EARTHQUAKE HAZARD CENTRE
NEWSLETTER

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Editorial

Confined Masonry and the World Housing Encyclopedia

In this newsletter we feature two important papers that were presented at the January 2017 World Conference on Earthquake Engineering, Santiago, Chile. The first article is the second of two on the Chilean experience of confined masonry buildings during damaging earthquakes. Confined masonry construction is widespread throughout Chile and although, like any construction method, is not always applied correctly, it has performed well in the recent large quakes to hit that country. The lessons learned after a total of eight earthquakes are very important for countries who are intending to build or are already building in confined masonry. As far as determining the number of confined masonry walls needed in a building the authors recommend that a minimum wall density per unit of floor plan of 0.85% be provided in each orthogonal direction. That percentage will vary for other countries depending on their degree of seismicity and the strengths of typical wall materials etc. Most of the other lessons learned relate to detailing of the tie beam and tie column reinforcing steel, the need for tie columns not to be placed too far apart especially for thin masonry walls, the suggestion to avoid hollow concrete blocks, and finally, the unique construction sequence of confined masonry where the concrete in the tie columns is cast against the sides of toothed masonry panels.

Then in the second article, readers are introduced to the NGO, the World Housing Encyclopedia (WHE). The introduction to the WHE explains the two main ways the organization contributes to improving the seismic resilience of housing. The first approach is through the on-line database containing several hundred reports of typical houses and apartment buildings throughout the world that interested people can learn from. Next are the WHE publications or ‘Tutorials’ which are really construction guidelines for common materials and structural systems used for housing.

The remainder of the article will be published in the next issue. It describes two recent publications that identify stumbling blocks for developing countries to achieve seismically safe housing. It asks a series of questions regarding how the WHE might make a greater difference to housing safety. As you read these questions, please can you reflect on the situation in your own locality. Perhaps there are ways that the WHE might be able to help the people in your town or city live in safer houses. If you have any ideas then please send them to andrew.charleson@vuw.ac.nz and I will forward them to others on the WHE Executive Committee. It could well be that the volunteers who constitute the WHE are able to assist.

Virtual Site Visit No. 46: Retrofitting a reinforced concrete frame building with eccentrically-braced frames

We visited this building on the southern edge of Wellington's CBD in our last site visit. At that stage we focussed on the new perimeter foundation beams to resist the shear and overturning forces from the four perimeter eccentrically-braced frames.

Now the retrofit project is almost complete (Figure 1).

Figure 1. One of the four perimeter lateral load resisting frames

What is most unusual about this retrofit structure is how the eccentrically-braced frame sits above the RC moment frame at ground floor. Almost always, engineers and architects would connect the braced frame directly to the top of the foundation beam. However, in this project the "normal" approach wouldn't work due to the diagonals of the braced frame disrupting vehicles driving to the ground floor car parks. Since the only structural systems suitable to withstand lateral loads are braced frames, shear walls or moment frames, moment frames were chosen for the ground floor.

Eccentrically-braced frames are popular due to their ductility in the event of seismic overload. Figure 2 shows the region that acts as a potential seismic fuse that will be distorted during the design earthquake.

Figure 2. The short length of beam between the diagonals will be distorted when it functions as a seismic fuse.

Since the structural engineer has designed seismic fuses at each beam level between the diagonals, every other part of the structure needs to be stronger so that only those fuses ever suffer damage. This means the columns on each side of the braced frame and their fixings to the RC moment frame must be stronger than the seismic fuses (Figure 3).

Figure 3. Connection between column and frame. The column is embedded the whole height of the RC column while a horizontal plate with many embedded bolts transfers horizontal forces into the diagonal brace.

Not only do connections need to be stronger than the fuses, but the entire moment frame itself must not be damaged before the fuses yield. The frame has therefore been designed to remain elastic in this overload scenario using the Capacity Design approach. Ensuring a hierarchy of damage like this is essential for sound seismic performance.

Continuation of a Summary of the paper "Confined Masonry Buildings: The Chilean Experience" By D. M. Astroza, F. Andrade and M.O. Moroni. Presented at the 16th World Conference on Earthquake Engineering, 16WCEE 2017, Santiago Chile, January 9th to 13th 2017.

Abstract

Confined masonry construction was introduced in Chile in the late 1930s. Confined masonry structures had a great performance during the 1939 Chillán earthquake, providing the first real test for this type of construction during large earthquakes. At that time, the Ordenanza General de Construcciones included some design requirements for low-rise confined masonry buildings up to 2 stories high. A more rational code based on the allowable stress method was published in 1997 and provided design requirements for buildings up to 4 stories high. The confined masonry structures built in Chile in the last 20 years have followed the prescriptions of this code.

The great earthquakes that hit the central and north part of Chile in 1985, 1987, 1997, 2010, 2014 and 2015 have shown the excellent behavior of these structures subjected to seismic loading, when their design fully satisfied the code requirements. Contrarily, the use of partially confined masonry walls, built with a tie-column at one end of the masonry panel and a vertical tensile bar at the other end, may lead to collapse or, in many cases, to significant damage.

Key components of confined masonry buildings are the horizontal (tie-beam) and vertical (tie-column) reinforced concrete elements. These components are cast in place after the masonry wall panels are built. Typical values for shear strength of Chilean masonry are between 0.5 and 1.0 MPa and the average value of wall density index (ratio between the cross sectional areas of all walls in one direction and the total floor area of the building) is about 3.5%.

Analytical models to simulate the seismic behavior of confined masonry buildings have been calibrated with low amplitude vibration data (i.e., ambient vibrations) and seismic records obtained at the Community Andalucia Building, the only confined masonry building instrumented with an accelerometer network in Chile.

Key words: confined masonry; seismic behavior, codes: Chile; mega earthquakes

Main Components of Confined Masonry Buildings (continued

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. RC tie-columns are spaced at 3.0 to 3.5m, although Chilean code NCh2123 allows a larger spacing up to 6.0m. Tie-columns have a rectangular cross section whose dimensions typically correspond to the wall thickness (150 to 200mm) and a depth equal to 200mm. Both tie-columns and tie-beams are reinforced with a minimum of four l0mm diameter longitudinal reinforcing bars and 6mm diameter stirrups spaced at 100mm at top and bottom of the tie-column and at 200mm in the middle.

In buildings with flexible diaphragms, e.g. timber roofs, the width of tie-beams at the roof level exceeds the wall thickness, e.g. 200 or 250mm, to prevent the occurrence of an out-of-plane failure mechanism.

When any dimension in the building plan is longer than 20.0m, RC walls at least 1.0m long must be located at each end to avoid cracking in the masonry panels due to shrinkage of reinforced concrete slabs.

Generally, floor systems consist of cast-in-place RC slabs with a thickness between 100 and 120mm or precast slabs with large hollow-masonry blocks laid horizontally between precast RC beams. Usually, unreinforced concrete foundations are used, unless in the presence of soft soil conditions (e.g. clay or silty soil), RC plinths are used to reduce settlements.

Earthquake Performance

Seismic behavior of masonry buildings depends mainly on the quality of the materials (mortar and units) and the type, amount, and distribution of reinforcement. However, in recent years, it has become evident that the effect of the focal mechanism of the earthquake also plays an important role. In effect, intraplate intermediate depth earthquakes produced more damage due to high frequency content and higher amplification of seismic waves than subduction interplate earthquakes.

The 1939 Chillán earthquake, an intermediate depth intraplate earthquake, produced the collapse of almost all unreinforced masonry buildings built since the early twentieth century in the epicentral area of the earthquake. This situation has not been observed during interplate earthquakes, such as 1906 Valparaiso earthquake. 1928 Talca earthquake, 1960 earthquakes in southern Chile, or 1985 Llolleo earthquake, in which many low-rise unreintorced masonry buildings resisted the shaking and stand until today. Although unreinforced masonry buildings are not currently constructed, it is useful to study their behavior in order to establish the seismic demands for rigid and brittle buildings, such as masonry buildings, when a small amount of reinforcement is used.

More information on the seismic behavior of confined masonry structures during the most important Chilean earthquakes in the last 75 years is given below:

1939 Chillán earthquake. This earthquake corresponds to a subduction intermediate depth intraplate earthquake with a magnitude 7.8 and it was one of the most destructive events that occurred in Chile. According to a damage assessment conducted by a commission appointed by the government at that time, the observed behavior of one-story masonry buildings in Chillan, located in the epicentral area, is summarised as follows:

- Out of a total of 154 dwellings, confined masonry representing 4.5% of the total housing, 83 were in good condition, 49 were damaged, 5 are currently semi-destroyed and in use and 17 were totally destroyed, i.e. 54% experienced no damage. Figure 4 shows a house of this type currently in use.
- The adobe and unreinforced masonry brick houses, representing 86.8% of households in the city, were seriously affected. Regarding adobe houses, 764 were damaged, 177 semi-destroyed, 1240 demolished, i.e. out of a total of 2181 houses, l00% were affected and 57% of them were seriously damaged. This situation was similar for unreinforced masonry houses, resulting in 44% of 844 homes collapsed.

Fig. 4. Old confined masonry house currently in use in Chillán

1965 La Ligua earthquake. This earthquake corresponds to an intraplate earthquake of intermediate depth of magnitude 7.1 with the epicentre about 140km from Santiago. Again, the effects of the earthquake were severe in adobe and unreinforced masonry houses, the latter behaving particularly badly even though most of them were reinforced with concrete tie-beams at the top of the walls forming a horizontal grid. About 21,000 masonry houses collapsed and 71,000 had to be repaired. This was unexpected behavior for one-story masonry buildings; although most of them did not have tie-columns at ends of masonry panels and at wall intersections. The results were especially bad in houses made of hollow concrete blocks, units that started to be used in those years. Typical patterns of damage were: in-plane shear failure, cracks by out-of-plane flexure, vertical cracks by lack of bond between masonry and concrete elements, damage in beam-column joints and vertical cracking at wall intersections.

1971 Papudo earthquake. This event was an interplate earthquake of magnitude 7.5 which hit mainly the Region V of Chile, affecting practically the same zone of the

1965 La Ligua earthquake. Again, masonry houses were damaged and of particular interest was the case of the destruction of about 1,000 houses located in the valley of the Choapa River (see Figure 5). The walls of these one-story houses were built with hand-made clay bricks, reinforced at the top of the walls with RC beams and with some vertical tensile steel bars placed at the wall intersections, within holes perforated in the bricks. The effects of poor quality of soils and inappropriate design of the foundations made the damage more severe.

Fig. 5. Observed damage during 1971 Papudo earthquake.

1985 Llolleo earthquake. This event corresponds to an interplate earthquake of magnitude 7.8. Its effects extended from Illapel to Talca, causing 147 victims and 2,000 injured in an exposed population of six million people. In the housing sector, about 66,000 houses were destroyed and 127,000 were damaged, especially in rural area and old part of cities. For instance, in Melipilla city were 10,800 houses damaged, 7,560 of them were adobe houses, leaving 89% of the population homeless.

After the earthquake, the Ministry of Housing appointed a special committee to review the seismic effects on social dwellings. About 84,000 units were reviewed, mostly located in Santiago, concluding that 50% of them suffered structural damage. Confined masonry buildings represent 27% of the total housing reviewed and 74% (9,928 units) of them were slightly damaged, but no collapses occurred. Most of the masonry buildings with severe damage were three or four-story high and they did not have tie-columns at one wall end or around window openings. In many cases, the only reinforcement was one steel vertical bar located inside of a hollow unit which did not satisfy the minimum recommended by the reinforced masonry code UBC-1979. This occurred because prior to 1986, there was no Chilean design code for reinforced and confined masonry buildings.

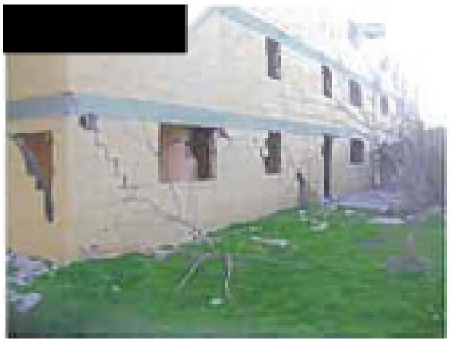
For this earthquake the observed damage included:

- Diagonal stepped bed-joint cracking in the masonry panel due to bad bond between mortar and units.
- Propagation of panel diagonal cracks into top and bottom of tie-columns.
- Crushing of hollow masonry units with a large percentage of voids and thin shells and webs in the most stressed zones of the masonry panel.
- Horizontal cracking at the joint between masonry wall and the RC floor slab or foundation.
- Cracking in walls due to out-of-plane seismic loads when the masonry panels were not properly confined or the separation between tie-columns was too large. Cracking, crushing and disintegration of concrete at the tie-beam/tie-column connections when reinforcement detailing was inappropriate.
- Inadequate quality of masonry materials (mortar, grout) and poor workmanship.

2010 Maule earthquake. Overall, the behavior of confined masonry buildings was very good in this M=8.8 interplate 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 of them suffered moderate to severe damage.

A few medium-rise confined masonry buildings of older vintages suffered moderate and repairable damage. For example, diagonal cracking in masonry walls was observed in four-story buildings in Huemul II complex, located in Santiago and built in 1947; the same damage occurred in the 1985 Llolleo earthquake and was subsequently repaired. Similar damage patterns were observed in the complex of four-story buildings called Roto Chileno (built in Santiago in 1960) and in the Costanera Norte complex,

Constitución



Santa Cruz

Fig. 6. Observed damage during 2010 Maule earthquake

built in Talca in 1956. The masonry walls of these old buildings were built using hand-made solid clay bricks and a low-strength mortar (cement:lime:sand mix ratio 1:1:6). In addition, RC tie-columns were provided only at wall intersections but not around the openings, thus these old buildings can be considered as "partially confined". Examples of severe damaged partially confined masonry buildings are shown in Figure 6.

On the other hand, some modern multi-story partially confined masonry buildings had an anticipated bad behavior and experienced significant damage at the ground floor level. For the first time in Chile, two three-story partially confined masonry buildings collapsed in an earthquake, causing the death of six adults and four children. Several complexes built with this type of masonry walls had to be demolished in different locations, such as Santa Cruz, Constitución, and San Antonio.

2014 Iquique earthquake. Although this was an 8.4 magnitude earthquake, in general damage was rather limited. Regarding confined masonry buildings, buildings with non-appropriate reinforcement located on non-competent soils suffered damage. For instance, in complex "Los Alelies" (5-story buildings), some partially confined walls were damaged specially in those buildings located in non-competent soils, and in Edificio Los Cóndores the damage occurred in short columns. In complex Dunas I, four story-high building experienced damage at the first floor due to the presence of a central opening without any confinement.

Lessons Learnt From Great Chilean Earthquakes

In summary, to limit damage caused by earthquakes in confined masonry buildings the following actions must be considered:

- Low resistance of the masonry and its variability makes necessary to control the wall density and quality of materials (unit and mortar). Based on the Chilean seismic experience, a wall density per unit of floor plan greater than 0.85 % on each direction is recommended
- The confining elements must be located close enough to avoid out-of-plane damage, especially when wall thickness is less than or equal to 150mm. Excessive spacing between tie-columns or lack of tie-beams may cause out-of-plane damage.
- Lack of tie-columns around window openings decreases the shear strength and the post-shear cracking displacement capacity. When the area of an opening is less than 5% of the masonry panel area and it is not located near to one end of the masonry panel, its effect can be ignored.
- It is recommended to include closer stirrups at both ends of tie-columns and a minimum cross sectional area of tie-column to avoid diagonal crack propagation that may appear at the masonry panel. These design details may reduce the level of damage and the strength or stiffness degradation of the wall, avoiding residual deformations difficult to repair.
- The detailing of reinforcement bars is essential in the zones where confinement elements meet and has been the

cause of bad behavior observed in many masonry houses since 1958.

- The vertical reinforcement bars placed inside vertical holes located at the ends of the masonry panels, in replacement of external concrete tie-column, has been ineffective. This type of reinforcement should not be used in masonry buildings with three or more stories.
- The lack of RC beams on the top of walls has caused severe damage, therefore it is recommended to use concrete tie-beams.
- The misbehavior of masonry walls built with hollow concrete blocks during all the Chilean earthquakes, since 1965, suggests that its use should be avoided. These walls suffer crushing after diagonal cracking takes place, causing significant post-cracking strength and stiffness degradation.
- The construction phase is very important and must be inspected. In this way, the concrete of tie-columns must be poured against a toothed vertical side of the masonry panel to integrate the slender tie-columns with the masonry panel and ensure an appropriate joint between them. The placement of concrete must be made very carefully due to small dimensions of confining elements. The construction sequence of confined masonry walls helps the inspection of reinforcement placement at different construction stages, since the use of steel bars and concrete is limited only to confining elements. This is an advantage compared to other building technologies, e.g. reinforced masonry.

First part of "Improving Housing Seismic Safety in Developing Countries: The World Housing Encyclopedia"

By A. Charleson, S. Brzev, K. Jaiswal and M. Greene. Presented in Paper No. 1239 from the 16th World Conference on Earthquake Engineering, Santiago Chile, January 9th to 13th 2017.

Abstract

The World Housing Encyclopedia (WHE), a joint project by EERI and IAEE, is reliant upon the contributions of volunteers who are committed to improving the knowledge base of housing construction practices in seismically active areas of the world. The mission of the WHE is to disseminate information about different housing construction types and encourage the use of earthquake-resistant technologies worldwide. Despite limited resources, the committed, skilled, and experienced WHE contributors have produced materials that are making a difference. The two primary initiatives of the WHE, a worldwide database of housing types and select predominant building type-specific guidelines and tutorials, are described in this paper. In addition to information about each of the WHE's main publications, their effectiveness and potential readership are also discussed. With these new developments and the impact that they have created over the years, the WHE is in an unique position to start thinking about the following questions:

- What are the pressing needs for improving the seismic safety of buildings in developing countries that could benefit from the WHE involvement?
- Where are the gaps in the current resources offered by the WHE?
- The WHE publications fall in the category of technical guidelines. Are there other areas of focus that might be more effective, such as helping prepare materials to raise public awareness for the need of better building standards?
- What other forms of assistance might the WHE be able to provide to improve seismic safety in developing countries?

The answers to these questions, along with the knowledge gathered through the process thus far, illustrate the many opportunities for the WHE and organizations with similar goals to improve the seismic safety of houses in developing countries.

Introduction

The World Housing Encyclopedia (WHE) initiative was launched in 2000 at the 12th World Conference on Earthquake Engineering held in Auckland, New Zealand. The overall vision of the WHE is to increase the seismic resilience of housing in developing countries. It continues to be a volunteering effort involving more than 200 earthquake engineering professionals from around the globe. Launched as an initiative of the

Earthquake Engineering Research Institute (EERI) and the International Association for Earthquake Engineering (IAEE), it continues to be sponsored by both organizations. The WHE initiative is overseen by a voluntary Executive Committee, which is supported by an EERI staff member and all other work is done by volunteers who contribute their time and expertise to grow the WHE repository. The original aim of the WHE was to develop a repository of world housing construction typologies. This task is well advanced with reports on approximately 160 housing types from 42 countries and territories. In the last few years, there has been an ongoing effort to produce tutorials for improving seismic safety of construction technologies that were identified to be most vulnerable and were covered in the housing reports. These tutorials are mainly related to non-engineered construction, and are intended to be used by a broad audience, including builders, architects, engineers, government officials, and homeowners.

The primary resource of the WHE is an online database that contains a detailed description of housing construction types from around the world. Reports of each type are presented using a standardized format. All relevant aspects of housing construction such as socio-economic issues, architectural features, structural systems, seismic deficiencies and earthquake resistant features, performance in past earthquakes, available strengthening technologies, building materials used, construction process and insurance, are covered in each report. In addition to the text and numerical information, several illustrations (photos, drawings, sketches) are also included. In 2015 an option for a short report was developed, to encourage more submissions. Submissions for both types of reports continue to be enthusiastically accepted. The reports aim to provide substantive in-depth understanding of various construction types and their relative vulnerability to earthquakes. For some construction types, this is one of the few, if not the only source of such detailed information in English. The framework created by this project provides an inexpensive and effective way for earthquake professionals in many countries to share knowledge on construction practices and retrofit techniques. The database, or encyclopedia as it is called, is an entirely on-line resource, accessible and free for anyone at www.world-housing.net. A summary publication of housing reports in 2004 gathers together reports of similar construction types for comparative purposes.

In addition to this housing database, a range of other on-line resources, known generically as 'Tutorials', have been developed. As of this writing, several tutorials related to improving seismic resistance of various construction technologies based on the best practices from various countries, are available on the web site. Some of these tutorials, such as the tutorial on adobe construction, are available in multiple languages (Spanish and English). Also concentrating on the needs of developing countries, a tutorial on reinforced concrete frame buildings was developed. This tutorial highlights the deficiencies associated with inadequately engineered RC frame construction which showed poor performance in the aftermath of the 1999 Turkey and Taiwan earthquakes and the 2001 Bhuj, India earthquake. Translated into Indonesian and Spanish, it addresses the technical challenges that this type of construction presents. Although used very extensively world-wide, masonry infill construction contains significant inherent flaws that are all too often exposed by damaging earthquakes. A tutorial on the construction and retrofit of stone buildings, was used as a reference by professionals interested in improving seismic safety of rural stone masonry dwellings after the 2015 Gorkha, Nepal earthquake.

(continued in the next issue...)

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

The Centre is a non-profit organisation based at the School of Architecture, Victoria University of Wellington, New Zealand.

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