Engineering Structures 157 (2018) 268–279

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effect of reinforcement anchorage end detail and spacing on seismic performance of masonry shear walls

Hany M. Seif ElDin, Khaled Galal*

Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Québec, Canada

A R T I C L E I N F O

Keywords:
Reinforced masonry
Shear walls
Cyclic loading
Seismic reinforcement
Anchorage end detail

A B S T R A C T

The most recent design codes for masonry structures necessitate the use of reinforced masonry (RM) shear walls in medium and high seismic areas. In addition, they provide requirements for the seismic reinforcement for walls. This paper investigates the in-plane seismic performance of fully grouted RM shear walls dominated by shear-flexural failure. The experimental work involved assessing the response of five single-story RM shear walls when subjected to in-plane axial compressive stress and cyclic lateral excitations. The studied parameters were the horizontal reinforcement anchorage end detail and the spacing of the horizontal and vertical reinforcement. Three anchorage end detail were evaluated in this study; 180° standard hook, 90° hook, and straight. Two vertical spacing of the horizontal reinforcement, 400 mm and 800 mm, and two horizontal spacing of the vertical reinforcement, 200 mm and 800 mm, were considered in the test matrix. Based on the test results, the 180° standard hook was the most efficient in terms of strength and ductility with a slight difference in the strength and 15% higher ductility than using the straight end detail. On the contrary, the spacing of the reinforcement had a significant effect on the behavior of tested walls. Walls that were constructed with closely spaced reinforcement were able to reach 15% and 80% higher strength and ductility than similar walls with large spacing when using the same reinforcement ratio. Hence, the current values for the maximum spacing of reinforcement in the Canadian Standards Association CSA S304-14 for the design of masonry structures need to be modified by specifying lower spacing limits.

1. Introduction

The poor performance of unreinforced masonry buildings during post-earthquake reconnaissance has led to the development of reinforced masonry (RM) systems. Similar to reinforced concrete buildings, RM shear walls are the key structural elements widely used to resist lateral loads in masonry buildings due to their capability to provide lateral strength, stiffness, and energy dissipation. Most of the design equations for in-plane shear strength, V_n, neglect the effect of the spacing of the vertical and horizontal reinforcement and also, the anchorage end detail of the horizontal reinforcement [1]; instead, they consider the reinforcement ratios. However, to account for these effects, the recent masonry design codes provide some provisions for seismic reinforcement.

Many experimental studies have been conducted to investigate the effect of several parameters on the seismic performance of RM shear walls [2–9]. Some of these experimental works studied the influence of the spacing of reinforcement on the seismic performance of RM shear walls and their test results concluded that the spacing of reinforcement has a considerable impact on their strength and ductility. Voon and Ingham [8] tested ten reinforced masonry walls under cyclic horizontal loading to evaluate their in-plane shear resistance. Out of these walls, two walls were constructed with approximately the same horizontal reinforcement ratio, ρ_h (0.05% and 0.06%), but with different distribution. First RM wall was constructed with 5 × R6 (ρ_h = 0.05%) horizontal bars while the second wall had 2 × D10 (ρ_h = 0.06%). Their test results showed that the wall with small spacing exhibited a more gradual strength degradation than the one with larger spacing. Similar experimental investigation was carried out by Shing et al. [9] and reported similar observation. Furthermore, there are few studies that have considered the effect of the horizontal reinforcement anchorage end detail on the in-plane shear behavior of RM walls, one of which is the experimental work conducted by [10] in which 90° bent, 180° hook, and end plate anchorages were investigated. Based on their results, for the walls with heavy lateral reinforcement, the end plate was the most effective anchorage end detail, whereas the 90° bent was the least effective. However, where the horizontal reinforcement was light, both the 180° hook and the end plate were more effective than the 90° bent

* Corresponding author.
E-mail address: khaled.galal@concordia.ca (K. Galal).

https://doi.org/10.1016/j.engstruct.2017.11.073
Received 11 March 2017; Received in revised form 9 November 2017; Accepted 30 November 2017

and showed similar performance. Still, it is important to mention that all three types of anchorage end details enhanced the pre-diagonal crack behavior of the RM walls that were dominated by shear failure in terms of strength and ductility. Although these studies highlighted the effect of the distribution and the anchorage end detail of the horizontal reinforcement on the in-plane behavior of RM shear walls, there is a need for more experimental studies that quantify these effects.

This paper aims to quantify experimentally the effect of the horizontal reinforcement anchorage end detail and the spacing of reinforcement on the in-plane seismic performance of fully grouted RM shear walls dominated by shear-flexural failure. The test results discusses the shear resistance shares provided by horizontal reinforcement, V_s, and masonry and axial compressive stress, V_{m+p}; the crack pattern; the stiffness degradation; and energy dissipation. Moreover, a brief discussion on the requirements for seismic reinforcement according to the Canadian standard CSA S304-14 [11] is presented, followed by recommendations for the upcoming edition.

2. Experimental work

2.1. Test matrix

The experimental work assesses the response of five full-scale fully grouted rectangular RM shear walls when subjected to in-plane axial compressive stress and cyclic lateral excitations. The main variables considered were the horizontal reinforcement anchorage end detail, the spacing of horizontal reinforcement, and the spacing of vertical reinforcement. Table 1 summarizes the reinforcement details of the tested walls, in addition to the theoretical lateral forces corresponding to the in-plane shear, flexural and sliding capacities according to the Canadian Standards CSA S304-14 [11]. As shown in this table, all the walls should have theoretically the same failure load. All the tested reinforced masonry walls had the same dimensions, 1.8 m × 1.6 m × 0.19 m, and were constructed with a constant horizontal reinforcement ratio of 0.13%. Each wall was constructed on a reinforced concrete (RC) foundation with dimensions of 2.3 m × 0.64 m × 0.45 m (see Fig. 1). The walls were subjected to cyclic lateral excitations at a height of 1.80 m from the top of the RC foundation in order to keep the shear span to depth ratio higher than 1.0 and were tested under a constant axial compressive stress of 1.0 MPa.

All the loads were transferred to the tested walls through a stiff built-up steel loading beam. The vertical reinforcement of the RM walls was anchored to the bottom flange of the loading beam. The first wall, W-Ref, was designed to be a reference wall for the remaining tested walls. Wall W-Ref had uniformly distributed horizontal reinforcing bars, 10 M@400 mm, with a standard 180° hook around the outermost vertical bars. The anchorage end detail of the horizontal reinforcement for walls W-90° and W-Str were 90° hook and straight bar, respectively. The standard 180° hook and 90° hook were detailed according to CSA S304-14 [11], where the hook tail length is bigger than $4d_b$ (45 mm) and $12d_b$ (135 mm) for the 180° hook and 90° hook, respectively, as shown in Fig. 2.

Table 1
Test matrix of five RM shear walls.

Wall ID	Reinforcement		Studied parameter			Theoretical capacities according to CSA S304-14		
	Vertical	Horizontal	Horizontal reinf. end detail	S_v[a]	S_h[a]	F_{Vn}[b]	F_{Mn}[c]	F_{Sn}[d]
			–	mm	mm	kN	kN	kN
W-Ref	20 M@200	10 M@400	180° hook	400	200	269	541	1469
W-90°	20 M@200	10 M@400	90° hook	400	200	269	541	1469
W-Str	20 M@200	10 M@400	Straight	400	200	269	541	1469
W-S_v800	20 M@200	15 M@800	180° hook	800	200	269	541	1469
W-S_h800	30 M@800	15 M@800	180° hook	800	800	269	462	1211

[a] S_v and S_h are the vertical and horizontal spacing of reinforcing, respectively, as shown in Fig. 1.
[b] Theoretical in-plane shear capacity assuming moderately ductile shear walls (R_d = 2.0).
[c] Theoretical lateral force corresponding to the flexural capacity assuming plane sections assumption.
[d] Theoretical lateral force corresponding to the sliding capacity.

The impact of the horizontal reinforcement anchorage end detail on the seismic response of RM shear walls was assessed based on the test results of walls W-Ref, W-90°, and W-Str. Unlike wall W-Ref, wall W-S_v800 was constructed with horizontal reinforcement of 15 M@ 800 mm, in order to study the effect of vertical spacing between horizontal bars when using the same horizontal reinforcement ratio. Wall W-S_h800 is a duplicate of wall W-S_v800, except that the vertical reinforcement was concentrated in the first, middle, and end cells. Each cell has a 30 M bar with a total vertical reinforcement ratio, ρ_v, of 0.61% compared to ρ_v of 0.79% for the rest of the tested walls. However, this slight difference in ρ_v can be neglected since most of the existing equations for predicting the nominal in-plane shear strength, V_n, including the design equations given in the Canadian standard CSA S304-14 [11] and the Masonry Standards Joint Committee MSJC-2013 [12], do not consider the contribution of the vertical reinforcement.

2.2. Properties of materials

All the tested walls and the required auxiliary specimens were designed in accordance with the Canadian Standards CSA S304-14 [11] and CSA A179-14 [13] and were constructed by certified masons using full-scale lightweight knock-out concrete masonry units (CMUs) with nominal dimensions of 390 mm × 190 mm × 190 mm. Before the construction of the tested walls, the knockout webs were removed to accommodate the horizontal reinforcement and to provide grouting continuity in the vertical and horizontal directions, consequently, preventing any weakness planes between the concrete masonry units (see Fig. 3). The blocks were joined together with 10 mm type S mortar joints and laid in a running bond pattern, then, all the cells were fully grouted using coarse grout that was mixed in the laboratory. The nominal compressive strength of the block, mortar, and grout were measured experimentally and the average values were found to be 16.7 (c.o.v. = 4.8%), 13.7 (c.o.v. = 7.8%), and 29.4 MPa (c.o.v. = 7.3%), respectively. Masonry prisms were built at the completion of laying each wall in order to measure the masonry compressive strength for the tested walls. Four concrete masonry units (CMUs) were stacked on top of each other using the same construction materials that were used to build the walls. The average masonry compressive strength was found to be 13.1 MPa (c.o.v. = 7.6%). The average experimental measured yield strength of the steel reinforcement was 430 MPa (c.o.v. = 3.2%).

2.3. Test setup

The RM walls were tested under in-plane vertical and lateral loads using three MTS hydraulic actuators as shown in Fig. 4. Two actuators were installed vertically to apply the axial compression force and the horizontal actuator was used to introduce cyclic horizontal displacements to simulate the seismic loads. The applied loads were transferred to the tested walls through a stiff built-up steel-loading beam that was restrained to any out-of-plane displacement using two out-of-plane steel back-to-back angles that connected the loading steel beam (through slotted holes) to a strong RC wall. To provide a fixed boundary condition at the base of the tested walls, each wall was constructed on a reinforced concrete (RC) foundation that was connected to a strong floor using a reusable RC footing with a depth of 600 mm.

2.4. Instrumentation and testing protocol

Two different types of instruments were used to measure the strains