EARTHQUAKE HAZARD CENTRE NEWSLETTER

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Contents

Editorial: Confined masonry construction - a better way of building

This newsletter is mainly concerned about confined masonry construction. The primary article reports on the excellent seismic performance of confined masonry buildings during the large 2010 Maule Earthquake in Chile.

Although confined masonry has been used in Chile for approximately 80 years and its use has spread to other countries, like Mexico, there is still much scope for broadening its application worldwide. For developing countries in seismic regions, confined masonry offers a far safer alternative to both unreinforced masonry construction and RC post and beam construction. The vulnerability of these construction types are highlighted after every damaging quake. Unreinforced masonry is rendered vulnerable by its lack of tension strength that can tie walls together, or floor and roofs to walls. RC post and beam doesn't usually perform much better, and this shouldn't come as a surprise. Recall the skeletal structural framework we see during construction – very slender columns supporting one or more suspended concrete floors. Although a more modern material like RC is incorporated, these buildings usually rely on masonry wall panels for horizontal bracing. Frequently, we see how these wall panels, which are not tied to the concrete structure, either fall out of or into buildings, causing serious damage and injuries. Also, because the placement of walls and openings within them are not regulated, the very walls intended to provide bracing in the event of a quake, can seriously damage the primary RC structure.

Confined masonry, where properly designed and built, offers a huge improvement in seismic performance. This is why it is being promoted and more resources are becoming available. Please visit the World Housing Encyclopedia Confined Masonry Tutorial website. Currently the publications *Construction and Maintenance of Masonry Houses* and *Seismic Design Guide For Low-Rise Confined Masonry Buildings* are available for free download. Another construction guide is in preparation and should be completed later this year. The other publication that should be consulted is *Earthquake Resistant Confined Masonry Construction*, by S. Brvez and published by the National Center of Earthquake Engineering, India (NICEE). It is also available free of charge. It was reviewed in this newsletter in April 2008.
The main finding regarding the Maule Earthquake, Chile, is that confined masonry performed very well. However, as for any construction type, examples of poor practice are observed, and recommendations for improvements are made. Provided we take note of past problems and improve our standards of design, this construction approach will provide economical buildings that will also be safe even in a large earthquake. The beauty of confined masonry is that it mainly utilizes one of the most common materials at our disposal, masonry, but then ties heavy, brittle and potentially dangerous masonry walls together to achieve safe construction. Confined masonry is a better alternative.

Virtual Site Visit No. 35: Seismic retrofitting of a low-rise unreinforced masonry building

This low-rise building is located in Wellington's CBD. It houses a bar on ground floor and a restaurant above. Since its construction material is unreinforced masonry, and due to other weaknesses from an earthquake point of view, Wellington City Council has assessed its condition as 'earthquake prone'. This has meant either demolition or strengthening.

The approach taken in this building is to provide new reinforced concrete shear walls to enable the structure to meet current standards of seismic resistance. On two perimeter walls of the building it is possible to construct external walls, while other walls have been constructed inside. Before wall construction begins, extensive foundation work is required. Small-diameter tension-capable piles are drilled at the ends of each wall and then the pile reinforcement is bound into new reinforced concrete foundation beams approximately 600 mm deep. Vertical starters from these beams rise up the walls to begin the vertical steel which is tied to horizontal bars that resist wall shear forces (Figure 1).

The new concrete walls must be strongly tied to the existing walls. That is achieved by horizontal grouting of steel bars into the masonry and tying the reinforcing cage to them (Figure 2).

Before applying the concrete, in the form of shotcrete, a finer steel mesh is placed to prevent the freshly-applied concrete peeling off and falling. Once the concrete is placed (Figure 3), and after a short wait, the outer surface is worked over with trowels to achieve a smooth finish.

With the new walls complete, seismic forces are transferred from the vulnerable walls into the reinforced concrete walls, and from their into the foundation beams and foundations to ground.

Fig. 1 The rear wall of the building and the reinforcing cage for a new concrete wall.

Fig. 2 Grouted-in bars, bent into the wall thickness, provide the temporary attachment points for the wall reinforcing and strongly connect new construction to the old.

Fig. 3 The concrete has just been applied. It is trowelled over to form a smooth finish.

A summary of the Seismic Performance of Confined Masonry Buildings from "Seismic Performance of Engineered Masonry Buildings in the 2010 Maule Earthquake" by M. Astroza, O. Moroni, S. Brzev, and J. Tanner, Published in Earthquake Spectra, pp. 5385-5406, June 2012.

Introduction

A majority of buildings affected by the 27 February 2010 earthquake can be classified as housing construction. Masonry is the most popular housing construction technology in Chile, accounting for 38.6% of the national housing stock. In particular, in the Maule Region most severely affected by the earthquake (total population of 908,097), masonry constitutes 50.4% of the total housing stock. Adobe and timber construction account for 22% and 21%, respectively, of the housing stock, while reinforced concrete (RC) construction accounts for 4% of the housing stock.

Typical forms of housing include low-rise single-family dwellings (up to two stories high), and medium-rise apartment buildings (three to five stories high). Older masonry buildings in the affected area (built before the 1950), either of unreinforced brick masonry or adobe construction, were severely damaged in the earthquake. A majority of masonry buildings built since the 1930s are of confined masonry construction. Reinforced masonry construction practice started in the 1970s, and it represents a small fraction of the building stock. Most of confined and reinforced masonry buildings is considered engineered construction, because the construction practice is based on the provisions of building codes and guidelines, some of which date back to the 1940s. In many cases, designs of engineered masonry buildings have been standardized because these buildings were built as social housing. These building designs are similar and can be used to compare seismic performance of similar buildings located at different sites.

Typical Building Construction

Masonry buildings in the earthquake-affected area can be classified as low-rise single-family dwellings and medium-rise apartment buildings. Single-family dwellings are in the form of either one-story detached houses or two-story houses in a row (i.e., townhouses). A typical confined masonry townhouse is shown in Fig. 4a. Plan dimensions for a typical unit are approximately 5 m × 6 m, while the clear floor height is on the order of 2.2 m to 2.3 m. The front façade of the house is usually perforated with openings, while the transverse walls are solid. One- and two-story dwellings have timber floors and pitched timber roofs with timber gables.

Apartment buildings are usually three- to four-story high, with two to six apartments per floor (depending on the building size). Typical plan dimensions are as follows: length ranging from 12 to 30 m and width from 5 m to 8 m. A typical three-story apartment building is shown in Fig. 4b. Most buildings have a regular and symmetric configuration. More than 80% buildings have a rectangular floor plan and regular configuration with insignificant eccentricity between the center of mass and the center of rigidity. In both directions, there are seismic force-resisting systems that provide a complete horizontal and vertical load path. The distance between transverse walls ranges from 7 m to 8 m. These buildings usually have RC floors and pitched timber roofs with timber trusses supported by RC perimeter beams. RC floors are either cast-in-place or precast, with large hollow masonry blocks (called bovedillas in Spanish) laid horizontally between precast reinforced concrete beams (this is known as "Tralix" system).

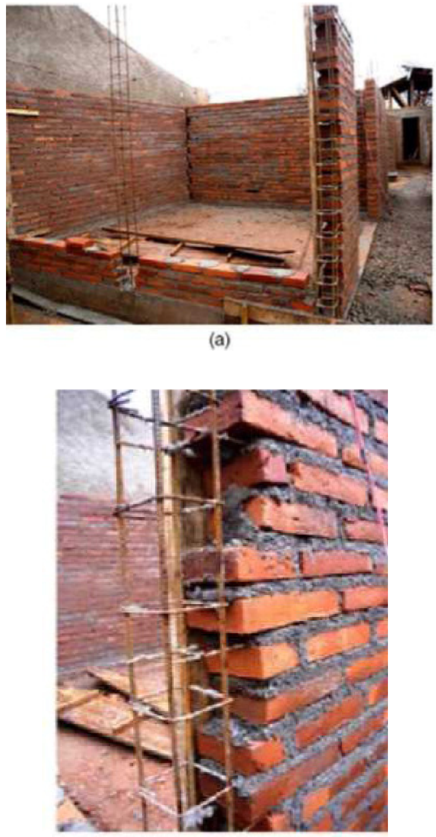
Fig. 4 Typical housing construction in Chile: (a) Two-story townhouses and (b) a three-story apartment building.

Confined Masonary

Chile has a long history of confined masonry construction practice. The use of confined masonry in Chile started in the 1930s, after the 1928 Talca earthquake (Mw 7.7), and it was initially used for low-rise single-family housing. The construction of medium-rise apartment buildings started in the 1970s in the capital Santiago, and in the 1990s in other urban areas. Good performance of low-rise confined masonry buildings in the 1939 Chillan earthquake (M 7.8) paved the road for the widespread use of this construction technology in Chile. Low-rise confined masonry construction maintained a good performance record in past earthquakes, including the 1985 Llolleo earthquake (Mw 8.0). Very few medium-rise confined masonry buildings existed in the epicentral zone of the 1985 earthquake, so it can be considered that three- and four-story confined masonry buildings had not been exposed to severe ground shaking in Chile prior to the February 2010 earthquake.

Key components of confined masonry buildings are masonry walls and RC confining elements (tie-columns and tie-beams). Unreinforced masonry wall panels are constructed first, one story at a time, followed by the cast in-place RC tie-columns, as shown in Fig. 5a. Finally, RC tie-beams are constructed on top of the walls, simultaneously with the floor/roof slab construction. The wall thickness depends on the type of masonry units used. Most common masonry units used for confined masonry walls are 140 mm machine-made hollow clay blocks (tiles), followed by the handmade solid clay bricks. Hollow concrete block units (usually 150 mm thick) are rarely used in the earthquake-affected area, although they were found in the walls of one of the collapsed confined masonry buildings in Santa Cruz. Chilean masonry standard prescribes values for compressive strength of masonry units ranging from 4.0 MPa for handmade clay bricks to 15.0 MPa for hollow clay tiles (based on the gross area), while the minimum mortar compressive strength is 10.0 MPa (corresponding to mortar mix 1:5 cement:sand).

A toothed interface between the walls and the tie-columns is used, as shown in Fig. 5b. Toothing enhances an interaction between masonry walls and RC confining elements and prevents vertical cracking at the wall ends; this was confirmed during the field visit. The construction sequence, a presence of toothing, size, and detailing of RC confining members are the key differences between confined masonry and RC frame construction with masonry infill walls, as shown in Fig. 6 (EERI 2011).



(a)

(b)

Fig. 5 Confined masonry construction: (a) Masonry wall is built first and (b) a toothed wall-to-tie-column interface.

RC confining members have an important role in enhancing the overall building stability and integrity. These members can effectively contain damaged masonry walls in-plane and out-of-plane, and ensure adequate wall connections to adjacent floors/roofs and foundations. Based on the field observations, RC tie-columns are provided at 3 m to 3.5 m on-center spacing. Typical cross-sectional dimensions range from 140 mm to 200 mm (length), while the depth is equal to the wall thickness. The longitudinal reinforcement in RC tie-columns consists of four 8 to 10 mm diameter bars, and the ties are typically provided at 150 mm to 200 mm spacing up the tie-column height. It was observed that uniform tie spacing was provided in the surveyed buildings, although the code prescribes a closer spacing at the tie-column ends. The tie size ranges from 6 mm diameter (for reinforcement cages assembled at the site) to 4.2 mm (for prefabricated reinforcement cages). RC tie-beams have similar reinforcement and dimensions like tie-columns. In buildings with timber roofs, the width of tie-beams at the roof level exceeds the wall thickness, for example, 200 mm or 250 mm wide RC tie-beams are supported by

140 mm thick walls. Typical steel grades used for the RC confining elements are 280 MPa yield strength and 420 MPa yield strength for the reinforcement cages assembled at the site, while 500 MPa yield strength is used for the prefabricated reinforcement cages.

Damage Observations

According to the official data, 208,582 housing units in total required repair or replacement after the earthquake. Damage observations made in this paper are based on field surveys of approximately 100 building complexes built in the 1990s located in the Regions VI and VII, which account for approximately 15,000 housing units or 70% of the total stock of social apartment buildings (three and four stories high) in the earthquake-affected area, providing shelter to 90,000 people.

By and large, confined masonry buildings performed very well in the earthquake. Most one- and two-story single-family confined masonry dwellings did not experience any damage, with the exception of a few buildings which suffered moderate damage. A large majority of three- and four-story confined masonry buildings also performed well, however a few buildings suffered moderate to severe damage. A few medium-rise confined masonry buildings of older vintages suffered a moderate repairable damage.

Masonary Walls: Damage Observations and Deficiencies

The most common damage pattern observed in unreinforced masonry walls in confined masonry buildings was in-plane shear cracking, which is characterized by diagonal (X-shaped) cracks. In-plane shear cracking occurs when the masonry tensile strength is exceeded due to the effect of combined shear and gravity loads. Alternatively, stair-stepped shear cracks develop due to sliding shear at the mortar bed joints due to a loss of bond at the mortar-to-unit interface. This type of damage was

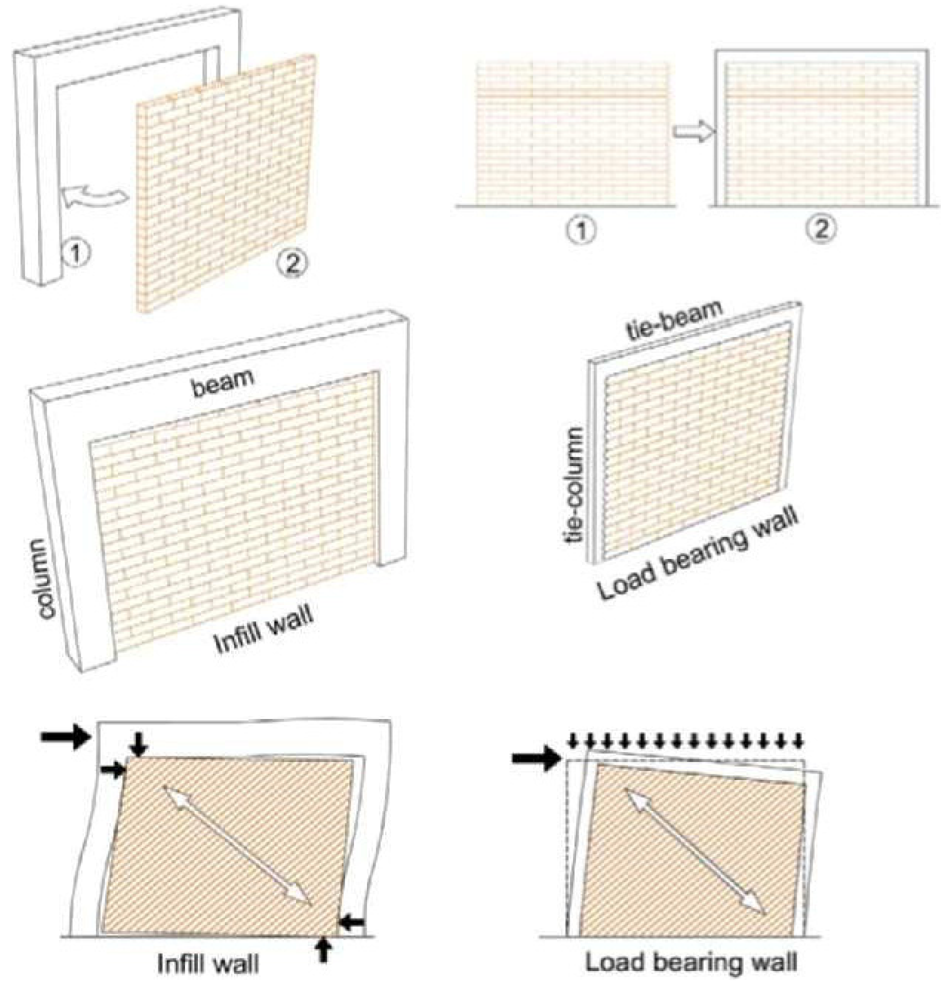


Fig. 6 A comparison: (a) Reinforced concrete frame construction with infill and (b) confined masonry construction.

mostly observed at the bottom floor level of three- and four-story buildings, as shown in Fig. 7a. Shear cracking was observed in walls built using all types of masonry units, including hollow clay tiles, clay bricks, and hollow concrete blocks. More extensive damage was observed when masonry walls were not confined at the openings (see Fig. 7b); this confirms the findings of a previous Chilean experimental study. Absence of RC tie-columns at openings is believed to be one of the main causes of severe damage in confined masonry buildings.

A few instances of wall damage due to out-of-plane seismic effects were observed. One notable example was a three-story building in Cauquenes with the damage concentrated at upper floors, as shown in Fig. 8a. The building had RC floors and a timber truss roof. Cracks in the third-floor wall panel extended into the RC tie-beam, as shown in Fig. 8b (note that the tie-beam is wider than the wall). The out-of-plane damage was observed in the transverse direction of the building (note that the building was severely damaged in longitudinal direction due to in-plane seismic effects).

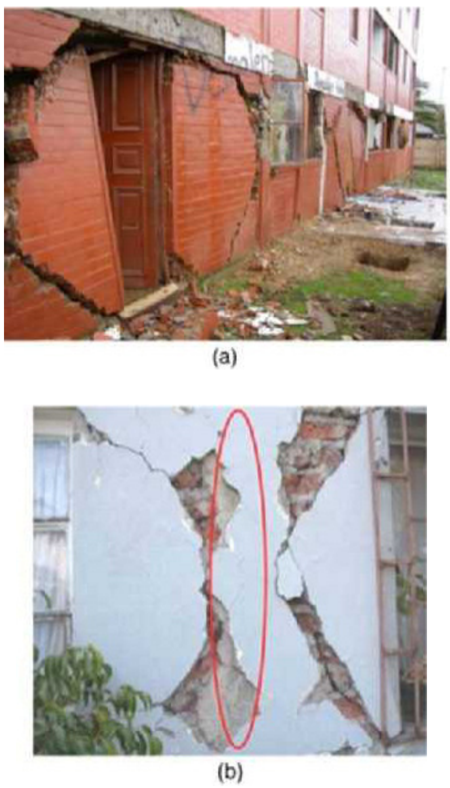


Fig. 7 In-plane shear cracking of masonry walls: (a) Damage at the ground floor level of a three-story building in Cauquenes and (b) shear cracking of an unconfined masonry pier (note a RC tie-column located at the center of the pier highlighted with an ellipse).

Reinforced Concrete Confining Elements: Damage Observations and Deficiences

Failure of RC tie-columns was observed in three- and four-story apartment buildings in which masonry walls suffered severe damage at the ground floor level. The size of tie-columns (140 mm × 140 mm or 150 mm × 150 mm) in a large majority of surveyed buildings was smaller than the minimum dimensions prescribed by the code, that is, the length equal to 200 mm and the width equal to the wall thickness (t). Exposed RC confining elements (tie-beams and tie-columns) in damaged buildings provided an opportunity to examine detailing of reinforcement in these elements. A few important deficiencies which contributed to a brittle failure of confined masonry walls are discussed below.

Inadequate confinement (tie size and spacing) at the ends of RC tie-columns was observed in all damaged buildings. The code and other design guidelines prescribe a closer tie spacing of 100 mm in end regions compared to the middle portion of a tie-column (200 mm). Buckling of longitudinal reinforcement was observed where size or spacing of ties at tie-column ends was inadequate, as shown in Fig 9a, and the masonry crushing was severe, as shown in Fig 9b. The buckling took place due to excessive combined compression and shear stresses developed

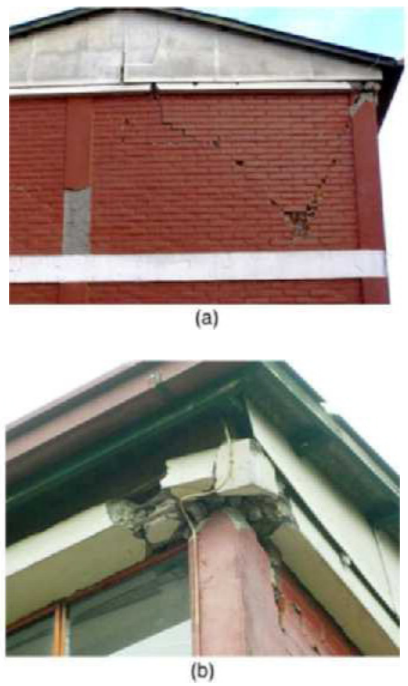


Fig. 8 Out-of-plane damage of confined masonry buildings: (a) Wall damage at the top floor level and (b) damage in the RC perimeter beam.

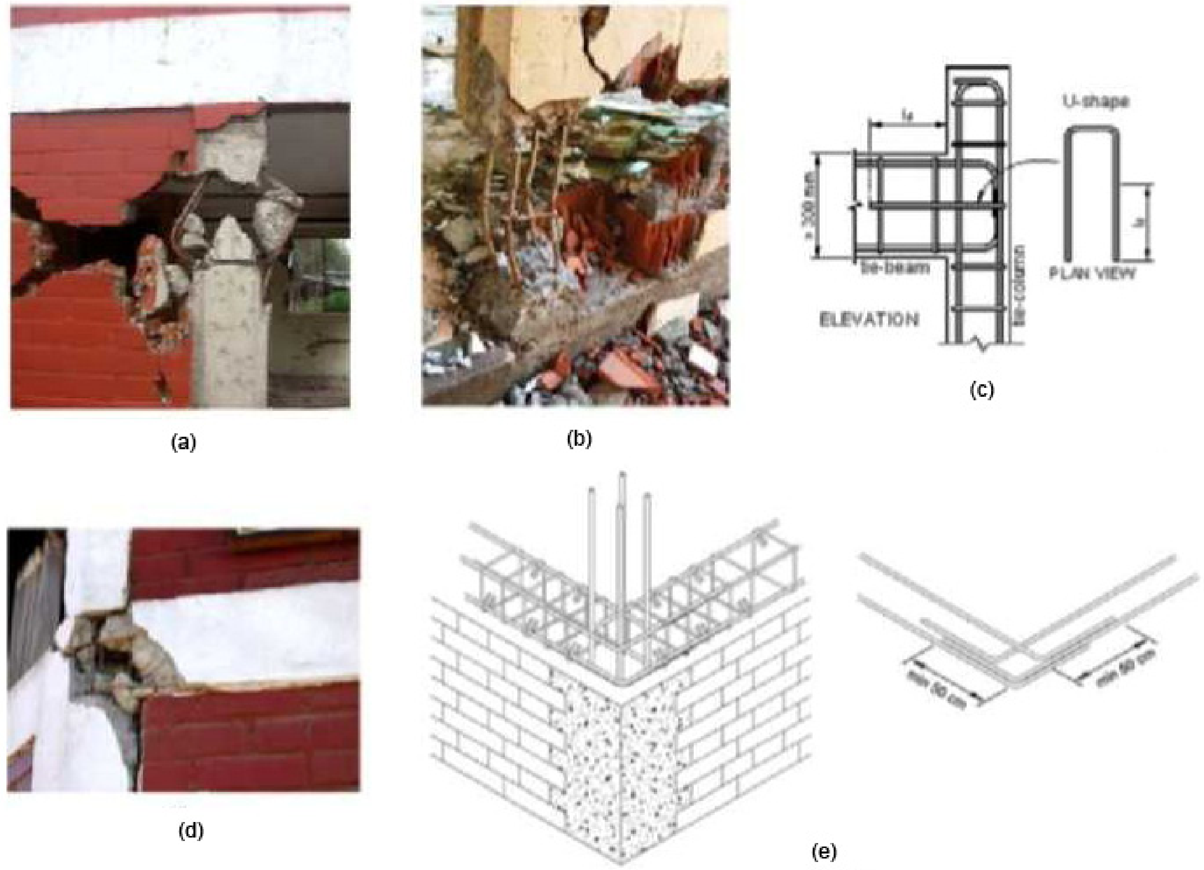


Fig. 9 Construction and detailing deficiencies in the RC tie-columns: (a) buckling of longitudinal bars; (b) severe crushing at the wall toe; (c) additional confinement for vertical reinforcement in the tie-beam and tie-column end joint region (EERI 2011); (d) discontinuous longitudinal reinforcement, and (e) recommended detailing practice.

in RC tie-columns after the masonry was crushed and disintegrated at the wall toe.

Inadequate detailing of reinforcement in tie-column-to-tie-beam joint zones was observed in all cases where the joints were exposed. An absence of ties in end columns is a deficiency, and it causes a severe damage in the joint zone. A good practice would be to provide additional ties, as shown in Fig 9c. Another deficiency is related to a lack of continuity in longitudinal reinforcement through tie-beam intersections with end columns, as shown in Fig. 9d. This is contrary to Chilean detailing provisions for reinforced concrete structures, which state that "longitudinal bars should have a 90º hooked anchorage at intersections to ensure the effectiveness of tie-beams to resist earthquake load," as shown in Fig 9e. It should be noted that reinforcement cages for tie-beams and tie-columns are often assembled off the building site, therefore additional "continuity reinforcement" should be provided once the cages are placed in the final position.

The quality of concrete construction in RC confining elements was found to be good, with a few exceptions. Excessively large aggregate size was observed in a few damaged RC tie-columns; this can result in inadequate consolidation and large voids in these critical elements. Inconsistent bar sizes was another observed problem.

Wall Density and Vulnerability Assessment

Wall density index is a ratio of cross-sectional areas for all walls in one orthogonal direction and the total floor area of the building. The required wall density for a particular building depends on the seismic hazard and type of soil at the building site, plus masonry shear strength and the number of stories.

The effect of the type of masonry unit on masonry shear strength was taken into account by reducing the wall area by a factor of 0.4 or 0.5 when hollow concrete or handmade clay bricks were used, respectively. Also, wide RC columns (if present) were not considered in the wall density calculations, as these elements become effective only after the crushing of masonry has taken place.

From descriptions of damage, it can be concluded that a wall density per unit floor index (d_n) of less than 0.75% results in an unsatisfactory seismic performance, that is, damage is more extensive (and the grade is higher) when MSK intensity is greater than VII. A building with d_n value higher than 0.9% in both directions is considered to be safe even at the highest earthquake intensities. However, a high wall density index in one direction only may not be sufficient to ensure seismic safety of a building. For example, d_n values for the collapsed confined masonry building in Constitución were 1.4% and 0.7% in the longitudinal and transverse direction, respectively. Note that the building collapsed after experiencing extensive damage in the transverse direction and losing its bottom floor.

Conclusions and Recommendations

The 27 February 2010 Maule earthquake exposed approximately 50% of the population of Chile and a major portion of the building stock in the country to significant ground shaking. It is estimated that only about 1% of the total building stock was damaged by the earthquake. This is considered to be a very good performance record for all building types, subject to an earthquake of significant magnitude (Mw 8.8), duration, and high ground accelerations. A large majority of engineered masonry buildings performed well in the earthquake. Low-rise confined masonry buildings either remained undamaged or suffered a minor damage. The same statement can be made for medium-rise buildings, with an exception of a few severely damaged buildings and two collapsed buildings.

Lessons learned from detailed studies on the damaged and collapsed buildings and observations related to seismic performance of engineered masonry buildings, and particularly confined masonry construction, are valuable for evaluating current design provisions and improving construction practices for confined masonry buildings in Chile and other countries. Key lessons and recommendations related to the performance of engineered masonry construction in the 2010 Maule earthquake can be identified as follows:

1. **Wall density is an important parameter that can be used to assess seismic vulnerability of confined masonry buildings.** The results of a seismic vulnerability study on confined masonry buildings affected by the earthquake indicate that a wall density per unit floor index (d_n) of less than 0.75% results in unsatisfactory seismic performance when MSK intensity is greater than VII. A building with d_n value of more than 0.9% in both directions is considered to be safe even at the highest earthquake intensities.
2. **Closer spacing of ties in end zones of RC tie-columns is critical for maintaining their stability and strength.** Inadequate confinement (tie size and spacing) at the ends of RC tie-columns was observed in all damaged buildings. Adequate bar size and tie spacing in the end zones of RC tie-columns is critical for preventing shear failure and buckling of longitudinal reinforcement in localized areas of tie-columns where masonry is completely disintegrated.
3. **RC confining elements, especially tie-columns, must have adequate size to prevent a loss of compression resistance in medium-rise confined masonry buildings.** The size of tie-columns (140 mm × 140 mm or 150 mm × 150 mm) in a large majority of surveyed medium-rise buildings (both damaged and undamaged) was smaller than the dimensions prescribed by the code (minimum tie-column size: 200 mm × t, where t denotes the wall thickness). In order to prevent the brittle failure of confined masonry wall panels and maintain integrity of RC tie-columns after masonry walls suffer a severe damage, tie-column dimensions must meet the minimum code requirements.
4. **Presence of RC tie-columns at door and window openings is critical for ensuring confining effect in the masonry walls.** Without the confinement provided by RC tie-columns, it is not possible to develop compressive struts in masonry wall panels; this is the key mechanism for lateral load resistance in confined masonry walls.

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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