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A SURVEY ON MASONRY LATERAL FORCE RESISTING SYSTEMS: CODES VS. RESEARCH PERSPECTIVE

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ABSTRACT

Post earthquake reconnaissance showed that reinforced masonry structures are able to behave inelastically with a ductile behaviour during a strong ground motion, which enables the structure to dissipate high energy. Simple solid cantilever masonry shear walls, perforated shear walls, and coupled shear walls are examples of the seismic force resisting systems (SFRS) used in reinforced masonry structures. In addition to their loadbearing function, these systems are used to provide the required lateral stiffness and strength for resisting the lateral loads arising from wind or earthquakes. The aim of this paper is to provide a state-of-the-art survey on the experimental and analytical research conducted on different SFRS for masonry structures addressing important issues that should be considered in the analysis and design of reinforced masonry walls.

KEYWORDS: concrete masonry, shear walls, seismic, failure modes, ductility, state-of-the-art.

INTRODUCTION

During past earthquake events, unreinforced masonry walls showed a poor seismic performance accompanied with very limited ductility [1]. On the other hand, the results of many experimental studies showed that reinforced masonry could provide adequate safety against seismic loads when properly proportioned, detailed, and constructed [2]. Therefore, the design codes recently permitted the construction of unreinforced masonry walls only for structures located in low seismic zones, while for medium and high seismicity, reinforced masonry shear wall system should be used to resist the seismic loads.

Masonry walls are expected to resist the lateral loads acting in the direction of the wall plane, in addition to their gravity loadbearing function. They are also required to resist out-of-plane bending due to wind loads, seismic earth pressures in case of masonry retaining walls, or the inertial response of walls to transverse seismic acceleration [3]. The expected ductility capacity of these masonry walls is an important issue that would control the magnitude of the seismic force to be used in their design. The higher ductility level that can be reached by the wall would result in a lower design seismic forces, and hence a more economic design. Considering the ductility capacity of RM walls, the behaviour of walls under the in-plane loading is different from their behaviour under the out-of-plane loading. Reinforced masonry walls are expected to have a high ductility capacity under in-plane loading which would enable the wall to dissipate high energy during an earthquake. This can be attributed to the high wall effective depth in the load direction which enables the wall reinforcement to reach high strain values beyond the yield strain before the masonry reaches its ultimate compressive strength, and this would lead to a high ductility level for the wall especially for flanged and confined walls. On the other hand, in case of out-of-plane loading, the small wall effective depth in the out-of-plane direction (usually half the wall thickness) theoretically would not allow the reinforcement to experience as much deformability as the case of in-plane loading.

The aim of this paper is to provide a state-of-the-art survey on the experimental and analytical research conducted on reinforced masonry (RM) shear walls addressing the different modes of failure observed for RM shear walls. The paper also summarizes the factors that affect the behaviour of RM shear walls that should be considered in their analysis and design.

DIFFERENT MASONRY SEISMIC FORCE RESISTING SYSTEMS (SFRSs)

Solid cantilever shear walls

Masonry buildings are mainly composed of shear walls that are provided in two orthogonal directions to act against the gravity loads and lateral loads due to wind or seismic action. These walls could be reinforced or unreinforced, fully grouted or partially grouted, and with or without boundary elements. In order to minimize the moment transfer between such walls when two walls or more exist in the same plane, they are connected by flexible floor slabs rather than by stiff beams. Also the wall openings should not be large so that the behaviour of the cantilever wall is not altered [4]. Solid cantilever shear wall system is considered as the simplest and most efficient seismic force resisting system used for masonry construction. Hence, a remarkable amount of experimental work has been done to study their performance under monotonic and cyclic excitations. The conducted research on RM cantilever shear walls showed that this system can behave inelastically with a ductile behaviour during a strong ground motion which would enable the structure to dissipate high energy, provided that proper design and reinforcement detailing are ensured.

Moment-resisting frames and coupled walls (perforated walls)

Masonry walls constructed with large openings can be considered either as moment resisting frames that are composed of piers and spandrels or as coupled walls. Generally, the seismic behaviour of moment resisting frames and coupled wall is more complicated than the behaviour of solid cantilever walls. For the analysis of perforated walls, the wall can be analyzed using the strut and tie model or analyzed as a frame that is designed for both shear forces and bending moments [5].

There are two possible failure mechanisms for the perforated walls; the first is when the wall piers are weaker than the spandrels, which is usually the case for unreinforced masonry buildings [6]. In this case, in order to have high ductility for the structural system, the piers should be designed to have a very high displacement ductility which was found to be extremely difficult to obtain [7]. Therefore, this structural system is only suitable if very low displacement ductility of the structure is required, which means that the structure should be designed to behave fully elastic [3]. The second failure mechanism is when the wall spandrels are weaker than the piers (occurs usually when the dimensions of the wall piers are relatively large). In this case, the system can be approximated as coupled wall, and the coupling beams (spandrels) should be designed to resist the acting shear forces to be transmitted by the coupling action, also the coupling beams should be properly detailed to ensure a sufficient level of ductility for the wall system. According to the Canadian Standards [8], the piers and spandrels must satisfy the minimum and maximum detailing requirements, and their factored flexure and shear capacities must exceed or be equal to the acting factored load.

MODES OF FAILURE FOR REINFORCED MASONRY (RM) WALLS

There are many parameters that control the failure mode for a specific masonry wall, such as the geometry of the wall (wall aspect ratio), the amount and distribution of reinforcement, the boundary conditions of the wall, the axial load carried by the wall, and the quality of construction. For unreinforced masonry walls, there are several brittle modes of failure that are not common for reinforced masonry construction, such as sliding failure at the bed joint and the rocking failure (loss of anchorage of reinforcement). For reinforced masonry shear walls, the two common failure modes that were reported from the experimental research work are the flexural failure and the shear failure.

Flexural failure

In this mode of failure, considerable bed joint cracks appear near the bottom part of the tensile zone of the wall, yielding of vertical reinforcement, and crushing of masonry in the compression zones could occur at the ultimate stages (plastic hinge formation). The outermost vertical reinforcing bars also might buckle if spalling of the outer shell and grout occurred. The flexural failure is the preferred mode of failure due to the ductility achieved by yielding of the vertical reinforcement and the formation of the plastic hinge. Therefore, the wall dimensions and reinforcement should be designed so that this type of ductile failure is assured in order to dissipate the earthquake energy efficiently. Figure 1 shows a reinforced masonry wall that failed in a flexural manner [9].

Shear failure

This mode of failure occurs usually for shear walls with low aspect ratio or walls with inadequate shear capacity. This type of failure is characterized by the diagonal shear cracks that form due to the principal tensile stresses, and hence the shear force acting on the wall is resisted by the compression struts formed between the cracks and the tension in the horizontal reinforcement. The shear failure might be due to yielding of horizontal reinforcement or crushing of masonry compression struts. The shear failure is brittle in nature and is usually accompanied by rapid strength degradation once the wall peak strength is reached. This would reduce the energy dissipated by the wall/structure when subjected to a severe ground motion. Therefore, the proper seismic design should avoid such mode of failure by applying the capacity design principle [10], which requires that the shear strength of the wall exceeds the lateral load required to develop the wall flexural hinge. Figure 2 shows the shear failure of the reinforced masonry wall tested by Shing et al. [11].

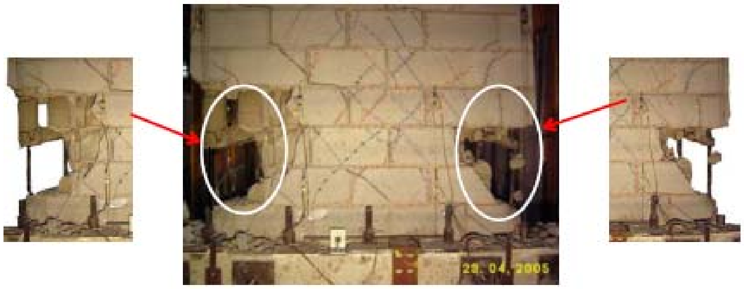

Figure 1: Flexural failure of RM wall [9]

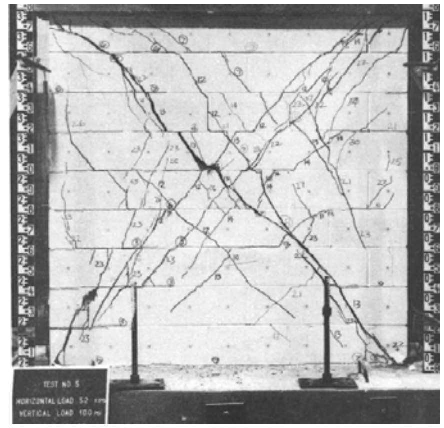

Figure 2: Shear failure of RM wall

FLEXURAL STRENGTH OF RM WALLS

The flexural strength of a reinforced masonry shear wall can be estimated using the simple flexure theory with reasonable accuracy and conservatism [12]. The theory assumes that the plane sections remain plane after deformations. This requires the knowledge of the compressive stress-strain curve for masonry which can be estimated from the equations given by previous researchers (e.g. [13]) based on the experimental value of the masonry compressive strength f_m'. The flexural capacity of a RM wall can be calculated using either the fiber model or using the assumption of the equivalent rectangular stress-block. In the fiber model, the wall member is discretized longitudinally into a finite number of elements, the stress-strain relationships for masonry elements and steel elements are defined, equilibrium is applied and the moment-curvature relationship of the member can be calculated at each axial load level. Shing et al. [14] concluded that the simple flexure formulas (based on the rectangular stress-block assumption and considering the steel strain hardening) are able to predict the flexural capacity effectively in case of relatively high axial load level (higher than 0.689 MPa). The flexural strength of RM shear walls increases with the higher axial load level applied on the wall and the amount of vertical reinforcement [11]. Priestley [15] found that the distribution of the vertical reinforcement has a slight effect on the flexural capacity for the typically low reinforcement percentage and the axial load level that is commonly expected for masonry buildings. Therefore, it is recommended that the flexural reinforcement be uniformly distributed along the wall length [3].

SHEAR STRENGTH OF RM WALLS

The shear strength of a RM wall is calculated as the sum of the residual strength of masonry (V_m), the contribution of the compressive axial load (V_p), and the resistance of the horizontal reinforcement (V_s). The residual strength of masonry is provided by several mechanisms, such as the compression shear transfer, the aggregate interlock forces, the dowel action of the vertical reinforcement which is affected by the amount of vertical reinforcement and the level of axial compressive stress acting on the wall. V_s is proportional to the amount of horizontal reinforcement, but it should not exceed an upper limit corresponding to the web crushing. Voon and Ingham [16] summarized some of the design expressions for the shear strength of RM shear walls that were derived based on experimental results. The presented equations included the equations given by Shing et al. [14], Matsumura [17], Anderson and Priestley [18], National Earthquake Hazards Reduction Program [19], New Zealand masonry design standard [20].

Sucuoglu and McNiven [2] stated that in case of high axial loads and low aspect ratios, the shear strength of the RM walls is affected mainly by the anchorage of horizontal reinforcement to the grout and the diagonal compressive strength of masonry, more than the effect of the amount of horizontal reinforcement.

DUCTILITY OF RM WALLS

The ductility capacity of a shear wall is an important measure for its ability to deform well inelastically and hence dissipate the earthquake energy efficiently, which indicate a better seismic performance during a severe ground motion. This requires a special attention to the detailing of reinforcement at the expected plastic hinge region at the wall base, and also checking that the wall's flexural capacity would be higher than its shear capacity. Based on the ductility level expected for a RM shear wall, a reduction in the design linear seismic force could be done to account for the wall nonlinear behaviour. In the Canadian Standards [8], a RM wall can be designed to have a limited ductility or moderate ductility with a force reduction factor of 1.5 and 2.0, respectively. It can be noticed by comparing the previous research done on RM and reinforced concrete (RC) walls that the properly detailed RM shear walls fails in a flexural manner can reach high levels of displacement ductility similar to RC walls. Despite this fact, the Canadian Standards [8] still does not consider the RM walls to be ductile compared to the RC shear walls. On the other hand, the design value for the ultimate ductility factor μ_u proposed by the Eurocode 8 [21] is ranged between 4 and 5 for the RM shear walls, which indicates that a high ductility level can be reached for the properly designed RM walls.

Sucuoglu and McNiven [2] found that the post-cracking deformation capacity was improved by increasing the amount of horizontal reinforcement to a certain limit. After exceeding this limit, the horizontal reinforcement does not reach the yield and hence reduce the post-cracking deformation capacity. Voon and Ingham [22] showed that the ductility of RM shear walls improved by increasing the amount of horizontal reinforcement. For the effect of distribution of shear reinforcement, they concluded that using shear reinforcement with small diameter and greater number would lead to a more gradual post-peak strength degradation, which would enhance the wall performance. It was found also that fully grouted wall construction is not a condition for the wall to reach a reasonable ductility level. A partially grouted reinforced wall can reach a sufficient ductility enables the wall to resist low to medium earthquake intensities, and this will lead to an economic deign of the wall [4].

Shedid et al. [23] studied the effect of adding flanges or boundary elements to the end zones of RM shear walls on the ductility of masonry walls. They found that adding such elements would lead to a significant enhancement in the wall ductility and to lower strength degradation. Such elements will also provide out-of-plane stability for the end of the wall and delay the buckling of vertical reinforcement.

SLIDING SHEAR RESISTANCE OF RM WALLS

Sucuoglu and McNiven [2] reported that the sliding shear failure for RM shear walls occurred when a high amount of horizontal reinforcement is used. In this case, the wall will not be able to deform well due to the inability of the horizontal reinforcement to yield. This will lead to the crushing of masonry at the toes, extending of a continuous horizontal crack near the wall base, and finally the sliding of the wall web with respect to its foundation. The Canadian Standard [8] calculates the sliding shear resistance for RM shear walls based on the level of axial load applied on the wall, the amount of vertical reinforcement, and the nature of the surface between the masonry units and the footing (roughened or smooth surface). For adequate design of a RM wall, the sliding shear failure should be avoided by ensuring that the sliding shear resistance would exceed the shear force corresponding to the flexural capacity.

EFFECT OF LEVEL OF AXIAL LOAD

The axial load carried by a RM wall is an important parameter that affects its seismic behaviour. Although the higher axial load can be beneficial in increasing the wall flexure and shear capacities, high levels of axial load can change the wall failure mode from mixed flexural/shear mode to the brittle shear failure, which indicates that the axial load has a more significant effect on the flexural strength than on the shear strength [11]. This can be attributed to the fact that high axial loads will result in earlier diagonal web crushing, less deformability, and hence a more brittle failure as shown in Figure 3 [2]. This will decrease the post-cracking deformation capacity of the wall, which reduce the wall ductility and decrease its energy dissipation capacity. The higher axial load also increases the wall yield displacement, as well as the load that causes the first crack [9, 22]. The sliding shear resistance of the wall also increases with the higher axial load level as the friction at the critical section will increase.

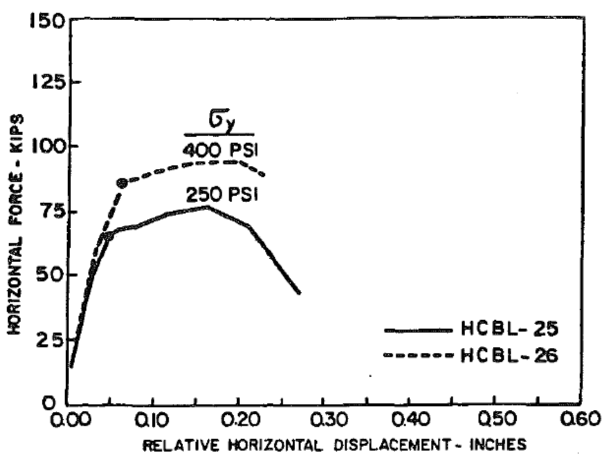

Figure 3: Effect of axial load level [2]

EFFECT OF GROUT CONFINEMENT

The grouted masonry compressive strength f_m' is the main parameter that affects the wall mechanical properties. The grouted masonry subjected to axial compressive load usually fails due to the lateral expansion of the grout against the masonry shell, which leads to a failure load lower than the sum of the individual masonry and grout capacities [24]. Priestley and Elder [13] used thin confining steel plates that are placed within the mortar bed to confine the grout. Dhanasekar and Shrive [24] inserted cages of fine wire mesh (FWM) or welded wire mesh (WWM) inside the masonry cells. They found that the compressive strength of the FWM and the WWM confined masonry improved by 29 and 38%, respectively. Priestley and Elder [13] found that the grout confinement resulted in a more gradual degradation of the masonry strength which would lead to a better seismic performance of the RM walls.

SUMMARY
A concise survey on the different seismic force resisting systems used for reinforced masonry (RM) structures was conducted. The paper included the common modes of failure for RM walls that were reported by previous researchers, and the factors affecting the type of failure of a wall. The paper also summarized the different parameters that affect the seismic behaviour of RM shear walls and their influence on the design criteria.

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