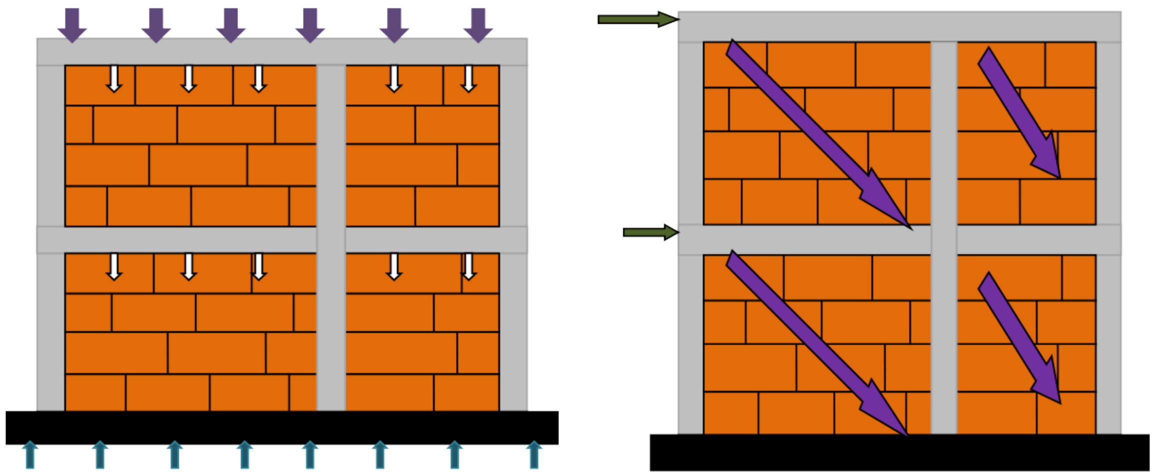
Chapter 2

Literature Review

2.1 General Discussion

Confined brick masonry (CBM) has become an increasingly popular affordable housing solution in many seismically active countries. This construction technique offers significant variations in material properties, tie-element detailing, and construction practices across different regions. Experimental and numerical studies have been conducted to understand the behaviour of CBM buildings. The structural resistance of CBM walls arises from the composite action of the masonry wall and adjacent reinforced concrete (RC) confining elements, such as tie-columns and tie-beams, in conjunction with plinth bands, sill bands, lintel bands, and roof slabs [5], [6], [19]–[23]. In CBM buildings, the concrete is cast in place after the masonry walls are constructed, resulting in an integral composite action between the RC and masonry elements, which enhances their interface connection. The masonry walls serve as the primary load-resisting members under both gravity and lateral earthquake loads as shown in Figure 2.1.

Under incremental cyclic lateral loading, compressive diagonal struts form in the masonry walls at right angles to the tensile stresses. Since masonry is weak in tension, cracks develop in the walls when stress demand exceeds capacity. Depending on the relative strength of the mortar joints, brick-mortar interface, and brick units, these diagonal shear cracks either fol-



(a) (b)

Figure 2.1: Flow of loads in CBM walls: a. vertical forces, b. lateral forces

low the path of bed and head joints (stepped) or pass through the bricks. The primary function of RC tie-elements is to confine the masonry walls, thereby improving their lateral stability, integrity, and connectivity with other walls and floor diaphragms. After severe damage to the masonry walls, tie-columns resist a significant portion of the loads acting on CBM walls [6]. These RC confining members act in tension and/or compression, depending on the direction of lateral forces and the magnitude of gravity loads [5], [6], [24]. Potential failure modes of CBM buildings have been identified in earthquake damage reports and research studies, including in-plane failure, overturning or out-of-plane (OOP) failure, diaphragm failure, connection failure, and non-structural failure as shown in Figure 2.2 [3], [5].

2.2 Experimental Study for Evaluating the Influence of Important Parameters

Meli et al. [6] provide a comprehensive summary of experimental studies conducted over the past three decades to understand the in-plane behaviour of CBM walls. Initially, the masonry wall in a CBM structure resists lateral earthquake loads, while the confining elements primarily maintain the wall's stability and integrity. When cracks develop in the masonry units or mortar joints, the panel becomes less effective at transferring forces. As lateral displacement

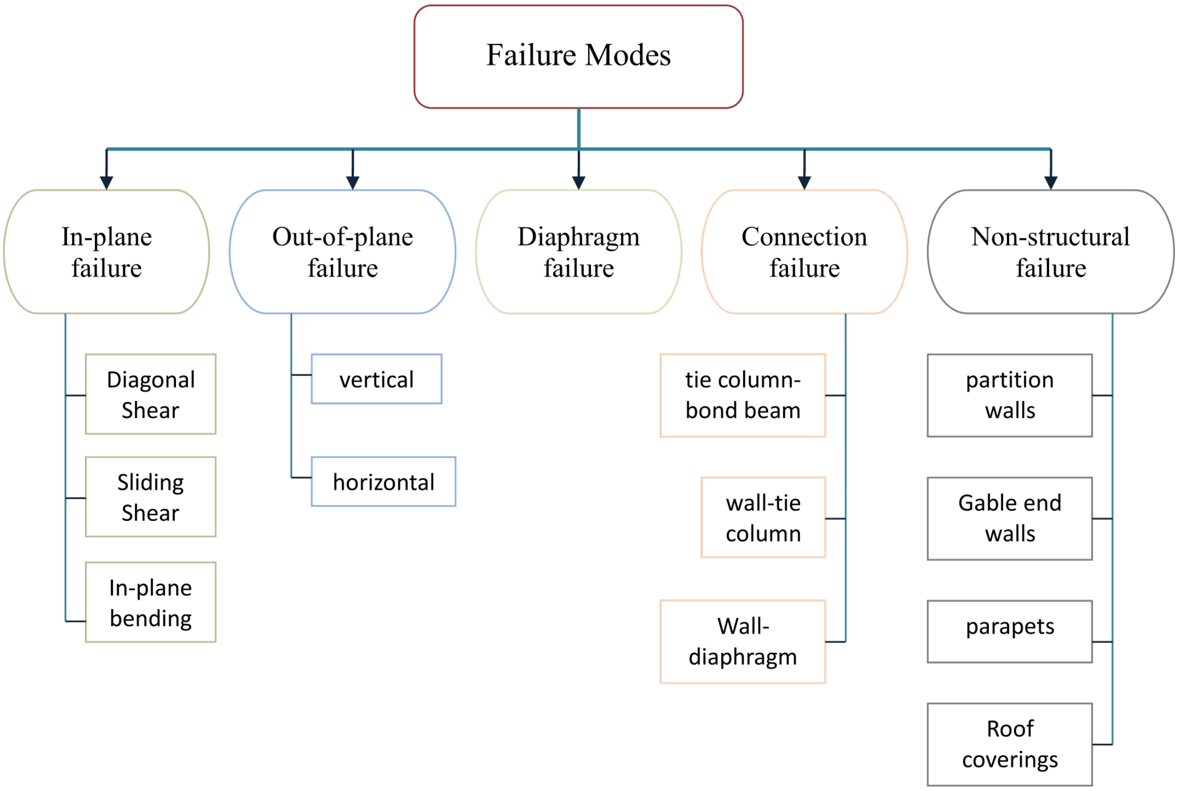


Figure 2.2: Different failure modes of CBM buildings

increases, the masonry panel begins to lose strength. At this point, the vertical reinforcement in the tie-columns engages to resist tensile and compressive stresses. Despite the lateral loads exceeding the wall's capacity, the confining effects of the tie-elements keep the walls intact and allow them to continue deforming until the loads diminish. This confining action gives CBM walls significantly higher strength and deformation capacity compared to unreinforced masonry (URM) walls, preventing collapse. Further lateral deformations can cause additional damage to both the masonry wall and tie-columns. Ultimate failure often occurs when tie-columns fail in shear due to the extension of diagonal shear cracks in the wall. Experimental studies have also examined the out-of-plane behaviour of CBM walls. Researchers have subjected CBM walls to monotonically increasing uniform static pressure using airbags [25]–[28] or to out-of-plane dynamic loads [29], [30]. The behaviour of a CBM building is influenced by parameters, *viz*, material properties, overburden pressure, geometric characteristics, the number and spacing of tie-columns, reinforcement detailing, openings, and the number of stories. This study focuses on the in-plane behaviour of CBM walls, reviewing experimental investigations to understand the influence of these parameters on the in-plane performance of CBM buildings.

2.2.1 Influence of Masonry Units and Mortar

CBM walls are constructed using masonry units, such as bricks or blocks, and mortar, which may be cement or lime-based with sand, soil, and water. The choice of materials depends on their availability, leading to various combinations of masonry units and mortar. Experimental studies indicate that the load resistance of CBM walls significantly depends on the strength of the masonry units and the quality of construction. For instance, shaking table tests conducted by Iiba et al. [31] with masonry units (Mexican or Japanese) and reinforcement methods showed that walls built with Japanese units (36 MPa) had 1.5 times higher lateral strength than those with Mexican units (5 MPa), due to the higher compressive strength of the Japanese units. Additionally, CBM walls made with low-strength hollow concrete blocks are generally more prone to brittle failures compared to those made with solid concrete or clay units [6]. Decanini et al. [32] studied the influence of masonry units and wall opening sizes by testing eight CBM wall specimens under lateral displacements. They found that walls made of solid clay bricks had 50% more strength against ultimate cracking compared to initial cracking, whereas walls made of hollow clay bricks had only 20% more strength. Similarly, Yáñez et al. [33] tested sixteen full-scale CBM specimens, considering wall types and masonry units, under horizontal cyclic load. They concluded that CBM walls made with hollow clay brick units exhibited higher lateral strength and energy dissipation capacity compared to those made with concrete masonry units, although the former experienced more significant degradation in strength and stiffness.

2.2.2 Influence of Aspect Ratio

An important geometric parameter for CBM walls is the aspect ratio, defined as the ratio of the wall height (excluding the tie-beam) to the wall length (excluding the end tie-columns). This ratio largely determines the failure mode of a CBM wall. Gavilán et al. [35] tested seven solid CBM walls with varying aspect ratios, applying lateral and vertical loads. Their findings indicated that as aspect ratio decreases, lateral strength increases while drift corresponding

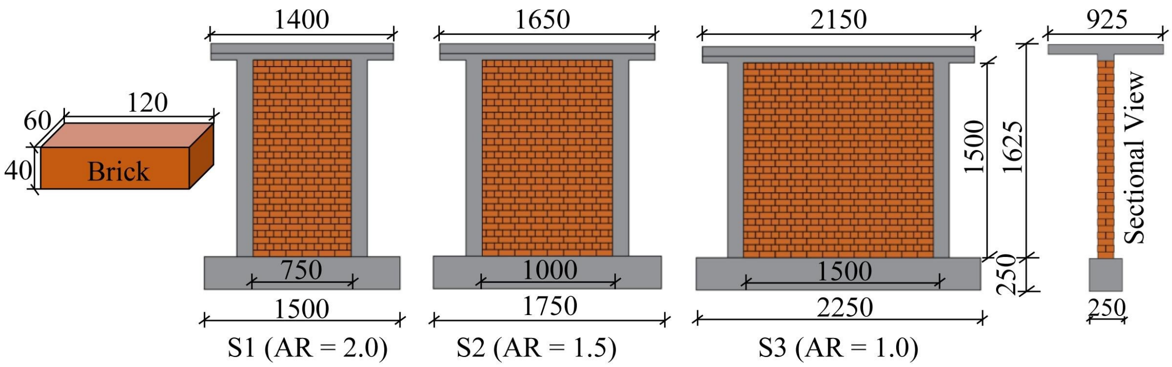


Figure 2.3: Geometric detailing of the walls in the study by Borah et al. [34]

to ultimate load decreases. Squat walls with intermediate tie-columns behaved as a single structure rather than isolated panels of the same aspect ratio. In another study, Varela Rivera et al. [36] found that slender CBM walls failed due to the yielding of longitudinal reinforcement followed by vertical and diagonal cracks, with failure characterized by concrete crushing in tie-columns. Test results showed increased flexural strength and decreased drift ratio (i.e. The drift ratio is defined as the ratio of maximum lateral drift to total height of the specimen) with a lower aspect ratio. Furthermore, Borah et al. [34] tested three half-scale CBM walls with varying aspect ratios (Figure 2.3) under quasi-static cyclic loading. Their findings revealed that a reduction in aspect ratio increased lateral strength, while the drift corresponding to rebar yielding in tie-columns decreased. Squat walls experienced early damage in tie-columns, leading to significant post-peak strength degradation and reduced energy dissipation. The damage pattern transitioned from flexural cracking in the tie-columns to shear cracking in the masonry as the wall configuration shifted from slender to squat.

2.2.3 Influence of Wall-to-Tie-Column Connection

Effective bonding between masonry walls and RC tie-elements is crucial for earthquake performance, preventing premature cracking and separation at the wall-to-tie-column interface. Wijaya et al. [37] studied four full-scale CBM walls with wall-to-tie connections, *viz*, no connection, short anchorage, zigzag toothed connection, and continuous anchorage. Their tests under in-plane quasi-static cyclic loads revealed that while the additional short anchor slightly improved lateral strength, the zigzag toothed connection did not, and the continuous anchorage provided the highest lateral load capacity. However, the zigzag toothed connection offered the highest lateral drift capacity. Singhal and Rai [30] also tested half-scale CBM wall specimens with varying densities of toothed connections. They concluded that higher toothing density improved post-peak in-plane load and controlled out-of-plane displacement at higher drift levels. Another study by Matošević et al. [38] on nine CBM walls with varying connection details found that although connection types did not significantly affect initial stiffness or maximum lateral resistance, they improved nonlinear behaviour and hysteretic energy dissipation.

2.2.4 Influence of Openings in Walls

Numerous studies, including seismic reconnaissance reports from previous earthquakes and research findings, have consistently indicated that CBM walls exhibit significant in-plane strength and out-of-plane strength [5], [39], [40]. Within CBM wall panels, the width of vertical masonry piers is crucial for the lateral load-resisting system. However, the presence of openings in these panels reduces the effective width of the piers, thereby diminishing their capacity to resist lateral loads [41]. Nevertheless, openings within these walls have been identified as a detrimental factor influencing their seismic resistance. Generally, openings, which are inevitable, decrease both the strength and stiffness of masonry walls [1], [6], [42]. Figure 2.4 illustrates the typical damage pattern of the walls with an opening observed during an earthquake. The diagonal cracks shown in Figure 2.4 are primarily due to large concentration of stresses at the corners of opening, which consequently lead to the failure of the masonry panel [43]–[45].

Past literature on masonry infilled RC frames clearly demonstrate the substantial impact of openings on structural behaviour, emphasising that the presence of openings significantly alters failure modes. Mallick & Garge [47] observed that placing openings toward the compression diagonal adversely affects composite action, suggesting optimal locations as the center of the lower half for doors and mid-height near the vertical edge for windows. Kakaletsis & Karayannis [48] noted a significant decrease in lateral stiffness and strength as opening size increased, recommending placing the opening near the infill edge for optimal seismic per-

Figure 2.4: Typical damage to infill walls with openings observed during the 2011 M6.9 Sikkim earthquake [46]

formance of CBM walls. Voon & Ingham [49] found that taller openings weakened walls by increasing diagonal strut angles, reducing the masonry pier's ability to resist horizontal shear. Sigmund & Penava [50] noted that the impact of openings on structural performance is minimal under low drift levels. However, at higher drift levels, openings diminish the system's energy dissipation capacity, leading to diverse failure mechanisms in infill walls contingent upon the height and position of the openings. Ahani et al. [51] highlighted that upper corner openings led to the most significant strength loss, with lateral strength becoming negligible for infills with over 40% openings.

The seismic behaviour of unreinforced masonry (URM) structures has been also explored in several studies. Liu and Crewe [52] found that in-plane capacity diminishes with increasing opening size, and the relationship between lateral capacity and opening percentage depends on the opening's location. Preciado and Sperbeck [53] noted that the failure mechanisms and behaviour of URM walls are closely tied to factors such as the quality of masonry units and mortar joints, the magnitude of vertical loading, and the existence of weak points introduced by features like windows and doors. Debnath et al. [54] observed that URM walls with a central opening retain over 80% capacity below a 25% opening percentage but drop to about 20% with an opening percentage exceeding 50%. Kayırga and Altun [40] conducted full scale experimental analyses, indicating that masonry buildings with diverse opening sizes and positions collapsed at a 1% drift ratio. Surendran et al. [55] highlighted the significant influence of opening geometrical properties on URM wall shear strength, with a 35% opening ratio resulting in a 72% reduction in capacity under vertical pressures. Considering irregular openings in URM walls, Parisi and Augenti [56] have shown that the in-plane seismic capacity of URM walls experiences a note-worthy reduction in terms of ultimate displacement capacity, displacement ductility, and force reduction factor as geometric irregularities increase. Preciado et al. [57] observed that in colonial churches and old masonry buildings, geometrical irregularities, height, and extensive openings contribute to the development of diagonal cracks, placing these structural elements in a precarious state of potential collapse.

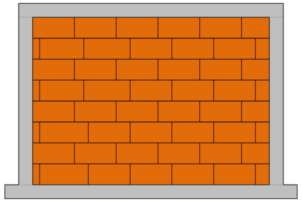
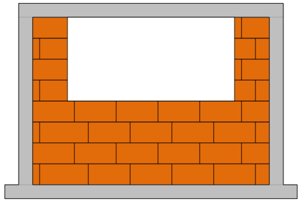
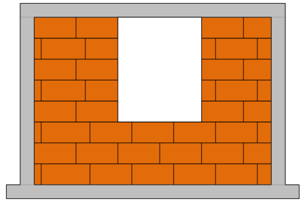
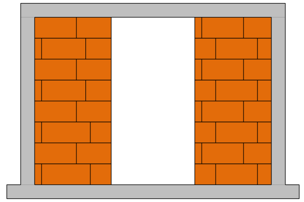
Although there has been considerable work carried out on the openings in the masonry infilled RC frames and URM walls, investigations into CBM walls with openings are relatively scarce. Few literature's in the recent past have carried out experimental work comparing CBM walls with and without openings and compared the CBM walls with RC infill wall. Eshghi & Pourazin [43] found that the load-deflection curves indicate the initial stiffness ratio of CBM walls with openings to solid CBM walls is approximately 0.59, and the peak lateral load ratio is about 0.64. Additionally, the ultimate deformation capacity of CBM walls with openings is roughly one-tenth of that of solid CBM walls. They also noted that while cracks in solid CBM walls tend to concentrate at upper bond-beam and tie-columns, in CBM walls with openings, cracks occur extensively, highlighting vulnerability at each opening corner. In their experimental study, Kuroki et al. [58] investigated the impact of openings on the behaviour of CBM walls under reversed cyclic loading using 10 half-scale specimens. Constructed with full-size solid clay bricks, the study revealed a notable decrease in shear strength for specimens with window openings, ranging from 15-40%. Additionally, specimens with confinement around the openings exhibited higher capacity compared to similar specimens without openings.

Singhal & Rai [44] conducted an experimental study on CBM walls, investigating the impact of toothing details and openings during bi-directional loading. Like RC infill walls, openings in CBM walls were found to reduce structural integrity. However, despite this, they exhibited superior performance compared to RC infill frames.

Okail et al. [59] analysed six CBM wall specimens, including two with openings and four solid ones. Five were made of solid clay bricks, and one utilised hollow concrete blocks. The specimens were subjected to monotonic lateral loading. The specimen with a window opening exhibited shear behaviour akin to solid specimens, with minimal impact on peak strength despite the opening constituting around 7% of the total panel area (17% decrease). Furthermore, the specimen with a door opening experienced a significant peak strength reduction of approximately 43% compared to the solid counterpart.

Yáñez et al. [33] tested sixteen full-scale specimens to study the impact of door and window openings on the strength and stiffness of confined masonry walls. Eight specimens used concrete blocks and eight hollow clay bricks, with varying patterns and small reinforcements around the openings. Table 2.1 shows the key response parameters. The results indicated that walls with small window openings ($Ao/Ap \leq 0.15$) had similar strength and stiffness to solid walls, while larger openings notably affected the in-plane response, particularly in hollow clay brick walls. Large openings (> 25% of the panel) caused a 40–50% strength decrease, though small openings (up to 11%) did not affect stiffness.

Table 2.1: The effects of opening in CBM walls

Specimens	 Pattern 1	 Pattern 2	 Pattern 3	 Pattern 4
Concrete block masonry				
Ao/Ap	-	0.38	0.15	0.20
Ultimate strength (kN)	123.2	78.00	120.20	101.70
Stiffness (kN/mm)	46.50	24.00	39.00	32.50
Hollow clay brick masonry				
Ao/Ap	-	0.35	0.14	0.15
Ultimate strength (kN)	176.50	92.00	146.20	125.00
Stiffness (kN/mm)	71.00	28.50	61.50	49.00

2.2.5 Influence of confinement around openings in walls

While many studies have assessed the influence of openings on the lateral load behaviour of masonry panels, little effort has been made to mitigate the deficiencies caused by these openings [58], [60]–[62]. Reinforced concrete members or bands are often used to strengthen walls with openings, preventing extensive cracking and crushing at the corners until larger deformations occur, thereby improving the seismic response. Proper confinement around openings helps to develop stronger compression struts in the masonry panel for lateral load transfer. Several national standards and technical manuals provide guidelines for confining openings [6], [15], [16]. However, there is some variation in these guidelines regarding the details of sill, lintel, and vertical confining elements at openings. Additionally, the appropriate size of openings that require tie-beams and tie-columns is not always clear. Eurocode 8 (CEN, 2004) suggests providing RC confining elements for openings larger than 1.5 m², while UNESCO guidelines [63] based on Tomaževič and Klemenc [19] research relax this requirement up to 2.5 m². Limited studies on confined masonry walls with openings [33], [42], [58] offer minimal guidance on the details of confining members at openings, highlighting the need for more research to resolve discrepancies regarding the maximum allowable size of openings for a given wall size, wall aspect ratio and the specifics of confining elements around them. Two common confining schemes are: (1) continuous tie-columns along the wall height with discontinuous tie-beams at the top and bottom of openings. (2) continuous sill and lintel beams along the wall length with discontinuous tie-columns on both sides of openings. Both schemes provide similar lateral strength, but the latter is more ductile, as the beams divide the wall into smaller panels with low aspect ratios, ensuring well-distributed diagonal shear cracks throughout the wall.

2.3 Comparison with other structural system

The in-plane performance of CBM walls compared to unreinforced masonry (URM) walls and infilled RC frame walls has been explored by researchers. Yoshimura and Kikuchi [64] tested nine specimens to compare the behaviour of CBM walls with URM walls and RC

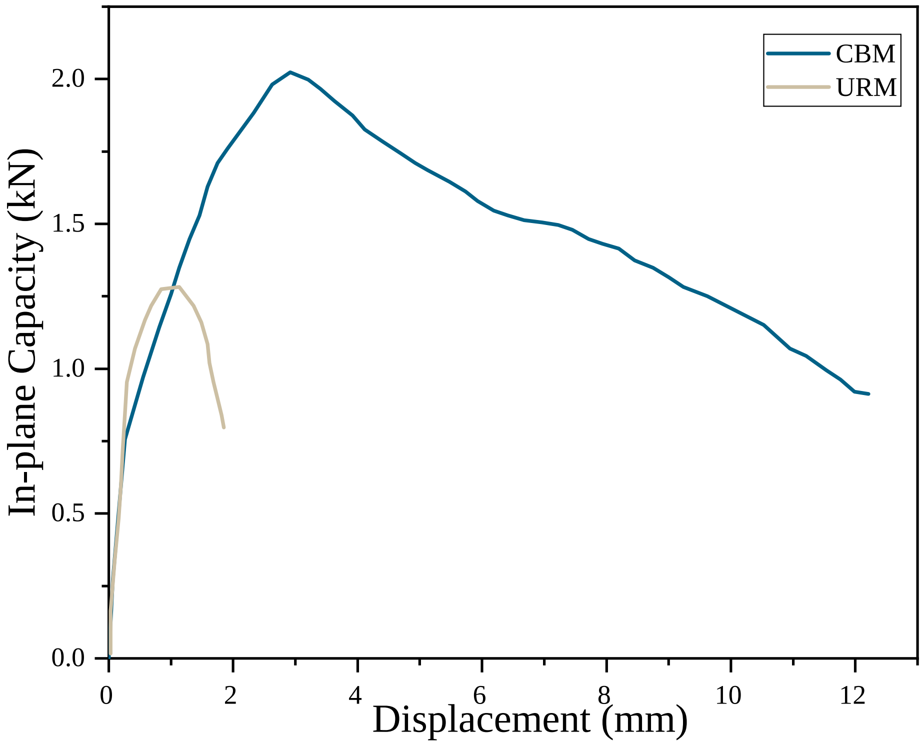


Figure 2.5: Comparison of the in-plane response of CBM and URM walls tested by Tomaževič and Klemenc [19]

ductile moment-resisting frames with identical cross-sectional details. The results demonstrated that CBM walls exhibited higher strength and ductility than both URM and infilled RC frame specimens, concluding that CBM construction is an excellent structural system. Tomaževič and Klemenc [19] tested three confined and three plain masonry wall specimens at a 1:5 scale, each with a height-to-length ratio of 1.5. These specimens were subjected to a constant vertical load (approximately 22% of the masonry compression strength) and cyclic horizontal displacements. Their study revealed that confining URM walls with RC tie-columns increased their lateral resistance by more than 1.5 times, deformation capacity by nearly five times, and energy dissipation capacity by six to seven times, as shown in Figure 2.5.

Yoshimura et al. [65] aimed to identify effective seismic strengthening methods for masonry walls in developing countries. They tested twenty-eight URM and CBM walls with an aspect ratio of approximately 0.77. The specimens included 2D and 3D walls, some with and some without wall reinforcing bars or U-shaped connecting bars. These were tested under repeated lateral forces and constant axial stress (0.48 MPa or 0.84 MPa). The results indi-

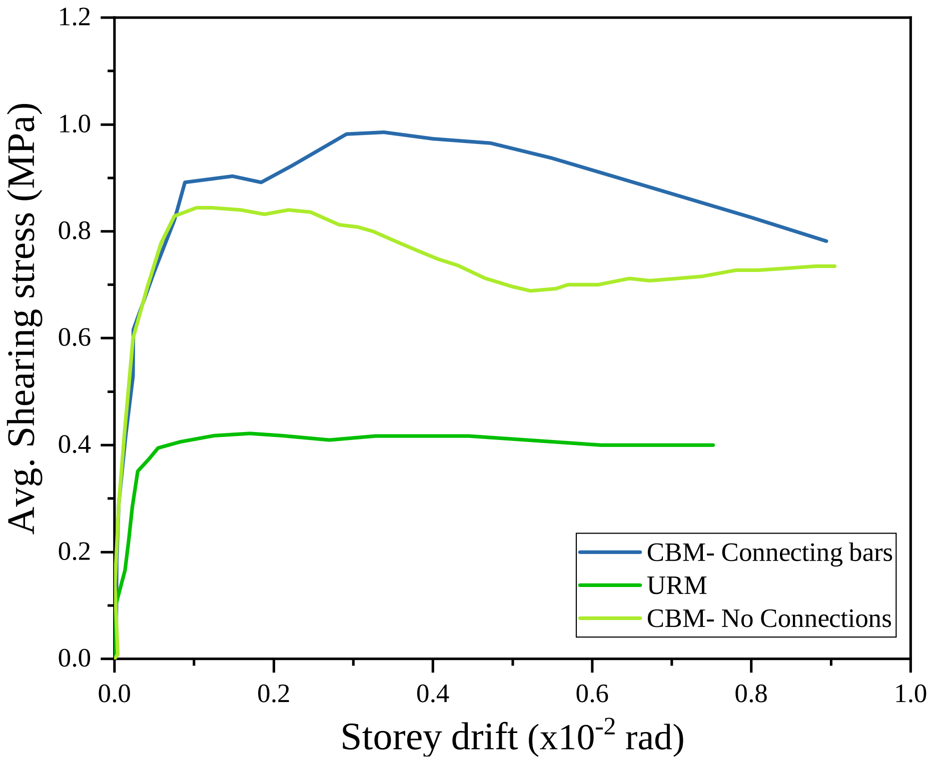


Figure 2.6: Comparison of the in-plane response of CBM and URM walls tested by: Yoshimura et al. [65]

cated that CBM wall systems with connecting bars at vertical wall-to-wall connections and horizontal wall reinforcing bars developed significantly higher ultimate lateral strength and better ductility compared to conventional URM specimens. Figure 2.6 shows the lateral load-versus-story drift plot for 2D URM and CBM wall specimens (with and without dowel bars) without horizontal reinforcement under an axial stress of 0.48 MPa. The figure illustrates that CBM specimens, with or without U-shaped connecting bars, outperformed URM walls in terms of lateral load-carrying capacity and ductility.

Goveia and Lourenço [66] tested sixteen walls, including URM and CBM walls with an aspect ratio of around one, made of lightweight concrete blocks at a 1:2 scale. These walls were subjected to a constant vertical load (about 30% of the masonry strength) and horizontal cyclic load. Another set of nine URM wall configurations included: four walls without bed joint reinforcement and unfilled vertical joints, three walls without bed joint reinforcement but with filled vertical joints, and two walls with light bed joint reinforcement and unfilled vertical joints. The set of seven CBM wall configurations included: two walls with unfilled vertical joints without bed joint reinforcement, three walls with unfilled vertical joints and light bed

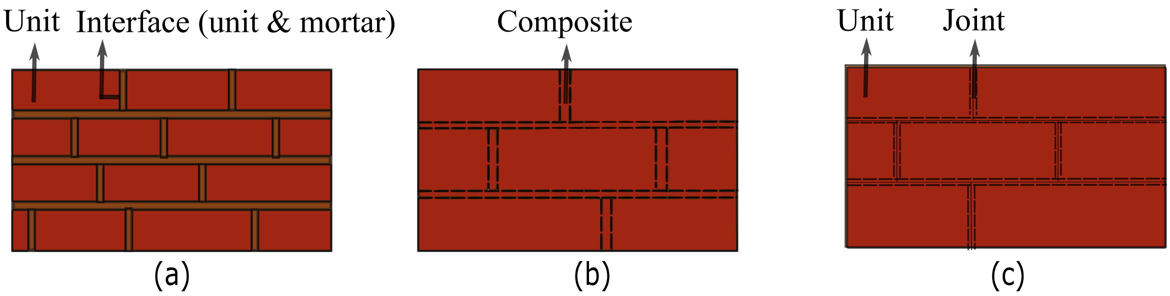


Figure 2.7: Schematic of 3D and 2D FE Modelling (a) Micro-model, (b) Macro-model, and (c) Simplified micro-model.

joint reinforcement anchored only in the masonry, and two walls with unfilled vertical joints and light bed joint reinforcement anchored to RC tie-columns. The study observed that confining URM walls with RC tie-elements improved their lateral capacity by 1.17 times and deformation capacity by 1.43 times compared to standard URM walls. In CBM walls without bed joint reinforcement, lateral capacity increased by about 1.22 times and deformation capacity by 1.43 times compared to similar URM walls.

2.4 Finite element modelling

The finite element (FE) method is a widely accepted approach for structural analysis, allowing for detailed examination of structures (2.7). FE analysis of masonry structures can be conducted at either the micro or macro level [67]–[69]. Micro-modeling is particularly suitable for small structural elements, as it closely represents the heterogeneous nature of masonry by using the properties of each constituent and interface. A simplified micro-modeling approach involves expanding bricks to half of the mortar thickness in both vertical and horizontal directions, with the mortar clamped into the mortar interface. Macro-modelling, on the other hand, is used to represent global structural behaviour. In this approach, individual units and joints are not distinguished, and material parameters are obtained from masonry tests under homogeneous stress states. Both modeling approaches have been extensively used by researchers to predict the structural performance of masonry walls.

Smoljanović et al. [70] employed a detailed micro-modeling approach to simulate the behaviour of CBM walls, discretising RC and masonry elements with linear elastic triangular elements. Material non-linearity, including fracture and fragmentation, was incorporated through contact elements smeared between discrete finite elements. The interface between masonry elements was modeled to account for joint cracking in tension and sliding along bed joints using the Coulomb dry friction model.

Tabrizi & Soltani [71] also used a micro-modeling approach to simulate masonry walls, where masonry blocks were modeled with a continuum model and potential cracks were smeared in the developed model. Masonry joint interfaces were modeled to consider shear sliding and joint opening, accurately predicting crack propagation and reinforcement bar yielding. In contrast, Okail et al. [59], Tripathy and Singhal [45], and Yacila et al. [72] developed FE macro models to simulate CBM wall behaviour using a slightly different approach. They employed continuum elements to model masonry panels and RC elements, with interfaces modeled using a traction separation law with hard contact in the normal direction. Frictional properties were assigned using the Mohr-Coulomb failure criteria in the tangential direction.

Medeiros et al. [73] adopted a similar approach, defining masonry and RC elements with the smeared crack model. Eshghi and Pourazin [43] introduced another variation by developing a 2D macro model for CBM walls, using plasticity-based material models along with the Coulomb friction model with tension cut-off mode for the interface zone between confining elements and the masonry panel. Janaraj & Dhanasekar [74] described calibrating a macro-modelling method for unconfined and confined masonry panels tested under diagonal compression. This study used smeared properties to define hollow and grouted masonry, accurately predicting the failure modes, shear strength, and deformation characteristics of CBM walls.

2.5 Research gap

Despite significant advancements in understanding the seismic performance of confined brick masonry (CBM) structures, several critical gaps persist. One key issue is the lack of detailed design recommendations for openings, an integral feature of masonry construction. Existing studies often neglect the impact of opening size, placement, and reinforcement on the seismic behavior of CBM structures, even though openings significantly alter stress distribution and may act as weak points during seismic events.

Similarly, the confinement detailing, essential for enhancing the ductility and seismic resilience of CBM structures, remains insufficiently addressed. Critical aspects such as optimized dimensions, reinforcement ratios, and the effective integration of tie beams and tie columns with masonry require further investigation, particularly for varying seismic intensities and construction practices.

Additionally, regional variability in material properties, such as differences in brick and mortar strength, is often generalised in existing studies, despite its profound influence on structural behavior. This oversight limits the applicability of research findings to diverse construction scenarios. Moreover, modern testing techniques, such as digital image correlation and hybrid simulations, remain underutilized in capturing detailed failure mechanisms.

Addressing these gaps through an integrated approach that combines advanced numerical modeling, experimental validation, and consideration of regional material variability is essential. Such efforts will pave the way for comprehensive, evidence-based design recommendations to enhance the seismic safety of CBM structures in earthquake-prone regions.

2.6 Summary

Previous research underscores extensive investigations into CBM structures, particularly in regions of Latin America prone to seismic activity. Researchers have discerned potential failure modes of CBM structures through rigorous experimentation and observations from seismic events. Numerous experimental studies have delved into how material properties, geometries, and loading conditions influence the structural behaviour of CBM walls, enriching our knowledge base. Although such tests have been insightful in understanding the response of CBM structures, carrying out parametric experimental studies can be costly and time-consuming [75]–[77]. On the other hand, advances in numerical modelling techniques like the finite element (FE) method have proved to be an alternate efficient, robust and less expensive technique for understanding CBM structures. A numerical modelling technique can be used, if not to replace the experimental tests, to complement them and, to substitute the economic resources with the computational resources [73]. Using a robust numerical technique, one can assess alternate designs, such as the effect of opening sizes, opening location, opening shape, aspect ratio and different materials on the response of CBM structures [78].

Following the development of a robust finite element (FE) model, this research aims to focus on several key areas:

1. Conducting a comprehensive numerical analysis to understand how the shape, size, and positioning of window and door openings affect the ultimate strength, stiffness, and energy dissipation capabilities of CBM walls. This study is essential for comprehending the seismic performance of CBM wall in a better manner. It is crucial to establish a correlation between opening size and ultimate strength.

2. Assessing the effectiveness of confinement configurations is necessary to address deficiencies in the global seismic response of confined masonry walls caused by openings.

3. The literature reveals considerable differences in the size and detailing of tie-elements. Therefore, it is crucial to thoroughly understand the behaviour of tie-columns to walls connection, as well as to determine and suggest the optimal and effective toothing schemes.

4. Investigating the effect of types of brick masonry in structural performance of the CBM walls towards a comprehensive understanding of their performance.

The FE modelling in this study delves deeper into these parametric effects, aiming to enhance the understanding of CBM wall structural performance.