Finite Element Modeling and Construction Aspects of Masonry Walls: An Overview

Amin Al-Fakih[1,2,*]

[1] Department of Civil and Environmental Engineering, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia

[2] Interdisciplinary Research Center for Construction and Building Materials, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia

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ABSTRACT

Masonry walls are a cornerstone of building construction worldwide, providing both structural and non-structural functions in diverse settings. Yet, masonry's inherent heterogeneity, arising from variations in units, mortar joints, and interfaces, presents significant challenges in accurately predicting its performance under service and extreme loads. This review focuses on two complementary perspectives: the construction aspects of various masonry wall systems (including infill, unreinforced, cavity, confined, and interlocking mortarless walls) and the finite element modeling techniques employed to capture masonry's mechanical behavior. The review found that the wall type has a significant impact on overall structural performance and seismic response. Moreover, it is found that micro-modeling approaches (both detailed and simplified) capture localized stress and strain states in the brick–mortar interface but entail higher computational costs. Macro-modeling provides a more practical, homogenized view for large-scale analysis, treating masonry as an anisotropic continuum. Numerous researchers have demonstrated that well-calibrated models can replicate experimental load-displacement behavior in both compressive and out-of-plane (OOP) bending scenarios. In particular, advanced contact formulations have been developed to address the progressive closure of mortarless joints, while plasticity-based models are widely employed to simulate cracking and crushing in conventional masonry under seismic loading. Collectively, these studies underscore that the choice of modeling strategy depends on the level of detail required, available computational resources, and the target performance metrics. By merging robust numerical methods with proven construction practices, researchers and engineers can better predict masonry's structural response.

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*Correspondence: Amin Al-Fakih (aminali.fakih@kfupm.edu.sa).

1 Introduction

Masonry structures have historically been fundamental to building construction around the world, fulfilling both structural and non-structural roles across diverse building types. In reinforced concrete (RC) frame systems, masonry infill walls are commonly utilized to partition spaces, improve thermal performance, and enhance the architectural appearance. Nevertheless, their structural contribution, particularly under seismic loading, has often been undervalued or neglected. RC frame buildings incorporating masonry infills have been widely constructed for commercial, industrial, and multi-family residential purposes across both seismic and non-seismic zones worldwide. The inclusion of masonry walls notably influences the seismic response of RC frames, generally improving lateral strength and stiffness compared to bare frames, yet simultaneously introducing brittle failure modes linked to the interaction between walls and frames [1]. In recent decades, masonry construction techniques have advanced considerably to align with contemporary requirements for more rapid, less labor-intensive, and cost-effective construction. Although traditional masonry systems are recognized for their robustness and simplicity, they exhibit certain shortcomings under dynamic or seismic forces. These challenges have prompted the development of newer technologies, such as surface-bonded masonry, fiber-reinforced polymer (FRP) strengthening, grouted masonry, and more recently, mortarless and interlocking masonry systems [2]. The interlocking mortarless system, in particular, has emerged as a novel concept that renders masonry construction more economical and expedient by eliminating the need for wet mortar joints, thus facilitating faster erection with less skilled labor. At the same time, increasing environmental concerns have prompted the reuse and recycling of construction waste materials. The integration of waste materials such as fly ash, crumb rubber, and construction debris into masonry production not only addresses sustainability challenges but also enhances certain mechanical properties of the resulting units. The use of recycled materials in interlocking bricks supports eco-friendly construction practices by reducing landfill waste, conserving natural resources, and decreasing carbon emissions associated with traditional construction processes.

Recent seismic events have underscored the critical importance of considering masonry infill walls in the design and analysis of RC structures. Studies have demonstrated that improperly detailed or neglected infill walls can lead to undesirable seismic performance, including short-column effects, torsional irregularities, and catastrophic out-of-plane (OOP) failures [3–5]. While fully infilled frames tend to perform better than partially infilled or bare frames under seismic loading [6,7], the interaction between infill panels and the surrounding frame elements remains complex and requires careful evaluation. Damage to infill panels has often been the primary source of post-earthquake repair costs, even when the primary structural frame remains largely intact, as reported by Ricci et al. [8] and Hermanns et al. [9].

Various types of masonry wall systems have been developed and studied to improve the seismic resilience and constructability of masonry structures. Conventional unreinforced masonry (URM) walls, while cost-effective and easy to construct, exhibit brittle behavior under seismic loading and often fail by shear, flexural cracking, or OOP instability [10,11–14]. Cavity walls (CWs), common in Europe and North America, improve thermal insulation and rainwater protection but are vulnerable to OOP collapse due to weak cavity ties [15,16]. Confined masonry walls (CMWs) offer enhanced seismic performance by integrating RC confining elements around masonry panels; however, substandard detailing can lead to premature failure through diagonal cracking, sliding shear, or OOP instability [17–21].

The development of interlocking (mortarless) masonry systems represents a significant advancement in masonry construction. These systems use specially shaped units that mechanically interlock with each other, eliminating the need for traditional mortar joints. Interlocking masonry can accelerate construction, reduce dependency on skilled labor, and enhance seismic performance by promoting controlled rocking and sliding mechanisms during earthquakes [2]. Moreover, interlocking units incorporating waste materials such as crumb rubber and fly ash contribute to sustainable construction and offer improved energy absorption and ductility characteristics under in-plane (IP) and out-of-plane (OOP) loading [22–24].

While experimental studies have provided valuable insights into the behavior of various masonry wall systems under different loading scenarios, numerical simulation techniques particularly finite element modeling (FEM) have become indispensable tools for advancing the understanding of masonry behavior. FEM enables detailed analyses of complex failure mechanisms, including cracking, crushing, and joint separation, under various loading conditions [25–29]. Recent studies, such as the three-dimensional nonlinear FEM simulation of URM walls under out-of-plane seismic loading, have further validated FEM's ability to capture progressive damage and failure with high accuracy [30]. Different modeling approaches, such as macro-modeling, simplified micro-modeling, and detailed micro-modeling, offer varying levels of accuracy and computational efficiency depending on the scale and purpose of the analysis [31–34]. Moreover, advanced techniques such as discrete element modeling (DEM) and hybrid finite-discrete element methods have further expanded the capabilities for simulating masonry structures subjected to extreme events [35,36,37–39].

Recent research has emphasized the critical role of joint behavior, geometric imperfections, and material heterogeneity in the seismic response of masonry walls, particularly in dry-stack and interlocking systems [40–42]. Innovative modeling strategies now incorporate contact elements, plasticity-based material models, and interface damage mechanics to accurately capture the progression of damage and collapse mechanisms in masonry systems under IP and OOP seismic loads [43–46].

Despite these advancements, challenges remain in achieving an optimal balance between model accuracy, computational efficiency, and practical applicability in engineering practice. Particularly for emerging interlocking masonry systems incorporating recycled materials, comprehensive experimental validation and advanced numerical modeling are still needed to fully understand their complex behavior under seismic and extreme loads. The present review provides a comprehensive overview that integrates two critical aspects of masonry wall research: (i) the construction and material innovations in masonry wall systems (infill, unreinforced, cavity, confined, and interlocking walls) and (ii) the evolution of FEM techniques for analyzing masonry behavior under various loading scenarios. By bridging construction innovations with numerical modeling advancements, this review highlights how improved material design and robust simulation tools can synergistically enhance masonry wall performance, particularly under seismic actions. The key objective is to present a unified perspective on both construction practices and modeling strategies, critically assessing their interrelationship and identifying future research directions necessary for developing resilient, sustainable, and economically viable masonry wall systems.

2 Types of Masonry in Building Materials

2.1 Infill Masonry Wall (IMW)

IMWs are widely employed in both non-engineered and engineered RC frame buildings. In these structures, masonry is used for constructing exterior walls and interior partitions. Although typically classified as non-structural elements, masonry infills significantly influence the seismic performance of RC frame buildings [3]. The masonry infill configurations include bare frames (Fig. 1a), partially infilled frames, and fully infilled frames (Fig. 1b). Among these, fully infilled frames present the lowest risk of collapse, whereas bare frames are the most vulnerable to seismic-induced failure. The masonry infills are composed of either unreinforced or reinforced burnt-clay bricks set in cement mortar [4]. Typically, the infill panels consist of brick, clay tile, or concrete block walls placed between the columns and beams of the RC frame. Despite their structural contribution during seismic events, these panels are generally excluded from the design process and are treated as architectural, non-structural components.

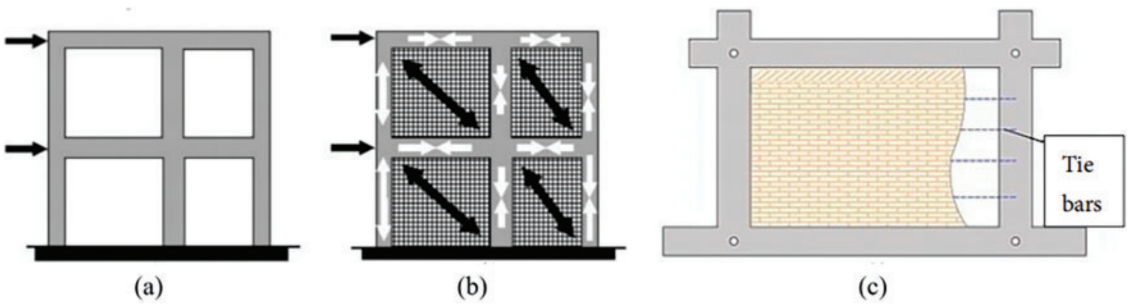

Figure 1: Configuration of IMWs with (**a**) bare frame [4], (**b**) fully infilled frame [4], and (**c**) tie bars [5]. Adapted with permission from Ref. [5]. Copyright ©2021, Elsevier B.V.

Stiff-wall-infilled frames were observed to exhibit more brittle behavior compared to their corresponding bare moment-resisting frames [47]. While stiff infill walls typically contribute additional lateral stiffness and strength, enhancing a structure's capacity to withstand static loads, they can have adverse effects under seismic conditions. In seismic events, stiff infills may attract higher-than-anticipated lateral forces and disrupt the expected load paths, potentially resulting in significant damage to both the infill and the surrounding frame elements. To address this problem, one proposed solution is to soften the upper stories by isolating the infill walls, as shown in Fig. 2. This method involves disconnecting each RC infill wall from the adjacent moment frame by creating two vertical slits along the sides of the wall and a horizontal separation above it. The widths of these separations can be tailored to accommodate the specific inter-story drift expected at each floor level.

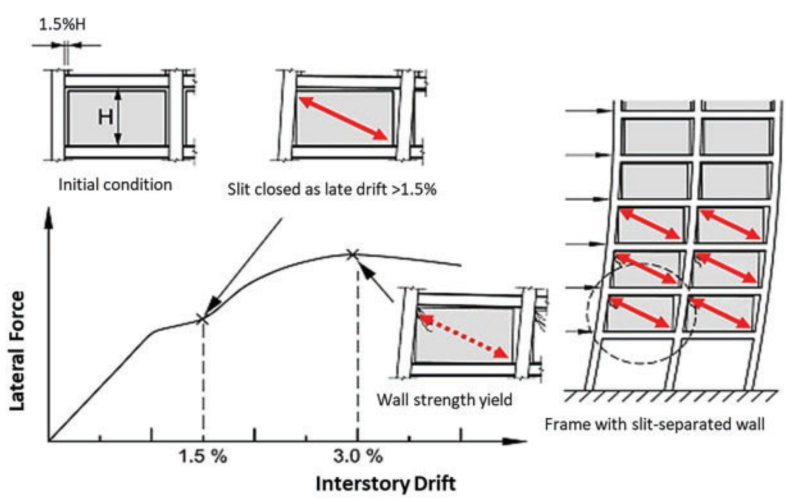

Figure 2: Ideal behavior of a steel frame with slit-separated RC wall [47]. Adapted with permission from Ref. [47]. Copyright ©2023, Elsevier B.V.

Murty and Jain [4] noted that masonry infill walls in RC structures can lead to several unfavorable effects during seismic events, including the short-column effect, soft-story behavior, torsional response, and OOP failure. These adverse outcomes are primarily associated with partially infilled frames and irregular distribution of infills either vertically or horizontally within buildings. In contrast, frames that are fully infilled with masonry have demonstrated improved seismic performance and a reduced likelihood of collapse compared to bare frames [6,7]. Although the surrounding structural elements exhibited only minor cracks, the infill walls themselves experienced substantial damage. This widespread damage to the masonry infills made buildings unsuitable for immediate reoccupation. Numerous case studies revealed that, even when ground motion intensity was insufficient to induce structural failure, inadequate anchorage and poor interaction between the infill walls and the RC frame led to the detachment of exterior walls, exposing the underlying concrete beams and columns [48].

Infills provide substantial lateral stiffness, resulting in their attracting a considerable portion of the lateral forces applied to a structure. When the infills are sufficiently robust, their strength contribution can be comparable to that of the bare structural frame. The failure mode of an infilled structure is determined by the relative strength between the frame and the infill material, as outlined in Table 1. Additionally, the overall ductility of the system is influenced by several factors: (a) the properties of the infill material, (b) the strength ratio between the frame and the infill, (c) the presence of ductile detailing within the frame when failure is governed by plastic hinging, (d) the reinforcement provided within the infill when cracking in the infills dictates failure, and (e) the spatial distribution of infills across the building's plan and elevation.

Table 1: Mode of failure of the IMW RC frame [4]

Frame type/Infill type	Weak infill	Strong infill
Weak frame	–	Diagonal cracking within infill panels Plastic hinge formation in columns
Frame with weak joints and strong members	Corner crushing at infill edges Cracking at beam-column connections	Diagonal cracking in infill Beam-column joint cracks
Strong frame	In-plane shear sliding of infill	–

In recent years, there has been growing interest in investigating IMWs, particularly regarding their impact on the seismic behavior of existing structures. The influence of IMWs on a building's seismic performance can be either beneficial or detrimental, depending on several factors, including construction details and mechanical characteristics such as the relative stiffness and strength between the structural frames and the infill walls, as well as the nature of the connection between the IMWs and the surrounding frame [8,49–53]. Observations from recent earthquakes indicate that many buildings that experienced significant damage or collapse did so largely due to the adverse effects of infill panels [54,55]. In some RC buildings subjected to seismic loading, most structural components displayed acceptable performance with minimal or no damage, while the IMWs sustained extensive damage, either IP or OOP. Commonly reported failures include the detachment of infill panels from the adjoining RC frame, diagonal cracking, and sliding cracks developing at the center of the panels, as illustrated in Fig. 3a–c [56]. These types represent common in-plane failure mechanisms of IMWs subjected to seismic action. In Fig. 3a, the visible gap between the infill panel and the surrounding RC frame indicates detachment caused by poor frame–infill interaction, often due to insufficient anchorage or the absence of shear connectors. This failure is typically observed when lateral drift during earthquakes causes the infill to separate from the boundary elements. Fig. 3b shows prominent diagonal cracking, a signature of shear-dominated failure resulting from concentrated in-plane stresses. This failure mode occurs when lateral seismic forces exceed the shear capacity of the infill. Fig. 3c illustrates a combination of diagonal and horizontal sliding cracks, reflecting a mixed failure mechanism attributed to insufficient bond strength and inadequate mortar adhesion under in-plane drift.

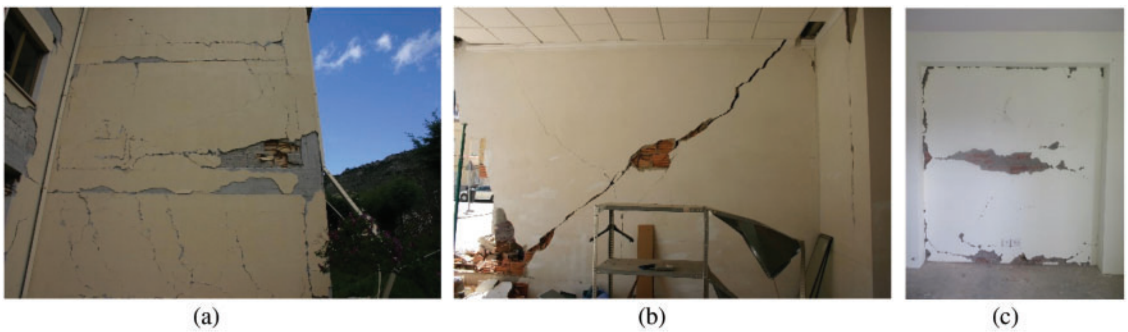

Figure 3: Common types of damage in IP IMWs: (**a**) separation from the surrounding RC frame due to earthquake in Italy, (**b**) diagonal cracks observed in Lorca, Spain, and (**c**) damage recorded during the Nepal earthquake [56]. Adapted with permission from Ref. [56]. Copyright ©2016, Elsevier B.V.

IMWs have long been employed in RC frames to serve as non-structural components. However, during seismic events, these walls experience significant OOP forces, which may lead to partial or total collapse, posing serious safety threats to occupants and property. As noted by Ricci et al. [8] and Hermanns et al. [9], OOP collapses have contributed to severe structural damage and casualties in past earthquakes. Traditional IMW specimens resisted OOP forces primarily through a two-way arching mechanism and bending action [5].

2.2 Unreinforced Masonry (URM) Wall

URM walls are extensively used worldwide, mainly serving as exterior enclosures and interior partitions (Fig. 4). In RC frame structures, this masonry infills are typically installed during the later phases of construction. Although they provide significant strength and stiffness, they are generally not considered essential elements of the structural system. As a result, removing an infill wall is often not viewed as a structural alteration. The primary roles of masonry infill walls include dividing interior spaces, improving thermal and acoustic insulation, and enhancing the visual appeal of building facades. Nevertheless, a typical URM wall characterized by its dimensions, boundary conditions, and material properties can contribute notable stiffness and resistance, mainly against IP loads, and to some extent against OOP forces [57]. Despite these advantages, URM walls have inherently low strength and are susceptible to brittle failure modes [57].

URM buildings often experience significant damage during earthquakes, primarily due to their inherent brittleness, low shear strength, and limited capacity for energy dissipation [10]. As a result, many URM walls require strengthening and retrofitting interventions. Severe damage is particularly evident when URM walls fail through an IP, shear-dominant mechanism [58]. The challenges associated with repairing damaged URM walls frequently necessitate their demolition and subsequent reconstruction [10]. Failures in URM structures can arise from insufficient wall strength under lateral IP or OOP loads, inadequate diaphragm stiffness, or weak connections between the walls and diaphragms [11–14].

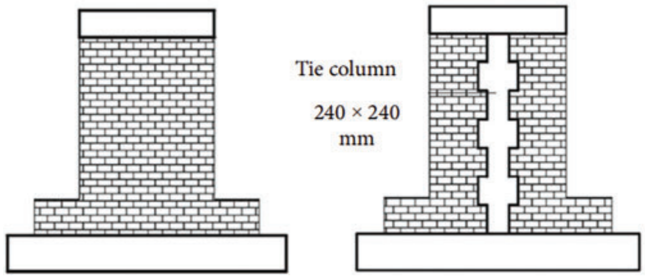

Figure 4: Typical configurations of unreinforced masonry walls [57]. Adapted with permission from Ref. [57]. Copyright ©2017, Elsevier B.V.

2.3 Cavity Wall (CW)

CW is commonly used in residential and low- to mid-rise buildings in Central and Northern Europe, particularly in countries such as the United Kingdom, Germany, and the Netherlands. These systems consist of an inner structural leaf and an outer non-load-bearing veneer, separated by a cavity and connected using metal cavity ties. This arrangement is designed to improve thermal insulation and moisture protection. Since the second half of the 19th century, load-bearing clay brick cavity-wall construction has been widely implemented in Europe, North America, Australia, and New Zealand. This method minimizes the amount of building materials used, lowers the thermal conductivity of masonry exterior walls, and confines moisture to the wall cavity, thereby safeguarding the building's interior. CWs offer three layers of rain protection: (i) runoff along the outer surface, (ii) absorption into the exterior leaf with drainage along its cavity-facing side, and (iii) the air gap acting as a capillary barrier. However, condensation within the cavity and water infiltration, often stemming from poor bricklaying, can cause corrosion of the metal cavity ties, as shown in Fig. 5a,b. The resulting corrosion, combined with inadequate boundary restraints, weakens the bond between the two masonry leaves, thereby heightening the seismic vulnerability of cavity-wall structures [15].

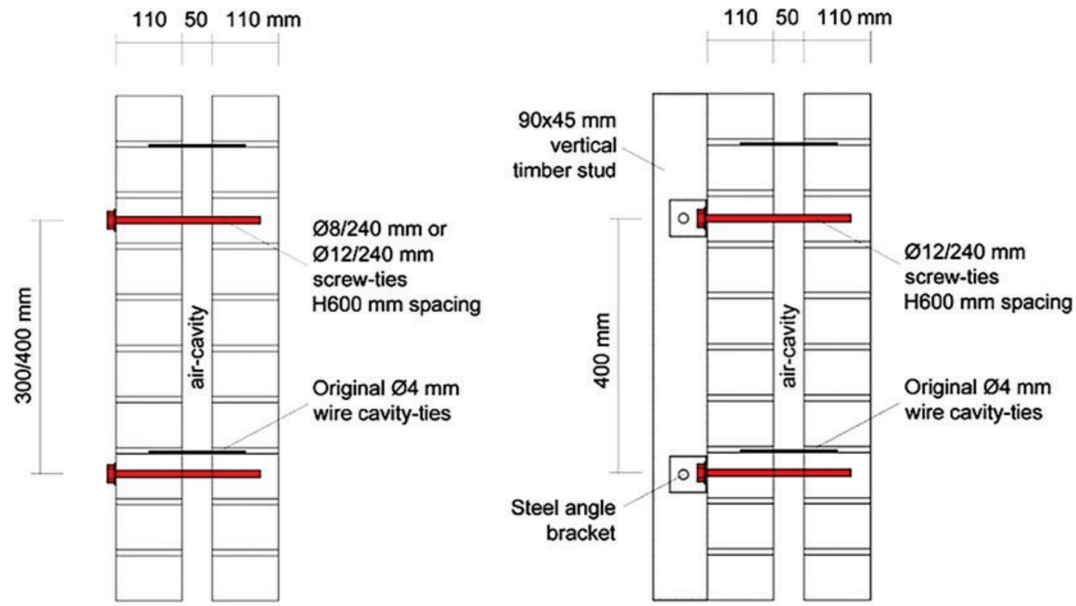

Figure 5: Cavity wall configurations [15]. Adapted with permission from Ref. [15]. Copyright ©2016, Elsevier B.V.

CW systems are especially vulnerable to OOP loads due to their slender profiles and low vertical loading, which restricts their capacity to develop significant IP strength. In this form of construction, a deliberate gap is maintained between two masonry leaves, with the cavity sometimes filled with insulating material. Typically, the outer leaf acts as a non-load-bearing brick veneer, whereas the inner leaf carries the structural loads from the floors and roof. It is not unusual for the two leaves to be built from different types of masonry; for example, in many European countries, the inner wall is frequently constructed using calcium silicate bricks or blocks, while clay bricks are used for the exterior leaf. The two leaves are usually linked together with metal cavity ties, which vary in material type, design, and spacing. Owing to their lightweight construction, excellent thermal insulation performance, and good resistance to wind-driven rain, CWs are commonly utilized in residential construction across Central and Northern Europe [16].

2.4 Confined Masonry Wall (CMW)

CMW buildings (illustrated in Fig. 6) represent a widely used form of residential construction globally. However, many of these structures have been constructed with outdated or deficient reinforcement practices, rendering them insufficient to accommodate the displacement demands imposed by major seismic events. Evidence from previous earthquakes indicates that poorly detailed CMW systems are particularly vulnerable to failures caused by OOP instability, IP diagonal tension cracking, and sliding shear mechanisms [17].

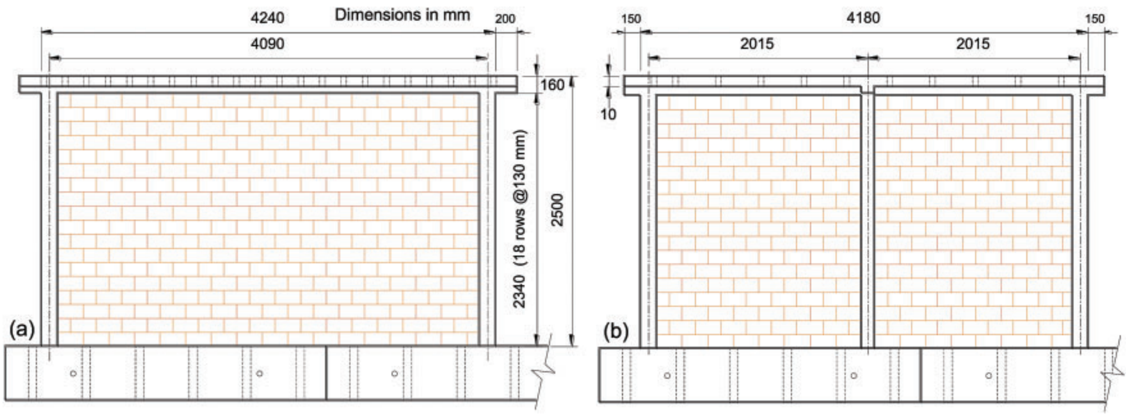

Figure 6: Typical configurations of confined masonry walls (**a**,**b**) [17]. Adapted with permission from Ref. [17]. Copyright ©2020, Elsevier B.V.

Three typical failure patterns observed in CMWs, as illustrated in Fig. 7, include:

(i) Inclined cracking within the infill panel often occurs alongside shear failure in the columns and, less frequently, plastic hinge development in the column members. This failure mode is mainly seen in brittle or non-ductile frames that are infilled with high-strength masonry panels.

(ii) Sliding of the masonry units along the horizontal direction may be associated with either flexural or shear distress in the columns. In some cases, crushing of the infill is also present. Such behavior has been documented in both weak frames with low-strength infills and in ductile, high-capacity frames incorporating weak masonry panels.

(iii) Localized crushing at the infill corners in combination with flexural failure of columns tends to occur in well-designed, ductile frame systems that are paired with rigid infill walls. This reflects a distinct failure mechanism seen under specific stiffness and strength interactions.

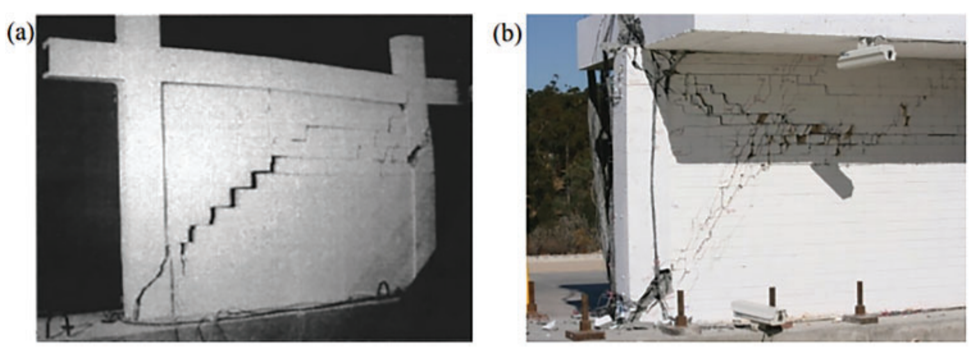

Figure 7: (Continued)

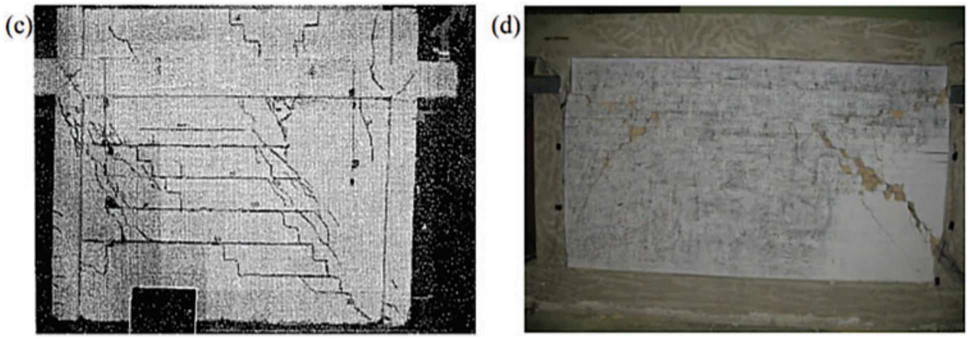

Figure 7: Failure mechanisms of the CMW frames observed in the experiments conducted by: (**a**) Al-Chaar et. al [18]; (**b**) Stavridis [20]; (**c**) Mehrabi [21]; and (**d**) Blackard et. al [59]. Adapted with permission from Refs. [18,20,21,59]. Copyright ©2002, 2009, 1996, and 2009, ASCEliberary, UC San Diego, and ACI

2.5 Interlocking Mortarless Masonry Wall (IMMW)

Over the past few decades, significant transformations have taken place in masonry construction, largely driven by the need for masonry to remain competitive with other structural materials such as steel and concrete. Additionally, the growing demand for faster, less labor-intensive, and more cost-effective building methods has contributed to the evolution of traditional masonry systems. These advancements have resulted in improvements in constructability, performance, and overall cost efficiency. To meet these evolving needs, several innovative techniques have been introduced and applied, including surface-bonded masonry, fiber-reinforced polymer-wrapped masonry, grouted masonry, and interlocking mortarless masonry (IMM) or dry-stack masonry (DSM) systems [2]. Among these, IMM or DSM systems have emerged as an innovative alternative to traditional mortared masonry, offering advantages in construction speed, cost, and seismic resilience [60–62]. These systems eliminate mortar by using specially shaped blocks that interlock mechanically [61,63–66]. The elimination of mortar and the use of locally available materials can lead to significant cost savings. For instance, interlocking compressed earth blocks can reduce construction costs by up to 20% compared to traditional masonry [67]. Interlocking mortarless masonry walls (IMMWs) represent an innovative structural system that has increasingly attracted interest due to its simplicity in construction, reduced labor demands, and environmental sustainability [60]. Unlike traditional mortared masonry, IMMWs rely on precision-shaped units that fit together through mechanical interlocking. Over the last two decades, research has expanded significantly on the structural behavior of IMMWs [65–73].

The ungrouted IMMWs/DSMW shows reduced capacity compared to conventional masonry but significantly improved ductility and post-failure energy absorption [23]. However, it can exhibit high compressive strength when grouted. Grouted dry-stack concrete block masonry wallettes demonstrated compressive capacities up to 152% higher than ungrouted ones [74–78]. The presence of flanges and appropriate aspect ratios can also enhance the strength of these walls [79–83]. In cases of eccentric compression, vertical splitting, face shell spalling, and global buckling were observed [63]. Multiple studies confirm that IMMWs provide comparable or superior performance to traditional masonry under various load conditions. For instance, grouted double-webbed mortarless blocks demonstrated higher axial capacities than single-webbed blocks, even though the latter had higher raw material strength [84]. Wall panels with openings exhibited reduced strength, while pilasters increased lateral resistance and stiffness [85]. The flexural behavior of IMMWs can be improved with the use of post tension, which enhances bending capacity and reduces the need for grout [77]. Shear parameters are influenced by axial compression, and the presence of grout can significantly improve shear strength [86]. In out-of-plane loading conditions, the flexural capacity of IMMWs, made of rubberized bricks, was shown to increase linearly with pre-compression load. Flexural cracking at mid-height dominated the failure modes, and the joint opening behavior was pronounced in taller panels [22].

IMMW systems have shown improved seismic performance due to their ability to dissipate energy and accommodate deformations. Confinement at the corners of dry-stacked masonry can enhance lateral load and drift capacity significantly [65]. Additionally, the use of post-tensioning instead of grout and reinforcement can further improve displacement ductility and energy dissipation [72,77]. Reinforced systems with large interlocking keys maintain structural integrity under cyclic in-plane loads [87]. Parametric seismic studies have highlighted how shear span ratio, axial precompression, and brick-to-brick friction influence lateral strength and ductility [88]. In composite systems, mortarless walls integrated with reinforced concrete frames enhance seismic resilience and reduce construction costs [89]. The use of large interlocking keys can provide additional shear resistance and improve hysteretic behavior [87].

Finite element modeling (FEM) has been crucial in validating experimental results and predicting structural behavior under varied loads. A comprehensive 3D nonlinear FEM developed by Al-Fakih using ANSYS successfully simulated compressive failure, stress distribution, and ductility of RCIB systems [90]. Additionally, customized FEM algorithms that incorporate nonlinear contact behavior and joint failures have improved the accuracy of compressive and flexural simulations [91]. Coupled wall–foundation–soil interaction models under seismic loading have further demonstrated how dry-joint friction and interface behavior influence displacement, stress transfer, and dynamic stability [92].

It can be concluded that failure mechanisms in IMWs typically involve flexural cracking, joint opening, and toe crushing behaviors that can be mitigated by introducing pilasters or applying vertical pre-compression. For walls already damaged in seismic events, ferrocement overlays provide an effective retrofit strategy that restores and even enhances structural capacity [68]. On the other hand, one of the main drawbacks of IMMW systems is their low bending capacity when relying solely on interlocking keys. This can be mitigated by grouting and reinforcing the hollow block cells, although this increases costs [77]. Additionally, IMMWs may have gaps that reduce thermal insulation efficiency. However, non-adhesive gap-fillers can be used to improve thermal properties, making them comparable to conventional concrete walls [93]. The IMMWs mechanism is shown in Fig. 8.

Figure 8: IMMWs mechanism [94]. Adapted with permission from Ref. [94]. Copyright ©2023, Sciepub

2.6 Practical Application Masonry Walls

The practical application of various types of masonry walls, including IMWs, URM Walls, CWs, CMWs, and IMMWs, can be understood through their specific uses, benefits, and challenges as illustrated in the Table 2. IMW is used to fill gaps between structural elements in framed structures, providing partitioning and protection from the external environment [95]. URM is commonly used as infill panels in reinforced concrete structures and as load-bearing walls in low-rise buildings [96]. URM is widely used in low-rise buildings for its combined structural, insulation, and aesthetic properties [97,98]. CMW is used in regions prone to seismic activity, combining masonry walls with reinforced concrete tie-columns and beams to enhance seismic performance [99]. Finally, IMMW is gaining global traction for cost-effective and sustainable housing, but it is not yet explicitly used worldwide. Generally, it is used for ease of construction and improved seismic performance due to the interlocking mechanism.

Table 2: Summary of masonry wall applications and features

Type	Application	Seismic performance	Key features
IMW	Partitioning, protection	Significant impact on strength and stiffness	Equivalent strut models for seismic analysis.
URM	Infill panels, load-bearing	Highly vulnerable, especially out-of-plane	Retrofit with FRP/geotextile for blast resistance.
CW	Low-rise buildings	Vulnerable if ties are inadequate	Excellent thermal insulation.
CMW	Seismic regions	Improved strength and deformation capacity	Use of tie columns and reinforced concrete bonds.
IMMW	Ease of construction, low to medium-rise buildings	Potentially better seismic performance	Interlocking mechanism. Uses grout and rebars.

3 Mitigation Approach for the Drawbacks of Conventional Masonry

One widely adopted approach to enhancing the seismic performance of IM-RC frames is to improve the load-bearing contribution of the infill walls. This is often achieved by forming a strong connection between the infill masonry and the surrounding RC frame (see Fig. 9a). Numerous studies have explored this method. For instance, Braga et al. [100] proposed the use of additional RC elements to separate and strengthen infill walls; Calvi and Bolognini [101] improved infill capacity by incorporating steel bars into the mortar joints and applying mesh reinforcement on the wall surfaces. Similarly, da Porto et al. [102] and Silva et al. [103] suggested installing both vertical and horizontal reinforcements within the masonry. Other studies, such as those by Valluzzi et al. [104] and Akhoundi et al. [105], examined plaster-based strengthening using textile meshes, while Ozkaynak et al. [106] used plaster reinforced with fiberglass and carbon fiber materials. These retrofitting techniques, especially those based on mesh or fiber systems, are commonly implemented in existing structures to improve their lateral performance. Although these reinforcement interventions significantly increase the stiffness and energy dissipation of the infills, it is important to acknowledge that once reinforced, the infill masonry becomes part of the lateral load-resisting system and must not be treated as a non-structural element. Despite their advantages, these methods often pose challenges in terms of cost, labor intensity, and compatibility with standard RC construction practices.

Recent studies by Sadoon et al. [107] introduced a method for strengthening URM walls by applying nano-silica-modified steel fiber reinforced mortar (NS-SFR). This novel plastering approach notably enhanced both the compressive strength and the lateral IP performance of URM walls subjected to cyclic loading, with shear capacity improvements reaching up to 132% when the treatment was applied to both faces. The technique presents a practical and efficient strengthening solution, utilizing relatively thin surface overlays.

An alternative method to enhance the seismic performance of masonry infill walls involves increasing their deformation capacity through specialized construction techniques (Fig. 9b). Mohammadi and Akrami [108,109] introduced a system incorporating a horizontal sliding interface formed by two prestressed steel plates that permits for frictional control of optimal IP seismic loads. Similarly, Preti et al. [110,111] established a design featuring multiple horizontal sliding planes within the wall, combined with lateral shear connectors to simultaneously transfer OOP forces. A related concept was proposed by Verlato et al. [112] and Morandi et al. [113], who designed specialized horizontal sliding interfaces and connection components using advanced and durable materials. In a different approach, Preti and Bolis [114] subdivided the wall with vertical sliding joints, enabling individual wall segments to rotate independently. In this configuration, OOP forces are transferred vertically to the frame's transom through shear connectors. These innovative solutions significantly enhance the deformability of masonry infills, thereby minimizing potential damage. However, the effectiveness of these systems is highly contingent on the precise and robust installation of the sliding mechanisms, whose long-term performance still requires validation in practical applications. Moreover, when window or door openings are present, additional edge profiles must be incorporated to ensure reliable boundary conditions [113].

The other strategy for enhancing the seismic performance of IM-RC frames involves decoupling the frame from the infill, thereby preventing frame deformations from inducing stresses within the masonry panel (Fig. 9c). The most straightforward method for achieving this decoupling is by introducing perimeter gaps around the infill, which are filled with soft materials to meet fire protection and sound insulation requirements. To ensure the transfer of OOP loads, steel L- or U-shaped profiles can be installed along the frame. Aliaari and Memari [115] demonstrated that this decoupling technique considerably mitigates damage to the infill. An early study by Tsantilis and Triantafillou [116,117] explored the insertion of cellular materials between the RC frame and the masonry infill, showing that such measures substantially reduced infill wall damage under IP loading, although their research did not address OOP forces an aspect they emphasized as important. Kuang and Wang [118] proposed another variation involving gaps between the infill and the columns, where OOP failure is controlled through additional steel anchors embedded in the masonry bed joints and rigidly attached to the frame. Despite the proven advantages of these decoupling techniques, their application in practice remains limited, mainly due to the high costs associated with materials and installation.

Recent work by Pantò et al. [48] introduced two additional strategies to address the challenges associated with IMWs. The first approach, termed the Uniko System (System-1), consists of a single-leaf masonry wall with a thickness of 100 mm, constructed using vertically perforated clay units (Fig. 10). These units feature a tongue-and-groove interlocking system aligned along the perforations, resulting in continuous vertical joints when the units are stacked vertically (Fig. 10a). This configuration is designed to facilitate sliding between masonry units, thereby potentially enhancing the energy dissipation capacity of the infill wall. The intention is for the infill to accommodate inter-storey drift without sustaining damage at drift levels that would typically compromise conventional infill walls. To further improve the OOP behavior, steel rebars are placed within external recesses along the faces of the masonry units and anchored to RC beams at the top and bottom. The Uniko System employs dry vertical joints and mortared bed joints, with the use of a general-purpose M10 mortar recommended. The second solution, referred to as the Térmico System (System-2), is based on maintaining a rigid connection between the infill and the RC frame through the integration of internal reinforcements and mechanical connectors. This system features a single-leaf clay masonry wall constructed with commercially available vertically perforated masonry units produced in Portugal (Fig. 10b). Similar to the Uniko System, M10 mortar is applied at the bed joints, while dry, interlocking head joints are maintained. To enhance both IP and OOP performance, truss-type reinforcements are embedded in the bed joints, and metallic connectors are installed at every second course where the bed joint reinforcement is located (see Fig. 10b). The masonry panels are constructed with 294 mm × 187 mm × 140 mm bricks and utilize murfor RND 0.5 100 reinforcements and murfor L + 100 anchors to link the infill to the RC frame at the reinforcement levels. The central concept of the Térmico System is to integrate the infill and frame into a unified system, thereby increasing initial stiffness, enhancing the ultimate load capacity, and controlling crack propagation and OOP collapse.

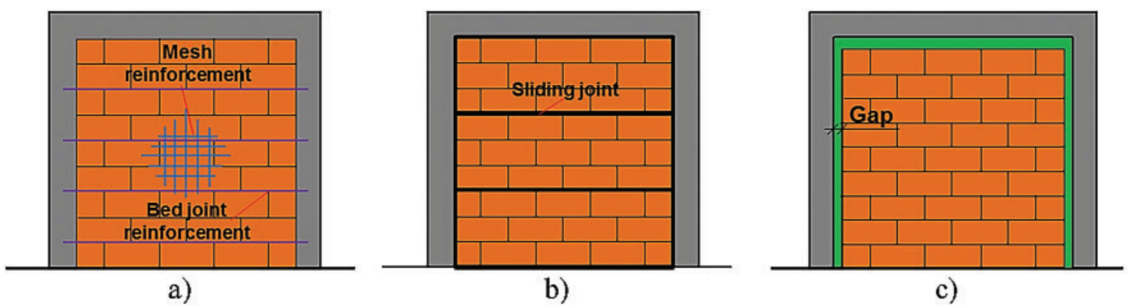

Figure 9: Techniques for enhancing the seismic performance of IM frames (**a**–**c**) [119]. Adapted with permission from Ref. [119]. Copyright ©2019, Elsevier B.V.

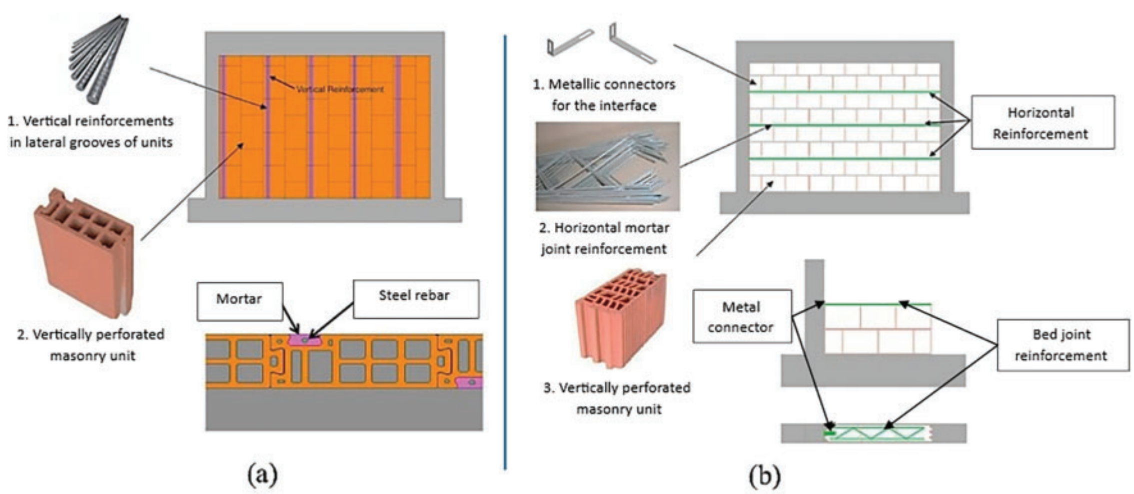

Figure 10: Typical interlocking masonry walls (**a**) System-1, (**b**) System-2 [48]. Adapted with permission from Ref. [48]. Copyright ©2019, Elsevier B.V.

Recent innovative configurations have emerged, such as damped infilled walls (DIWs) as shown in Fig. 11, which challenge the assumptions of traditional OOP resistance mechanisms of IMWs. For instance, Preti and Bolis [114] introduced a configuration involving vertical sliding joints with wooden planks that displayed coupled bending and arching responses. Zhou et al. [5] investigated the flexibility and energy dissipation of a DIW system by introducing damping layer joints (DLJs). These joints were constructed with either modified asphalt waterproofing (MAW) or mortar. DIWs with MAW-based DLJs demonstrated significantly reduced stiffness (about 28%–30% of IMWs) and lower peak OOP capacity, while DIWs with mortar-based DLJs, however, closely resembled traditional IMWs in behavior. DIWs demonstrated ductile behavior and remained stable under OOP displacements equal to 1.2 times the wall thickness. Consequently, existing predictive models for OOP behavior are inadequate for these newer systems [114,120].

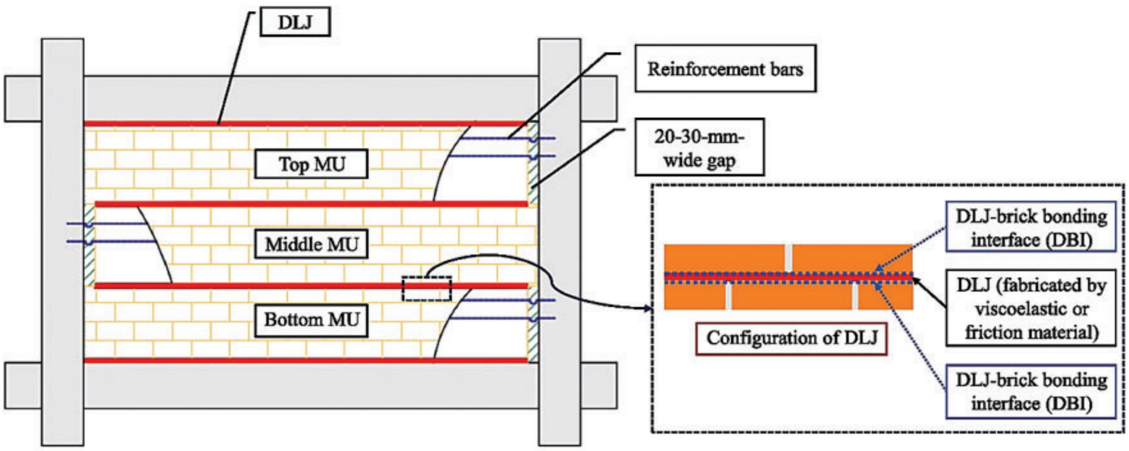

Figure 11: Damped infilled walls using damping layer joints [5,121]. Adapted with permission from Refs. [5,121]. Copyright ©2021, Elsevier B.V.

As a result, several recent studies have focused on developing novel systems aimed at addressing or at least mitigating the critical issues previously identified. However, there is still no general agreement on an optimal solution capable of simultaneously reducing the IP and OOP seismic vulnerabilities of masonry infills while maintaining adequate thermal and acoustic performance and ensuring long-term durability. Existing solutions proposed in the literature can generally be categorized into three main groups. The first category encompasses systems designed to enhance the IP and OOP resistance of the infill (Fig. 12a). This is typically achieved by incorporating vertical and/or horizontal reinforcement such as steel bars, light trusses, or steel wire meshes [101,103,122] into the masonry panel, or by applying fiber and composite material meshes, including Carbon Fiber Reinforced Polymer (CFRP) systems (e.g., Yuksel et al. [123]) and Fiber Reinforced Cementitious Matrix (FRCM) systems (e.g., Koutas et al. [124], De Caso and Nanni [125]). Although these reinforcement techniques significantly improve both the IP and OOP strength of masonry infills, they do not address the adverse infill-frame interaction caused by large thrust forces exerted on the frame; in fact, reinforcing the infill could potentially exacerbate these negative effects.

A second group of contemporary solutions documented in the literature (e.g., FEMA [126], Nasiri and Liu [127], Tsantilis and Triantafillou [116]) focuses on decoupling the masonry infills from the surrounding structure by introducing flexible joints at the wall-frame interface, complemented by appropriate OOP restraints to maintain the panel's stability (see examples in Fig. 12b). These systems are intended to minimize detrimental infill-frame interactions and reduce IP damage to the masonry. Nevertheless, these approaches still require extensive experimental validation and face several technological and design-related challenges that hinder their practical application. Key issues include determining appropriate joint dimensions that can effectively prevent harmful interactions while ensuring OOP stability and permitting IP differential movement between the infill and the frame. Finally, a third category of innovative systems seeks to mitigate infill-frame interaction by incorporating "sliding" or "weak plane" joints. These techniques aim to localize IP deformations and damage within predefined planes, thereby preserving the integrity of the masonry panel without entirely losing its contact with the frame.

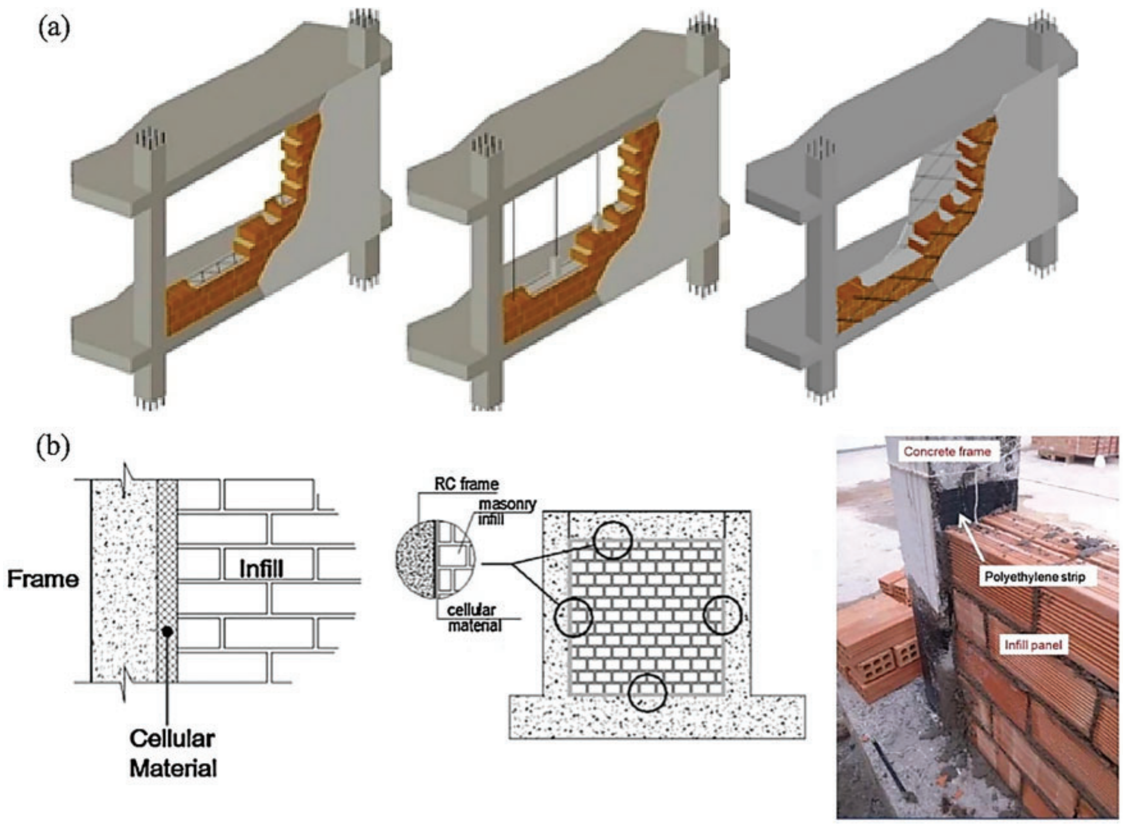

Figure 12: (**a**) Solutions with enhanced IP/OOP resistance; (**b**) "uncoupled" solution with flexible joints [116]. Adapted with permission from Ref. [116]. Copyright ©2018, Elsevier B.V.

Additionally, Al-Fakih [63] explored rubberized concrete interlocking masonry systems that integrate crumb rubber and fly ash to improve energy absorption and ductility under eccentric and axial loads. These dry-stack interlocking walls demonstrated excellent resilience against localized failure and improved crack propagation control, suggesting potential for enhanced deformation capacity in seismic scenarios. In addition, recent experimental work by Al-Fakih et al. [22–24] demonstrated that innovative dry-stack rubberized concrete masonry walls offer promising decoupling benefits due to their inherent ability to accommodate relative movement between units without complete structural collapse. Such systems, while originally targeting material sustainability through waste reuse, show favorable deformation behavior and post-peak residual strength under eccentric, axial, and OOP loads, supporting future designs involving engineered separation and controlled sliding.

Various traditional methods are available to enhance the seismic performance of existing URM walls. These include surface treatments such as ferrocement and shotcrete, grout injection techniques, external reinforcement, and center coring. However, numerous researchers have highlighted the drawbacks associated with these conventional approaches, including reduced available space, negative impacts on architectural aesthetics, increased structural mass, and susceptibility to corrosion. In contrast, modern fiber reinforced polymers (FRP) offer promising alternatives for retrofitting masonry structures and bring several well-recognized advantages compared to traditional methods [128].

In recent years, textile reinforced mortar (TRM) and fabric reinforced cementitious matrix (FRCM) have emerged as promising non-invasive strengthening techniques for masonry structures, particularly in seismic-prone regions. These systems consist of high-performance fiber meshes (e.g., carbon, basalt, or glass) embedded in an inorganic mortar matrix, typically lime or cement-based. When applied externally to existing masonry walls, TRM/FRCM improves tensile strength, crack control, ductility, and energy dissipation capacity, making them suitable for both IP and OOP strengthening applications [129–133]. Studies have shown significant improvements in shear strength and drift capacity in URM walls retrofitted with FRCM. Additionally, large-scale testing work confirmed that FRCM-strengthened masonry exhibits stable post-peak behavior and enhanced residual load capacity, offering a reliable solution for seismic retrofitting. Due to their mechanical efficiency and minimal alteration to wall geometry, TRM/FRCM systems are gaining acceptance in building codes (e.g., ACI 549.4R, ICC-ES AC434), particularly in Europe and the United States. Their application spans from school retrofitting projects in Italy to reinforced historic façade preservation in the Middle East and North Africa.

Recent advancements in retrofitting techniques have led to the development of inorganic matrix composite (IMC) systems, which aim to simultaneously enhance the seismic resilience and thermal performance of existing masonry structures. These systems typically involve the application of fiber-reinforced mortars, such as TRM and FRCM, combined with innovative binders like geopolymer-based mortars (Fig. 13) that possess low thermal conductivity [134]. The experimental results demonstrated significant improvements in both in-plane shear strength and thermal resistance compared to traditional lime-based systems.

Figure 13: Textile reinforced mortar (TRM) and fabric reinforced cementitious matrix (FRCM) retrofitting techniques [134]. Adapted with permission from Ref. [134]. Copyright ©2021, Springer

4 Finite Element Models for Masonry

4.1 Numerical and Modelling Approaches

In the numerical modeling of masonry structures, two primary classifications emerge: numerical methods and modeling approaches (Fig. 14). Numerical methods constitute the backbone of computational analysis techniques adopted for masonry, encompassing several distinct strategies [34]. The finite element method (FEM) [26,28,29,135,136] is the most extensively employed technique, wherein masonry structures are discretized into smaller elements, allowing for the solution of complex mechanical behavior under diverse loading scenarios. In contrast, the discrete element method (DEM) [35,36,137] models masonry as an assembly of discrete units or blocks, capturing discontinuities, separation, and sliding phenomena, which are critical for analyzing failure mechanisms in masonry walls. Limit Analysis focuses on assessing the ultimate load-bearing capacity of masonry structures by identifying potential collapse mechanisms without simulating the entire deformation process. Additionally, the applied element method (AEM) merges concepts from FEM and DEM [37–39,138,139] to allow the simulation of both continuum deformation and discontinuum failure processes, making it particularly effective in scenarios involving large deformations and progressive collapse.

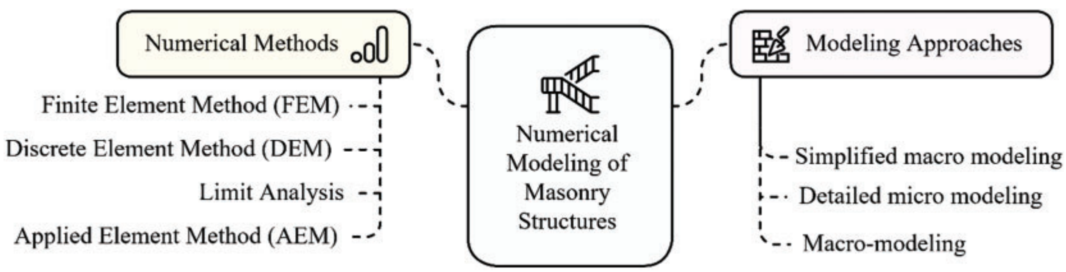

Figure 14: Numerical modeling of masonry structures

Alongside numerical methods, modeling strategies have been developed to idealize masonry materials and their interactions within computational simulations. To address the inherent complexity of masonry, three principal modeling approaches are commonly employed: detailed micro-modeling [34,140], simplified micro-modeling [34,141], and macro-modeling [31–34]. In detailed micro-modeling, both masonry units and mortar joints are represented as continuum elements, while the interfaces between units and mortar are modeled using discontinuous elements (Fig. 15b). This method accounts for the Young's modulus, Poisson's ratio, and inelastic properties of both components. In simplified micro-modeling (Fig. 15c), while the bricks remain individually modeled, the mortar joints and interfaces are represented as separate elements, simulating the contact area without capturing the Poisson effect of mortar on bricks. Micro-modeling techniques are most appropriate for small-scale masonry elements where detailed heterogeneous stress and strain fields are of interest. However, these approaches require extensive experimental data derived from laboratory testing of individual constituents and small masonry samples and are computationally demanding in terms of memory and processing time. In contrast, macro-modeling is more suited for large-scale and practical analyses, where the interaction between masonry units and mortar can be considered negligible with respect to the global structural behavior (no explicit distinction between units and joints is made, see Fig. 15d). Here, masonry is treated as an anisotropic composite material, establishing relationships between average strains and stresses. The material parameters for macro-models are typically obtained from large-scale masonry tests conducted under homogeneous stress conditions. A complete macro-model must capture orthotropic behavior, reflecting different tensile and compressive strengths along the material axes and distinct inelastic responses in each direction. Macro-modeling is favored for practical applications due to its lower computational requirements and simplified mesh generation process [142–144]. The recent studies have further demonstrated its effectiveness in predicting the nonlinear behavior of URM structures, particularly under seismic loading conditions, while maintaining computational efficiency [145].

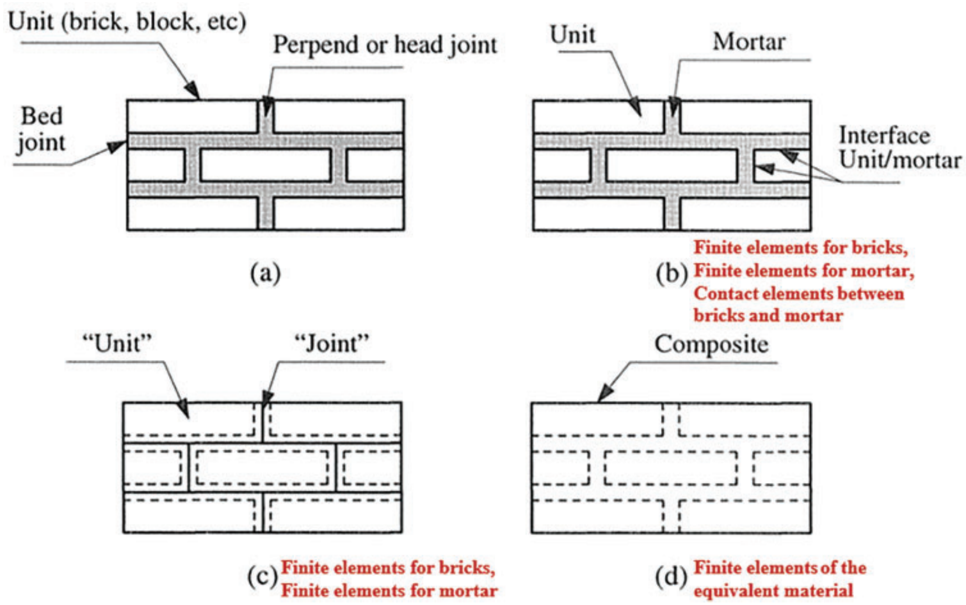

Figure 15: Various modeling techniques used for masonry structures: (**a**) physical masonry specimen; (**b**) detailed micro-modeling approach; (**c**) simplified micro-modeling method; (**d**) macro-modeling representation [adapted from [140,142]]

Most reviewed FEM studies employ displacement or residual force-based convergence criteria, with typical tolerances ranging from 10^{-3} to 10^{-6} depending on the software and nonlinear complexity [136,146]. End criteria often involve reaching peak load capacity or a specified displacement limit indicative of failure. Material inputs generally include elastic modulus, Poisson's ratio, compressive/tensile strengths, and frictional properties at interfaces, with data sourced from experimental tests or code-based estimations [90,146–148]. Validation is commonly achieved by comparing simulation results to load-displacement curves, crack propagation patterns, and failure modes observed in laboratory testing [149]. While some detailed models use interface elements (e.g., contact pairs with Mohr-Coulomb or cohesive zone laws), others adopt simplified homogenized inputs for macro-modeling [143,146,150].

4.2 Compressive Behavior Models

Masonry, whether traditional or mortarless interlocking, naturally exhibits anisotropic, heterogeneous, and discontinuous characteristics. These complexities primarily stem from the interactions among its basic components: masonry units, mortar joint fillers, and grout. The FEM has been extensively applied by researchers to model and analyze the behavior of these interfaces. In dry-stacked masonry, the behavior at bed joints becomes even more complicated, as does the stress distribution in neighboring units, due to inevitable air gaps where initial contact is absent. Upon loading, these gaps gradually close in a process known as "seating", converting the interlocking system into a progressive contact issue.

Currently, computer-based simulation has become an effective and practical approach for studying the structural behavior of materials such as concrete, steel, and masonry. As a result, FE analysis tools have grown both in capability and accessibility. A variety of commercial FEM software now allows for detailed masonry modeling, providing researchers valuable insights without sole reliance on experimental testing. Despite the long-standing use of mortarless masonry, there remains a scarcity of studies specifically addressing its modeling through FE analysis, with existing numerical research primarily focusing on block types used in wall construction.

Senthivel and Lourenço [136] performed nonlinear FE simulations to examine stone dry-stack masonry shear walls under combined axial and lateral loads. Using a micro-modeling strategy and a multi-surface interface model where masonry units were treated as elastic and joints as inelastic, their results closely matched experimental outcomes.

Similarly, Martínez and Atamturktur [146,151] validated FE models against experimental results for reinforced dry-stacked concrete masonry walls subjected to OOP forces. Their modeling approach employed a perfect plasticity framework based on the Willam-Warnke failure criterion. Concrete masonry units and grout were modeled with the SOLID65 element from the ANSYS 15.0 suite, while the brick-to-brick interfaces were simulated using surface contact elements (CONTA174 and TARGE170). They found that increasing the compressive strength of both units and grout improved lateral load capacity and wall ductility, with their numerical results showing strong agreement with laboratory data.

At Drexel University, Oh [152] developed a FEM for simulating interlocking mortarless blocks, integrating geometric imperfections of dry joints. While the model proved effective for small masonry assemblies, it lacked consideration of material nonlinearity, limiting its predictive capability near ultimate load and failure analysis. Separately, Alpa et al. [153] introduced a macro-model based on homogenization techniques that treated joints and blocks as a single continuous medium. Although their model captured joint movement mechanisms under the assumption of perfect joint behavior, it was less applicable for structural analysis due to its neglect of progressive failure, nonlinearity, and joint imperfections.

Thanoon et al. [147,148] devised an incremental-iterative 2D plane stress FE approach to predict the behavior and failure of interlocking mortarless masonry under compression. Their model integrated nonlinear progressive contact behavior at dry joints, considering geometric imperfections observed experimentally. The proposed method addressed material nonlinearity in orthogonal directions and captured effects like microcrack confinement and post-peak softening through an equivalent uniaxial strain concept. It also accounted for progressive failures such as block cracking and crushing, with the Mohr-Coulomb criterion used for interface modeling. Their simulations closely aligned with experimental observations of interlocking masonry prisms.

Additionally, in the work of Ben Ayed et al. [40], combined experimental and FEMs to study how local stress concentrations around clearances influence the compressive response of interlocking masonry. Using ABAQUS's "Interaction" module for surface-to-surface contacts, they found that the linear elastic model with yield tensile stress slightly underestimated the experimental pseudo-linear load capacity. They also introduced a simplified spring model to estimate the apparent vertical Young's modulus of interlocking systems (ISEB walls).

Following experimental investigations by Andreev et al. [41], FE simulations were carried out to examine the impact of joint geometry and material stiffness on dry joint closure behavior in refractory ceramic masonry. Using ANSYS with an elastic-plastic material model, the study reproduced joint closure curves that closely matched experimental trends, notably capturing the curve flattening characteristic.

In more recent work, Chewe Ngapeya et al. [42] developed a three-dimensional micro-model using ANSYS 17 to assess the influence of geometric imperfections, specifically block height variations (ΔH) and surface roughness (Δh), on dry-stacked masonry wall performance. Masonry blocks were represented using SOLID65 elements (simulating crushing and cracking), while dry joints were modeled with LINK elements for load transfer across real contact surfaces (Fig. 16). Their findings indicated a 97% correlation between simulation and experimental results in terms of compressive strength and failure modes. Furthermore, the study emphasized that variations in block height significantly impact load transfer mechanisms, primarily by affecting the actual contact between masonry courses.

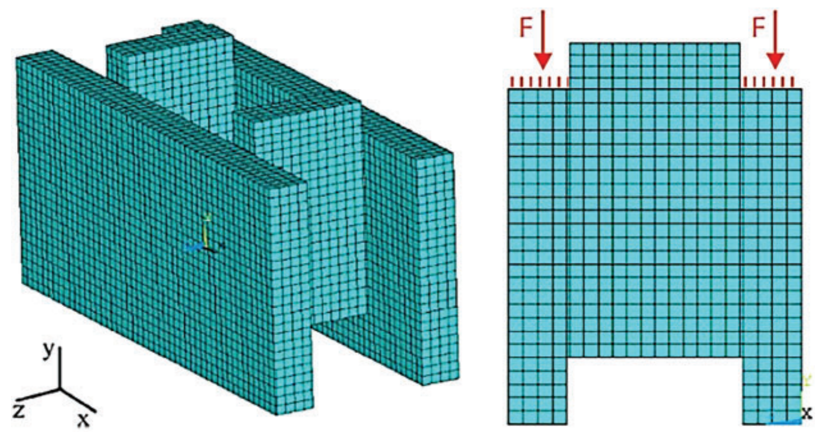

Figure 16: 3-D model of the developed dry-stack masonry block [42]. Adapted with permission from Ref. [42]. Copyright ©2018, Elsevier B.V.

Al-Fakih and Al-Osta [90] developed a FEM to assess the structural behavior of rubberized concrete interlocking masonry under vertical loading conditions. The authors employed a three-dimensional micro-modeling approach using ABAQUS, where individual masonry units and mortar joints were explicitly modeled with solid elements to capture localized stresses and crack propagation (Fig. 17). Special emphasis was placed on modeling the interlocking mechanism between blocks to simulate the actual load transfer behavior without relying on mortar at head joints. The study revealed that the developed FEM could accurately predict the structural response, including load–displacement behavior, crack patterns, and failure mechanisms, with results closely matching experimental findings. Moreover, the results highlighted that the addition of rubber particles into the concrete mix improved the energy absorption and ductility of the masonry system, offering an effective and sustainable alternative for seismic-resistant construction applications.

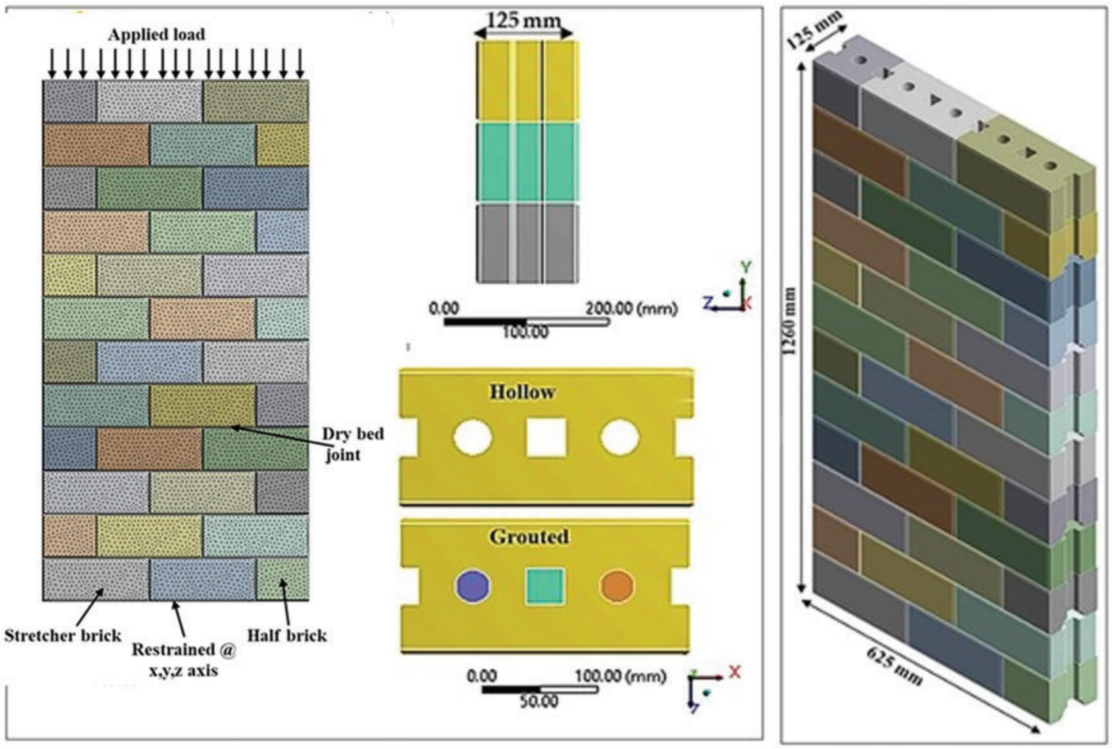

Figure 17: FE model configuration of rubberized concrete interlocking masonry walls under compression [90]. Adapted with permission from Ref. [90]. Copyright ©2022, MDPI

4.3 Out-Of-Plane (OOP) Load Behavior Models

Noor-E-Khuda et al. [149] investigated the OOP behavior of mortarless masonry walls using an explicit FEM approach, comparing the results with experimental data. The observed failure mode shown in Fig. 18b revealed a typical one-way bending failure characterized by a distinct horizontal opening along the mid-span bed joint, closely matching the strain localization pattern predicted by the FEM result shown in Fig. 18a. The load-displacement curves (Fig. 19) indicated that the lateral load increased to 9 kPa in the experimental tests and 11 kPa in the FEM simulations within the elastic range, corresponding to mid-span deflections of 0.6 and 0.9 mm, respectively. The ultimate OOP strengths recorded were 26 kPa experimentally and 23.6 kPa from the FEM model, both associated with a mid-span deflection of 9 mm. Overall, the EFE model successfully replicated the displacement ductility observed in the experimental tests and proved effective in predicting inelastic displacement behavior.

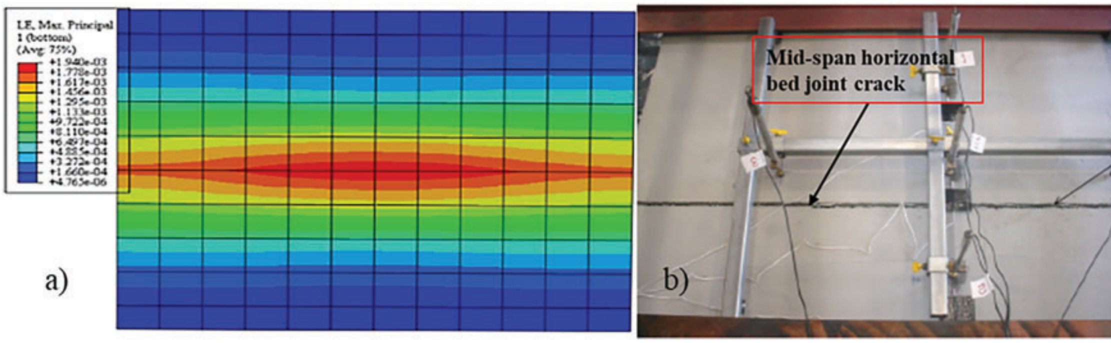

Figure 18: Failure mode of mortarless wall (**a**) FEM model, (**b**) Experimental [149]. Adapted with permission from Ref. [149]. Copyright ©2016, Elsevier B.V.

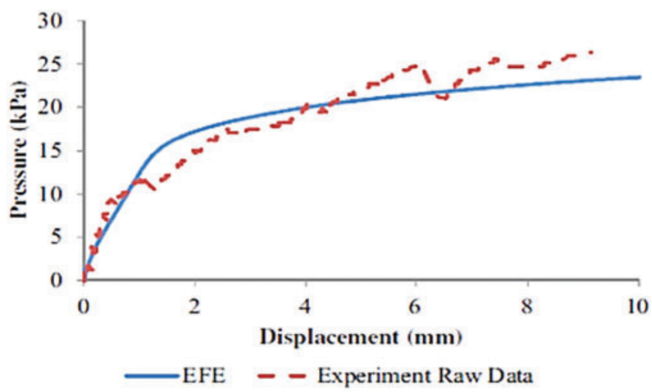

Figure 19: Load-displacement response of mortarless masonry wall [149]. Adapted with permission from Ref. [149]. Copyright ©2016, Elsevier B.V.

Martínez and Atamturktur [146] conducted a combined experimental and numerical investigation to examine the flexural performance, including failure modes and lateral displacement behavior, of dry-stacked concrete masonry walls subjected to OOP loading, as illustrated in Fig. 20. Their study observed unit compression failure on one side of the wall and tensile failure within the pure bending zone, resulting from hinge-like rotations along the bed joints (Fig. 21). This failure mechanism led to separations at the bed joints, ultimately reducing the lateral load-carrying capacity of the dry-stacked masonry walls. Furthermore, experimental results demonstrated that reinforced dry-stacked concrete masonry walls could sustain lateral loads beyond the elastic range, exhibiting notable displacement ductility. These outcomes support the conclusion that "dry-stacked masonry construction possesses adequate structural integrity to warrant inclusion in building codes".

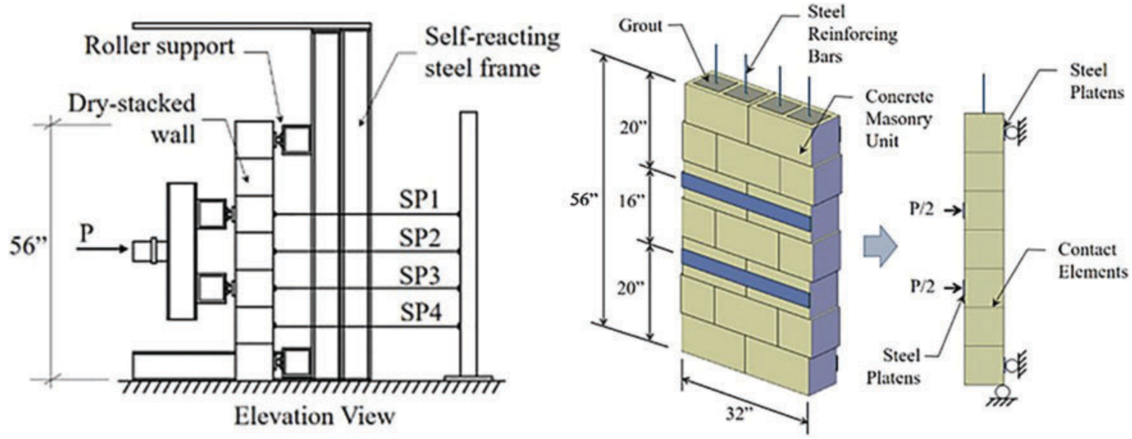

Figure 20: Dry-stacked wall test setup under OOP loading [146]. Adapted with permission from Ref. [146]. Copyright ©2019, Elsevier B.V.

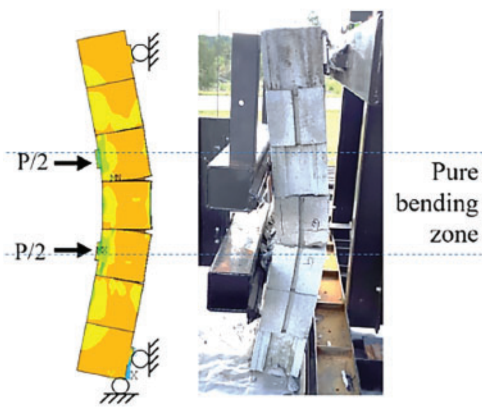

Figure 21: Failure modes of the dry-stacked wall test under OOP loading [146]. Adapted with permission from Ref. [146]. Copyright ©2019, Elsevier B.V.

Safiee et al. [85] conducted additional experimental studies on the OOP behavior of interlocking mortarless masonry wall panels. The panels, measuring 1.0 m in height, 1.2 m in width, and 150 mm in thickness, included both hollow and partially grouted configurations. Tests were performed under a constant vertical pre-compressive load combined with OOP lateral loading (Fig. 22). The investigation focused on lateral load-carrying capacity, mid-height deflection, dry joint separation between block layers, and observed failure modes. The behavior of dry joint openings was interpreted through an arching mechanism, characterized by the formation of a three-hinged arch. During early loading stages, the panels exhibited increased stiffness due to the vertical pre-compression, which delayed the onset of joint separation. For example, under a 0.5 MPa pre-compression load, the maximum moment reached 6.01 kN·m for the unreinforced interlocking hollow wall (WOP1) and 6.83 kN·m for the reinforced wall (WOP2), corresponding to ultimate lateral loads of 18.03 kN and 20.48 kN, respectively, as presented in Fig. 23.

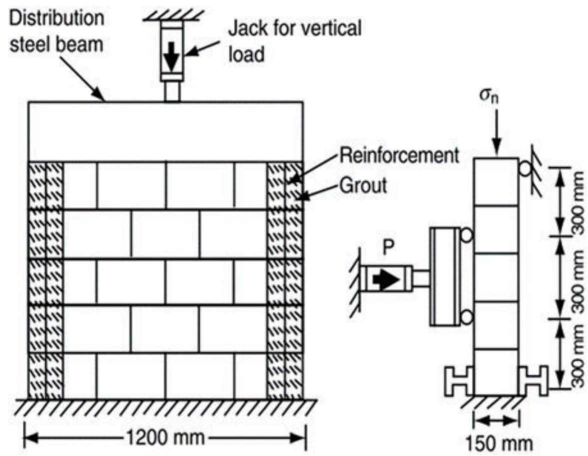

Figure 22: Test set-up of interlocking masonry wall under OOP load with precompression load [85]. Adapted with permission from Ref. [85]. Copyright ©2011, Sage

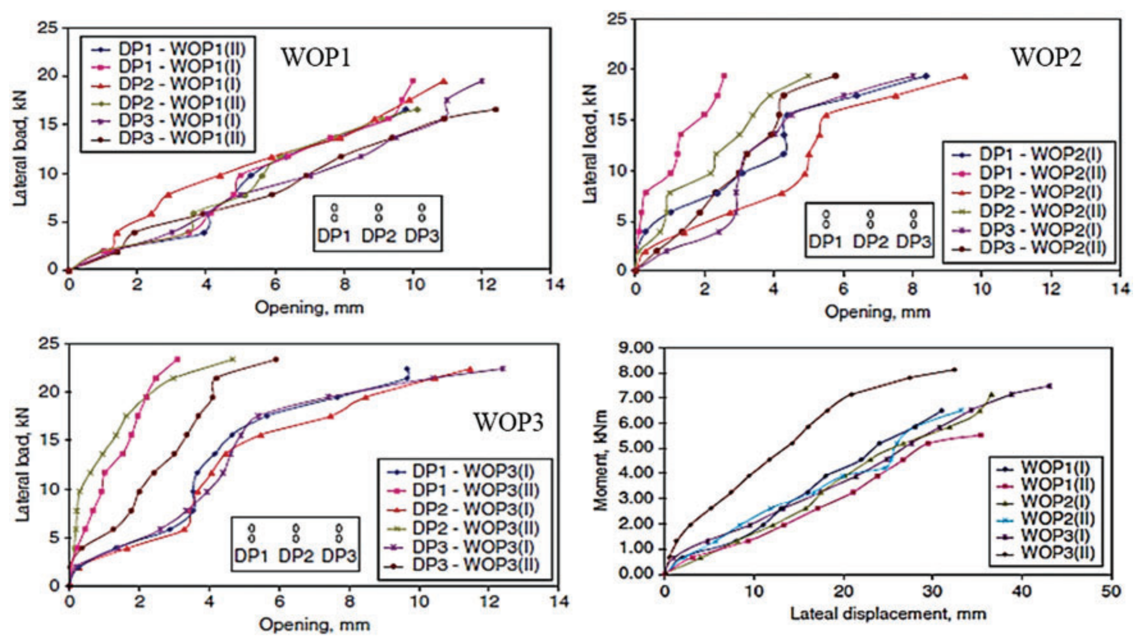

Figure 23: Opening and lateral displacement of an interlocking masonry wall under OOP load [85]. Adapted with permission from Ref. [85]. Copyright ©2011, Sage

4.4 Seismic Behavior Models

FEMs are powerful tools for predicting the seismic behavior of masonry walls. They offer an efficient, cost-effective alternative to experimental testing, helping engineers understand failure mechanisms under earthquake loads. FE simulations using ANSYS accurately predict cracking loads, displacement, stress distribution, and crack propagation in masonry walls under seismic action [154]. Nonlinear FE analysis shows that properties of tie elements (like cross-sectional area and concrete strength) significantly impact the seismic response of CMWs [155]. Direct modeling of IMWs in

RC buildings leads to better seismic behavior prediction compared to indirect or macro-modeling approaches [156]. Another FE simulation conducted in ANSYS effectively predicted cracking loads, displacement, and stress distribution in composite masonry walls strengthened with cold-rolled steel sheets [157].

Direct modeling of IMWs in RC buildings leads to better seismic behavior prediction compared to indirect or macro-modeling approaches [158]. Micro-modeling techniques simulate individual masonry units and mortar joints, providing detailed insights into localized failures. Studies demonstrate that micro-modeling effectively captures crack initiation, propagation, and hysteretic behavior under cyclic loading [159–161]. Conversely, macro-modeling approaches, which treat masonry as a homogenized continuum, offer computational efficiency and have been successfully applied to large-scale structures with acceptable accuracy [162,163]. Meso-modeling techniques, lying between macro- and micro-scales, have also been explored, balancing accuracy and computational demand by modeling mortar joints explicitly but homogenizing bricks [164]. Discrete element modeling (DEM) methods represent another advanced approach, particularly effective for URM structures. DEM captures block separation, rocking, and sliding phenomena during seismic excitation [165–167]. Hybrid modeling, combining FE and DEM, further improves predictions for complex or historical masonry structures with irregular geometries [168].

Several advanced constitutive models have been developed for seismic modeling of masonry, including continuum damage mechanics models [169], plasticity-based models [43,44], and combined damage-plasticity frameworks [45,46]. Interface modeling strategies, which model the bond behavior between bricks and mortar, provide a more realistic representation of masonry behavior under dynamic loading [170]. Cohesive zone models (CZM) are commonly adopted for simulating interfacial debonding and fracture [141,171].

Various software platforms support seismic modeling of masonry structures. ANSYS and ABAQUS are widely used for nonlinear static and dynamic analyses, demonstrating high accuracy in simulating cracking and collapse mechanisms [172–174]. DIANA FEA offers specialized tools for masonry modeling, particularly for historic structures requiring delicate interventions [175,176]. OpenSees has been extensively used to simulate the nonlinear dynamic response of masonry infilled RC frames, offering flexible material and element modeling options [177,178]. MIDAS FEA has also been utilized for detailed seismic assessment of masonry walls [179–182].

Experimental validation of seismic behavior models remains critical. Numerous studies show good agreement between FE model predictions and laboratory test results for blast loading [183], seismic loading [157,184], IP [185] and OOP [186,187] responses. Parametric studies using validated models reveal that factors such as aspect ratio, opening size, and vertical load significantly influence masonry seismic performance. Research has also emphasized the importance of modeling scale effects, where material properties and failure mechanisms may vary with specimen size.

Global collapse mechanisms in masonry structures under seismic loading are critical to understanding failure progression. Observed mechanisms include out-of-plane rocking of facade walls, dome collapse due to lack of tension capacity in dome rings, and global failure initiated by diagonal cracking at wall junctions. For instance, Fig. 24 illustrates real-case failure modes such as minaret collapse, dome separation, and wall instability in historical Turkish mosques [30,145]. In this regards, FE simulations by Kocaman and Gürbüz (2024) [30] demonstrate that square-plan, single-dome mosques exhibit V-shaped and Λ-shaped cracking patterns, dome-pulley detachment, and eventual global failure under high-intensity motions. Moreover, Nonlinear dynamic and pushover analyses can simulate total building collapse, showing that URM structures collapse under rare earthquakes, while retrofitted structures (e.g., with precast steel reinforced concrete panels) survive [188]. Studies on towers and historic churches show the importance of modeling overturning and shear failure as global mechanisms [189,190]. The effects of windows and openings are also considered in FEM and study found that masonry towers with windows experience more ductile performance and delay brittle failure due to stress redistribution [191]. These representative mechanisms emphasize the need for seismic models that accurately capture both in-plane and out-of-plane interactions, joint separation, and progressive cracking.

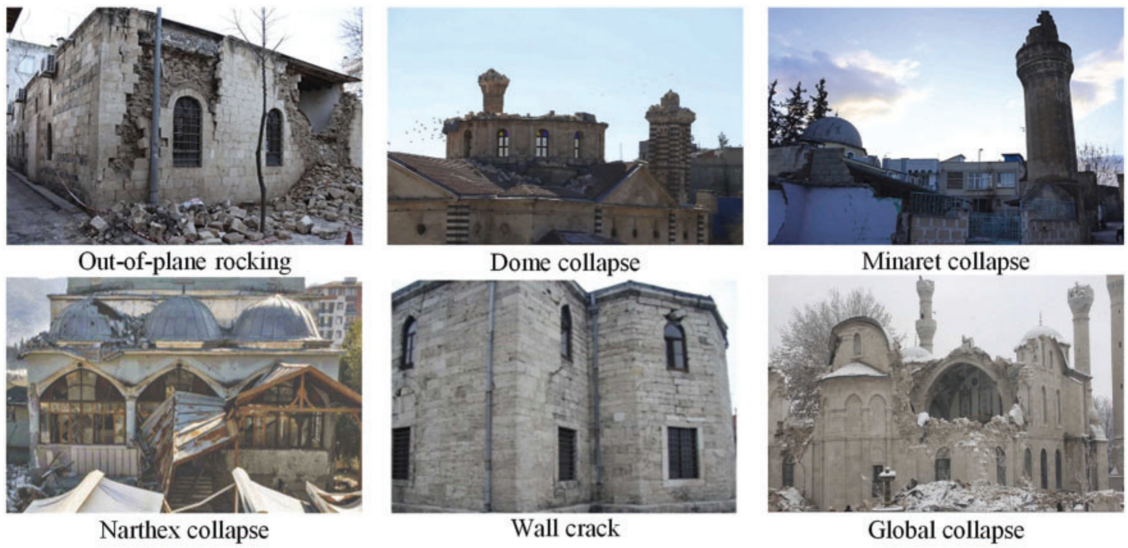

Figure 24: Real collapse mechanisms of masonry buildings under seismic loadings [30]. Adapted with permission from Ref. [30]. Copyright ©2014, Elsevier B.V.

Recent developments incorporate machine learning techniques to enhance seismic behavior modeling [192–194]. It is stated that data-driven approaches enable faster predictions of masonry damage patterns and performance levels without full-scale FE simulations. Additionally, integration of AI-based surrogate models with traditional FE analysis offers promising avenues for rapid seismic risk assessment.

Overall, the development and refinement of seismic behavior models, including advanced FE techniques, DEM, hybrid methods, and AI-enhanced simulations, have greatly expanded the ability to predict, analyze, and design masonry structures to perform better under earthquake loading.

5 Conclusions

This review has critically evaluated both the construction aspects and FEM techniques of masonry walls, providing a unified perspective that connects experimental advancements with numerical simulation efforts. Several key conclusions can be drawn from the existing body of work:

Masonry wall systems, including IMW, URM, CWs, CMWs, and interlocking mortarless walls, continue to play a vital role in the performance and resilience of structures worldwide. Each system presents distinct advantages and challenges, particularly under seismic loading. Infill walls enhance stiffness and strength but may introduce brittle failure mechanisms if not properly accounted for. URM walls, while common and cost-effective, demonstrate brittle behavior and require retrofitting or strengthening for adequate seismic resilience. CWs improve thermal performance but pose vulnerabilities in OOP seismic actions due to weak connections. CMWs offer superior seismic resistance provided adequate reinforcement detailing is implemented.

Interlocking mortarless masonry systems have emerged as a promising innovation to enhance constructability, reduce reliance on skilled labor, and promote sustainable practices through the incorporation of recycled materials such as fly ash and crumb rubber. Experimental studies have validated the superior energy dissipation, deformation capacity, and post-cracking stability of interlocking systems under seismic loads.

FEM has advanced significantly, providing powerful tools to simulate the complex nonlinear behavior of masonry walls. Detailed micro-modeling approaches accurately capture local stress concentrations, joint behavior, and progressive damage mechanisms but require significant computational resources. Simplified micro-models and macro-models offer acceptable accuracy for larger structures at reduced computational cost. Discrete element methods (DEM) and hybrid FEM-DEM approaches are particularly effective for modeling discontinuous behavior such as joint sliding, rocking, and collapse.

Recent research has underscored the importance of modeling joint imperfections, contact behavior, and material nonlinearity for accurately predicting masonry performance under both IP and OOP seismic loads. Interface modeling strategies and cohesive zone models further enhance the predictive capability of numerical simulations.

Despite these advancements, significant gaps remain in the experimental validation and numerical simulation of modern masonry wall systems, especially those incorporating alternative or recycled materials. Moreover, the complex interaction between innovative masonry walls and surrounding structural frames under multi-directional loading requires further investigation.

6 Recommendations

Based on the findings of this review, the following recommendations are proposed to advance the field of masonry construction and modeling:

1. There is a critical need for comprehensive experimental work for evaluating the performance of masonry units made with recycled and alternative materials, such as crumb rubber, fly ash, waste glass, and bio-based additives. These studies should address:
    - Long-term durability under environmental exposure (e.g., carbonation, moisture ingress).
    - Seismic performance under cyclic in-plane and out-of-plane loading.
    - Fire resistance, thermal insulation, and acoustic behavior.
    - Furthermore, large-scale structural testing of walls incorporating these sustainable units should be prioritized to establish design parameters suitable for structural applications.
2. To improve predictive accuracy, future studies should focus on developing hybrid modeling frameworks that combine finite element (FEM), discrete element (DEM), and damage-plasticity models. Key areas of advancement include:
    - Models capturing joint opening, block rocking, and degradation mechanisms in interlocking and mortarless systems.
    - Calibrated models for retrofit simulations involving FRPs, sliding interfaces, and damped infilled panels.

- Integration with probabilistic frameworks and performance-based design will also allow for more reliable seismic risk assessments.

3. Future work should explore the integration of smart materials (e.g., shape memory alloys, fiber-optic sensors, self-healing mortars) into masonry construction. Real-time monitoring through embedded sensors or wireless sensor networks could enable early damage detection, health monitoring, and predictive maintenance, especially in heritage or critical infrastructure.
4. Despite the proven effectiveness of systems such as interlocking mortarless masonry or retrofitted infill walls, there is a lack of standardized design codes. Collaborative efforts are needed to:
    - Propose strength and ductility reduction factors, load-resistance parameters, and detailing requirements.
    - Develop prescriptive retrofit guidelines for both historic and modern masonry based on experimental evidence.
    - Harmonize global best practices into codified design provisions for sustainable and resilient masonry.
5. It is recommended to adopt multi-objective frameworks to simultaneously optimize mechanical performance, cost, energy consumption, and environmental impact. Life Cycle Assessment (LCA) tools should be integrated to:
    - Quantify embodied carbon savings from using recycled and low-cement materials.
    - Assess cradle-to-grave performance, including reuse, recycling, or safe demolition of masonry systems.
    - Inform green building rating systems and sustainable procurement policies.
6. There is strong potential for integrating machine learning (ML) and AI-based surrogate models into the analysis and design of masonry systems. Recommended directions include:
    - Developing ML models to predict failure patterns, crack propagation, and residual capacity from limited datasets.
    - Training neural networks on experimental and numerical databases to enable rapid assessment of large-scale masonry walls.
    - Incorporating uncertainty quantification and decision-support tools for seismic retrofitting prioritization.

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