

Integration of structural requirements and conservation criteria in masonry wall interventions: A pilot study considering five in-plane strengthening methods

Nuria Chiara Palazzi ^a, Rolando Alvarado ^b, Cristián Sandoval ^{b,*}, Pere Roca ^c

^a Faculty of Architecture, Art, Design and Communications, Campus Creativo, Universidad Andrés Bello, Ernesto Pinto Lagarrigue 230, Santiago, Chile

^b Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Casilla 306, Correo 22, Santiago, Chile

^c Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Jordi Girona 1-3, Barcelona 08034, Spain

ARTICLE INFO

Keywords:

Unreinforced masonry
Strengthening techniques
Intervention Quality Index (IQI)
Conservation-oriented assessment

ABSTRACT

Unreinforced masonry (URM) structures constitute a large portion of existing buildings and exhibit high seismic vulnerability due to their limited lateral resistance. Although several strengthening techniques have been proposed to enhance their shear capacity and ductility, comparative assessments that also consider conservation-related constraints remain limited. This study addresses this gap by applying the Intervention Quality Index (IQI) to provide an integrated evaluation of structural effectiveness and conservation compatibility of five commonly used strengthening techniques: reinforced plaster (RPL), fibre-reinforced polymers (FRP), fibre-reinforced cementitious matrices (FRCM), steel strips (SST), and near-surface mounted (NSM) strips. The IQI framework combines a Normalized Structural Index (SI_{nm}) and a Conservation Factor (CF). The structural index is derived from a systematic review of 709 experimental tests on strengthened URM specimens subjected to diagonal compression and in-plane cyclic loading under constant axial load, with consideration of gains in load capacity and ductility. Conservation aspects are quantified through expert-based evaluation using a structured questionnaire.

The results show that FRCM provides the most balanced performance between structural performance and conservation requirements, achieving high structural efficiency ($SI_{nm} = 0.92$ for low-quality masonry under in-plane loading) and the highest CF value (0.71), resulting in an IQI of 0.65. NSM shows high conservation compatibility but limited structural contribution, likely influenced by the scarcity of available experimental data. SST exhibits significant strength enhancement with moderate conservation compliance, whereas RPL and FRP, despite structural improvements, present low CF values and consequently low IQI scores. The proposed framework supports an evidence-based comparison of strengthening techniques and can assist in selecting seismic retrofit solutions for masonry structures.

1. Introduction

Unreinforced masonry (URM) is one of the oldest and most widely used construction techniques worldwide, deeply rooted in traditional building practices across various cultures. URM structures encompass both architectural landmarks and existing buildings, making a significant contribution to global built heritage. Approximately 70% of the world's population resides in URM buildings [1], many of which were constructed before the introduction of seismic codes [2–4]. Among URM structures, historical buildings often lack the structural conditions

required to withstand seismic events, posing challenges for both preservation and safety. Unfortunately, a significant number of these buildings have been severely damaged or destroyed by moderate to strong earthquakes, as documented in recent reports [5–8]. Several critical factors, including the distribution of structural walls in plan, masonry quality, integrity of connections between vertical-orthogonal and wall-to-wall elements, and the presence of rigid diaphragms, among others, govern the seismic behavior of URM historic buildings. The interplay of these elements dictates the overall seismic performance and level of vulnerability of each structure.

* Corresponding author.

E-mail address: cristian.sandoval@uc.cl (C. Sandoval).

¹ The author Cristián Sandoval is an editor of this journal. In accordance with the journal's policy, he was blinded to the entire peer review process.

To address these structural deficiencies, numerous strengthening strategies have been developed over the years to enhance the seismic resilience of URM buildings. These strategies can be categorized into three main groups [9–11]: (1) techniques aimed at increasing shear strength and/or ductility; (2) methods aimed at recovering/conferring integrity to the fabric or the wall, seeking to ensure a good seismic performance of the whole structural system; and (3) strategies aimed at reducing seismic demands. This study specifically focuses on the first group of interventions, i.e., those strengthening techniques that enhance shear resistance and/or ductility, as these are the most widely applied approaches for improving the in-plane performance of URM walls under seismic loading.

Significant advancements have been made in the field of seismic strengthening of masonry structures over the past few years. In general, evaluations of available strengthening methods have focused almost exclusively on structural performance criteria. However, in the case of historical buildings, a compromise is often required between the structural requirements and conservation criteria. These criteria emphasize fundamental principles such as authenticity, compatibility, minimal intervention, and reversibility, as outlined by ICOMOS [12] and ISCARSHAH [13]. Consequently, the structural strengthening of historic buildings is a complex procedure that requires standardized tools to quantitatively assess improvements in structural capacity and compliance with modern conservation principles.

Several studies have provided comprehensive reviews of available strengthening methods for enhancing the structural performance of URM structures [9,10,14–16]. Most reviews tend to focus primarily on the structural performance of available techniques, offering a descriptive perspective that highlights the advantages, disadvantages, and drawbacks of each. Some review studies also address the cost and constructability of strengthening solutions. These studies have shown that the effectiveness of different techniques can vary significantly depending on the masonry materials and the strengthening configuration used (i.e., materials, layout, anchors, etc.). Due to the extensive information available, recent studies, such as those conducted by Dadras et al. [17] and Del Zoppo et al. [18], have compiled experimental data from the literature to compare the effects of different strengthening solutions on structural parameters, such as stiffness, ductility, and shear capacity. These studies note that the high variability in the parameters used in experimental programs makes direct comparisons of experimental results difficult, underscoring the need for more targeted experimental campaigns. In the case of heritage structures, a recent work conducted by Yavartanoo & Kang [11] qualitatively examined various strengthening interventions and their compatibility with conservation principles. However, there is a clear need for an integrated evaluation framework that informs decision-making processes and accounts for both structural and conservation requirements.

Within this scenario, this work assesses the extent to which existing strengthening techniques—developed and mainly tested in non-heritage contexts—can be effectively applied to architectural heritage interventions, considering both structural effectiveness and alignment with modern conservation principles. For this purpose, the Intervention Quality Index (IQI) method, first introduced by Palazzi et al. [19], is used as a quantitative framework. The IQI method consists of two main components: (1) the Normalized Structural Index (SI_{nm}), which quantifies the structural effectiveness of an intervention in terms of strength and ductility improvements, and (2) the Conservation Factor ($CF(t,s)$), which evaluates compliance with key heritage conservation criteria, including authenticity, minimal intrusion, compatibility, balanced visual impact, and removability. By integrating these two dimensions into a single metric, the IQI provides a structured, objective framework for prioritizing strengthening techniques and offers a holistic approach to assessing their overall suitability for heritage masonry interventions.

This research considers a set of five in-plane strengthening methods aimed at improving the structural performance of masonry elements while adhering to conservation principles, utilizing the IQI method. The

five techniques considered correspond to the first category of interventions (i.e., those aimed at improving shear strength and/or ductility), which are: reinforced plasters (RPL), steel strips (SST), fiber-reinforced polymer bands (FRP), fiber-reinforced composite materials (FRCM), and near-surface mounted strips (NSM). To achieve this, after the introduction and a detailed presentation of the IQI methodology, the five strengthening techniques are described, followed by an extensive literature review of 65 journal articles spanning from 2000 to 2023, compiled from academic sources such as Scopus and Web of Science (WOS). This review includes 709 experimental test results from diagonal compression (DCT) and in-plane cyclic lateral load tests (INP) to assess the effectiveness of each technique in improving the shear strength and ductility of URM walls. Subsequently, a focus group of 20 professionals (architects and engineers) working in heritage interventions in Chile evaluated the impact of these techniques on modern conservation principles through a survey, leading to the calculation of the Conservation Factor. Once the structural and conservation factors were determined for each method, the IQI was calculated, enabling a comparative analysis of their overall performance. The results provide a novel decision-making framework for selecting optimal strengthening strategies that enhance seismic safety while minimizing the impact on the heritage values of URM buildings.

The findings of this study highlight potential trade-offs between structural requirements and conservation principles. While specific techniques offer significant improvements in seismic resistance, they often pose challenges for reversibility and compatibility with the original materials. Conversely, interventions that align more closely with conservation principles may, in some cases, not provide the same level of structural enhancement. By quantitatively assessing these trade-offs, the IQI methodology contributes to a more balanced and comprehensive approach to selecting and designing retrofitting solutions for historic buildings. Beyond its immediate application, this research offers a valuable tool for conservation practitioners, engineers, and policy-makers, enabling them to make informed decisions on seismic risk mitigation for heritage structures while ensuring compliance with modern conservation standards.

2. Conservation principles and IQI method

This section outlines a set of criteria or principles currently used to assess suitable structural interventions for heritage URM structures. Furthermore, the IQI method is also introduced.

2.1. Structural conservation principles

Based on a comprehensive review of the ICOMOS Charter [12], conservation principles aimed at preserving the values and attributes of heritage structures are identified: *authenticity*, *non-intrusiveness*, *compatibility*, *balanced visual impact*, and *removability*. In the following, the conservation criteria are stated and discussed, analyzing the effect that complying with them has on the structural behavior induced by a reinforcement system:

- *Authenticity* [Au] of the original features of the building (materials, geometry, and constructive details), which must be preserved, “ensuring that the original mechanical and resisting principles governing the structure’s response are not altered and original structural elements are not made redundant” [20].

When an intervention is supported by the historical context and constructive culture to which the building belongs, i.e., it is a traditional reinforcement technique that corresponds to a very efficient structural solution, despite modifying the structural response of the original structure, authenticity is preserved.

- *Non-intrusiveness* [N-I] principle refers to the extent of penetration of retrofitting interventions within the original materials, as well as the degree of alteration to their integrity and original compactness.

- **Compatibility [Co]** between new retrofitting materials and existing elements is related to chemical, physical, mechanical, rheological, and thermal properties. The retrofits and structural elements “not only do no harm to the original ones, but they also act as sacrificial elements in the presence of external actions, i.e., they should act as fuses of the structural system” [20]. Furthermore, structural compatibility can reduce structural discontinuities, which are preferential pathways for damage during seismic movements, and ensure integration between structural elements, resulting in a more monolithic behavior of masonry walls.
- **Balanced visual impact [BVI]** of retrofitting interventions enables the easy detection of the original constructive systems of the building. Also, it identifies possible structural heterogeneities resulting from post-earthquake repairs (the main vulnerability feature in URM structures subjected to seismic motions). The respect of the “balanced visual impact” principle considers the simultaneous check of two conditions: (i) the *recognizability* of the intervention and (ii) the *respect for the aesthetic qualities* of the monument and the context. In this sense, the intervention is integrated harmoniously without disturbing the overall vision or imposing it, but it can still be distinguishable from the original.
- **Removability/Retractability [Re]**. In the field of structural consolidation, the principle of *reversibility* is one of the most debated conservation issues because new interventions are always invasive and non-reversible to some extent. Therefore, the scientific community considers this principle unrealistic [13], as any intervention, even the least invasive one, inevitably causes some alteration to the structure. It is accepted that *full reversibility* cannot be guaranteed. Thus, a new criterion is introduced: *removability/retractability* [13]. It considers the possibility of removing and replacing the adopted retrofits, which should cause only minor, repairable damage to the original structure, if more technologically advanced and respectful solutions are found in the future.

As Roca [21] notes, it is recognized that applying all the mentioned principles simultaneously and strictly may be difficult or impossible in practice. For this reason, using a quantitative tool such as the IQI method would enable the objective prioritization of interventions, striking an appropriate balance between structural requirements and compliance with the conservation criteria.

It is also important to note that, from a structural standpoint, the degree to which each principle is respected affects the expected mechanical response of intervened masonry walls. The principles of compatibility and non-intrusiveness have the most direct impact, as they can control material response and their interfaces, limit stress concentrations, and reduce the likelihood of premature cracking or detachment under seismic actions. Conversely, authenticity, balanced visual impact, and removability contribute more indirectly, reinforcing the legibility, coherence, and long-term maintainability of the intervention without significantly altering the structure's behavior. These considerations, as will be seen in Section 6, are considered when assigning scores to the different categories associated with conservation principles.

2.2. Intervention Quality Index (IQI) method

The starting point of any strengthening intervention on the built heritage is the prior identification of its tangible (geometry, materials, construction techniques, environment) and intangible (ancient knowledge and technology, construction traditions and techniques, original and subsequent uses) values and attributes. This identification serves as a basis for defining and designing retrofitting strategies that protect and preserve these values and characteristics for future generations. In this context, a structural reinforcement project—primarily aimed at ensuring human safety—must achieve optimal compliance with structural requirements while minimizing its impact on heritage assets. This key principle aligns with the ISCARCH guidelines' *minimum intervention*

criterion [13].

The conservation and protection of architectural heritage have been a central concern of international organizations such as UNESCO, ICCROM, and ICOMOS, which have established fundamental conservation principles through international charters, declarations, and guidelines [22,23]. These principles are intended to guide interventions for the conservation and restoration of built heritage. However, these organizations lack legally binding instruments and cannot enforce compliance, except for sites registered on the World Heritage List. Thus, it falls to national authorities and local governments to ensure the application of conservation principles within their cultural and regulatory frameworks. It is therefore necessary to mention that the conservation criteria adopted in this study reflect culturally grounded interpretations and should not be regarded as universally prescriptive. The IQI framework is intentionally flexible: practitioners may adapt, include, or exclude conservation principles according to national regulations or local conservation cultures without compromising the method's validity (i.e., it can be adapted to any context where the integration of international conservation charters into regulatory frameworks or professional practice is heterogeneous).

In the field of seismic assessment, recent studies have highlighted that many historic structures—even those that have undergone consolidation and repair—continue to exhibit inadequate performance during seismic events. In response, various guidelines and standards have been developed worldwide to establish criteria for strengthening interventions. Examples include *New Zealand's Building Seismic Performance regulations* [24], the *American Society of Civil Engineers' Building Code Requirements for Masonry Structures* [25], and the *European Code for the Seismic Retrofit of Existing Buildings* [26]. Among these, some regulations explicitly address the structural interventions in historical structures, such as the *Italian Code and Circ. 26/2010* [27], the *Peruvian National Building Code for earthen structures* [28], and the *Chilean Standard for the Structural Intervention of Historical and Existing Buildings* [29]. Additionally, UNESCO's *Guidelines for Earthquake-Resistant Non-Engineered Construction* and ICOMOS' *Principles for the Analysis, Conservation, and Structural Restoration of Architectural Heritage* provide methodologies for damage assessment and repair, correlating post-seismic scenarios with appropriate traditional and modern reinforcement techniques.

Despite increasing professional and scientific interest in this subject, achieving a balance between structural requirements and minimal intervention, consistent with ICOMOS conservation principles, remains a significant challenge. Most studies evaluating reinforcement strategies focus on qualitative assessments, with few attempts to quantify their impact on heritage values. One of the few studies that has addressed this problem is due to Baquedano et al. [30], who analyzed various reinforcement techniques for historic adobe buildings using multi-criteria decision analysis to determine the most effective approach based on structural behavior, material compatibility, cultural heritage values (intrusiveness and reversibility), and cost-effectiveness.

As commented, Palazzi et al. [19] introduced the Intervention Quality Index (IQI), a composite indicator that integrates structural and conservation performance into a unified metric. The IQI is calculated as follows:

$$IQI(t, s) = SI_{nm}(t) \times CF(t, s) \quad (1)$$

where $IQI(t, s)$ represents the Intervention Quality Index for technique t under weighting scenario s , $SI_{nm}(t)$ is the Normalized Structural Index, and $CF(t, s)$ is the Conservation Factor. The structural index $SI_{nm}(t)$ is obtained by computing the Safety Index Increment $\Delta \bar{I}_s(t)$, defined as the increase in load-bearing capacity or ductility:

$$\Delta \bar{I}_s(t) = \frac{R_t}{R_0} \text{ or } \frac{\mu_t}{\mu_0} \quad (2)$$

where R_t and μ_t correspond to the peak strength and ductility of the

specimen strengthened with technique t , while R_0 and μ_0 are the peak strength and ductility of the original unreinforced specimen. Then, post-intervention performance is calculated based on a target strength, which can be defined on a case-by-case basis according to the local cultural context (either by applying some specific standard or through engineering judgment). It is worth noting that, in the present study, a target strength of $1.4R_0$ has been adopted based on the minimum increase observed across most investigated strengthening methods, which is close to 40%, as discussed in Section 5. Further details on the derivation of the Normalized Structural Index used in this study are provided in Annex 1.

The Conservation Factor $CF(t, s)$ evaluates compliance with conservation principles derived from international guidelines: authenticity [Au], non-intrusiveness [NI], compatibility [Co], balanced visual impact [BVI], and removability/retractability [Re]. For each principle k , compliance is qualitatively assessed using three expert judgment categories: full respect, partial respect, and no respect. These categories are mapped to discrete numerical scores: $Au \in \{2, 1, 0\}$, $Co \in \{3, 1.5, 0\}$, $NI \in \{3, 1.5, 0\}$, $BVI \in \{2, 1, 0\}$, and $Re \in \{2, 1, 0\}$. As discussed in Section 2.1, the wider scales assigned to compatibility and non-intrusiveness reflect their more direct influence on the structural response—governing material continuity, interface behavior, and the likelihood of stress concentrations. In contrast, authenticity, balanced visual impact, and removability/retractability are expressed through narrower scales, as their contribution to structural behavior is more indirect and primarily related to legibility, coherence, and long-term maintainability. It is worth noting that the detailed description of each level of compliance for each principle is available in Table 2, Section 6.

Because the criteria have different maximum values, scores are normalized using $\hat{\gamma}_k(t) = \gamma_k(t)/\gamma_{k,\max}$, where $\gamma_k(t)$ is the score assigned to the k -th criterion based on the judgment category and $\gamma_{k,\max}$ is the maximum score possible for that principle. The Conservation Factor ($CF(t, s)$) is then computed through a simple additive weighting scheme, as follows:

$$CF(t, s) = \sum_{k=1}^N \hat{\gamma}_k(t) w_k(s) \quad (3)$$

where $w_k(s)$ is the weight of each criterion in scenario s and $\sum w_k(s) = 1$.

Based on the IQI values, four categories of compliance are defined: Category A ($0.75 < IQI \leq 1.00$) indicates full compliance with both structural requirements and conservation principles; Category B ($0.50 < IQI \leq 0.75$) indicates satisfactory performance in both dimensions; Category C ($0.25 < IQI \leq 0.50$) indicates partial compliance or insufficient safety; and Category D ($0.00 < IQI \leq 0.25$) indicates unsatisfactory results in both criteria.

In this study, the IQI method is used to evaluate the performance of five common strengthening techniques (described in Section 3) that aim to quantitatively improve shear strength and/or ductility in masonry wall interventions. To this end, an experimental database is constructed that includes in-plane cyclic tests and diagonal compression tests. Alongside this, the main characteristics of each dataset are presented for each strengthening technique (Section 4). Then, the efficiency of these techniques is assessed in terms of shear strength and ductility increment (Section 5). Finally, the impact of each strengthening technique on modern conservation principles is evaluated through a survey of experts (Section 6), and the IQI for each method is calculated (Section 7).

3. Description of the strengthening methods

From the available literature, strengthening techniques are often assessed on a case-by-case basis rather than following a standardized classification, with a strong focus on enhancing the in-plane or out-of-plane response of individual structural elements, such as walls or panels. In laboratory conditions, innovative techniques represent the most significant proportion of reported applications in scientific publications. In-plane cyclic tests (INP) with axial pre-loading and diagonal

compression tests (DCT) are preferred to evaluate the increase in element resistance and/or ductility. Five strengthening techniques were considered in this study, which are described below:

- **Reinforced plasters (RPL).** This technique consists of a thin layer of cementitious mortar or concrete that incorporates a steel reinforcing mesh tied to a series of steel connectors embedded in the underlying masonry [31]. RPL applications may include the use of shotcrete, ferrocement, and engineered cementitious composites (ECC) overlays, which are typically applied to one or both faces of URM. Shotcrete overlays are sprayed onto the surface of a masonry wall over a mesh of reinforcing bars. The process involves surface preparation, which includes removing dust, filling voids, and installing a wire mesh before spraying the shotcrete layer (Fig. 1). This approach is more convenient and less costly than cast-in-situ jackets [33]. In ferrocement overlay, reinforcing steel mesh is attached to the masonry surface, followed by a manually applied plaster coating [32, 34]. ECC shotcrete is a cement composite reinforced with synthetic fibers [35]. The main disadvantage of RPL techniques is mass addition, which leads to higher inertia forces. In historic constructions, these techniques are highly intrusive, non-removable, and physically, mechanically, and thermally incompatible with historical masonry. Differences in stiffness and thermal expansion coefficients between the reinforcement layer and the original masonry can generate additional stresses at the interface, increasing the risk of premature detachment or structural damage. Furthermore, the application process is labor-intensive and time-consuming, making this method unsuitable for the restoration of exposed façades on heritage structures due to the significant alteration of the building's aesthetic appearance.
- **Fiber-reinforced polymers (FRP).** This technique is one of the most extensively studied strengthening methods in recent years, consisting of a polymer matrix, typically an epoxy resin, reinforced with synthetic fibers made from carbon, glass, aramid, or basalt sheets. These reinforcements can be applied in diagonal, horizontal, vertical, or wrapped (full-face) arrangements (Fig. 2) on one or both sides of a wall. As a retrofitting solution, FRP offers a high strength-to-weight ratio, rapid installation, and minimal disruption to building operations [37]. However, FRP suffers from several issues, including anchorage problems, limited energy dissipation, and brittle failure [33]. Additionally, FRP retrofitting is costly, requires specialized technical expertise, and obstructs the natural transpiration of masonry. Moreover, it is not removable, and the compatibility between resin and masonry is not fully understood. Despite its structural benefits, FRP is considered unsuitable for heritage buildings due to its irreversibility, aesthetic impact, and lack of compatibility with historical masonry materials.
- **Fabric-Reinforced Cementitious Matrix (FRCM).** This method is an emerging and viable alternative to traditional FRP strengthening systems. Unlike FRP, which relies on polymeric resins, FRCMs utilize an inorganic matrix—typically composed of cement or lime mortar—combined with a fiber mesh (Fig. 3). This composition offers several advantages, including improved compatibility with masonry, enhanced performance at elevated temperatures, better vapor permeability, and stronger adhesion to uneven substrates [18]. Reinforcement fibers used in FRCMs include glass, carbon, basalt, and PBO (p-phenylene-2,6-benzobisoxazole). Additionally, high-strength steel wires have been proposed for structural applications, whose arrangement can be in a strip configuration [39,40]. Their superior mechanical properties drive the growing popularity of FRCM systems over FRPs, thanks to their wet lay-up process and their ability to mitigate stiffness mismatches with the underlying masonry or concrete. However, despite these advantages, critical aspects, such as their constitutive behavior, failure mechanisms, and interface



Fig. 1. – (a) Reinforced plaster application of wire mesh and (b) application of plaster [32].

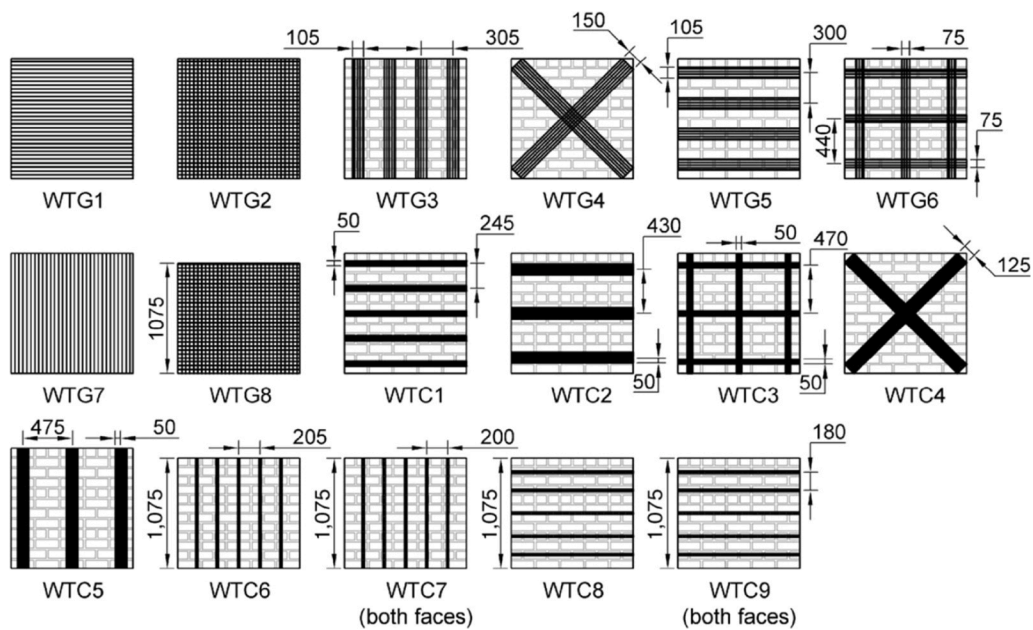


Fig. 2. FRP retrofit details (all dimensions in mm); wallette height is 1170 mm unless otherwise noted [36].

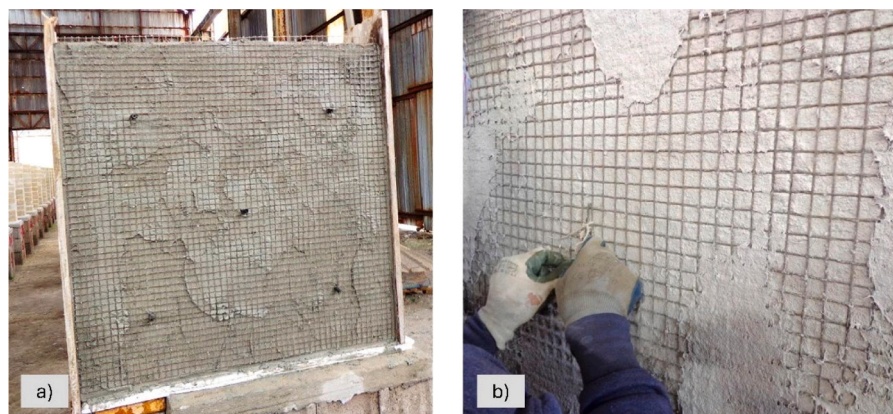


Fig. 3. Procedure for the application of the TRM system [38].

debonding with the substrate, remain insufficiently studied. Further research is needed to establish clear qualification criteria for these materials, as there is currently no consensus within the academic and

engineering communities regarding their standardization. In URM structures, FRCMs have demonstrated positive contributions to structural performance. However, concerns persist regarding the

level of intrusiveness and removability of these systems when used in heritage constructions. While they offer a less invasive alternative to FRPs, their long-term reversibility and potential impacts on historical materials require further investigation before they can be universally adopted for the conservation of heritage buildings.

- **Steel strips (SST).** This reinforced method is centered on the use of stainless-steel strips. They are thin, steel elements mechanically anchored to the wall and arranged in different configurations, including diagonal, horizontal, and vertical cross patterns, applied on both sides of the masonry (Fig. 4). When provided with stainless steel, it allows long-term durability, making it suitable for both exterior and unprotected environments.

The SST technique is often used in combination with other reinforcement methods, such as grouting or grout injections, particularly when preserving the masonry's exposed appearance is a priority. The strips are secured using standard anchor bolts and/or steel through-rods. Unlike alternative techniques that may be ineffective, overly invasive, or irreversible—making them unsuitable from a conservation perspective—SST reinforcement addresses concerns regarding compatibility, intrusiveness, and removability in historical constructions. This method introduces a limited disturbance to the original fabric, limited to anchorage drillings, while also adding a low mass, further enhancing its suitability for heritage preservation.

- **Near-surface mounted (NSM).** This reinforcement technique, also known as structural repointing, is a method that combines traditional repointing with the inclusion of reinforcing bars in the bed joints [42]. The process typically involves removing mortar from an existing horizontal joint to a specified depth, inserting a reinforcement element into the cavity, and applying a groove filler to restore the joint's appearance (Fig. 5). While structural repointing is a well-established strengthening technique for masonry, existing literature suggests that experimental data remain limited—particularly regarding the effectiveness of reinforcing steel bars as shear reinforcement and their performance in thick masonry elements [43]. Research on this technique has explored a variety of reinforcement and filler materials in solid and hollow clay brick masonry, as well as in hollow concrete blocks. Reinforcement materials studied include Glass-Fiber Reinforced Polymer (GFRP) bars—both smooth and sand-coated, including pre-stressed applications—twisted stainless steel bars, helical steel bars, Carbon-Fiber Reinforced Polymer (CFRP) bars, and basalt-fiber bars. Filler materials have ranged from epoxy-based pastes and conventional cement-based mortars to latex-modified cement pastes, thixotropic grouts, hydraulic lime, and pozzolanic mortars. Widely used for strengthening historic masonry constructions, NSM reinforcement is particularly suited for walls with regular horizontal joints. The technique is considered moderately invasive and largely reversible,

as both the mortar and the embedded reinforcement bars can be removed if necessary. This removability, along with its relatively low impact on the original structure, makes NSM reinforcement a favorable option for conservation-sensitive applications where maintaining the integrity of historic masonry is a priority.

4. Experimental database

4.1. Database overview

A comprehensive review of the above strengthening strategies was conducted using results from 65 academic papers published between 2000 and 2023. The studies are summarized in Table 1. Experimental campaigns of URM elements under cyclic lateral load with pre-compression (INP tests: 25 papers) and diagonal compression (DCT tests: 40 papers) were included, with a total of 709 specimens analyzed, being 546 tested under DCT (77%) and 163 under INP conditions (23%) (Fig. 6a).

The specimens were categorized into three groups (Fig. 6b): non-intervened control URM specimens (REFE), specimens subjected to specific damage thresholds and then repaired and retested (REPA), and specimens retrofitted before testing (RETRO). Most results focus on retrofitted specimens, driven by the high prevalence of DCT tests, which are generally conducted to induce extensive damage. In contrast, INP tests are displacement-controlled, targeting specific damage thresholds that facilitate repair and retesting. Despite this, repaired specimens are scarcely addressed in the literature (5%, as shown in Fig. 6b), even though interventions are typically motivated by repairing existing damage rather than proactive retrofitting before earthquake events.

Recent studies have shown a growing interest in innovative strengthening techniques, such as FRCM and FRP, particularly in DCT tests (Fig. 6c). However, these methods raise concerns about their compatibility, removability, and the potential for aesthetic alteration of heritage structures. RPL and NSM have also been widely investigated in both INP and DCT tests, whereas SST, despite its reliability in conservation principles, remains less explored. In the dataset, DCT and INP tests were performed on specimens with aspect ratios (height-to-length) ranging from 0.9 to 1.2 and from 0.5 to 2.0, respectively.

The prevalence of solid clay units (SCL) in URM specimens is noticeable throughout the evaluated period of available literature (see Fig. 7a), accounting for 61% of the total dataset, followed by Hollow clay units (HCL) at 17%. This trend seems reasonable, considering that clay units are commonly found in heritage structures. Both SCL and HCL units displayed an average compressive strength in the ranges of 6.7–49.0 MPa and 2.0–28.6 MPa, respectively.

Other unit materials were found in a small percentage (6%) of tests following either hollow concrete blocks (HRC) or solid concrete units (SRC); and solid tuff units (STU), a common material found in the south of Italy [78], have been found in the dataset with a range in compressive strength between 2.0 – 8.0 MPa. Mortars were typically found in

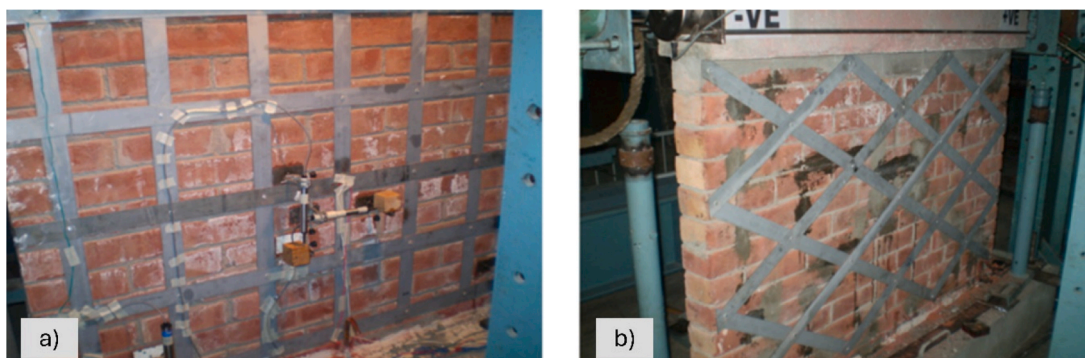


Fig. 4. Steel strips: (a) Square Steel Mesh, (b) diagonal Steel Mesh [41].

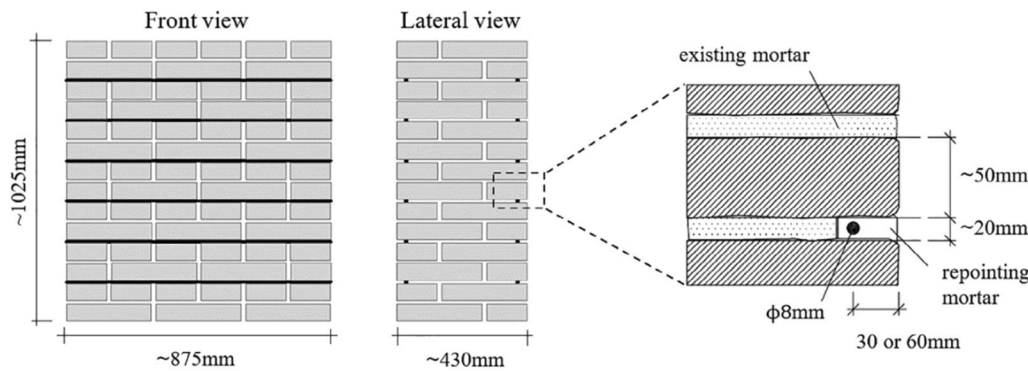


Fig. 5. Details of near-surface mounted (NSM) intervention [43].

Table 1
Comprehensive Review of In-Plane Strengthening Strategies for URM Structures (2000–2023): Reinforced Plasters (RPL), Fiber-Reinforced Polymers (FRP), Fabric-Reinforced Cementitious Matrix (FRCM), Steel Strips (SST), and Near-Surface Mounted (NSM).

Reinforced plasters (RPL)	
RPL-INP	Moeini et al. [44], Deng et al. [45], Hasnat et al. [46], ElGawady et al. [33], Choi et al. [47], Facconi et al. [48], Shabdin et al. [49], Messali et al. [50]
RPL-DCT	Sandoval et al. [51], Shermi & Dubey [52], Kadam et al. [53], Biolzi et al. [31], Lin et al. [35]
Fiber-reinforced polymers (FRP)	
FRP-INP	Zamani & Yamaguchi [54], Mossallam & Banerjee [55], ElGawady et al. [56], Farooq et al. [57], Alcaino & Santa Maria [37], Zhou et al. [58], Wang et al. [59], Marcari et al. [60]
FRP-DCT	Mahmood & Ingham [36], Valluzzi et al. [61], Kalali & Kabir [62], Gattesco et al. [63], Santa Maria et al. [64], Silva et al. [65], Jafari et al. [66]
Fabric-reinforced cementitious matrix (FRCM)	
FRCM-INP	Ismail & Ingham [67], Papanicolaou et al. [68]
FRCM-DCT	Almeida et al. [69], Gattesco & Boem [70], Corradi et al. [71], Menna et al. [38], Sagar et al. [72], Micelli et al. [73], Incerti et al. [74], Del Zoppo et al. [75], Borri et al. [76], Babaeidarabad & Nanni [77], Prota et al. [78], Faella et al. [79], Marcari et al. [80], Shabdin et al. [81], García-Ramonda et al. [39], Donnini et al. [82], Castori et al. [83]
Steel strip (SST)	
SST-INP	Taghdi et al. [84], Farooq et al. [41], Darbhanzi et al. [85]
SST-DCT	Borri et al. [86]
Near-surface mounted (NSM)	
NSM-INP	Konthesingha et al. [87], Jing et al. [88], Yao et al. [89], Soti & Barbosa [90]
NSM-DCT	Soleymani et al. [91], Misnon et al. [92], Shahzamani & Eftekhari [93], Petersen et al. [94], Dizhur et al. [95], Turco et al. [96], Li et al. [97], Casacci et al. [98], Sandoval et al. [43], Ismail et al. [99]

proportions based on cement:sand (CEB) ratios between 1:1–1:7 and observed average compressive strength between 1.5 – 18.7 MPa; cement:lime:sand (LMCB) ratios between 1:1:6–1:2:10 with average compressive strength between 0.8 – 8.6 MPa and, lime-based mixtures with lime:sand ratios between 1:3–1:5 (Fig. 7b) with average compressive strength between 0.9 and 7.8 MPa. While the above mixtures are equally distributed in the dataset, other binder materials are scarce, consisting mainly of pozzolan and gypsum. Mortar mixtures were typically designed to achieve low compressive strengths, as observed in heritage structures. Masonry compressive strength, as a composite (i.e., bricks and mortar), ranged from 1.2 to 32.1 MPa across the entire dataset. Another variable that can influence masonry behavior is the bond pattern. Most tests have been carried out on running bond (RUN) masonry, which accounted for specimens with thicknesses up to

380 mm. English (ENG), Flemish (FLE), and common (COM) bond patterns were used for higher thicknesses, accounting for the header position (HEAD) of the units (Fig. 7c). Consequently, a maximum thickness of 470 mm was observed in the experimental campaigns. It is important to note that historic URM structures generally have wall thicknesses of up to meters, which have not been explicitly addressed in the literature.

When considering a strengthening solution, one must expect its application in a restricted area or limitations in the number of faces in the URM walls due to heritage protection. Single-face applications (1S) can be preferred over double-face (2S) ones (see Fig. 7d), which appear balanced when the INP tests dataset is observed in the literature, with 44% and 56%, respectively. DCT tests seem to be overrepresented in double-faced applications, accounting for 72% of the dataset. It is noted that further research is needed in single-faced applications for diagonal compression tests.

Each subset of interventions has been investigated under many variables, which complicates its direct comparison. However, in the following section, a summary of the main characteristics of each intervention is presented for the reader's knowledge.

4.2. Reinforced plasters (RPL)

The data subset comprises 136 reinforced plaster specimens: 42 underwent INP tests, and 94 underwent DCT tests. The tested URM primarily consists of solid clay units (SCL), representing 79% of the dataset, followed by hollow clay units (HCL) at 20%. Bed-joint mortars are mainly composed of cement:sand mixtures (CEB) in 71% of cases and lime-based mixtures (LMCB) in 34% of tests. Bond patterns vary significantly, with English bond (ENG) comprising 38%, running bond (RUN) 25%, and common bond (COM) 18%.

Retrofitting interventions involved shotcrete/ferrocement (CEM), engineered cementitious composites (ECC), high-performance mortars (HPM), and micro-concrete (MICRO) (Fig. 8). More than two-thirds of the specimens were strengthened using a double-sided scheme, with Portland cement-based admixtures being the preferred choice. The plaster thickness ranged between 10 mm and 60 mm, and the plaster compressive strength ranged from 11.6 MPa to 60.8 MPa. While significant plaster thickness may contribute to added mass and potentially increase seismic loads, this effect has not been explicitly assessed in the literature. Steel wire mesh (STEEL), with a tensile strength ranging from 520 MPa to 1000 MPa, remains the most common reinforcement, typically anchored with bolts. Additionally, stainless steel wire mesh (STAIN) and fiber reinforcements (with tensile strengths up to 2800 MPa) have also been tested. Reinforcement ratios in INP tests were generally below 0.1% of the gross section, while DCT tests exhibited higher ratios, ranging from 0.1% to 0.5%.

Several studies [33,44–50] have investigated the effectiveness of RPL in strengthening URM walls through in-plane (INP) tests for clay and concrete URM wall specimens with aspect ratios ranging from 0.6 to 2.0. These studies examined steel laminates comprising two layers with

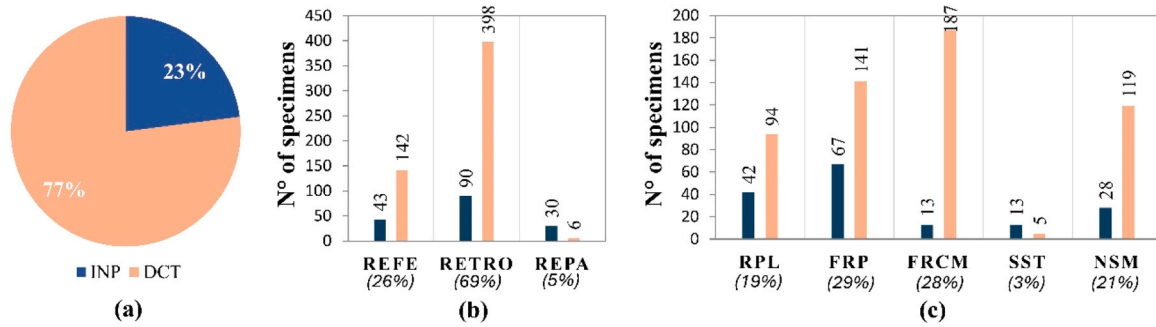


Fig. 6. Composition of the database according to: (a) type of test, i.e., diagonal compression (DCT) or in-plane cyclic lateral load (INP) tests; (b) types of specimen i.e., reference specimens (REFE), repaired specimens (REPA) and retrofitted specimens (RETRO); (c) strengthening techniques: reinforced plasters (RPL), fiber reinforced polymer bands (FRP), fiber reinforced composites materials (FRCM), steel strips (SST), and near-surface mounted (NSM).

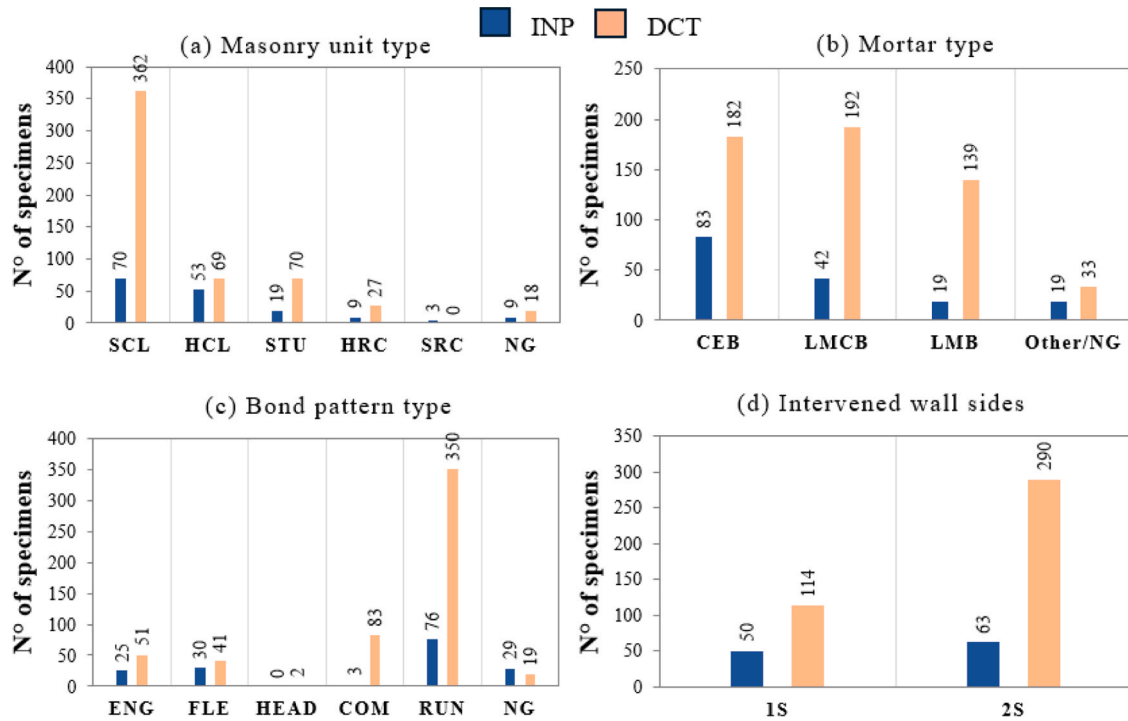


Fig. 7. Masonry feature distribution considering (a) masonry unit: solid clay (SCL), hollow clay (HCL), solid tuff (STU), hollow concrete (HRC) or solid concrete units (SRC) and not given (NG); (b) mortar type: cement:sand (CEB), cement:lime:sand (LMCB), lime:sand (LMB); (c) masonry pattern: English (ENG), Flemish (FLE), header (HEAD), common (COM), running (RUN) and not given (NG); and (d) intervened wall sides: single-face applications (1S) or double-face (2S).

tensile strengths ranging from 521 MPa to 2800 MPa. Meanwhile, DCT tests were conducted by [31,35,51–53] on solid clay unit URM walls retrofitted with single- and double-sided steel layers. In these tests, reinforcement tensile strength ranged from 558 MPa to 1005 MPa, displaying lateral load capacity improvements of up to 4.15 times that of control specimens in INP tests and a maximum increase of 15.28 times in diagonal load capacity for DCT tests.

4.3. Fiber reinforced polymer bands (FRP)

The FRP sub-set comprised 208 specimens, including 67 for INP tests and 141 for DCT tests, exhibiting high variations among tested variables, including fabric type, configuration of the reinforcement (i.e., horizontal/vertical/diagonal strips or full wrapping of the specimen), and amount of reinforcement (number of layers). The tested URM walls were mostly composed of SCL units (48% of the dataset), followed by HCL at 23%. Bed-joint mortars were predominantly cement:sand mixtures (CEB) in 63% of cases, followed by lime-based mixtures (LMCB) with

lime:sand ratios in 22% of the tests. Most tests were conducted on running bond masonry (RUN, 72%).

An equal number of specimens have been tested in both single-sided and double-sided schemes for INP tests, while DCT tests are controlled by double-faced applications. The most common fabric materials in the subset are carbon (CAR) and glass (GLA) fibers, with small additions of aramid (ARA), basalt (BAS), and polyvinyl alcohol (PVA) strips (Fig. 9). FRP strips are usually available in high tensile strengths. Within this subset, tensile strengths of up to 5000 MPa can be found, whose efficiency may be arguable in terms of early failure modes such as delamination or debonding. The modulus of elasticity of the fabric was mainly kept below 100 GPa; however, one-third of the specimens were retrofitted using fabric with a modulus of elasticity around 250 GPa. In any case, compatibility between the fabric's modulus of elasticity and that found in the masonry substrate is not explicitly addressed by the authors.

Several studies have investigated FRP retrofitting techniques for URM walls, including works by [37,54–60], which focused on INP tests

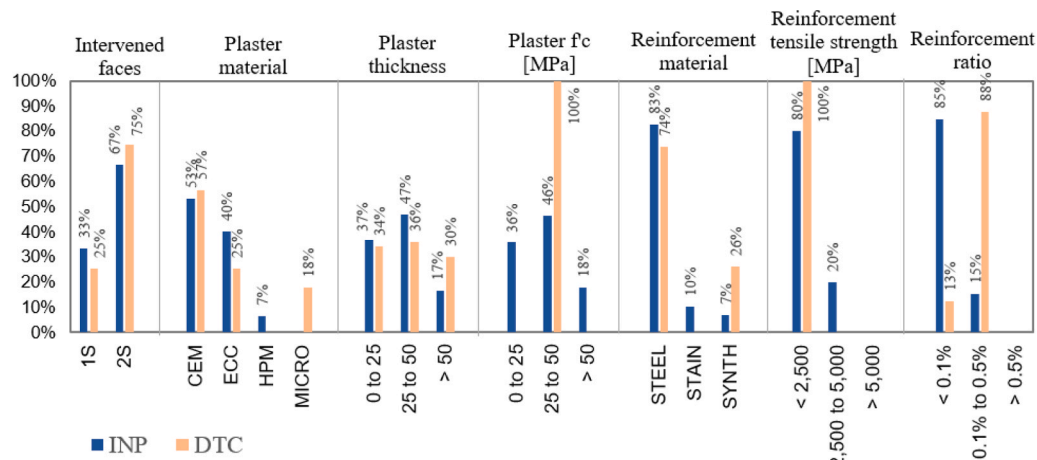


Fig. 8. Reinforced plasters (RPL) sub-set distribution.

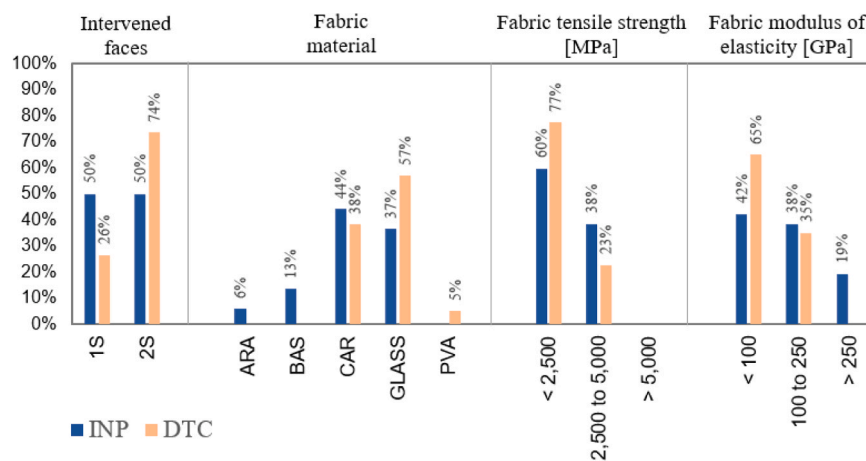


Fig. 9. Fiber-reinforced polymers (FRP) sub-set distribution.

of clay- and concrete-URM wall specimens with aspect ratios ranging from 0.70 to 1.40. These studies explored FRP fabrics such as carbon, glass, aramid, and basalt sheets applied in diagonal, horizontal, vertical, or full-face wrapped configurations, with laminates consisting of one or two layers and tensile strengths varying between 510 MPa and 4300 MPa. In DCT tests, [36,61–66] tested solid clay unit URM walls retrofitted with single- and double-sided applications, using carbon, glass, and polyvinyl alcohol composites in diagonal, wrapped, and meshed configurations, with some specimens reinforced with up to six

FRP layers. Tensile strengths ranged from 400 MPa to 3430 MPa, and test results indicated lateral load capacity increment between 1.12 and 5.93 times that of control specimens in INP tests, and 0.87–4.32 times in diagonal load capacity in DCT tests.

4.4. Fiber-reinforced composite materials (FRCM)

The FRCM subset predominantly comprises specimens tested under DCT, accounting for 187 out of the 200 specimens reviewed, while only

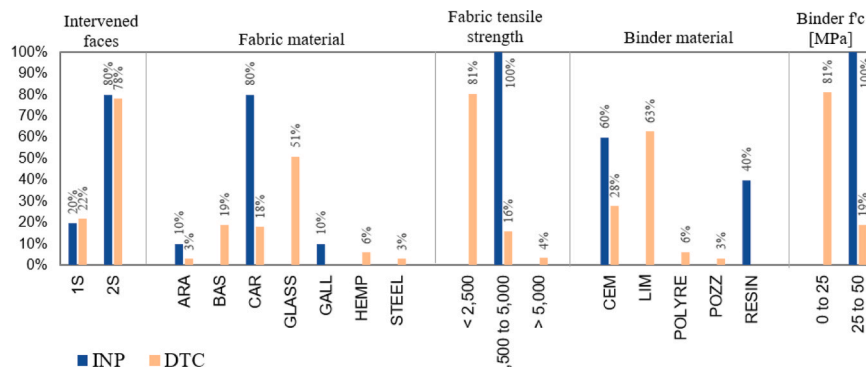


Fig. 10. Fiber reinforced composite materials (FRCM) sub-set distribution: one (S1) or two (S2) intervened faces; composite type: aramid (ARA), basalt (BAS), carbon (CAR), glass (GLA), galls (GALL); f'c of matrix, ft of strips; and matrix types.

13 were tested under INP. In terms of masonry typology, solid clay units (SCL) represent 53% of the dataset, followed by stone units (STU) at 35%. Most of the tests were conducted on running bond masonry (RUN, 74%), with bed-joint mortars primarily composed of lime-based mixtures (LMB) in 58% of cases, while lime-cement-based mortars (LMCB) were used in 22% of the specimens. In this subset, most double-faced applications are remarkable for both INP and DCT tests (Fig. 10). Similar to FRP applications, carbon and glass fabrics are usually chosen as reinforcement materials. Aramid (ARA), basalt (BAS), and the use of galls (GALL), hemp (HEMP), and even steel chords (STEEL) have also been tested to a minor extent.

Usually, fully covered specimens with a single layer of composite are applied; however, some specimens were reinforced with two or four layers as a variable in the study. Fabric tensile strength is similar to that found in the FRP subset. Inorganic matrix layers were applied in a thickness much smaller than the RPL subset, ranging from 4 mm to 40 mm. This characteristic is most advantageous in reducing inertial forces due to added mass. Most matrices are made up of cement (CEM) and lime (LIM) mixtures, but also, pozzolan (POZZ), an inorganic binder reinforced with polymers (POLYRE), and even resin (RESIN) have also been tested. The variation in matrix compressive strength ranges from 2.7 MPa to 44 MPa.

[38,39,69–83] investigated a set of URM wall specimens constructed with concrete block, solid clay, and solid tuff units. The specimens comprised single and double-wythe masonry leaves. The FRCM strengthening technique was applied to both single and double-sided specimens using carbon, glass, and basalt fibers. The tensile strength of the fiber strips ranged from 739 MPa to 5800 MPa, while the mortar matrix compressive strength ranged between 8.0 MPa and 39.4 MPa. As a result, the ratio of increase in maximum diagonal load compared to the unreinforced specimen was found between 0.89 and 65.74. It is essential to note that, in some instances, FRCM systems can be anchored into URM walls using transverse fiber connections. INP tests were found in lower amounts, as reported by Ismail and Ingham [67] and Papanicolaou et al. [68], in URM wall specimens made from solid and hollow clay units with aspect ratios of 1.43 and 1.63, respectively. Within these campaigns, aramid and carbon fabric composite strips were tested and applied to one side and both sides of specimens. The tensile strength of strips ranged from 2070 MPa to 3350 MPa. URM wall specimens were built in single and double-wythe configurations. Additionally, in these tests, the lateral load capacity ratios ranged from 1.30 to 25.42 times those of the control specimens, representing a significant increase.

4.5. Steel strips (SST)

The steel strips subset represents the least studied intervention, with

only 18 test results reported in the reviewed literature. Of these, 13 specimens were tested under in-plane (INP) conditions, while 5 underwent diagonal compression (DC) tests. The tested masonry consisted of SCL units (89% of the subset) and lime-cement-based (LMCB) bed-joint mortars (72% of the specimens). In terms of bond patterns, 44% of the specimens were constructed in a running bond (RUN) arrangement, while ENG and FLE patterns were each used in 28% of the cases. INP tests are mostly implemented in single-sided configurations, whereas DCT tests are only found in double-sided applications (Fig. 11). Steel strips are arranged in various patterns, including diagonal and meshed (horizontal and vertical or diagonal), and are typically anchored through steel bolts inserted into drilled holes filled with epoxy resin. Low-carbon steel (STEEL) and stainless steel (STAIN) have been tested as preferred materials. The average yield stress of steel elements was found to range from 227 MPa to 797 MPa. Reinforcement ratios were kept low in the range of 0.05% - 0.16%.

INP tests using this technique have been carried out by [41,84,85] on hollow concrete and solid clay URM wall specimens with aspect ratios between 0.57 and 1.0. Tested configurations included diagonal and vertical strip arrangements on one or both sides of the walls. The strip width ranged from 25 mm to 220 mm, with a thickness of 3.81 mm. There are a few concerns about the anchorage system, but it is typically provided using 5 mm to 9.5 mm diameter steel bolts, fixed through the thickness of the wall, or epoxy resin. Improvements in structural parameters for INP tests ranged from 0.84 to 12.83 times that of the control specimen. Borri et al. [86] conducted DCT on masonry walls, diagonally reinforced on the tension side on both faces, and reported diagonal load capacity increases ranging from 1.37 to 1.71 times. The limited number of studies on SST reinforcement suggests the need for further research to understand better its impact on the structural performance of URM walls.

4.6. Near-surface mounted (NSM)

The near-surface mounted (NSM) subset comprised 147 test results, with 28 specimens subjected to in-plane (INP) tests and 119 to diagonal compression (DCT) tests. Predominantly tested masonry is composed of solid clay units (71% of the dataset), lime-cement-based mortars (LMCB, 66% of the cases), and running bond (RUN, 60% of the specimens) arrangement. It is worth noting that many variables are related to the application of the technique, including the reinforcement element and shape, the number of inserted bars, the groove dimension, and the embedment material.

A balanced distribution between single-sided and double-sided applications is observed in both INP and DCT tests for this intervention (Fig. 12). Embedded reinforcement elements are found, including a

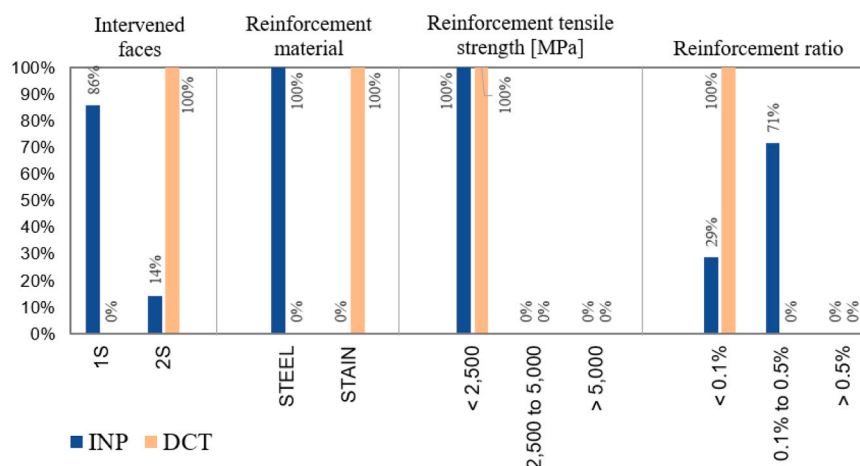


Fig. 11. Steel strips (SST) sub-set distribution, (b) and (c) diagonal configurations of interventions; (d) and (e) meshed configurations.

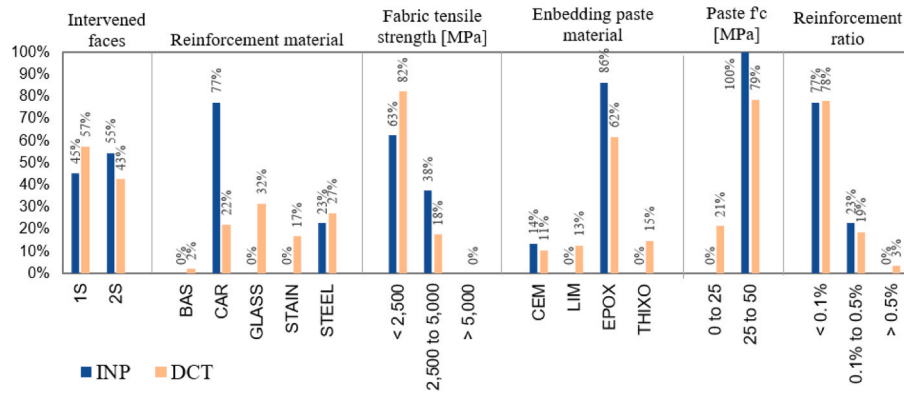


Fig. 12. – Near surface mounted (NSM) sub-set distribution: side one (S1) or two (S2) of intervened faces; basalt (BAS), carbon (CAR), glass (GLA), stainless steel (STAIN), steel (STEEL); cement-based mortar (CEM), natural lime (LIM), epoxy resins (EPOX), and thixotropic mixtures (THIXO).

large proportion of tests with composites made of carbon (CAR) and glass (GLA) in the form of strips (rectangular) or round bars, and a minority of basalt (BAS) elements. Steel (STEEL), stainless steel (STAIN), and bars have also been explored in this technique. Reinforcement tensile strengths are typical of those described above in other subsets. Groove-filling material is found in one-third of the subset, based on cement-based mortar (CEM), natural lime (LIM), and thixotropic mixtures (THIXO). At the same time, most tests have been carried out using epoxy resins (EPOX). Epoxy displayed a high compressive strength of 70–100 MPa, in contrast to other paste mixtures, which ranged from 5 to 48 MPa. Finally, low reinforcement ratios below 0.10% accounted for more than three-quarters of both INP and DCT tests, due to limited space to allocate reinforcing elements (bed-joint).

The performance of the NSM reinforcement technique as a strengthening method for enhancing the shear response of URM elements has been investigated primarily through diagonal compression tests. For this review, experimental campaigns carried out by [43, 91–99] were selected. Within this set of tests, URM walls composed of single-, double-, or triple-masonry leaves can be found, built with solid clay and hollow concrete units glued with a lime-mortar mix. Tested reinforcement configurations included the insertion of CFRP strips (15 mm/30 mm × 1.2 mm), rectangular CFRP (15 mm × 2.8 mm), circular GFRP elements (φ 6.35 mm), as well as steel and galvanized steel bars and ladders (φ 3.6 mm - 6.35 mm). Reinforcement elements were allocated in saw-cut grooves with variable depths between 6 and 35 mm and widths between 6 and 9.5 mm. The tensile strength of the tested reinforcement elements ranged between 824 MPa and 3100 MPa. The reinforcement ratio for URM walls ranged between 0.003% and 0.10% (1–7 reinforcement elements in one direction). The reinforcement arrangement included both horizontal and vertical directions. Glue materials for joint filling included epoxy, lime, cement, and latex plus cement mix. Measured split tensile strengths ranged from 5.6 MPa to 18.5 MPa. The shear strength increase ratio found for these specimens was 0.63–9.71 times that of control specimens. Konthesingha et al. [87] conducted an extensive experimental campaign on full-scale URM wall specimens subjected to cyclic lateral loads and constant vertical actions. Single-wythe, solid clay walls, with an aspect ratio between 0.5 and 1.0, were reinforced using NSM with CFRP rectangular bars within 15 mm / 30 mm × 8 mm epoxy-filled grooves. Typical bar sections used were 15 mm × 1.4 mm. URM walls were reinforced in horizontal and horizontal plus vertical patterns with reinforcement ratios ranging from 0.022% to 0.088%. The measured tensile split strength was found to be 24 MPa. The resulting lateral load ratio ranged from 0.86 to 1.24, similar to that of the control specimens.

5. Structural factors: load capacity and ductility

An overview of the contribution of each strengthening technique in

terms of the load capacity factor (R_t / R_0), and the ductility factor (μ_t / μ_0) is presented below. As explained in Section 2.2, R_t refers to the peak strength of the retrofitted or repaired specimen, R_0 represents the peak strength of the control specimen (or the average of control specimens), μ_t corresponds to the ductility of the retrofitted or repaired specimen, and μ_0 is the ductility of the control specimen (or the average of control specimens). While the load capacity factor is evaluated at maximum capacity between the retrofitted/repaired and control specimens, the ductility factor is calculated using various methods, based on ultimate displacement at 75%, 80%, or 85% of the maximum load. It is worth noting that, due to the high data dispersion observed in the experimental results, values of load and ductility factors within a range of three times the standard deviation of each subset were considered representative in this article.

Perhaps the most important mechanical property in the structural design of masonry is its compressive strength f_m [100–102]. Even in the absence of experimental results, this property is often used to estimate other key mechanical properties, such as elastic modulus, shear strength, and tensile strength. Since most experimental campaigns report masonry's compressive strength, this parameter has been selected as an indicator of masonry's structural quality to evaluate and compare the effects of the different strengthening techniques investigated. Consequently, the contribution of each method to the structural performance of the tested specimens is conveniently related to the masonry compressive strength declared in each experimental campaign. This simplification may be a limitation of the study, but exploring these relationships provides an initial screening test for a complex problem, such as comparing the effect of different strengthening techniques on the shear capacity of walls built with various types and qualities of masonry. Furthermore, for the purposes of this study, the masonry quality of specimens has been categorized into three levels according to compressive strength: low ($f_m \leq 5$ MPa), moderate ($5 \text{ MPa} < f_m \leq 10$ MPa), and high ($f_m > 10$ MPa).

Fig. 13 depicts the relationship between the compressive strength of masonry (f_m) and the strength increment (R_t / R_0) assessed under INP and DCT testing for all the analyzed techniques. The trend lines in Fig. 13a reveal distinct load-capacity behaviors for each technique under the INP test. FRCM (blue dashed line) demonstrates a rapid decline in effectiveness as f_m increases but exhibits higher capacity factors in low-strength masonry than the other strategies. SST (green dashed line) and RPL (yellow dashed line) show a relatively similar positive slope, indicating an improvement in capacity for masonry specimens with higher compressive strength, with SST slightly outperforming RPL in load capacity factors across all f_m ranges. FRP (purple dotted line) remains relatively constant across all f_m ranges, though with limited gains. NSM (black dashed line) performs consistently but shows no significant improvements, reflecting clear limitations in its

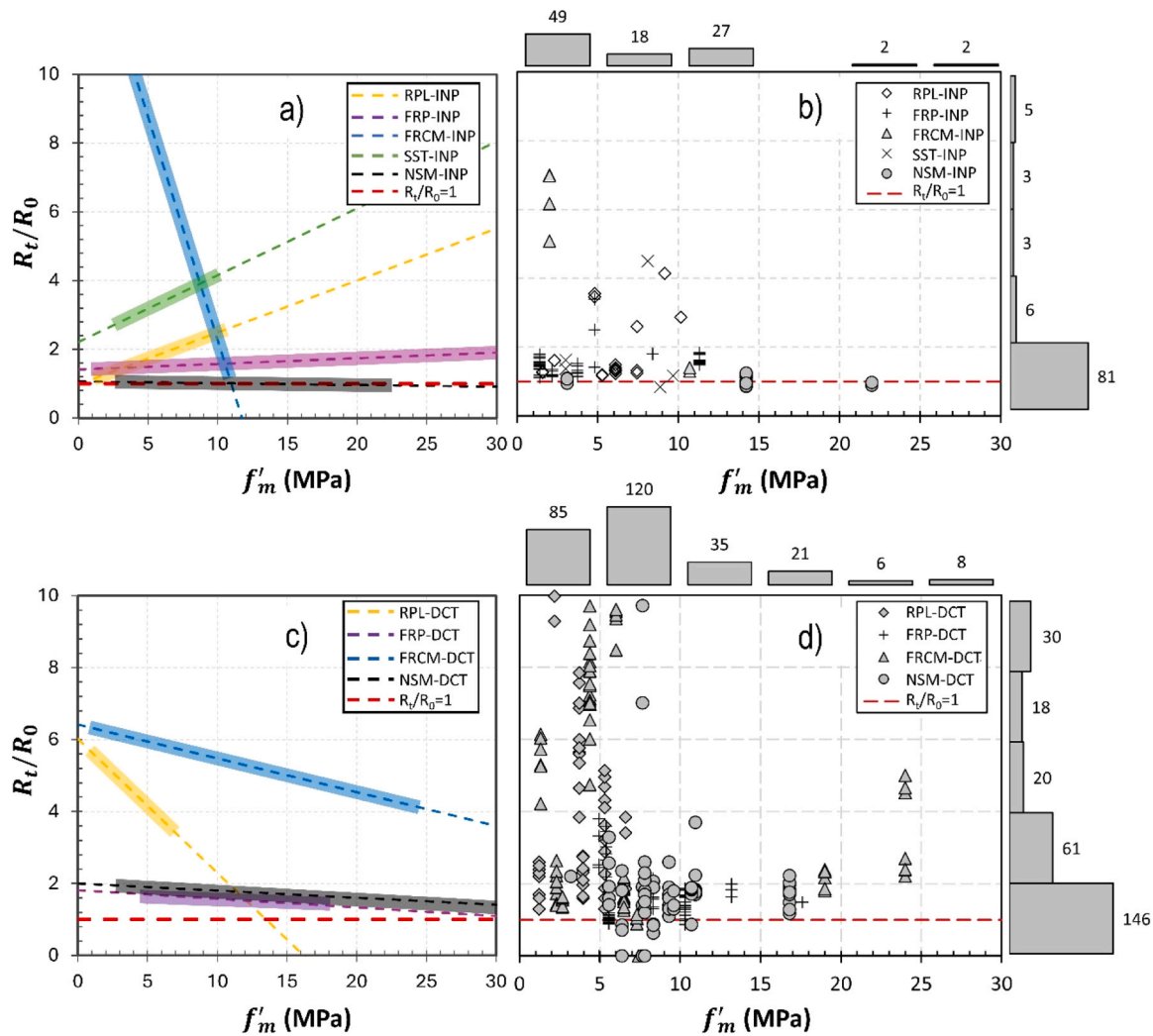


Fig. 13. Relationship between strength increment (R_t/R_0) and masonry compressive strength (f'_m) for the analyzed strengthening techniques (RPL, FRP, FRCM, SST, and NSM): (a) trend lines and (b) scatter plot under INP tests; and (c) trend lines and (d) scatter plot under DCT tests (the experimental ranges are shown in wider lines).

effectiveness. In the scatter plot in Fig. 13b, most data points are concentrated in the $f'_m < 5$ MPa range, indicating that the tested specimens had low compressive strength. Variability in the strength increment (R_t/R_0) is significant in this range, especially for FRCM and RPL. For $f'_m > 15$ MPa, the available data are scarce; therefore, the observed negligible strength increments should be interpreted as a preliminary tendency, indicating a potentially limited impact of these techniques on masonry elements with high compressive strength, while acknowledging that further experimental evidence is required to confirm this behavior. Among the methods, RPL and FRCM exhibit the most significant variability, whereas SST and FRP deliver more consistent, but smaller, increments in low-strength masonry.

The trend lines in Fig. 13c illustrate the performance of the different reinforcements when applied to unreinforced masonry specimens subjected to diagonal compression. In DCT tests, all results tend to decrease as f'_m increases. Both RPL-DCT and FRCM-DCT show a steeper decline in the strength increment as the compressive strength of masonry increases. In contrast, FRP-DCT and NSM-DCT exhibit more stable responses across a broader range of f'_m , suggesting they may be more suitable for applications requiring consistent performance. SST-DCT results in terms of load capacity were either not available or not representative of the database. The scatter plot, Fig. 13d, shows data concentrated in the $f'_m < 10$ MPa range, where variability in

effectiveness is high. For higher f'_m values (20–35 MPa), results are sparse, and strength increments are modest, suggesting limited impact for high-strength masonry. It is important to note that the regression lines in Fig. 13a and c have been extended beyond the limits of the available experimental data solely to illustrate the trends suggested by the available data set; therefore, they are not intended for predictive use. In these figures, the parts within the experimental ranges (thick lines) and the extrapolations have been indicated differently for each trend line.

Fig. 14 explores the relationship between ductility increment (μ_t/μ_0) and compressive strength (f'_m) under INP and DTC tests, respectively. In Fig. 14a, only RPL-INP showed a positive trend in ductility with higher f'_m . Conversely, FRP-INP, SST-INP, and NSM-INP exhibited a declining trend, indicating limited effectiveness in improving ductility as f'_m increases. However, in the low-strength masonry range ($f'_m < 5$ MPa), there is evidence of a significant contribution to ductility. In Fig. 14b, the scatter plot highlights a concentration of results in the low f'_m range, where considerable variability is observed. Conversely, DCT tests (Fig. 14c) tend to increase ductility as f'_m increases, except for NSM-DCT. RPL-DCT and FRP-DCT demonstrate high effectiveness in improving ductility for low-strength masonry ($f'_m < 5$ MPa), exhibiting a sharp increase for higher values. FRCM-DCT shows a more gradual increase in

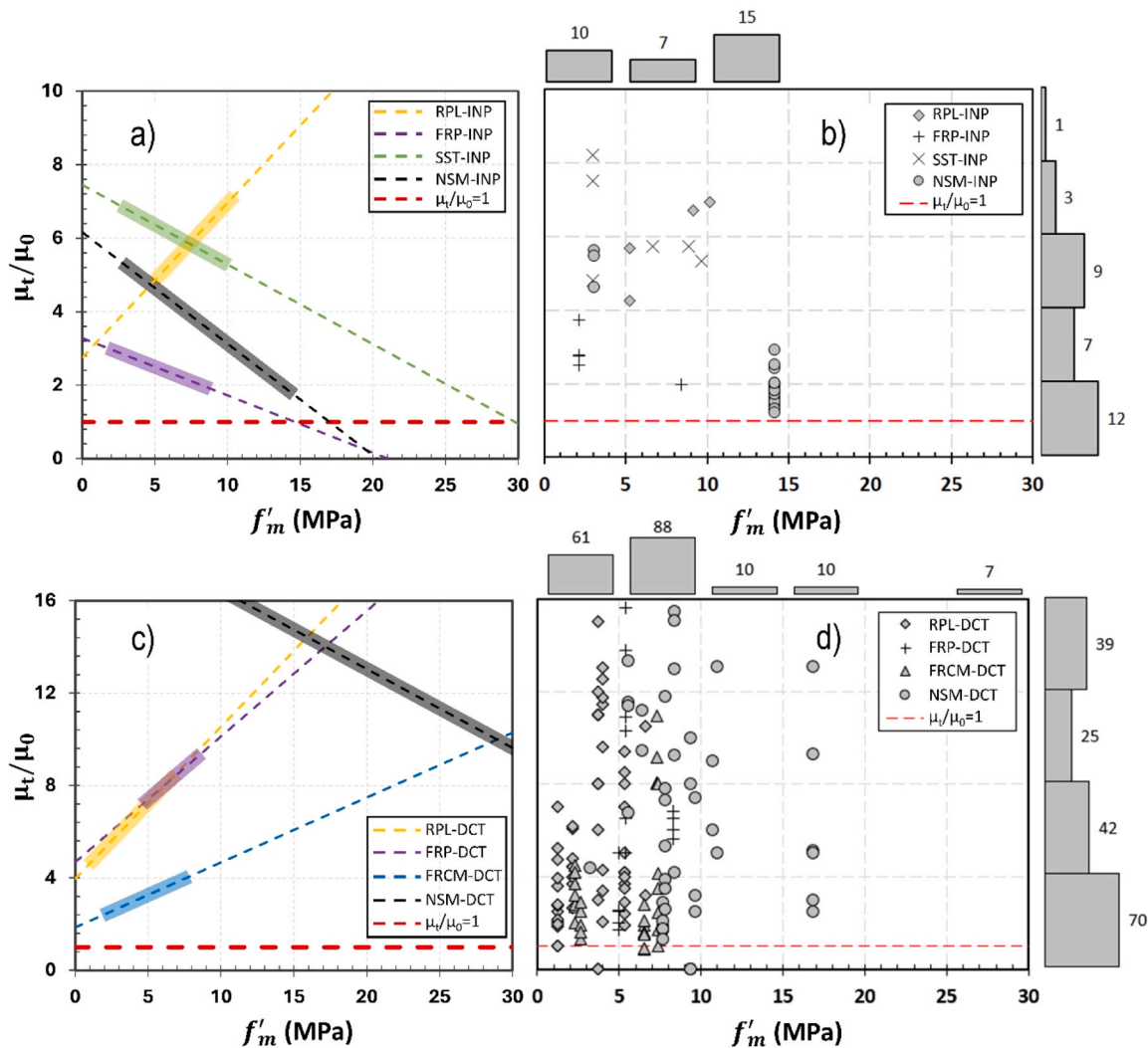


Fig. 14. Relationship between ductility increment (μ_t/μ_0) and compressive strength (f'_m) for the analyzed strengthening techniques (RPL, FRP, FRCM, SST, and NSM): (a) trend lines and (b) scatter plot under INP tests; and (c) trend lines and (d) scatter plot under DCT tests (the experimental ranges are shown in wider lines).

performance, offering moderate and more consistent results across a broader range of f'_m . NSM-DCT displays very high values of ductility in low-strength masonry compared to other strategies, standing as a preferable technique in this f'_m range. The scatter plot, Fig. 14d, further reveals significant variability in the data and very few incursions into the high f'_m ranges. Again, the regression lines in Fig. 14a and c have been extended beyond the available experimental data.

The comparison of INP and DCT results obtained for R_t/R_0 versus f'_m for the analyzed strengthening techniques is shown in Fig. 15a-d, to verify consistency. The trend lines, considering the type of test, behave as follows:

- RPL-INP and RPL-DCT are not consistent in the load capacity factor. While INP tests showed an increasing trend as f'_m increased, DCT tests displayed a decreasing trend. Furthermore, DCT tests indicate that the RPL strategy is unsuitable in terms of capacity for $f'_m > 15$ MPa, since no positive contribution is expected for further ranges.
- FRP-INP and FRP-DCT displayed a relatively constant trend, even though it is positive for INP and negative for DCT. However, it can be observed that the strategy is applicable across all f'_m ranges; however, the load factor barely surpasses twice the capacity of the control specimens for both tests.

- FRCM-INP and FRCM-DCT consistently indicate a downtrend in capacity factor for higher-quality masonry. However, INP results suggest that the strategy is unsuitable for $f'_m > 10$ MPa. It is worth noting that FRCM, in low-quality masonry, is a technique with the highest capacity ratios, easily outperforming the other strategies.
- NSM-INP and NSM-DCT show remarkable consistency in trending lines and load capacity values. The trend is relatively constant across all f'_m . However, the NSM technique achieves a maximum capacity that is only 2 times that of the control specimen, which is low compared to other strategies for low-strength masonry.

Fig. 15e-g shows the trend lines of μ_t/μ_0 versus f'_m for the analyzed strengthening techniques under INP and DCT tests. The following findings can be summarized from these results:

- RPL-INP and RPL-DCT show a consistent positive trend in ductility factor towards higher values of f'_m , being RPL-DCT slightly steeper. However, for low-strength masonry, ductility increments of up to 5 times those of the control specimens are observed, indicating a significant improvement in the deformation capacity of the specimens.
- FRP-INP and FRP-DCT show opposite trends in terms of f'_m ranges. INP tests resulted in a downtrend in the ductility factor, showing no significant results for $f'_m > 15$ MPa. DCT tests displayed a steep

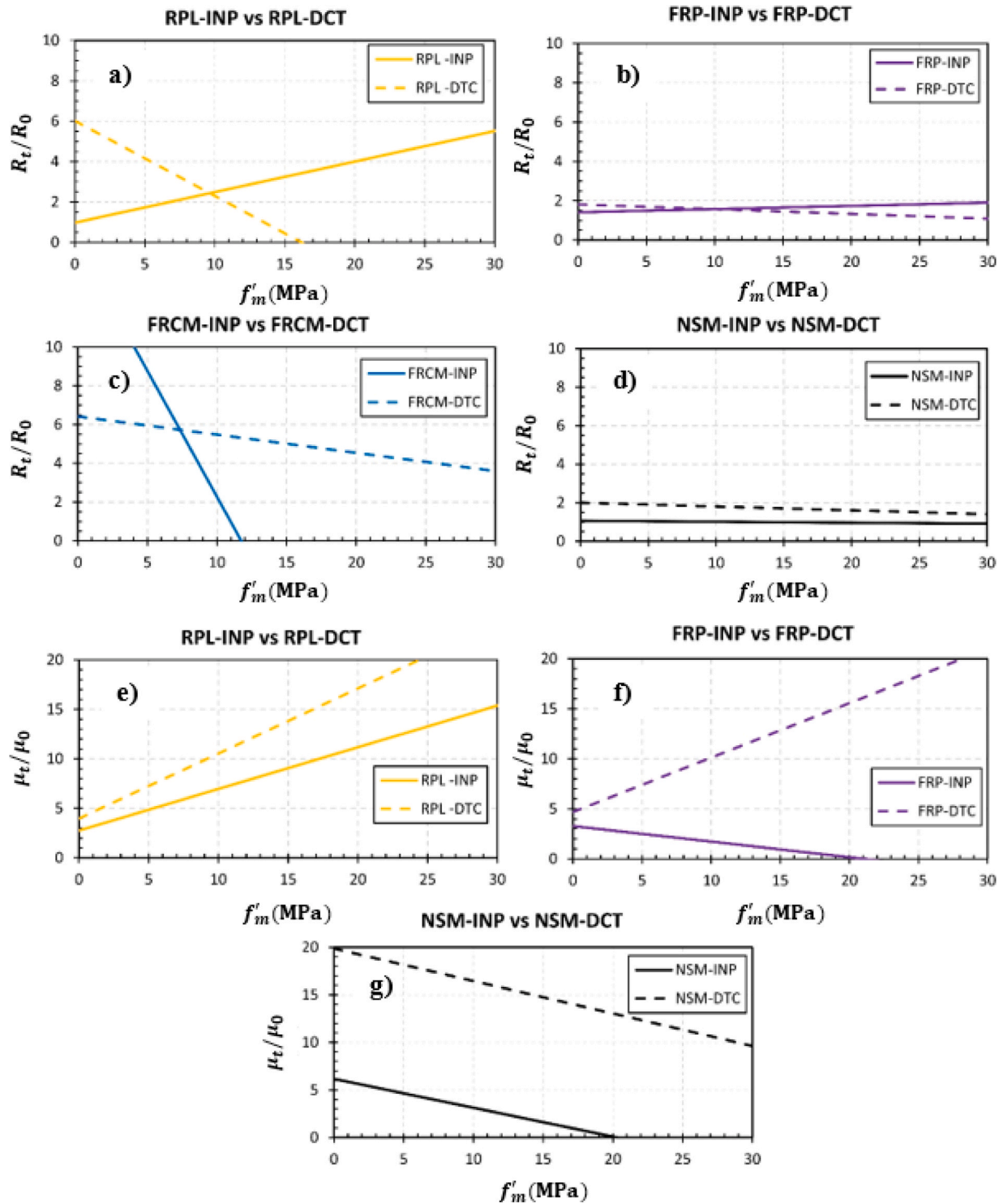


Fig. 15. – Comparison of load capacity increase (R_t/R_0) (a-d) and ductility increase (μ_t/μ_0) (e-g) trends under in-plane cyclic lateral load tests (INP) and diagonal compression tests (DCT) for the strengthening techniques analyzed.

positive trend as f'_m increased. Similar to RPL in the low-strength masonry range, the FRP strategy shows a significant improvement in ductility, up to five times that of the control specimens.

- NSM-INP and NSM-DCT exhibit a consistent decline over f'_m ranges at a relatively similar rate. INP tests seem to be suitable for a maximum f'_m up to 20 MPa. In low-strength masonry, the DCT test displayed a significantly higher ductility factor. In contrast, INP tests

showed a similar increase to that observed in the impact of the above strategies on retrofitting techniques and conservation principles.

6. Expert survey

To evaluate the impact of the retrofitting techniques described in Section 3 on modern conservation principles, a focus group of 20 Chilean professionals—10 architects and 10 engineers/civil constructors from public institutions such as the *Ministry of Public Works* (MOP) and

the *National Monuments Council* (CMN), as well as leading private firms—was conducted. This panel was intentionally selected as a specialized expert sample, prioritizing professional experience and direct involvement in strengthening projects of heritage buildings over numerical representativeness. As this work constitutes a pilot study focused on the Chilean context, the survey outcomes reflect culturally embedded conservation practices; however, the methodology is fully replicable and can be expanded to other contexts to explore cross-cultural variability and territorial correlations in expert judgment. Participants assessed the alignment of each technique with conservation principles through a structured survey, providing qualitative insights into their compatibility with heritage values.

As commented in Section 2, the degree of compliance with conservation principles in each intervention is qualitatively evaluated using three judgment categories: full respect (R), partial respect (PR), and no respect (NR) (see Table 2). These categories are directly linked to performance levels based on expert assessments, where the score assigned to the k -th principle is denoted as

γ_{PIk} . The conservation factor (CF) is then calculated using Eq. 3, ensuring that each conservation principle's contribution is proportionally weighted.

6.1. Survey form

To assess expert perceptions of the five reinforcement strategies applied to unreinforced masonry walls within heritage conservation projects, a structured survey was designed. The survey consisted of two sections: the first gathered general information about respondents while ensuring data anonymity (email, profession, country of training in the field of conservation, and country of residence), and the second involved a qualitative evaluation of the reinforcement interventions aimed at increasing the shear strength and/or ductility of URM structures. Selected for their expertise in heritage conservation and structural engineering, the participants evaluated each intervention in accordance with the fundamental conservation principles—*authenticity*, *non-invasiveness*, *compatibility*, *balanced visual impact*, and *removability*—as defined in Section 2. Additionally, respondents evaluated the structural performance of each technique based on its effects on ductility, strength, and stiffness. Respondents did not have access to the results of the literature review of the methods tested while completing the survey. If they had no prior experience with a specific intervention, they were invited to indicate this and refrain from evaluating the method. As illustrated in Fig. 16, which presents two sample evaluations of the Near-Surface Mounted and FRCM-LIM reinforcement techniques, experts assessed each method's alignment considering key conservation principles and its structural effectiveness, following a brief description and an image of its application.

6.2. Survey results

The results from the focus group evaluation of the five reinforcement techniques concerning the conservation principles reveal distinct differences in performance, as shown in Fig. 17. Overall, NSM and FRCM consistently demonstrate a better alignment with conservation principles, showing higher levels of “respect” and “partial respect” for authenticity, non-intrusiveness, compatibility, and balanced visual impact, and less for removability. NSM and FRCM reinforcements are considered less invasive, more compatible with the original materials, and capable of preserving the aesthetic and structural integrity of heritage buildings.

In contrast, RPL and FRP emerge as the least favorable techniques, exhibiting high levels of “No respect” in most categories, particularly in terms of authenticity, non-intrusiveness, and removability. Both methods significantly alter the original features of the building and are more challenging to remove without causing significant damage. Other techniques, such as FRCM+CEM and SST, exhibit varying degrees of

Table 2

Conservation principles ID, judgment category (JC), conservation principle scores (γ_{PIk}) given to each JC, and a description for each conservation principle of performance levels [19].

ID	JC	γ_{PIk}	Performance level description
Authenticity	R	2	Original features of the building (materials, geometry, and constructive details) are not altered, ensuring the original mechanical and resisting principles governing the structure's response (static and dynamic behavior).
	PR	1	Original features of the building (materials, geometry, constructive details) are partially altered, ensuring the original mechanical principles governing the structure's response (static behavior).
	NR	0	The original characteristics of the building (materials, geometries, construction details) are altered, modifying the original mechanical and resistant principles that govern the structure's response (static and dynamic behavior).
Non-Invasiveness	R	3	The intervention does not penetrate inside the original materials, not altering its integrity and original compactness.
	PR	1.5	The intervention partially penetrated inside the original materials, with only minor alteration of their integrity and original compactness.
	NR	0	The intervention penetrated inside the original materials, altering its integrity and compactness.
Balanced visual impact	R	2	The intervention is recognizable and, at the same time, harmoniously integrated with the building's aesthetic qualities and its context, without disturbing the overall vision or imposing on it.
	NR	0	The intervention is either not clearly distinguishable (i.e., false historian) or is clearly distinguishable but disturbs the overall vision of the building, imposing on it.
Compatibility	R	3	Retrofitting intervention is compatible mechanically (e.g., appropriate stiffness, weight, cohesion and deformability in relation to the original structure), physically (e.g., compatible porosity and pore size distribution, minimal impact on moisture transport such as absorption and drying rate, no significant thermal or hygric expansion), chemically (e.g., compatible chemical composition, absence of harmful reactions, and acceptable solubility), as well as rheologically and thermally with the existing structure.
	PR	1.5	Retrofitting intervention is mechanically compatible with the original ones, while presenting slight or moderate incompatibility in physical, chemical, rheological, or thermal characteristics (e.g., variations in porosity and pore size distribution, changes in drying and hygroscopic behavior, differing chemical properties without causing harmful reactions or byproducts).
	NR	0	High level of conflict between the original structure and the retrofitting intervention under dynamic actions.
Removability/Retractability	R	2	New intervention can be removed, generating only minor and repairable damage to the original structure, guaranteeing the possibility of removing the retrofits if better solutions are found in the future.
	PR	1	New interventions can be removed generating moderate damage to the original structure whose repair requires the use of a special technique or interventions.
	NR	0	New intervention cannot be removed or requires generation of severe damage for removal.

B.1. NEAR-SURFACE MOUNTED or reinforced repointing technique combines traditional repointing with incorporating fiber or steel reinforced bars embedded within the horizontal mortar joints. The technique can increase the lateral load-bearing capacity of masonry junctions.



(From Soti et al., 2020)

	Very low resp...	Low respect	Moderate res...	High respect	Very high res...
Authenticity	☐	☐	☐	☐	☐
Non-intrusive...	☐	☐	☐	☐	☐
Compatibility	☐	☐	☐	☐	☐
Balanced visu...	☐	☐	☐	☐	☐
Removability/...	☐	☐	☐	☐	☐

Structural performance:

	Decrease	Original condition mai...	Increase
Ductility	☐	☐	☐
Strength	☐	☐	☐
Stiffness	☐	☐	☐

B.3.1 FRCM with lime mortar. Fiber-reinforced composite materials (carbon, glass, or basalt fibers) with lime mortar are strengthening interventions that contribute to increase the shear resistance capacity and ductility and improve the post-cracking behavior and compressive strength of the wall.



(From CNR, 2020)

	Very low resp...	Low respect	Moderate res...	High respect	Very high res...
Authenticity	☐	☐	☐	☐	☐
Non-intrusive...	☐	☐	☐	☐	☐
Compatibility	☐	☐	☐	☐	☐
Balanced visu...	☐	☐	☐	☐	☐
Removability/...	☐	☐	☐	☐	☐

Structural performance:

	Decrease	Original condition mai...	Increase
Ductility	☐	☐	☐
Strength	☐	☐	☐
Stiffness	☐	☐	☐

Fig. 16. Examples of survey forms for NSM and FRM techniques.

partial respect, indicating moderate performance but with room for improvement, particularly in areas such as compatibility and visual impact. While SST demonstrated moderate performance, it faced criticism for its intrusiveness and limited reversibility. NSM emerged as the highest-rated technique, achieving consistently strong evaluations in authenticity, non-intrusiveness, and reversibility. Importantly, the purpose of this work is not to suggest the use of one technique over another but to provide tools and data to facilitate the informed selection of the most appropriate reinforcement technique. This selection should be made consciously, after a thorough assessment of the advantages and disadvantages of each method, with consideration of both safety requirements and conservation goals.

7. Assessment of Intervention Quality Indexes (IQI)

To ensure a consistent and comparable assessment of the efficiency of different strengthening techniques from both structural and conservation standpoints, the Intervention Quality Indexes were estimated using Eq. 1. In this formulation, the average increase in the safety index ($\Delta\bar{I}_s$) is calculated using the Normalized Structural Index (SI_{nm}), which enables a statistically based evaluation of the structural capacity improvement derived from experimental results collected through the literature review presented in Section 4. The SI_{nm} is based on a reliability indicator (β), defined as the ratio between the mean and the standard deviation of a normalized performance function ($\beta = \mu_g/\sigma_g$), and was calculated for each strengthening technique applied to masonry samples of varying quality. For this study, masonry quality was categorized into three levels according to compressive strength: low ($f_m \leq 5$ MPa), moderate ($5 \text{ MPa} < f_m \leq 10$ MPa), and high ($f_m > 10$ MPa). For each case, the normalized strength was computed as $r_m = R_t/R_0$, where R_t is

the strength of the reinforced specimen, and R_0 is the strength of the corresponding unreinforced control specimen. As established in Section 2.2, the performance function is defined as $g = r_m - 1.4$, where $1.4R_0$ represents the target post-retrofit strength. Subsequently, the Normalized Structural Index (SI_{nm}) was calculated for each reinforcement technique and masonry type (in Table 3) using Eq. 4:

$$SI_{nm} = (\beta_{nt} - \beta_{\min})/(\beta_{\max} - \beta_{\min}) \quad (4)$$

where $\beta_{\min}$ and $\beta_{\max}$ represent the minimum and maximum reliability values across the entire dataset, and β_{nt} is the reliability index according to the masonry quality level n and strengthening method t . It should be noted that Annex 1 explains in more detail the derivation of the Normalized Structural Index used in the present research.

The analysis of the SI_{nm} for the five techniques—RPL, FRP, FRCM, SST, and NSM—reveals significant variability in structural performance, considering both masonry strength and the type of mechanical test. FRCM emerges as the most structurally consistent and effective technique, achieving the highest SI_{nm} under in-plane cyclic loading for low-strength masonry (0.92), and maintaining robust performance under diagonal compression tests across all strength levels (0.53 for $f_m \leq 5$ MPa, 0.20 for $5 < f_m \leq 10$ MPa, and 0.49 for $f_m > 10$ MPa). RPL also demonstrates good behavior under in-plane cyclic tests, with SI_{nm} values of 0.81 and 0.74 for low and medium-strength masonry, respectively. Still, its performance decreases under diagonal compression, particularly for low-strength masonry ($SI_{nm} = 0.33$). FRP, on the other hand, shows a highly variable response: while it reaches excellent values under INP tests for both low-strength (0.74) and high-strength masonry (1.00), it exhibits extreme sensitivity to shear-dominated loading, with SI_{nm} dropping to 0.00 and 0.03 under DCT for medium and high-strength masonry, respectively. SST performs relatively well in cyclic condi-

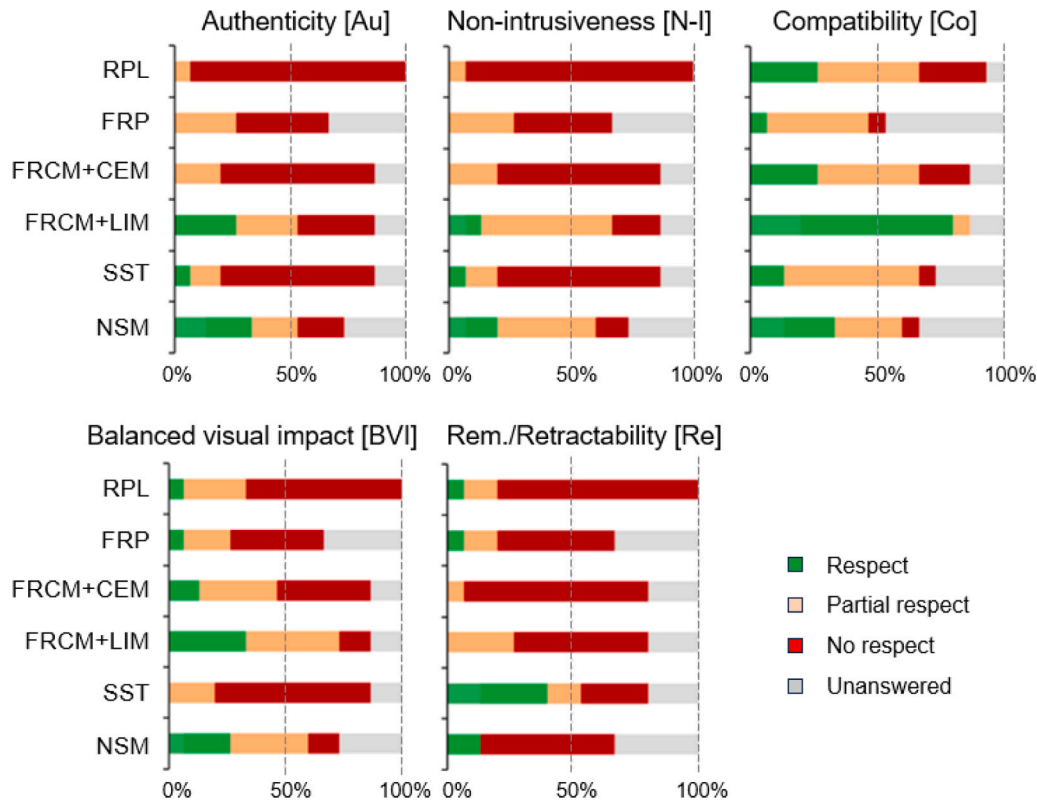


Fig. 17. Results from the focus group of 20 Chilean professionals specializing in conservation, evaluating the alignment of five reinforcement techniques with conservation principles.

Table 3

Normalized structural index (SI_{nm}) calculation for each reinforcing technique.

Technique	Normalized structural index (SI_{nm})					
	INP tests			DTC tests		
	f'_m	$5 < f'_m$	f'_m	f'_m	$5 < f'_m$	f'_m
	≤ 5	≤ 10 MPa	> 10	≤ 5	≤ 10	> 10
	MPa	MPa	MPa	MPa	MPa	MPa
RPL	0,81	0,74	—	0,33	0,62	—
FRP	0,74	—	1,00	1,00	0,00	0,03
FRCM	0,92	—	0,59	0,53	0,20	0,49
SST	0,75	0,79	—	—	—	—
NSM	0,00	—	0,19	—	0,07	0,19

tions (0.75 for low and 0.79 for medium strength), though no data is available for its diagonal performance. NSM consistently yields the lowest structural indices, with values ranging from 0.0 to 0.19, indicating a minimal contribution to seismic resistance under all conditions. The SI_{nm} , derived from INP and DCT tests, shows that FRCM outperforms other interventions in terms of seismic performance. Under INP tests with low-strength masonry ($f'_m \leq 5$ MPa), FRCM achieves the highest SI_{nm} value (0.92), followed by RPL (0.81) and SST (0.75). However, for medium- to high-strength masonry ($5 < f'_m \leq 10$ MPa and $f'_m > 10$ MPa), data availability is limited for some techniques. Nevertheless, FRCM maintains competitive performance with SI_{nm} values of 0.53 and 0.49 under DCT tests. In contrast, NSM exhibits very low structural effectiveness, with SI_{nm} values ranging from 0.0 to 0.19 across all scenarios.

Once the normalized structural indices were computed, the conservation factors for each reinforced intervention were derived based on the outcomes of expert-based focus group assessments (in Table 4), following Eq. 3. Compliance with conservation principles—assessed through a weighted combination of authenticity, non-intrusiveness, compatibility, visual impact, and reversibility—resulted in a CF of

Table 4

Conservation Factor (CF) calculation for each reinforced technique.

Technique	Au	N-I	Co	BVI	Re	γ_{Pl_k}	CF
RPL	0	0	1,5	0	0	1,5	0,13
FRP	0	0	1,5	0	0	1,5	0,13
FRCM	2	1,5	3	2	0	8,5	0,71
SST	0	0	1,5	0	2	3,5	0,29
NSM	2	1,5	3	2	0	8,5	0,71

0.71 for both FRCM and NSM, the highest among all techniques. Conversely, RPL and FRP yielded the lowest CF values (0.13), reflecting limited alignment with heritage conservation criteria.

Finally, the Intervention Quality Indices were estimated and shown in Table 5. When combining structural and conservation criteria using the Intervention Quality Index ($IQI = SI_{nm} \times CF$), FRCM emerges as the only technique to achieve consistently high performance across both dimensions. Specifically, it reaches IQI values of 0.65 (INP, $f'_m \leq 5$ MPa), 0.42 (DCT, $f'_m \leq 5$ MPa), and 0.35 (DCT, $f'_m > 10$ MPa), whereas RPL and FRP remain below 0.13 in all cases. NSM, despite its excellent CF, only

Table 5

Intervention quality index for each reinforced technique.

Technique	$IQI = SI_{nm} \times CF$					
	INP test			DCT tests		
	f'_m	$5 < f'_m$	f'_m	f'_m	$5 < f'_m$	f'_m
	≤ 5	≤ 10 MPa	> 10	≤ 5	≤ 10	> 10
	MPa	MPa	MPa	MPa	MPa	MPa
RPL	0,10	0,09	—	0,04	0,08	—
FRP	0,09	—	0,13	0,13	0,00	0,00
FRCM	0,65	—	0,42	0,38	0,14	0,35
SST	0,22	0,23	—	—	—	—
NSM	0,00	—	0,13	—	0,05	0,14

reaches marginal IQI values (e.g., 0.0–0.14), indicating limited strength contribution based on the available data. However, this evaluation does not fully reflect NSM's potential to enhance ductility and improve seismic response. Due to the lack of data on ductility-related performance, its overall structural contribution may be underestimated. Caution is therefore needed to avoid unfairly associating NSM with poor structural performance. Based on this integrated analysis, FRCM is identified as the most balanced and effective solution for the seismic strengthening of historic masonry buildings, offering a compromise between structural enhancement and conservation ethics. NSM may be recommended when minimal intervention and reversibility are prioritized over structural gain, particularly in heritage sites with low seismic demand.

To assess the influence of weight variability on the IQI ranking, a parametric sensitivity analysis was performed. Each weight w_k was perturbed by $\pm 25\%$ of its baseline value while all other weights were held constant, and the resulting set was renormalized to ensure $\sum_{k=1}^N w_k^{(s)} = 1$. This yielded a total of 11 scenarios: one baseline (original proportional weights), one equal-weight scenario, and for each of the five criteria (Au, NI, Co, BVI, Re), one scenario with the weight increased by $+25\%$ and another with the weight decreased by -25% . For each scenario, the conservation factor (CF) and the IQI were recalculated for the five strengthening techniques considered (RPL, FRP, FRCM, SST, NSM). In formal terms, if $\hat{\gamma}_t = [\hat{\gamma}_1(t), \hat{\gamma}_2(t), \dots, \hat{\gamma}_N(t)]$ is the normalized conservation score vector for technique t , and $w^{(s)} = [w_1^{(s)}, w_2^{(s)}, \dots, w_N^{(s)}]$ is the weight vector for scenario s , then:

$$CF(t, s) = \hat{\gamma}_t \cdot w^{(s)}, \quad IQI(t, s) = SI_{nm}(t) \times (\hat{\gamma}_t \cdot w^{(s)}) \quad (5)$$

where $SI_{nm}(t)$ represents the normalized structural performance index of each strengthening technique. This formulation highlights the linear relationship between conservation weighting and the final IQI, emphasizing the modulating rather than determining role of the conservation component.

The results summarized in Table 6 show that variations in the conservation weights modify the CF values but do not alter the final ranking of techniques. FRCM consistently achieves the highest IQI (0.65), followed by SST, while RPL and FRP obtain lower values due to their reduced compatibility. NSM shows high CF values but negligible IQI due to its minimal structural contribution. These outcomes confirm that the IQI ranking is primarily governed by structural performance, while the conservation weighting acts as a modulating parameter rather than a determining factor.

8. Future work

The results of this study highlight a series of structural and meth-

odological gaps that the wider scientific community must address to enhance the reliability, comparability, and applicability of strengthening assessments for heritage masonry structures. The analysis of 709 experimental tests reveals a marked scarcity of data for certain intervention types—particularly SST under diagonal compression, NSM under in-plane cyclic loading, URM specimens with compressive strengths exceeding 15 MPa, and multi-wythe masonry representative of thick historic walls. Repaired specimens, which are central to post-earthquake scenarios, also remain significantly underrepresented. These gaps limit the statistical robustness of structural indicators and underscore the need for coordinated experimental campaigns to expand the empirical basis for understanding strengthened heritage assemblies across a broader range of material, geometric, and damage conditions. Moreover, the structural response of each strengthening technique may be influenced by configuration-related aspects—such as anchorage details or reinforcement layout—that are not consistently reported in the literature. Because of this limited reporting, these factors could not be incorporated into the SI_{nm} assessment; however, more systematic documentation in future studies would enable performance evaluations that better reflect configuration-specific behavior.

The findings also indicate that inconsistencies in test reporting pose an additional challenge to cross-study comparison. The findings also indicate that inconsistencies in test reporting pose an additional challenge to cross-study comparison. Although both in-plane and diagonal compression tests rely on maximum applied load to quantify strength gains, displacement and ductility are reported heterogeneously, often using non-comparable ultimate displacement criteria or being omitted altogether. This lack of standardization hinders the development of deformation-based performance metrics and complicates integrating strength and ductility into structural indices. Harmonized displacement definitions applicable across testing configurations would allow the scientific community to overcome these inconsistencies and to incorporate both contributions more consistently into performance evaluation frameworks.

On the conservation side, the approach adopted in this study recognizes that territorial and cultural contexts shape conservation practices, and that countries do not necessarily adhere to the same charters, regulatory frameworks, or intervention traditions. For this reason, the authors will extend the scope of the research by exposing the proposed framework to a wider range of territorial and cultural settings. An expanded survey, with members and specialists operating across diverse institutional and geographic contexts, could help to evaluate how conservation principles are interpreted across different professional environments. This effort could also enable the analysis of the applicability of the present methodology—and of additional strengthening techniques—under varying conservation traditions and regulatory conditions, thereby informing a more broadly relevant and internationally

Table 6
Sensitivity analysis of conservation weighting.

		wBase	Au + 25%	Au -25%	NI + 25%	NI -25%	Co + 25%	Co -25%	BVI + 25%	BVI -25%	Re + 25%	Re -25%
w_k	wAu	0,167	0,200	0,130	0,157	0,178	0,157	0,178	0,160	0,174	0,160	0,174
	wNI	0,250	0,240	0,261	0,294	0,200	0,235	0,267	0,240	0,261	0,240	0,261
	wCo	0,250	0,240	0,261	0,235	0,267	0,294	0,200	0,240	0,261	0,240	0,261
	wBVI	0,167	0,160	0,174	0,157	0,178	0,157	0,178	0,200	0,130	0,160	0,174
	wRe	0,167	0,160	0,174	0,157	0,178	0,157	0,178	0,160	0,174	0,200	0,130
CF	RPL	0,13	0,120	0,130	0,118	0,133	0,147	0,100	0,120	0,130	0,120	0,130
	FRP	0,13	0,120	0,130	0,118	0,133	0,147	0,100	0,120	0,130	0,120	0,130
	FRCM	0,71	0,720	0,696	0,696	0,722	0,725	0,689	0,720	0,696	0,680	0,739
	SST	0,29	0,280	0,304	0,275	0,311	0,304	0,278	0,280	0,304	0,320	0,261
	NSM	0,71	0,720	0,696	0,696	0,722	0,725	0,689	0,720	0,696	0,680	0,739
IQI	RPL	0,10	0,097	0,106	0,095	0,108	0,119	0,081	0,097	0,106	0,097	0,106
	FRP	0,09	0,089	0,097	0,087	0,099	0,109	0,074	0,089	0,097	0,089	0,097
	FRCM	0,65	0,662	0,640	0,640	0,664	0,667	0,634	0,662	0,640	0,626	0,680
	SST	0,22	0,210	0,228	0,206	0,233	0,228	0,208	0,210	0,228	0,240	0,196
	NSM	0,00	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

adaptable Conservation Factor (CF).

These community-level research needs and author-driven developments build upon the contributions of the present study and point toward increasingly informed, transparent, and evidence-based decision-making in the structural conservation of architectural heritage.

9. Summary and conclusions

A comprehensive literature review has been conducted on reported results of experimental campaigns for in-plane strengthening interventions on URM walls, tested under in-plane cyclic with constant gravity loads (INP) and diagonal compression (DCT), to quantitatively assess the structural capacity improvements as well as the adherence to ICOMOS modern conservation principles for a selected set of strengthening interventions: reinforced plasters (RPL); fiber reinforced polymer bands (FRP), fiber reinforced composite materials (FRCM), steel strips (SST), and near-surface mounted (NSM). These strategies are mainly found in the literature and fall under the category of innovative techniques in heritage conservation practices. To integrate both dimensions into a single comparative metric and avoid technique-specific conclusions, the novel Intervention Quality Index (IQI) was applied to each strengthening intervention. Within the IQI method, the structural performance is evaluated via the Normalized Structural Index (SI_{nm}) and the conservation impact is evaluated through the Conservation Factor (CF). The product of both factors yields an IQI-index value ranging from 0 to 1, where 0 indicates an intervention that does not meet safety requirements or comply with conservation principles, and 1 indicates an intervention that fully meets both dimensions.

Beyond reporting the performance of individual techniques, the main contribution of this study is to demonstrate the IQI as a structured, normalized, and scalable evaluation framework capable of combining heterogeneous structural evidence and conservation-based expert judgment. By integrating SI_{nm} and CF, the IQI provides a transparent synthesis of trade-offs between seismic performance and conservation compatibility, which are otherwise difficult to assess jointly. The sensitivity analysis confirmed that variations in conservation weighting modify absolute CF values but do not alter the relative ranking of techniques, evidencing the robustness of the index. These results highlight the IQI's capacity to guide reproducible, balanced evaluations rather than endorse specific interventions.

Results from 709 specimens were extracted from 65 academic articles to gain a thorough understanding of trends in testing conditions, specimen characteristics, and preferred strengthening properties. In-plane load tests are commonly found in literature, led by diagonal compression tests (DCT) on URM wallets (77%) and followed by lateral cyclic loading tests for natural-scale URM walls (INP) (23%). INP tests are typically conducted at various vertical stress levels to account for axial loading in real-world cases. In general, INP and DCT tests followed a similar approach: evaluating a set or individual non-intervened control specimens, then testing a set of repaired or retrofitted specimens. URM specimens, comprising burnt solid clay units, highly dominate the existing database, alongside hollow clay units and hollow concrete units. For mortar joints, either cement-based, lime-based, or a combination of lime-cement is found in similar proportions. The running bond type is also a dominant characteristic among English, Flemish, or common types. In terms of preferred strengthening interventions, FRP, FRCM, and NSM occur in similar proportions across all specimens, accounting for 29%, 28%, and 21%, respectively.

To evaluate the Safety Increment Index ($\Delta \bar{I}_s$), a Normalized Structural Index (SI_{nm}) was defined, allowing for the statistical evaluation of the structural performance of repaired or retrofitted specimens in the database. In this article, the contribution of each technique in structural terms was reviewed by the load capacity factor (R_t/R_0) and the ductility factor (μ_t/μ_0). The load capacity factor is a straightforward calculation that indicates the number of times the maximum load capacity of a

repaired or retrofitted specimen exceeds that of the control specimen. If not explicitly provided by the authors, a manual calculation was conducted after carefully revising each specimen result. Similarly, the ductility factor was considered, but only if explicitly calculated by the authors. The ductility factor is not a straightforward value, as different definitions of ductility have been found (e.g., ultimate displacement considered at different load drops: 75%, 80%, or 85%). For convenience, the masonry quality of specimens was categorized into three levels according to compressive strength: low ($f_m \leq 5$ MPa), moderate (5 MPa < $f_m \leq 10$ MPa), and high ($f_m > 10$ MPa).

For the calculation of the Normalized Structural Index (SI_{nm}), only load capacity factors were included, as they are most representative in the database along the masonry quality scales. In the range of low-quality masonry, FRCM strategy emerges as the most suitable to increase load capacity (INP: 0.92, DCT: 0.53), followed by RPL (INP: 0.81, DCT: 0.33), SST (INP: 0.75) and FRP (INP: 0.74, DCT: 1.00). For moderate quality masonry, only RPL (INP: 0.74, DCT: 0.62) and SST (INP: 0.79) results were consistently found in that range, posing the strategy as a good choice in that range. FRCM (INP: 0.59, DCT: 0.49) and FRP (INP: 1.00, DCT: 0.03) interventions appear to be suitable strategies for the high-quality masonry. NSM seems not ideal for load increment in low- and moderate-quality masonry, but with limited contribution in $f_m > 10$ MPa (INP: 0.19, DCT: 0.19). Therefore, the IQI framework approach enables consistent comparison despite data heterogeneity and reveals how structural efficiency varies across masonry strength ranges and test configurations.

The conservation factor (CF) was derived from the results of an expert-based focus group that evaluated the compliance of each intervention with modern conservation principles, including authenticity, non-intrusiveness, compatibility, visual impact, and reversibility. The degree of compliance was qualitatively evaluated in three categories: respect (R), partial respect (PR), and no respect (NR), which were then associated with a corresponding score (γ_{pl_k}). The conservation factor (CF) was then calculated by proportionally weighting each conservation principle's contribution. By incorporating CF into the IQI, the method systematically integrates heritage-based criteria that are typically excluded from structural assessments, enabling a balanced comparison across interventions.

When the Intervention Quality Index is computed, the combined influence of SI_{nm} and CF highlights how interventions perform when both seismic performance and conservation compatibility are considered simultaneously. This joint interpretation—rather than the characterization of individual techniques—is the central purpose of the IQI and the core contribution of this study.

This article is not intended to promote a specific type of strengthening intervention, but rather to provide a stepping stone for quantitatively evaluating a set of interventions that account for structural improvements in URM elements and compliance with modern conservation principles. Through the integrated IQI assessment, the study illustrates how heterogeneous structural results and conservation considerations can be jointly interpreted within a unified methodological framework, supporting transparent and informed decision-making without privileging any specific strengthening technique. Even though the authors acknowledge that many factors may still sway the results, such as the data scatter across all masonry ranges and the heterogeneity in intervention characteristics, the evaluation of structural performance in experimental campaigns remains a concern. These issues may provide a call to action for the scientific community to put additional effort into addressing these gaps and unifying result reports, thereby facilitating a direct comparison of strategies for further evaluation.

CRedit authorship contribution statement

Nuria Chiara Palazzi: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation,

Conceptualization. **Pere Roca**: Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **Rolando Alvarado**: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cristián Sandoval**: Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

Acknowledgements

This research received financial support from the Agencia Nacional

de Investigación y Desarrollo de Chile (ANID) through *Fondecyt Regular* grant No. 1221407, and the research grant Núcleos/UNAB/2024/81360982 from Universidad Andrés Bello. Rolando Alvarado acknowledges the funding provided by the scholarship ANID-PFCHA/Doctorado Nacional/2019–21190320. Cristián Sandoval also thanks the support provided by *Vicerrectoría de Investigación* through *Concurso Pasantías Breves en el Extranjero y Visitas de Investigación de Profesores Extranjeros, Convocatoria 2023*.

The derivation of the Normalized Structural Index was a contribution by Prof. Víctor Aguilar, Ph.D. (Assistant Professor at Department of Civil Engineering, Universidad de Concepción, Chile, victoraguilar@udec.cl, ORCID: <https://orcid.org/0000-0001-7509-9103>).

ANNEX 1. : Derivation of the Normalized Structural Index (SI_{nm})

The Normalized Structural Index (SI_{nm}) was proposed to enable a statistically consistent comparison of various in-plane strengthening methods for masonry walls. This index is based on structural reliability theory and captures the mean improvement and the uncertainty associated with experimental outcomes [103–105].

Let R_0 be the strength of the unreinforced masonry specimen (control), and R_t the strength of the specimen reinforced using technique t . The post-intervention performance is evaluated with respect to a reference target strength, defined in this study as $1.4R_0$, corresponding to a 40% increase. The associated performance function is given by:

$$g = \frac{R_t}{R_0} - 1.4 = r_t - 1.4$$

Since r_t is a random variable with known mean μ_r and standard deviation σ_r , the reliability of Eq. (3) can be evaluated through the index $\beta_t = (\mu_r - 1.4)/\sigma_r$. This formulation enables the comparison of heterogeneous experimental results through a unified normalization procedure:

$$SI_{nm}(t) = \frac{\beta_{nt} - \beta_{\min}}{\beta_{\max} - \beta_{\min}}$$

where $\beta_{\min}$ and $\beta_{\max}$ represent the minimum and maximum reliability indices observed in the database. This procedure yields a dimensionless normalized structural index ranging from 0 to 1.

Assuming g follows a normal distribution, the reliability index β is computed as:

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{\mu_r - 1.4}{\sigma_r}$$

This index reflects how much the expected performance surpasses the reference threshold, measured in units of standard deviation. It is inversely related to the probability of failure, expressed as $P_f = P(g < 0) = \Phi(-\beta)$, where Φ is the standard normal cumulative distribution function. The probability of failure in this context represents the likelihood that a given strengthened wall fails to achieve or exceed a 40% increase in strength compared to its original unstrengthened condition. It is important to note that the value 1.4 used in the formulation is a referential benchmark introduced for comparative purposes in this study. In actual strengthening projects, this target threshold must be defined on a case-by-case basis by the structural engineer and the conservation architect in charge of the intervention. The value should reflect the specific safety, conservation, and performance requirements of each project.

To allow for comparison across all techniques and masonry qualities, the reliability indices β_{nt} (where n denotes the masonry quality level and t the reinforcement technique) are normalized using the minimum and maximum values across the dataset:

$$SI_{nm} = (\beta_{nt} - \beta_{\min}) / (\beta_{\max} - \beta_{\min})$$

This normalization ensures that the structural index lies between 0 and 1, making it suitable for integration into a global Intervention Quality Index (IQI) that also incorporates conservation criteria.

Data availability

Data will be made available on request.

References

- [1] M.M. Maras, H.C. Kilinc, Comparison on repair and strengthening techniques for unreinforced masonry structures, *Int. J. Eng. Res. Appl.* 6 (2016) 1–5.
- [2] R. Sisti, M. Di Ludovico, A. Borri, A. Prota, Seismic performance of strengthened masonry structures: actual behaviour of buildings in Norcia and Campi Alto during the 2016 Central Italy seismic sequence, *Bull. Earthq. Eng.* 20 (2022) 321–348, <https://doi.org/10.1007/s10518-021-01248-0>.
- [3] J. Ortega, G. Vasconcelos, H. Rodrigues, M. Correia, Assessment of the efficiency of traditional earthquake resistant techniques for vernacular architecture, *Eng. Struct.* 173 (2018) 1–27, <https://doi.org/10.1016/j.engstruct.2018.06.101>.
- [4] D. D'Ayala, E. Speranza, Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings, *Earthq. Spectra* 19 (2003) 479–509, <https://doi.org/10.1193/1.1599896>.
- [5] C. Sandoval, R. Valledor, D. Lopez-Garcia, Numerical assessment of accumulated seismic damage in a historic masonry building. A case study, *Int. J. Archit. Herit.* 11 (2017) 1177–1194, <https://doi.org/10.1080/15583058.2017.1356945>.
- [6] A. Preciado, J.C. Santos, C. Silva, A. Ramírez-Gaytán, J.M. Falcon, Seismic damage and retrofitting identification in unreinforced masonry Churches and bell towers by the september 19, 2017 (Mw = 7.1) Puebla-Morelos earthquake, *Eng. Fail. Anal.* 118 (2020) 104924, <https://doi.org/10.1016/j.engfailanal.2020.104924>.

- [7] M. Günaydin, B. Atmaca, S. Demir, A.C. Altunışık, M. Hüsem, S. Adanur, Z. Ateş, Angin, Seismic damage assessment of masonry buildings in Elazığ and Malatya following the 2020 Elazığ-Sivrice earthquake, Turkey, *Bull. Earthq. Eng.* 19 (2021) 2421–2456, <https://doi.org/10.1007/s10518-021-01073-5>.
- [8] N.C. Palazzi, P. Favier, L. Rovero, C. Sandoval, J.C. de la Llera, Seismic damage and fragility assessment of ancient masonry churches located in central Chile, *Bull. Earthq. Eng.* 18 (2020) 3433–3457, <https://doi.org/10.1007/s10518-020-00831-1>.
- [9] C. Wang, V. Sarhosis, N. Nikitas, Strengthening/retrofitting techniques on unreinforced masonry structure/element subjected to seismic loads: a literature review, *Open Constr. Build. Technol. J.* 12 (2018) 251–268, <https://doi.org/10.2174/1874836801812010251>.
- [10] P.D. Gkourmelos, T.C. Triantafyllou, D.A. Bournas, Seismic upgrading of existing masonry structures: A state-of-the-art review, *Soil Dyn. Earthq. Eng.* 161 (2022) 107428, <https://doi.org/10.1016/j.soildyn.2022.107428>.
- [11] F. Yavartanoo, T.H.-K. Kang, Retrofitting of unreinforced masonry structures and considerations for heritage-sensitive constructions, *J. Build. Eng.* 49 (2022) 103993, <https://doi.org/10.1016/j.jobe.2022.103993>.
- [12] ICOMOS Charter, Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, (2003).
- [13] ICOMOS/ISCARSAH, Guidelines for the analysis, conservation and structural restoration of architectural heritage, ISCARSAH- International Committee on Analysis and Restoration of Structures of Architectural Heritage, ICOMOS (2024) 1–47.
- [14] S.W. Chuang, Y. Zhuge, Seismic Retrofitting of Unreinforced Masonry Buildings – A Literature Review, *Aust. J. Struct. Eng.* 6 (2005) 25–36, <https://doi.org/10.1080/13287982.2005.11464942>.
- [15] 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, <https://doi.org/10.1016/j.ijdr.2013.12.004>.
- [16] A. Keshmiry, S. Hassani, U. Dackermann, J. Li, Assessment, repair, and retrofitting of masonry structures: a comprehensive review, *Constr. Build. Mater.* 442 (2024) 137380, <https://doi.org/10.1016/j.conbuildmat.2024.137380>.
- [17] S. Dadras Eslamlou, M.J. Masia, Y.Z. Totoev, A.W. Page, Effect of retrofitting on the structural factors for seismic assessment of unreinforced masonry structures: a review, *Aust. J. Struct. Eng.* 20 (2019) 26–53, <https://doi.org/10.1080/13287982.2019.1565288>.
- [18] M. Del Zoppo, M. Di Ludovico, A. Prota, Analysis of FRCM and CRM parameters for the in-plane shear strengthening of different URM types, *Compos. B Eng.* 171 (2019) 20–33, <https://doi.org/10.1016/j.compositesb.2019.04.020>.
- [19] N.C. Palazzi, G. Misseri, C. Sandoval, U. Toniatti, J.C. De la Llera, L. Rovero, A new method for assessing compatibility of consolidation procedures with conservation principles: intervention quality index (IQI). 12th International Conference on Structural Analysis of Historical Constructions, 2021.
- [20] D. D'Ayala, Conservation principles and performance based strengthening of heritage buildings in post-event reconstruction, in: *Perspectives on European Earthquake Engineering and Seismology*, 1, Springer International Publishing, 2014, pp. 489–514.
- [21] P. Roca, The ISCARSAH guidelines on the analysis, conservation and structural restoration of architectural heritage. 12th International Conference on Structural Analysis of Historical Constructions, International Centre for Numerical Methods in Engineering (CIMNE), 2021, pp. 1629–1640.
- [22] ICOMOS, International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter), (1964).
- [23] ICOMOS, Historic Gardens (Florence Charter), (1981).
- [24] SNZ, NZS 4219:2009: Seismic Performance of Engineering Systems in Buildings, (2009).
- [25] MSJC, Building Code Requirements for Masonry Structures (ACI 530–05/ASCE 5–05/TMS 402–05), American Concrete Institute, USA, 2005.
- [26] CEN, Eurocode 8: Design of structures for earthquake resistance – part 3: assessment and retrofitting of buildings., (2005).
- [27] NTC, Norme Tecniche per le Costruzioni D.M. 14 gennaio 2008. n. 29 del 4/02/2008 Suppl. ord. n° 30 alla G.U. Roma, Italy: Consiglio Superiore dei Lavori Pubblici., (2008).
- [28] MVCS, Norma Técnica E.080: Diseño y construcción con tierra reforzada. Ministerio de Vivienda, Construcción y Sanamiento. Perú., (2017).
- [29] INN, NCh3389. Intervención en Construcciones Patrimoniales y Edificaciones Existentes. Requisitos del Proyecto Estructural., (2020).
- [30] P. Baquedano Juliá, S. Stellacci, E. Poletti, Evaluation of retrofitting techniques for historical adobe constructions using a multi-criteria decision analysis: the case study of Chile, *Int. J. Arch. Herit.* 18 (2024) 40–63, <https://doi.org/10.1080/15583058.2022.2103476>.
- [31] 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, <https://doi.org/10.1016/j.conbuildmat.2022.129839>.
- [32] M. Ashraf, A.N. Khan, A. Naseer, Q. Ali, B. Alam, Seismic behavior of unreinforced and confined brick masonry walls before and after ferrocement overlay retrofitting, *Int. J. Arch. Herit.* 6 (2012) 665–688, <https://doi.org/10.1080/15583058.2011.599916>.
- [33] M.A. ElGawady, P. Lestuzzi, M. Badoux, Retrofitting of masonry walls using shotcrete, NZSEE Conference (2006).
- [34] L. Pérez-Pinedo, C. Sandoval, R. Alvarado, L. Vargas, S. Calderón, E. Bernat, Seismic strengthening of partially grouted masonry walls with openings: Evaluation of ferrocement and BTRM solutions, *J. Build. Eng.* 88 (2024) 109235, <https://doi.org/10.1016/j.jobe.2024.109235>.
- [35] Y.-W. Lin, L. Wotherspoon, A. Scott, J.M. Ingham, In-plane strengthening of clay brick unreinforced masonry wall-ettes using ECC shotcrete, *Eng. Struct.* 66 (2014) 57–65, <https://doi.org/10.1016/j.engstruct.2014.01.043>.
- [36] H. Mahmood, J.M. Ingham, Diagonal compression testing of FRP-retrofitted unreinforced clay brick masonry wall-ettes, *J. Compos. Constr.* 15 (2011) 810–820.
- [37] P. Alcaino, H. Santa-Maria, Experimental response of externally retrofitted masonry walls subjected to shear loading, *J. Compos. Constr.* 12 (2008) 489–498, [https://doi.org/10.1061/\(ASCE\)1090-0268\(2008\)12:5\(489\)](https://doi.org/10.1061/(ASCE)1090-0268(2008)12:5(489)).
- [38] C. Menna, D. Asprone, M. Durante, A. Zinno, A. Balsamo, A. Prota, Structural behaviour of masonry panels strengthened with an innovative hemp fibre composite grid, *Constr. Build. Mater.* 100 (2015) 111–121, <https://doi.org/10.1016/j.conbuildmat.2015.09.051>.
- [39] L. Garcia-Ramonda, L. Pelá, P. Roca, G. Camata, In-plane shear behaviour by diagonal compression testing of brick masonry walls strengthened with basalt and steel textile reinforced mortars, *Constr. Build. Mater.* 240 (2020) 117905, <https://doi.org/10.1016/j.conbuildmat.2019.117905>.
- [40] L. Pérez-Pinedo, C. Sandoval, L. Vargas, R. Alvarado, In-plane cyclic response of partially grouted masonry walls repaired and retrofitted with SRG strips, *Eng. Fail. Anal.* 182 (2025) 110078, <https://doi.org/10.1016/j.engfailanal.2025.110078>.
- [41] S.H. Farooq, A. ElGawady Mohamed, M. Ilyas, Seismic In-plane performance of retrofitted masonry walls, *KSCE J. Civ. Eng.* 18 (2014) 226–237, <https://doi.org/10.1007/s12205-014-0120-3>.
- [42] M. Maragna, S. Casacci, C. Gentilini, In-plane shear behaviour of masonry wall panels strengthened by structural repointing, *Int. J. Mason. Res. Innov.* 1 (2016) 253–276.
- [43] C. Sandoval, R. Serpell, G. Araya-Letelier, S. Calderón, Shear behavior of single- and triple-thickness masonry panels strengthened by bed-joint structural repointing, *Constr. Build. Mater.* 286 (2021) 122925, <https://doi.org/10.1016/j.conbuildmat.2021.122925>.
- [44] M. Ehteshami Moieni, S.A. Razavi, M. Yekrangnia, P. Pourasgari, N. Abbasian, Cyclic performance assessment of damaged unreinforced masonry walls repaired with steel mesh reinforced shotcrete, *Eng. Struct.* 253 (2022) 113747, <https://doi.org/10.1016/j.engstruct.2021.113747>.
- [45] M. Deng, Z. Dong, P. Ma, Cyclic loading tests of flexural-failure dominant URM walls strengthened with engineered cementitious composite, *Eng. Struct.* 194 (2019) 173–182, <https://doi.org/10.1016/j.engstruct.2019.05.073>.
- [46] A. Hasnat, T. Das, R. Ahsan, A.T. Alam, H. Ahmed, In-plane cyclic response of unreinforced masonry walls retrofitted with ferrocement, *Case Stud. Constr. Mater.* 17 (2022) e01630, <https://doi.org/10.1016/j.cscm.2022.e01630>.
- [47] H.-K. Choi, B.-I. Bae, C.-S. Choi, Lateral Resistance of Unreinforced Masonry Walls Strengthened With Engineered Cementitious Composite, *Int. J. Civ. Eng.* 14 (2016) 411–424, <https://doi.org/10.1007/s40999-016-0026-1>.
- [48] L. Facconi, F. Minelli, S. Lucchini, G. Plizzari, Experimental Study of Solid and Hollow Clay Brick Masonry Walls Retrofitted by Steel Fiber-Reinforced Mortar Coating, *J. Earthq. Eng.* 24 (2020) 381–402, <https://doi.org/10.1080/13632469.2018.1442264>.
- [49] M. Shabdin, N.K.A. Attari, M. Zargar, Experimental study on seismic behavior of Un-Reinforced Masonry (URM) brick walls strengthened with shotcrete, *Bull. Earthq. Eng.* 16 (2018) 3931–3956, <https://doi.org/10.1007/s10518-018-0340-x>.
- [50] F. Messali, G. Metelli, G. Plizzari, Experimental results on the retrofitting of hollow brick masonry walls with reinforced high performance mortar coatings, *Constr. Build. Mater.* 141 (2017) 619–630, <https://doi.org/10.1016/j.conbuildmat.2017.03.112>.
- [51] O.J. Sandoval, C. Takeuchi, J. Carrillo, B. Barahona, Performance of unreinforced masonry panels strengthened with mortar overlays reinforced with welded wire mesh and transverse connectors, *Constr. Build. Mater.* 267 (2021) 121054, <https://doi.org/10.1016/j.conbuildmat.2020.121054>.
- [52] C. Shermer, R.N. Dubey, In-plane behaviour of unreinforced masonry panel strengthened with welded wire mesh and mortar, *Constr. Build. Mater.* 178 (2018) 195–203, <https://doi.org/10.1016/j.conbuildmat.2018.04.081>.
- [53] S.B. Kadam, Y. Singh, B. Li, Strengthening of unreinforced masonry using welded wire mesh and micro-concrete – Behaviour under in-plane action, *Constr. Build. Mater.* 54 (2014) 247–257, <https://doi.org/10.1016/j.conbuildmat.2013.12.033>.
- [54] G. Zamani-Ahari, K. Yamaguchi, Experimental investigation on cyclic in-plane behavior of URM walls retrofitted with AFPR, *Case Stud. Constr. Mater.* 17 (2022) e01558, <https://doi.org/10.1016/j.cscm.2022.e01558>.
- [55] A. Mosallam, S. Banerjee, Enhancement in in-plane shear capacity of unreinforced masonry (URM) walls strengthened with fiber reinforced polymer composites, *Compos. B Eng.* 42 (2011) 1657–1670, <https://doi.org/10.1016/j.compositesb.2011.03.015>.
- [56] M.A. ElGawady, P. Lestuzzi, M. Badoux, Static Cyclic Response of Masonry Walls Retrofitted with Fiber-Reinforced Polymers, *J. Compos. Constr.* 11 (2007) 50–61, [https://doi.org/10.1061/\(ASCE\)1090-0268\(2007\)11:1\(50\)](https://doi.org/10.1061/(ASCE)1090-0268(2007)11:1(50)).
- [57] S.H. Farooq, M. Ilyas, S. Amir, Response of Masonry Walls Strengthened with CFRP and Steel Strips, *Arab. J. Sci. Eng.* 37 (2012) 545–559, <https://doi.org/10.1007/s13369-012-0190-9>.
- [58] D. Zhou, Z. Lei, J. Wang, In-plane behavior of seismically damaged masonry walls repaired with external BFRP, *Compos. Struct.* 102 (2013) 9–19, <https://doi.org/10.1016/j.compstruct.2013.01.031>.
- [59] Q. Wang, Z. Chai, Y. Huang, Y. Huang, Y. Zhang, Seismic shear capacity of brick masonry wall reinforced by GFRP, *Asian J. Civ. Eng. (Build. Hous. J.)* 7 (2006) 563–580.

- [60] G. Marcari, G. Manfredi, A. Prota, M. Pecce, In-plane shear performance of masonry panels strengthened with FRP, *Compos. B Eng.* 38 (2007) 887–901, <https://doi.org/10.1016/j.compositesb.2006.11.004>.
- [61] M.R. Valluzzi, D. Tinazzi, C. Modena, Shear behavior of masonry panels strengthened by FRP laminates, *Constr. Build. Mater.* 16 (2002) 409–416, [https://doi.org/10.1016/S0950-0618\(02\)00043-0](https://doi.org/10.1016/S0950-0618(02)00043-0).
- [62] A. Kalali, M.Z. Kabir, Experimental response of double-wythe masonry panels strengthened with glass fiber reinforced polymers subjected to diagonal compression tests, *Eng. Struct.* 39 (2012) 24–37, <https://doi.org/10.1016/j.engstruct.2012.01.018>.
- [63] N. Gattesco, I. Boem, A. Dudine, Diagonal compression tests on masonry walls strengthened with a GFRP mesh reinforced mortar coating, *Bull. Earthq. Eng.* 13 (2015) 1703–1726, <https://doi.org/10.1007/s10518-014-9684-z>.
- [64] H. Santa María, G. Duarte, A. Garib, Experimental investigation of masonry panels externally strengthened with CFRP laminates and fabric subjected to in-plane shear load, in: 8th US National Conference on Earthquake Engineering, San Francisco, 2004: p. 1042.
- [65] P.F. Silva, P. Yu, A. Nanni, Monte Carlo Simulation of Shear Capacity of URM Walls Retrofitted by Polyurea Reinforced GFRP Grids, *J. Compos. Constr.* 12 (2008) 405–415, [https://doi.org/10.1061/\(ASCE\)1090-0268\(2008\)12:4\(405\)](https://doi.org/10.1061/(ASCE)1090-0268(2008)12:4(405)).
- [66] A. Jafari, A.V. Oskouei, M. Bazli, R. Ghahri, Effect of the FRP sheet's arrays and NSM FRP bars on in-plane behavior of URM walls, *J. Build. Eng.* 20 (2018) 679–695, <https://doi.org/10.1016/j.job.2018.09.018>.
- [67] N. Ismail, J.M. Ingham, In-plane and out-of-plane testing of unreinforced masonry walls strengthened using polymer textile reinforced mortar, *Eng. Struct.* 118 (2016) 167–177, <https://doi.org/10.1016/j.engstruct.2016.03.041>.
- [68] C.G. Papanicolaou, T.C. Triantafyllou, M. Papathanasiou, K. Karlos, Textile reinforced mortar (TRM) as strengthening material of URM walls: out-of-plane cyclic loading, *Mater. Struct.* 41 (2007) 143–157, <https://doi.org/10.1617/s11527-007-9226-0>.
- [69] J.A.P.P. Almeida, E.B. Pereira, J.A.O. Barros, Assessment of overlay masonry strengthening system under in-plane monotonic and cyclic loading using the diagonal tensile test, *Constr. Build. Mater.* 94 (2015) 851–865, <https://doi.org/10.1016/j.conbuildmat.2015.07.040>.
- [70] N. Gattesco, I. Boem, Experimental and analytical study to evaluate the effectiveness of an in-plane reinforcement for masonry walls using GFRP meshes, *Constr. Build. Mater.* 88 (2015) 94–104, <https://doi.org/10.1016/j.conbuildmat.2015.04.014>.
- [71] M. Corradi, A. Borri, G. Castori, R. Sisti, Shear strengthening of wall panels through jacketing with cement mortar reinforced by GFRP grids, *Compos. B Eng.* 64 (2014) 33–42, <https://doi.org/10.1016/j.compositesb.2014.03.022>.
- [72] S.L. Sagar, V. Singhal, D.C. Rai, P. Gudur, Diagonal Shear and Out-of-Plane Flexural Strength of Fabric-Reinforced Cementitious Matrix-Strengthened Masonry Wall, *J. Compos. Constr.* 21 (2017), [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000796](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000796).
- [73] F. Micelli, M.S. Sciolti, M. Leone, M.A. Aiello, A. Dudine, Shear behaviour of Fiber Reinforced Mortar strengthened masonry walls built with limestone blocks and hydraulic mortar. *Brick and Block Masonry—Trends, Innovations and Challenges*, 2016.
- [74] A. Incerti, A.R. Tilocca, F. Ferretti, C. Mazzotti, Influence of Masonry Texture on the Shear Strength of FRCM Reinforced Panels, in: 2019: pp. 1623–1631. https://doi.org/10.1007/978-3-319-99441-3_174.
- [75] M. Del Zoppo, M. Di Ludovico, A. Balsamo, A. Prota, Experimental In-Plane Shear Capacity of Clay Brick Masonry Panels Strengthened with FRCM and FRM Composites, *J. Compos. Constr.* 23 (2019), [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000965](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000965).
- [76] A. Borri, M. Corradi, R. Sisti, C. Buratti, E. Belloni, E. Moretti, Masonry wall panels retrofitted with thermal-insulating GFRP-reinforced jacketing, *Mater. Struct.* 49 (2016) 3957–3968, <https://doi.org/10.1617/s11527-015-0766-4>.
- [77] S. Babaeidarabad, A. Nanni, In-plane behavior of unreinforced masonry walls strengthened with fabric-reinforced cementitious matrix (FRCM), *Acids Spec. Publ.* 299 (2015) 69–80.
- [78] A. Prota, G. Marcari, G. Fabbrocino, G. Manfredi, C. Aldea, Experimental In-Plane Behavior of Tuff Masonry Strengthened with Cementitious Matrix-Grid Composites, *J. Compos. Constr.* 10 (2006) 223–233, [https://doi.org/10.1061/\(ASCE\)1090-0268\(2006\)10:3\(223\)](https://doi.org/10.1061/(ASCE)1090-0268(2006)10:3(223)).
- [79] C. Faella, E. Martinelli, E. Nigro, S. Paciello, Shear capacity of masonry walls externally strengthened by a cement-based composite material: An experimental campaign, *Constr. Build. Mater.* 24 (2010) 84–93, <https://doi.org/10.1016/j.conbuildmat.2009.08.019>.
- [80] G. Marcari, M. Basili, F. Vestroni, Experimental investigation of tuff masonry panels reinforced with surface bonded basalt textile-reinforced mortar, *Compos. B Eng.* 108 (2017) 131–142, <https://doi.org/10.1016/j.compositesb.2016.09.094>.
- [81] M. Shabdin, M. Zargar, N.K.A. Attari, Experimental diagonal tension (shear) test of Un-Reinforced Masonry (URM) walls strengthened with textile reinforced mortar (TRM), *Constr. Build. Mater.* 164 (2018) 704–715, <https://doi.org/10.1016/j.conbuildmat.2017.12.234>.
- [82] J. Donnini, G. Maracchini, S. Lenzi, V. Corinaldesi, E. Quagliarini, TRM reinforced tuff and fired clay brick masonry: Experimental and analytical investigation on their in-plane and out-of-plane behavior, *Constr. Build. Mater.* 272 (2021) 121643, <https://doi.org/10.1016/j.conbuildmat.2020.121643>.
- [83] G. Castori, M. Corradi, E. Sperazini, Full size testing and detailed micro-modeling of the in-plane behavior of FRCM-reinforced masonry, *Constr. Build. Mater.* 299 (2021) 124276, <https://doi.org/10.1016/j.conbuildmat.2021.124276>.
- [84] M. Taghdi, M. Bruneau, M. Saatcioglu, Seismic Retrofitting of Low-Rise Masonry and Concrete Walls Using Steel Strips, *J. Struct. Eng.* 126 (2000) 1017–1025, [https://doi.org/10.1061/\(ASCE\)0733-9445\(2000\)126:9\(1017\)](https://doi.org/10.1061/(ASCE)0733-9445(2000)126:9(1017)).
- [85] A. Darbhanzi, M.S. Marefat, M. Khanmohammadi, Improving in-plane seismic response of unreinforced masonry walls using steel strips, *Adv. Struct. Eng.* 23 (2020) 2709–2723, <https://doi.org/10.1177/1369433220920995>.
- [86] A. Borri, M. Corradi, G. Castori, A. Molinari, Stainless steel strip – A proposed shear reinforcement for masonry wall panels, *Constr. Build. Mater.* 211 (2019) 594–604, <https://doi.org/10.1016/j.conbuildmat.2019.03.197>.
- [87] K.M.C. Konthesingha, M.J. Masia, R.B. Petersen, N. Mojsilovic, G. Simundic, A. W. Page, Static cyclic in-plane shear response of damaged masonry walls retrofitted with NSM FRP strips – An experimental evaluation, *Eng. Struct.* 50 (2013) 126–136, <https://doi.org/10.1016/j.engstruct.2012.10.026>.
- [88] J. Jing, C. Zhou, C. Zhang, T. Li, In-plane cyclic behavior of brick walls strengthened with CFRP plates embedded in the horizontal mortar joint, *J. Build. Eng.* 63 (2023) 105476, <https://doi.org/10.1016/j.job.2022.105476>.
- [89] X. Yao, Z.-X. Guo, S.H. Basha, Q. Huang, Innovative seismic strengthening of historic masonry walls using polymer mortar and steel strips, *Eng. Struct.* 228 (2021) 111507, <https://doi.org/10.1016/j.engstruct.2020.111507>.
- [90] R. Soti, A.R. Barbosa, Experimental and applied element modeling of masonry walls retrofitted with near surface mounted (NSM) reinforcing steel bars, *Bull. Earthq. Eng.* 17 (2019) 4081–4114.
- [91] 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, <https://doi.org/10.1016/j.conbuildmat.2023.130362>.
- [92] N.A. Misnon, M. Giarretton, D. Shedde, J. Ingham, D. Dizhur, Shear testing of URM wall, *Structures* 27 (2020) 1613–1622, <https://doi.org/10.1016/j.istruc.2020.07.059>.
- [93] S. Shahzamani, M.R. Eftekhari, Experimental study on using steel wires via the NSM method to improve the behaviour of masonry panels, *Constr. Build. Mater.* 385 (2023) 131473, <https://doi.org/10.1016/j.conbuildmat.2023.131473>.
- [94] R.B. Petersen, M.J. Masia, R. Seracino, In-Plane Shear Behavior of Masonry Panels Strengthened with NSM CFRP Strips. I: Experimental Investigation, *J. Compos. Constr.* 14 (2010) 754–763, [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000134](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000134).
- [95] D. Dizhur, M. Griffith, J. Ingham, In-Plane Shear Improvement of Unreinforced Masonry Wall Panels Using NSM CFRP Strips, *J. Compos. Constr.* 17 (2013), [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000400](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000400).
- [96] V. Turco, S. Secondino, A. Morbin, M.R. Valluzzi, C. Modena, Flexural and shear strengthening of un-reinforced masonry with FRP bars, *Compos. Sci. Technol.* 66 (2006) 289–296, <https://doi.org/10.1016/j.compscitech.2005.04.042>.
- [97] T. Li, N. Galati, J.G. Tumialan, A. Nanni, Analysis of unreinforced masonry concrete walls strengthened with glass fiber-reinforced polymer bars, *Acids Struct. J.* 102 (2005) 569–577.
- [98] S. Casacci, C. Gentilini, A. Di Tommaso, D.V. Oliveira, Shear strengthening of masonry wall, *Constr. Build. Mater.* 206 (2019) 19–34.
- [99] N. Ismail, R.B. Petersen, M.J. Masia, J.M. Ingham, Diagonal shear behaviour of unreinforced masonry wall, *Constr. Build. Mater.* 25 (2011) 4386–4393.
- [100] M. Sýkora, D. Diamantidis, M. Holický, J. Marková, Á. Rózsás, Assessment of compressive strength of historic masonry using non-destructive and destructive techniques, *Constr. Build. Mater.* 193 (2018) 196–210, <https://doi.org/10.1016/j.conbuildmat.2018.10.180>.
- [101] S. Calderón, C. Sandoval, G. Araya-Letelier, V. Aguilar, A detailed experimental mechanical characterization of multi-perforated clay brick masonry, *J. Build. Eng.* 63 (2023) 105505, <https://doi.org/10.1016/j.job.2022.105505>.
- [102] D. Müller, C.-A. Graubner, Assessment of masonry compressive strength in existing structures using a Bayesian Method, *Asce. Asme. J. Risk Uncertain. Eng. Syst. A Civ. Eng.* 7 (2021), <https://doi.org/10.1061/AJRUAE.6.0001113>.
- [103] C.A. Cornell, A probability-based structural code, *Acids J. Proc.* 66 (1969), <https://doi.org/10.14359/7446>.
- [104] J.R. Benjamin, C.A. Cornell, *Probability, Statistics, and Decision for Civil Engineers*, 1970.
- [105] A. Nowak, K.R. Collins, *Reliability of Structures*, 2nd., 2013.