International Guideline for Seismic Design of Low-Rise Confined Masonry Buildings in Regions of High Seismic Risk

Svetlana Brzev
Department of Civil Engineering, British Columbia Institute of Technology, Canada

Roberto Meli
Instituto de Ingeniería, UNAM, Mexico

SUMMARY:
This paper presents an overview of the development and content of a global design guideline for confined masonry buildings sponsored by the Confined Masonry Network (www.confinedmasonry.org) under the auspices of EERI and IAEE. The authors of the paper co-chaired a committee of thirteen international experts responsible for the development of Seismic Design Guide for Low-Rise Confined Masonry Buildings which offers prescriptive design recommendations for low-rise buildings (one- and two-storey high). The design provisions are related to the building layout, wall density, and size of confined masonry structural components, as well as reinforcement size and detailing. The document addresses variations in seismic hazard and construction practices in various countries. The guideline is expected to be of interest to individuals and organizations interested to introduce confined masonry construction in countries and regions where this technology is currently not in use.

Keywords: Confined masonry, seismic design, low-rise buildings

1. DEVELOPMENT OF THE GUIDE

Poor performance of unreinforced masonry and poorly-built reinforced concrete (RC) frame construction in past earthquakes caused high human and economic losses and prompted a need for alternative building technologies with enhanced seismic performance. One such technology is confined masonry, which has emerged as a building system that offers an alternative to both unreinforced masonry and reinforced concrete (RC) frame construction.

Confined masonry construction has evolved though an informal process based on its satisfactory performance in past earthquakes. The first reported use of confined masonry construction was in the reconstruction of buildings destroyed by the 1908 Messina, Italy earthquake (M 7.2), which killed over 70,000 people. Confined masonry construction has been practiced in Mediterranean Europe (Italy, Slovenia, Serbia), Latin America (Mexico, Chile, Peru, Argentina, and other countries), the Middle East (Iran), south Asia (Indonesia), and the Far East (China). It is important to note that confined masonry construction practice exists in countries and regions of extremely high seismic risk. Several examples of confined masonry construction around the world, from Argentina, Chile, Iran, Peru, Serbia and Slovenia, are featured in the World Housing Encyclopedia (EERI/IAEE 2000).

In January 2008, an International Strategy Workshop on the Promotion of Confined Masonry was organized at Kanpur, India, by the National Information Centre of Earthquake Engineering, India, the World Housing Encyclopedia project of EERI and IAEE, and the World Seismic Safety Initiative. A group of international experts from India, the USA, Switzerland, Peru, Mexico, China, Indonesia, and Canada created a Confined Masonry Network with two major objectives: i) to improve the design and construction quality of confined masonry where it is currently in use, and ii) to introduce it in areas where it can reduce seismic risk. The web site www.confinedmasonry.org has been created as a growing repository of resources related to confined masonry construction, including training materials, guidelines, and research papers. Besides compiling the existing resources on confined masonry, the group committed to developing global guides for seismic design and construction of confined masonry structures, state-of-the-art papers on confined masonry and research needs, and several awareness initiatives. The network provides a platform for discussion on issues related to confined masonry design and construction in seismic areas.

Seismic Design Guide for Low-Rise Confined Masonry Buildings (EERI 2011), referred to as the Guide in this paper, was developed by a group of thirteen international experts in earthquake engineering and confined masonry structures. The recommendations in the Guide are based on design codes and research studies from countries and regions where confined masonry construction has been practiced for several decades, including Mexico, Peru, Chile, Argentina, Iran, Indonesia, China, Algeria and Slovenia.

As the initial step in the development of the Guide, the committee performed a review and comparison of seismic design provisions related to confined masonry contained in international codes and standards from China, Mexico, Chile, Peru, Colombia, Iran, Algeria and Europe (Eurocode). The comparison covers structural design and construction requirements, including types of masonry units and mortar and their mechanical properties (e.g. minimum masonry compressive and shear strength); mechanical properties of concrete and steel; wall dimensions (height, thickness) and slenderness ratio (height/thickness ratio); wall density; and tie-columns and tie-beams (size and detailing requirements).

Subsequently, the group developed the Guide which contains prescriptive design recommendations for low-rise buildings. The Guide addresses differences in seismic hazard level, construction materials (e.g. strength of masonry and reinforced concrete materials), and construction practices such as different floor/roof systems (light wooden roof versus reinforced concrete slabs). This paper presents an overview of the Guide and outlines the key recommendations.

2. PURPOSE AND SCOPE OF THE GUIDE

The purpose of the Guide is to:

- Explain the mechanism of seismic response of confined masonry buildings for in- and out-of-plane seismic effects and other relevant seismic response issues,
- Recommend prescriptive design provisions for low-rise buildings related to the wall layout and density, and prescribe minimum size requirements for structural components of confined masonry buildings (tie-columns, tie-beams, walls), reinforcement size and detailing, and
- Provide a summary of the seismic design provisions for confined masonry buildings from relevant international codes.

The Guide has been divided into three chapters. Chapter 1 provides an overview of confined masonry buildings and the key structural components, and discusses seismic performance of confined masonry buildings in past earthquakes. Chapter 2 presents general requirements related to confined masonry construction. Chapter 3 contains prescriptive recommendations for low-rise non-engineered confined masonry buildings (up to two stories high), which are built without input from qualified engineers and thus no design calculations or procedures are required. It is expected that many single-family dwellings are built in this manner. Note that rational analysis and design procedures for medium-rise engineered confined masonry buildings are outside the scope of this document, however a separate guideline is under development. Also, a construction guideline, a companion document to this design guideline is currently being developed. These two documents, as well as any future updated versions of the design guide which is the scope of this paper, are going to be published on the web site of the Confined Masonry Network (www.confinedmasonry.org).

The intended audiences for the Guide are design engineers, academics, code development organizations and non-governmental organizations in countries that do not have seismic design provisions for confined masonry construction. However, it is expected that the Guide is going to be a useful reference for design engineers and other professionals in those countries where confined masonry has been practiced and seismic design codes and standards addressing confined masonry construction are already in place.

3. CHAPTER 1: AN OVERVIEW OF CONFINED MASONRY CONSTRUCTION

Chapter 1 of the Guide provides an overview of confined masonry construction, its components and performance in past earthquakes. This material is largely based on a NICEE publication (Brzev 2008) and is intended for readers without any background on the subject.

Confined masonry construction consists of masonry walls and horizontal and vertical RC confining members built on all four sides of a masonry wall panel, as shown in Figure 1. Confined masonry walls can be constructed using different types of masonry units, but the most common types of units used in practice are solid clay bricks or hollow clay tiles, and concrete blocks. Vertical members, called tie-columns, resemble columns in RC frame construction, except that they tend to be of far smaller cross-sectional dimensions and are built after the masonry wall has been constructed. Horizontal elements, called tie-beams, resemble beams in RC frame construction.

In worldwide applications, confined masonry is used for non-engineered low-rise construction (one- to two-storey high) and also for engineered construction such as mid-rise apartment buildings (up to six stories high). The application of confined masonry does not require advanced construction skills and can be used as an alternative for both unreinforced masonry and RC frame construction.

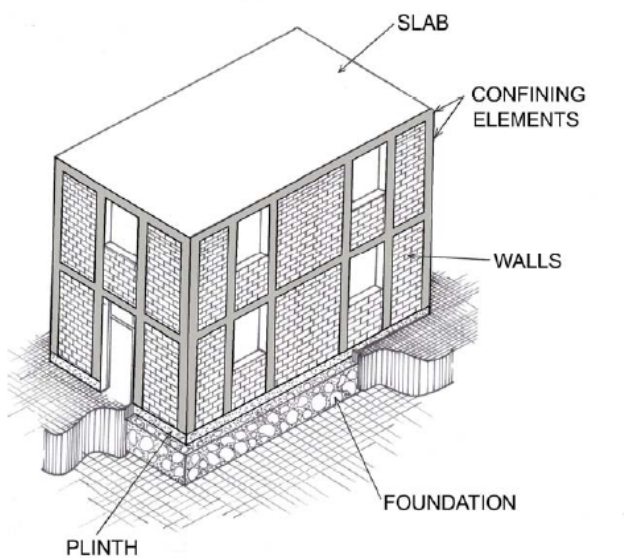


Figure 1. A typical confined masonry building (Blondet, 2005)

The appearance of a finished confined masonry building and a RC frame with masonry infills may look alike, however these two construction systems are substantially different, as illustrated in Figure 2. Note that Figure 2a) shows features of RC frames with infills, while Figure 2b) shows confined masonry construction. The main differences are related to i) the construction sequence, and ii) the manner in which these structures resist gravity and lateral loads. The differences related to the construction sequence are as follows:

- In confined masonry construction, masonry walls are constructed first, one storey at a time, followed by the cast in-place RC tie-columns. Finally, RC tie-beams are constructed on top of the walls, simultaneously with the floor/roof slab construction.
- In RC frame construction infilled with masonry wall panels, the frame is constructed first, followed by the masonry wall construction.

Seismic response of confined masonry buildings is different from RC frames with masonry infills for the following reasons:

- Due to smaller cross-sectional dimensions, RC tie-columns in confined masonry construction are slender and cannot provide an effective frame action. Tie-beam-to-tie-column connections are pinned (similar to post-and-beam timber construction), as opposed to the moment connections in RC frames.
- Tie-columns are cast against a rough (toothed and/or doweled) surface, and are integrated into the masonry wall in confined masonry construction, while infill walls are usually not integrated into an RC frame.
- Gravity loads in confined masonry construction are mostly carried by the masonry walls, while infills in RC frames carry mostly self-weight.
- When subjected to lateral seismic loads, walls in confined masonry buildings act as shear walls, similar to unreinforced or reinforced masonry walls or RC shear walls, while infill wall panels in RC frame buildings act as diagonal struts.

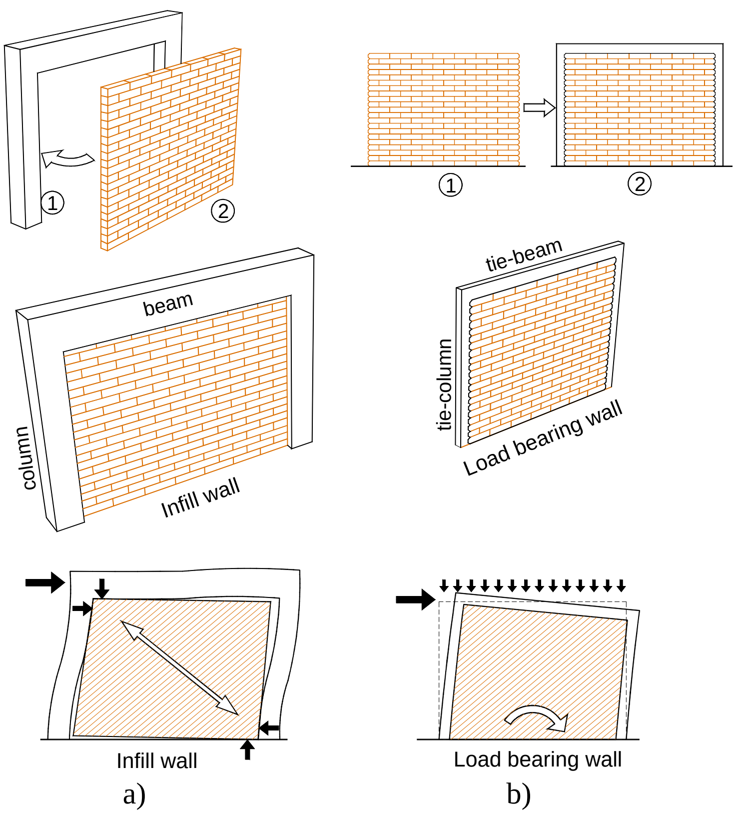


Figure 2. A comparison of RC frames with masonry infills (a), and confined masonry construction (b): construction sequence (top); size of confining elements (middle), and the seismic response (bottom) (EERI, 2011)

Well built confined masonry buildings were able to survive the effects of major earthquakes without collapse, and in most cases without significant damage. Confined masonry tends to be quite forgiving of minor design and construction flaws, as well as material deficiencies provided that the buildings have regular floor plan and sufficient wall density. Confined masonry was exposed to several significant earthquakes, including the 2010 Maule, Chile earthquake (M 8.8). The earthquake-affected area was populated by many low-rise confined masonry buildings, which performed very well in the earthquake. Figure 3a) shows a two-storey confined masonry house in Curepto which remained virtually undamaged, while the adjacent adobe house collapsed; see Brzev, Astroza, and Moroni (2010) and Astroza et al. (2012) for more details on performance of confined masonry buildings in the 2010 Chile earthquake. A similar observation was made after the 2007 Pisco, Peru earthquake (M 8.0), where confined masonry buildings performed very well compared to other types of masonry buildings which were badly damaged or collapsed. Figure 3b) shows a four-storey confined masonry building in Ica which remained virtually undamaged in the earthquake.

a)

b)

Figure 3. Performance of confined masonry buildings in recent significant earthquakes: a) the 2010 Maule, Chile earthquake (M.O. Moroni Yadlin), and b) the 2007 Pisco, Peru earthquake (D. Quiun)

It is important to understand how seismic forces are resisted by a confined masonry structure. Seismic behavior of a confined masonry wall panel can be explained by composite (monolithic) action of a masonry wall and adjacent RC confining elements. This composite action exists due to the toothing between the walls and the tie-columns - that is one of the key features of confined masonry construction. Shear resistance of a confined masonry wall panel (3) can be determined as the sum of contributions of the masonry wall (1) and the adjacent RC tie-columns (2), as shown in Figure 4. It can be seen that the stiffness and strength of a confined masonry panel decrease following the onset of diagonal cracking in the wall (point 1). However, the load-resisting capacity of the panel is maintained until the critical regions of the confining elements experience significant cracking (point 2). This shows that a significant lateral deformation and ductility can be attained before the failure of a properly designed and constructed confined masonry panel (point 3). It can be concluded that critical regions in a confined masonry structure are end zones of tie-columns (top and bottom region at each floor level). Proper detailing of these regions is critical for minimizing damage in confined masonry buildings, as evidenced by past earthquakes.

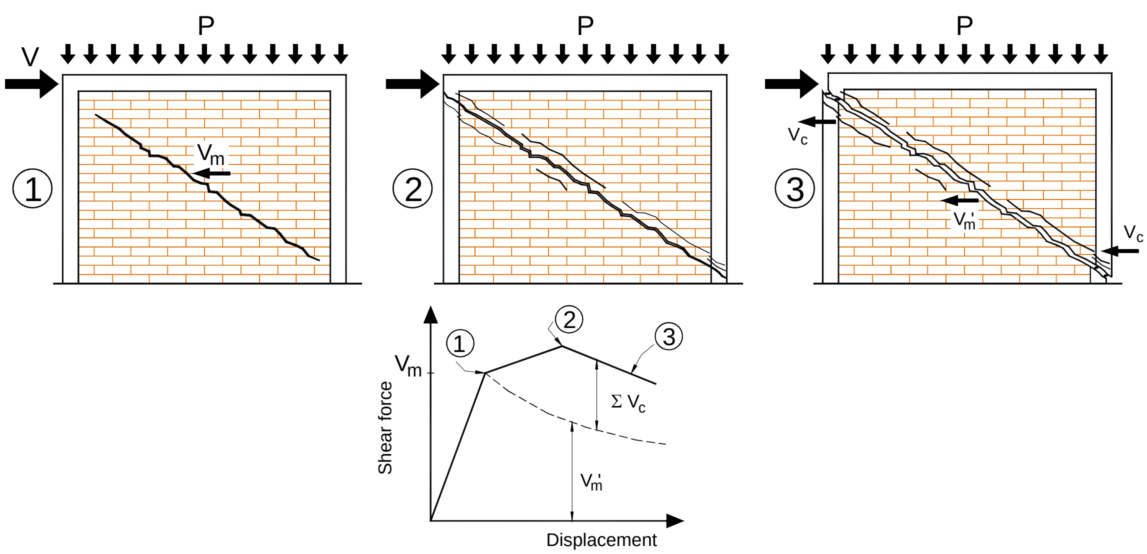


Figure 4. Mechanism of shear resistance for a confined masonry wall panel: 1) diagonal cracking in the masonry wall; 2) diagonal cracks have propagated from the wall into the tie-columns, and 3) shear failure of the RC tie-columns and the confined masonry wall panel

4. CHAPTER 2: GENERAL REQUIREMENTS

Chapter 2 outlines a number of general requirements, including design and performance objectives, seismic hazard, general planning and design aspects, and materials. These requirements are summarized below:

1. *Design and performance objectives:* the recommendations of the Guide are based on the *life safety* performance objective, which means that building collapse should be avoided in the case of a major earthquake and occupants should be able to safely evacuate the building.
2. *Seismic hazard:* four seismic hazard levels have been considered in the Guide, based on the Global Seismic Hazard Program (GSHAP 1999):
    a. Low: peak ground acceleration (PGA) less than 0.08g
    b. Moderate: PGA in the range from 0.08 to less than 0.25g
    c. High: PGA in the range from 0.25 to 0.4g
    d. Very high: PGA exceeds 0.4g

    The focus of the Guide is on confined masonry construction in the regions of moderate and high seismic hazard.
3. *General planning and design aspects:* experience from past earthquakes has confirmed that the initial conceptual design of a building is critical for its satisfactory performance during an earthquake. Architects play an important role in developing conceptual design and defining the overall shape, size and dimensions of a building. Regular building layout is one of the key requirements for satisfactory earthquake performance. Both desirable and undesirable solutions are presented in the Guide.
4. *Materials:* this section discusses the properties of masonry materials, concrete, and steel, which are acceptable for confined masonry construction. The key mechanical properties of masonry, including the unit compressive strength, mortar strength, masonry compressive and shear strength, are also discussed, and minimum requirements are specified. It is expected that material testing is unlikely for non-engineered masonry construction, however simple field tests can be used to confirm that the minimum material requirements have been met.

5. CHAPTER 3: PRESCRIPTIVE RECOMMENDATIONS FOR NON-ENGINEERED LOW-RISE CONFINED MASONRY BUILDINGS

This chapter contains recommendations for low-rise (one or two-storey high) non-engineered confined masonry buildings. The key building components, masonry walls and confining elements, are addressed in detail.

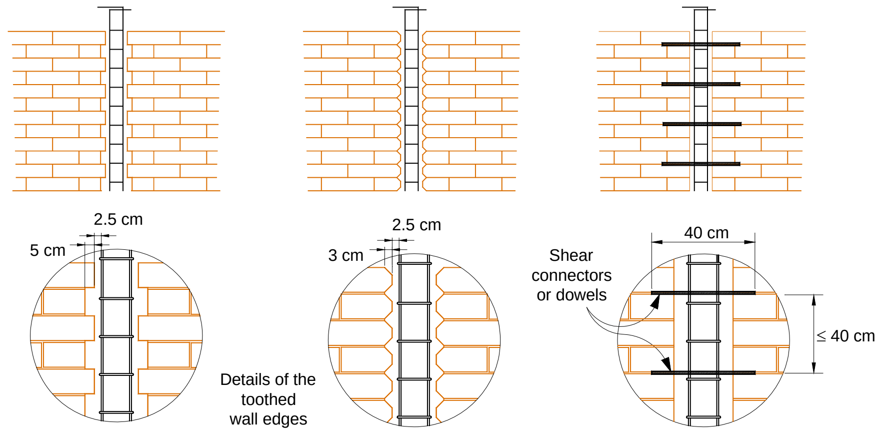
5.1. Masonry walls

The items related to confined masonry walls include: wall density requirements, spacing of cross-walls, dimensions and height/thickness ratio, parapets and gable walls, walls with openings, and toothing at the wall-to-tie-column interface. Wall density is one of the key parameters influencing the seismic performance of confined masonry buildings. Evidence from past earthquakes has shown that confined masonry buildings which had adequate wall density, were able to sustain the effects of major earthquakes without collapse. Wall density index is a ratio of the total wall area in each orthogonal direction and the building plan area, and its required value depends on seismic hazard, soil type, number of stories, building weight, and masonry shear strength. Three soil types have been considered in the Guide: i) rock or firm soil, ii) compact granular soil, and iii) soft clay. Gravity load-bearing capacity has been considered in determining the wall density requirements. The key wall recommendations contained in Chapter 3 are summarized in Table 5.1.

Table 5.1. Recommendations for Confined Masonry Walls

Item	**Recommendation**
Wall density index	Depends on number of stories, type of masonry units and mortar, and type of soil (ranges from 1 to 9.5 %)
Spacing of transverse walls	Buildings with flexible diaphragms: 4.5 to 6.0 m
Wall dimensions	Minimum 110 mm
Wall height/thickness ratio	Maximum 25
Walls with openings	The effect of opening can be ignored, provided that the opening area is less than 10% of the panel surface area and that it is located outside the diagonals

Good bonding between a masonry wall and adjacent RC tie-columns is important for satisfactory earthquake performance, and for delaying undesirable cracking and separation at the wall-to-tie-column interface. Bonding is an essential feature of confined masonry construction and it can be achieved by toothing at the wall-to-tie-column interface, as shown in Figure 5. Toothed edges should be left on each side of the wall at the interface with the tie-columns. Toothing length should be equal to one-quarter of the masonry unit length, but not less than 50 mm, as shown in Figure 5 a) and b). Horizontal reinforcement anchored into tie-columns, also known as dowels, can be used instead of toothing, as shown in Figure 5c).



a) b) c)

Figure 5. Toothing in confined masonry walls: a) machine-made hollow units, b) hand-made solid units, and c) provision of horizontal reinforcement when toothing is not possible (EERI, 2011).

5.2. Confining elements

The Guide contains recommendations regarding spacing, dimensions, and reinforcement requirements for confining elements (tie-columns and tie-beams). Spacing requirements are summarized in Figure 6. Reinforcement requirements are related to size and detailing of longitudinal and transverse reinforcement in tie-columns and tie-beams. Although RC confining elements are predominantly axially loaded and there is no moment transfer in the tie-beam-to-tie-column connections, proper detailing of these connections is very important for satisfactory earthquake performance.

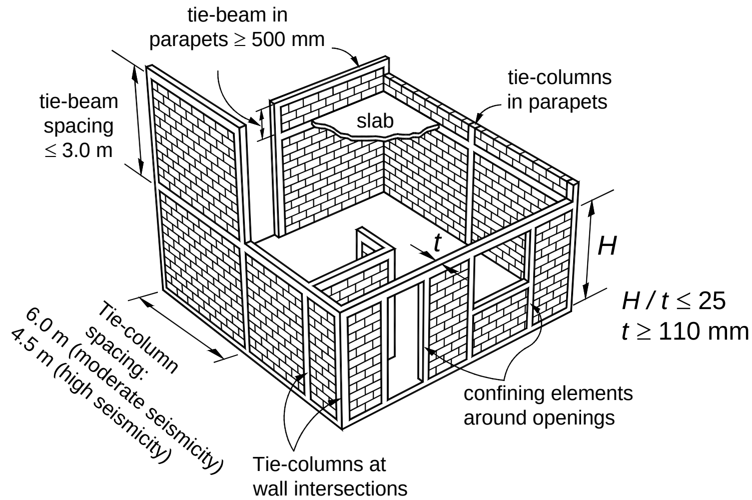


Figure 6. Key recommendations for non-engineered confined masonry buildings (EERI, 2011, adapted from NTC-M, 2004).

6. CONCLUSIONS

This paper outlines the first-of-a-kind effort to develop a global design guide for confined masonry buildings in regions of high seismic risk. The consensus-based recommendations were developed by an international group of experts and are based on the review of international design codes and guidelines and the state-of-the-art body of knowledge on the subject. The expected audience includes design engineers, academics, code development organizations and non-governmental organizations in countries where seismic design provisions for confined masonry construction are not available. This is a public domain document and it can be used and translated by interested parties free of charge. As of this writing, there is an ongoing initiative to translate the guide in Gujarati language in India and promote its use in Gujarat through a government agency called Gujarat State Disaster Management Authority.

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