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Review

Review of Out-of-Plane Strengthening Techniques of Unreinforced Masonry Walls

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Abstract: When a seismic load is applied horizontally or laterally on unreinforced masonry walls (URM), the walls behave in two different ways, viz., in-plane (IP) and out-of-plane (OoP). This review beneficially provides a literature overview of the most cited research papers on Scopus, and the database is evaluated with VOSviewer software for scientometric analysis. This review paper delves into the practical applications of various types of reinforcement for masonry walls, specifically focusing on four commonly used systems: externally bonded strengthening techniques using fiber-reinforced polymers (FRP), steel-reinforced grout (SRG), fabric-reinforced cementitious mortar (FRCM), and textile-reinforced mortars (TRM). The main objective of the paper is to explore the efficacy of these reinforcement techniques in strengthening masonry walls, and to provide a comprehensive overview of their respective advantages and limitations. A further detailed study of the extent of the literature is performed about the effect of the different strengthening systems on the mechanical properties of different categories of masonry walls like a cement block, stone, and clay brick are described and categorized. The efficiency of OoP strengthening can depend on various factors, such as the types of masonry units, the rendering mortar, the type of strengthening system, the bond between the different materials interfaces, the geometry of the wall, and the loading conditions. By utilizing the practical method of Dematel (Decision-making trial and evaluation laboratory) analysis, this review can delve deeply into the impact of various factors and precisely identify the crucial components of the cause-and-effect connection. The results indicate that the bond between material interfaces is the critical factor. This meticulous and structured review offers valuable perspectives for researchers and engineers, showcasing current research trends and presenting potential avenues for future exploration.

Keywords: unreinforced masonry walls (URM); out-of-plane (OoP); strengthening technique; externally bonded system; textile-reinforced mortar (TRM); fiber-reinforced polymers (FRP); masonry review; masonry state of the art; Dematel; scientometric analysis; Scopus; VOSviewer

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1. Introduction

One of the main parts of structures is masonry construction, which is used worldwide because of low maintenance, durability, strength, aesthetic purpose, low cost, and fire-resistant properties. Unreinforced masonry (URM) walls face numerous challenges from weathering, ageing, and use. These challenges can be divided into two categories: in-plane (IP) and out-of-plane (OoP) loads [1–5]. For URM walls that encounter lateral loads, their lack of tensile capacity makes them brittle and prone to failure. Failures in masonry walls can be caused by ageing, poor maintenance, or natural disasters, resulting in two main types of failure: in-plane and out-of-plane. Out-of-plane failure is more common and can occur during earthquakes, leading to property damage and loss of life [6–10]. Therefore, it is crucial to reinforce masonry walls to ensure their safety and longevity. In recent years, various strengthening techniques have been developed and widely used. These techniques, including reinforcing cementitious composites, grout injection, and coatings, have different subcategories that can significantly enhance the performance of masonry structures [11–16].

Advanced performance of masonry walls strengthened with organic and inorganic coating, when subjected to transverse loading, has already been experimentally explored [17–20]. The authors observed that different types of organic and inorganic coating not only improved the load-carrying capacity but also the durability performance, while prevention of the masonry walls from external harmful agents is achieved via the coating technique [21–24]. The cheapest approach to strengthening masonry walls is the use of steel reinforcement grout (SRG) with plates, and meshes are applied for seismic strengthening of unreinforced masonry walls subjected to out-of-plane loading [25–29].

Prefabricated FRP composites can deliver an efficient solution for the strengthening of masonry walls. The practice of pre-fabricated FRP composites in the historical masonry wall reinforcement helped protect the walls' original appearance and maintain the cultural heritage [30–34]. Fiber-reinforced polymers (FRP) are commonly used by engineers to strengthen masonry walls. This is a highly recommended method due to its many benefits, including lightweight, ease of installation, durability, high strength-to-weight ratio, and compatibility. By reinforcing masonry walls with FRP, the risk of collapse can be significantly reduced, which in turn minimizes damage to nearby properties [35–37]. The use of composite materials is a modern alternative solution that provides many advantages over traditional reinforcements [38]. Strengthening masonry walls extends their service life, increases flexural capacity, and decreases the need for costly replacements or demolition. Combining grouting with FRP reinforcement can further enhance the load-carrying capacity of masonry walls [39–42]. Additionally, reinforcement and coating can increase the resistance to out-of-plane loads, increasing the stiffness of masonry walls. The use of inorganic coating and carbon fiber-reinforced polymer (CFRP) sheets can improve the strength characteristics of masonry walls and lower the risk of failure. Using FRP and epoxy resin can also enhance the strengthening capacity of masonry walls [43–45].

However, a beneficial process for strengthening, especially brick and stone URM walls subjected to out-of-plane loading, is the FRCM (fabric-reinforced cementitious mortars) or TRM (textile-reinforced mortar) for strength enhancement. It is a promising approach where a thin mortar layer is a matrix in which the fabric or the textile composites are embedded. Advanced composite materials of fibers, for example, carbon, glass, basalt, and polypara-phenylene-benzo-bisthiazole (PBO), are used to compose the available textiles [46–48]. The strengthening system of the advanced materials is applied as a single- or double-side strengthening system over the wall surface as a jacket, which can enhance the masonry stiffness and strength, while also protecting against environmental harmful reasons.

Nevertheless, the selection of the suitable reinforcement method for a masonry wall is a multifaceted process and depends on numerous parameters, including the structural and mechanical properties of the reinforcement material, the compatibility with the masonry wall, and the ease of installation and maintenance. It is essential to carefully consider the advantages and disadvantages associated with each technique before making a final decision. Figure 1 summarizes these advantages and disadvantages for easy reference.

1.1. Classification of the Strengthening Techniques of Masonry Walls

Unreinforced masonry walls can suffer from deterioration due to several factors, including out-of-plane (OoP) loads like seismic or wind forces. However, reinforcements of different layouts have been proven to enhance the transverse loading strength of the walls. Figures 2 and 3 [3] depict the presence of horizontal reinforcement in masonry walls.

Research has shown that incorporating vertically reinforced steel bars into masonry walls results in a notable increase in stiffness and flexural strength. This, in turn, decreases the likelihood of the wall collapsing. This reinforcement increases the flexural capacity and tensile strength of the walls, which is crucial in resisting lateral forces [49,50]. A recent study found that the usage of multiple steel wires or bars spaced at nearer distances for strengthening masonry walls resulted in enhanced strength and stiffness of walls compared to single bars or wires spaced at greater distances. The efficiency of CFRP as a vertical reinforcement for strengthening technique for the masonry walls is used to enhance the flexural capacity, thereby reducing the risk of damage or collapse of the masonry wall [51–53].

Strengthening technique	Advantages	Disadvantages
FRP	✓ Small dimensions	× Limited dimensions
	✓ Eliminating buckling damage	× Only a main fiber direction
	✓ Lower cost	× Incompatibility between resin and masonry substrate.
	✓ Ease of installation	× Costly material
	✓ Corrosion resistance	× Poor resistance to the high temperature
	✓ Strength, ductility and stiffness enhancement	× Inability to be applied on a wet surface
SRG	✓ Increase strength, and very good ductility and stiffness	× The high cost is due to installation process.
	✓ Minimum effect on column aesthetic as a result of compatibility between the grout material and the concrete.	× Rusting and corrosion
	✓ Very good resistance to the elevated temperature.	× Long time for curing
		× Heavy weight
FRCM/TRM	✓ Ultraviolet (UV) radiation resistance	× Long time for curing
	✓ Compatibility and permeability with the masonry substrate	
	✓ Fiber strands oriented in two directions mutually orthogonal	
	✓ Enhances strength, ductility and stiffness	
	✓ Very good resistance to the elevated temperature.	
	✓ Easy application	
	✓ Corrosion resistance	

Figure 1. Advantages and disadvantages of strengthening systems.

Horizontal reinforcement using steel or FRP is recommended as an out-of-plane retrofit in existing masonry walls significantly increasing the stiffness, ductility, and strength of masonry walls. Another study recommended that CFRP fabrics could be used in combination with other reinforcement methods to attain optimal performance, as a viable reinforcement method for masonry structures subjected to lateral loading [54]. Various horizontal reinforcement arrangements were tested with continuous horizontal reinforcement arrangements displaying higher strength and ductility than those with discontinuous or no horizontal reinforcement [55].

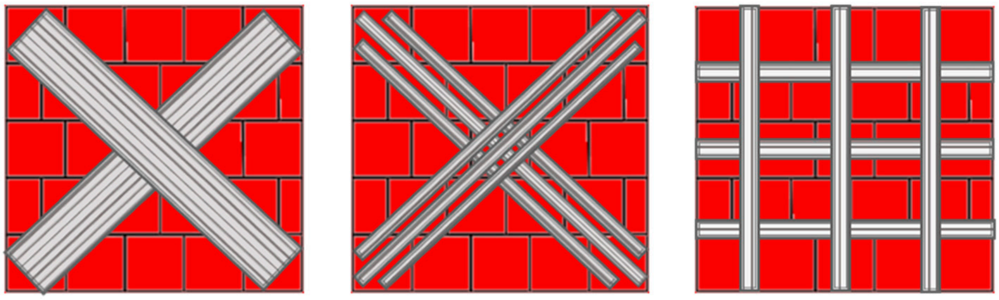


Figure 2. Strengthening layouts of FRP application over the masonry wall surface.

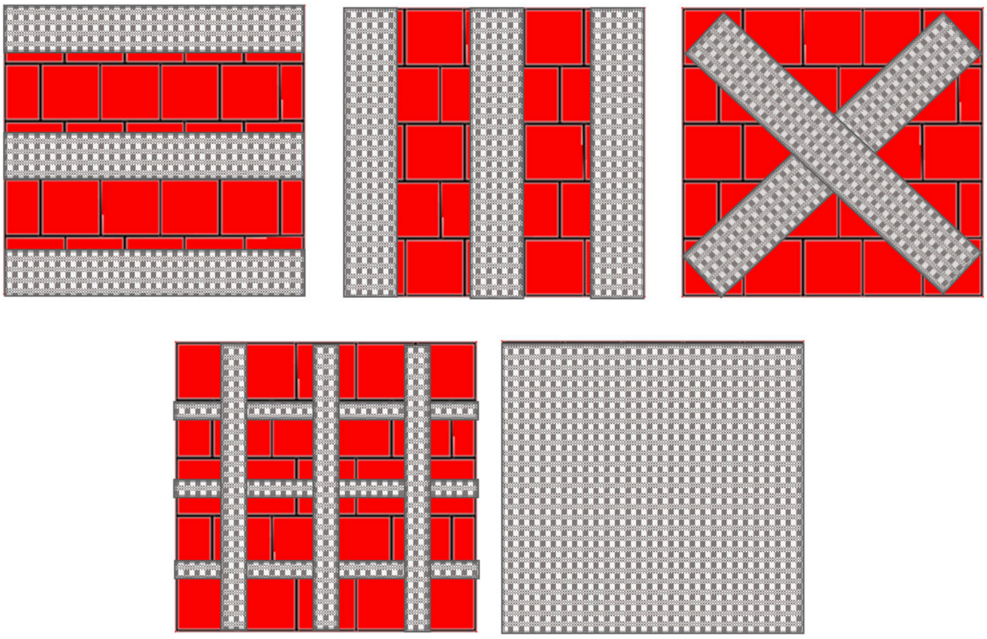


Figure 3. Strengthening layouts of FRCM/TRM application over the brick masonry wall surface.

A new method has been developed that combines in-plane (IP) and out-of-plane (OoP) reinforcement systems using flexible glass fiber-reinforced polyurethanes (FRPU) protected efficiently the clay-block infills against failure for very high inter-story drifts and accelerations when imposed to seismic loads [56]. Moreover, other studies have investigated the effectiveness of the nano-reinforced fibrous mortar coating method in enhancing the shear strength of unreinforced masonry walls [57–60]. One example of composite brick masonry walls with brick, FRP, mesh, and fabric-reinforced cementitious matrix (FRCM) masonry is detailed in [61]. The OoP performance of the retrofitting system consisted of a mechanical coupling between the active confinement of the masonry system of steel straps and CFRP strips clearing up the delamination interruption when the transfer of stresses from the steel straps to the CFRP strips occurs on both sides of a bent beam [62]. The combination of shotcrete and FRCM mesh with carbon FRP strips as a strengthening technique enhances the mechanical and durability performance of composite masonry walls (Figure 4) [63]. The use of horizontal steel reinforcement and GFRP reinforcement in composite brick masonry walls was effective in enhancing the transverse loading capacity of the composite masonry walls, with GFRP reinforcement providing better performance [64]. A comparison of the three different strengthening systems was made, with TRM reinforcement showing the maximum midspan deformation, while the best ductility and maximum load resistance were attained, respectively, after reinforcements with high-strength and high-toughness engineered cementitious composites (ECCs) or fiber-reinforced mortars [65,66].

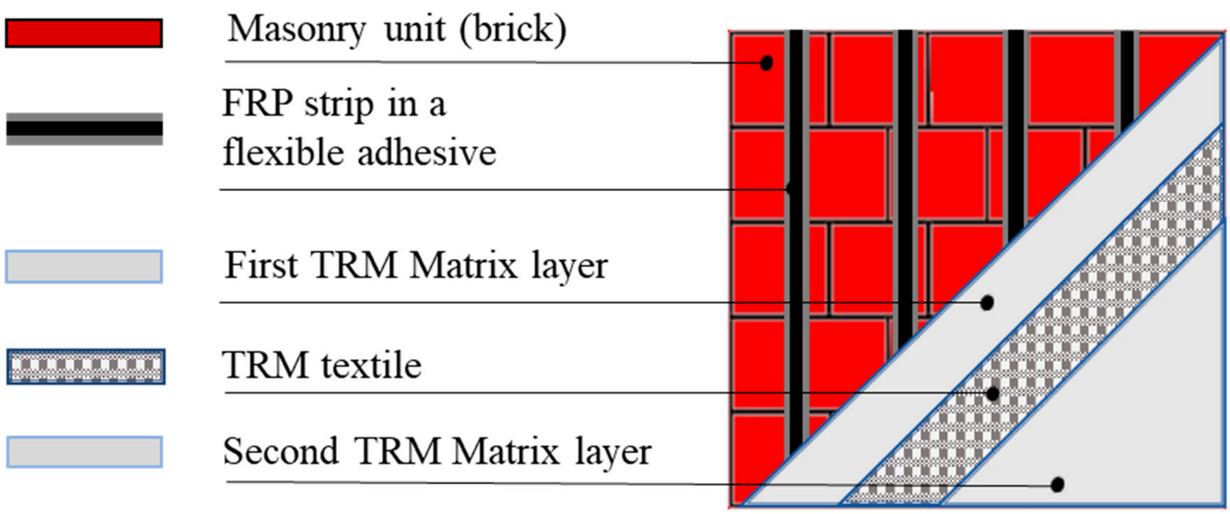


Figure 4. Combined strengthening systems on brick masonry walls.

Hence, it can be concluded that various reinforcement types and layouts increase masonry walls' compressive, tensile, flexural, and shear strength. Additionally, the stability, stiffness, and masonry wall ductility are enhanced with the help of the different categories of reinforcement observed.

1.2. Objective of the Study

This comprehensive review delves into various methods for OoP reinforcing masonry walls, offering valuable insights into the impact of different techniques and types of walls on their mechanical properties. By analyzing the influence of different parameters, the review provides crucial guidance in evaluating the different strengthening methods for different types of masonry walls. The review provides valuable highlights on the advantages and disadvantages of the provided techniques to upgrade the URM walls' properties including energy efficiency, load-carrying capacity, stiffness, and durability. Summarizing a review of strengthening techniques for various categories of reinforcement and masonry walls is essential to address the current need to retrofit and reinforce existing masonry walls. The purpose of this research is to evaluate the various techniques for strengthening different types of masonry walls. The study will examine the existing literature on a variety of walls and strengthening methods, including FRP, SPG, NSM, FRCM/TRM, CRM, meshes, and other materials. Each method will be evaluated based on its effectiveness when applied to different types of masonry walls with varying mechanical properties (tensile, compression, shear, flexure), materials (units and mortars), and functions (reinforced and unreinforced) under different loading conditions. The findings of this review will assist in selecting the best strengthening method for different types of masonry walls.

1.3. Research Significance

With the increasing anxiety over the transverse load vulnerability of masonry buildings, many researchers and engineers explore various strengthening methods to enhance strength performance and reduce the risk of OoP damage. Although several researchers have tried to investigate the different strengthening systems for OoP response evaluation of URM walls, including review papers, some issues have not already been covered. Because of this multifactorial issue with many parameters included, this review highlights the factors that have a significant impact, which leads to an appropriate strengthening system for each type of URM wall. The objective of this document is to conduct a thorough evaluation of the experimental and analytical research that has been carried out in recent times to enhance our comprehension of the out-of-plane reaction of reinforced URM walls. To conduct this research, an extensive database of more than 441 papers dealing with different strengthening systems for OoP response enhancing URM walls of different units, mortars, geometry, and loading conditions have been studied through software for scientometric analysis. For the deep and valuable investigation of this multifactorial process, all the individual parameters that influence the strengthening effectiveness and consequently the choice of strengthening system application were studied via Dematel (Decision making trial and evaluation laboratory) analysis for classifying cause–effect chain mechanisms among the factors. This novel technique evaluates the interdependent relations between factors and finds the critical ones through a visual structural model considering parameters such as the masonry unit type, rendering mortar type, strengthening system, the bond between different materials interfaces, masonry geometry, and loading conditions. With the abovementioned recommended scientific analysis, this paper contributes to highlighting the advantages and disadvantages of each strengthening system without proposing a strengthening method but to lead to the parameters that should be considered and the methodology to choose the optimum one.

2. Scientometric Analysis of the Literature Overview

The literature overview has been directed with the scientometric analysis of the numerous research papers concerning this issue. Specifically, the search tool that aided in producing a database of 133 from 441 more cited papers was Scopus. The search was filtered using the keywords "Out-of-plane", "masonry walls", and "strengthening" in combination. The limitations were the years of publications 2018–2023 (last 5 years), the subject area being limited to engineering, the document types being limited to research articles and reviews, and the language being limited to English (Figure 5). Figure 6 illustrates the Top 10 most cited authors with the count of documents coming from a bibliographic analysis with Scopus.

The network visualization displays items with their labels and default circles, which are sized according to the weight of the item, are depicted in Figure 7. Items with higher weight have larger labels and circles. Some items may not display their label to prevent overlap. The color of an item corresponds to its cluster. Links between items are represented by lines, and only the 400 strongest links are displayed. Figure 7 provides an example of network visualization, where the distance between two journals indicates their relatedness in terms of co-citation links. The closer the two journals are, the stronger their relatedness, and the strongest co-citation links are represented by lines [67,68].

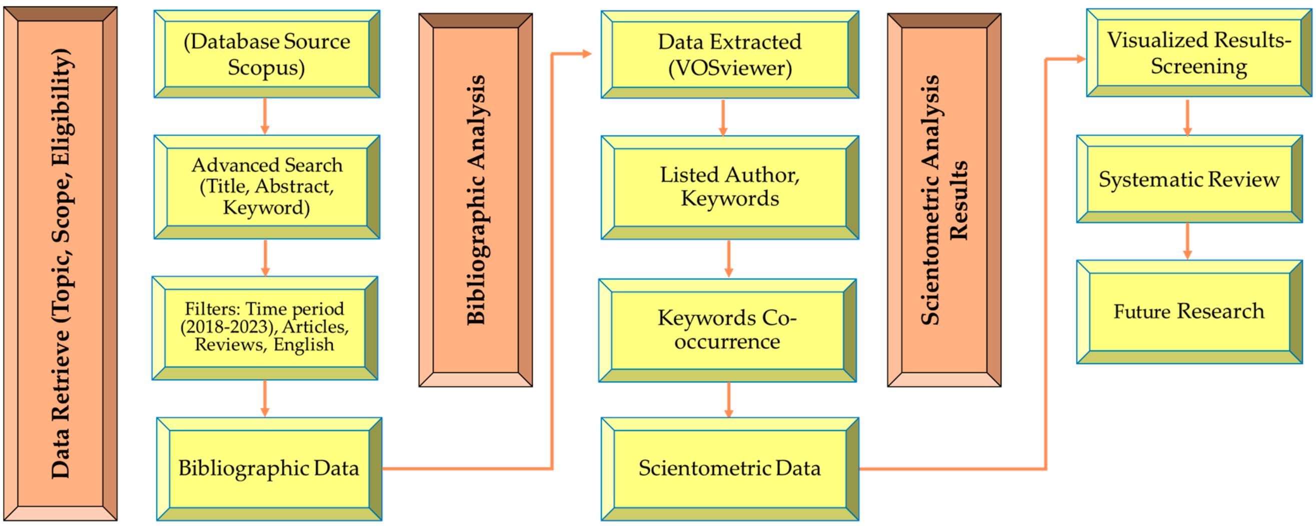
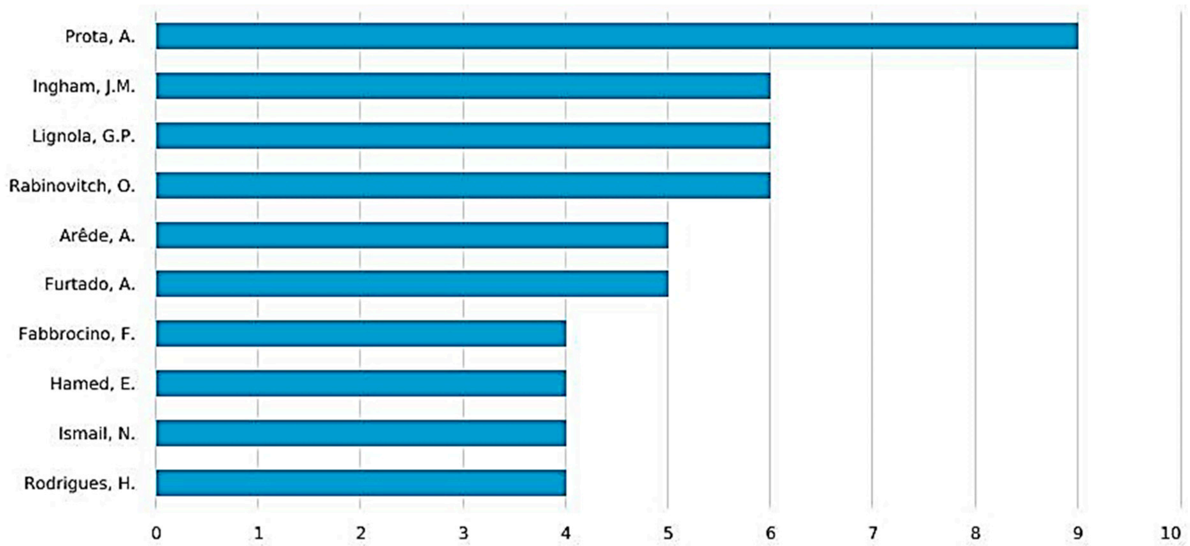


Figure 5. Flow chart of the scientometric analysis methodology.



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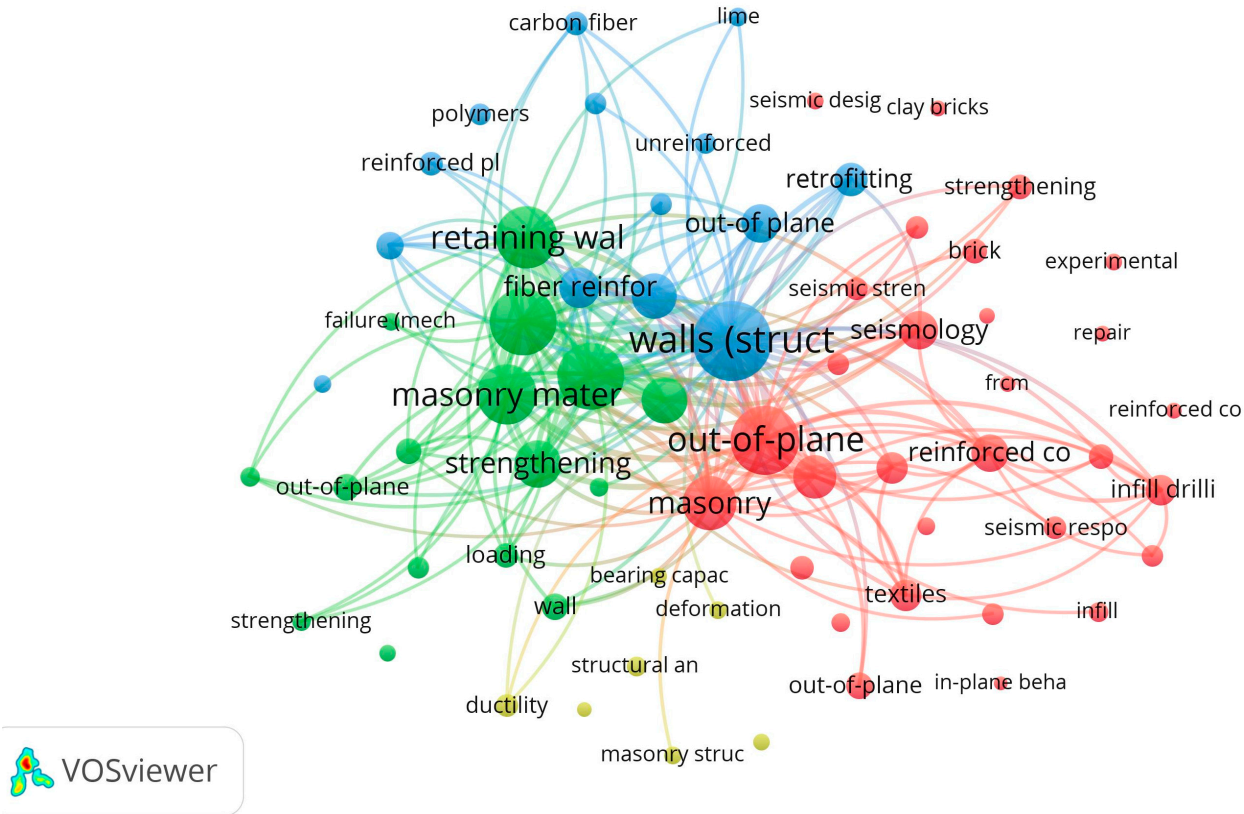

Figure 7. VOSviewer visualization of the co-occurrences of keywords network of the cited papers published in Scopus 2018–2023.

3. Classification of Masonry Walls Based on the Construction Materials

3.1. Concrete Block Masonry Walls

The experimental study of strengthening methods like SRG, FRP, and TRM has increased the out-of-plane capacity of the brick, stone, or cement block masonry walls, depending on the categories of strengthening materials used, the orientation of the reinforcement, the number of reinforcing layers, and the type of adhesive matrix [69–71]. The different horizontal reinforcement arrangements have significantly enhanced the stiffness, ductility, and flexural capacity of the walls based on the spacing and configuration of the reinforcement elements [9,16,63].

3.2. Stone Masonry Walls

The historical, architectural, and cultural significance of stone masonry structures is widely acknowledged. However, their irregular construction and weak mortar joints render them susceptible to damage during seismic events. The technique of steel reinforcement grouting significantly enhanced the ductility behavior, flexural strength, and deformation capacity, making it more resilient to collapse. Moreover, research has indicated that the inclusion of fiber-reinforced polymer (FRP) composites in stone masonry walls can significantly augment their load-bearing ability, as well as enhance their rigidity and flexibility, without introducing extra weight to the overall structure. The combination of FRP and horizontal reinforcement for strengthening stone masonry walls improves the load-carrying capacity subjected to out-of-plane loading. Flexural strength, shear strength, ductility, and load-carrying capacity of solid masonry walls improved with the help of CFRP or GFRP strengthening of masonry walls and enhanced the resistance against out-of-plane loading [29,70]. On the other hand, by overcoming the FRP usage disadvantages, reinforcing walls with multiple layers of TRM under lateral loading significantly increases load-carrying capacity, even by three times more than the plain URM wall, which is a solution that has been proven through experimental testing [71,72].

3.3. Clay Brick Masonry Walls

The efficacy of FRP composites in strengthening clay brick masonry walls can significantly improve the load-carrying capacity of the clay brick masonry walls. The combination of inorganic mortar and textile (TRM), which effectively improves the mechanical performance of reinforced masonry walls, has recently been investigated (Figure 8) [73,74]. One way to strengthen a brick masonry wall is to use steel plates or straps to connect its separate components either vertically or horizontally and attach them to nearby walls or the foundation. Another technique involves using steel ties to connect the inner and outer layers of the brick wall, also located vertically or horizontally, can significantly improve the out-of-plane resistance of brick masonry elements [75–77]. Strengthening URM walls by bonding FRP sheets onto their surface proves to be an efficient method of enhancing their seismic behavior. It can effectively prevent the collapse of URM walls during seismic activity [78]. The selected positions of strengthening techniques adopted for the masonry walls in transverse bending from the literature are shown in Table 1.

Table 1. Selected positions of the strengthening techniques adopted in different types of masonry walls.

Authors	Masonry Wall Type	Strengthening Techniques	Strengthening Layouts
[9]	Hollow concrete block	CFRP	Horizontal and vertical (grid)
[10]	Solid brick	CFRP	Anchored CFRP sheets
[42]	Concrete blocks	GFRP, CFRP	Vertical layers
[54]	Solid clay brick	BFRP	Vertical, diagonal, and grid reinforcement
[61]	Cement-clay interlocking bricks	SRG	Vertical steel bars, wire mesh
[65]	Clay brick	GFRP + FRCM	Vertical GFRP strips and single-sided grid overlay
[70]	Solid brick, rubble stones, cobblestones	GTRM	External glass grid
[72]	Stone	BTRM	External basalt grid
[75]	Solid clay brick	BTRM	External basalt grid

4. Mechanical Properties of Strengthened URM Walls

The objective of implementing a strengthening system is to improve the mechanical performance of in- and out-of-plane unreinforced masonry (URM) structures. Extensive research studies, both experimental and analytical, have been carried out to demonstrate the efficacy of such systems in enhancing compressive, tensile, shear, and flexural strength, as well as improving stiffness, deformability, and ductility.

Basalt and glass, as the typical textiles used in the TRM strengthening technique, were used for out-of-plane loading of masonry walls, thus increasing the shear bond capacity of masonry walls with FRCM systems [79–81]. Whatever the strengthening method adopted for the strengthening of masonry walls, confinement pressure was increased, resulting in an increase in the compressive strength of masonry walls. The influence of confinement was more pronounced in walls made with hollow blocks relating to walls made with solid bricks. The usage of FRP, TRM, and SRG retrofitting methods can increase the compressive strength of masonry walls significantly due to the confinement effect and ability to reallocate to the load uniformly across the masonry walls [82–84]. To improve the wall's tensile strength, different methods can be used such as reinforcing with FRP composites, improving construction techniques, and using stronger masonry elements. A study in the recent literature showed that applying FRP sheets to hollow brick masonry walls was an effective way to enhance their tensile strength [85].

When an OoP load is applied to the masonry wall, one of the predominant failures observed is a shear failure, and then a strengthening technique is required for the masonry wall to improve its shear strength [3]. The shear behavior of masonry walls strengthened with metal straps indicates that the strengthening method effectively increased the shear strength of the walls. Transverse strengthening using steel wire mesh and FRP composites increases the masonry walls' shear capacity [61]. Additionally, the shear response of FRCM-strengthened walls is also investigated in terms of shear strength capacity exhibiting up to 412% compared to the plain wall [86]. By utilizing both steel fibers and steel plates, the shear capacity of masonry walls under transverse loading can be significantly reinforced. This also alters the diagonal cracking to slide along the retrofit element. The FRP technique results in an increase in shear strength by up to 260%, which is attributed to a shift in the failure mode from shear diagonal cracking to splitting failure [87].

Out-of-plane strengthening methods are deployed to improve the flexural strength of masonry walls against lateral loading by using efficient strengthening techniques such as FRP composites, steel plate bonding (SPB), and the TRM technique. Depending on the type of strengthening but also the type of masonry wall, it has been proven that there are a range of values indicating the increase in the flexural strength of the masonry piers compared to the existing capacity without reinforcement up to 80%. The use of FRP composites in masonry walls can increase their flexural strength by up to 50% [49]. A new strengthening resolution with CFRP pultruded tubes as an alternative to steel rebars to advance the orthogonal wall connection was studied. An assessment of the efficacy of the application of FRP reinforcement on masonry panels strengthened by bonding unidirectional CFRP strips to their surface with an epoxy adhesive proved that CFRP strips significantly improved the shear and flexural strength of the masonry panels [36,37]. FRP rods have already been used to enhance the flexural strength from about 4.5 to 46 times compared to the unstrengthened walls, while it improved about 2.9 to 6.4 times when basalt fiber-reinforced polymer (BFRP) was used [54]. The strengthening technique using BFRP improved the flexural strength of the URM wallets by up to 640%, deformability by up to 300%, and energy absorption capacity by up to 214% [48]. Several studies have shown that applying FRCM has a significant impact on the flexural strength of masonry walls. Comparing FRP and FRCM methods with steel plate-bonded strengthened URM walls, both methods have been found to enhance flexural strength, ductility, and energy dissipation capacity more effectively.

5. Parameters Influencing the Effectiveness URM Strengthening

There are numerous factors contributing to the effectiveness of the strengthened masonry walls subjected to out-of-plane loading. Selecting the suitable reinforcement method for a masonry wall is a complicated process depending on numerous parameters, including the structural and mechanical properties of the reinforcement material, the compatibility with the masonry wall, and the advantages of each technique in terms of cost, installation, and maintenance.

5.1. Masonry Walls Geometry

Masonry wall geometry features like wall thickness, height to length of the masonry wall (aspect ratio), and openings comprise significant influential parameters on the mechanical performance of the masonry walls subjected to out-of-plane loading. An increase in masonry wall thickness results in an increase in flexural strength and an increase in the stiffness of unreinforced masonry walls under transverse loading. Altering the geometry of hollow clay brick masonry walls results in higher strength and stiffness. Masonry walls with lower aspect ratios exhibited better out-of-plane capacity than the masonry walls with higher aspect ratios. The existence of openings in the masonry walls reduces the mechanical strength of the masonry walls and the location, and the dimension of the openings had a higher effect on the masonry structural response than the number of openings in the masonry walls [3,4]. A higher moment of inertia of rectangular masonry walls results in more resistance to bending when compared to the circular or elliptical cross-section.

5.2. Masonry Rendering Mortars

The properties of the rendering material can have an influence significantly on the mechanical properties of the wall, predominantly its capacity to resist out-of-plane loading. An increase in the thickness of rendering material results in an increase in resistance against the transverse loading of walls. It is also reported in the literature that the rendered material made of lime-based material was more resistant against out-of-plane loading of masonry walls when compared to cement-based materials. Rendered mortar material made of a strong and stiff nature results in enhanced behavior concerning mechanical properties concerning masonry walls subjected to out-of-plane loading. Rendering mortar material made of steel fibers or FRP materials results in much better mechanical properties in terms of tensile, flexural, and shear strength when compared to that of conventional rendering mortar material.

5.3. Bond between Materials Interfaces

It is also noted in the literature that the bond between the masonry units, rendering mortar, and strengthening mortar also plays a vital role in contributing to the mechanical properties [2,3,82,87]. The better adhesion between the rendered mortar to the masonry units results in better resistance to the out-of-plane loading. Bonding of the FRCM strengthening system on the masonry wall's surface improves the strength, ductility, and stiffness subjected to OoP load [88,89]. Strengthening mortar materials made of a smooth surface between the masonry units and rendering materials delivers better results when bonded to the rough surface between the masonry units and the mortar rendering materials. All the examined techniques of upgrading the structural strength are in essence successful only when the substrate of the masonry is well structured with a proper connection of the vertical walls and the horizontal diaphragms, but also, the critical area of the crown binds and holds the vertical walls very well in seismic loading [90,91].

5.4. Loading and Boundary Conditions

The effect of eccentricity distance from the axis of the URM walls plays a vital role in the resistance of out-of-plane loading. An increase in the eccentric distance results in a reduction in the flexural capacity of the masonry walls. In addition, how a structure is loaded and the various combinations of loading can have a significant impact on the reinforced response of an unreinforced masonry (URM) system. Furthermore, the failure mode of the masonry walls depends upon the type of boundary conditions. These factors should be carefully considered in the design and analysis of URM structures to ensure optimal performance and safety. The horizontal diaphragms play a crucial role in the seismic response of masonry structures by transmitting the seismic actions to the vertical resisting elements. Inadequate connections between walls and horizontal diaphragms (floors and roofs) can cause walls to vibrate independently, making them more vulnerable to out-of-plane collapse. Insufficient structural support can lead to partial or complete collapses of roofs and floors, a factor that has been identified as a major contributor to fatalities in earthquake events [92].

6. Dematel Analysis

As noticed, several factors influence the strengthening effectiveness, and therefore, the appropriate choice, which is more valuable, is to investigate all the parameters with a trustworthy tool. The complexity of this multifactorial issue has been studied using an effective method of Dematel (Decision-making trial and evaluation laboratory) analysis, for identifying cause–effect chain components among the factors. This technique evaluates the interdependent relationships among factors and finds the critical ones through a visual structural model. The individual factors considered are as follows: A: masonry unit type; B: mortar unit type; C: strengthening system; D: bond between different materials interfaces; E: masonry geometry; and F: loading and boundary conditions.

The model of significant relations is represented in the following diagram in Figure 8, where the values of the degree of importance of each factor and the net effects that each factor contributes to the system are cited on the horizontal and the vertical axis, respectively. The points determined by the coordinate system with (the degree of importance, net effects) coordinates indicate the position and interaction of each factor [93].

For the interpretation of the results derived from the diagram, the factors can be evaluated based on the following aspects:

- The importance degree of each factor is depicted horizontally indicating both the factor's impact on the whole system and other system factors' impact on the factor. In terms of the degree of importance, D is ranked in the first place, and F, C, A, E, and B, are ranked in the next places.
- The degree of a factor's influence on the system is depicted on the vertical vector. In general, the positive values represent a causal variable, and the negative values an effect. In this study, E and F are considered causal variables, and A, B, C, and D are regarded as an effect.

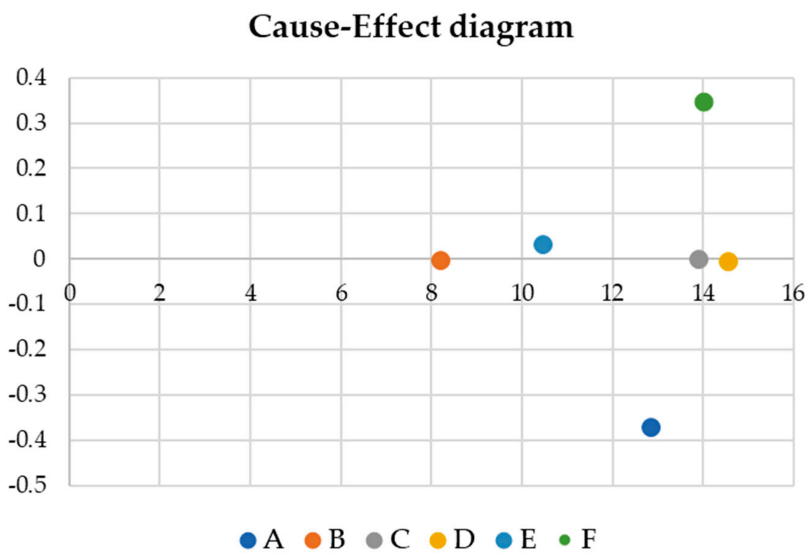

Figure 8. Cause–effect diagram of the causal relations between the variables A, B, C, D, and F.

6.1. Previous Studies

The transverse load strengthening of masonry walls has been the subject of wide research in recent years, and numerous studies have reviewed the accessible techniques and materials for this purpose. To summarize the review results from previous studies, the following discussions are required.

A review examined the use of different categories of FRP for the transverse strengthening of masonry walls. To improve the strength of low-strength masonry walls, the application of FRP can significantly enhance the mechanical, stiffness, and durability properties of walls, as reported in the review [35]. Lime-based mortars are a strengthening technique for out-of-plane masonry walls, and they improve the strength, ductility, and energy dissipation capacity of walls. The review also noted the application of lime-based mortars requires cautious consideration of the compatibility between the existing masonry and the mortar [32]. Another review found that steel reinforcement can increase the load-carrying capacity of masonry walls significantly under transverse loads, but the efficiency of the reinforcement depends on parameters like the type and placement of the reinforcement.

Another review found that FRCM systems can effectively improve the strength, durability, and stiffness of masonry walls, predominantly in the case of irregular and low-strength masonry. However, the review also noted that additional research is required to estimate the long-term durability of FRCM systems. Finally, the use of lime-based grouts for the transverse load strengthening of masonry walls. The review found that lime-based grouts can efficiently fill voids or gaps and cracks in masonry walls, leading to increased strength and stiffness [94–96].

The presented data can be applied in future relevant research to this field for newly developed models with a more specific analysis of the parameters based on the current research, trying to present all aspects of your current research to future researchers [53].

6.2. Recommendations for the Future Studies

A significant body of literature exists on the subject of out-of-plane reinforcing URM walls through a variety of techniques, as evidenced by numerous studies. Nevertheless, several areas remain where transverse load reinforcement for masonry walls is necessary. Examples of such areas include the following.

- It has been documented in the literature that there are various methods for strengthening masonry walls in the short term, but their long-term durability and efficiency are still uncertain. It is suggested that future studies should be conducted to evaluate the long-term performance of different strengthening methods under varying environmental conditions when subjected to transverse loading. This will provide a better understanding of the most effective and reliable methods for long-term use.
- It would be beneficial for future research to investigate new and economical methods for fortifying current masonry walls with ease. This would provide more practical and budget-friendly options for increasing the resilience of masonry constructions.
- Understanding the implications of heterogeneity and variability in masonry properties is crucial. Masonry walls can exhibit various levels of strength, durability, and stiffness due to differences in the materials utilized. Therefore, it is vital to investigate how these variations may impact the efficacy of different strengthening techniques and identify strategies to mitigate their impact.
- The optimization of strengthening techniques: Future studies can focus on recognizing the most effective strengthening techniques for precise categories of masonry walls and developing guidelines for their application.
- The development of a hybrid model for masonry walls: A hybrid model that combines experimental testing and numerical analysis has also been proposed. The hybrid model also involves two or more strengthening techniques which involve numerical, analytical, and experimental simulations.

- The present study has proven the importance of the factors that affect the effectiveness of each reinforcement. It is suggested to take into account all the important parameters that affect their appropriate choice. For this purpose, experimental and analytical research that would focus on the investigation of these factors would help in this critical issue. In addition, and equally important, it is important to clarify the factors that contribute to this multifactorial issue, adding in more detail other subcategories of factors.

7. Summary and Discussion

This review deals with out-of-plane strengthening techniques for unreinforced masonry walls. To summarize the review results from previous studies, the following discussions are required. The review focuses on the categories that are widely used after the scientometric analysis from the literature overview using SCOPUS and VOSviewer tools. The results indicated that researchers are focused on the externally bonded strengthening techniques applied to masonry walls such as FRCM, TRM, and SRG, which are applied in different layouts. The abovementioned thoughts are derived from the literature, and recommendations for further research are included.

Firstly, the application of the selected reinforcement techniques was listed with their advantages and disadvantages. Additionally, the performance of the URM walls strengthened with these novel techniques in terms of mechanical strengths (tensile, compression, flexure, and shear) provides a guide to the optimal choice of an appropriate technique. Finally, the examination of the crucial parameters that affect the choice of the appropriate reinforcement was conducted with Dematel analysis software. The factors that were taken into account are the different types of masonry units and rendering mortars, the bond between the different materials interface, the masonry wall geometry characteristics, and the loading and boundary conditions of URM walls. With a detailed analysis of the key parameters that influence the OoP URM strengthening response indicating the appropriate system for each case, this review leads future experimental movements and gives recommendations. The analysis has indicated that the sufficient bonding of the different interfaces of the strengthening matrix and the masonry wall materials is the most crucial factor in safely transferring the loads from the URM walls to the strengthening system.

In conclusion, it is important to declare that although the appropriate strengthening system choice remains a multiparametric issue, researchers should consider the factor of the bonding between materials interface for effective strengthening. With the selection of an appropriate strengthening technique for the given structure, engineers could prescribe a secure future for the every masonry construction.

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Nomenclature

OoP	out-of-plane
FRP	fiber-reinforced polymers
SPB	steel plate bonding
FRM	fiber-reinforced mortar
TRM	textiles-reinforced mortars
PBO	polypara-phenylene-benzo-bisthiazole
CFRP	carbon fiber-reinforced polymer
SRG	steel-reinforced grout
FRCM	fabric-reinforced cementitious mortar
CRM	composite-reinforced mortar
URM	unreinforced mortar
FRPU	fiber-reinforced polyurethanes
BFRP	basalt fiber-reinforced polymer
GFRP	glass fiber-reinforced polymer
ECC	engineered cementitious composites
Dematel	Decision-making trial and evaluation laboratory

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