Chapter 1

Introduction

1.1 General Discussion

Masonry has long been a favoured construction material due to its simplicity, durability, easy availability, fire resistance, aesthetic appeal, and economic benefits. Despite these advantages, unreinforced masonry (URM) structures have shown poor seismic performance, leading to significant loss of life and property in past earthquakes. To address the shortcomings of the URM system, innovative methods for reinforcing masonry panels have been developed over the years.

Two popular methods for enhancing the seismic performance of masonry buildings are reinforced masonry (RM) and confined brick masonry (CBM). Reinforced masonry involves placing steel bars along with concrete grout in specially designed hollow masonry units. In contrast, CBM structures are constructed in a manner almost opposite to reinforced concrete (RC) frame infill structures. In CBM construction, the wall is built first, followed by casting the concrete beams and columns around the wall panel. As the concrete cures, it shrinks slightly, thereby confining the masonry within the surrounding beams and columns [1]. Ideally the panel should be encased by both a beam and columns, but when used in retrofit for existing URM structures, confining vertical elements (RC tie-columns) on the sides of the openings are not always feasible. Figure 1.1 illustrates the construction sequence of CBM,

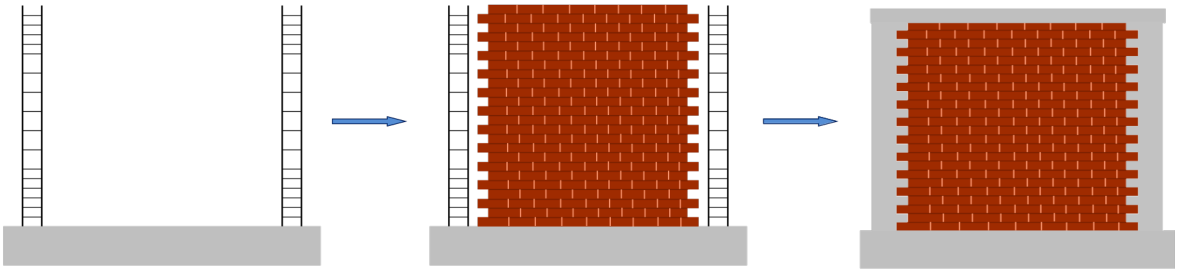

Figure 1.1: CBM construction sequence

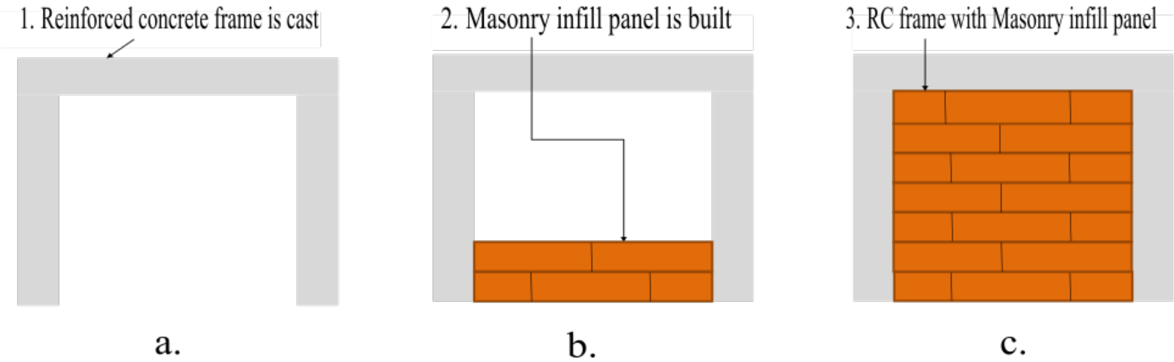

Figure 1.2: Reinforced concrete frame masonry infill construction sequence [1]

contrasting with the sequence for a reinforced masonry infill wall panel shown in Figure 1.2.

The CBM system was first introduced in Italy as an alternative to URM buildings, which were nearly destroyed in the 1908 Messina earthquake [2]. Thanks to its satisfactory performance in subsequent earthquakes, such as the 1939 Chilean earthquake, CBM construction gained popularity for low-rise residential buildings in many countries across South and Central America, Asia, and Eastern Europe. Matthews et al. [3] reported that during one of the Chilean earthquakes, only 16% of CBM houses were partially or completely collapsed, compared to a collapse rate of 57% for unreinforced brick masonry buildings and 65% for adobe masonry structures.

Over the years, engineered CBM buildings around the world have performed reasonably well during past earthquakes (Figure 1.3a, 1.3b). Consequently, CBM has been embraced as an affordable and resilient seismic solution for low-rise buildings in many countries. However, some of these buildings have suffered severe damage due to the absence of tie-columns around the openings (Figure 1.3c). Additionally, buildings with inadequate size and spacing of tie-columns, weaker masonry, and poor workmanship have also experienced varying de-

(a) (b)

(c) (d)

Figure 1.3: Performance of CBM structures during past earthquakes: (a) six storey CBM building remained undamaged in 2007 M8.0 Pisco, Peru earthquake while the adjacent adobe building collapsed [5], (b) undamaged CBM school survived after 2003 M6.5 Bam, Iran earth- quake whereas nearby structures totally collapsed [8], (c) Absence of RC tie-column resulted in damage to CBM building in the 2010 Chile earthquake [9] and, (d) damage to ground floor of a medium rise CBM apartment in 2010 Maule, Chile, earthquake [9]

grees of damage in past earthquakes [4]. Such damage in CBM buildings typically occurs at the first-storey level (Figure 1.3d) and represents two major failure modes related to shear and flexure [5]–[7].

In India, CBM is known but its usage is very limited compared to other countries such as Mexico, Pakistan, Indonesia, and Chile. Figure 1.4 shows typical CBM buildings used in Chile. The survival of these multi-story buildings after the 2011 earthquake, as reported in Tanner's study [10], raises concerns about the limited use of CBM in India. Possible reasons for this could include insufficient understanding, lack of skill, coordination challenges between trades, and perceived costs. Developing a fundamental understanding of CBM could

Figure 1.4: Typical CBM Buildings in Chile (left: 2 story apartments, right: 4 story apartment) [1]

pave the way for its extensive use as an alternative in retrofitting and strengthening structures, especially for essential seismically better performing facilities such as schools, hospitals, and fire stations, many of which are constructed of masonry.

1.2 Motivation

According to the 2011 census of India, masonry houses constitute 85.3% of the total 247 million housing units, while concrete and other construction materials make up only 14.7%. Among these masonry constructions, 47.5% of households use burnt bricks, while the remaining households use either stone or adobe masonry. Most of these masonry houses are unreinforced, which performed very poorly during past seismic events such as the Latur (1993), Chamoli (1999), Bhuj (2001), Kashmir (2005), and India-Nepal border (2011) earthquakes. Additionally, more than 59% of India's landmass is prone to earthquakes of moderate to very high intensity according to the Indian seismic zone map. Therefore, there is an urgent need for a simpler construction system to reduce the seismic vulnerability of masonry buildings, minimise damage, and ease post-earthquake recovery efforts.

CBM construction has evolved based on its satisfactory performance in past earthquakes [12], [13] and is included in various building codes such as the Argentinean code (Inpres-Cirsoc 1983), Colombian code (AIS 1998), Chinese code (NSPRC 2001), Chilean code (INN 2003), Eurocode 8 (CEN 2004), Mexican Building Code (NTC-M 2004), and Peruvian Building

(a) (b)

Figure 1.5: a. Typical construction sequence of a CBM wall, with concrete poured after masonry erection, and b. construction of a student hostel at IIT Gandhinagar [11]

Regulations (SENCICO 2006). The CBM system is considered a highly appropriate alternative to URM due to the following reasons:

1. ***Ease of Training***: CBM construction is similar to unreinforced masonry except for the inclusion of RC confining elements. Local masons can be quickly trained and become accustomed to it. Figure 1.5a, 1.5b shows CBM construction where RC tie-beams and tie-columns are cast at critical locations after the erection of the masonry wall.

2. ***Improved Seismic Performance***: CBM structures have demonstrated better seismic performance compared to other masonry building types, with only a marginal increase in construction costs, making them economically feasible. Experimental results by Alcocer and Zepeda [14] indicated that CBM with RC tie-columns is superior to reinforced and grouted masonry with hollow units, thus preferred in higher seismic zones.

Despite being considered an earthquake-resistant engineered solution since the 1940s, the behaviour of CBM under in-plane and out-of-plane loads is still not well understood, especially when openings are present. Available guidelines on CBM buildings by Blondet [15], Meli et al. [6], and Schacher [16] are empirical and lack proper analytical and experimental validation. These guidelines offer simplified design rules for CBM buildings, but they are usually intended for specific regions and have some disagreements, particularly regarding connection details at the wall-to-tie-column interface, the maximum size of unconfined openings, and details of appropriate confinement around openings.

For example, guidelines by Bothara et al. [17] for URM buildings and Schacher [16] for CBM buildings propose continuous horizontal bands above and below openings along with vertical confining members extending only for the height of the opening. In contrast, other manuals and codes for CBM [6], [15], [18] require openings to be located at or near the floor slab, with vertical tie-columns along both sides of openings extending to the full story height. These do not insist on providing continuous horizontal bands (Figure 1.4b). Most analytical and experimental studies have focused on the in-plane response of CBM walls. Important aspects such as cross-section details of tie-columns and beams have been widely investigated, but the role of toothing at the wall-to-tie-column interface, the effect of openings, and the effectiveness of various confinement configurations around openings have not been studied in detail. Several guidelines and design codes have been developed over the years in different countries to provide basic design details on CBM and promote its construction practice. However, these guidelines exhibit significant variability and contain many gaps. Additionally, most design codes and guidelines offer prescriptive design methods using general thumb rules. There is a need to further develop design guidelines to reduce reliance on the limited guidelines and codes developed by a few countries, particularly concerning confinement around openings. Furthermore, it is necessary to assess the effectiveness of these design guidelines and provisions in ensuring the seismic safety of CBM buildings. These issues form the motivation for the present study, which systematically carries out experimental, analytical, and numerical investigations to recommend possible solutions to the identified problems related to the seismic analysis and design of CBM buildings.

1.3 Objectives of present study

Although CBM buildings began as an informal construction practice, their performance under lateral loads has proven to be significantly superior to that of URM buildings and poorly constructed non-ductile masonry-infilled RC frame buildings. This notable improvement in performance has sparked considerable interest within the research community and construction industry, leading to efforts to enhance analysis and design methodologies and to understand the impact of key parameters on the seismic behaviour of CBM buildings.

In the past, some analysis and design guidelines for CBM buildings have been developed. However, these guidelines are often based on general rules of thumb and simplified assumptions, making them primarily applicable to only one- to two-story buildings. There is a need for systematic research to develop robust numerical and analytical methods for the seismic analysis of CBM walls. Additionally, it is crucial to move away from the prescriptive design approach commonly used in many countries and develop an engineered design approach for CBM walls.

Given these considerations, the primary objectives of this study are as follows:

1. ***Development of a Numerical Model***: To create a simple numerical model for the nonlinear lateral load analysis of confined masonry buildings, considering key parameters, including the effects of gravity loads.

2. ***Impact of Openings***: To investigate the effect of size, shape, and position of openings on the in-plane behaviour and seismic response of CBM walls.

3. ***Confinement Around Openings***: To examine the impact of confinement schemes around openings, identifying the most economical and structurally viable options.

4. ***Toothing Schemes***: Analyse toothing schemes for confined brick walls, determining the most effective based on literature and code recommendations.

5. ***Brick Masonry Types***: Study the influence of types of brick masonry and mortar mix on CBM wall.

By achieving these objectives, the study aims to enhance the understanding and application of CBM buildings, ensuring their effective use in earthquake-prone areas and contributing to safer and more resilient construction practices.

1.4 Organisation of the thesis

The thesis is organised into eight chapters as follows:

Chapter 1: This section presents a comprehensive overview of the thesis, outlining its overall structure and detailing the primary objectives. It delves into the challenges associated with the numerical modelling of CBM walls. Additionally, it discusses the multitude of parameters that influence the design of CBM walls, providing an in-depth analysis of how each factor impacts the structural performance. By addressing these aspects, this section sets the foundation for the detailed investigations and findings presented in the subsequent chapters.

Chapter 2: This chapter offers a comprehensive review of the existing literature pertinent to the subject of study, laying the groundwork for the research conducted in this thesis. It specifically concentrates on the in-plane behaviour of CBM walls, meticulously examining experimental investigations. By scrutinising these studies, the chapter aims to elucidate the impact of geometrical and structural parameters on the in-plane performance of CBM buildings. This review offers key insights into how these factors impact the structural integrity and resilience of CBM walls, guiding the analytical and experimental work in the thesis.

Chapter 3: In this chapter, various modelling approaches used to predict the behaviour of CBM structures have been reviewed, highlighting their limitations. Furthermore, a macro-model approach is presented, where masonry and reinforced concrete (RC) tie contacts are treated as a single monolithic element. This assumption is backed by previous experimental studies, which confirm that concrete and masonry behave monolithically during seismic events. The proposed model reduces computational demands and facilitates comprehensive parametric studies with a wide range of geometrical configurations and material properties, enabling a deeper exploration of the behaviour of CBM systems.

Chapter 4: In this chapter, a detailed numerical analysis is carried out to evaluate the impact of window and door openings on the seismic performance of CBM walls. The shape, size, and positioning of these openings play a crucial role in determining the ultimate strength, stiffness, and energy dissipation capacity of the walls. A key focus of this analysis is to establish a clear correlation between the size of the openings and the resulting reduction in the ultimate strength of CBM walls. Additionally, the study investigates the effects of asymmetric opening placements, exploring how non-uniform positioning alters the structural behaviour, stiffness, and failure mechanisms. This comprehensive investigation provides insights into optimising the design of CBM walls for improved seismic resilience.

Chapter 5: In this chapter, the limitations in existing research on the confinement of CBM structures are addressed, particularly the lack of comprehensive understanding regarding effective strategies to mitigate structural damage during seismic events. To bridge this gap, a thorough parametric analysis has been conducted to explore various confinement schemes for CBM walls. The objective is to identify strategies that are not only structurally efficient but also economically feasible. Through this investigation, the aim is to develop confinement schemes that enhance the seismic performance and structural integrity of CBM walls, thereby promoting safer and more resilient construction practices. This research contributes to both improving the seismic resilience of CBM structures and offering practical, field-ready solutions, advancing building design and construction standards.

Chapter 6: In this chapter, the investigation focuses on the effects of different types of toothed connections on the tie-column and masonry wall interface, employing an extensive finite element analysis. Several key parameters, including wall openings, wall thickness, and the horizontal and vertical dimensions of the toothing, are examined to ensure a thorough and reliable evaluation. Furthermore, the study assesses the influence of these connection schemes on the ultimate strength, stiffness, and energy dissipation capacity of CBM walls. A comparative analysis is carried out, examining the performance of confined wall panels across various connection types. These include smooth connections at the masonry-concrete interface without toothing, smooth connections incorporating steel dowels in the bed joints, as well as both machine-made and hand-made tooth-type joints. The goal of this comparison is to offer recommendations on connection preferences, filling a gap in the literature, as this aspect has not been explored in previous studies nor covered in existing confined masonry standard codes.

Chapter 7: In this chapter, the use of CBM walls in construction is discussed, where concrete confines the walls, and the masonry supports both gravitational and seismic loads. Understanding the impact of masonry properties on CBM wall performance is key to ensuring safety and structural integrity. This study also investigates the effect of varying masonry properties, particularly different mortar types, on CBM wall performance.

Chapter 8: his chapter aims to evaluate the behaviour of CBM walls through comprehensive numerical and analytical investigations. It summarises the findings of the study, outlines the major conclusions drawn from the research, discusses the limitations encountered during the analysis, and offers recommendations for future research. Finally, recommendations for future research are proposed, emphasising the need for further studies to refine modelling techniques and explore additional parameters that could enhance the seismic resilience of CBM walls. This forward-looking approach aims to contribute to the development of more effective design practices and standards for CBM structures in earthquake-prone regions.