, P. Roca, D. Alarcón, Automated data analysis for static structural health monitoring of masonry heritage structures, Struct. Control Health Monit. 27 (10) (2020) e2581.

[105] C. Scuro, F. Lamonaca, S. Porzio, G. Milani, R. Olivito, Internet of Things (IoT) for masonry structural health monitoring (SHM): Overview and examples of innovative systems, Constr. Build. Mater. 290 (2021) 123092.

[106] P. Barsocchi, G. Bartoli, M. Betti, M. Girardi, S. Mammolito, D. Pellegrini, G. Zini, Wireless sensor networks for continuous structural health monitoring of historic masonry towers, Int. J. Archit. Herit. 15 (1) (2021) 22–44.

[107] A. Monaco, G. Bertagnoli, L. La Mendola, M.C. Oddo, A. Pennisi, Preliminary validation of an innovative stress sensor for the structural health monitoring of masonry buildings, Procedia Struct. Integr. 44 (2023) 806–813.

[108] S. Hassani, U. Dackermann, M. Mousavi, J. Li, A systematic review of data fusion techniques for optimized structural health monitoring, Inf. Fusion (2023) 102136.

[109] D. Loverdos, V. Sarhosis, Automatic image-based brick segmentation and crack detection of masonry walls using machine learning, Autom. Constr. 140 (2022) 104389.

[110] A. Rezaie, M. Godio, R. Achanta, K. Beyer, Machine-learning for damage assessment of rubble stone masonry piers based on crack patterns, Autom. Constr. 140 (2022) 104313.

[111] D. Loverdos, V. Sarhosis, Geometrical digital twins of masonry structures for documentation and structural assessment using machine learning, Eng. Struct. 275 (2023) 115256.

[112] A.H. Asjodi, K.M. Dolatshahi, Extended fragility surfaces for unreinforced masonry walls using vision-derived damage parameters, Eng. Struct. 278 (2023) 115467.

[113] E. Valero, A. Forster, F. Bosché, C. Renier, E. Hyslop, L. Wilson, High level-of-detail BIM and machine learning for automated masonry wall defect surveying, in: Proceedings of the International Symposium on Automation and Robotics in Construction, Berlin, Germany, 2018, pp. 20–25.

[114] M. Mishra, A.S. Bhatia, D. Maity, Predicting the compressive strength of unreinforced brick masonry using machine learning techniques validated on a case study of a museum through nondestructive testing, J. Civ. Struct. Health Monit. 10 (3) (2020) 389–403.

[115] S.N. Somala, K. Karthikeyan, S. Mangalathu, Time period estimation of masonry infilled RC frames using machine learning techniques, in: Structures, vol. 34, Elsevier, 2021, pp. 1560–1566.

[116] A.A. Daware, Deriving Generalized Temperature-dependent Material Models for Masonry through Fire Tests and Machine Learning (Ph.D. thesis), Clemson University, 2021.

[117] A.A. Mahamat, M.M. Boukar, Machine learning techniques versus classical statistics in strength predictions of eco-friendly masonry units, in: 2021 16th International Conference on Electronics Computer and Computation, ICECCO, IEEE, 2021, pp. 1–4.

[118] L. Chomacki, J. Rusek, L. Słowik, Machine learning methods in damage prediction of masonry development exposed to the industrial environment of mines, Energies 15 (11) (2022) 3958.

[119] O. Coskun, A. Aldemir, Machine learning network suitable for accurate rapid seismic risk estimation of masonry building stocks, Nat. Hazards (2022) 1–27.

[120] C. Achille, A. Adami, S. Chiarini, S. Cremonesi, F. Fassi, L. Fregonese, L. Taffurelli, UAV-based photogrammetry and integrated technologies for architectural applications—methodological strategies for the after-quake survey of vertical structures in Mantua (Italy), Sensors 15 (7) (2015) 15520–15539.

[121] A. Khan, S. Gupta, S.K. Gupta, Multi-hazard disaster studies: Monitoring, detection, recovery, and management, based on emerging technologies and optimal techniques, Int. J. Disaster Risk Reduct. 47 (2020) 101642.

[122] D. Loverdos, V. Sarhosis, Automation in documentation of ageing masonry infrastructure through image-based techniques and machine learning, in: European Workshop on Structural Health Monitoring, Springer, 2023, pp. 727–735.

[123] I.N. Qader, K. Mediha, F. Dagdelen, Y. AYDOĞDU, A review of smart materials: Researches and applications, El-Cezeri 6 (3) (2019) 755–788.

[124] A. Davis, M. Mirsayar, D. Hartl, A novel structural health monitoring approach in concrete structures using embedded magnetic shape memory alloy components, Constr. Build. Mater. 311 (2021) 125212.

[125] J.D.S. Vincent, M. Rodrigues, Z. Leong, N.A. Morley, Design and development of magnetostrictive actuators and sensors for structural health monitoring, Sensors 20 (3) (2020) 711.

[126] M. Ju, Z. Dou, J.-W. Li, X. Qiu, B. Shen, D. Zhang, F.-Z. Yao, W. Gong, K. Wang, Piezoelectric materials and sensors for structural health monitoring: Fundamental aspects, current status, and future perspectives, Sensors 23 (1) (2023) 543.

[127] X. Chen, L. Luo, Z. Zeng, J. Jiao, M. Shehzad, G. Yuan, H. Luo, Y. Wang, Bio-inspired flexible vibration visualization sensor based on piezo-electrochromic effect, J. Materiomics 6 (4) (2020) 643–650.

[128] A. Meoni, A. D'Alessandro, R. Kruse, L. De Lorenzis, F. Ubertini, Strain field reconstruction and damage identification in masonry walls under in-plane loading using dense sensor networks of smart bricks: Experiments and simulations, Eng. Struct. 239 (2021) 112199.

[129] A. Downey, A. D'Alessandro, S. Laflamme, F. Ubertini, Smart bricks for strain sensing and crack detection in masonry structures, Smart Mater. Struct. 27 (1) (2017) 015009.

[130] E. García-Macías, F. Ubertini, Earthquake-induced damage detection and localization in masonry structures using smart bricks and kriging strain reconstruction: A numerical study, Earthq. Eng. Struct. Dyn. 48 (5) (2019) 548–569.

[131] F. Ubertini, A. D'Alessandro, A. Downey, E. García-Macías, S. Laflamme, R. Castro-Triguero, Recent advances on SHM of reinforced concrete and masonry structures enabled by self-sensing structural materials, in: Proceedings, vol. 2, (no. 3) MDPI, 2017, p. 119.

[132] O. Sass, H. Viles, Wetting and drying of masonry walls: 2D-resistivity monitoring of driving rain experiments on historic stonework in Oxford, UK, J. Appl. Geophys. 70 (1) (2010) 72–83.

[133] A.S. Rodríguez, B.R. Rodríguez, M.S. Rodríguez, P.A. Sánchez, Laser scanning and its applications to damage detection and monitoring in masonry structures, in: Long-Term Performance and Durability of Masonry Structures, Elsevier, 2019, pp. 265–285.

[134] A. Meoni, A. D'Alessandro, N. Cavalagli, M. Gioffré, F. Ubertini, Shaking table tests on a masonry building monitored using smart bricks: Damage detection and localization, Earthq. Eng. Struct. Dyn. 48 (8) (2019) 910–928.

[135] N. Caterino, I. Iervolino, G. Manfredi, E. Cosenza, Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting, Comput.-Aided Civ. Infrastruct. Eng. 24 (6) (2009) 432–445.

[136] R. Islam, Inventory of FRP Strengthening Methods in Masonry Structures, 2008.

[137] M. Corradi, E. Mustafaraj, E. Speranzini, Sustainability considerations in remediation, retrofit, and seismic upgrading of historic masonry structures, Environ. Sci. Pollut. Res. 30 (10) (2023) 25274–25286.

[138] M.R. Valluzzi, C. Modena, G. de Felice, Current practice and open issues in strengthening historical buildings with composites, Mater. Struct. 47 (2014) 1971–1985.

[139] R. Plesu, G. Taranu, D. Covatariu, I.-D. Gradinariu, Strengthening and rehabilitation conventional methods for masonry structures, Buletinul Institutului Politehnic din lasi. Sectia Constructii, Arhitectura 57 (4) (2011) 165.

[140] S. Bhattacharya, S. Nayak, S.C. Dutta, A critical review of retrofitting methods for unreinforced masonry structures, Int. J. Disaster Risk Reduct. 7 (2014) 51–67.

[141] Y.-W. Lin, L. Wotherspoon, A. Scott, J.M. Ingham, In-plane strengthening of clay brick unreinforced masonry wallettes using ECC shotcrete, Eng. Struct. 66 (2014) 57–65.

[142] Y. Lin, D. Lawley, L. Wotherspoon, J.M. Ingham, Out-of-plane testing of unreinforced masonry walls strengthened using ECC shotcrete, in: Structures, vol. 7, Elsevier, 2016, pp. 33–42.

[143] A. Ghezelbash, K. Beyer, K.M. Dolatshahi, M. Yekrangnia, Shake table test of a masonry building retrofitted with shotcrete, Eng. Struct. 219 (2020) 110912.

[144] M. ElGawady, P. Lestuzzi, M. Badoux, Retrofitting of masonry walls using shotcrete, in: 2006 NZSEE Conference, Paper, vol. 45, 2006.

[145] M. Shabdin, N.K. Attari, M. Zargaran, Experimental study on seismic behavior of Un-Reinforced Masonry (URM) brick walls strengthened with shotcrete, Bull. Earthq. Eng. 16 (9) (2018) 3931–3956.

[146] S.R.S. Rezaee, M. Soltani, M. Nikooravesh, Cyclic in-plane behavior of unreinforced and confined masonry walls retrofitted by shotcrete: Experimental investigation, Eng. Struct. 264 (2022) 114432.

[147] D. Huang, A. Albareda, O. Pons, Experimental and numerical study on unreinforced brick masonry walls retrofitted with sprayed mortar under uniaxial compression, Buildings 13 (1) (2023) 122.

[148] R.G.D. Libre, L.F. Lopez, C.J.D. Cacanando, M.A.B. Promentilla, E.J. Guades, L.E.O. Garciano, J.M.C. Ongpeng, et al., In-plane shear behavior of unreinforced masonry wall strengthened with bamboo fiber textile-reinforced geopolymer mortar, Buildings 13 (2) (2023) 538.

[149] L. Estevan, F.J. Baeza, D. Bru, S. Ivorra, Stone masonry confinement with FRP and FRCM composites, Constr. Build. Mater. 237 (2020) 117612.

[150] C. Mazzotti, B. Ferracuti, A. Bellini, Experimental bond tests on masonry panels strengthened by FRP, Composites B 80 (2015) 223–237.

[151] F.G. Carozzi, P. Colombi, C. Poggi, Calibration of end-debonding strength model for FRP-reinforced masonry, Compos. Struct. 120 (2015) 366–377.

[152] B. Ghiassi, J. Xavier, D.V. Oliveira, A. Kwiecien, P.B. Lourenço, B. Zajac, Evaluation of the bond performance in FRP–brick components re-bonded after initial delamination, Compos. Struct. 123 (2015) 271–281.

[153] Z. Al-Jaberi, J.J. Myers, M.A. ElGawady, Experimental and analytical approach for prediction of out-of-plane capacity of reinforced masonry walls strengthened with externally bonded FRP laminate, J. Compos. Construct. 23 (4) (2019) 04019026.

[154] P. Croce, New frontiers of composites applications in heritage buildings: Repair of exposed masonry of St. Nicola Church in Pisa, J. Compos. Sci. 5 (8) (2021) 218.

[155] A.A. Dezfouli, S.M.J. Issazadeh, A. Azizi, H. Azizi, Comparison of efficiency of shotcrete and FRP system for strengthening of masonry structures by ABAQUS software, Math. Stat. Eng. Appl. 71 (3s) (2022) 732–755.

[156] L.A.S. Kouris, T.C. Triantafillou, State-of-the-art on strengthening of masonry structures with Textile Reinforced Mortar (TRM), Constr. Build. Mater. 188 (2018) 1221–1233.

[157] L. Garmendia, I. Marcos, E. Garbin, M.R. Valluzzi, Strengthening of masonry arches with textile-reinforced mortar: experimental behaviour and analytical approaches, Mater. Struct. 47 (2014) 2067–2080.

[158] C.G. Papanicolaou, T.C. Triantafillou, M. Papathanasiou, K. Karlos, Textile Reinforced Mortar (TRM) versus FRP as strengthening material of URM walls: Out-of-plane cyclic loading, Mater. Struct. 41 (2008) 143–157.

[159] R. Islam, Inventory of FRP Strengthening Methods in Masonry Structures (Master's thesis), Universitat Politècnica de Catalunya, 2008.

[160] M.J. Drerup, A.E. Díaz de León, To seal or not to seal: A practical study of masonry surface treatments, in: Forensic Engineering 2009: Pathology of the Built Environment, 2010, pp. 96–104.

[161] A. Garofano, Structural Behaviour of Masonry Walls Stregthened with Mortar Layers Reinforced with FRP Grids (Master's thesis), Universitat Politècnica de Catalunya, 2011.

[162] R. Amiraslanzadeh, T. Ikemoto, M. Miyajima, A. Fallahi, A comparative study on seismic retrofitting methods for unreinforced masonry brick walls, in: 15th World Conf. on Earthquake Engineering, International Association for Earthquake Engineering, Tokyo, 2012, pp. 2–10.

[163] A. Klisińska-Kopacz, R. Tišlova, Effect of hydrophobization treatment on the hydration of repair roman cement mortars, Constr. Build. Mater. 35 (2012) 735–740.

[164] F. Iucolano, B. Liguori, C. Colella, Fibre-reinforced lime-based mortars: A possible resource for ancient masonry restoration, Constr. Build. Mater. 38 (2013) 785–789.

[165] M.L. Santarelli, F. Sbardella, M. Zuena, J. Tirillò, F. Sarasini, Basalt fiber reinforced natural hydraulic lime mortars: A potential bio-based material for restoration, Mater. Des. 63 (2014) 398–406.

[166] H. Maljaee, B. Ghiassi, P.B. Lourenço, D.V. Oliveira, FRP–brick masonry bond degradation under hygrothermal conditions, Compos. Struct. 147 (2016) 143–154.

[167] Y.D. Aktas, H. Zhu, D. D'Ayala, C. Weeks, Impact of surface waterproofing on the performance of brick masonry through the moisture exposure life-cycle, Build. Environ. 197 (2021) 107844.

[168] R. Mohammadi-Firouz, E.N. Pereira, J.A. Barros, Experimental assessment of the thermo-mechanical bond behavior of NSM CFRP with cement-based adhesives, Constr. Build. Mater. 364 (2023) 129980.

[169] M. Barazesh, I. Shamim, S.A. Anvar, Masonry infill walls enhanced with the reinforced shotcrete in blast incidents, Iran. J. Sci. Technol. Trans. Civ. Eng. (2023) 1–18.

[170] M.A. Çakıroğlu, G. İnce, H.T. Kabas, A.A. Süzen, Experimental examination of the behavior of shotcrete-reinforced masonry walls and XgBoost neural network prediction model, Arab. J. Sci. Eng. 46 (11) (2021) 10613–10630.

[171] T.C. Triantafillou, K. Karlos, K. Kefalou, E. Argyropoulou, An innovative structural and energy retrofitting system for URM walls using textile reinforced mortars combined with thermal insulation: Mechanical and fire behavior, Constr. Build. Mater. 133 (2017) 1–13.

[172] X. Wang, C.C. Lam, V.P. Iu, Comparison of different types of TRM composites for strengthening masonry panels, Constr. Build. Mater. 219 (2019) 184–194.

[173] A.C. Isfeld, E. Moradabadi, D.F. Laefer, N.G. Shrive, Uncertainty analysis of the effect of grout injection on the deformation of multi-wythe stone masonry walls, Constr. Build. Mater. 126 (2016) 661–672.

[174] B. Silva, M. Dalla Benetta, F. da Porto, M.R. Valluzzi, Compression and sonic tests to assess effectiveness of grout injection on three-leaf stone masonry walls, Int. J. Archit. Herit. 8 (3) (2014) 408–435.

[175] L. Miranda, J. Milosevic, R. Bento, Cyclic behaviour of stone masonry walls strengthened by grout injection, Mater. Struct. 50 (1) (2017) 1–17.

[176] J. Gonzalez-Libreros, T. D'Antino, F. Focacci, C. Carloni, C. Pellegrino, Structural repointing of masonry structures, in: Key Engineering Materials, vol. 817, Trans Tech Publ, 2019, pp. 412–420.

[177] M. Gams, M. Tomaževič, A. Kwiecień, Strengthening brick masonry by repointing–an experimental study, in: Key Engineering Materials, vol. 624, Trans Tech Publ, 2015, pp. 444–452.

[178] S. Casacci, C. Gentilini, A. Di Tommaso, D.V. Oliveira, Shear strengthening of masonry wallettes resorting to structural repointing and FRCM composites, Constr. Build. Mater. 206 (2019) 19–34.

[179] D. Kalliontzis, A.E. Schultz, Improved estimation of the reverse-cyclic behavior of fully-grouted masonry shear walls with unbonded post-tensioning, Eng. Struct. 145 (2017) 83–96.

[180] G. Soltanzadeh, H.B. Osman, M. Vafaei, Y.K. Vahed, Seismic retrofit of masonry wall infilled RC frames through external post-tensioning, Bull. Earthq. Eng. 16 (3) (2018) 1487–1510.

[181] S. Farough, M. Ilyas, A. Ghaffar, Technique for strengthening of masonry wall panels using steel strips, Asian J. Civ. Eng. (Build. Hous.) (2006).

[182] A. Gupta, V. Singhal, Strengthening of confined masonry structures for in-plane loads: A review, in: IOP Conference Series: Materials Science and Engineering, vol. 936, (no. 1) IOP Publishing, 2020, 012031.

[183] R. Marques, P.B. Lourenço, Structural behaviour and design rules of confined masonry walls: Review and proposals, Constr. Build. Mater. 217 (2019) 137–155.

[184] M. Khan, M. Ali, Optimization of concrete stiffeners for confined brick masonry structures, J. Build. Eng. 32 (2020) 101689.

[185] A. Gul, B. Alam, I.U. Khan, S.A.A. Shah, S.W. Khan, K. Shahzada, Improving seismic capacity of dry stacked interlocking masonry structure through confinement at corners, Soil Dyn. Earthq. Eng. 165 (2023) 107710.

[186] U.A.L. Sheikh, Influence of openings on earthquake performance of confined masonry structures, 2023.

[187] Z. Al-Jaberi, J.J. Myers, Prediction of compressive strength and evaluation of different theoretical standards and proposed models of brick columns confined with FRP, FRCM, or SRG system, Case Stud. Construct. Mater. (2023) e01875.

[188] A. Cascardi, F. Micelli, M.A. Aiello, FRCM-confined masonry columns: Experimental investigation on the effect of the inorganic matrix properties, Constr. Build. Mater. 186 (2018) 811–825.

[189] L.N. Koutas, D.A. Bournas, Confinement of masonry columns with textile-reinforced mortar jackets, Constr. Build. Mater. 258 (2020) 120343.

[190] B. Erdil, F. Korkut, M. Aydin, N. Yaltay, Structural performance of masonry buildings under harsh climate and seismic loads, Iran. J. Sci. Technol. Trans. Civ. Eng. (2022) 1–19.

[191] M. Maragna, S. Casacci, C. Gentilini, In-plane shear behaviour of masonry wall panels strengthened by structural repointing, Int. J. Masonry Res. Innov. 1 (3) (2016) 253–276.

[192] S. Nayak, S.C. Dutta, Improving seismic performance of masonry structures with openings by polypropylene bands and L-shaped reinforcing bars, J. Perform. Construct. Facilities 30 (2) (2016) 04015003.

[193] L. Todisco, E. Stocks, J. León, H. Corres, Enhancing the structural performance of masonry structures by post-tensioning, Nexus Netw. J. 20 (3) (2018) 671–691.

[194] B. Doran, N. Yuzer, S. Aktan, D. Oktay, S. Ulukaya, Numerical modeling of traditional masonry walls strengthened with grout injection, Int. J. Archit. Herit. (2019).

[195] A. Ahmed, K. Shahzada, Seismic vulnerability assessment of confined masonry structures by macro-modeling approach, in: Structures, vol. 27, Elsevier, 2020, pp. 639–649.

[196] A. Shahri, A. Massumi, M. Soltani Mohammadi, P. Homami, Experimental evaluation of nonlinear behavior of unreinforced masonry (URM) walls retrofitted using center-core technique, J. Struct. Construct. Eng. 8 (Special Issue 2) (2021) 59–80.

[197] S. Petrovčič, V. Kilar, Design considerations for retrofitting of historic masonry structures with externally bonded FRP systems, Int. J. Archit. Herit. 16 (7) (2022) 957–976.

[198] T. Cosgun, O. Uzdil, B. Sayin, K.K. Zengin, Seismic vulnerability assessment of a masonry structure and an FRP-strengthening proposal, Case Stud. Construct. Mater. 17 (2022) e01680.

[199] M.G. Vetr, A. Yarmohamadi, S. Mohammadikish, Experimental and numerical study on seismic response of RC frames strengthened by shotcrete sandwich panel infills and CFRP strips, in: Structures, vol. 38, Elsevier, 2022, pp. 1244–1256.

[200] K.K. Yun, M.S. Hossain, S. Han, C. Seunghak, Rheological, mechanical properties, and statistical significance analysis of shotcrete with various natural fibers and mixing ratios, Case Stud. Construct. Mater. 16 (2022) e00833.

[201] K. Liu, Q. Xu, G. Wang, F. Chen, Y. Leng, J. Yang, K. Harries, Types and characteristics of bamboo materials for construction uses, in: Contemporary Bamboo Architecture in China, Springer, 2022, pp. 7–30.

[202] Y. Yang, Z. Qiu, W. Hu, Y. Tao, R. Jiang, J. Lin, F. Liu, H. Fan, Braided GFRP sleeving reinforced curved laminated bamboo beams: An efficient way to attenuate delamination, Compos. Struct. 300 (2022) 116141.

[203] M. Roik, S. Hine, Maintenance, repair and refurbishment of masonry façades to avoid severe seismic damages, in: Structures and Architecture a Viable Urban Perspective?, CRC Press, 2022, pp. 755–762.

[204] J. Xue, H. Ling, X. Zhao, F. Zhang, H. Zhou, Seismic performance on stone masonry loess cave retrofitted using composite materials, J. Build. Eng. 46 (2022) 103704.

[205] C. Tedeschi, E. Garavaglia, et al., A probabilistic approach to investigate the physical compatibility between bedding and re-pointing mortars, in: Durability, Monitoring and Repair of Structures, RILEM Publications SARL, 2019, pp. 700–707.

[206] M.F. Ali, A. Moussa, M. Abdelhafez, Alternative lime based grouts used in re-pointing of deteriorated ancient mortars and their structural effects on composite unreinforced masonry walls of Mekaad Radwan, Ottoman Cairo, Egypt (case study), Procedia-Soc. Behav. Sci. 225 (2016) 410–420.

[207] T. Imjai, U. Chaisakulkiet, R. Garcia, K. Pilakoutas, Strengthening of RC members using post-tensioned metal straps: State of the research, Lowland Technol. Int. 20 (2, Sep) (2018) 109–118.

[208] M. Kohail, H. Elshafie, A. Rashad, H. Okail, Behavior of post-tensioned dry-stack interlocking masonry shear walls under cyclic in-plane loading, Constr. Build. Mater. 196 (2019) 539–554.

[209] G.-a. Liu, X. Wang, Z. Yang, L.-y. Wang, Y.-w. Zhou, G.-b. Chen, Experimental study on seismic performance of confined masonry walls with window openings strengthened by using hybrid-fiber modified reactive powder concrete, Front. Mater. 9 (2022) 5.

[210] A. Chourasia, S. Singhal, J. Parashar, Experimental investigation of seismic strengthening technique for confined masonry buildings, J. Build. Eng. 25 (2019) 100834.

[211] Z. Ahmad, K. Shahzada, B. Gencturk, A. Naeem Khan, R. Rehan, M. Fahad, M. Ashraf, Z. Ali, Seismic capacity assessment of unreinforced concrete block masonry buildings in Pakistan before and after retrofitting, J. Earthq. Eng. 19 (3) (2015) 357–382.

[212] S. Nayak, S.C. Dutta, Failure of masonry structures in earthquake: A few simple cost effective techniques as possible solutions, Eng. Struct. 106 (2016) 53–67.

[213] M. Corradi, A. Di Schino, A. Borri, R. Rufini, A review of the use of stainless steel for masonry repair and reinforcement, Constr. Build. Mater. 181 (2018) 335–346.

[214] S. De Santis, P. Casadei, G. De Canio, G. De Felice, M. Malena, M. Mongelli, I. Roselli, Seismic performance of masonry walls retrofitted with steel reinforced grout, Earthq. Eng. Struct. Dyn. 45 (2) (2016) 229–251.

[215] C. Akcay, T.S. Bozkurt, B. Sayin, B. Yildizlar, Seismic retrofitting of the historical masonry structures using numerical approach, Constr. Build. Mater. 113 (2016) 752–763.

[216] R. Marques, Masonry box behavior, in: Encyclopedia of Earthquake Engineering, Springer, Berlin/Heidelberg, Germany, 2014.

[219] F. Peña, P.B. Lourenço, N. Mendes, D.V. Oliveira, Numerical models for the seismic assessment of an old masonry tower, Eng. Struct. 32 (5) (2010) 1466–1478.

[220] S. Mahini, A. Eslami, H. Ronagh, Lateral performance and load carrying capacity of an unreinforced, CFRP-retrofitted historical masonry vault – A case study, Constr. Build. Mater. 28 (1) (2012) 146–156, http://dx.doi.org/10.1016/j.conbuildmat.2011.08.013, URL: https://www.sciencedirect.com/science/article/pii/S0950061811004454.

[221] G. Achs, C. Adam, Rapid seismic evaluation of historic brick-masonry buildings in Vienna (Austria) based on visual screening, Bull. Earthq. Eng. 10 (2012) 1833–1856.

[222] F. da Porto, M. Munari, A. Prota, C. Modena, Analysis and repair of clustered buildings: Case study of a block in the historic city centre of L'Aquila (Central Italy), Constr. Build. Mater. 38 (2013) 1221–1237, http://dx.doi.org/10.1016/j.conbuildmat.2012.09.108, URL: https://www.sciencedirect.com/science/article/pii/S0950061812007866, 25th Anniversary Session for ACI 228 – Building on the Past for the Future of NDT of Concrete.

[223] S. Santos-Assunçao, V. Perez-Gracia, O. Caselles, J. Clapes, V. Salinas, Assessment of complex masonry structures with GPR compared to other non-destructive testing studies, Remote Sens. 6 (9) (2014) 8220–8237, http://dx.doi.org/10.3390/rs6098220, URL: https://www.mdpi.com/2072-4292/6/9/8220.

[224] E. Bassoli, L. Vincenzi, M. Bovo, C. Mazzotti, Dynamic identification of an ancient masonry bell tower using a MEMS-based acquisition system, 2015, http://dx.doi.org/10.1109/EESMS.2015.7175882.

[225] F. Cakir, E. Uckan, J. Shen, S. Seker, B. Akbas, Seismic performance evaluation of slender masonry towers: A case study, Struct. Des. Tall Special Build. 25 (4) (2016) 193–212.

[226] P.G. Asteris, M.G. Douvika, M. Apostolopoulou, A. Moropoulou, Seismic and restoration assessment of monumental masonry structures, Materials 10 (8) (2017) 895.

[227] H. Tsang, E. Gad, J. Wilson, J. Jordan, A. Moore, A. Richards, Mine blast vibration response spectrum for structural vulnerability assessment: Case study of heritage masonry buildings, Int. J. Archit. Herit. 12 (2) (2018) 270–279.

[228] R. Napolitano, M. Hess, B. Glisic, Integrating non-destructive testing, laser scanning, and numerical modeling for damage assessment: The room of the elements, Heritage 2 (1) (2019) 151–168, http://dx.doi.org/10.3390/heritage2010012, URL: https://www.mdpi.com/2571-9408/2/1/12.

[229] A. Armanasco, D. Foppoli, A flat Jacks method for in situ testing of brick masonry shear characteristics, Constr. Build. Mater. 262 (2020) 119840, http://dx.doi.org/10.1016/j.conbuildmat.2020.119840, URL: https://www.sciencedirect.com/science/article/pii/S0950061820318456.

[230] P. Barsocchi, G. Bartoli, M. Betti, M. Girardi, S. Mammolito, D. Pellegrini, G. Zini, Wireless sensor networks for continuous structural health monitoring of historic masonry towers, Int. J. Archit. Herit. 15 (1) (2021) 22–44, http://dx.doi.org/10.1080/15583058.2020.1719229.

[231] B. Yildizlar, B. Sayin, C. Akcay, A case study on the restoration of a historical masonry building based on field studies and laboratory analyses, Int. J. Archit. Herit. 14 (9) (2020) 1341–1359.

[232] B. Gunes, T. Cosgun, B. Sayin, O. Ceylan, A. Mangir, G. Gumusdag, Seismic assessment of a reconstructed historic masonry structure: A case study on the ruins of Bigali castle mosque built in the early 1800s, J. Build. Eng. 39 (2021) 102240.

[233] F. Romis, S. Caprili, W. Salvatore, T.M. Ferreira, P.B. Lourenço, An improved seismic vulnerability assessment approach for historical urban centres: The case study of Campi Alto di Norcia, Italy, Appl. Sci. 11 (2) (2021) 849.

[234] G. Brando, G. Cocco, C. Mazzanti, M. Peruch, E. Spacone, C. Alfaro, K. Sovero, N. Tarque, Structural survey and empirical seismic vulnerability assessment of dwellings in the historical centre of Cusco, Peru, Int. J. Archit. Herit. 15 (10) (2021) 1395–1423.

[235] E.A. Godínez-Domínguez, A. Tena-Colunga, L.E. Pérez-Rocha, H.I. Archundia-Aranda, A. Gómez-Bernal, R.P. Ruiz-Torres, J.L. Escamilla-Cruz, The September 7, 2017 Tehuantepec, Mexico, earthquake: Damage assessment in masonry structures for housing, Int. J. Disaster Risk Reduct. 56 (2021) 102123.

[236] V. Lupăşteanu, R. Lupăşteanu, C. Chingălată, Condition assessment of buildings in Romania: A proposed method and case study, J. Build. Eng. 47 (2022) 103814.

[237] V. Cardinali, M. Castellini, M.T. Cristofaro, G. Lacanna, M. Coli, M. De Stefano, M. Tanganelli, Integrated techniques for the structural assessment of cultural heritage masonry buildings: Application to Palazzo Cocchi-Serristori in Florence, J. Cult. Herit. Manag. Sustain. Develop. 13 (1) (2023) 123–145.

[238] K. Evgeny, M. Ernest, P. Valerii, M. Ilshat, I. Ruslan, A.R. De Azevedo, Experimental investigation of the deformability of the masonry vault in church historical building, Case Stud. Construct. Mater. 18 (2023) e01833.

[239] L. Lulić, I. Lukačević, D. Skejić, M. Stepinac, Assessment of existing masonry resistance using partial factors approaches and field measurements, Buildings 13 (11) (2023) 2790.

[240] M. Branco, L.M. Guerreiro, Seismic rehabilitation of historical masonry buildings, Eng. Struct. 33 (5) (2011) 1626–1634, http://dx.doi.org/10.1016/j.engstruct.2011.01.033, URL: https://www.sciencedirect.com/science/article/pii/S0141029611000629.

[241] Characterization of repair mortars for the assessment of their compatibility in restoration projects: Research and practice, Constr. Build. Mater. 25 (12) (2011) 4338–4350, http://dx.doi.org/10.1016/j.conbuildmat.2011.01.008, URL: https://www.sciencedirect.com/science/article/pii/S0950061811000201, Masonry Research and Practice.

[242] C. Torney, A.M. Forster, C.J. Kennedy, E.K. Hyslop, "Plastic" repair of natural stone in Scotland: Perceptions and practice, Struct. Surv. (2012).

[243] D. Bournas, Strengthening of existing structures: Selected case studies, in: Textile Fibre Composites in Civil Engineering, Elsevier, 2016, pp. 389–411.

[244] D. Theodossopoulos, J. Sanderson, M. Scott, Strengthening masonry cross vaults damaged by geometric instability, Key Eng. Mater. 624 (2014) 635–643.

[245] P. Bocca, S. Valente, A. Grazzini, A. Alberto, Detachment analysis of dehumidified repair mortars applied to historical masonry walls, Int. J. Archit. Herit. 8 (3) (2014) 336–348.

[246] A. Formisano, A. Marzo, Simplified and refined methods for seismic vulnerability assessment and retrofitting of an Italian cultural heritage masonry building, Comput. Struct. 180 (2017) 13–26.

[247] E. Valero, F. Bosché, A. Forster, Automatic segmentation of 3D point clouds of rubble masonry walls, and its application to building surveying, repair and maintenance, Autom. Constr. 96 (2018) 29–39.

[248] D. De Domenico, N. Impollonia, G. Ricciardi, Seismic retrofitting of confined masonry-RC buildings: The case study of the university hall of residence in Messina, Italy, Int. J. 36 (1) (2019) 54–85.

[249] A. Aşıkoğlu, Ö. Avşar, P.B. Lourenço, L.C. Silva, Effectiveness of seismic retrofitting of a historical masonry structure: Kütahya Kurşunlu Mosque, Türkiye, Bull. Earthq. Eng. 17 (2019) 3365–3395.

[250] M. Ferraioli, A. Lavino, D. Abruzzese, A.M. Avossa, Seismic assessment, repair and strengthening of a medieval masonry tower in southern Italy, Int. J. Civ. Eng. 18 (2020) 967–994.

[251] E. Bertolesi, B. Torres, J.M. Adam, P.A. Calderón, J.J. Moragues, Effectiveness of Textile Reinforced Mortar (TRM) materials for the repair of full-scale timbrel masonry cross vaults, Eng. Struct. 220 (2020) 110978.

[252] S. Wang, S. Wang, Z. Lu, W. Yao, B. Liu, B. Li, Characterization of sticky-rice lime binders from old masonry relics in north China: The primary contribution for conservation, Constr. Build. Mater. 250 (2020) 118887.

[253] G.B. Motra, S. Paudel, Performance evaluation of strengthening options for institutional brick masonry buildings: A case study of Pulchowk Campus, Prog. Disaster Sci. 10 (2021) 100173.

[254] G. Longobardi, A. Formisano, Seismic vulnerability assessment and consolidation techniques of ancient masonry buildings: The case study of a Neapolitan Masseria, Eng. Fail. Anal. 138 (2022) 106306.

[255] O. Uzdil, T. Cosgun, B. Sayin, C. Akcay, Seismic performance evaluation and strengthening proposal for a reconstruction project of a historic masonry building demolished in the 1940s, J. Build. Eng. 66 (2023) 105914.

[256] G. Cianchino, M.G. Masciotta, C. Verazzo, G. Brando, An overview of the historical retrofitting interventions on Churches in Central Italy, Appl. Sci. 13 (1) (2022) 40.

[257] S. Pescari, L. Budău, C.-B. Vîlceanu, Rehabilitation and restauration of the main façade of historical masonry building–Romanian national Opera Timisoara, Case Stud. Construct. Mater. (2023) e01838.

[258] Z. Li, Y. Li, X. Bai, Repair of damp-proof layers of historic masonry buildings in Shanghai, China, in: Proceedings of the Institution of Civil Engineers-Civil Engineering, Thomas Telford Ltd, 2023, pp. 1–6.

[259] N. Gattesco, E. Rizzi, L. Facconi, F. Minelli, A. Dudine, Investigating the effectiveness of a CRM system: Full scale reverse cyclic tests on a two-storey rubblestone masonry building, Procedia Struct. Integr. 44 (2023) 2222–2229.

[260] P. Besen, P. Boarin, Integrating energy retrofit with seismic upgrades to future-proof built heritage: Case studies of unreinforced masonry buildings in Aotearoa New Zealand, Build. Environ. 241 (2023) 110512.

[261] M. Núñez García, S. Saloustros, F. Mateos Redondo, J.A. Alonso Campanero, J. Ortega, F. Greco, C. Aranha, I. Martínez Cuart, Seismic retrofit of existing structures based on digital surveying, non-destructive testing and nonlinear structural analysis: The case of Gjirokastra Castle in Albania, Appl. Sci. 12 (23) (2022) 12106.

[262] Y.Y.A. Abdel-Aty, Proposals for seismic retrofitting of timber roofs to enhance their in-plane stiffness and diaphragm action at historical masonry buildings in cairo, J. Cult. Herit. 32 (2018) 73–83.