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Response of thin lightly-reinforced concrete walls under cyclic loading

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ABSTRACT

During the last two decades, thin concrete walls have been frequently used to brace mid- to high-rise buildings in some Latin American countries. This structural system differs significantly in terms of wall geometry and reinforcement layout from traditional cast-in-place reinforced concrete wall buildings. Limited experimental data on this wall system and the absence of post-earthquake field observations make it difficult to assess whether such walls behave similarly to the walls designed according to the current local design code. The paper presents and discusses the results of an experimental program comprising quasi-static cyclic tests of four slender, thin and lightly-reinforced concrete walls with different geometrical configurations, steel properties and reinforcement layouts, which correspond to a common construction practice in Colombia. The seismic response of the specimens was assessed in terms of crack propagation and failure modes, hysteretic and backbone curves, contribution of rocking, flexural, shear and sliding components to lateral drift, stiffness degradation, and energy dissipation capacity. The results suggest that the response of these reinforced concrete walls does not meet the performance specified in the Colombian regulation if they are designed to reach the maximum lateral drift allowed by the code.

1. Introduction

One alternative for industrialized and low-cost housing in Latin America includes concrete wall buildings using slender and thin lightly-reinforced walls which are cast conforming the architectural layout of the residential units. This construction method uses steel or aluminum modular formwork that can be assembled in different configurations. The main advantage of this method is the significant reduction of the construction time as nonstructural divisions or facades are considerably reduced or are not required. This type of buildings has been constructed in low, moderate and high seismicity regions following specifications for reinforced concrete walls defined by the Colombian Code (NSR-10) for Earthquake-Resistant Construction [1]. Provisions for concrete structures in all versions of NSR have been based on a previous version of ACI 318. The current version of the provisions for concrete structures, which updated a previous version issued in 1998, are based on the 2008 version of ACI 318 [2]. Reinforced concrete buildings designed according to the NSR-10 regulation are supposed to have the capability of reaching a maximum lateral drift of 1.43% for the design earthquake with a return period of 475 years, without collapsing and limiting the structural damage.

The walls in the structural system under discussion have several characteristics that introduce significant differences in terms of geometry and reinforcement distribution when compared to the traditional cast-in-place reinforced concrete (RC) wall buildings considered by the ACI 318 provisions. One of the main differences is the use of walls with significantly reduced thickness (t_w) that can be as low as 70 mm with a typical range between 100 and 150 mm [3]. Such reduced thickness can be specified by designers, as the code does not have an explicit minimum value for this parameter for reinforced concrete walls.

Typically, these walls only have a single curtain of web reinforcement which is spliced to started bars of 6.3 mm (#2) or 9.5 mm (#3) diameter which extend from the foundation up to the second third of the first floor height, ensuring the required lap splice length according to the code. This single curtain of reinforcement usually consists of meshes made of cold-drawn electro welded wires, which provide the minimum steel ratio required by the local regulations. To meet the ultimate flexural demand, additional reinforcement made of deformed

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bars are sometimes placed at the wall edges or at connections between walls. Walls with confined boundary elements are scarce or when present, the effectively confined core area is limited or non-effective because of the small available thickness [4]. Due to the architectonic and structural dual purpose of the walls, another key characteristic of this particular system is that walls are usually connected at one or both edges forming I-, T-, C-, L-shaped or any other irregular shaped cross-sections. The wall characteristics and irregularity of wall cross-sections is also typical for other countries in South America like Chile [5] and Peru [6].

Evaluation of buildings from earthquakes in Chile (2011) and New Zealand (2011) indicated that structural damage of concrete walls was associated to high axial loads, low wall area per floor, irregular element configuration and distribution and high slenderness of the walls [7–10]. Even if the buildings affected during these earthquakes have different configurations with respect to the Colombian case, the observed damage indicates that the transverse slenderness of the walls at the critical section, existing in the Colombian buildings, could facilitate out-of-plane instability when subjected to seismic load reversals. Additionally, other aspects of their response associated to specific features of the local design and construction methodology are worth investigating. According to complementary studies carried out by Arteta et al. [3] and Arteta [11], the Colombian thin-wall archetype has low gravity axial loading (axial load ratio below 10%), non-ductile welded-wire meshes (WWM) as longitudinal and transverse reinforcement, and predominantly low longitudinal reinforcement ratio. Additional ductile bars at the edges can be observed in the reinforcement layout of some buildings but boundary elements are absent for most cases.

The laboratory experimental data and post-earthquake field observations of walls with the above characteristics is limited, especially for thin walls with a single curtain of reinforcement and M/VL_w ratios larger than two. A previous test program carried out at EPFL [12,13] addressed the seismic response of one typical wall configuration of Colombian buildings through unidirectional and bidirectional tests on two walls of 80 mm and 120 mm thick. These tests showed that the walls could be prone to out-of-plane buckling and limited displacement capacity, below 0.7% drift ratio. However, during this latter program, only one wall configuration was considered and the longitudinal steel was significantly more ductile than typically used in Colombian construction practice. A more recent program [14,15] focused on uniaxial tension-compression tests on a series of 12 isolated boundary elements with different thicknesses, steel reinforcement ratios, and rebar eccentricities. These tests reported the behavior of specimens representing the boundary elements, but they evidently miss the effect of the entire wall; in particular, as discussed by Rosso et al. [15], the influence of the vertical displacement profiles imposed on wall boundary elements is significantly distinct from the imposed displacement on uniaxial tests. McMenamin [16] carried out tests on several slender precast cantilever walls; however, only two of them had an M/VL_w ratio of 2.5. The height to thickness ratio was 50 and the vertical steel ratios were 1.1% and 0.6%. The former specimen presented reinforcement buckling and concrete spalling failure for a drift below 2% while the latter specimen presented reinforcement fracture failure for a drift below 1%. Both tests did not show a significant out-of-plane response. Carrillo and Alcocer [17] reported on results of quasi-static and dynamic tests of walls with H/L_w ratios varying between 0.5 and 2 and with web shear reinforcement made of a single curtain of welded-wire meshes; however, walls were tested under low axial loads that are characteristic of low-rise housing. Tomazevic et al. [18] evaluated the seismic behavior of ten (10) rectangular reinforced concrete shear-walls with H/Lw ratio of 1.4 and double curtain of wire mesh. They analyzed the influence of different parameters such as the amount and distribution of the steel and the axial load ratio on the seismic response. The amount of horizontal and vertical reinforcement varied from 0.26% and 0.38% and two axial load ratio were considered (0.07 and 0.14 $f_c'A_g$). Six unconfined specimens were tested. The specimens with unconfined boundary elements and low axial load ratio reached a maximum lateral drift of 1.0% and presented a rupture of extreme tensioned vertical reinforcement, which generated a severe strength degradation.

Although these references provide information about performance and failure modes of the tested walls, the main characteristics of these specimens have significant differences to the walls of interest in this study including axial load ratios, reinforcing steel ratios, steel mechanical properties, transverse section geometry and steel distribution among others. The lack of experimental and numerical information for the specific type of walls of interest, hinders the possibility of verifying if the available design guidelines are directly applicable to system described above, as these guidelines have been defined based on information from walls with significantly different geometrical characteristics and reinforcement arrangements [19–21,7].

This paper shows and discusses the results of an experimental program comprising quasi-static cyclic tests of four slender and lightly-reinforced concrete thin walls with different geometrical configurations, reinforcement mechanical properties and distribution, which are representative of the type of buildings described above. The seismic response of the specimens was assessed in terms of crack propagation and failure modes, hysteretic curves, contribution of rocking, flexural, shear and sliding components to lateral drift, stiffness degradation, and energy dissipation capacity.

2. Experimental program

The experimental program comprised the tests of four reinforced concrete (RC) walls with characteristics similar to the construction practice of buildings with thin and slender RC walls with single curtain of web reinforcement. The specimens were tested under pseudo-static reversed-cyclic loading in the Structural Mechanics Lab at the EIA University in Colombia. The test setup includes a combination of axial load, shear force and flexural moment gradient that can be considered as representative of the seismic force distribution in walls within a real building designed according to the current practice in seismic regions in Colombia.

2.1. Variables of interest and specimen definition

The main characteristics of the wall specimens were defined based on the statistical analysis of a database that comprised 28 RC thin-walled buildings constructed in Colombia [3]. The buildings analyzed vary between 5 and 18 stories, with wall area densities in the longitudinal (D_l) and transverse (D_s) directions between 1.5 and 6%, with an average of 3.6% and a coefficient of variation of 0.27. The length of flanged walls carrying most of the base shear is in the range $2 \leq L_w \leq 8$ m, with a typical length of 4.5 m. The clear height of each story is 2.4 m, with almost no variation from one structure to another. The expected gravity axial load on the walls vary between 2 and 11% of $A_g f'_c$, where A_g is the gross area of the cross-section, and f'_c is the nominal concrete strength at ground floor. All walls have distributed steel in the web and the flange. Excluding the wall edges, longitudinal steel ratio of distributed steel in the web (ρ_w) varies between $0.2\% \leq \rho_w \leq 0.7\%$, with a typical value of 0.25% (minimum code requirement). The analysis of the database also included representative values of the thickness of flanged walls, shear span ratio, steel reinforcement ratio, number of reinforcement curtains, as well as estimations of neutral axis depth from basic section analysis. Such analysis resulted in the definition of the specimen with the characteristics shown in Table 1.

Geometry, steel layout and type of steel reinforcement were defined as the key variables to evaluate in the experimental program. Regarding the geometry, specimens W4, W5 and W6 were conceived to characterize full scale T-shaped walls with a thickness of 100 mm, length of 2.5 m and clear inter-story height (H_w) of 2.4 m (see Fig. 1). These three walls were named sequentially following a previous experimental