Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1494

DEVELOPMENT OF A GLOBAL DESIGN GUIDELINE FOR CONFINED MASONRY BUILDINGS IN REGIONS OF HIGH SEISMIC RISK

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ABSTRACT

This paper presents an overview of the development of a global design guideline for confined masonry buildings sponsored by the Confined Masonry Network (www.confinedmasonry.org) under the auspices of EERI and a few other organizations. The authors of the proposed paper are co-chairing a committee of thirteen international experts responsible for developing the *Seismic Design Guide for Confined Masonry Buildings*. The guide contains design provisions related to the layout, wall density, and size of confined masonry structural components (RC tie-columns and tie-beams, and masonry walls), reinforcement size and detailing. The guide includes prescriptive design recommendations for low-rise buildings, and rational procedures for seismic design of engineered mid-rise buildings. The guideline addresses variations in seismic hazard and construction practices such as strength of masonry and reinforced concrete, and the type of horizontal diaphragm (light wooden roofs versus reinforced concrete slabs).

Development of the Guide

Several past earthquakes revealed the poor performance of unreinforced masonry as well as poorly-built reinforced concrete (RC) frame construction, which 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 (Magnitude 7.2), which killed over 70,000 people. Over the last thirty years, confined masonry construction has

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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 Confined Masonry Buildings (EERI 2009), referred to as the Guide in this paper, was developed by a group of thirteen international experts in the areas of 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; tie-columns and tie-beams (size and detailing requirements).

In a second step, the group developed the Guide containing design provisions related to the layout, wall density, and size of confined masonry components (RC tie-columns and tie-beams, and masonry walls), reinforcement size and detailing. These prescriptive recommendations are intended for low-rise buildings, while rational procedures are recommended for the seismic design of medium-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).

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 (one- to two-story high) regarding the layout and wall density, and prescribe minimum size requirements for key structural components (tie-columns, tie-beams, and walls), reinforcement size and detailing in the form of prescriptive provisions,
- Recommend rational procedures for seismic design of mid-rise buildings (up to five stories high), and
- Provide a summary of the seismic design provisions for confined masonry buildings contained in the relevant international codes.

The Guide is divided into four 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 a prescriptive recommendation 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. Chapter 4 outlines additional design procedures and requirements for engineered confined masonry buildings. It is expected that mid-rise buildings of this type (up to five stories high) can be designed and built following the recommendations provided in this document and other relevant national codes and standards.

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 is practiced, and where seismic design codes and standards addressing confined masonry construction are already in place.

Chapter 1: an Overview of Confined Masonry Construction

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

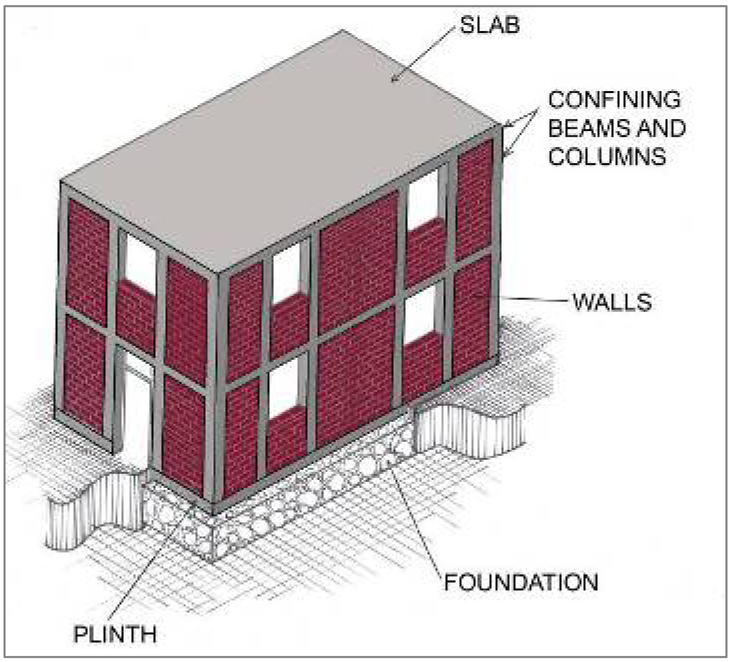
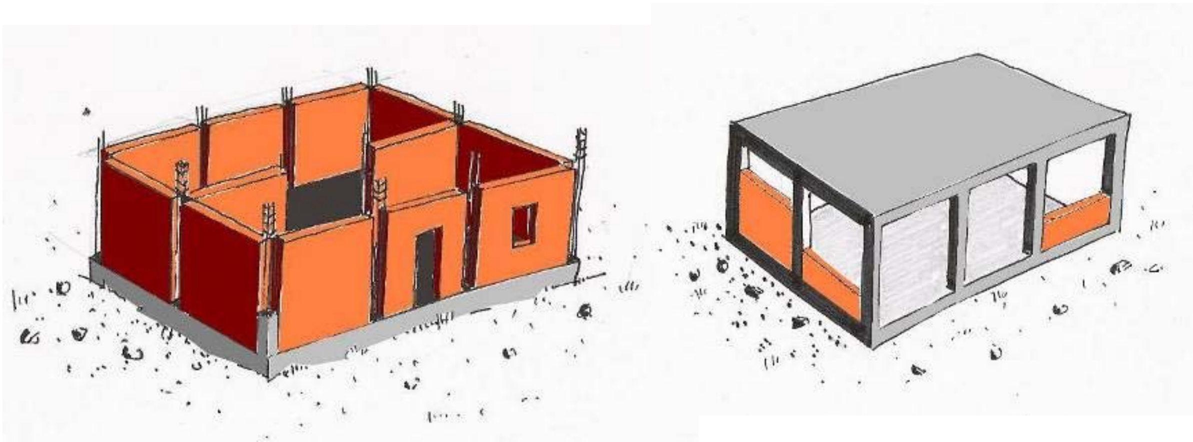


Figure 1. A typical confined masonry building.

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. The main differences are related to the construction sequence, as well as to the manner in which these structures sustain gravity and lateral loads. In confined masonry construction, masonry walls are constructed first; subsequently, RC tie-columns are cast in place (see Figure 2a). Finally, RC tie-beams are constructed on top of the walls, simultaneously with the floor/roof slab construction. The construction sequence in RC frame construction is different: the concrete construction is completed first and masonry walls are built at the end, as shown in Figure 2b. Confining elements are not designed to act as a moment-resisting frame; as a result, detailing of the reinforcement is less complex. It should be noted that the most important difference between the confined masonry walls and infill walls is that infill walls are non-load-bearing walls, while the confined masonry walls are load-bearing walls.



a) b)

Figure 2. Differences in construction sequence: a) confined masonry construction, and b) reinforced concrete frames with masonry infills (Credit: Tom Schacher).

The seismic performance of confined masonry buildings depends on several factors, including seismic hazard (earthquake intensity at the specific site), soil conditions, and the type of roof/floor system (rigid or flexible diaphragm). The quality of building materials and construction is extremely important - well-built confined masonry buildings should be able to sustain the effects of major earthquakes without collapse. A confined masonry building subjected to earthquake ground shaking can be modeled as a vertical truss, as shown in Figure 3a). Masonry walls act as diagonal struts resisting compression, while RC confining members act in tension or compression, depending on the direction of lateral earthquake forces. In multi-story confined masonry buildings, the cracking is concentrated at the ground floor level and significant lateral deformations take place. Under severe earthquake ground shaking, the collapse of mid-rise confined masonry buildings due to the soft story effect is similar to the mechanism observed in RC frames with masonry infills, as shown in Figure 3b). This mechanism has been confirmed by experimental studies (Alcocer et al. 2004) and post-earthquake reconnaissance studies. It was reported after the 2003 Tecomán, Colima, Mexico earthquake, that a three-storey confined masonry apartment building in Colima experienced significant damage at the ground floor level (EERI 2006).

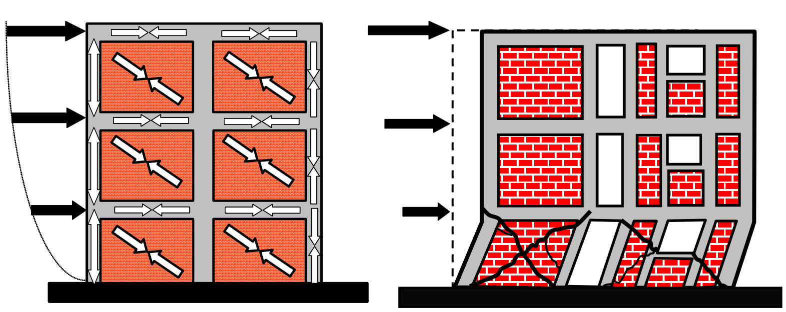


Figure 3. Confined masonry building: a) vertical truss model (Murty and Jain 2000), and b) collapse at the ground floor level (Alcocer et al. 2004).

In-plane shear damage of confined masonry walls is the most common type of damage observed in past earthquakes, and it is characterized by distributed diagonal cracking in the wall. Severe damage was mostly observed in buildings with incomplete or missing confining elements, as shown in Figure 4.

a) b)

Figure 4. In-plane shear damage of confined masonry construction: a) the 1999 Tehuacan, Mexico earthquake (Alcocer et al. 2001), and b) the 2001 El Salvador earthquakes (EERI 2001).

Out-of-plane failure of confined masonry walls has been observed almost exclusively in confined masonry buildings with flexible diaphragms. The out-of-plane response of confined masonry walls is displacement-controlled and can be explained by the arching mechanism. Structural damage due to the out-of-plane seismic effects was observed in some Indonesian earthquakes (e.g. 2007 West Sumatra and the 2009 Padang earthquake).

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. <u>Design and performance objectives:</u> 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. <u>Seismic hazard:</u> 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 0.09 to 0.25g
    c. High: PGA in the range from 0.26 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. <u>General planning and design aspects:</u> 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. Material testing is not going to be possible for non-engineered masonry construction, but simple field tests can be used to confirm that the minimum material requirements have been met.

Chapter 3: Prescriptive Recommendations for Non-Engineered Low-Rise Confined Masonry Buildings

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

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 shows 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 1.

It is a good construction practice to provide toothing at the wall-to-tie-column interface. Toothing is required for low-strength masonry walls built using hand-made bricks. Toothed edges should be left on each side of the wall. It is recommended that the length of toothing should be equal to ¼ brick or 50 mm, as shown in Figure 5. In some cases, it is challenging to construct the toothed interface, as documented by SENCICO (2008). Horizontal reinforcement anchored into tie-columns, also known as dowels, can be used instead of toothing, however it is believed that dowels are not necessary for low-rise buildings (up to two stories high).

Table 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%)
Spacing of transverse walls	Buildings with flexible diaphragms: 4.5 to 6.0 m
Wall dimensions	Minimum 120 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

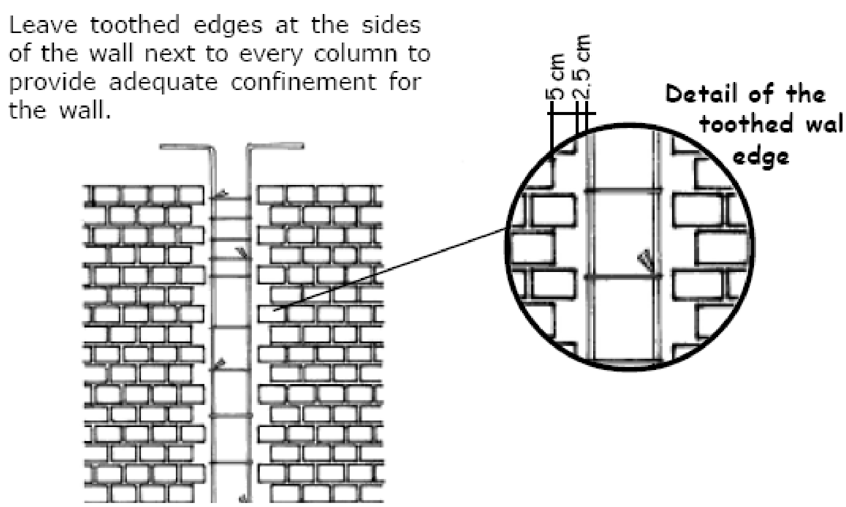


Figure 5. Toothing in confined masonry walls (Blondet 2005).

Confining Elements

The recommendations regarding the confining elements (tie-columns and tie-beams) are related to spacing, dimensions, and reinforcement requirements. 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.

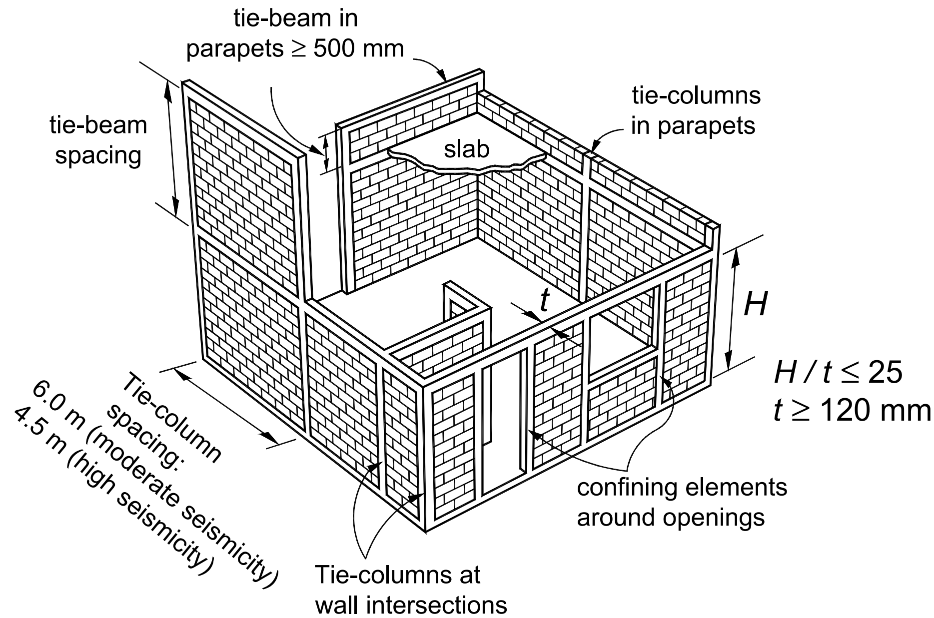


Figure 6. Key recommendations for non-engineered confined masonry buildings (this drawing will be redrawn before the final submission).

Chapter 4: Seismic Design of Engineered Confined Masonry Buildings

This chapter contains additional requirements for engineered confined masonry buildings. These are mid-rise buildings (three stories and higher) designed by qualified engineers. The topics include factors influencing seismic design (building importance, type of foundation soil, and response reduction factor), and design procedures for building components (walls and confining elements). The wall design section addresses topics such as shear strength and out-of-plane resistance; the latter topic is of particular importance for confined masonry buildings with flexible diaphragms. The recommended procedures are based on a review of existing codes and guidelines. This chapter also outlines design approaches for confined masonry buildings subjected to gravity and lateral loads. Finally, critical issues related to the construction and inspection of confined masonry buildings are summarized in the checklist included in the Guide.

Conclusions

The Guide described in 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 recommendations have been developed as a consensus of the international group of experts on this subject and are based on a review of international design codes and guidelines and additional studies performed by the group. The primary audience 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 professionals in countries where confined masonry practice is well-established.

Acknowledgments

The authors would like to acknowledge the contribution of their colleagues who participated in the development of the Guide, including Miha Tomazevic (Slovenia), Maximiliano Astroza (Chile), Daniel Quiun (Peru), Luis Yamin (Colombia), Junwu Dai (China), Mohammed Farsi (Algeria), Teddy Boen (Indonesia), A.S. Moghadam (Iran), Tim Hart (USA), Ahmed Mebarki (France), and Francisco Crisafulli (Argentina). The financial support for the development of the Guide provided by Risk Management Solutions is gratefully acknowledged. The authors appreciate the support provided by the Earthquake Engineering Research Institute, which coordinated the development of the Guide, and in particular to Marjorie Greene for her invaluable input and assistance in the course of this project. The authors are grateful to Prof. Sudhir Jain, Director, IIT Ahmedabad, India and Co-chair of the Confined Masonry Network, for his vision, initiative and encouragement.

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