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Confined Masonry Construction
PAGER Structure Type RM3
WHE-EERI Structure Class 10

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Research Scope

Within this study, "confined masonry" is distinguished from masonry infill walls. With masonry infill wall construction, the reinforced concrete frame is constructed prior to the masonry infill. CM construction consists of assembly of the masonry wall *first*, followed by pouring of the confining elements. CM specifically experiences both flexural and shear deformations, while a masonry infill wall deforms in a shear mode within a frame that deforms in flexure, resulting in separation of the frame and infill wall (Alcocer and Meli 1995). This study considers CM construction only.

This study includes experimental results of CM walls with unreinforced wall panels. If desired, numerous experimental results exist of CM with panel reinforcement. Similarly, numerous investigations have been undertaken to improve typical CM structures through innovative retrofit schemes. These studies have not been included. The focus of this literature review was to characterize typical CM building performance. Emphasis was placed on common construction practices, not necessarily code-designed or engineered structures. CM construction is widespread globally, but is particularly prevalent in Mexico, Central and South America. For this reason, the majority of investigations considered herein are from these locations.

Throughout Latin America, in typical suburban locations CM structures are typically single-family dwellings of two stories. In urban environments, multi-family structures up to 5 stories are widespread. Thus, this investigation considers the behavior of 1-5 stories. Numerous types of masonry units are used throughout Latin America, and globally. These include solid and hollow concrete block, solid and hollow clay brick, sand-lime block, pumice, ceramic, and clay tile, amongst others. The most prevalent type of masonry units used in CM construction in Latin America, and which this study considers, is hollow concrete block and hand- and machine-made solid clay brick.

Low-height CM residential structures loaded lightly, with large wall densities, and with regular elevations and floor plans have historically performed well throughout Latin America. Poor seismic performance is noted when plan irregularities are severe and material and construction deficiencies exist. The primary mode of failure, however, is soft-story formation as a consequence of deterioration of the first-floor masonry panels due to inclined cracking. Injuries and deaths are sustained commonly by out-of-plane failure of masonry walls, or individual masonry units. Complete collapse or "pancaking" of the ground floor is uncommon.

Confined Masonry Materials and Distribution

Geographic prevalence of masonry unit types in Latin America:[1]

	Chile	Colombia	Costa Rica	Guatemala	Mexico	Nicaragua	Peru
Conc. Block	1	1	1	1	1	1	2*
Conc. Brick		2*			1*		2*
Clay Block	1	2	2	2	1	2	
Clay Brick	1	1	1	1	1	1	1*
Sand-Lime		2*			2*		1*

(1) Widely used, (2) Limited use
* This information is assumed based on the reported distribution of all masonry construction types (i.e., not merely confined masonry).[2]

Typical concrete block and solid clay brick strength values by country, as well as Seismic Reduction values:

Country	Brick/ Block	Masonry Shear Str., v_m	Masonry Compr. Strength, f_m	Seismic Reduction Factor, R [3]
Chile [4]	Clay Br.	0.78 MPa	3.0 MPa	4-5
	Conc. Bl.	0.66	9.0	
Colombia [5]	Clay Br.	0.9	13.0	2.5
	Conc. Bl.	0.66	8.0	
Mexico [6]	Clay Br.	0.65	2.5	Q = 2
	Conc. Bl.	0.57	7.0	
Peru [7]	Clay Br.	0.80	6.0	2.5 low axial
	Conc. Bl.	0.75	10.0	1.8 large axial

Additional information available but not shown, for different countries: [1]

[1] Yamin, et al, 1994.
[2] Casabone, 1994.
[3] Bariola, 1994.
[4] Hidalgo, 1994.
[5] Garcia and Yamin, 1994.
[6] Meli, 1994.
[7] Gallegos, 1994.

- Typical masonry unit dimensions
- Typical volume proportions and properties of mortar types

Typical Reinforcement Types: [1]

- Deformed Steel Reinforcing Bars: typically these bars have a minimum specified yield strength of 420 MPa (60 ksi) with diameters from 9 to 25.4 mm (3/8 to 1 in).
- Deformed Reinforcing Wires/Wire Fabric: typically have minimum specified strength of 525 MPa (75 ksi).
- Plain Bars and Wires: typically available in 6.5 and 9.5 mm (1/4 and 3/8 in) diameter usually of Grade 40 steel (280 MPa). These wires are typically cold-worked and are therefore very fragile
- Typical longitudinal reinforcement includes four bars in each confining element.
- Transverse reinforcement is common and typically uniformly spaced (amount unknown). In some countries there is a concentration of transverse reinforcement at column ends (e.g., Peru).

General Research Findings

- Importantly, nearly all experimental investigations considered in this investigation ceased testing before specimens reached a complete damage state. What experimenters describe as "ultimate" performance typically corresponds to 80% of peak strength; a handful report to 85% strength. We are aware of no investigations in literature that brought specimens to actual collapse or global instability.
- Summary of parameters that influence the performance of CM walls under in-plane lateral cyclic loading:[2]
  - Type of brick unit.
  - Horizontal steel reinforcement: the inclusion of steel bars along the horizontal mortar joint and fixed at the tie-end columns increases lateral loading capacity at first cracking and lateral shear strength. Horizontal steel reinforcement also increases lateral deformation capacity at lateral strength, beginning when first-cracking commences.
  - Vertical compressive stress: as axial compression increases, lateral loading capacity at first cracking and lateral strength increases (for hand- and machine-made clay, and concrete bricks). However, increase axial compression diminishes wall deformation capacity for machine-made bricks (measured from the lateral drift at first cracking to that corresponding to the lateral strength).
  - Aspect ratio: flexural deformation (and failure) becomes important at aspect ratios larger than 1.0. Lateral loading capacity at first cracking and lateral strength decreases with more slender walls. However, no clear relationship exists between the aspect ratio and lateral deformation capacity.
- Another study found that cracking strength is nearly independent of the amount of interior reinforcement; thus, the wall capacity depends on the masonry unit shear strength, mortar shear strength, and vertical compressive stress.

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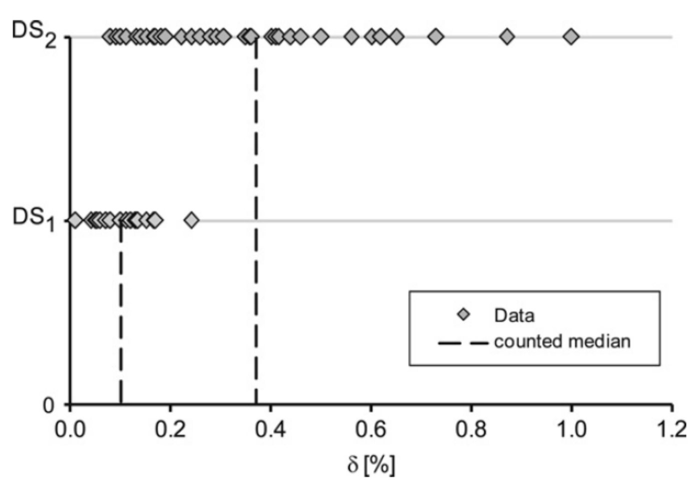
[1] Yamin, et al, 1994.
[2] Ruiz-Garcia & Negrete, 2009.

- Initial stiffness appears to be independent of amount and type of horizontal wall reinforcement. Nonetheless, horizontally reinforced specimens dissipate more post-cracking energy than unreinforced wall panels.
- Database results suggest that the maximum shear strength is on average, 1.3 times the cracking strength of panels due to post-cracking contribution of tie columns acting in confinement.
- The amount of tie-column longitudinal reinforcement has proven insignificant to ultimate deformation capacity.[1]
- Ultimate drift ratio for specimens with horizontal wall reinforcement are equal or higher than 0.008, but for unreinforced specimens the average value is 0.006.
- The wall density per unit weight per floor is a good indicator of the expected seismic behavior. CM building capacity depends on wall density per unit weight per floor and on shear wall coupling type. Based on observed damage from past earthquakes, a wall density per unit weight per floor less than 0.008 m^2/ton (0.0056 psi) indicates the onset of heavy damage.[2]
- R = 1.8 for walls with no horizontal reinforcement and with large axial load, = 2.5 for unreinforced walls with low axial load, = 2.5 for horizontally reinforced walls. This is based on the equal energy principle, as calculated by San Bartolome, et al.

Summary of Select Experimental Investigations

A statistical study by Ruiz-Garcia and Negrete examined 118 in-plan wall experiments and produced fragility functions for two damage states, 1) DS1, the beginning of diagonal cracking (i.e., yield), and 2) DS2, at maximum load capacity. Their results account for brick type, horizontal steel reinforcement, vertical loading, and wall aspect ratio. The brick types considered include hand- and machine-made solid clay bricks, and machine-made concrete block. This investigation also reported the central tendency and logarithmic standard deviation for each brick and configuration type (see table below). Shown below is the distribution of lateral drift corresponding to DS1 and DS2 for hand-made clay brick with no reinforcement (Figure 2, Ruiz-Garcia & Negrete, 2009):



[1] Riahi, et al 2009.
[2] Moroni, et al 2000.

Statistical parameters of drift capacity corresponding to DS1 and DS2 for CM walls built with three types of brick units; β_s represents the specimen-to-specimen epistemic uncertainty (Table 6, Ruiz-Garcia & Negrete, 2009):

Brick type	Condition	Damage state	$\mu_{\ln \delta}$ (%)	β_s	Number of specimens (n)
Hand-made clay brick	1	DS_1	0.09	0.46	44
		DS_2	0.31	0.67	43
	2	DS_1	0.17	0.30	17
		DS_2	0.54	0.29	17
	5	DS_1	0.08	0.38	14
		DS_2	0.25	0.94	10
Industrialized clay brick	1	DS_1	0.11	0.84	27
		DS_2	0.30	0.62	27
	2	DS_1	0.07	0.80	12
		DS_2	0.36	0.74	12
	3	DS_1	0.16	0.66	15
		DS_2	0.27	0.50	15
	4	DS_1	0.07	0.49	17
		DS_2	0.61	0.62	17
	5	DS_1	0.05	0.24	9
		DS_2	0.61	0.69	9
Concrete block	1	DS_1	0.09	0.69	66
		DS_2	0.37	0.52	58
	2	DS_1	0.09	0.69	31
		DS_2	0.36	0.58	31
	3	DS_1	0.10	0.68	35
		DS_2	0.39	0.44	27
	4	DS_1	0.11	0.84	12
		DS_2	0.31	0.36	12
	5	DS_1	0.11	0.87	9
		DS_2	0.30	0.39	9

1 – Specimens without $\rho_h = 0$ (tested with and without vertical compressive stress); 2 – specimens with $\rho_h = 0$ and $\sigma_v = 0$; 3 – specimens with $\rho_h = 0$ (tested with vertical compressive stress); 4 – specimens with horizontal steel reinforcement (tested with and without vertical compressive stress); 5 – specimens with horizontal steel reinforcement (tested without vertical compressive stress).

In another stastical study, Riahi, et al (2009) compiled results from 102 experiments throughout Latin America. They considered single wall, in-plane tests loaded monotonically and reverse-cyclically. Through regression analysis they derived equations for the shear strength and deformation at cracking, maximum, and ultimate damage levels; ultimate was defined as 80% peak strength. These equations account for vertical loading (i.e., story height), masonry shear and compressive strength, reinforcement ratio and concrete strength of the confining elements, and masonry unit type. These equations were coupled with mechanical properties of typical CM construction materials by country to produce plots of 1, 2, and 4 story structures in select countries.

Rodriguez (2004) examined the results of nine experimental tests on confined solid clay brick masonry. Each of these specimens was subjected to in-plane, reversed cyclic loading, and were tested in Mexico, Chile, and Colombia. Aspect ratios varied from 0.8 to 1.4; five of the nine specimens were 1.0. Longitudinal reinforcement ratios also varied. From the hysteresis cycles, the maximum strength was identified; collapse was taken as 80% of peak strength. The average value of interstory drift reported by this compilation study is 0.0052 with a coefficient of variation of 0.08.

Numerous studies are available that report typical drift values for each performance level. These studies commonly provide a statistical compilation of a number of experimental tests, yet typical force values are not reported alongside the drift values. One study in particular reported median drift values based on 52 experimental tests of ceramic brick and concrete block; reinforced walls were included. The median drift value for concrete block at maximum and ultimate (i.e., 80% of peak strength) performance levels is 0.0012 and 0.0049, respectively. These values are conservative with respect to other results reported in this investigation.

Parameter Selection for Conversion from Base-Shear to Spectral Space

Confined masonry structures are very similar in construction and performance as the HAZUS-defined structure type C3:[1]

This is a "composite" structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the concrete frame "braced" by the infill acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate (due to compression failure of the masonry "struts") and the frame loses stability, or when the concrete columns suffer shear failures due to reduced effective height and the high shear forces imposed on them by the masonry compression struts.

For comparison, HAZUS parameters are shown for both C3 and URM structures.

Description	HAZUS Label	Stories	Period T_e (sec)	Modal Weight α_1	Modal Height α_2	Ductility μ^*
Concrete Frame w/URM Infill	C3L	1-3	0.35	0.75	0.75	5.0
	C3M	4-7	0.56	0.75	0.75	3.3
URM Bearing Walls	URML	1-2	0.35	0.50	0.75	5.0
	URMM	3+	0.50	0.75	0.75	3.3

Values selected for low/pre-code (identical)
Values taken from HAZUS-MH MR-3, Tables 5.5 and 5.6

In HAZUS, the effective mass and height factors, α_1 and α_2 are both taken to be 0.75 for both C3 and URM structures, as shown in the table above. However, these modal factors presented in Table AppIB-7 of the SEAOC Blue Book and discussed in Robert Englekirk's text appear more refined and accurate for the structures we are considering (i.e., 1, 2, and 3+ stories).[2] Thus, our calculations reflect selection of the Blue Book parameters for a displacement shape similar to *Shape 1* (see Table AppIB-7, SEAOC Blue Book). While this deflected shape is intended for a moment frame system, it also reflects the failure mechanism we are considering: damage concentration at the first level (i.e., soft story). Based on available experimental results – which assume, test for, and report damage to the first

[1] NIBS & FEMA HAZUS-MH MR3, 2003.
[2] SEAOC, 1999 & Englekirk, 2003.

level – our calculations account for wall displacement at the first level only. Hence, the effective height is taken to be a single story. The effective mass reflects the height the investigators intended to replicate. In other words, if a single wall was tested and vertically loaded to represent a 4-story structure, then the effective mass reflects a 4-story structure while the effective height remains at 1-story.

To be consistent with use of the Blue Book's parameters, we have also used the effective mass parameter, "k3" which corresponds to *Shape 1*. The modal factors used in this investigation are as follows:

# Stories	Effective Height Factor, k1	Effective Mass Factor, k3
1	1.0	1.0
2	0.83	0.90
3	0.78	0.85
4	0.75	0.85
5	0.73	0.85

For comparison, HAZUS has identified the following spectral coordinates for the capacity curve formation for C3 and URM structures. In general, these values agree with findings from this investigation (see spectral plots). Ultimate drift values appear larger than what we found, however, most experimental tests defined ultimate or collapse as 80% of peak strength.

Low/Pre-Code Design (identical) (Tables 5.7c and d):

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	Dy (in)	Ay (g)	Du (in)	Au (g)
C3L	0.12	0.100	1.35	0.225
C3M	0.26	0.083	1.95	0.188
URML	0.24	0.200	2.40	0.400
URMM	0.27	0.111	1.81	0.222

Table of κ values used by HAZUS for URM and C3 for low- and pre-code design (Table 5.18, HAZUS-MH MR3 Technical Manual, 2003):

Building Type			Low-Code Design			Pre-Code Design		
No.	Label	Description	Short	Moderate	Long	Short	Moderate	Long
22	C3L	Concrete Frame with	0.5	0.3	0.1	0.4	0.2	0.0
23	C3M	Unreinforced Masonry	0.5	0.3	0.1	0.4	0.2	0.0
24	C3H	Infill Walls	0.5	0.3	0.1	0.4	0.2	0.0
34	URML	Unreinforced Masonry	0.5	0.3	0.1	0.4	0.2	0.0
35	URMM	Bearing Walls	0.5	0.3	0.1	0.4	0.2	0.0

Summary of Parameters for use with HAZUS

HAZUS Parameter	Definition	Notes from this investigation
Dy	displacement at yield point of capacity curve in displacement spectra space	"Yield" was typically defined and chosen as first diagonal cracking
Ay	acceleration at yield point of capacity curve in displacement spectra space	
Du	displacement at ultimate point of capacity curve in displacement spectra space	"Ultimate" or "Collapse" was typically defined by experimenters at 80% peak strength
Au	acceleration at ultimate point of capacity curve in displacement spectra space	
Sdc	Damage-State Median spectral displacement at collapse	
BE	Small-displacement elastic damping ratio	Some tests indicate 4%; more info sought
kshort	Degradation factor associated with short-duration shaking, corresponding with $M \leq 5.5$	0.4 (see HAZUS Table 5.18 excerpt)
kmed	Degradation factor associated with medium-duration shaking, corresponding with $5.5 \leq M \leq 7.5$	0.2
klong	Degradation factor associated with long-duration shaking, corresponding with $7.5 \leq M$	0
L15	Fraction of indoor occupants killed, given collapse	n/a
θ 14	Median spectral displacement at which structural component enters complete damage state	Approximately 1.0 in, but tests typically not brought to complete damage
β 14	Logarithmic standard deviation of spectral displacement at which structural component enters complete damage state	Beta values available for yield & max
Pc	Fraction of buildings (by area) in complete damage state that collapse	n/a
Natural Period	T= 2*pi*(disp/acc*g)^1/2; Through experimental or period obtained through dynamic modeling	Chilean structures measured in field: median elastic T = 0.098s & 0.157s for 3 & 4 story
Ductility Factor	μ = Ratio between max displacement and yield displacement	μ = 3-6 from experimental wall tests
Strength Reduction Factor	R = (mu-1)*(T/Tc)+1, if T < Tc R = mu if T >= Tc Tc - Chara. Period of ground motion e.g., 0.6-0.7 s	Published values reported by country; Tc not considered at this time
Failure Mode	Describe it: For example, out-of-plane failure, Pancake, Failure in Torsional mode or any other mechanism (also refer fig 1-4 in data spreadsheet)	In-plane wall tests forced shear failure of wall panels and RC columns; pancake mechanism.

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