Seismic Performance of Confined Masonry Buildings in the February 27, 2010 Chile Earthquake

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Background

- Magnitude 8.8 earthquake
- 521 deaths
- 5 collapsed buildings
- 100 severely damaged buildings
- Approximately 1% of the total building stock in the earthquake-affected area either damaged or collapsed
Note: The superimposed rectangle has dimensions 600 km by 200 km.
Seismic Intensity Map (MSK Scale)

- Santiago
- Rancagua MSK 6.5
- Talca MSK 8.0
- Constitucion MSK 9.0
- Cauquenes MSK 8.0
- Santa Cruz MSK 7.5

Paper by Astroza et al.
EERI web site Chile eq.
Over 12 million people were estimated to have experienced shaking of MMI intensity VII or stronger (about 72% of the total population of Chile).

Source: PAGER (USGS)
Confined Masonry (CM) Construction in Chile

- Widely used for construction of low-rise single family dwellings (up to two-storey high), and medium-rise apartment buildings (three- to four-storey high).

- CM construction practice started in the 1930s, after the 1928 Talca earthquake (M 8.0).

- Good performance reported after the 1939 Chillan earthquake (M 7.8) and this paved the path for continued use of CM in Chile.

- The area affected by the Maule earthquake was exposed to several major earthquakes in the past, including the 1985 Llolleo earthquake (M 7.8).
Confined Masonry Construction in Chile (Cont’d)

- Good performance track record in past earthquakes based on single family (one- to two-storey) buildings.

- Three- and four-storey confined masonry buildings exposed to severe ground shaking for the first time in the February 2010 earthquake (construction of confined masonry apartment buildings in the earthquake-affected area started in 1990s).

Modern masonry codes first issued in 1990s – prior to that, a 1940 document “Ordenanza General de Urbanismo y Construcción” had been followed.
Seismic Performance of Confined Masonry Construction

- By and large, confined masonry buildings performed well in the earthquake.

- Most one- and two-storey single-family dwellings did not experience any damage, except for a few buildings which suffered moderate damage.

- Large majority of three- and four-storey buildings remained undamaged, however a few buildings suffered severe damage, and two three-storey buildings collapsed.
Confined Masonry Buildings: Key Components
Confined Masonry: Key Components

- **Masonry walls** – built using a variety of masonry units with a typical thickness of 140 mm

- **Tie-columns** - vertical RC confining elements at 3 to 3.5 m spacing

- **Tie-beams** - horizontal RC confining elements provided at the floor/roof level (typical floor height 2.2 to 2.3 m)
Confined Masonry: Key Design Provisions

Masonry Units

Hollow clay blocks
Clay bricks
Concrete blocks
Confined Masonry: Construction Sequence

Foundation construction, showing RC tie-column reinforcement
Confined Masonry: Construction Sequence

Masonry wall construction in progress
Toothed Masonry Construction: Toothed at the Wall to Tie-Column Interface

Toothed enhances interaction between masonry walls and RC confining elements.
Steel Reinforcement

Common steel grades:

- A44-28H: yield strength 280 MPa
- A63-42H: yield strength 420 MPa
- AT56-50H: high-strength steel used for tie-beam and tie-column prefabricated reinforcement cages and ladder reinforcement (yield strength 500 MPa)
Steel Reinforcement Cages: Examples
Floor Systems

- Wood floors in single-family buildings (two-storey high)
- Concrete floors in three-storey high buildings and up (either cast-in-situ or precast)
- Precast concrete floors consist of hollow masonry blocks, precast RC beams, and concrete overlay (“Tralix” system)
“Tralix” Floor System
“Tralix” Floor System (Cont’d)
Timber Roof Trusses (Typical)
Low-Rise Confined Masonry Construction

Single-storey rural house
Two-storey townhouses (semi-detached): small plan dimensions (5 m by 6 m per unit)
Typical Damage Patterns in Low-Rise Buildings

Horizontal crack at the timber gable-to-masonry wall interface
Typical Damage Patterns in Low-Rise Buildings

In-plane shear cracking in masonry piers (note absence of tie-columns at the openings)
Medium-rise Confined Masonry Buildings
Damage Patterns

Typical damage patterns:

- in-plane shear failure of masonry walls, and
- damage to the RC confining members

(particularly tie-columns)
In-Plane Shear Cracking: a Case Study from Santiago

- Typical four-storey buildings in Santiago
- Recorded PGA approx. 0.3g
In-Plane Shear Cracking (ground floor level)
In-Plane Shear Cracking (third floor level)

Another building in the same complex (damage occurred at the third floor level only)
In-Plane Shear Cracking: Damage Pattern at the Third Floor Level
In-Plane Shear Cracking – the Effect of Confinement

Non-confined openings

Confined openings
In-plane shear failure of masonry walls at the base level - hollow clay blocks (Cauquenes)
In-plane shear failure of masonry walls at the base level (cont’d)
In-plane shear failure: hollow clay block masonry
In-plane shear failure: clay brick masonry
In-plane shear failure: hollow concrete blocks
Out-of-Plane Wall Damage

- An example of out-of-plane damage observed in a three-storey building
- The damage concentrated at the upper floor levels
- The building had concrete floors and timber truss roof
- The same building suffered severe in-plane damage

Damage at the 2nd floor level
Out-of-Plane Damage (cont’d)

Damage at the 3rd floor level
Buckling of a RC Tie-Column due to the Toe Crushing of the Masonry Wall Panel
Tie-Column Failure
Shear Failure of RC Tie-Columns
Causes of Damage

1. Inadequate wall density
2. Poor quality of masonry materials and construction
3. Inadequate detailing of reinforcement in confining elements
4. Absence of confining elements at openings
5. Building layout issues
6. Geotechnical issues
1. Inadequate Wall Density Index

\[ d = \frac{A_w}{nA_p} \]

Low \( d \) values (0.5 to 0.7 \%) observed in severely damaged/collapsed buildings (\( n \) denotes number of floors)
2. Poor Quality of Masonry Materials and Construction
3. Inadequate Anchorage of Tie-Beam Reinforcement
3. Inadequate Anchorage of Tie-Beam Reinforcement (another example)
3. Tie-Beam Connection: Drawing Detail

Tie-Beam Intersection: Plan View

Tie-Beam Intersection: Plan View

CRUCE T

2+2 Ø 8.0 L=100

CRUCE L

3+3 Ø 9.2 L=100

SLO DONDE SE INDICA
3. Tie-Column-to-Tie-Beam Connection: Drawing Detail
(prefabricated reinforcement)

Note additional reinforcing bars at the tie-beam-to-
tie-column joint

(in this case, prefabricated reinforcement cages were used for tie-beams and tie-columns)
3. Tie-Column-to-Tie-Beam Reinforcement: Anchorage

Alternative anchorage details involving $90^\circ$ hooks (tie-column and tie-beam shown in an elevation view) - note that no ties in the joint area were observed.
3. Deficiencies in Tie-Beam-to-Tie-Column Joint Reinforcement Detailing
3. RC Tie-Columns: Absence of Ties in the Joint Area
3. Tie-Column Reinforcement: Drawing Detail

- Note prefabricated tie-column reinforcement: 8 mm longitudinal bars and 4.2 mm ties at 150 mm spacing
- Additional ties to be placed at the site per drawing specifications
4. Absence of Confining Elements at the Openings
4. Absence of Confining Elements at the Openings

(another example)
5. Effect of Building Layout: Four Buildings in Cauquenes

Severely damaged building
5. Effect of Building Layout: Four Buildings in Cauquenes (cont’d)

Moderately damaged buildings
Multi-storey Confined Masonry Buildings: Soft Storey Collapse Mechanism
Engineered Confined Masonry Buildings – Evidence of Collapse

- Two 3-storey confined masonry buildings collapsed in the February 2010 Chile earthquake (Santa Cruz and Constitución)

- Most damage concentrated in the first storey level
Building Complex in Constitución: Three-Storey Confined Masonry Buildings

Note a steep slope on the west and north sides!
Three Building Blocks: A, B and C

A  
	damaged

B

collapsed

C
Building Plan – Collapsed Building

RC Tie-Columns:
P1 = 15x14 cm
P2 = 20x14 cm
P4 = 15x15 cm
P5 = 70x15 cm
P6 = 90x14 cm
Building C Collapse

Building C collapsed at the first floor level and moved by approximately 1.5 m towards north
Building C Collapse (cont’d)

approx. 5 meters
Probable Causes of Collapse

1. Geotechnical issues: a localized influence of the unrestrained slope boundary and localized variations in sub-surface strata might have generated localized variations of horizontal (and possibly vertical) ground accelerations

2. Inadequate wall density (less than 1% per floor)
Collapse of a Three-Storey Building in Santa Cruz
Collapsed Three-Storey Building
Soft Storey Collapse
(ground floor missing)
Probable Causes of Collapse

- Poor quality of construction (both brick and concrete block masonry)
- Low wall density (less than 1% per floor)

Note: only one (out of 32) buildings in the same complex collapsed!
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