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SEISMIC BEHAVIOUR AND DESIGN OF CONFINED MASONRY BUILDINGS: A REVIEW

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ABSTRACT

Confined masonry (CM) is a construction system which consists of masonry wall panels enclosed by vertical and horizontal reinforced concrete confining elements. The presence of these confining elements distinguishes CM from unreinforced masonry system and makes this technology suitable for the construction of structures in regions subjected to intense seismic or wind actions. The technology has been applied in many countries and has been adapted to meet local construction practices and needs. The purpose of the paper is to review past research studies related to the behaviour of confined masonry and the main contributions towards the understanding and characterization of the performance of the CM structures subjected to the effect of axial loading, bending and shear due to in-plane and out-of-plane lateral loading. The paper analyzes the key parameters which were considered in past research studies and discusses their influence on seismic behaviour of CM buildings. Needs for future research related to CM structures are identified.

KEYWORDS: *confined masonry, in-plane shear behaviour, in-plane flexural behaviour, out-of-plane resistance, walls with openings, seismic design*

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INTRODUCTION

Confined masonry (CM) construction technology has evolved over the last 100 years through an informal process based on its satisfactory performance in the 1908 Messina, Italy earthquake, and is currently practiced in many regions, including Latin America, Europe, Middle East, and Far East. CM system consists of loadbearing masonry walls which are constructed first, one floor at a time, followed by the cast-in-place reinforced concrete (RC) tie-columns. Finally, RC tie-beams are constructed on top of the walls, simultaneously with the floor/roof slab construction. Horizontal and vertical RC confining elements (tie-beams and tie-columns) provide confinement to masonry walls and significantly contribute to their lateral load resistance. There are specific rules regarding the placement and spacing of RC confining elements in a CM building. For example, RC tie-columns should be provided at wall intersections, door and window openings, free ends of the walls, and at intermediate locations in long walls. A review of international seismic design codes and guidelines for CM buildings is presented in [1]. The evidence from past earthquakes reported good performance of CM structures which were designed and constructed according to the codes [2, 3]. Although CM buildings experienced damage in major earthquakes, such as the 2010 Maule, Chile earthquake (M 8.8), collapse of these buildings is rare and the number of fatalities and overall losses are small given the earthquake intensity [4]. The authors believe that CM technology provides a viable alternative to inadequately engineered infilled RC buildings and unreinforced masonry construction for low- to mid-height buildings in countries and regions with high seismic hazard.

The purpose of this paper is to review past research studies related to the behaviour of CM structures subjected to effects of axial loading, flexure and shear due to in-plane and out-of-plane lateral loading. The paper discusses relevant parameters which were identified in past research studies and their influence on seismic behaviour of CM buildings. This paper complements previous review studies on the seismic behavior of CM structures which were focused on European experience and code development (e.g. [5]) and presents key research evidence from Latin American countries from the 1960s to date. The paper is focused on engineered CM structures, which have been designed according to the codes and guidelines, as opposed to non-engineered CM structures which are constructed without engineering input and are found in many countries.

IN-PLANE SHEAR BEHAVIOUR

The most common lateral load-resisting mechanism for CM walls is diagonal tension shear failure mechanism, as confirmed by previous experimental studies on CM walls subjected to lateral loads [6]. This mechanism is characterized by the development of inclined cracks in masonry walls which propagate into RC tie-columns before the imminent failure [2] (Figure 1). It is important to note that some codes, e.g. Méxican [7] and Perúvian [8], define the shear strength of CM walls without horizontal reinforcement as the strength at the onset of diagonal cracking, while the maximum shear strength (which takes into account reinforcement contribution) is used for walls with horizontal reinforcement. The diagonal tension shear strength is usually determined as the sum of several components, including the masonry τ_m, the axial stress τ_p, and the horizontal reinforcement τ_s, as follows

$$\tau_R = \tau_m + \tau_p + \tau_s \tag{1}$$

Masonry component

The masonry contribution can be presented as follows

$$\tau_m = a v_m f \tag{2}$$

Where a is an empirical constant, v_m is the diagonal compression strength, and f is a factor that takes into account the wall's height-to-length (*H/L*) ratio (aspect ratio). The notion that the shear strength of a wall at the onset of cracking is related to the masonry tensile strength and the applied axial stress was proposed based on the stress analysis at the centre of a wall [9]. In walls without axial compression, the shear strength depends only on the masonry tensile strength. The empirical constant a is determined from experimental studies and is usually in the range from 0.3 to 0.5. The shear strength v_m is obtained from diagonal compression tests and is a function of $\sqrt{f'_m}$, where f'_m is specified compressive strength of masonry.

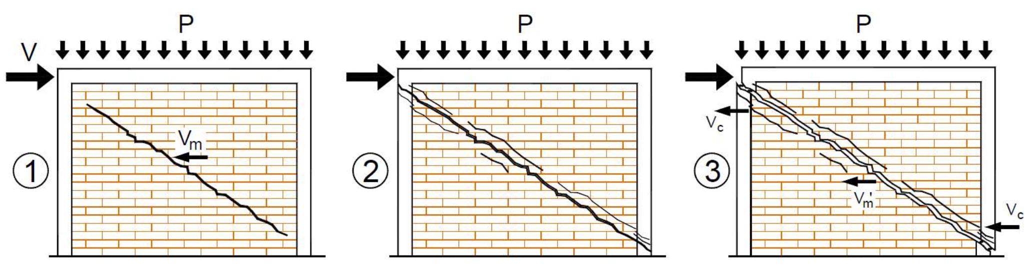

Figure 1: Mechanism of shear resistance for a CM wall panel: 1) the onset of diagonal cracking; 2) diagonal cracks have propagated from the wall into the tie-columns, and 3) shear failure of the CM wall panel [2]

<u>*The effect of wall aspect ratio*</u>

The general form of the equation used to determine f factor, which takes into account the effect of aspect ratio, can be presented as follows

$$f = \left(b + c \cdot \frac{M}{VL} \right) \qquad \frac{M}{VL} < 1 \tag{3}$$

Where b and c are empirical constants determined from experimental studies and M/VL is the shear span ratio, in which M is the internal moment at the specific section being analyzed, usually at the base of the wall, V is the shear force, and L denotes the wall length.

By analyzing data from the past experimental studies on walls with different aspect ratios *(H/L)*, Alvarez concluded that the shear strength increased with a decrease in the wall aspect ratio [10]. In an experimental program in which aspect ratio was the main variable [11], the authors arrived at a similar conclusion for squat walls ($H/L \leq 1$), which is in line with the provisions of some reinforced masonry codes, e.g. [12]. Another study [5] considered numerous test data and confirmed the effect of aspect ratio on the masonry shear strength, however they considered the effect of aspect ratio as an independent term. The shear span ratio *(M/VL)* (instead of the aspect ratio) can be used to take into account different boundary conditions when M/V is considered as effective wall height [11].

Shear-moment interaction

The Peruvian code includes a reduction in the shear strength for slender walls due to shear-moment interaction, based on a numerical study [13]. Other authors have also proposed a similar factor as a part of the masonry shear strength equation [14], but it is applicable only to slender walls. The effect of shear span ratio ($M/VL > 1$) was attributed to shear-moment interaction in reinforced masonry walls [15]. Pérez Gavilán [16] proposed an expression for reducing the shear strength of masonry walls based on the hypothesis that first diagonal cracks initiate at a fixed lateral displacement, irrespective of the type of loading. Pérez Gavilán & Cardel [17] found that the interaction term may be important for squat walls with aspect ratios in the range from 0.5 to 1.0.

The effect of ductility

Several authors had proposed a reduction in the masonry shear strength for reinforced masonry walls based on ductility demand [18, 19]. Reinforced masonry walls are usually designed to achieve desirable flexural failure mechanism, in which a plastic hinge develops at the base of the wall. Widening of the flexural-shear cracks which occurs after a few loading cycles causes a decrease in the capacity for shear transfer by aggregate interlock, and consequently the shear strength reduces. This is acknowledged in the conceptual model for concrete shear strength proposed by the Applied Technology Council [20]. CM walls are usually not designed to fail in flexure, due to their low shear capacity when compared to their flexural strength. Although CM walls may achieve relatively high ductility [21] there are no plastic hinges, hence this concept is not applicable to CM walls failing in shear. However, Riahi, Elwood & Alcocer [22] found a clear inverse relationship between the ductility and peak shear strength.

The axial stress component

The effect of applied axial stress on the behaviour of CM walls in elastic stage can be explained by the theory of elasticity. Once the cracking has been initiated, the axial stress delays the initiation of diagonal cracks and reduces crack widths by improving the force transfer by friction across the cracks by means of aggregate interlock mechanism [23, 24]. Increased axial stress level is also related to a more brittle behaviour. The axial stress contribution can be presented as follows

$$\tau_p = d\sigma_0 \tag{4}$$

Where d is an empirical constant in the range from 0.2 to 0.4 and σ_0 is the applied axial stress acting on the wall. The axial stress component has been found to have a significant effect on the shear strength of masonry walls [5, 19, 22, 25]. According to the New Zealand code [26] axial stress is assumed to be transmitted by means of a compression strut with an inclination (angle) α with regards to the horizontal axis, which depends on the end conditions (cantilever/fixed). The horizontal component of the strut force ($\tan \alpha \cdot \sigma_0$) is taken as the shear resistance of the wall due to the axial stress.

Reinforcement contribution

CM walls may contain horizontal reinforcement, usually in the form of joint reinforcement (JR), which is embedded in mortar bed joints and anchored into the RC tie-columns. The reinforcement contribution to the shear strength may be presented as follows

$$\tau_s = e\rho_h f_{yh} \tag{5}$$

Where e is an empirical constant, ρ_h is the horizontal reinforcement ratio, and f_{yh} is the yield stress. For reinforced masonry walls, c is typically in the range from 0.4 to 0.8 [12, 26, 27]. A few researchers proposed mechanical models for establishing the contribution of reinforcement to shear strength [28, 29], however the model is mostly based on the experimental evidence [30-36]. The equations for calculating shear strength due to horizontal reinforcement are based on the assumption of a single diagonal crack under 45° angle with regards to the horizontal axis [19]. It is considered that the reinforcement is activated once the crack extends across the wall length [32], as confirmed by measured strains in reinforcement during the testing [37]. However, in case of a sliding failure mode JR cannot engage in resisting internal shear forces in a wall. It has been observed that the reinforcement can still enhance the displacement capacity of the wall [38], but does not seem to increase the ductility [21]. It was suggested that the contribution of horizontal reinforcement depends on the masonry compressive strength [30]. The limit for maximum amount of horizontal reinforcement was established, beyond which no further increase in strength could be attained [37].

The effect of RC tie-columns

RC tie-columns are important components of CM walls which influence their in-plane shear strength and displacement capacity. The studies have shown that tie-columns prevent the wall disintegration and provide additional shear capacity in the post-cracking stage [39-41]. Based on a statistical analysis of experimental test data it was concluded that tie-column longitudinal reinforcement has a significant effect on the shear capacity of CM walls [22]. However, a recent review involving a significant amount of test data concluded that the tie-column longitudinal reinforcement does not have a significant effect on the shear capacity of CM walls [5].

IN-PLANE FLEXURAL BEHAVIOUR

Flexural behaviour of CM shear walls is characterized by the horizontal cracking at the base of the wall in the mortar bed joints and a subsequent yielding of the tie-column longitudinal reinforcement in the tension zone. The failure may occur when either concrete or masonry under compression reach their ultimate strain limits or when the tie-column reinforcement reaches the ultimate tensile strain (Figure 2 a). Although flexural behaviour of CM walls has been recognized by several researchers [25, 42, 43], available experimental evidence related to this subject is rather scarce. A literature review of experimental studies on CM walls with flexural behaviour indicated that the masonry compressive strength f'_m is an important factor which influences the chances for the occurrence of flexural failure mechanism [5]. Additional important factors include geometric characteristics, such as the distance between tie-columns, wall aspect ratio (*H/L*), or shear span ratio (*M/VL*). Other aspects include the axial stress level, longitudinal reinforcement ratio, and the presence of horizontal joint reinforcement in masonry walls. The review of previous experimental studies on 29 CM wall specimens with flexure-dominant behaviour revealed that the aspect ratio ranged from 0.95 to 2.3, while the level of axial compression varied from 0 to 0.84 MPa [25, 44-46].

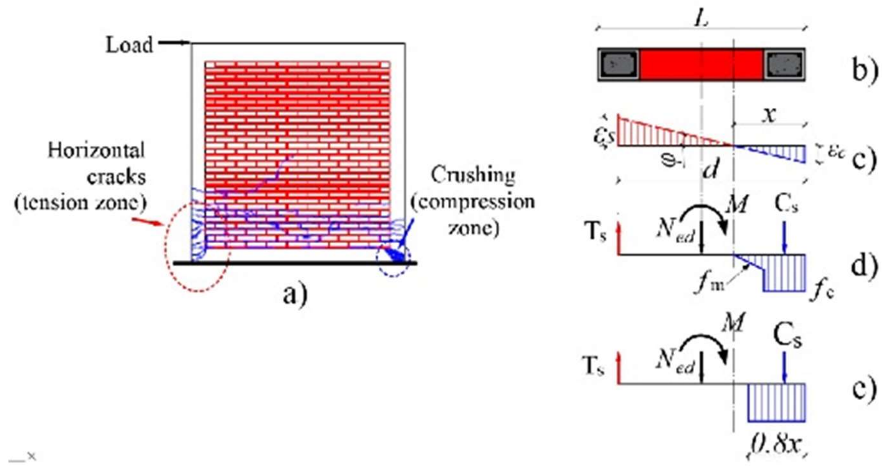

Figure 2: Flexural behaviour of CM shear walls: a) damage pattern [45]; b) typical cross-section; c) strain distribution; d) internal forces and e) equivalent rectangular stress block.

Several design codes follow the approach for estimating the flexural strength of a CM wall from an equilibrium of internal forces acting on a wall section (Figure 2 b, c, and d) [47]. Marques and Lourenco [5] proposed a different equation for estimating flexural strength M_{Rd} in CM walls, which is based on the original proposal by Tomaževič [42], which considers uniform compressive stress in masonry and concrete (equivalent rectangular stress block), as follows (Figure 2 e)

$$M_{Rd} = A_s f_y \left(d - 0.4x\right) + N_{Ed}\left(\frac{L}{2} - 0.4x\right) \tag{6}$$

where A_s is the longitudinal reinforcement area in a RC tie-column, d is the effective depth, x is the length of the compression zone, N_{Ed} is the axial load, and L is the wall length. This equation was proposed for inclusion in the new generation of Eurocode 6 standard for design of masonry structures.

BEHAVIOUR OF CM WALLS UNDER OUT-OF-PLANE (OOP) LATERAL LOADING

Experimental studies showed that OOP failure of CM walls is associated with the formation of bi-directional compression strut mechanism and a rotation of the wall segments [52]. The proposed numerical method builds on a compression strut method for estimating OOP strength of masonry infills in RC frames, which is based on the arching mechanism [55]. The OOP failure mechanism depends on the stiffness of RC confining elements: when the stiffness is large, failure of the CM wall is characterized by masonry crushing (similar to failure mechanism of infilled RC frames), otherwise a snap-through failure mechanism, characterized by large OOP displacements, may be expected. The behaviour of CM walls subjected OOP loading depends on several factors, including the boundary conditions, axial compression level, wall aspect ratio, stiffness of RC confining elements, and the effect of prior in-plane damage. The most critical parameters are discussed next.

Boundary conditions: CM walls subjected to monotonic OOP loading behave similar to two-way slabs with different support conditions. CM panels supported on all sides are common in CM building applications where RC tie-beams are cast integrally with RC floor slabs, while CM panels supported on three sides simulate the behaviour of CM buildings with flexible floor or roof diaphragms. Varela-Rivera et al. [48] studied the OOP behaviour of 6 full-size squat CM wall specimens (aspect ratio of approximately 0.5) which were subjected to increasing monotonic uniform OOP pressure applied via air bags. Although the cracking pattern was initially different for specimens supported on 3 and 4 sides, the magnitude of ultimate pressure was very similar (difference less than 10%). It is important to note that the ultimate pressure was approximately four times higher than the cracking pressure, which indicates a significant capacity reserve in the post-cracking stage.

Wall aspect ratio: majority of past experimental studies on CM walls under OOP loading were focused on squat wall specimens with aspect ratio less than 1.0 [48-50]. An experimental study was performed on OOP behaviour of CM walls with higher aspect ratios (1.4 and 2.0) and axial compression levels [51]. It was observed that, as the aspect ratio increased, the OOP strength increased while the OOP deformation capacity decreased.

The effect of testing method: majority of past experimental studies subjected CM wall specimens to increasing monotonic OOP pressure applied by means of air bags [48-50]. The failure mechanism for specimens supported on 4 sides was similar to that characteristic for the two-way slabs subjected to gravity loading [48]. At the higher loading levels vertical and horizontal displacements developed in the specimens, and the OOP failure was characterized by a two-way arching mechanism. As the wall segments rotated, compressive strut stresses in wall segments increased and eventually reached the masonry compressive strength. The failure was accompanied by masonry crushing. However, a shaking-table testing study on single-storey CM building models [52] showed that CM wall specimens subjected to OOP ground excitation developed horizontal cracks close to the wall to tie-beam interface. It can be concluded that the OOP damage pattern depends on the testing method.

The effect of combined in-plane and OOP loading: An experimental study was performed on 3 scaled CM wall specimens and an infilled RC frame specimen subjected to combined effect of in-plane reversed cyclic loading and OOP dynamic loading through shaking table testing [53]. All CM specimens sustained the maximum in-plane drift of 1.75% and did not experience OOP failure, while RC frame specimen experienced large OOP displacements and was likely to fail due to overturning of the infill. On the contrary, CM wall specimens experienced small OOP displacements, however longitudinal bars in RC tie-columns ultimately fractured due to large in-plane overturning moments.

THE EFFECT OF SIZE AND LOCATION OF OPENINGS IN CM WALLS

The size and location of openings are critical for both in-plane and out-of-plane seismic resistance of CM panels. It is believed that the openings decrease lateral resistance of CM walls and weaken their effectiveness during earthquakes [2, 56]. Shear capacity of a CM wall with openings was found to be proportional to its net area [53]. An analytical study used the Strut-and-Tie Model to simulate the behaviour of CM panels with openings [57]. Horizontal and vertical RC confining elements are critical for increasing the lateral strength of CM walls with openings [43, 58]. Placing confinement on all sides of the opening is by 40% more effective than an alternative provision of a tie-beam at lintel level [59]. Experimental studies have shown that shear resistance and stiffness of walls with openings were preserved when openings were located closest to the end of a wall panel [60]. Design guidelines recommend that larger openings which exceed 10% of the CM panel area should be enclosed by RC tie-columns, otherwise these panels should not be considered as lateral load-resisting elements in seismic design [2]. Smaller openings located outside the critical diagonals can be ignored. Openings should be aligned vertically up the building height.

CONCLUSIONS: FUTURE RESEARCH NEEDS

A review performed in this paper has confirmed substantial research evidence related to seismic behaviour of CM walls, however the authors have identified the following topics of relevance for future research studies:

- In-plane shear: more studies are needed on CM specimens constructed using perforated clay blocks which are widely used in Latin America and Europe; effect of geometry of masonry units on the shear strength (bricks vs blocks, perforated units); a rational mechanical model to understand the shear contribution of horizontal reinforcement; an interaction of in-plane shear and flexure;
- In-plane flexure: more experimental studies are needed to study behaviour of CM walls with different aspect ratios and axial load levels; the effect of horizontal reinforcement on the flexural strength also needs to be studied;
- Out-of-plane behaviour: more dynamic shaking table studies are needed, with the specimens constructed using clay bricks and blocks; the effect of stiffness of confining elements needs to be further studied;
- Walls with openings: more studies on the in-plane and OOP behaviour of walls with openings, considering different size and location of openings; effect of confining elements (size and location) needs to be verified, and
- The effect of combined in-plane and OOP loading on seismic behaviour of CM walls need to be further studied.

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